



Using PMU Data to Increase Situational Awareness

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PSERC Project S-36



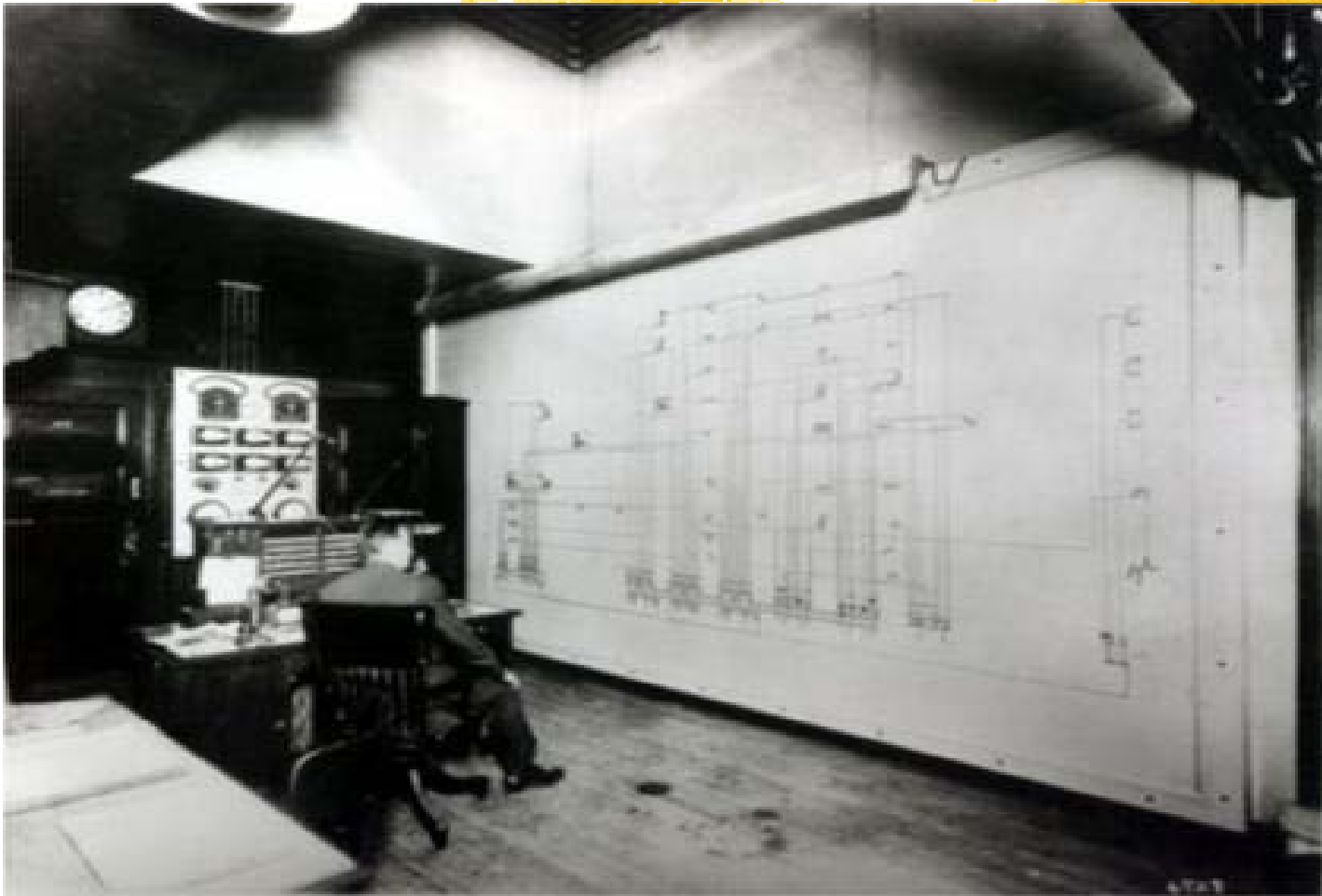
- Project University PIs
 - Tom Overbye, Pete Sauer (University of Illinois at Urbana-Champaign)
 - Chris DeMarco, Bernie Lesieutre (University of Wisconsin-Madison)
 - Mani Venkatasubramanian (Washington State)
 - Ian Hiskens (University of Michigan)
- Project also depended on the support of PSERC companies and our graduate students

Situational Awareness (SA)



- A simple definition of SA is “knowing what is going on around you.” A more detailed definition involves comprehending enough of the complex system status to make informed decisions in a time critical manner to positively affect the system state.
- A key question then is whether the PMU data helps operators and engineers make better, more timely decisions; or does it just add to the information clutter, wasting time.

Where We've Come From



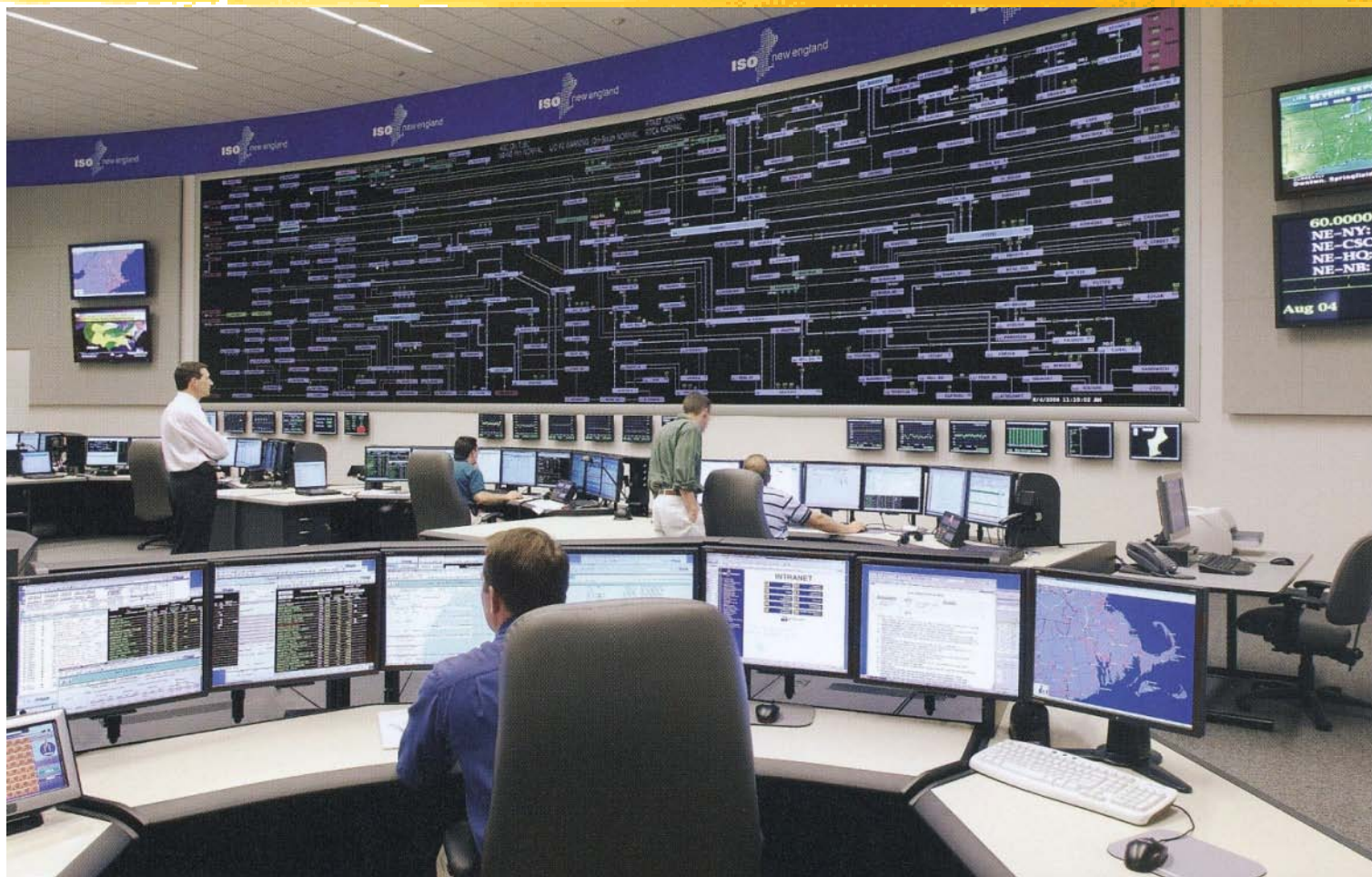
Commonwealth Edison Control Room, Circa 1920

Moving Forward Seventy Years



Commonwealth Edison Control Center, Late 1990's

Where We Are At



ISO New England Control Center, late 2000's
(Source-ISO New England Brochure)

Adding in PMUs



- SCADA analog measurements have been used for several decades with scan rates of once every few seconds
- PMUs add much faster scan rates (30 samples per second) and direct measurement of bus angle across systems
- Talk does not discuss application of PMUs in state estimation, originally described by Phadke, Thorp, and Karimi in 1986.

Application of PMU Data



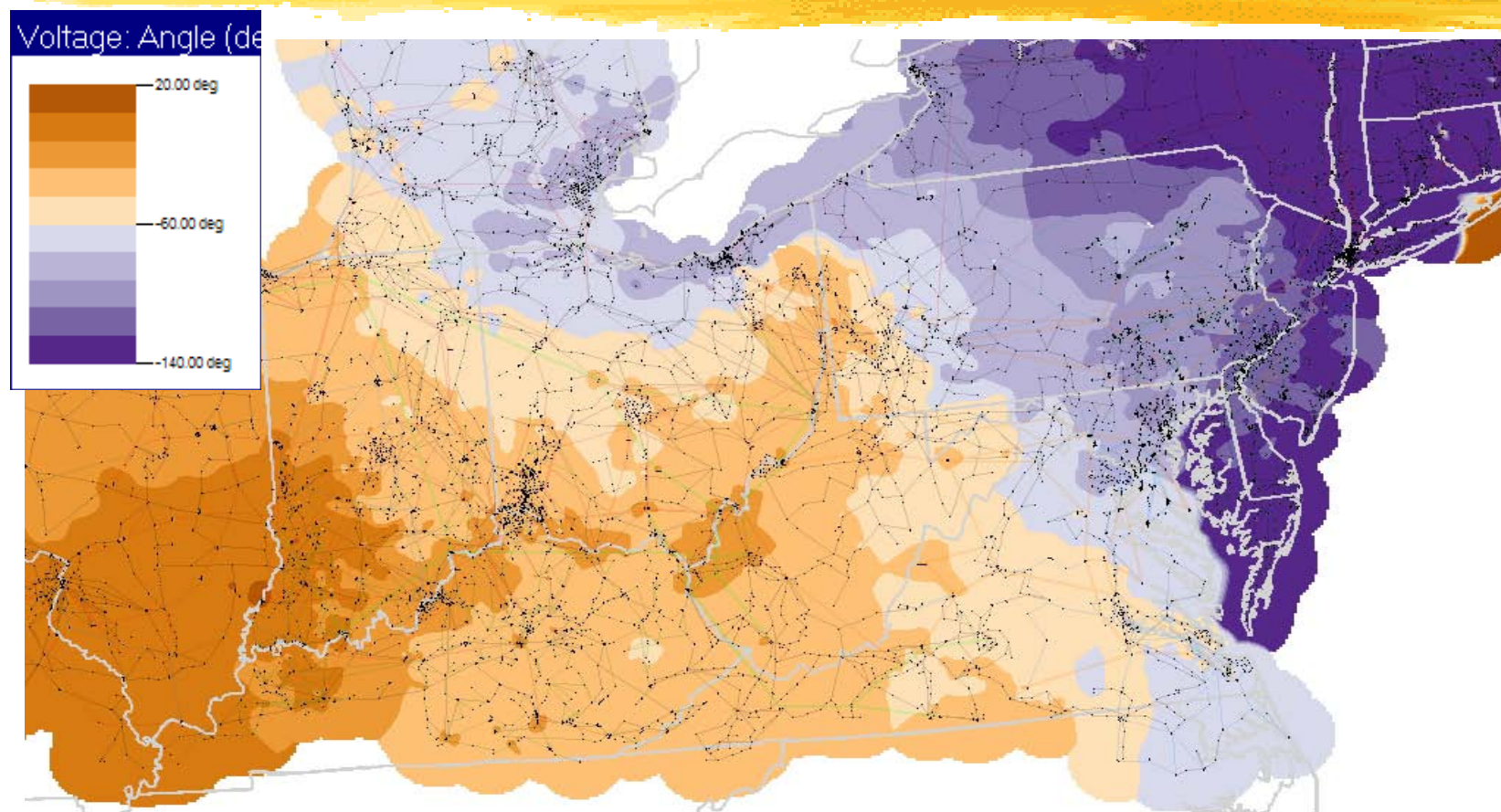
- To improve SA, PMU information can be used in a number of ways
 - Real-time, direct visualization, in essentially a raw form (i.e., bus angles).
 - Real-time, but embedded in other applications, such as SE or for assessing system dynamics
 - Real-time, but embedded in data-mining applications to give historical info in real-time
 - Off-line, to develop better system models and understanding; this includes post-event analysis

What Does A Bus Angle Indicate?



- Straightforward (if we allow for a dc power flow approximation): $\theta = \mathbf{B}^{-1} \mathbf{P}$
 - Incremental variations similar for full ac case
- The equation indicates that the angle at a particular bus is the vector product of a row of the inverse of the B matrix with the net power injection vector $\mathbf{P}$.
- B matrix is sparse, its inverse is not.
- Angles are given with respect to a system reference, Brown's Ferry here (18137)

A Power Flow Bus Angle Contour



Bus phase angles contain global information about the system state, but decoding this information can be difficult.

Example: Wemp. 345 Angle = -25.2°



Impact on 36406

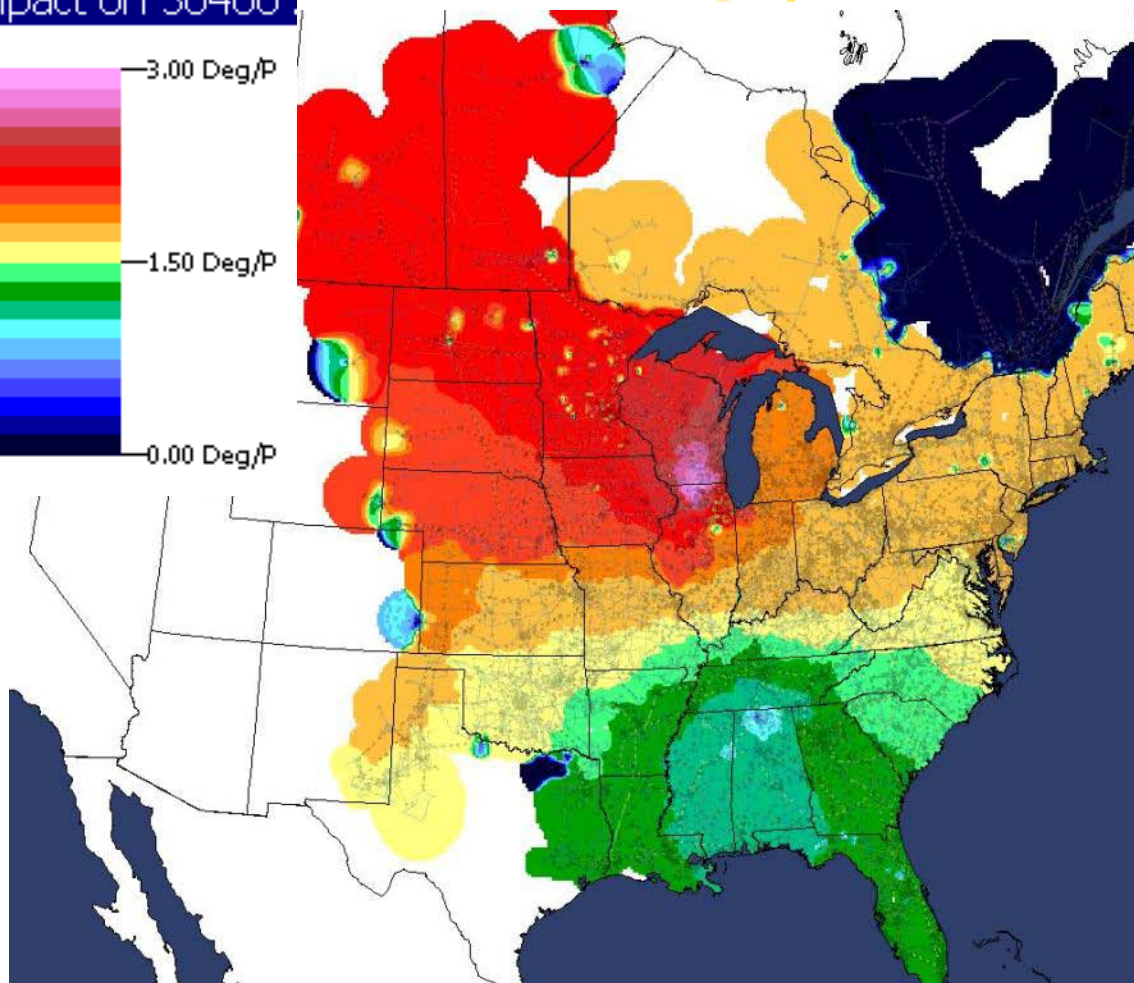
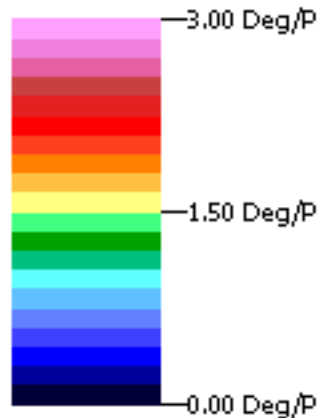


Figure contours the impact of power injections at different locations on the angle at bus 36406 (i.e., a row from the inverse of the B matrix). Note most locations matter! Angle provides system-wide information!

Angle Difference: Wemp. to Burn. 345



Impact on Angle D

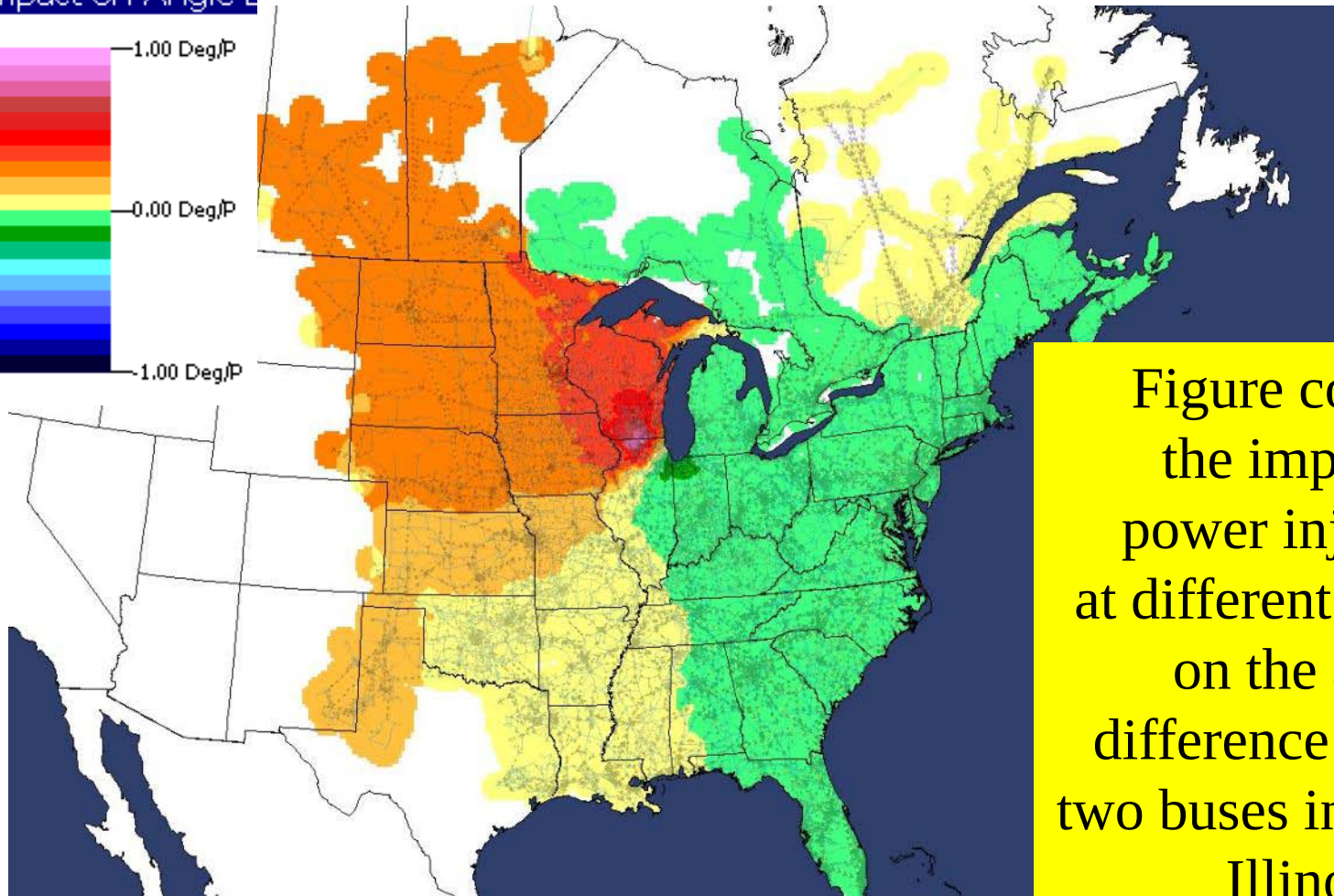
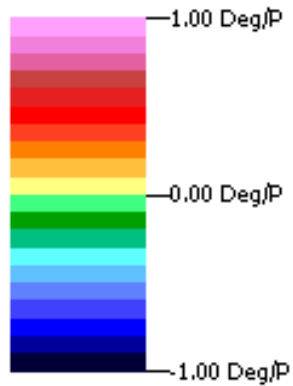


Figure contours the impact of power injections at different locations on the angle difference between two buses in Northern Illinois.

Visualization Cautions



- Just because data can be shown in visual (graphical) form does not mean it should be
- There is actually very little in the human factors literature with regard to power system visualizations.
- Doing formal human factors experiments is quite time consuming, and ultimately of somewhat limited value in determining the usefulness of visualizations in a control center setting.

Data Should Support the Task

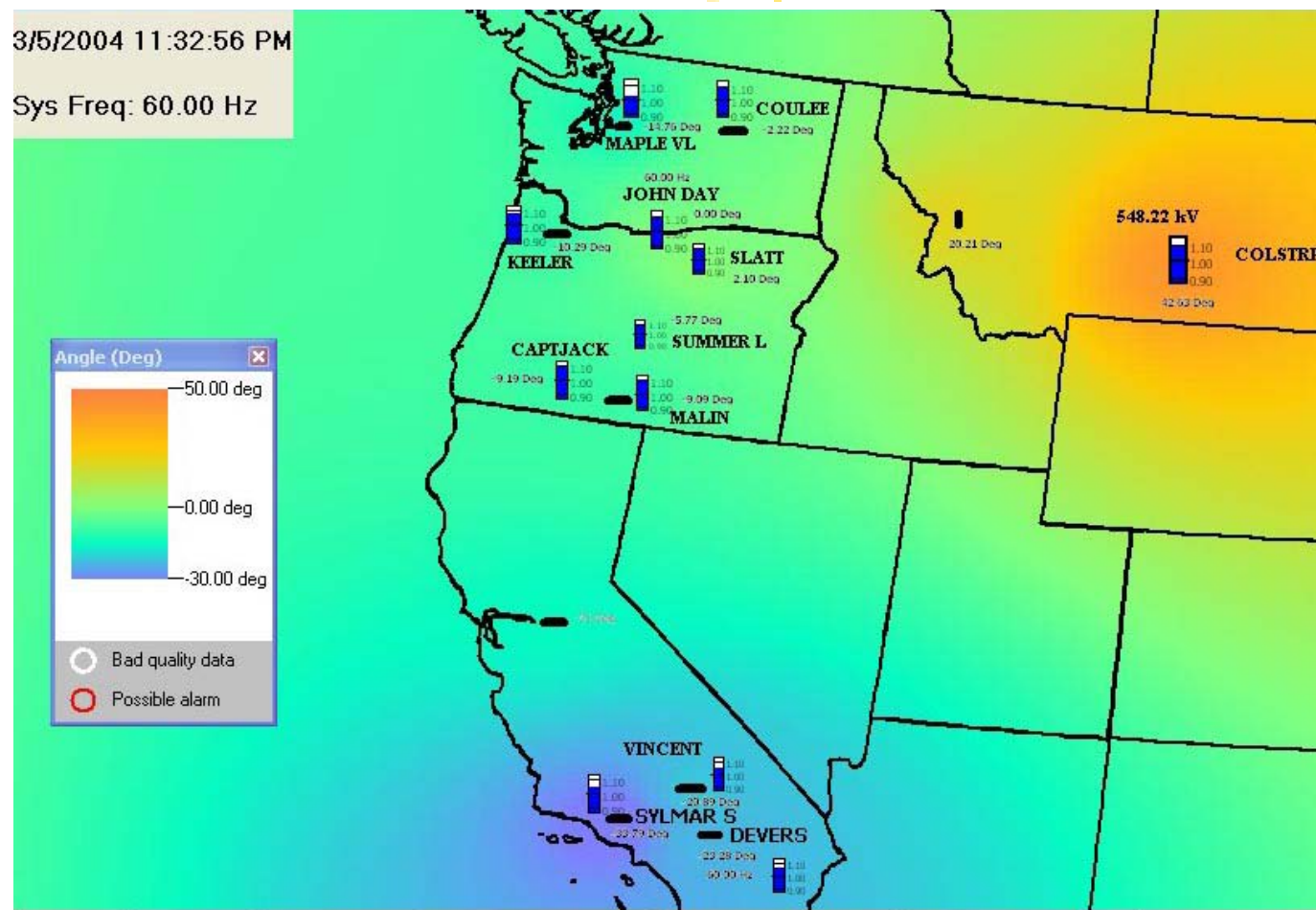
- Understanding the entire task (processes) in which the visualizations are embedded is key.
 - What is the “information access” cost?
 - How will the information be used and shared?
 - Is it raw data, or derived values?
 - Should the visualizations sit on top of a model, or is a standalone process sufficient?
 - Ultimately, what are the desired tasks that need to be accomplished?

State of Art: Angle Contours



3/5/2004 11:32:56 PM

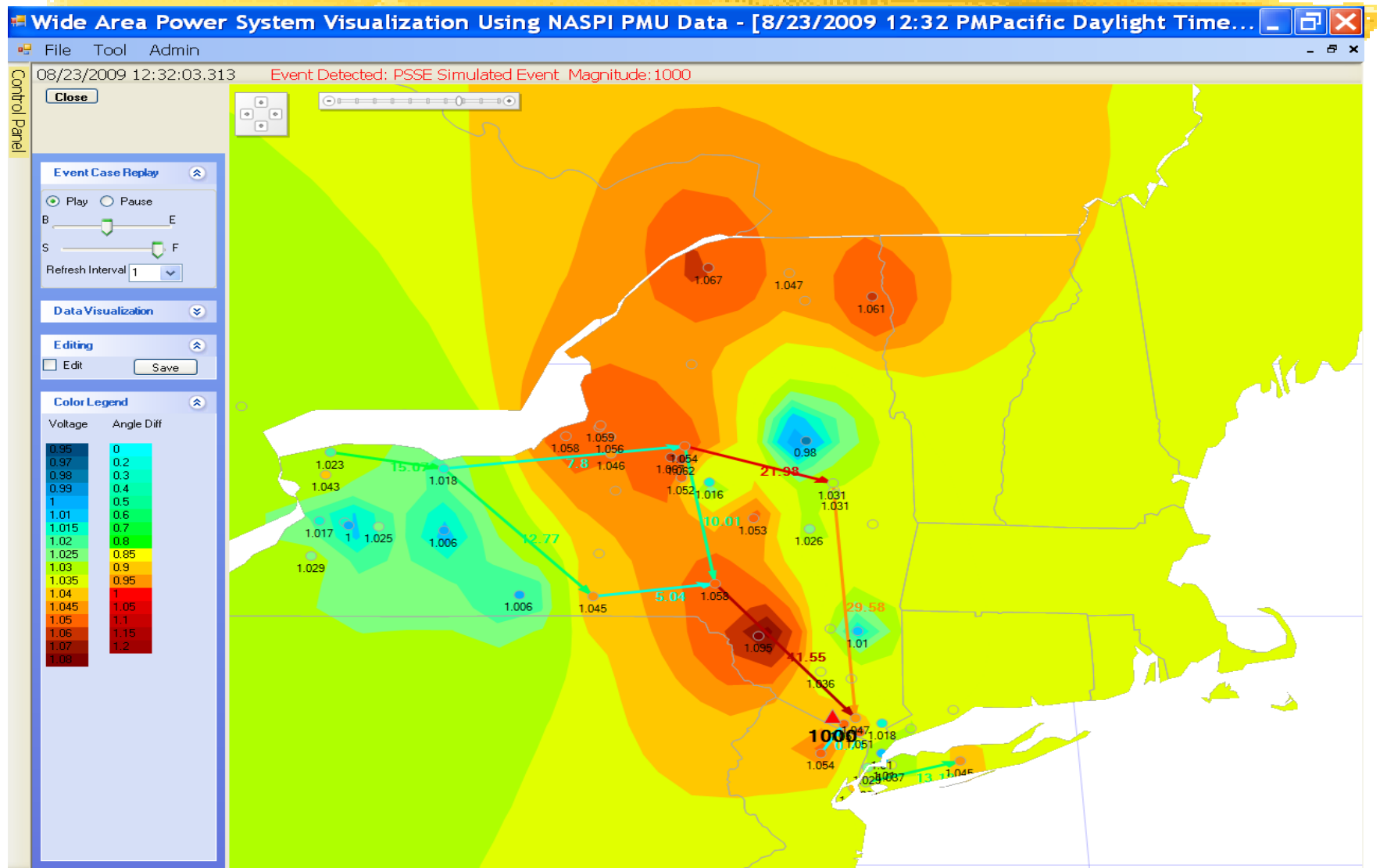
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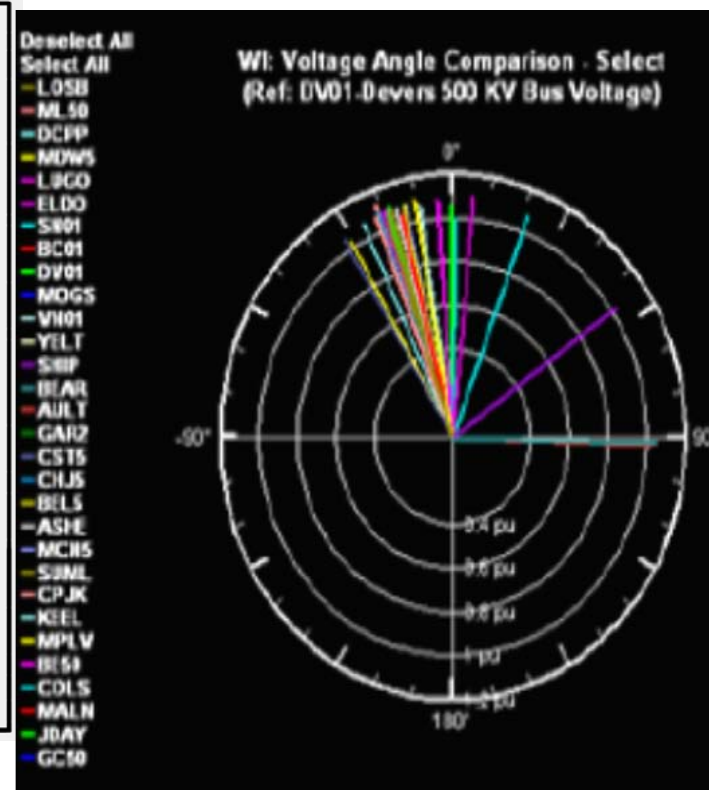
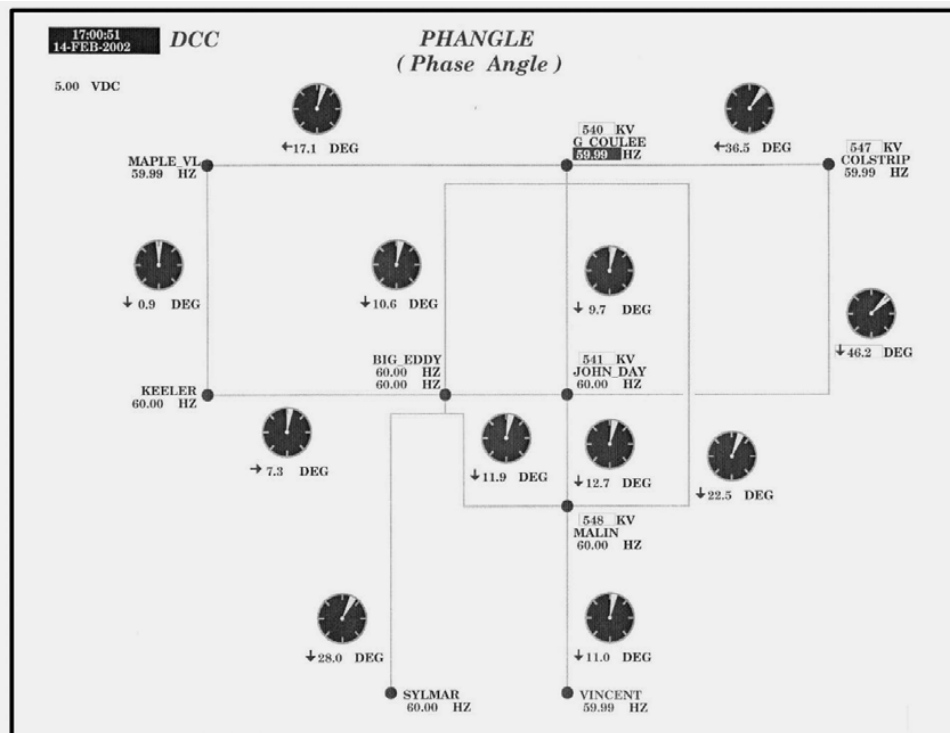
Contours can be quite helpful in showing animations of power system oscillations

Wilson, Martin, Klump, NAPS, August 2004

State-of-Art: Contours (EPRI)



State-of-Art: Dials and Pie Charts



Wilson, Martin, Klump,
NAPS, August 2004

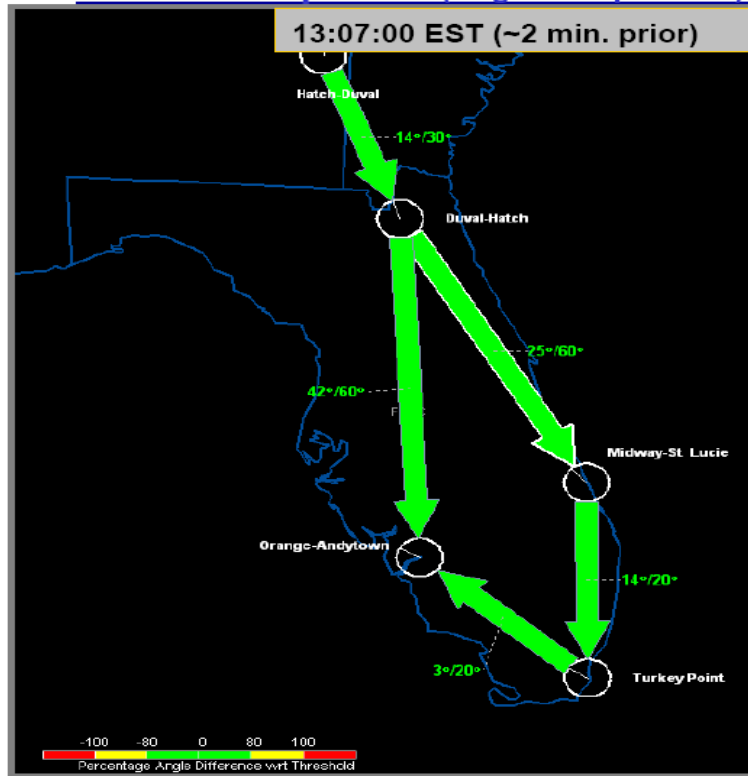
Parashar, DOE OE Review, October 2008
Also DOE Secretary Chu, October 2009

State-of-Art: Dynamic Line Formatting

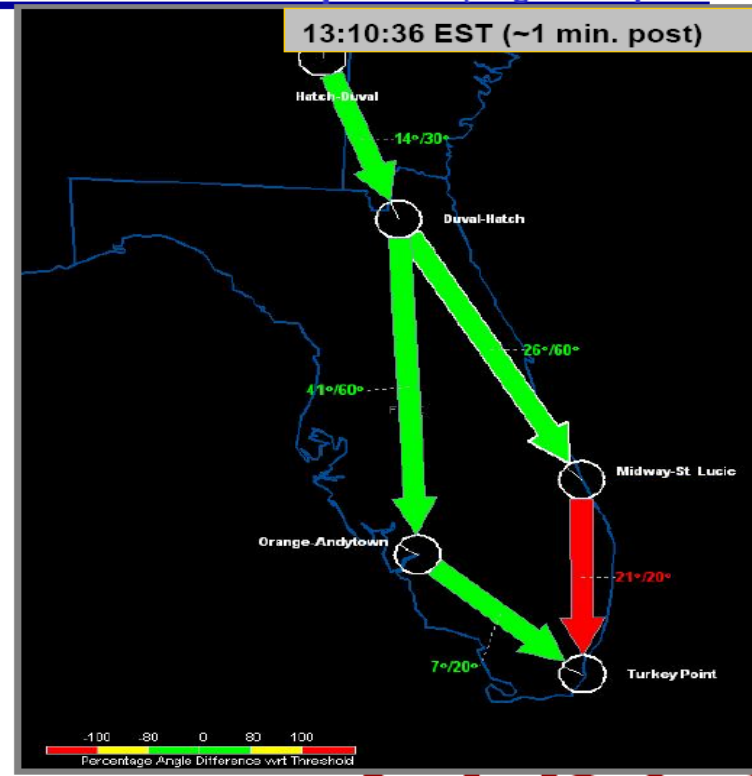


RTDMS Display during Florida Event

Pre-Event Snapshots (Angular Separation)



Post-Event Snapshots (Angular Separation)

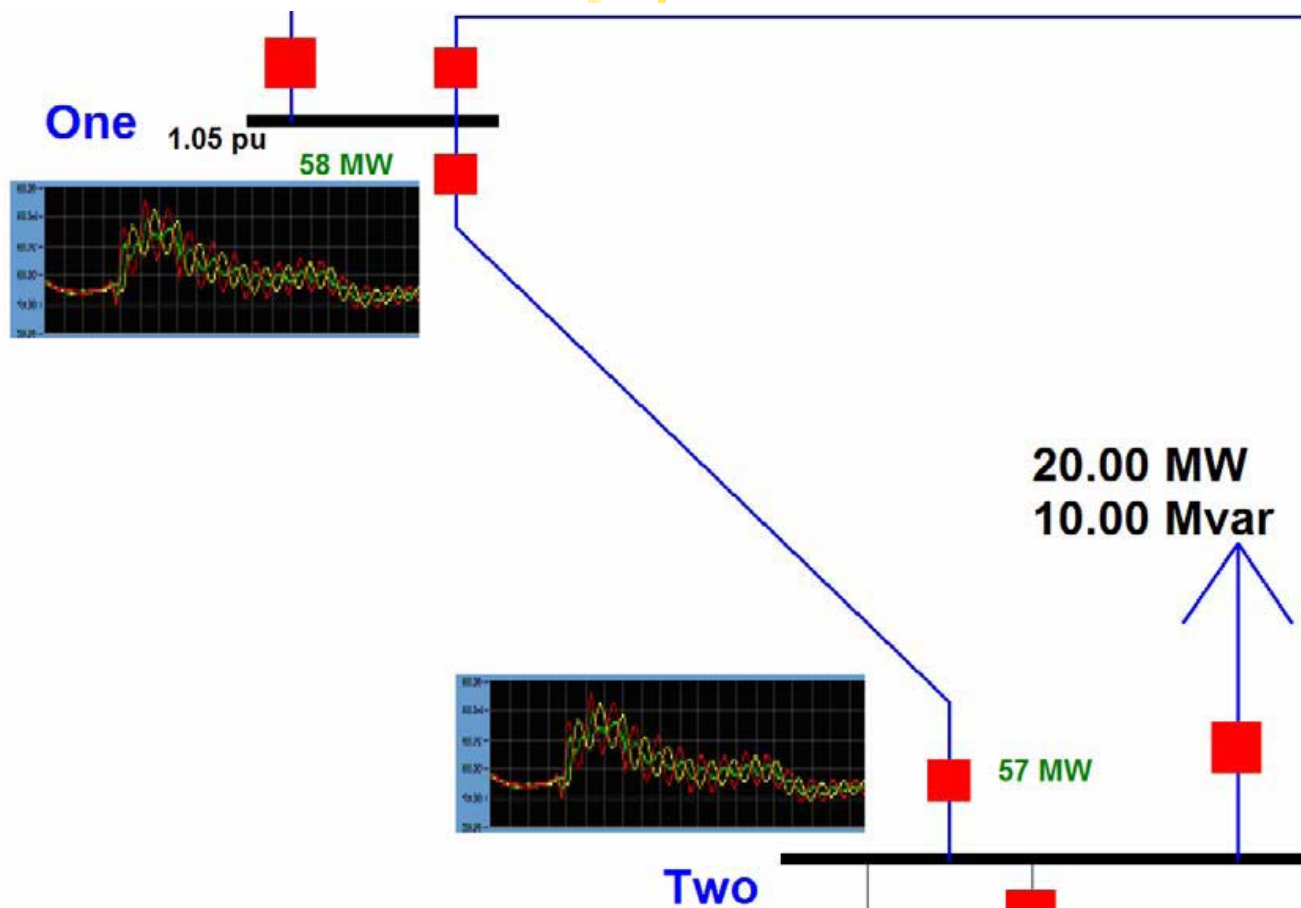


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Parashar, DOE OE Review, October 2008

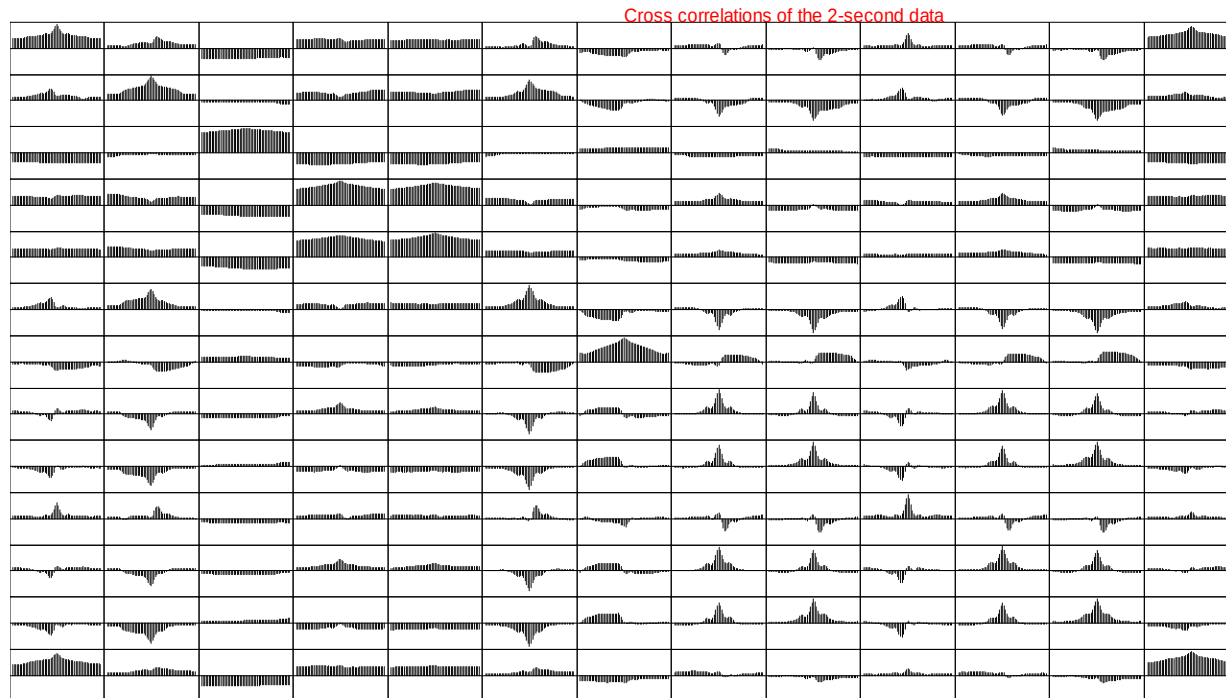
State-of-Art: Embedded Charts



Klump, Wilson, 38th HICSS, Jan 2005

State-of-Art: Sparklines

- Sparklines are word-sized graphics that show the time variation in a value.



We still need to explore applying these in a GIS context

True GIS vs. Pseudo-GIS Displays



- Power system visualizations have traditionally been done using a “pseudo-GIS” (one-line diagram) approach.
- There is a growing trend towards integrating power system information into true GIS visualizations.
- Usefulness depends on application. For some applications, like fault location, they can be useful, but there are often significant shortcomings when used with pmu data.

True GIS vs. Pseudo-GIS

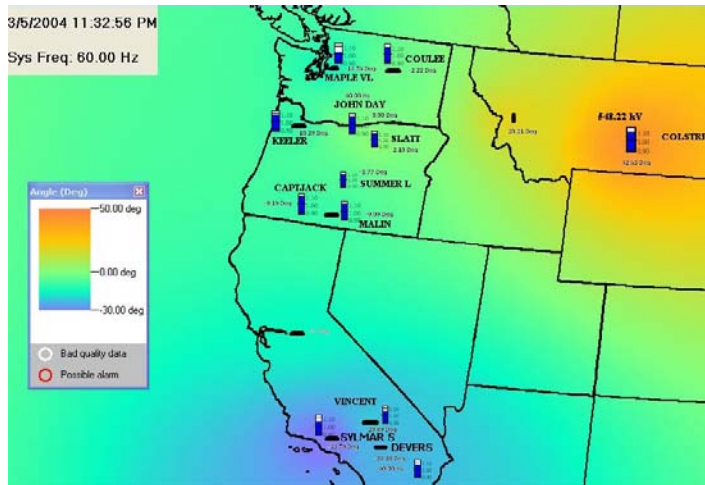


Two Pseudo-GIS Examples

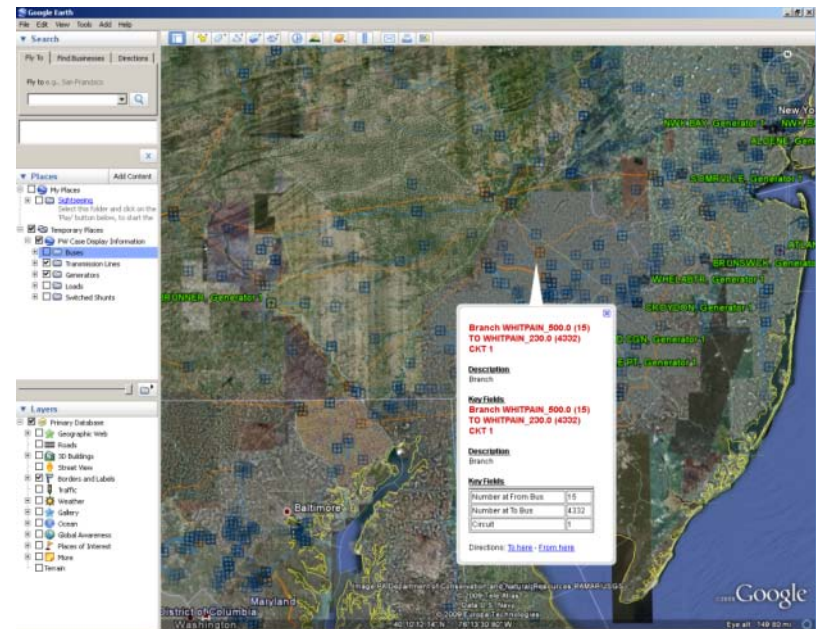


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Sys Freq: 60.00 Hz



True GIS Example

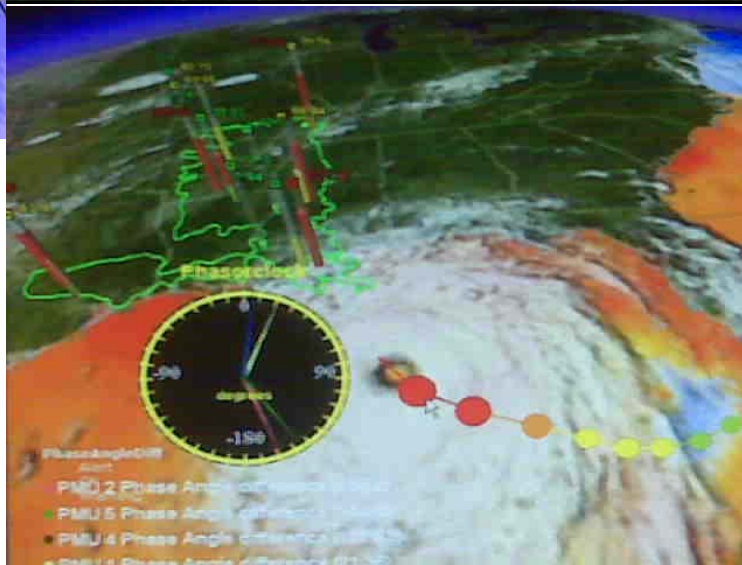


Satellite background can camouflage data; also interesting electric data occurs in a small geographic area

3D Display of PMU Data

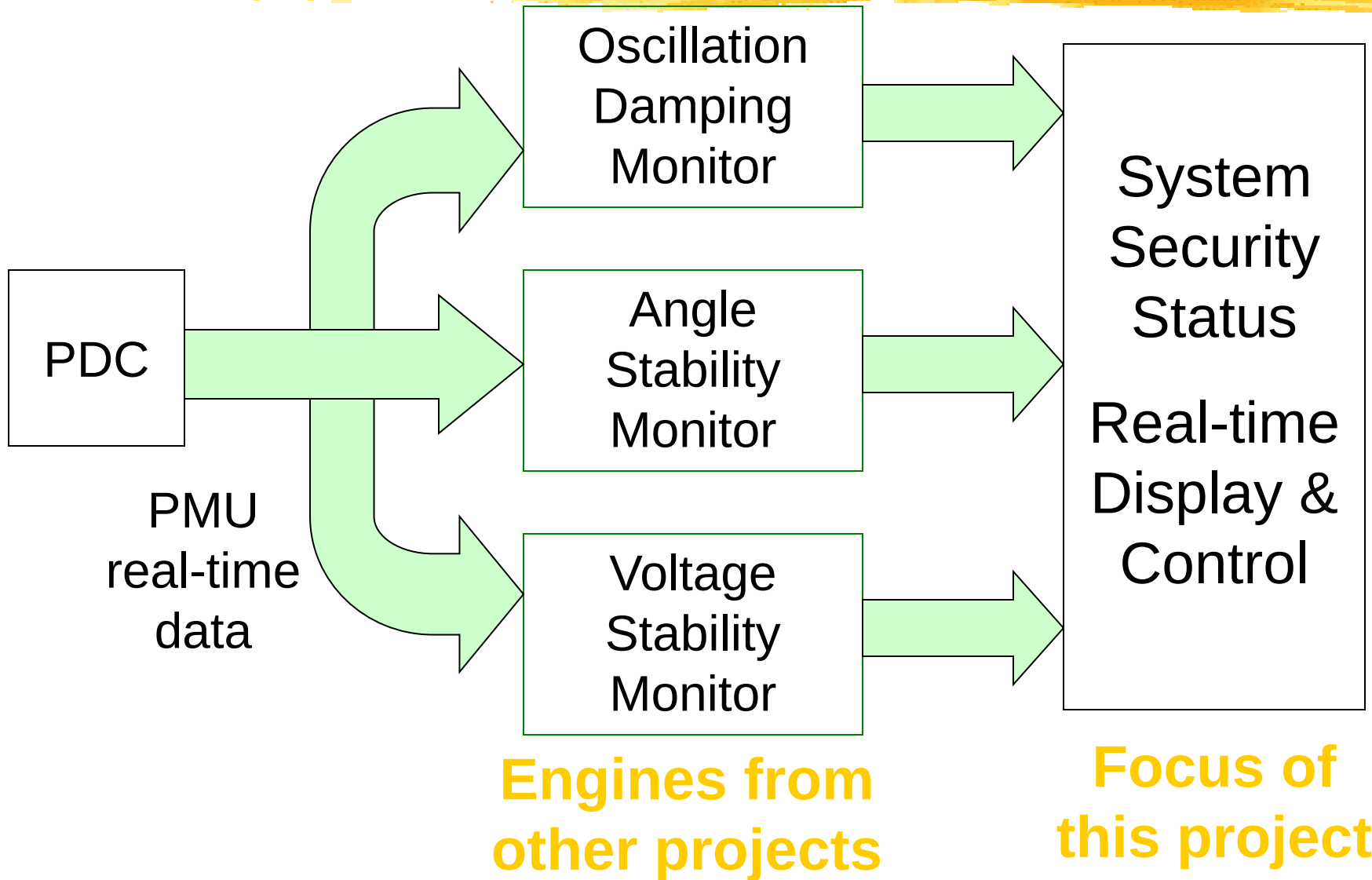


- Results on 3D are mixed.
- Advantages: 1) useful for showing relationships between multiple variables, 2) our brains are designed for interacting with 3D (i.e., we live in a 3D world), 3) increasing common and fast interface.
- Disadvantages: 1) perceptual ambiguities of depth, size and distance occur, 2) objects in foreground can obscure those in background, 3) can induce vertigo on large screens.



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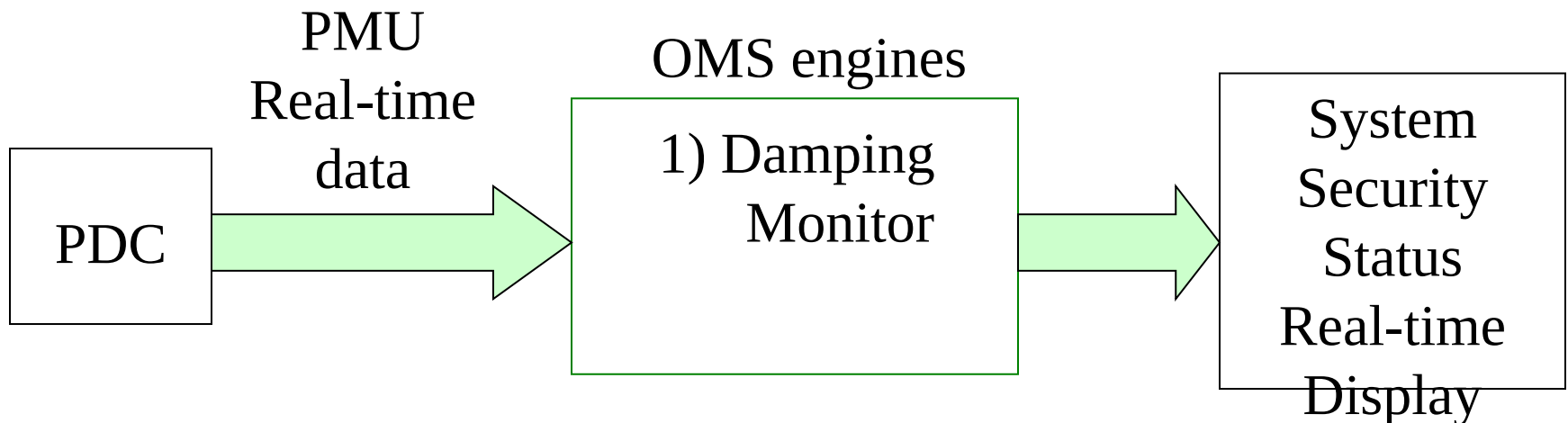
Real-time Security Monitors at WSU



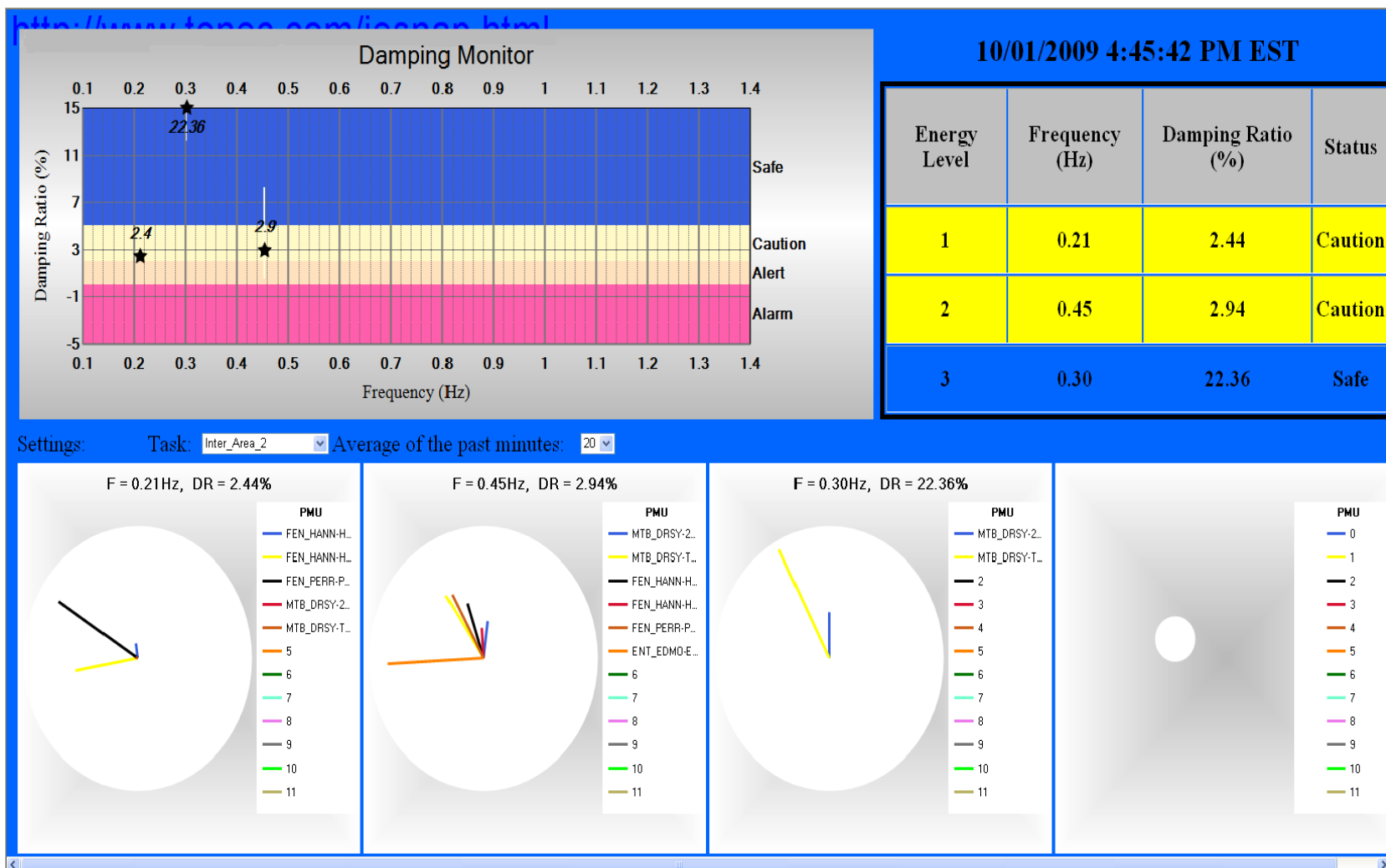
Oscillation Monitor Interface Issues



- Previous PSERC projects S29 and S31 (Co-funding from current projects from BPA, TVA, Entergy, and CERTS)
- Prototype implementation ongoing at TVA and BPA with real-time displays.
- Mode shape. Local mode or Inter-area? Which part of system critical? What operator actions? What control actions?



OMS Real-time GUI at TVA



PMU Data for Improved Models

- PMU data can help improve SA by giving better system models, that in-turn can allow for on-line stability applications
- Existing transient stability data has a number of errors, most of which are transparent to the users because of auto-correction in transient stability packages
 - Example large interconnect case had 1459 dynamic data “errors”, including about 140 on synchronous machine impedances

Breaking the Wall Between Operations and Planning



- Historically planning and operations have used different power system models
 - Operations uses detailed node/breaker model, with the EMS providing a set of integrated applications; topology processing needed to deal with circuit breakers; uses a real-time operating system and databases; some data visualization (e.g., one-lines)
 - Planning uses a simplified bus/branch model, with stand alone, PC-based software, file structures for case storage; little visualization; no need to deal with circuit breakers, etc.

Requirements for Unification



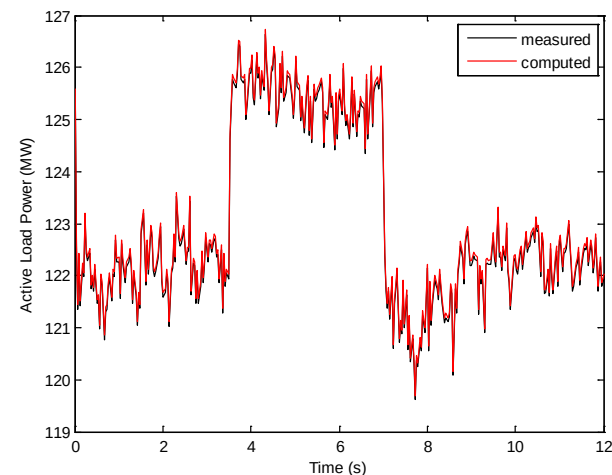
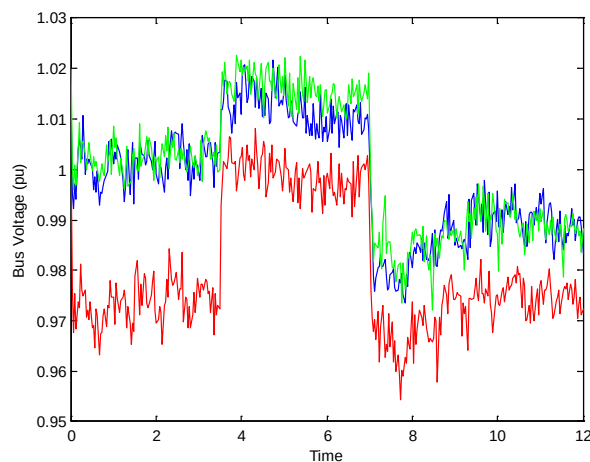
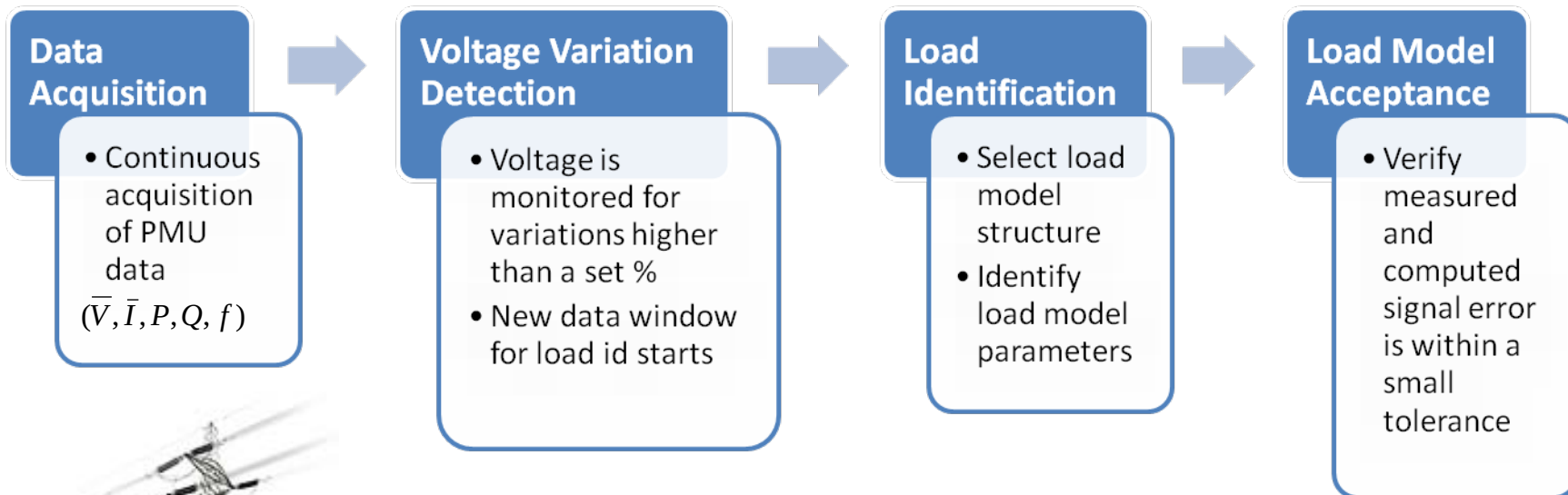
- Single model for operations and short-term planning
- Same application capable of performing the same type of analysis in operations and planning stages
- Seamless exchange of data between planning and operation
 - Allows better use of historical data in planning
- Solution tracking ability for diverse temporal, study, or contingency scenarios

A Solution: Same Model Topology Processing



- Dynamic topology processing allows the use of full topology models in the planning environment, with the software making the system look (to the planners) like the familiar bus/branch arrangement
 - Allows for the integration of PMU data
 - This requires dynamic processing and good visualization to hide the unwanted nodes
 - Such processing can be done quite quickly, for example reducing a 80,000 node model to 10,000 buses in 0.2 seconds.

Real-Time Load Modeling



Load Models

Static

- ZIP

$$P = a \left(\frac{V}{V_0} \right)^2 + b \left(\frac{V}{V_0} \right) + c$$

- EXP

$$P = P_0 \left(\frac{V}{V_0} \right)^n$$

- IEEE

$$P = P_0 \left(a_1 \left(\frac{V}{V_0} \right)^{n_1} + a_2 \left(\frac{V}{V_0} \right)^{n_2} + a_3 \left(\frac{V}{V_0} \right)^{n_3} \right) (1 + a_4 \Delta f)$$

Dynamic

- GNLD

$$P = P_0 \left(\frac{V}{V_0} \right)^{\alpha_t} + z_p$$

$$T_p \dot{z}_p = -z_p + P_0 \left(\frac{V}{V_0} \right)^{\alpha_s} - P_0 \left(\frac{V}{V_0} \right)^{\alpha_t}$$

Note: Similar expressions for the reactive load power

Load as Reactive Resource



- Motivation: Increased PMU deployments will increase system real-time observability
 - To take advantage of this we need more real-time control
- At residential level several types of devices can provide quick reactive power control
 - For example, PV inverters and PHEVs
 - Inverters for distributed generation
- Control reactive power output of inverters to restore or improve system voltages

Load as Reactive Resource



- Loads and inverters at the residential level can provide reactive support to the grid
- Such capability is not currently utilized
- Coordinated use of distributed reactive power resources can allow a more comprehensive form of reactive power control
- A possible use of quick-acting reactive power controls could be to stop voltage collapse

PMUS: Load as Reactive Resource



- PMUs help enable this concept by providing real-time information about the reactive power loads available to provide support
- We define reactive support regions in the transmission system where each region's controller is responsible for obtaining the necessary reactive support for devices in its region

Application of SVD to PMU



Premise in work: In characterizing quasi-steady state grid performance, SVD analysis particularly well suited to handling large PMU data sets.

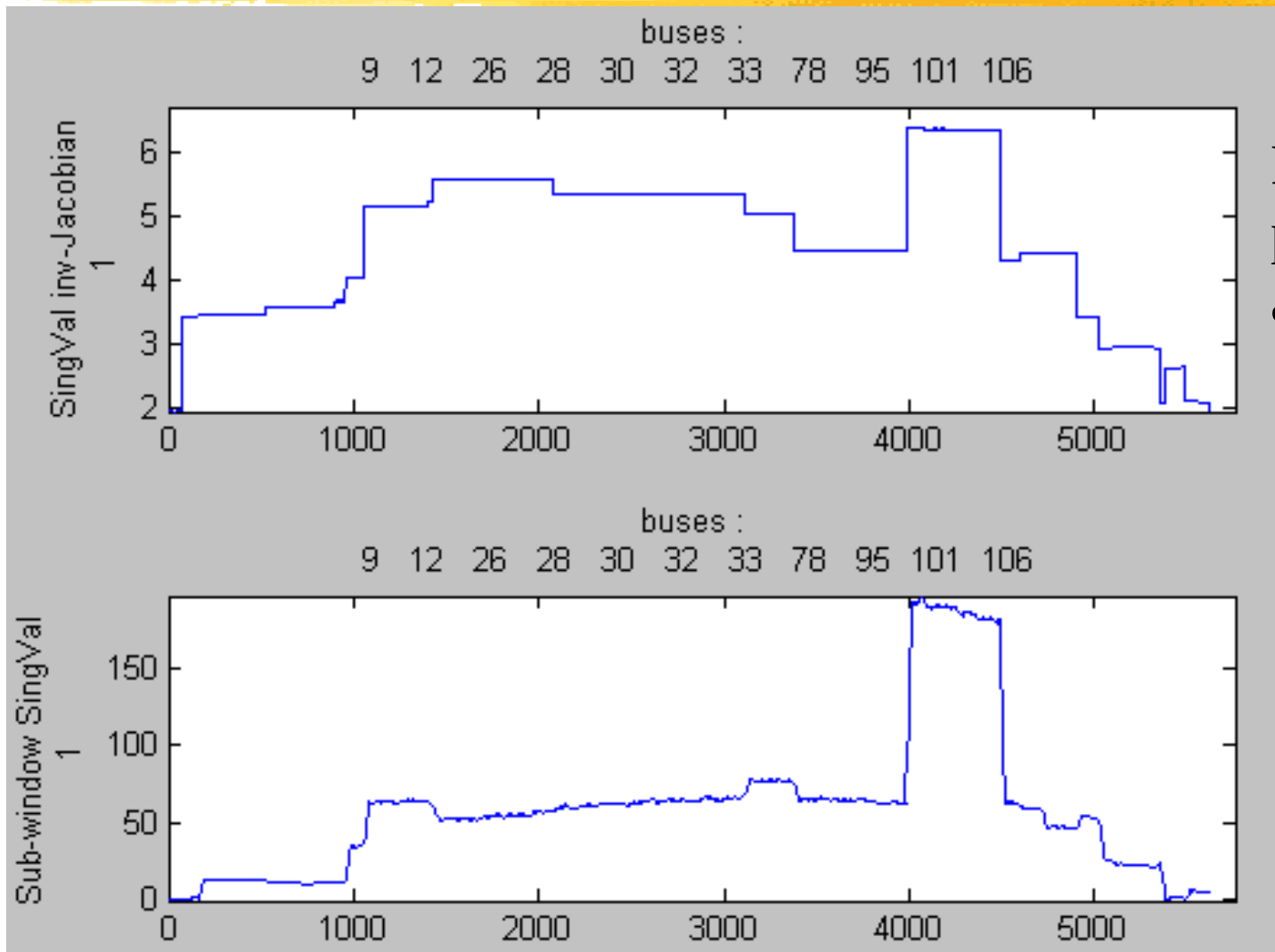
Claim: A windowed SVD computation on PMU data tracks a well-established performance metric, whose computation traditionally would require state estimation of operating point, with full network and load models.

Application of SVD to PMU



- View PMU data as a time series “output,” with vector of PMU measurements at time sample k comprising $\underline{m}[k]$. A window of such vectors composes matrix $\mathbf{M}[k]$.
- VERY simple idea: watch for degradation in operating condition to show up as changes in σ 's and $\mathbf{U}$. Initial efforts seek relation to an established performance metric, hence focus on the largest singular value and vector.

SVD IEEE 118 Bus Experiment



PMU
penetration
at 11 of
118 buses

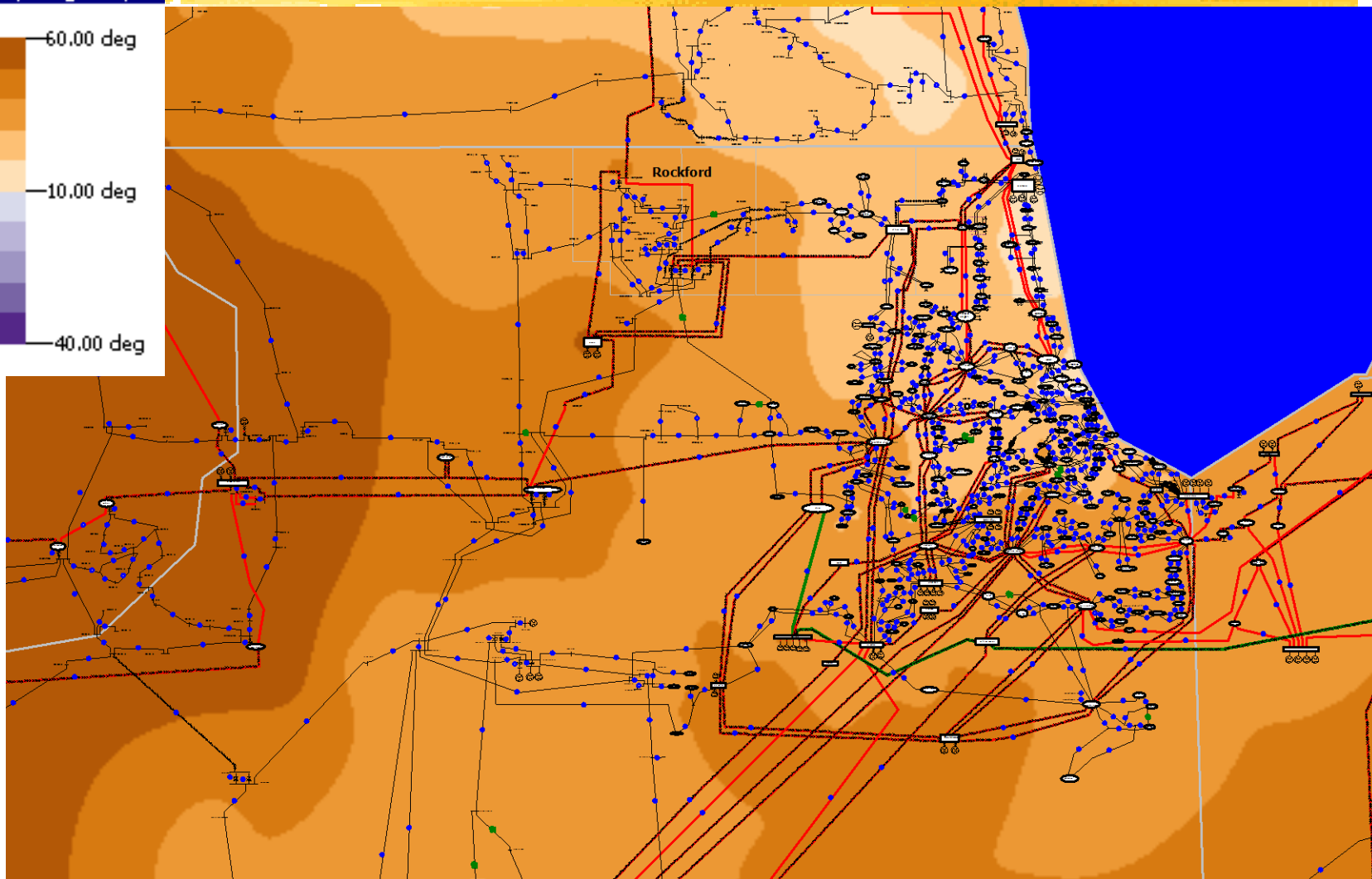
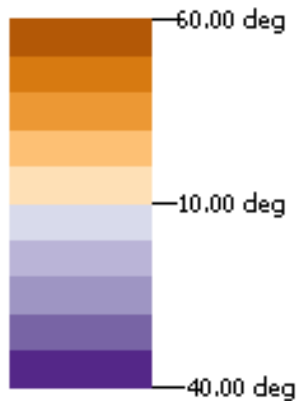
Quick Estimation (QE) of Power State



- State estimation (SE) is not appropriate for all situations: 1) smaller utilities without SE, 2) for external parts of system without SE observability, 3) SE fails to converge, 4) market participants
- This task explores how PMU measurements, combined in a power flow case can be used to at least approximate the current operation condition

QE: Starting Case

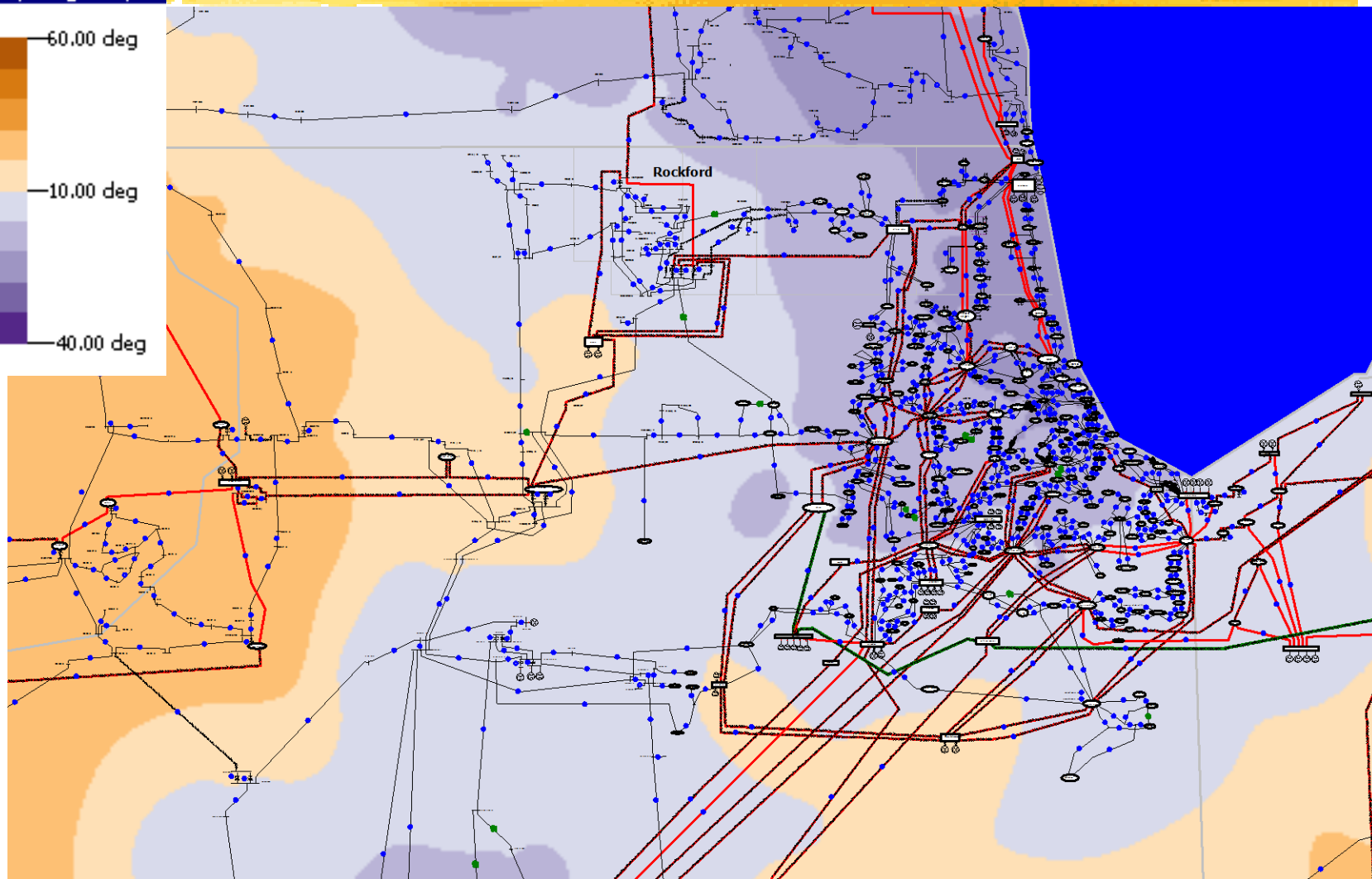
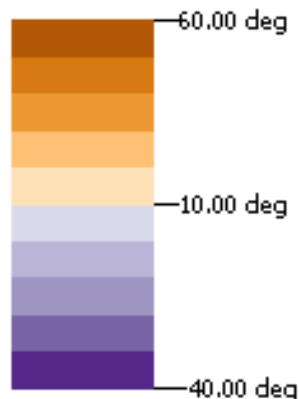
Voltage\Angle (deg)



QE: Actual with 2000 MW Transaction



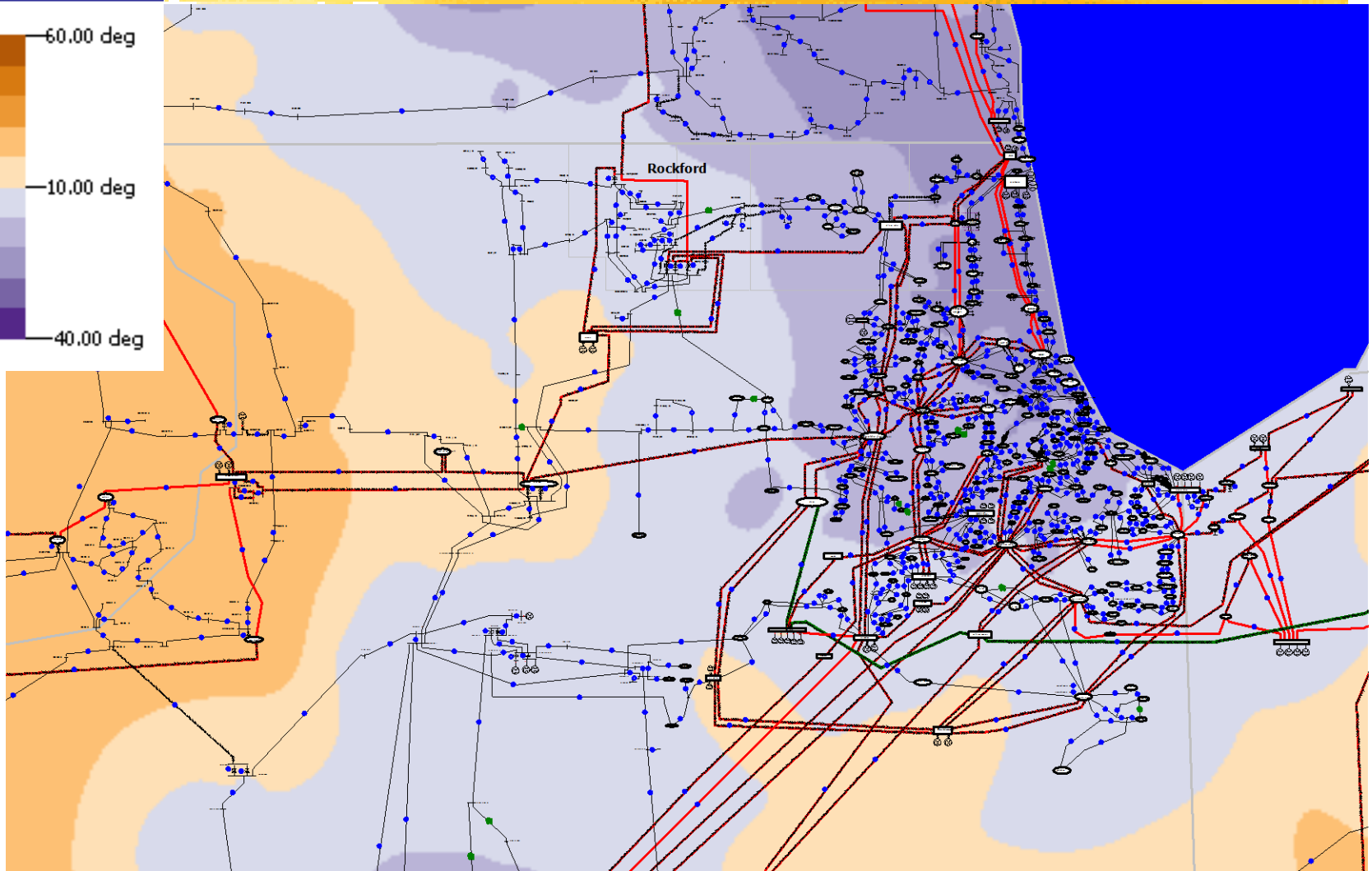
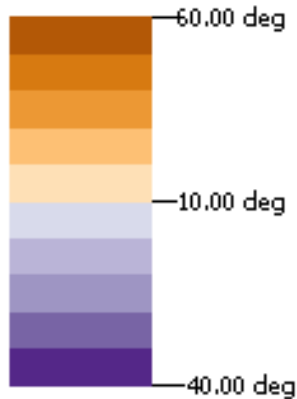
Voltage\Angle (deg)



QE: PMU-Estimated with Transaction



Voltage\Angle (deg)



Questions?

