Visualization of Time-Varying Power System Information

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Overview

- Power system operations are generating more data than ever
  - In operations thousands of PMUs are now deployed
  - In planning many thousand of studies are now routinely run, with a single transient stability run creating millions of data values
- How data is transformed into actionable information is a crucial, yet often unemphasized, part of the software design process
- Presentation addresses some issues associated with dealing with this data

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 (like adding up the flows into a bus)

The Information Visualization Process

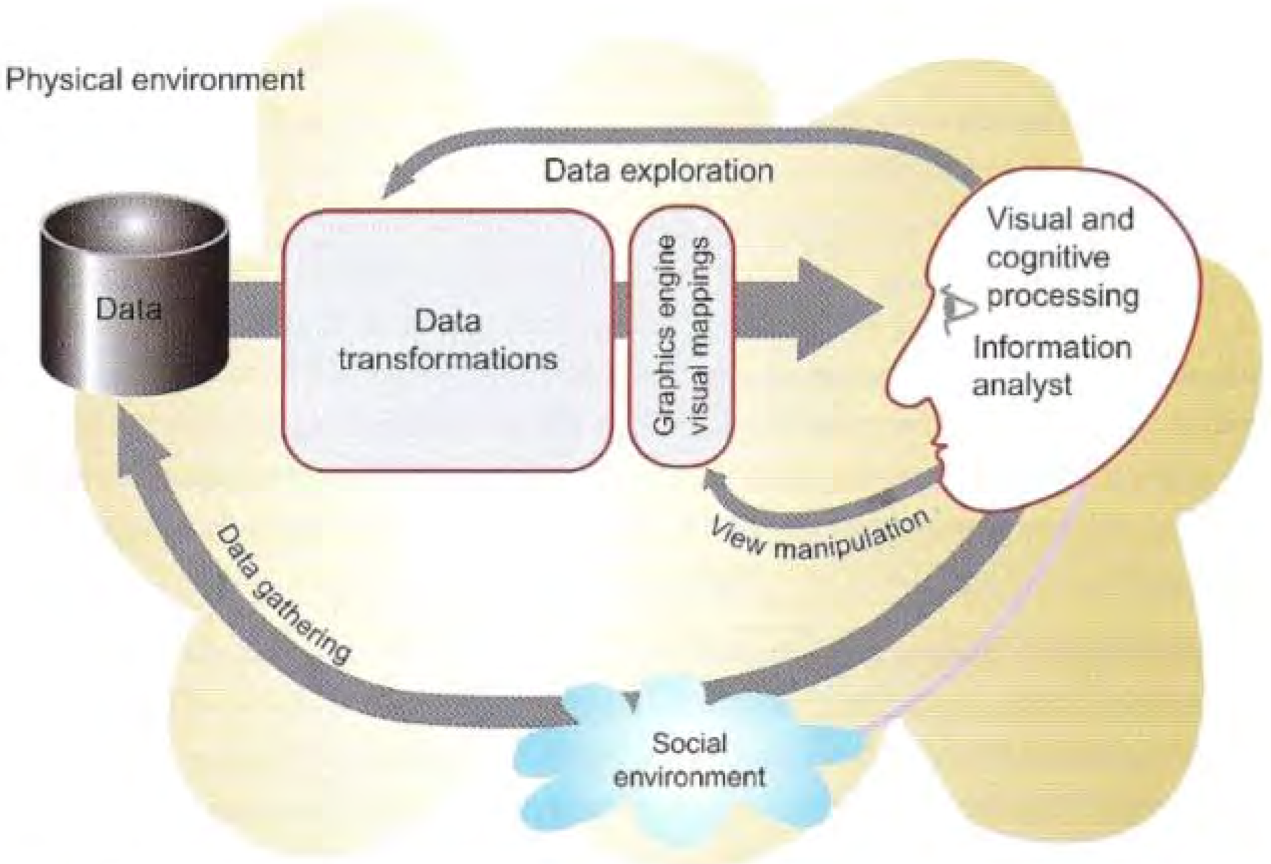


Figure 1.2 The visualization process.

Image source: Colin Ware, *Information Visualization*, Third Edition, 2013

Power System Visualization History: Time Varying Information

When computers were first used in system dispatch centers, they augmented the traditional analog systems. These systems were referred to as digital-directed analog control computers. As the digital computer became more reliable, it assumed full control.

PSE&G Control Center in 1988

Utility Control Room, 1960's

Left Source: W. Stagg, M. Adibi, M. Laughton, J.E. Van Ness, A.J. Wood, "Thirty Years of Power Industry Computer Applications," IEEE Computer Applications in Power, April 1994, pp. 43-49

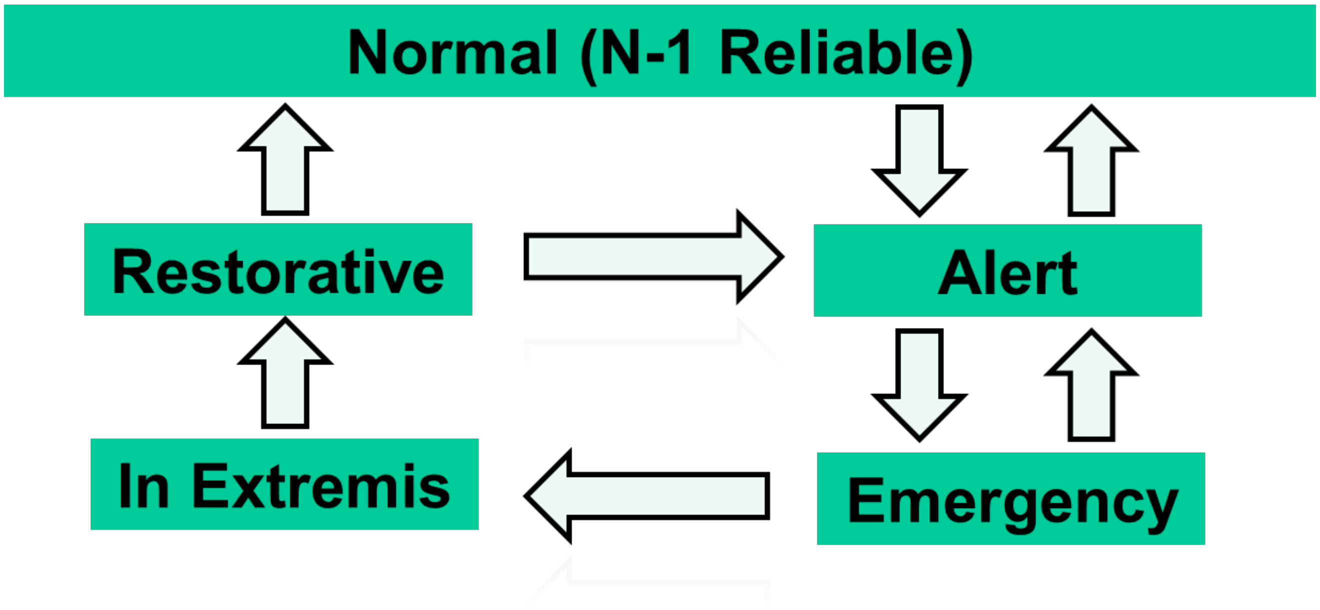
Right Source: J.N. Wrubel, R. Hoffman, "The New Energy Management System at PSE&G," IEEE Computer Applications in Power, July 1988, pp. 12-15.

2010's: PJM Control Center: Electronic Strip-Charts

Image Source: http://tdworld.com/site-files/tdworld.com/files/imagecache/large_img/uploads/2013/07/pjmcontrolroom117.jpg

Power System Operating States

- Effective visualization for operations requires considering the different operating states



- Effective visualization is most needed for the more rare situations

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

Blackouts and Operator Intervention

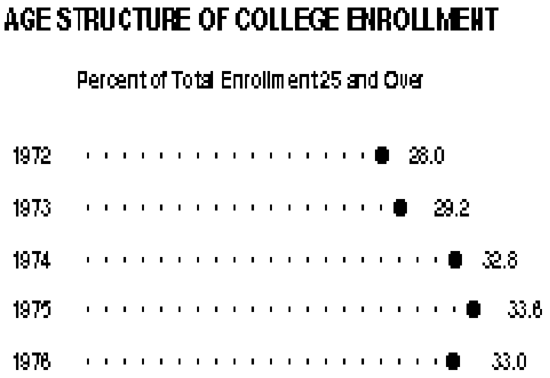
- Many large-scale blackouts have time scales of several minutes to a few dozen minutes
  - this time scale allows for operator intervention, but it must occur quickly to be effective (extreme emergency control)
- Operators can’t respond effectively if they do not know what is going on– they need “situational awareness”

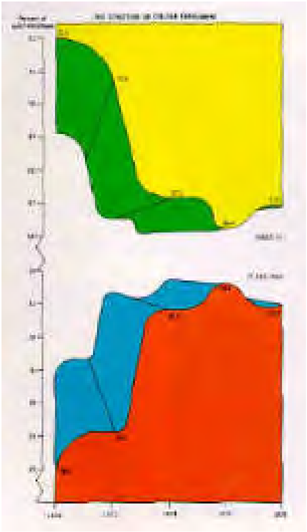
Extreme Emergency Control

- How the control room environment might be different during such an event
  - advanced network analysis applications could be unavailable or overwhelmed
  - system state could be quite different, with unfamiliar flows and voltages
  - lots of alarms and phone calls
  - high level of stress for control room participants with many tasks requiring their attention
  - large number of decision makers might be present
- Designing software for extreme conditions is challenging since conditions seldom encountered

A Visualization Caution!

- 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





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

Human Factor Testing Caution

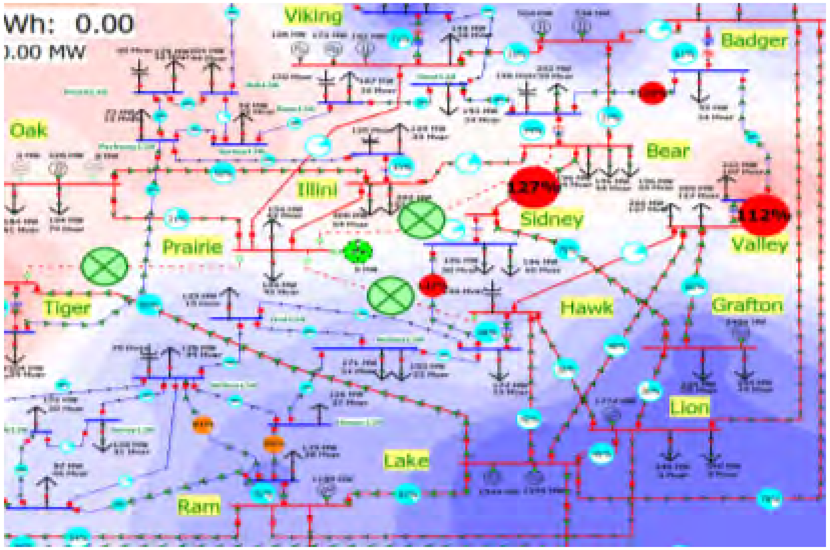
- There is actually very little in the human factors literature with regard to power system visualizations.
- Doing formal human factors assessments and experiments is quite time consuming, and ultimately of somewhat limited value in determining the usefulness of visualizations in a control center setting
- We need to develop a community of power system engineers and human factor experts!

Access to Cases and Data: Need for Synthetic Models

- Working with actual cases and data preferred
- However, getting access to power system cases and data has been getting more difficult
  - I'm personally thankful for the many cases we've received under NDAs; recently the issue of FISMA compliance has been raised
- Even when cases/data is available, publishing results can be an issue
- Need for synthetic cases, particularly for dynamics
- University of Illinois is developing public domain cases

Illini 42 Bus Case

- It is a 345/138 kV fictitious case with dynamics
- This case will be used here to demonstrate some of the techniques presented here
- The case, which contains an interactive transient stability level blackout scenario, and a movie, can be downloaded at

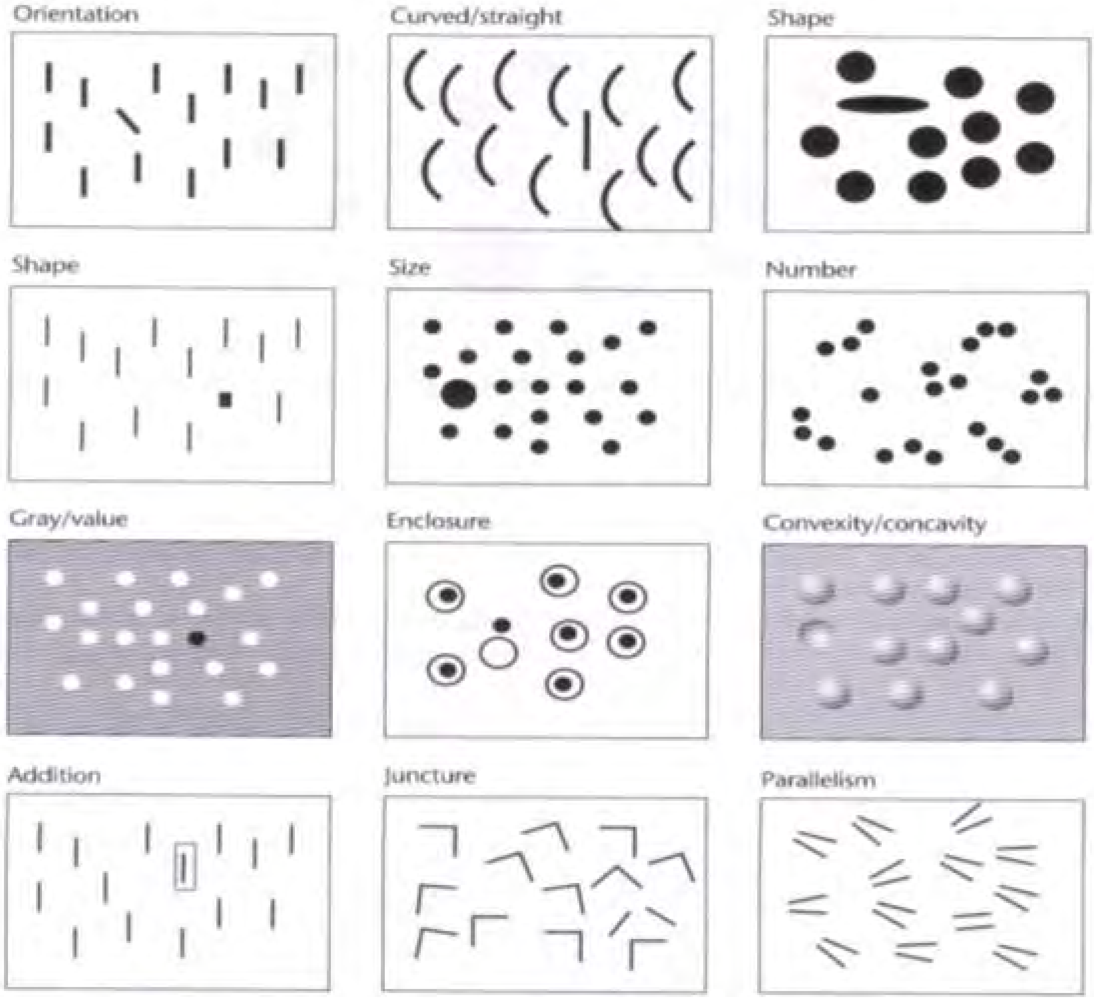


http://publish.illinois.edu/smartergrid/Power-Dynamics-Scenarios/

Visualization Background: Preattentive Processing

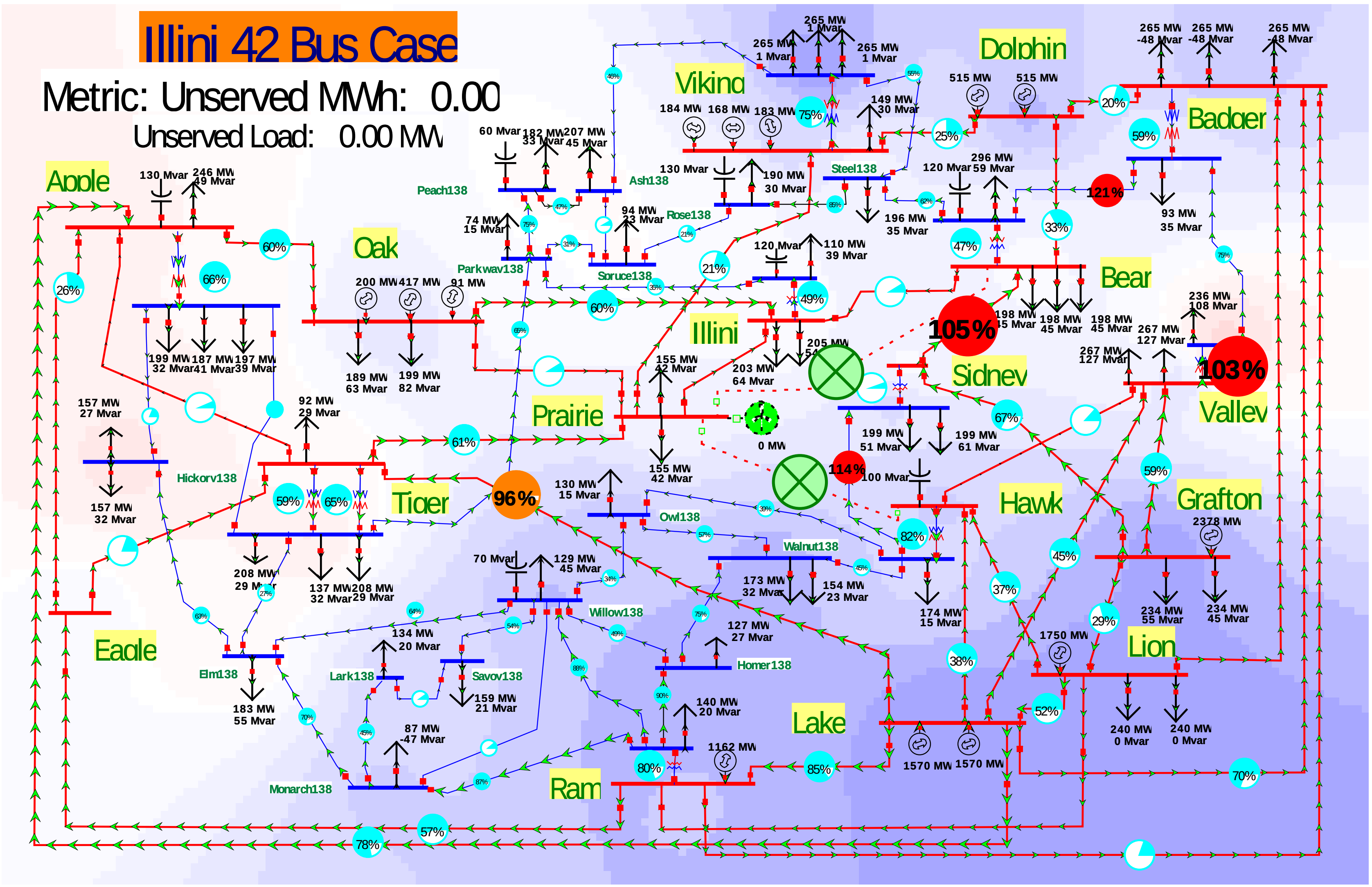
- Good reference book: Colin Ware, *Information Visualization: Perception for Design*, Third Edition, 2013
- When displaying large amounts of data, take advantage of preattentive cognitive processing
  - With preattentive processing the time spent to find a “target” is independent of the number of distractors
- Graphical features that are preattentively processed include the general categories of form, color, motion, spatial position

All are Preattentively Processed Except Juncture and Parallelism



Source: *Information Visualization* by Colin Ware, Fig 5.5

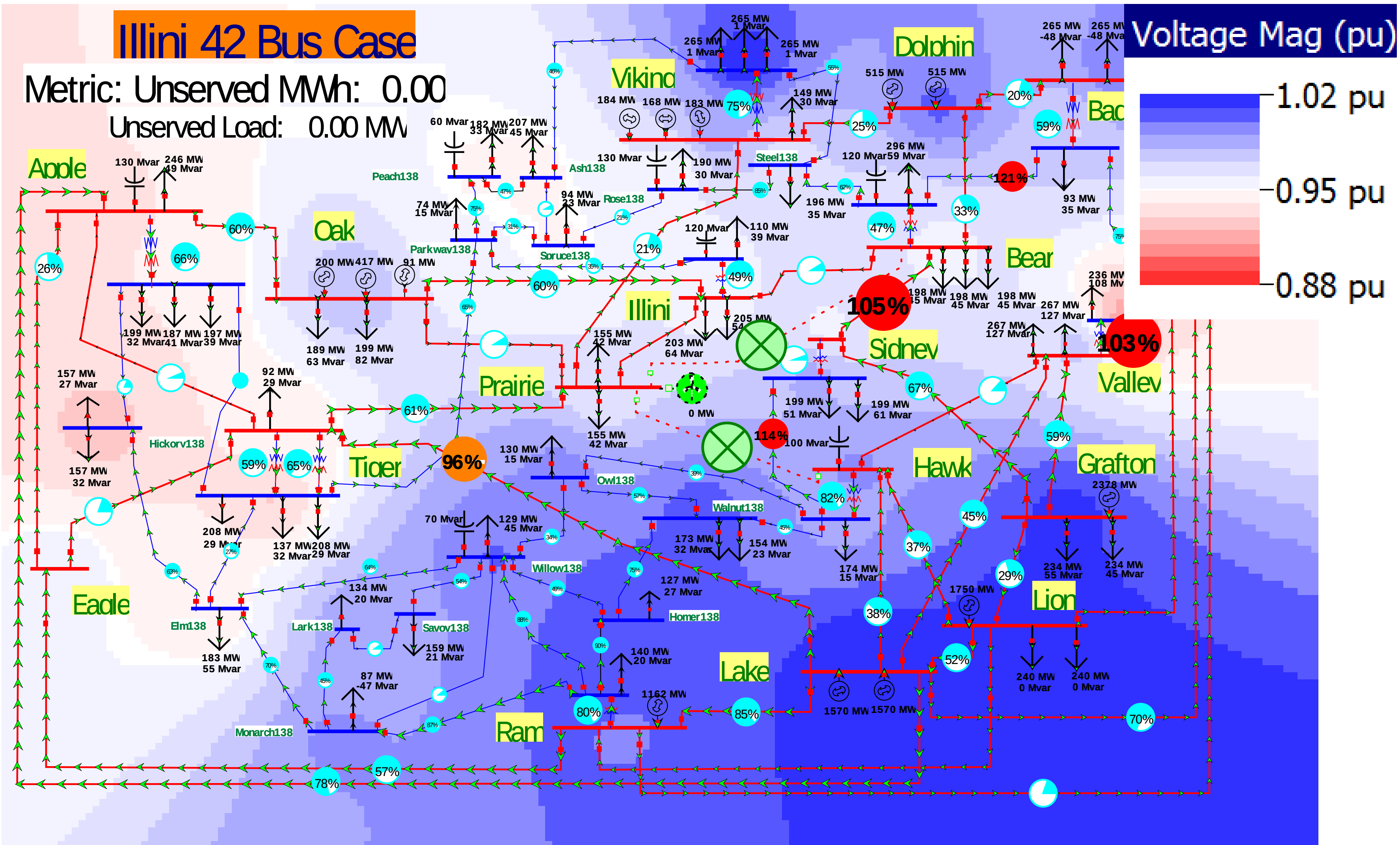
Preattentive Processing with Color and Size



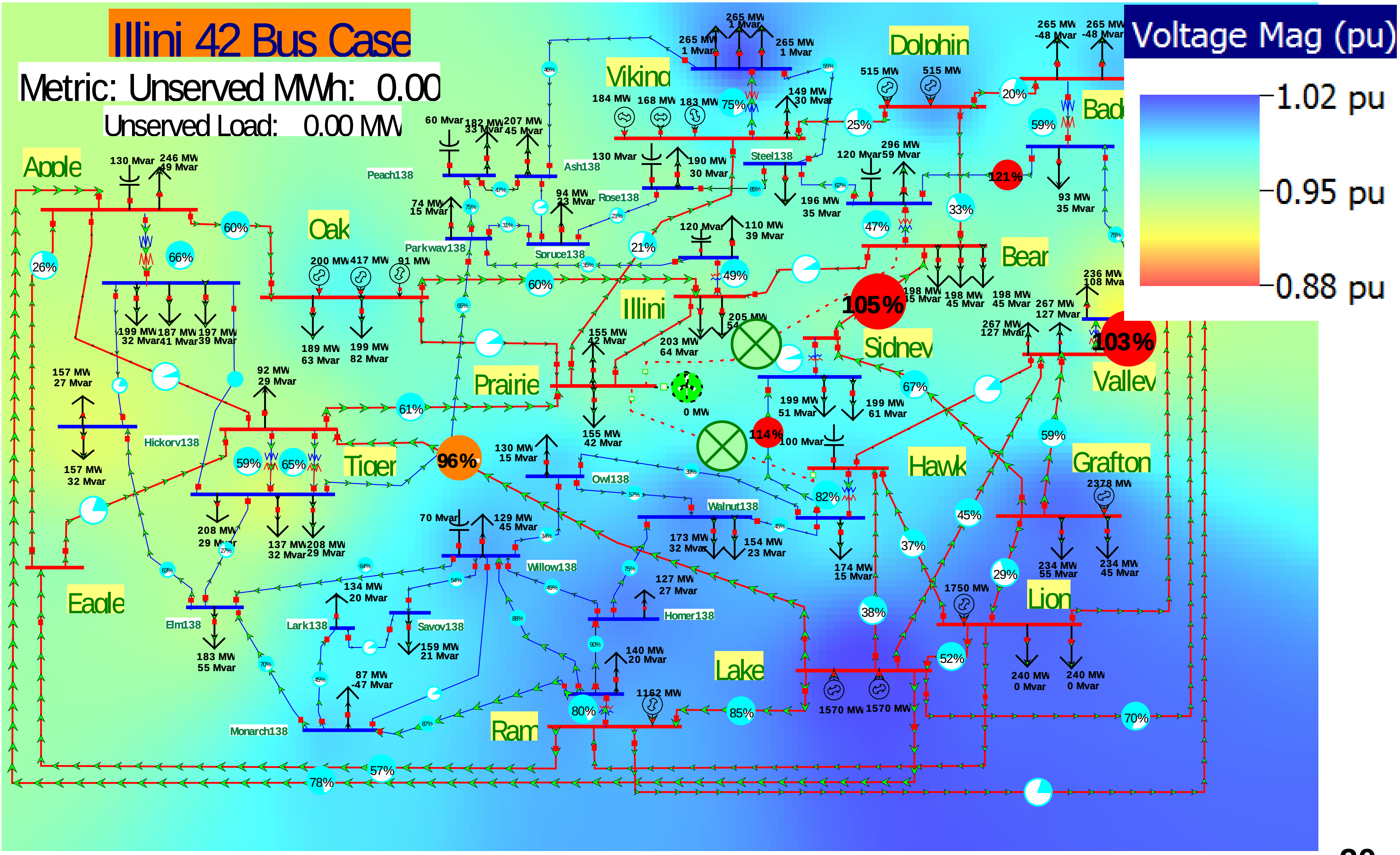
Use of Color

- 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 forms
  - Multi-color scales (like a spectrum) have advantages (more steps) but also disadvantages (effectively comparing values) compared to bi-color sequences

Color Sequence Example: Blue/Red, Discrete



Color Sequence Example: Spectrum, Continuous



Visual Working Memory and Change Blindness

- The visual working memory (what we retain about images) is limited to a small number of simple objects or patterns, perhaps 3 to 5.
- Because we remember so little, it is possible to make large changes to displays and people will generally not notice unless they are fixated upon it.
- Fast animation (without flicker) can help reduce this.

Change Blindness Example: With Flicker Hard to Detect

Source: http://nivea.psycho.univ-paris5.fr/ECS/ECS-CB.html

Large Changes can be Hard to Detect with Local Disruptions

Source: http://nivea.psycho.univ-paris5.fr/ECS/ECS-CB.html

Change Blindness Comments

- Change blindness is most likely under high task load conditions with improbable events
- Less likely to occur when change is more salient (turning on a light is better than turning it off; changing “on” to “off” is not very salient).
- Changes in main field of vision easiest to detect
- Experts in domain are less likely to experience change blindness

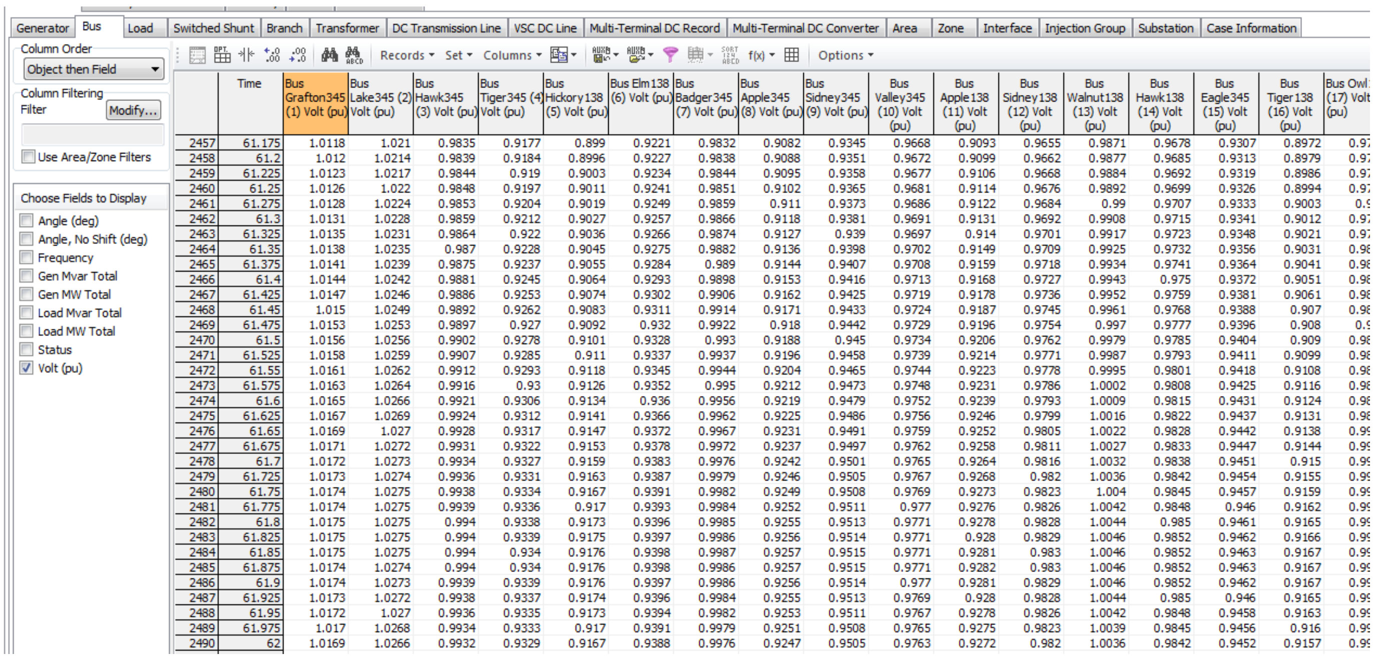
Reference: Wickens, Hollands, Banbury, Parasuraman, *Engineering Psychology and Human Performance*, 4th Edition, 2013

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!

Tabular Displays

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

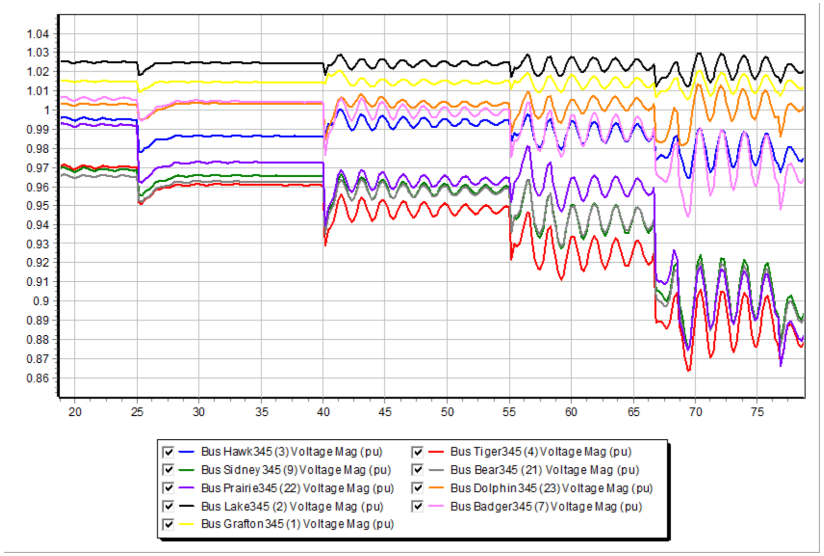


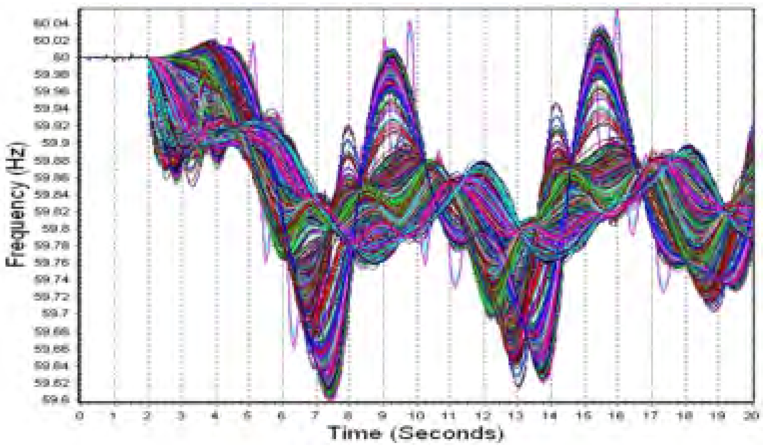
	Time	Bus Grafton345 (1) Volt (pu)	Bus Lake345 (2) Volt (pu)	Bus Hawk345 (3) Volt (pu)	Bus Tiger345 (4) Volt (pu)	Bus Hickory138 (5) Volt (pu)	Bus Elm138 (6) Volt (pu)	Bus Badger345 (7) Volt (pu)	Bus Apple345 (8) Volt (pu)	Bus Sidney345 (9) Volt (pu)	Bus Valley345 (10) Volt (pu)	Bus Apple138 (11) Volt (pu)	Bus Sidney138 (12) Volt (pu)	Bus Walnut138 (13) Volt (pu)	Bus Hawk138 (14) Volt (pu)	Bus Eagle345 (15) Volt (pu)	Bus Tiger138 (16) Volt (pu)	Bus Owl (17) Volt (pu)
2457	61.175	1.0118	1.021	0.9835	0.9177	0.899	0.9221	0.9832	0.9082	0.9345	0.9668	0.9093	0.9655	0.9871	0.9678	0.9307	0.8972	0.97
2458	61.2	1.012	1.0214	0.9839	0.9184	0.8996	0.9227	0.9838	0.9088	0.9351	0.9672	0.9099	0.9662	0.9877	0.9685	0.9313	0.8979	0.97
2459	61.225	1.0123	1.0217	0.9844	0.919	0.9003	0.9234	0.9844	0.9095	0.9358	0.9677	0.9106	0.9668	0.9884	0.9692	0.9319	0.8986	0.97
2460	61.25	1.0126	1.022	0.9848	0.9197	0.9011	0.9241	0.9851	0.9102	0.9365	0.9681	0.9114	0.9676	0.9892	0.9699	0.9326	0.8994	0.97
2461	61.275	1.0128	1.0224	0.9853	0.9204	0.9019	0.9249	0.9859	0.911	0.9373	0.9686	0.9122	0.9684	0.99	0.9707	0.9333	0.9003	0.9
2462	61.3	1.0131	1.0228	0.9859	0.9212	0.9027	0.9257	0.9866	0.9118	0.9381	0.9691	0.9131	0.9692	0.9908	0.9715	0.9341	0.9012	0.97
2463	61.325	1.0135	1.0231	0.9864	0.922	0.9036	0.9266	0.9874	0.9127	0.939	0.9697	0.914	0.9701	0.9917	0.9723	0.9348	0.9021	0.97
2464	61.35	1.0138	1.0235	0.987	0.9228	0.9045	0.9275	0.9882	0.9136	0.9398	0.9702	0.9149	0.9709	0.9925	0.9732	0.9356	0.9031	0.98
2465	61.375	1.0141	1.0239	0.9875	0.9237	0.9055	0.9284	0.989	0.9144	0.9407	0.9708	0.9159	0.9718	0.9934	0.9741	0.9364	0.9041	0.98
2466	61.4	1.0144	1.0242	0.9881	0.9245	0.9064	0.9293	0.9898	0.9153	0.9416	0.9713	0.9168	0.9727	0.9943	0.975	0.9372	0.9051	0.98
2467	61.425	1.0147	1.0246	0.9886	0.9253	0.9074	0.9302	0.9906	0.9162	0.9425	0.9719	0.9178	0.9736	0.9952	0.9759	0.9381	0.9061	0.98
2468	61.45	1.015	1.0249	0.9892	0.9262	0.9083	0.9311	0.9914	0.9171	0.9433	0.9724	0.9187	0.9745	0.9961	0.9768	0.9388	0.907	0.98
2469	61.475	1.0153	1.0253	0.9897	0.927	0.9092	0.932	0.9922	0.918	0.9442	0.9729	0.9196	0.9754	0.997	0.9777	0.9396	0.908	0.9
2470	61.5	1.0156	1.0256	0.9902	0.9278	0.9101	0.9328	0.993	0.9188	0.945	0.9734	0.9206	0.9762	0.9979	0.9785	0.9404	0.909	0.98
2471	61.525	1.0158	1.0259	0.9907	0.9285	0.911	0.9337	0.9937	0.9196	0.9458	0.9739	0.9214	0.9771	0.9987	0.9793	0.9411	0.9099	0.98
2472	61.55	1.0161	1.0262	0.9912	0.9293	0.9118	0.9345	0.9944	0.9204	0.9465	0.9744	0.9223	0.9778	0.9995	0.9801	0.9418	0.9108	0.98
2473	61.575	1.0163	1.0264	0.9916	0.93	0.9126	0.9352	0.995	0.9212	0.9473	0.9748	0.9231	0.9786	1.0002	0.9808	0.9425	0.9116	0.98
2474	61.6	1.0165	1.0266	0.9921	0.9306	0.9134	0.936	0.9956	0.9219	0.9479	0.9752	0.9239	0.9793	1.0009	0.9815	0.9431	0.9124	0.98
2475	61.625	1.0167	1.0269	0.9924	0.9312	0.9141	0.9366	0.9962	0.9225	0.9486	0.9756	0.9246	0.9799	1.0016	0.9822	0.9437	0.9131	0.98
2476	61.65	1.0169	1.027	0.9928	0.9317	0.9147	0.9372	0.9967	0.9231	0.9491	0.9759	0.9252	0.9805	1.0022	0.9828	0.9442	0.9138	0.99
2477	61.675	1.0171	1.0272	0.9931	0.9322	0.9153	0.9378	0.9972	0.9237	0.9497	0.9762	0.9258	0.9811	1.0027	0.9833	0.9447	0.9144	0.99
2478	61.7	1.0172	1.0273	0.9934	0.9327	0.9159	0.9383	0.9976	0.9242	0.9501	0.9765	0.9264	0.9816	1.0032	0.9838	0.9451	0.915	0.99
2479	61.725	1.0173	1.0274	0.9936	0.9331	0.9163	0.9387	0.9979	0.9246	0.9505	0.9767	0.9268	0.982	1.0036	0.9842	0.9454	0.9155	0.99
2480	61.75	1.0174	1.0275	0.9938	0.9334	0.9167	0.9391	0.9982	0.9249	0.9508	0.9769	0.9273	0.9823	1.004	0.9845	0.9457	0.9159	0.99
2481	61.775	1.0174	1.0275	0.9939	0.9336	0.917	0.9393	0.9984	0.9252	0.9511	0.977	0.9276	0.9826	1.0042	0.9848	0.946	0.9162	0.99
2482	61.8	1.0175	1.0275	0.994	0.9338	0.9173	0.9396	0.9985	0.9255	0.9513	0.9771	0.9278	0.9828	1.0044	0.985	0.9461	0.9165	0.99
2483	61.825	1.0175	1.0275	0.994	0.9339	0.9175	0.9397	0.9986	0.9256	0.9514	0.9771	0.928	0.9829	1.0046	0.9852	0.9462	0.9166	0.99
2484	61.85	1.0175	1.0275	0.994	0.934	0.9176	0.9398	0.9987	0.9257	0.9515	0.9771	0.9281	0.983	1.0046	0.9852	0.9463	0.9167	0.99
2485	61.875	1.0174	1.0274	0.994	0.934	0.9176	0.9398	0.9986	0.9257	0.9515	0.9771	0.9282	0.983	1.0046	0.9852	0.9463	0.9167	0.99
2486	61.9	1.0174	1.0273	0.9939	0.9339	0.9176	0.9397	0.9986	0.9256	0.9514	0.977	0.9281	0.9829	1.0046	0.9852	0.9462	0.9167	0.99
2487	61.925	1.0173	1.0272	0.9938	0.9337	0.9174	0.9396	0.9984	0.9255	0.9513	0.9769	0.928	0.9828	1.0044	0.985	0.946	0.9165	0.99
2488	61.95	1.0172	1.027	0.9936	0.9335	0.9173	0.9394	0.9982	0.9253	0.9511	0.9767	0.9278	0.9826	1.0042	0.9848	0.9458	0.9163	0.99
2489	61.975	1.017	1.0268	0.9934	0.9333	0.917	0.9391	0.9979	0.9251	0.9508	0.9765	0.9275	0.9823	1.0039	0.9845	0.9456	0.916	0.99
2490	62	1.0169	1.0266	0.9932	0.9329	0.9167	0.9388	0.9976	0.9247	0.9505	0.9763	0.9272	0.982	1.0036	0.9842	0.9452	0.9157	0.99

The information access cost for the task at hand is key!

Time-based graphs

- Graphs can be quite helpful for showing exact values if no more than about ten individual signals are shown
  - In larger sets outliers may be missed
- Showing more values can be helpful in identifying response envelope
  - Graph at left shows 2400 signals



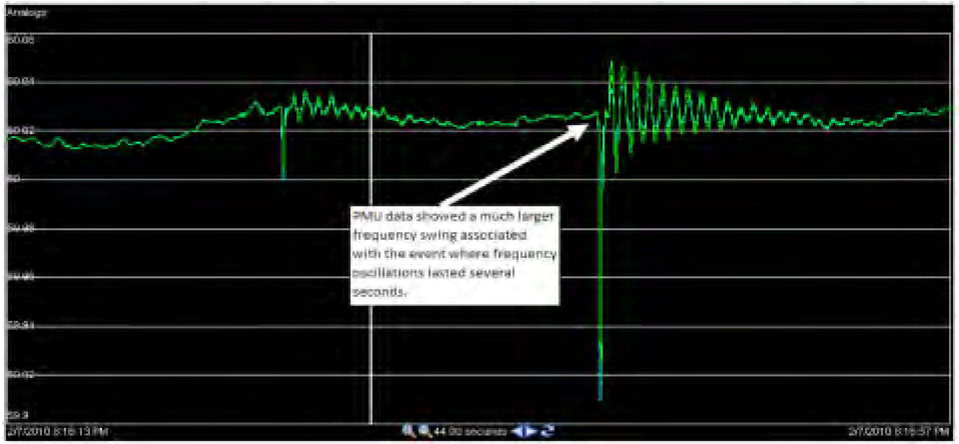


Animation loops

- 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 Loops: SCADA vs. PMUs

- A potential visualization change is how much future displays are visualized at PMU rates (30 times per second) versus SCADA rates (every 4-12 seconds)

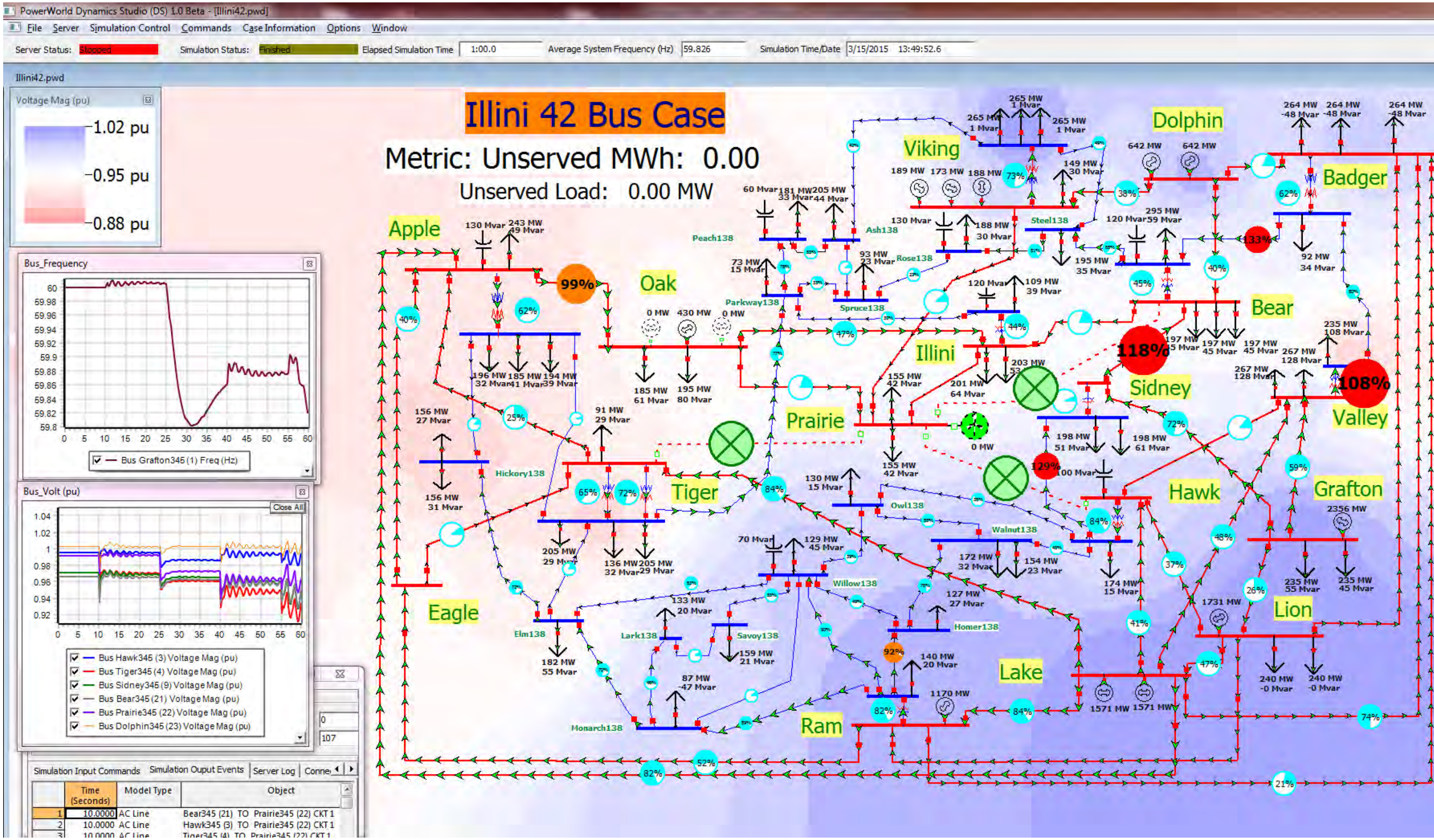


Animation Loop Example

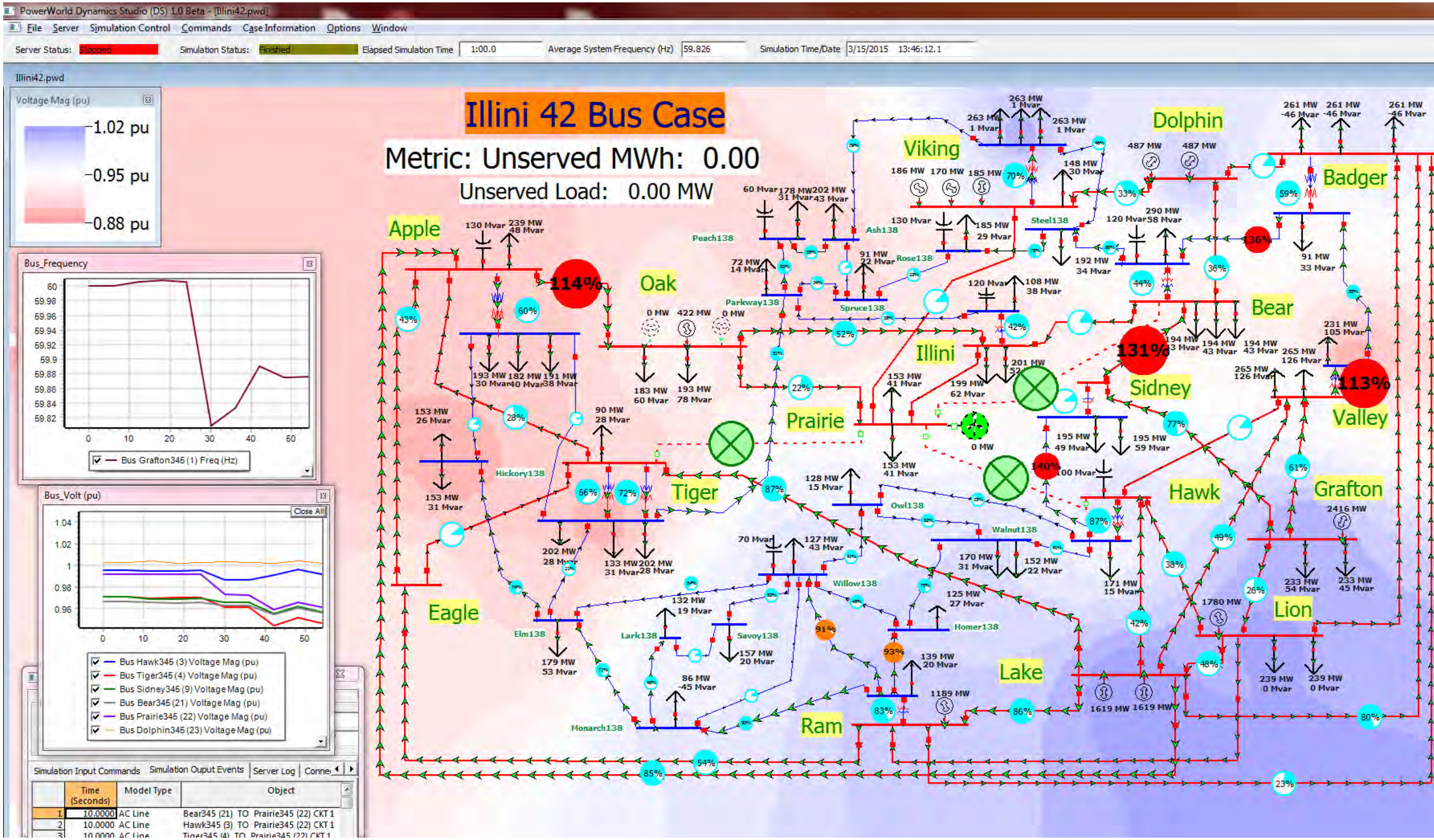
- Below link provides an interactive 42 bus, 345/138 kV, transient stability level fictitious case in which you can try to prevent a tornado from blacking-out the system
  - Two examples compare a simulation in which the display is refreshed at 5 times per second versus once every 6 seconds
  - Without intervention the case has a system-wide blackout in about 90 seconds

Case (Illini 42 Bus Tornado) and movie available at http://publish.illinois.edu/smartergrid/Power-Dynamics-Scenarios

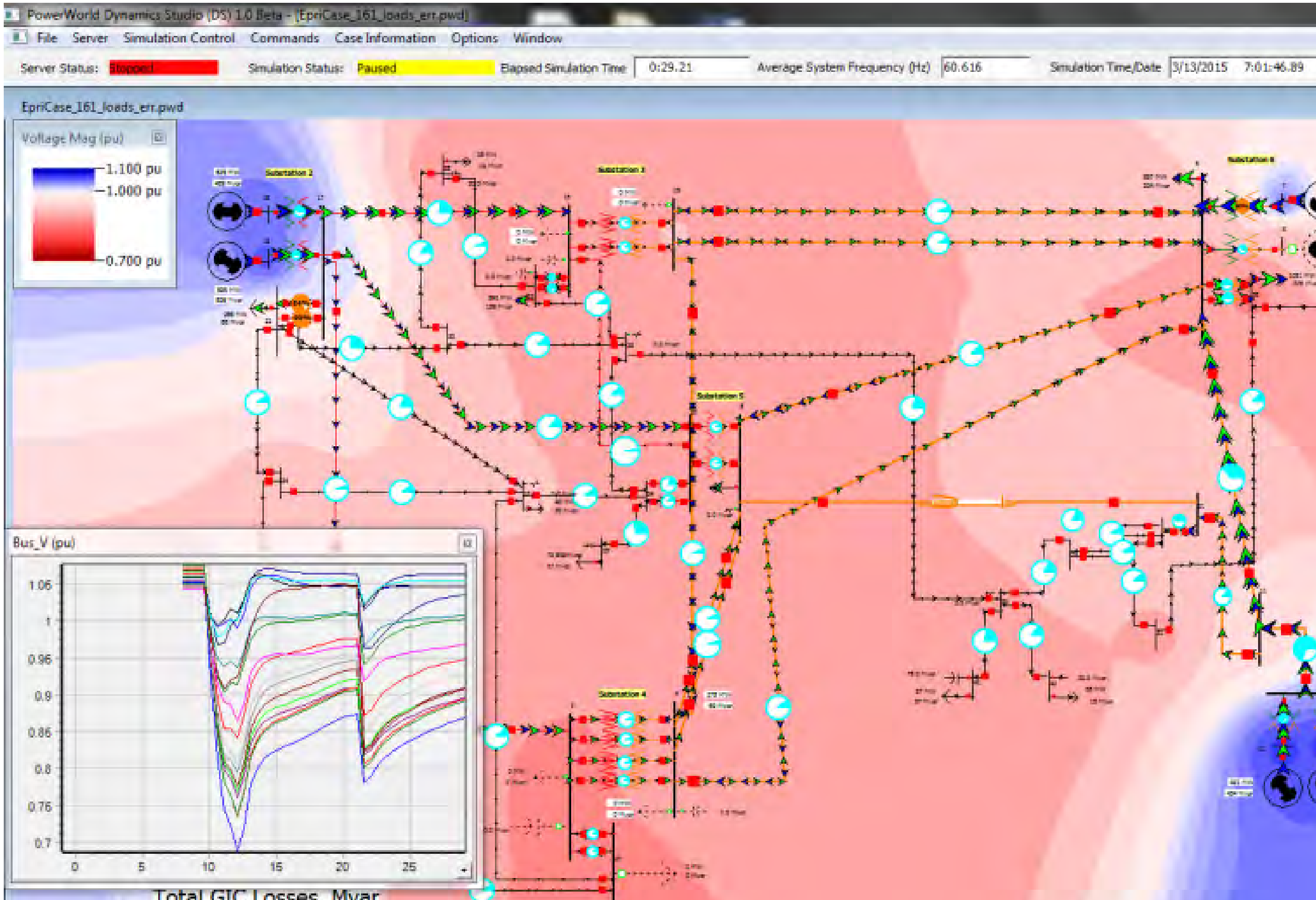
42 Bus Illini Tornado Case: Fast Refresh Rate



42 Bus Illini Tornado Case: SCADA Refresh Rate



Black Sky Animation Loop: High Altitude Electromagnetic Pulse (HEMP)



EMP E3 is similar to GMD, except with a rise time of seconds, and hence can be studied with transient stability

Case and movie available at http://publish.illinois.edu/smartergrid/Power-Dynamics-Scenarios

Data Analysis Algorithms

- Usually there is too much data to make sense of without some type of analysis
- Several terms are used to denote the idea of discovering insight from data:
  - Statistics, data mining,
    knowledge discovery,
    data analytics, machine learning
    big data
- Large field, so will just present a few examples

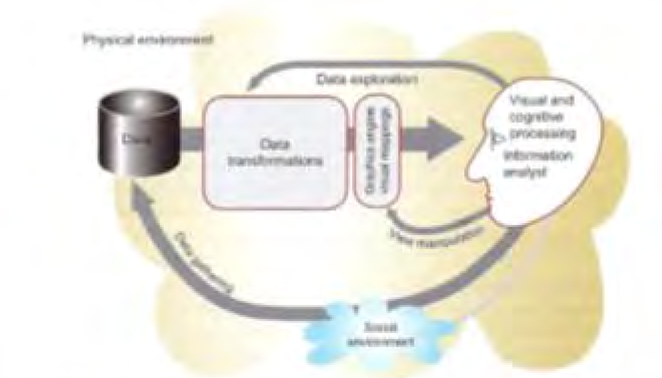


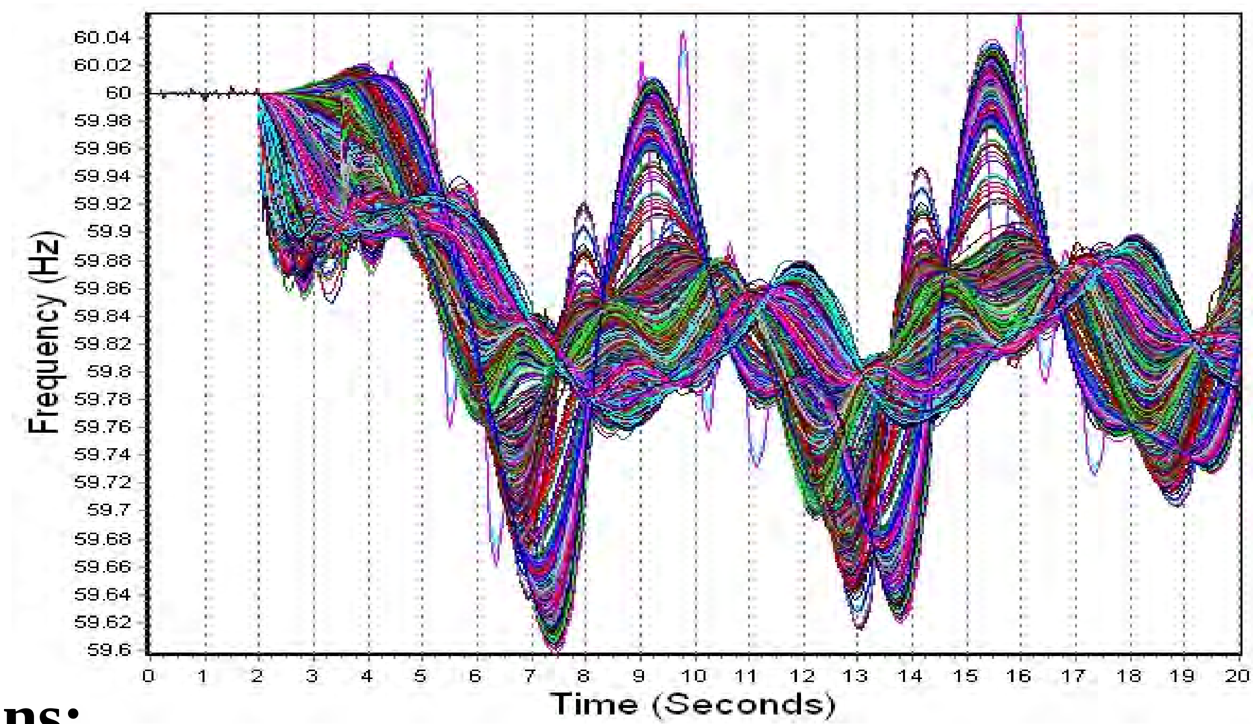
Figure 1.2 The visualization process.

Image source: Colin Ware, *Information Visualization*, Third Edition, 2013

Clustering Example: Transient Stability, PMU, or SCADA Analysis

- A single transient stability solution can generate large amounts of output data
- In real-time a similar situation occurs with PMU data, or on a longer time frame with SCADA
- How much this data needs to be considered is application dependent
  - In operations the concern may just be OK or Not OK
  - In planning more detailed analysis may be required. Issue is how to determine if the results are "correct"?
- Clustering is an example of unsupervised machine learning to make the data more manageable

Frequency Graph of Data for 2400 Generators

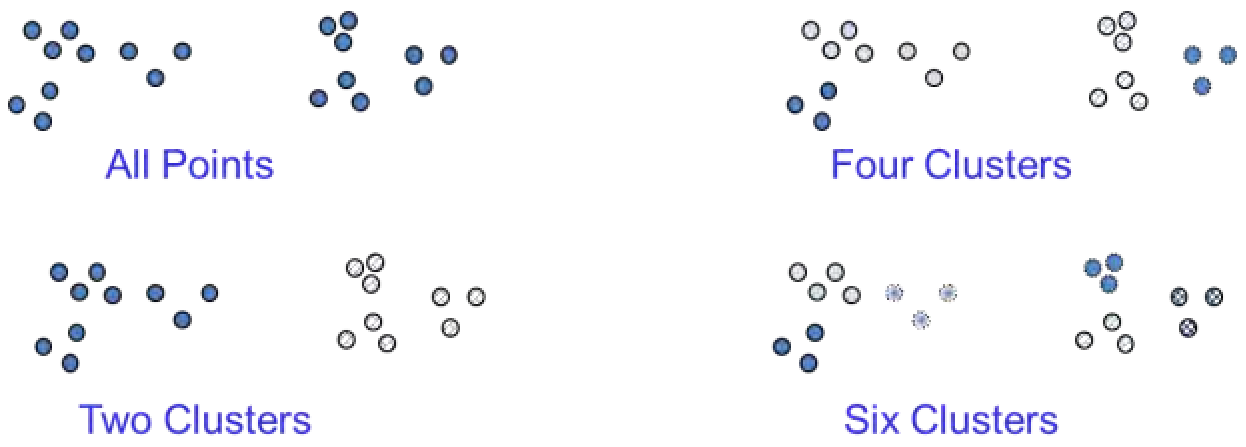


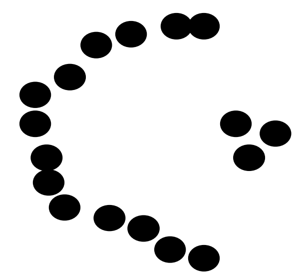
Questions:

- Is the system responding as expected?
- How to separate out the patterns?
- How to incorporate geographic information in the visualization?

Solution: Apply Data Mining Clustering Techniques

- Clustering is the process of grouping a set of objects so similar objects are together, and dissimilar objects are not together
- There is no perfect clustering method or even a single definition for what constitutes a cluster





Two Clusters?

Clustering Algorithms

- There are a variety of clustering algorithms. Two common algorithms are
  - K-Means
    - The number of clusters must be specified
    - Very fast and simple in practice
    - Different initial clusters may lead to different results
  - QT: Quality Threshold
    - Form an unknown number of potentially large clusters that meet a “quality standard” which is a specified threshold cluster diameter
    - Requires more computation

Clustering Applied to Transient Stability Results

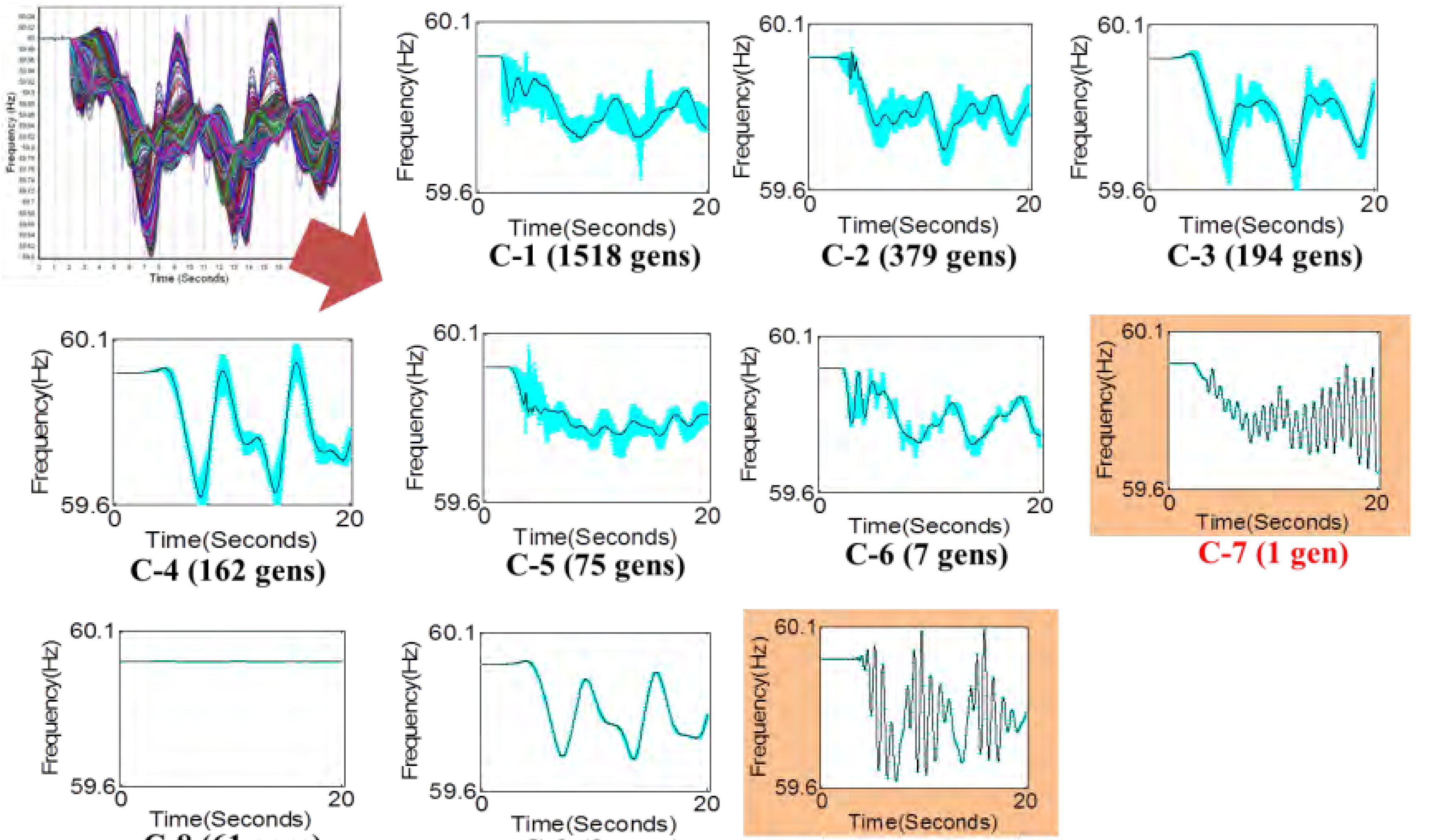
- Idea is to cluster the signal (e.g. generator frequency responses) using a Euclidean distance similarity measure, summing the values over time

$$d_E = \sqrt{\sum_{t=1}^{\tau} \left(x_{p_t} - x_{q_t}\right)^2}$$

$\mathbf{x}_p$ and **$\mathbf{x}_q$** are τ-dimensional sampled time vectors

- K-means clustering is used to pre-group the signals responses to a more reasonable number (say from 2400 to 300 signals)
- QT clustering is then used to determine signal sets that have similar frequency responses

Clustering Applied to Results, Ten Distinct Responses Identified



C-1 (1518 gens)

C-2 (379 gens)

C-3 (194 gens)

C-4 (162 gens)

C-5 (75 gens)

C-6 (7 gens)

C-7 (1 gen)

C-8 (61 gens)

C-9 (3 gens)

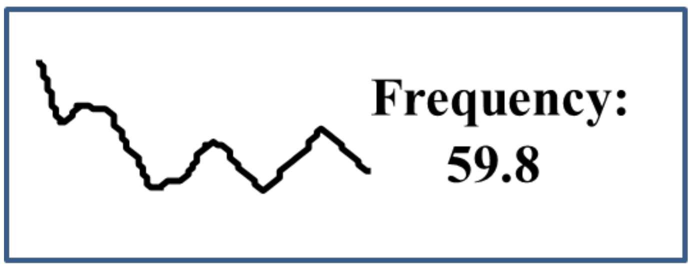
C-10 (1 gen)

Results Combined with Visualization with Spark-Lines

- Spark-lines (from E. Tufte, *Beautiful Evidence*, 2006) are "intense, word-sized graphics"

Frequency: 59.8

Display of value only

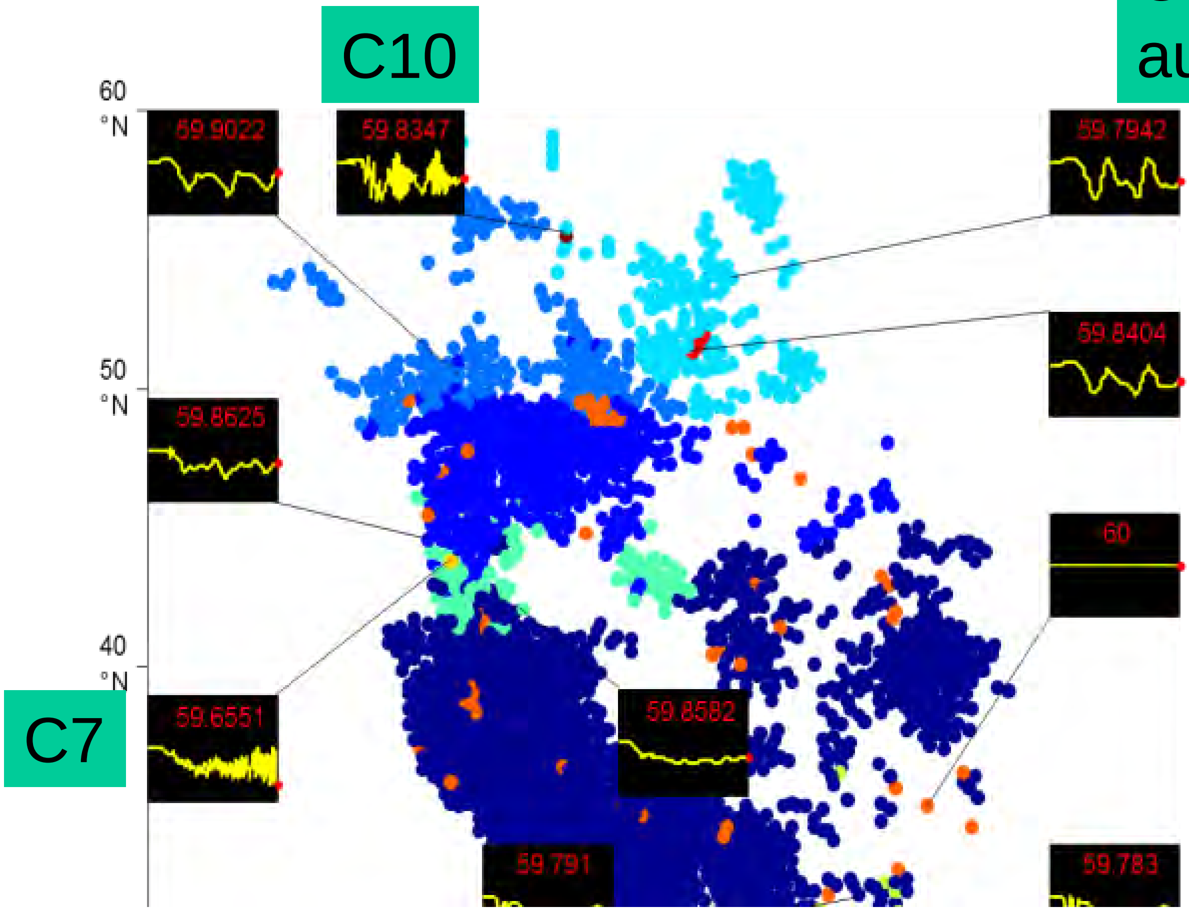


Display of value and trend

Display of value and trend highlighting present value

Spark-line plot

2400 Generator Results Visualized in a Geographic Context



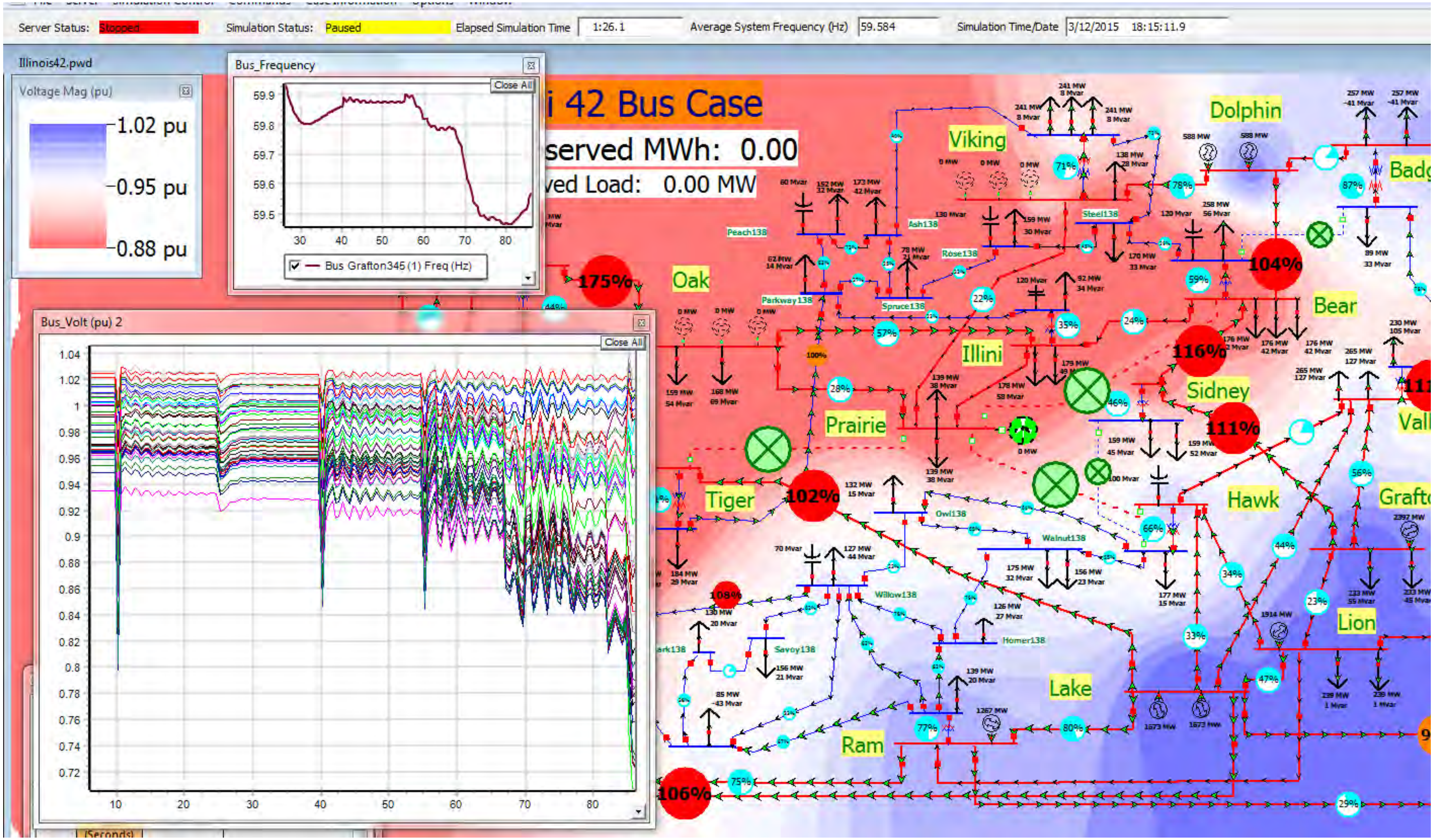
Outliers are detected automatically

- 10 distinct frequency responses identified
- Visualized on actual geographic location with "spark-lines"
- Different color dots = generators of a cluster

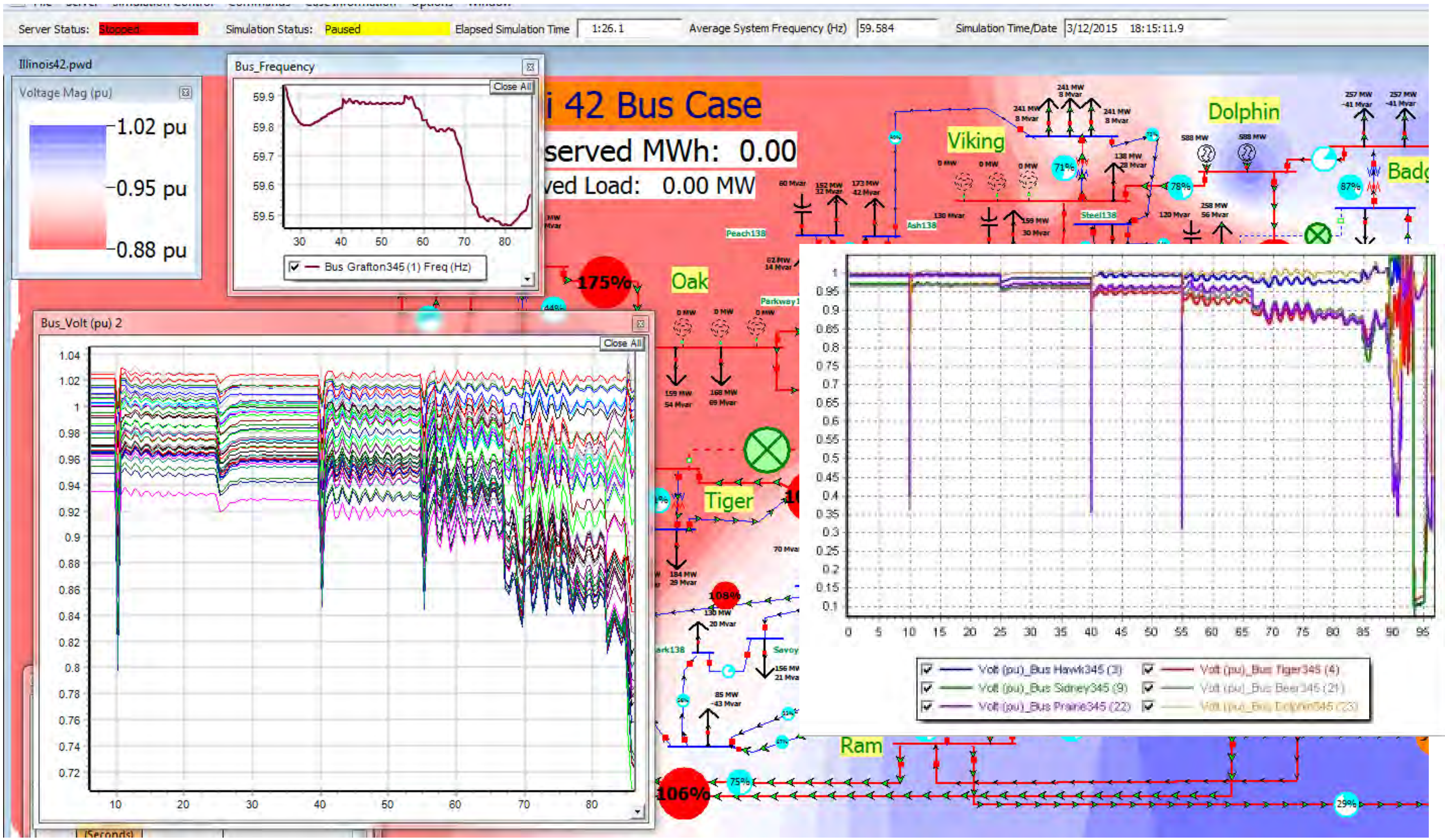
Application to Voltage Magnitude Alarming

- Clustering can also be used with SCADA data to dynamically cluster areas of abnormal voltage
- Alarms could then just be issued on the cluster, with drill down ability to get details
- As the system evolves cluster membership may change
- This avoids missing outliers, since every bus is in a cluster, yet also can reduce the number of alarms

42 Bus Example Case: Near Collapse

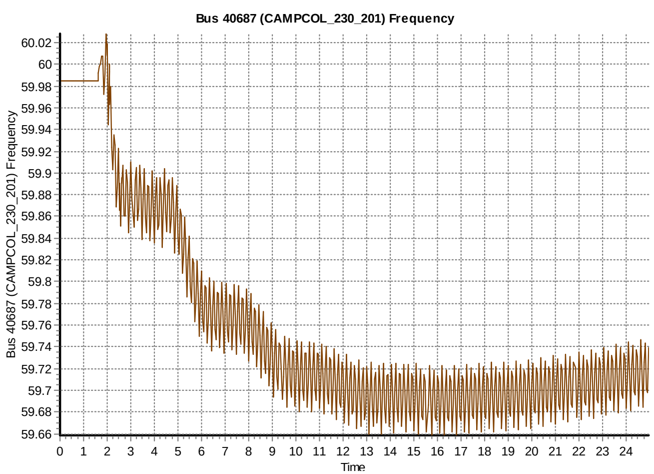


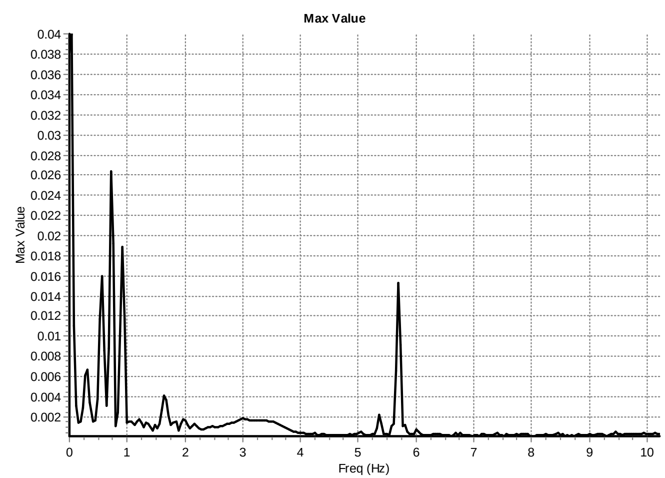
Clustering Just Shows Those That Are Close (Over a Time Period)



Frequency Domain

- Frequency domain techniques, such as Fast Fourier Transforms (FFTs) can be used to detect unusual behavior
  - Can be used with PMU values to detect unusual frequencies
  - Can be used with transient stability to locate outliers

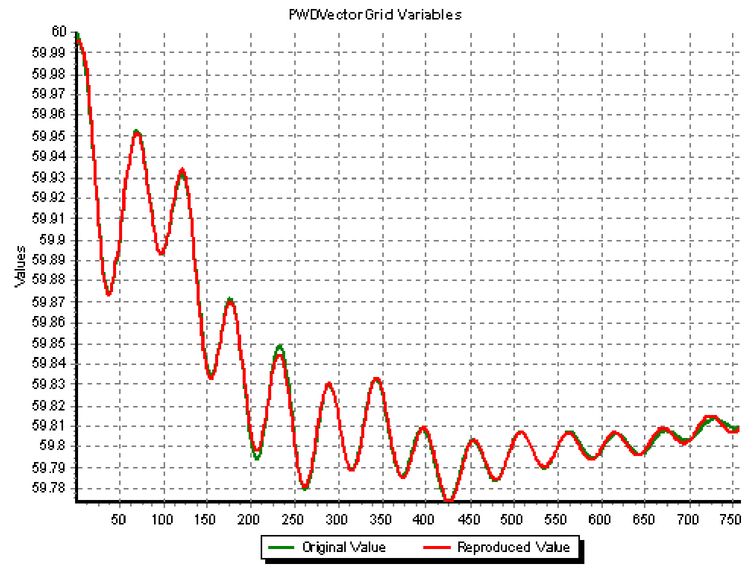


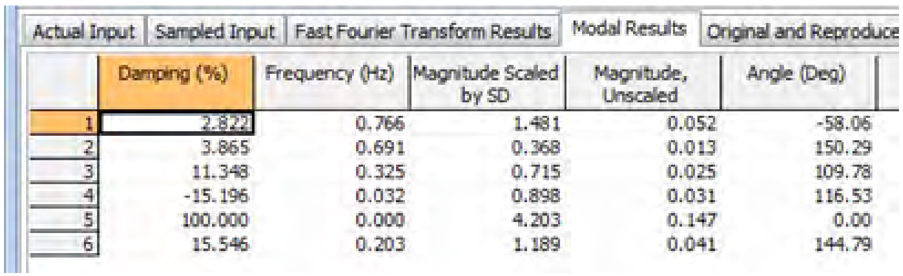


Thousands of signals can be considered quickly

Signal Based Ringdown Modal Decomposition

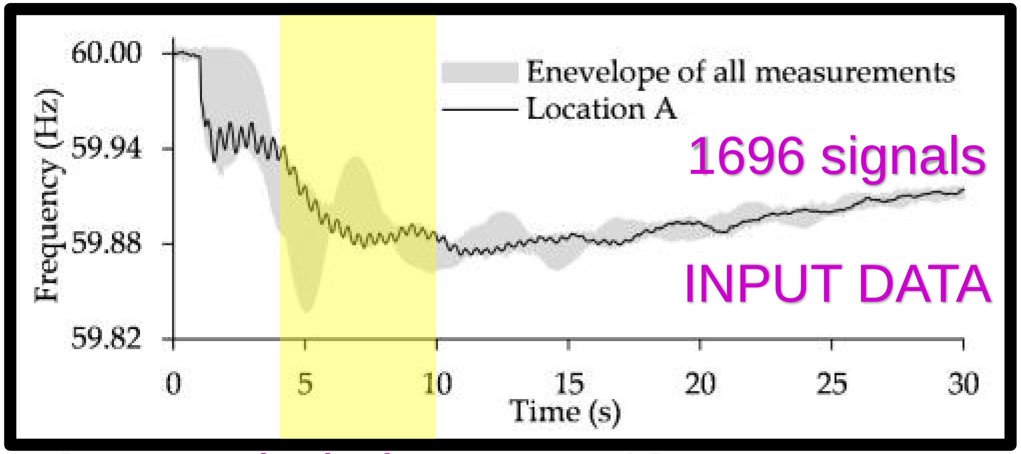
- Idea is to determine the frequency and damping of power system signals after an event
  - Reproduce a signal, such as bus frequency, using exponential functions
- A number of different techniques have been proposed to do this for power systems, starting with Prony analysis in the late 1980's





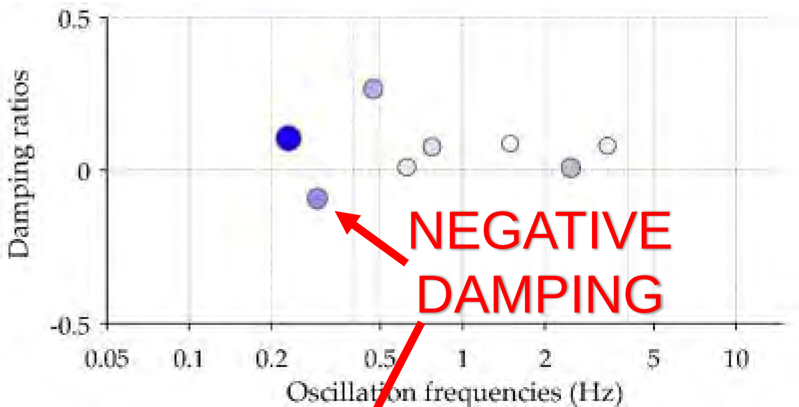
	Damping (%)	Frequency (Hz)	Magnitude Scaled by SD	Magnitude, Unscaled	Angle (Deg)
1	2.822	0.766	1.481	0.052	-58.06
2	3.865	0.691	0.368	0.013	150.29
3	11.348	0.325	0.715	0.025	109.78
4	-15.196	0.032	0.898	0.031	116.53
5	100.000	0.000	4.203	0.147	0.00
6	15.546	0.203	1.189	0.041	144.79

Oscillation/Stability Analysis (Dynamic Mode Decomposition)

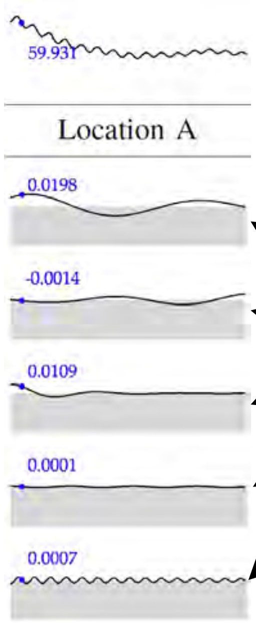


6-second window at t = 10 s

VISUAL: Plot of damping ratios vs. oscillation frequencies



NEGATIVE DAMPING



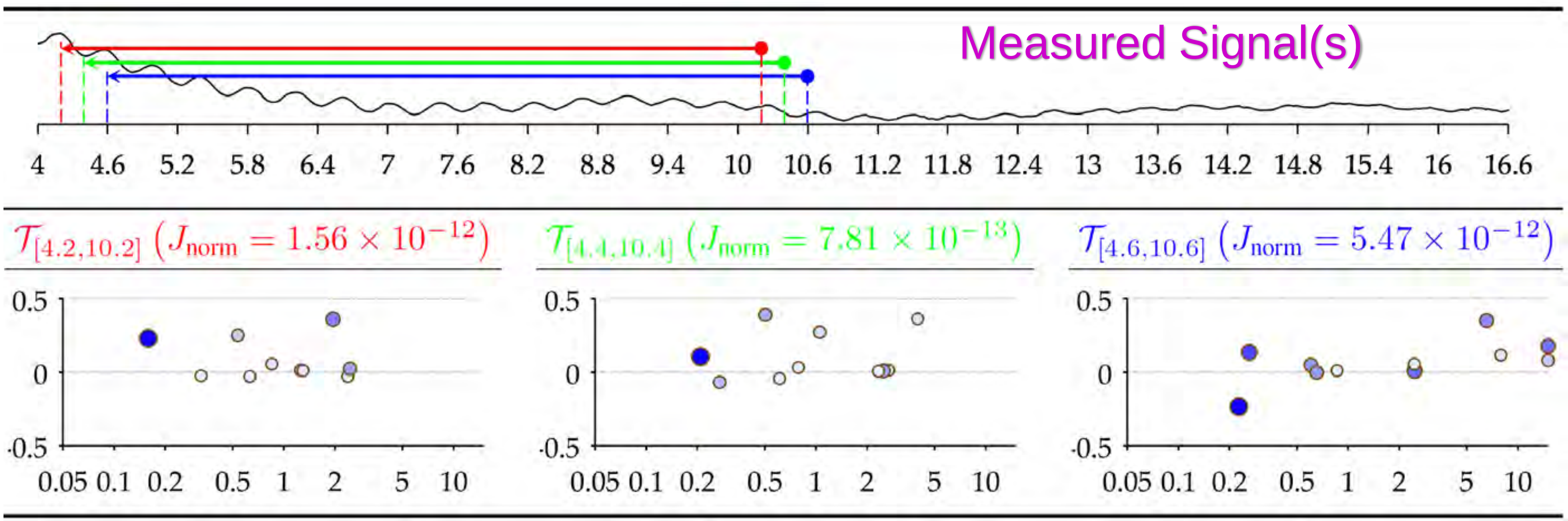
Modes	Oscillation frequency (Hz)	Damping ratio
1	0.23072	0.10387
2	0.29410	-0.092304
3	0.47078	0.26472
4	0.62376	0.00099628
5	2.7486	0.0069160

MODAL ANALYSIS OUTPUT

REAL-TIME

Modal composition

Real-Time Modal Content Monitoring



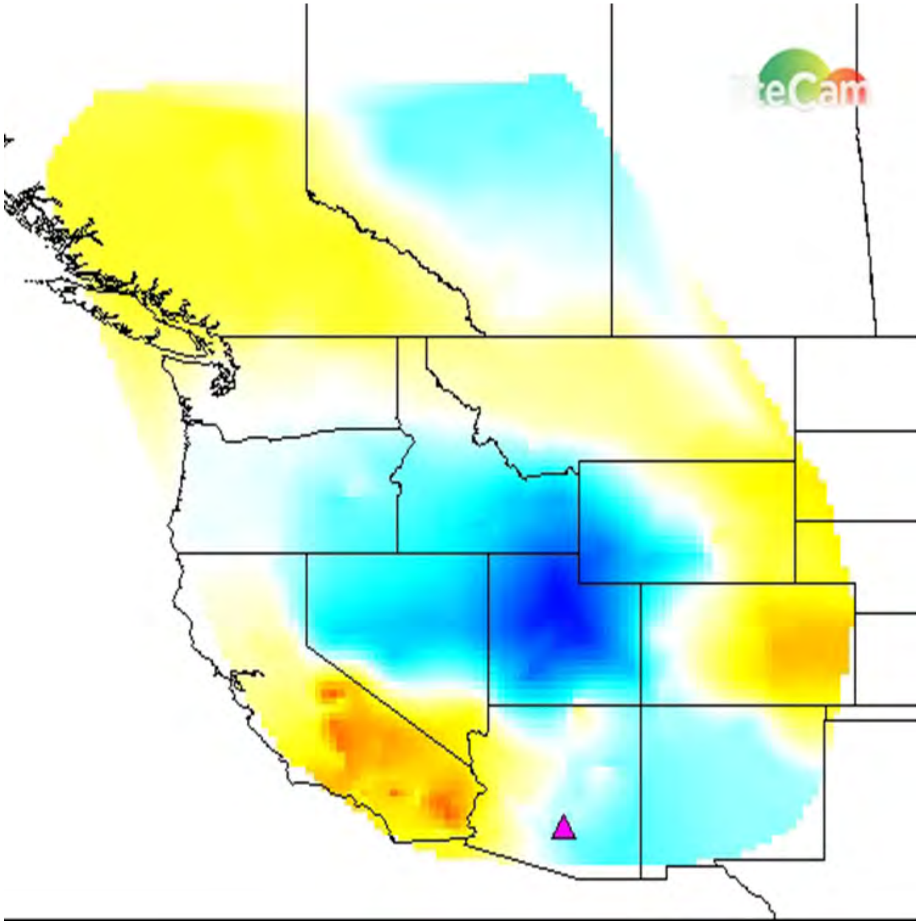
t = 10.2 s t = 10.4 s t = 10.6 s

Evolution of modal content through time (with 6-second window)

- Real-time tracking (all 1696 measured signals)
  - damping ratios and oscillation frequencies
- Wide-area modal content alarms

Spatio-Temporal Visualization of Modal Participation

- Mode 4
  - Oscillation frequency
    - 0.62376 Hz
  - Damping ratio
    - 0.00099628 (very low)
- 6-second window
- At t = 10 s



Conclusion

- 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 dynamics cases are needed to help provide input for such research

Questions?