Data Challenges for Wide-Area Modeling, Analysis and Control using Synchrophasors

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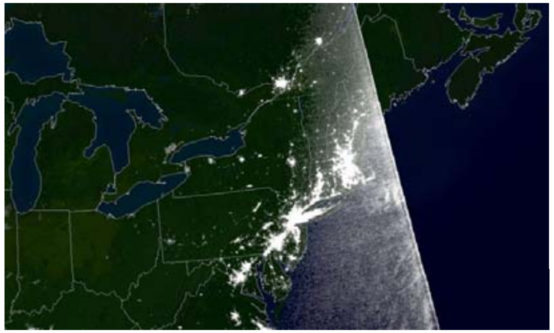
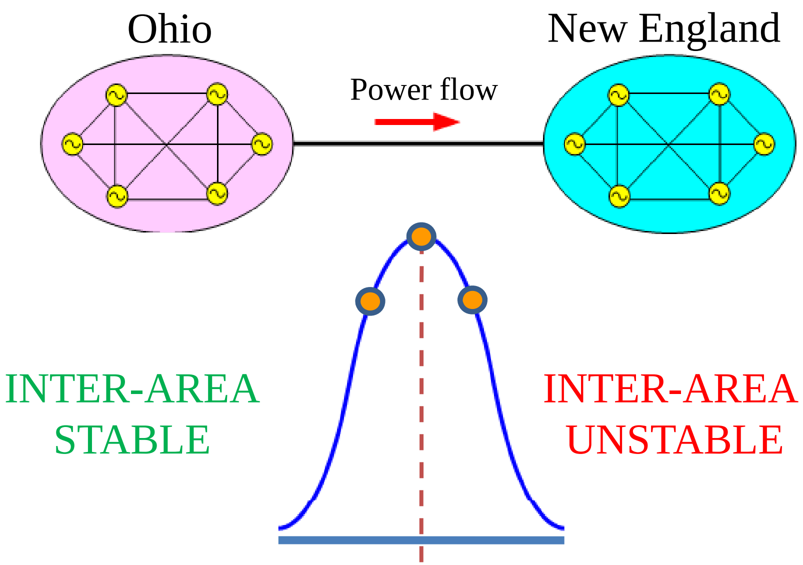
Carnegie Mellon University, PA
14st March, 2012

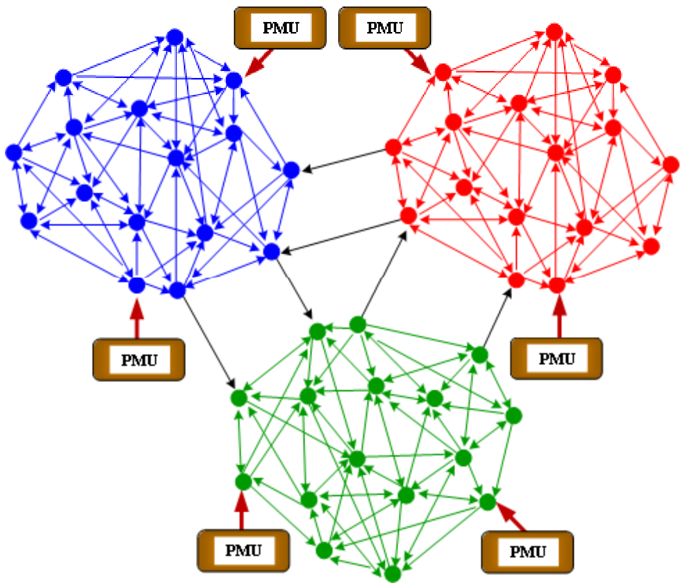
Main trigger: 2003 Northeast Blackout

NYC before blackout



NYC after blackout



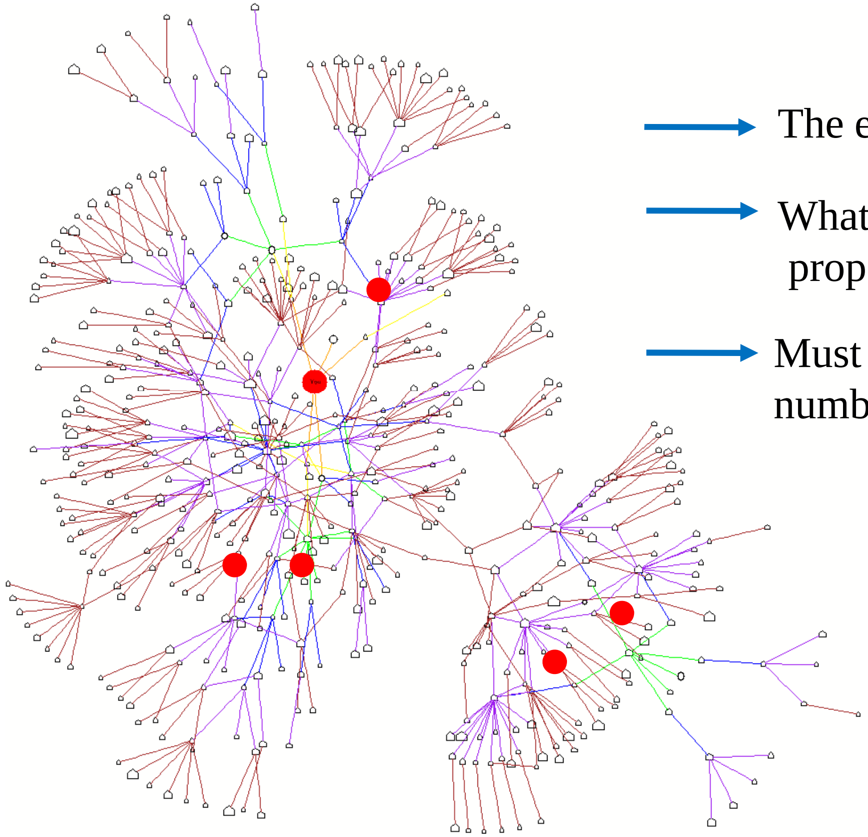


Hauer, Zhou & Trudnowsky, 2004
Kosterev & Martins, 2004

→ Lesson learnt:

1. Wide-Area Dynamic Monitoring is important
2. Clustering and aggregation is imperative

Advanced Transmission & Distribution

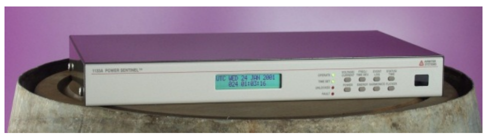


Wide-Area/ Global View

- The electric power network is a large interconnected graph
- Whatever I do is going to affect my neighbors & propagate the disturbance
- Must be able to measure transient signals at limited number of buses

- **Phasor Measurement Units**
- High sampling rate digital devices
- GPS synchronized
- 30-60 samples per second

Phadke et al., 1981
Zhou, Pierre & Trudnowsky, 2006
Phadke & Thorpe, 2007

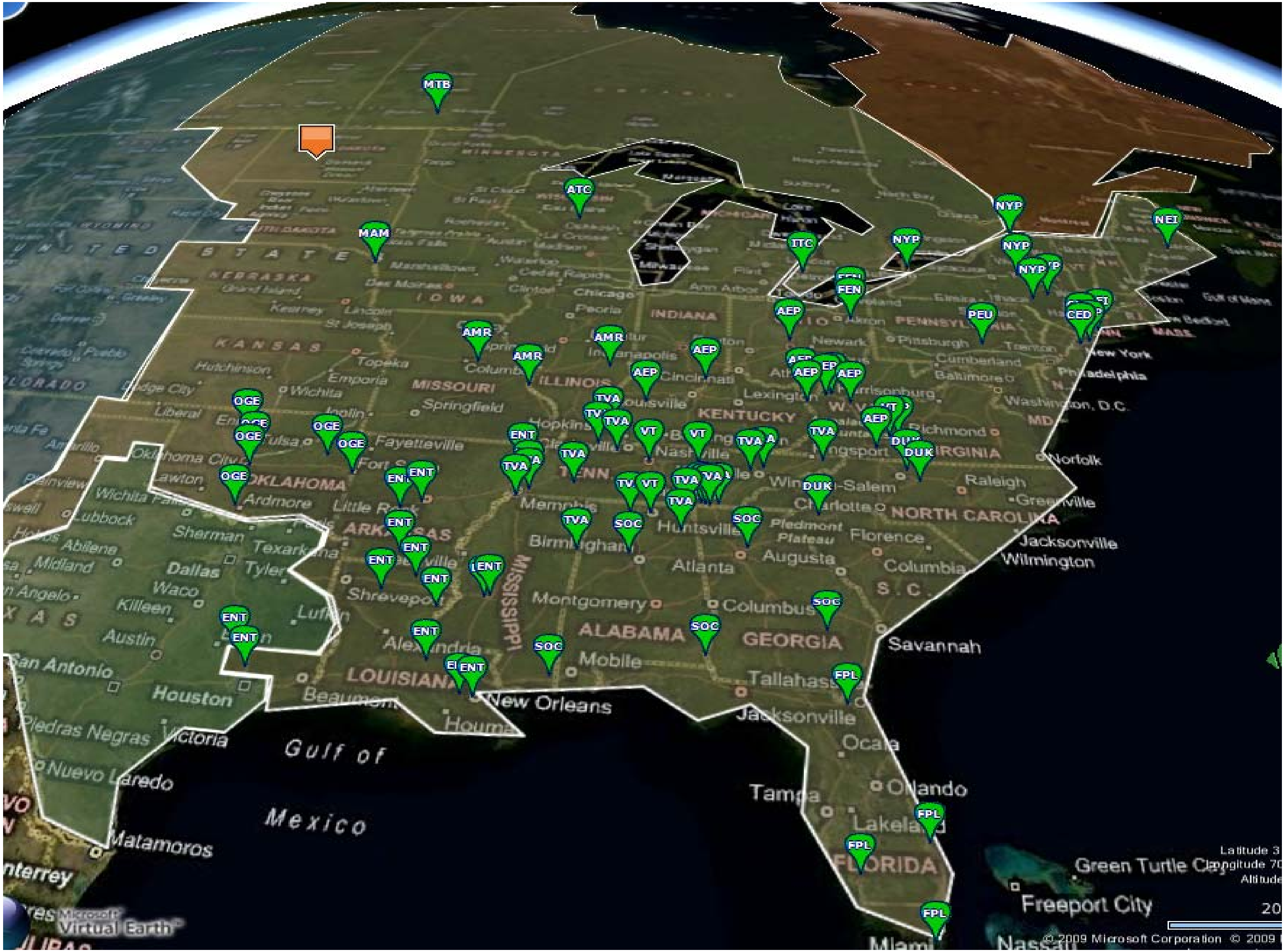


Arbiter

ABB

Schweitzer

→ Global behavior must be understood from the *limited local* measurements



MTB
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MINNESOTA
IOWA
KANSAS
NEBRASKA
MISSOURI
ILLINOIS
INDIANA
KENTUCKY
OKLAHOMA
TENN
ALABAMA
GEORGIA
LOUISIANA
NORTH CAROLINA
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Indianapolis
Cincinnati
Louisville
Lexington
Nashville
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Huntsville
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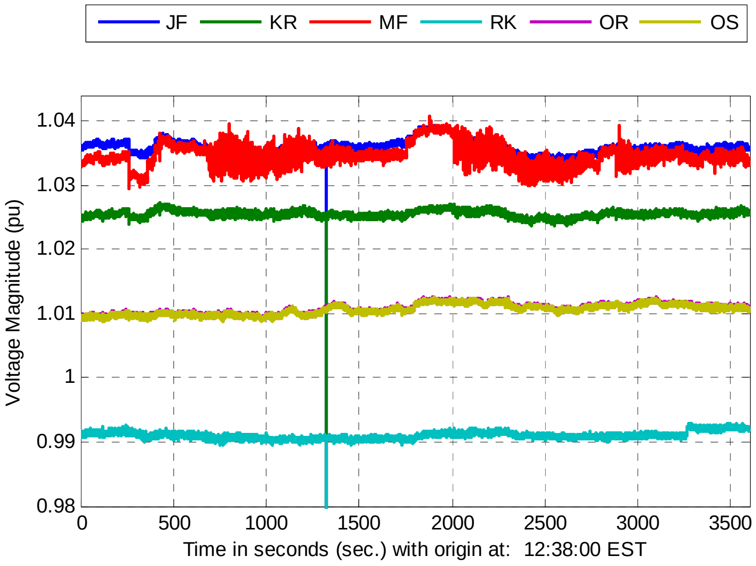
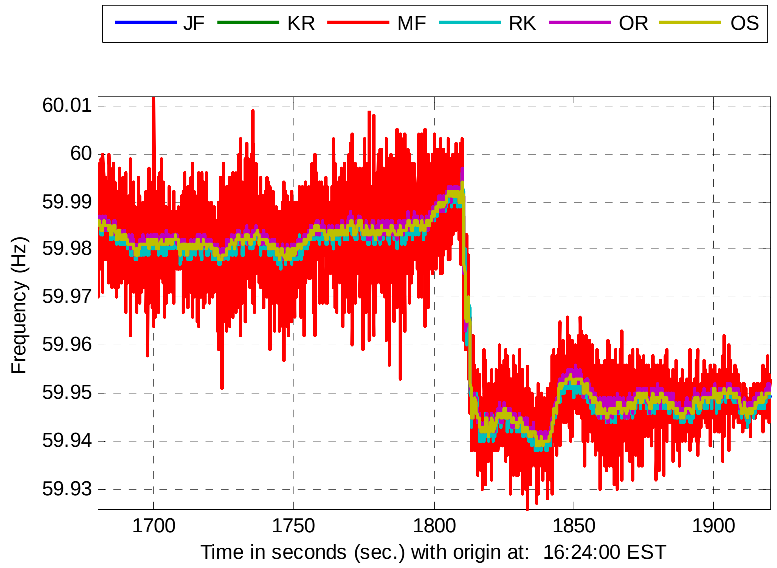
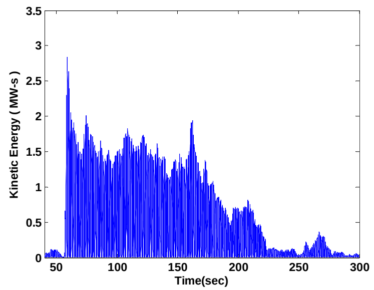
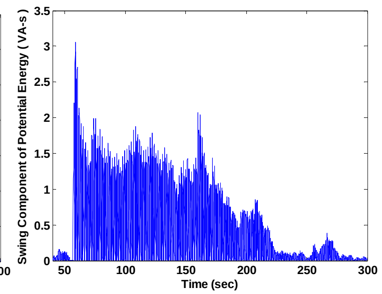




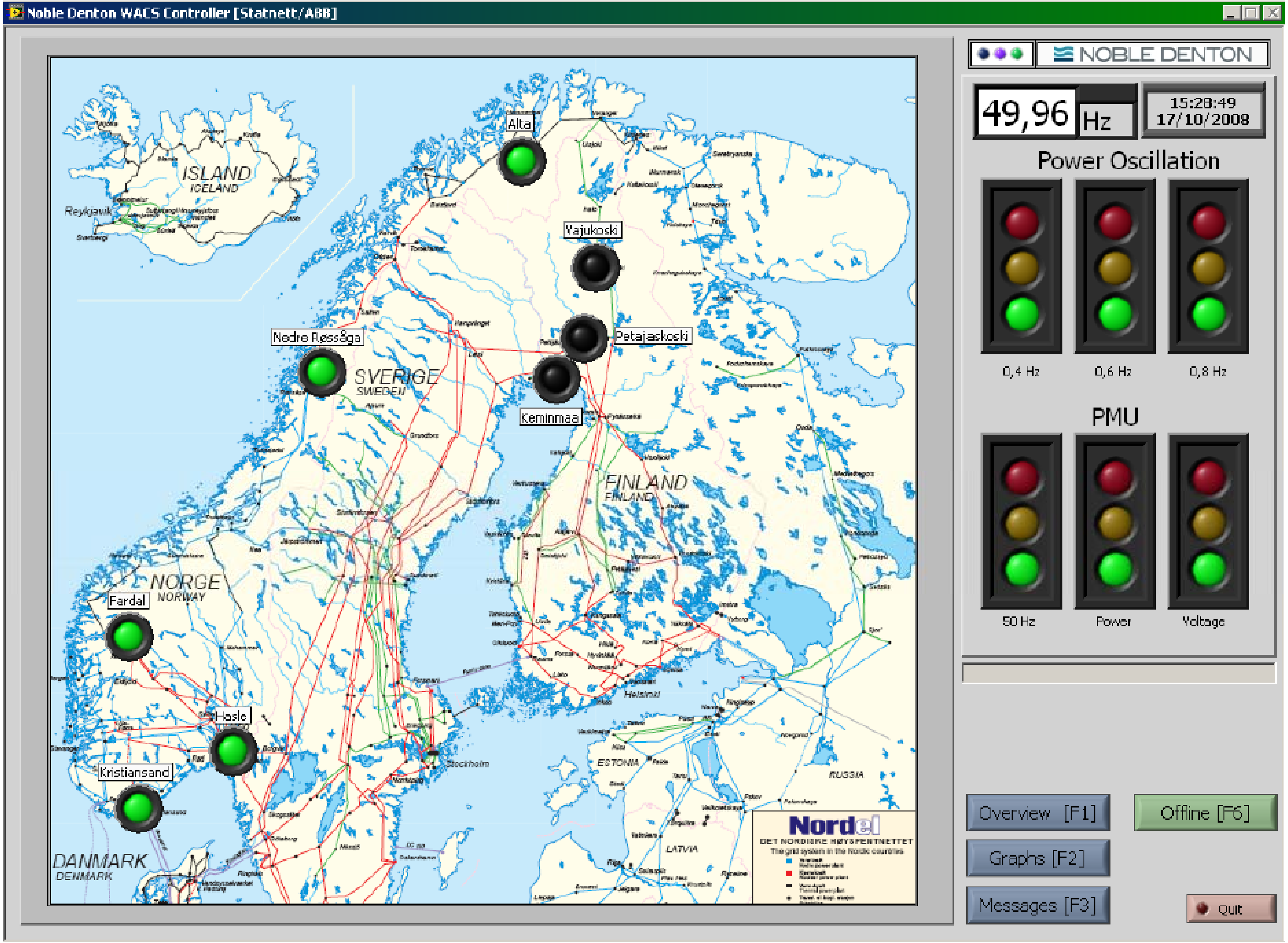
- System wide visibility
- Real time streaming information
- Rapid assessment of actual system conditions through visualization of information
- Event triggered alarms
- Performance Metrics



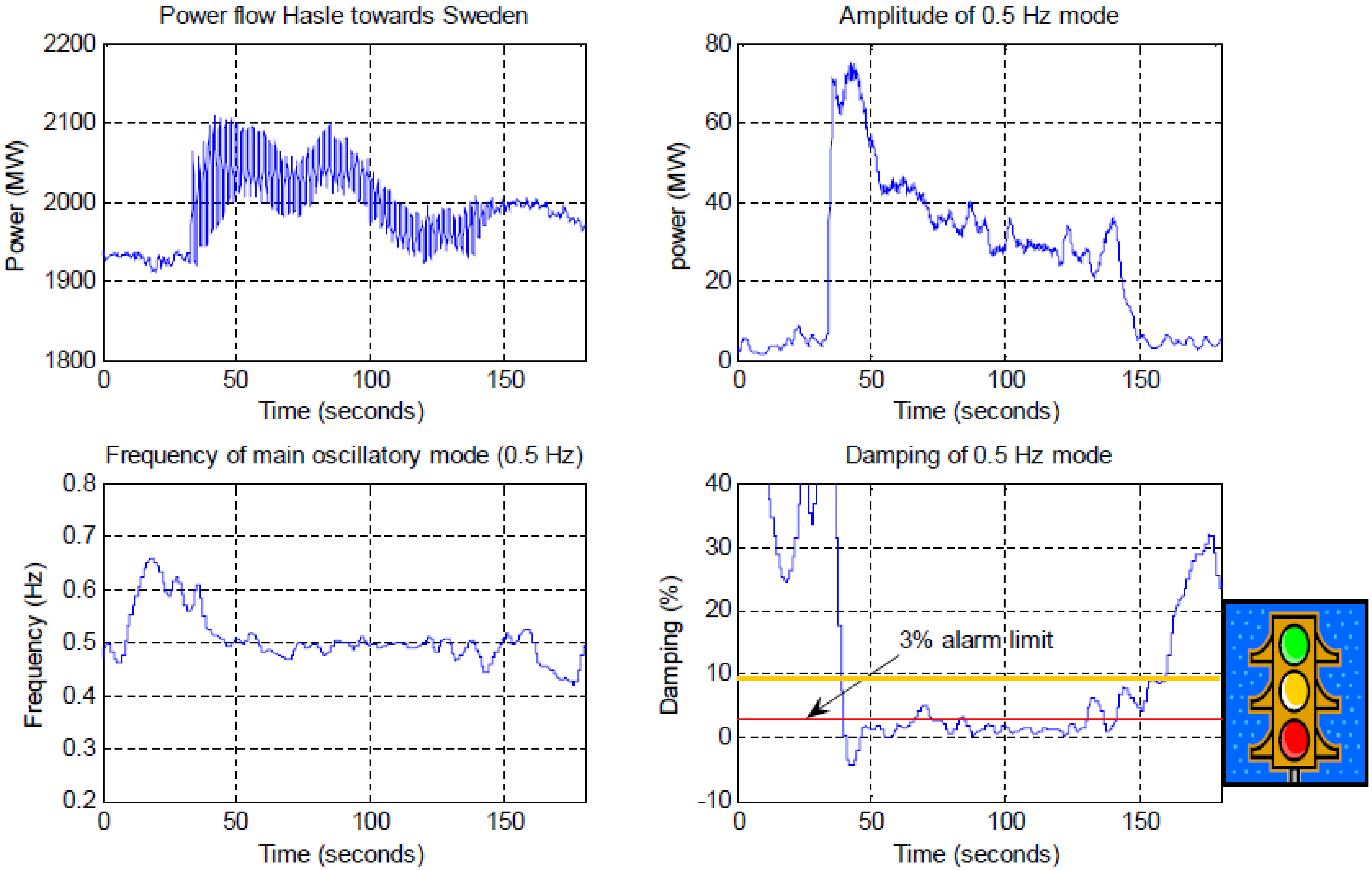


NASPI – North American Synchrophasor Initiative (www.naspi.org)
- jointly held by NERC and DOE 3 times a year

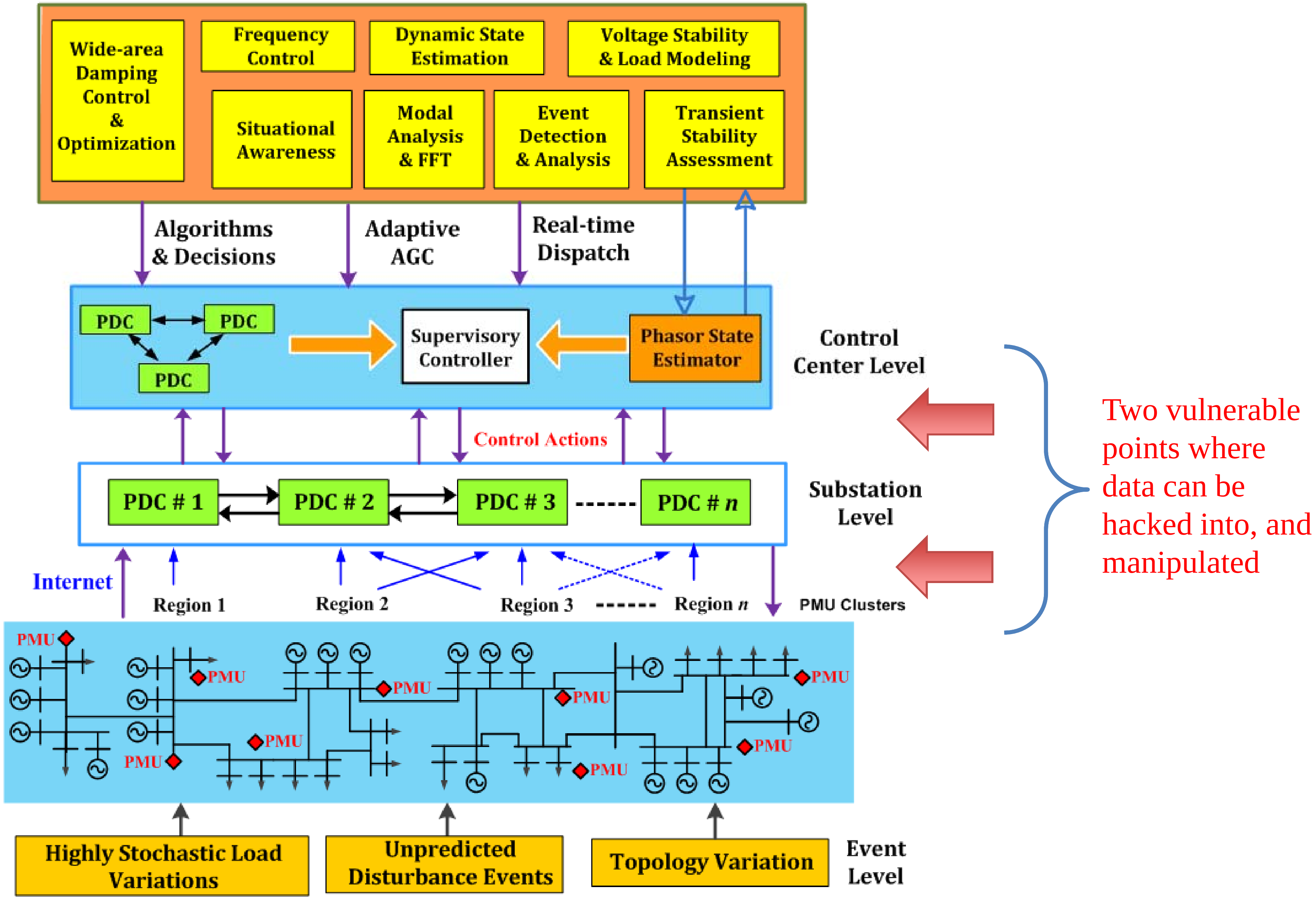
Disturbance events	Maximum swing energy in Transfer Path 1	Maximum swing energy in Transfer Path 2
1	3 MW-s	0.198 MW-s
2	3.5 MW-s	17 MW-s


Noble Denton WACS Controller [Statnett/ABB]
NOBLE DENTON
49,96 Hz
15:28:49
17/10/2008
Power Oscillation
0,4 Hz
0,6 Hz
0,8 Hz
PMU
50 Hz
Power
Voltage
Overview [F1]
Graphs [F2]
Messages [F3]
Offline [F6]
Quit
Alta
Vajukoski
Petajaskoski
Keminmaa
Nedre Røssåga
Fardal
Hasle
Kristiansand
ISLAND
ICELAND
SVERIGE
SWEDEN
FINLAND
NORGE
NORWAY
DANMARK
DENMARK
ESTONIA
LATVIA
RUSSIA
Stockholm
Helsinki
Reykjavik
Nordel
DET NORDISKE HØYSPENTNETTET
The grid system in the Nordic countries

Power oscillation monitoring function



Distributed Architecture for PMU Applications

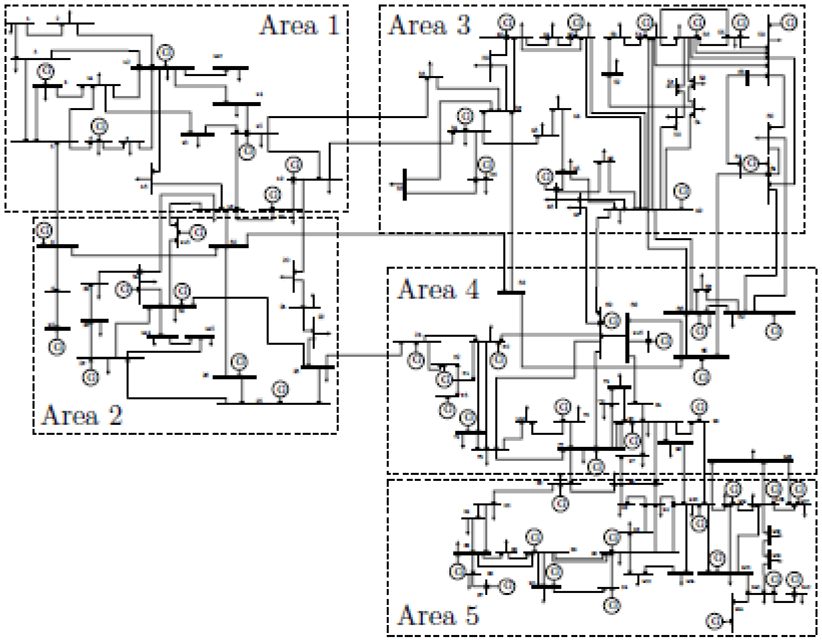


Ongoing PMU Projects

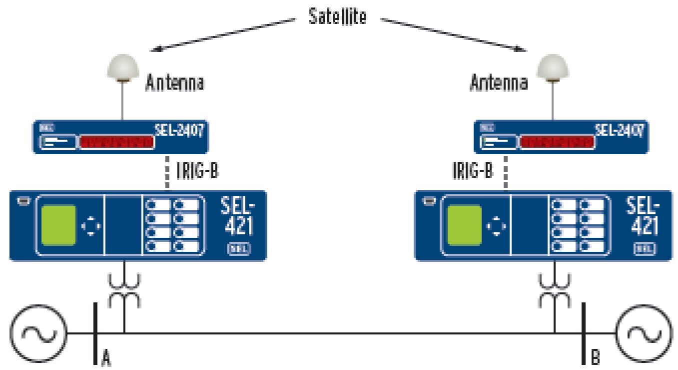
Wide-area Modeling

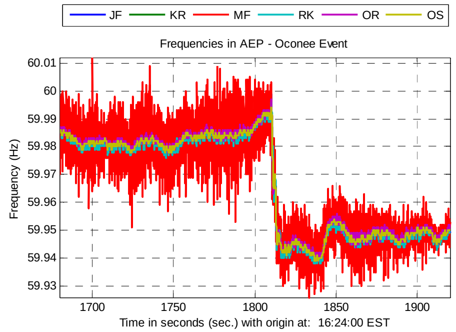
Wide-area Monitoring
Distributed State Estimation

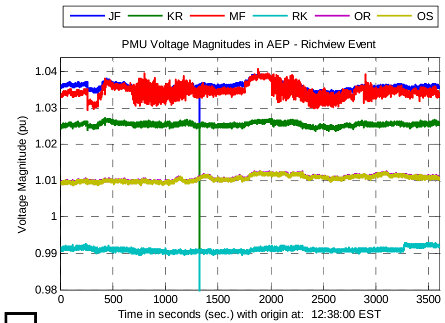
Wide-area Control



64 Bus New England Power System Model



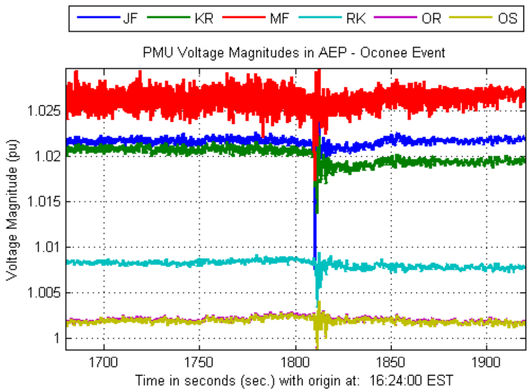


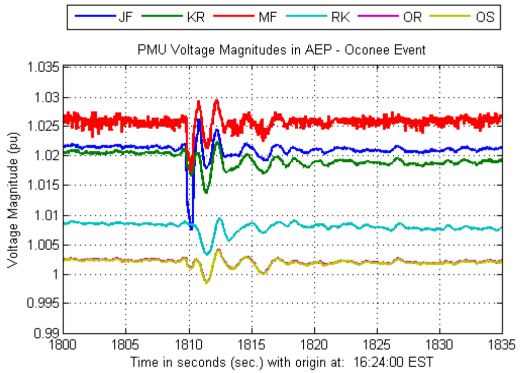


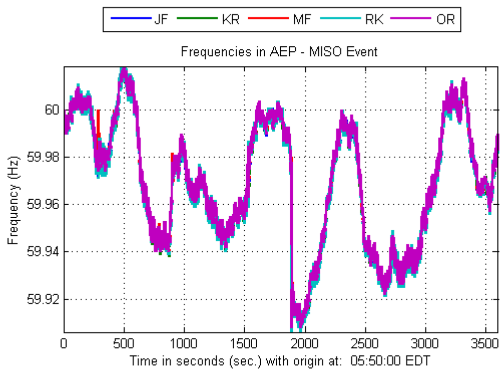
- Security if imperative for all three applications (real-time and offline)

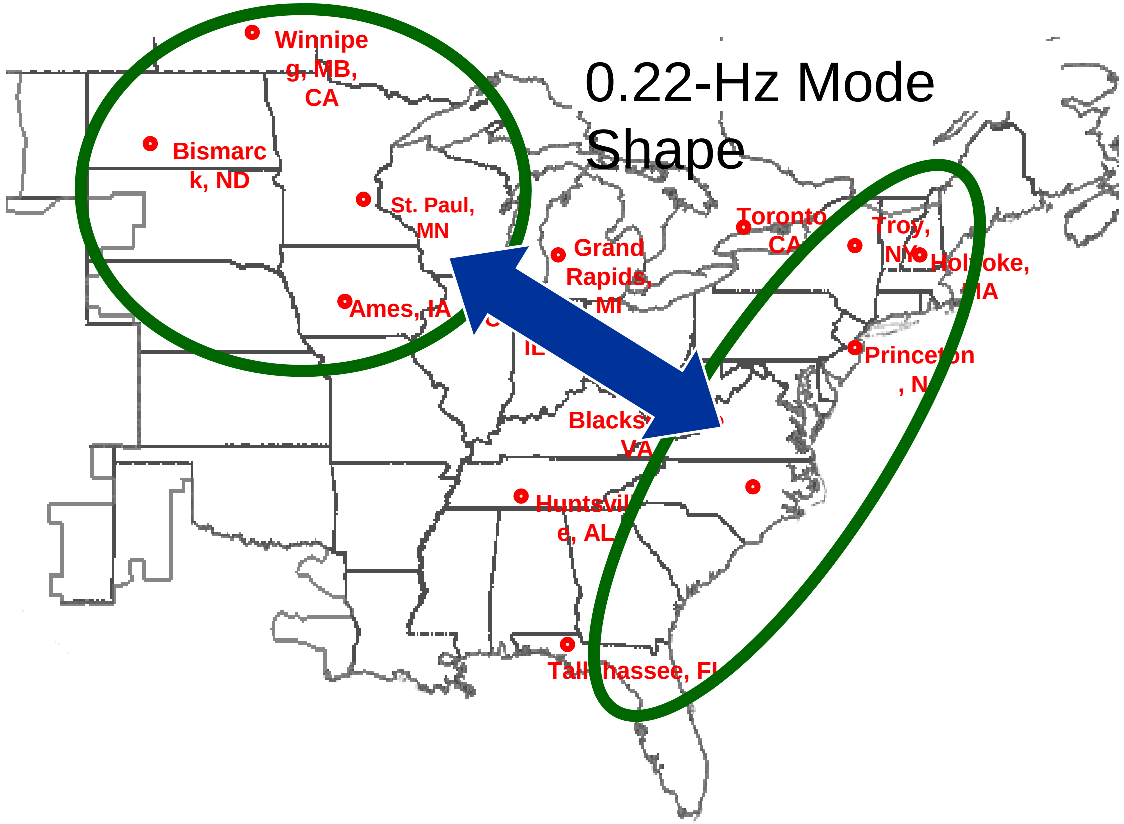
Derive Dynamic Mathematical Model of the Clusters

System-wide Oscillation Detection - *How power generation clusters oscillate*



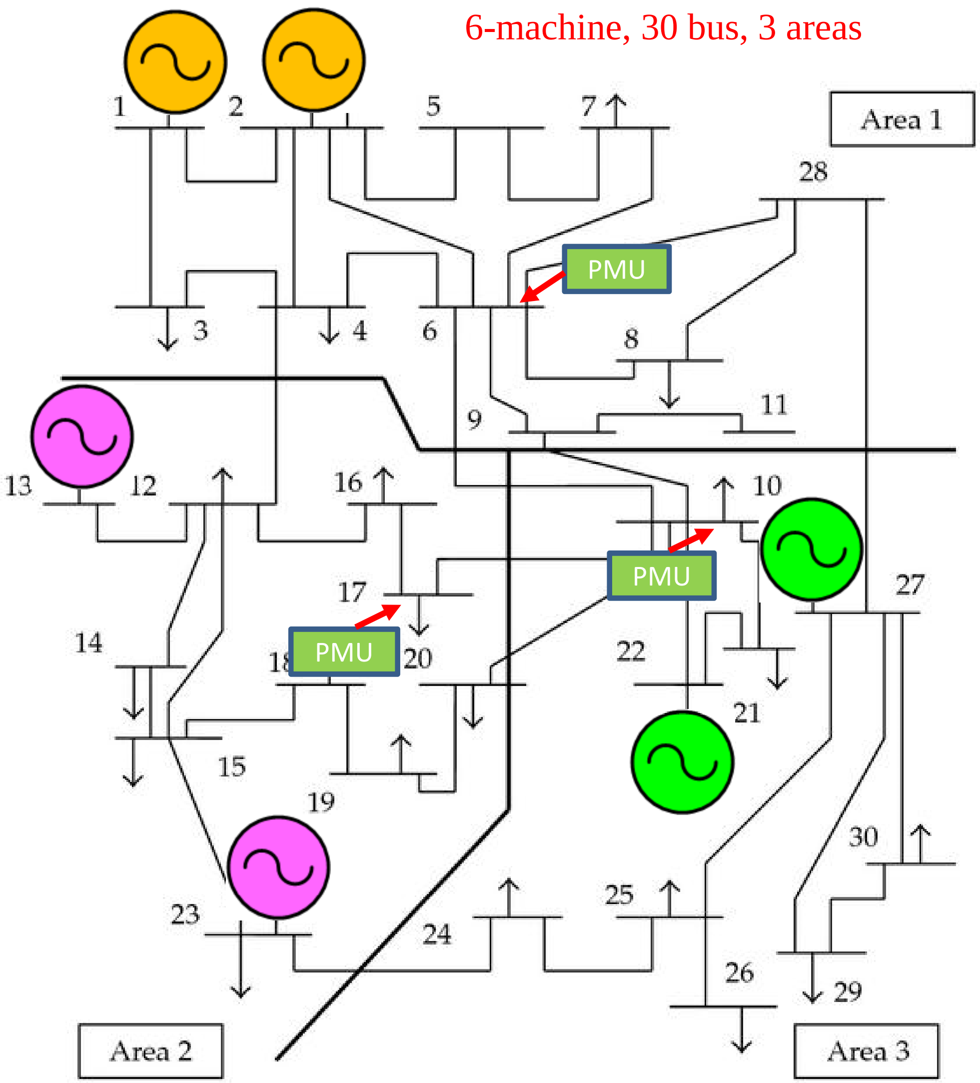






- How do different oscillating zones of the system oscillate with respect to each other after a disturbance just like an interconnected pendulum
- Dynamic PMU data are ideal for answering these questions
- Highly useful for system level studies for operation & planning

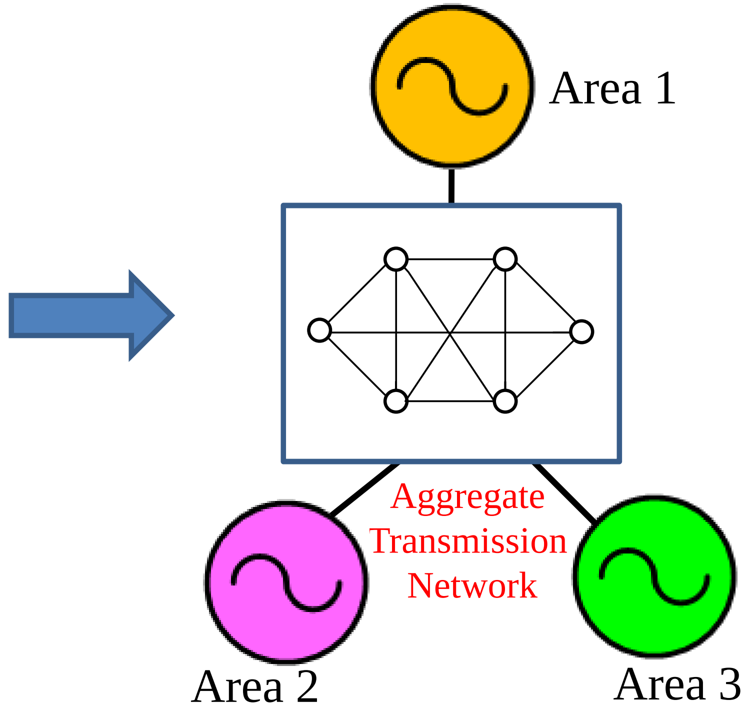
Model Aggregation using distributed PMU data



Problem Formulation:

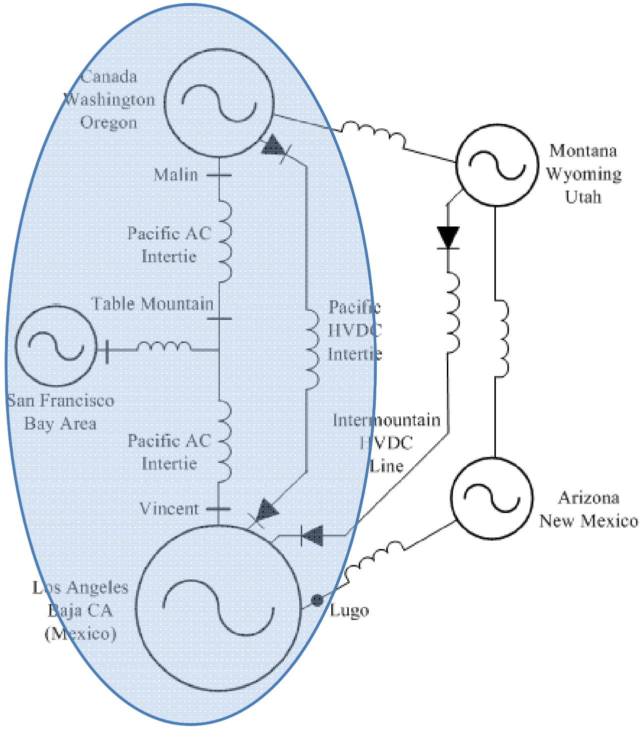
1. Model Reduction

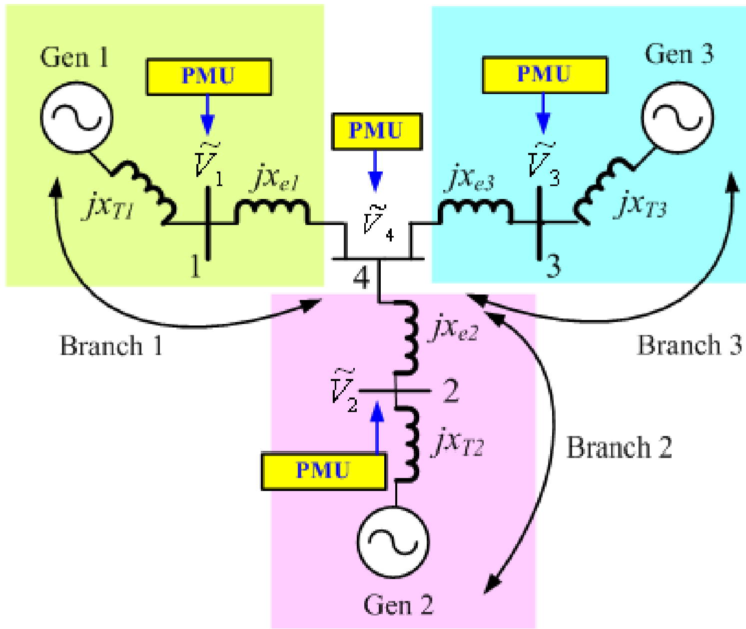
- How to form an aggregate model from the large system



Two-Dimensional Models

More than Two Areas: Pacific AC Intertie





Salient Points

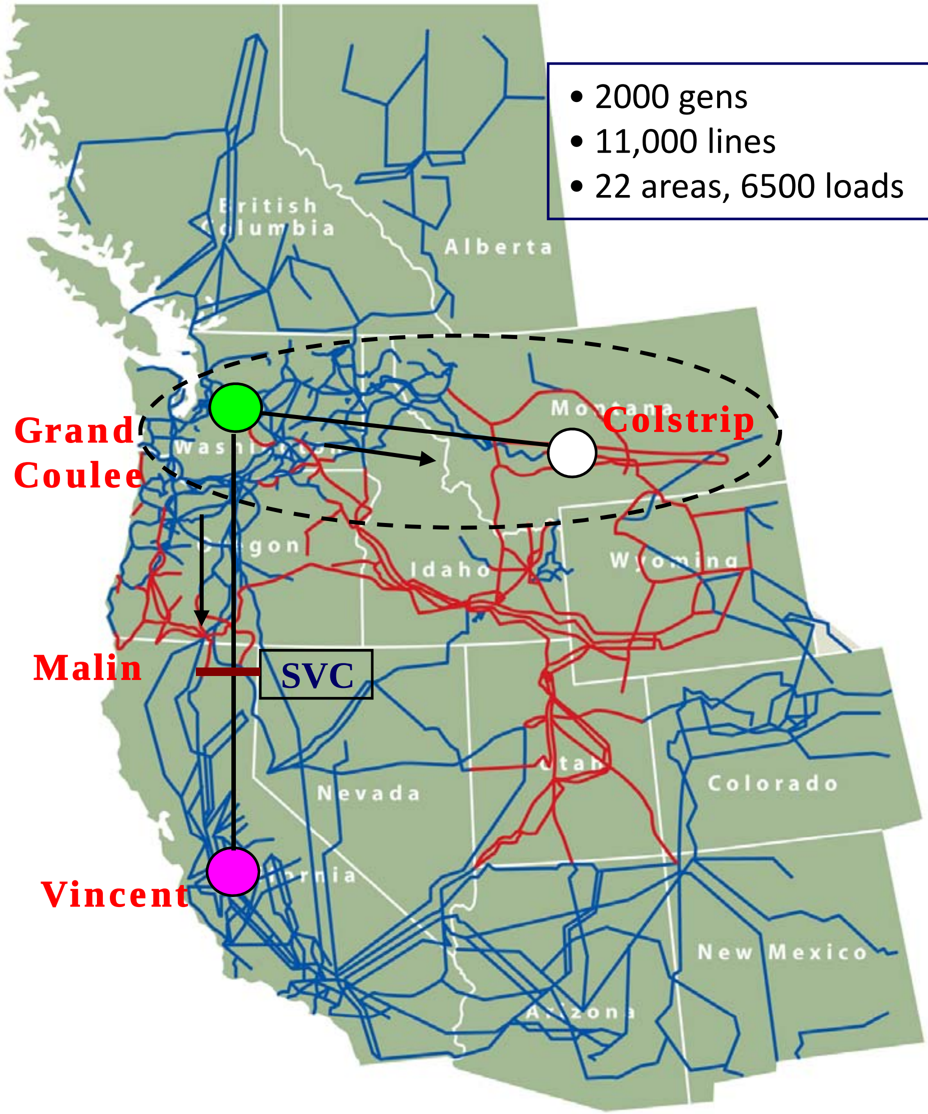
- Current in each branch is different
- No *single* spatial variable *a*
- Derivations need to be done *piecewise* (each edge of the star)
- Two interarea modes/ relative states – δ_1 & δ_2

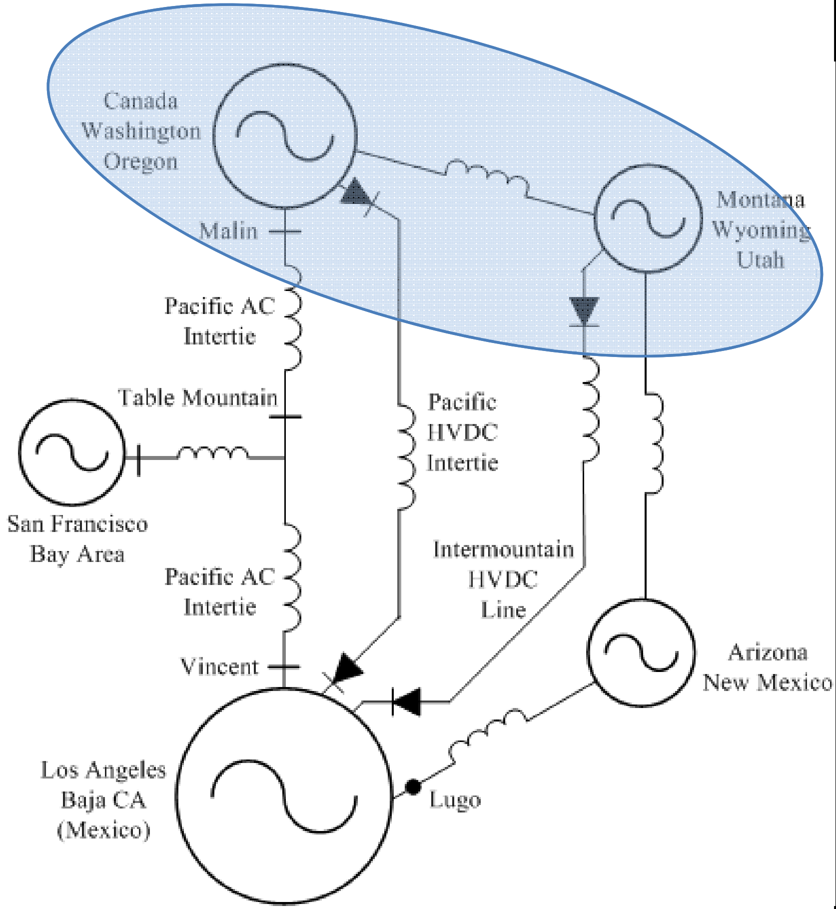
$$V_n = J_1(x)\Delta\delta_1(t) + J_2(x)\Delta\delta_2(t)$$

$$\frac{V_n^{\,3}}{V_n^{\,4}} = \frac{J_1^{\,3}(x)\Delta\delta_1(t^*) + J_2^{\,3}(x)\Delta\delta_2(t^*)}{J_1^{\,4}(x)\Delta\delta_1(t^*) + J_2^{\,4}(x)\Delta\delta_2(t^*)}$$

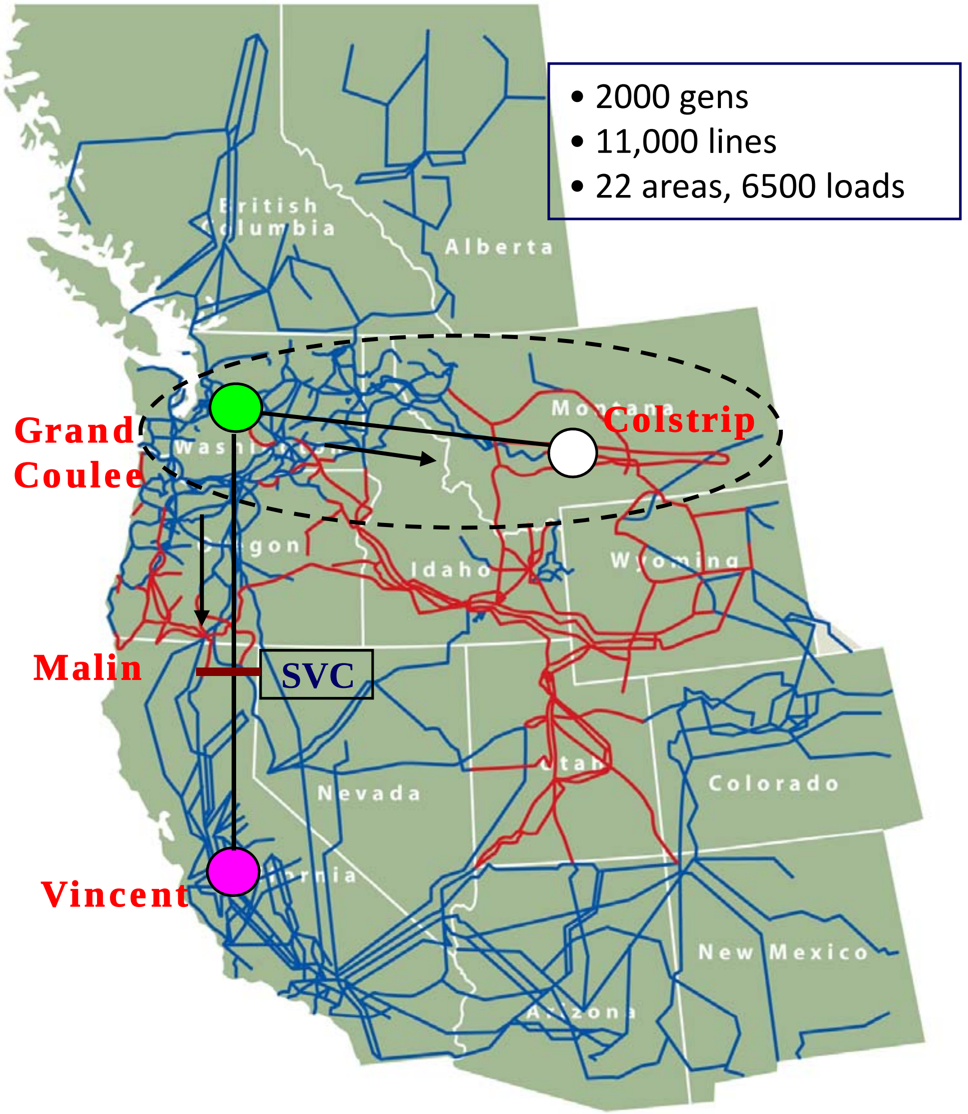
Time-space separation property lost!

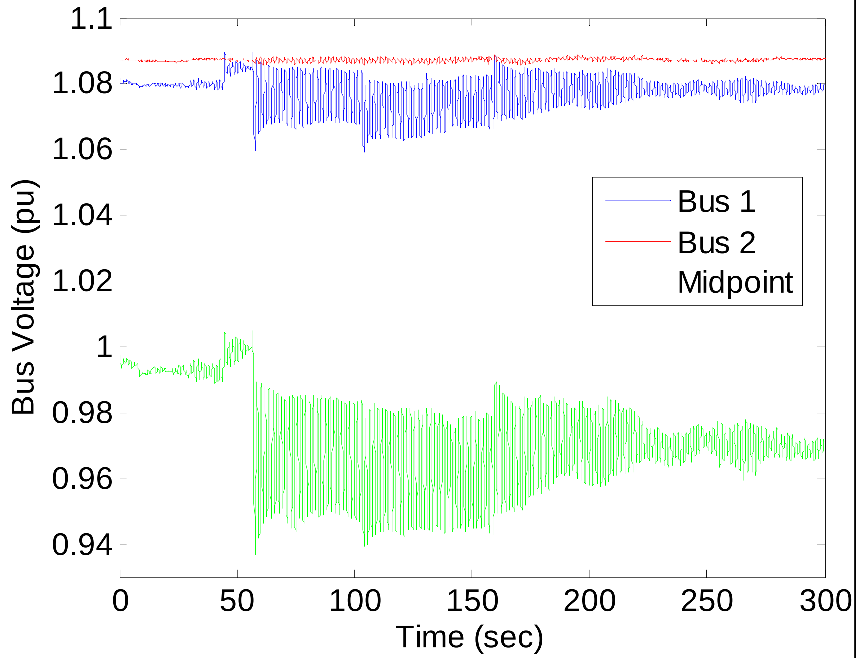
Application to WECC Data





Application to WECC Data

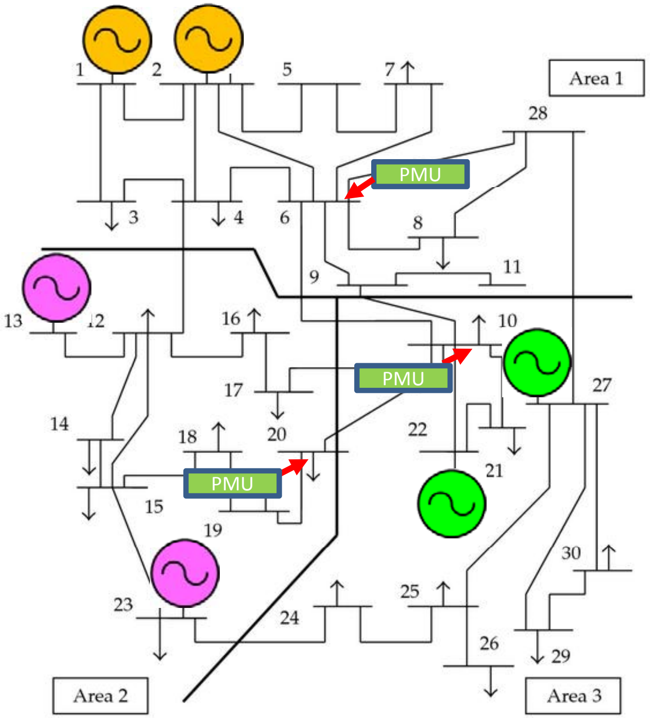




Needs processing to get usable data

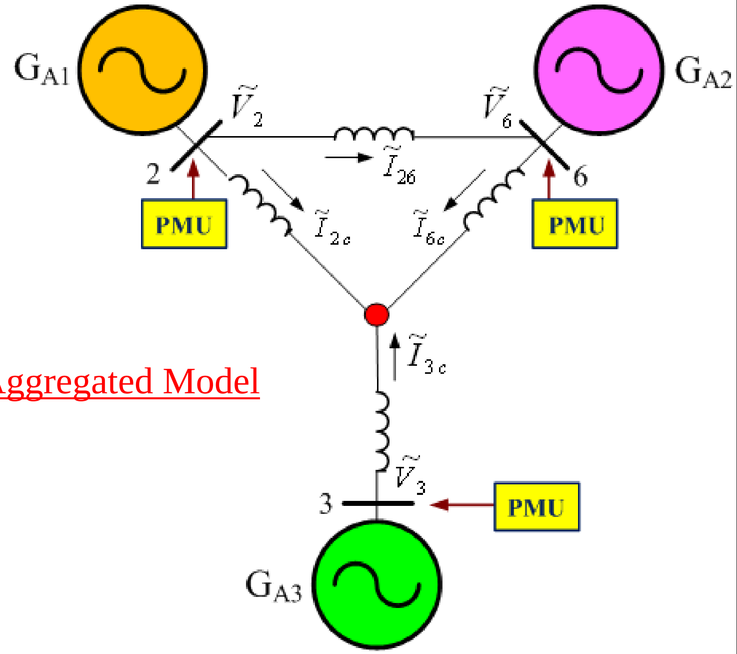
- Sudden change/jump
- Oscillations
- Slowly varying steady-state (governer effects)

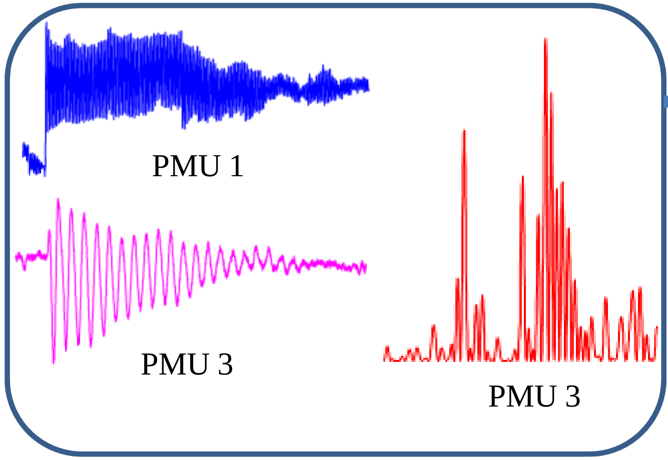
Application for Stability Assessment



Full Model

Aggregated Model



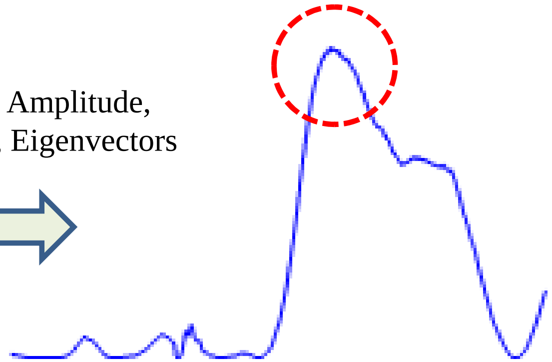


Signal Processing

+

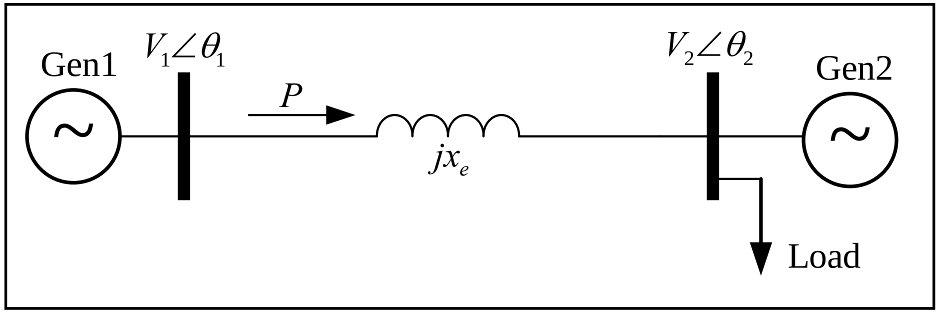
Aggregated Model

Modes, Amplitude, Residues, Eigenvectors



Metrics indicating the dynamic interaction between the areas

Energy Functions for Two-machine System



$$\dot{\delta} = \Omega\delta, \quad 2H\dot{\omega} = P_m - \frac{E_1E_2\sin(\delta)}{x_e'}$$

$$P = \frac{E_1E_2\sin(\delta)}{x_e'}$$

$$S = S_1 + S_2 = \sum_{j=1}^{n(n-1)/2} \int_{\delta_{ij}*}^{z_j} \psi_j(k)\,dk + \sum_{j=1}^{n} \frac{M_j}{2}\xi_j^2$$

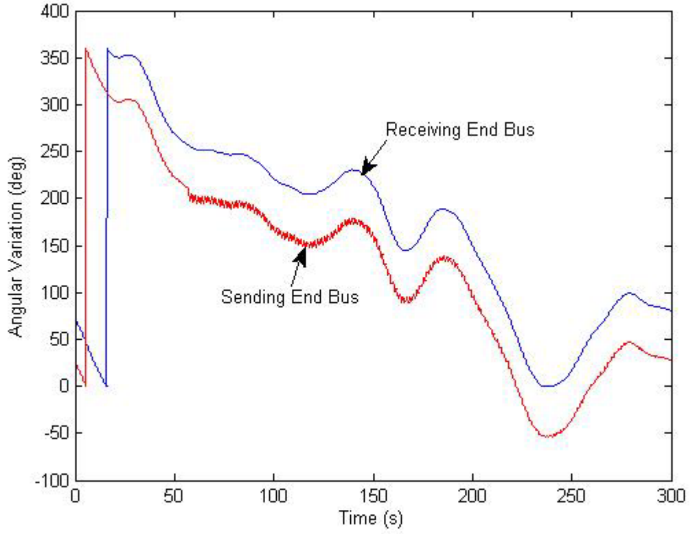
$$= \underbrace{\frac{E_1E_2}{x_e'}[\cos(\delta_{op}) - \cos(\delta) + \sin(\delta_{op})(\delta_{op} - \delta)]}_{\text{Potential Energy}} + \underbrace{H\omega^2}_{\text{Kinetic Energy}}$$

Using IME algorithm: x_e' E_1, E_2, $\delta = \delta_1 - \delta_2$, δ_{op}, $\omega = \omega_1 - \omega_2$ & H are computable from

x_e, V_1, V_2, $\theta = \theta_1 - \theta_2$, θ_{op}, $v = v_1 - v_2$ & ω_s

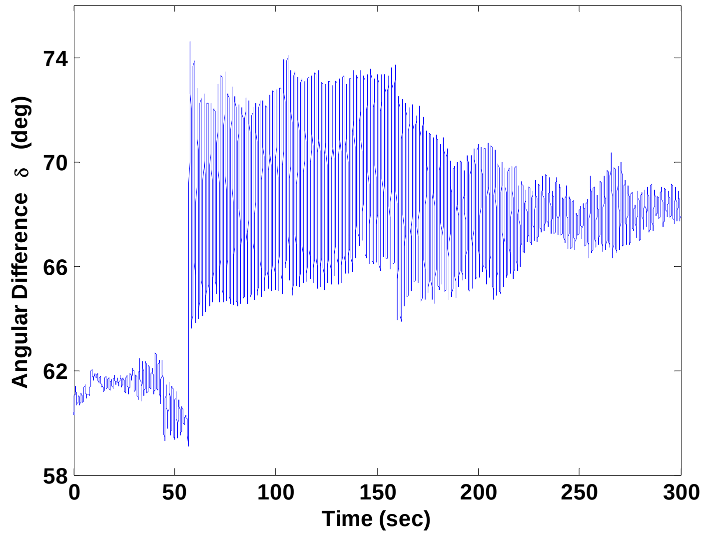
- Note : θ_{op} = *pre-disturbance angular separation*

Energy Functions for WECC Disturbance Event

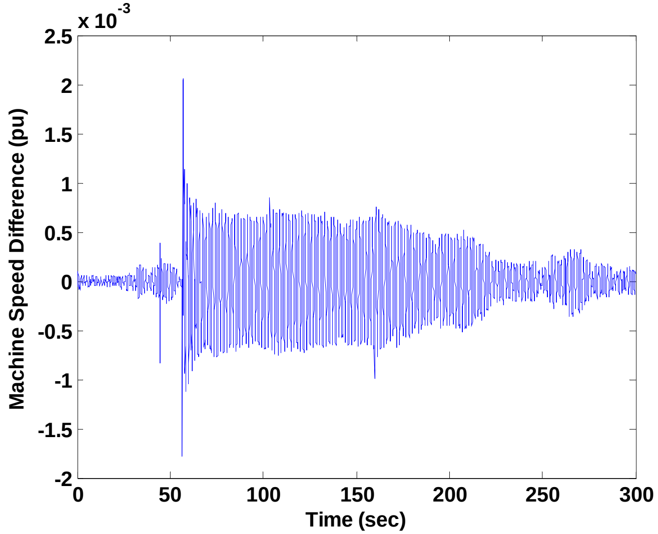


Sending End and Receiving End
Bus Angles

IME

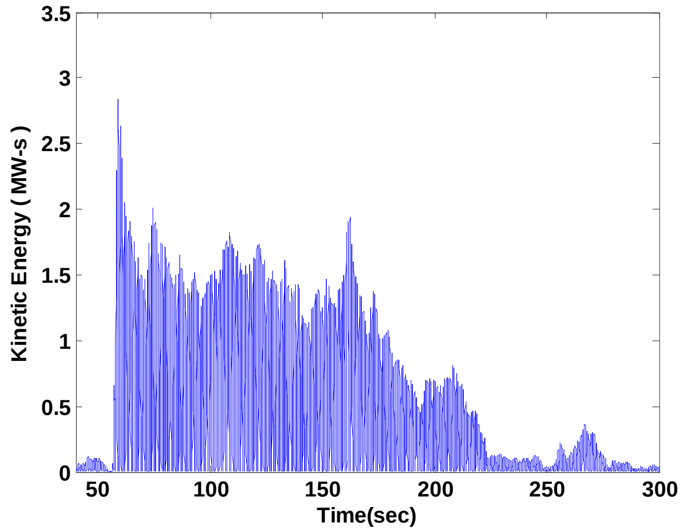


Angle difference between
machine internal nodes

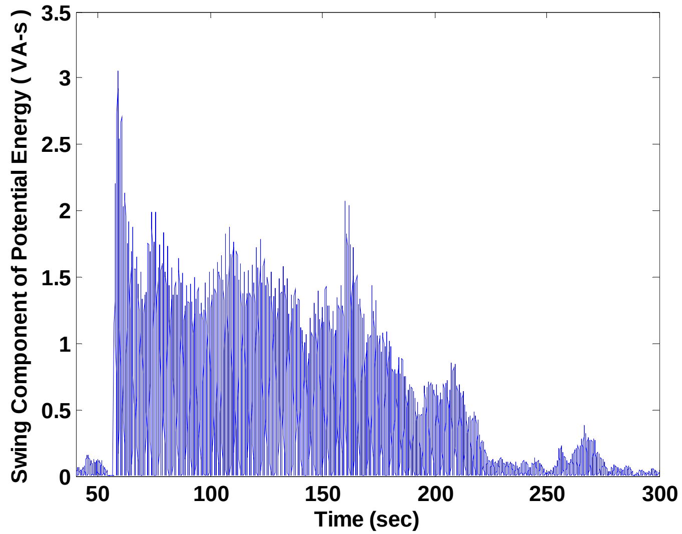


Machine speed difference

Energy Functions for WECC Disturbance Event

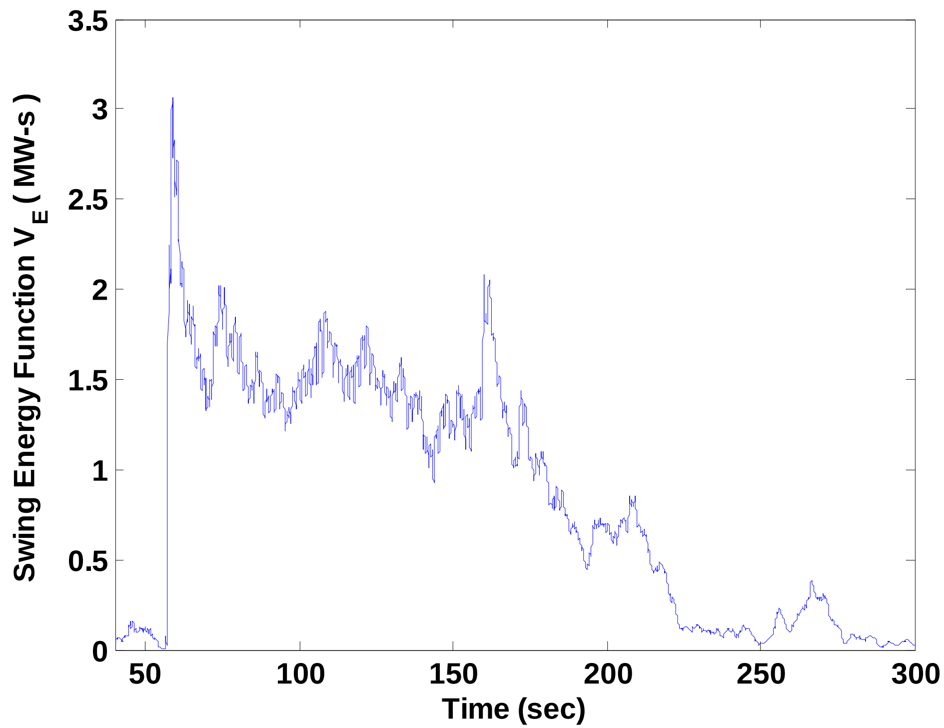


Kinetic Energy



Potential Energy

Total Energy = Kinetic Energy + Potential Energy

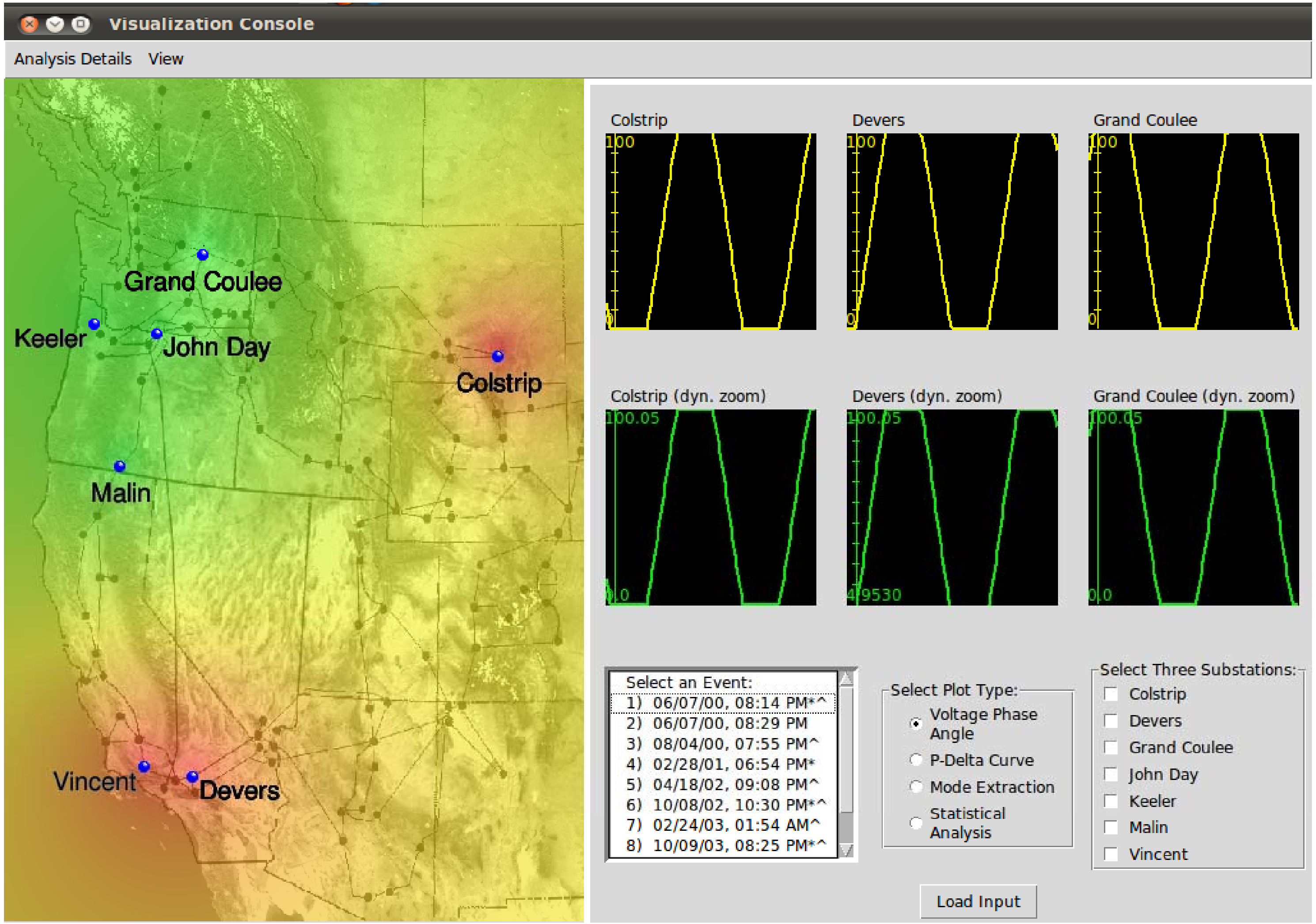


- Total energy decays exponentially – *damping stability*
- Total energy does not oscillate – *Out - of - phase osc.*

  – *Damped pendulum*

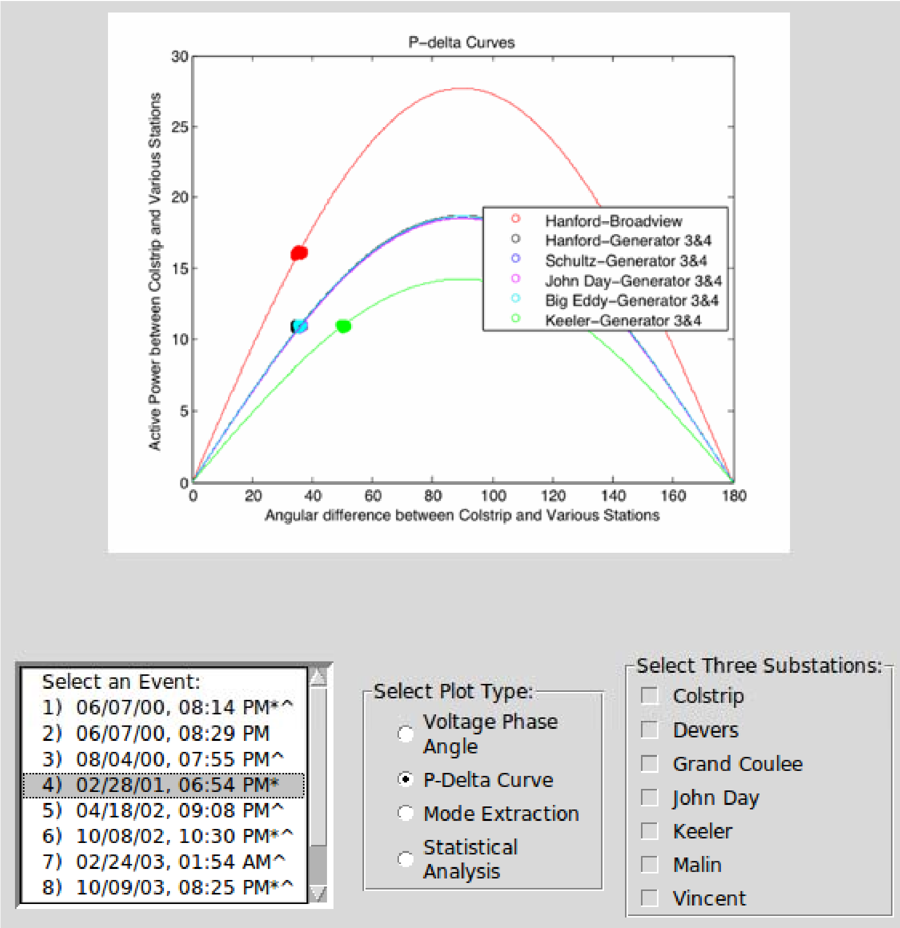
WatchDog: A Software Visualization Tool for Wide- Area Monitoring

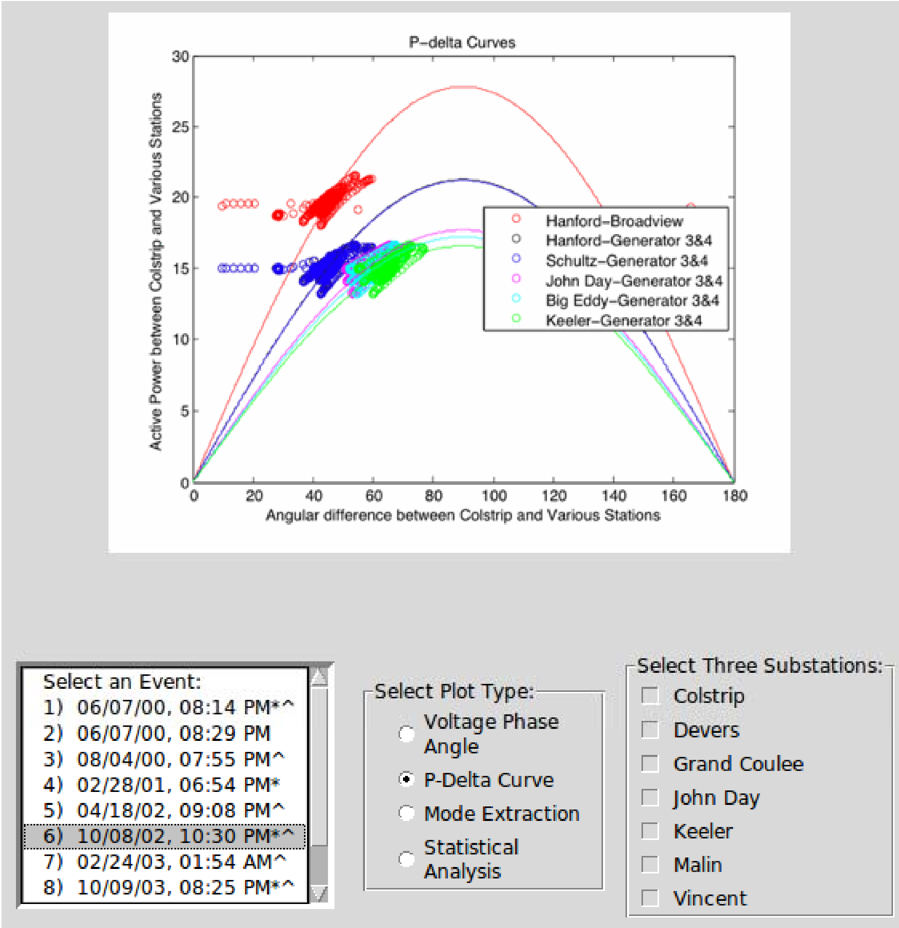
- Joel Anderson and A. Chakrabortty



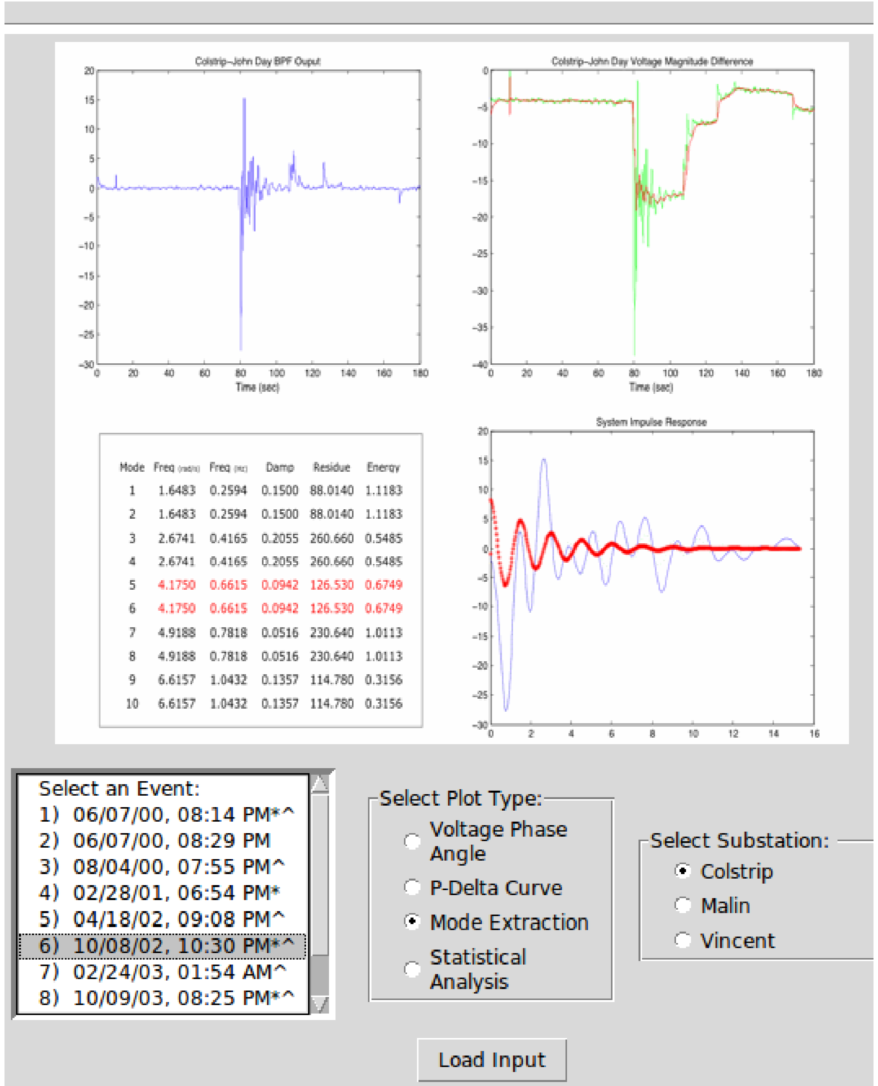
- Phase Angle Contour Videos
- Power-angle Curves
- Modal Analysis through ERA
- Inter-area response Visualization
- Statistical Analysis/baselining
- Streaming real-time data from 7 PMU stations
- 3D baselining plots
- PMU Placement Algorithms

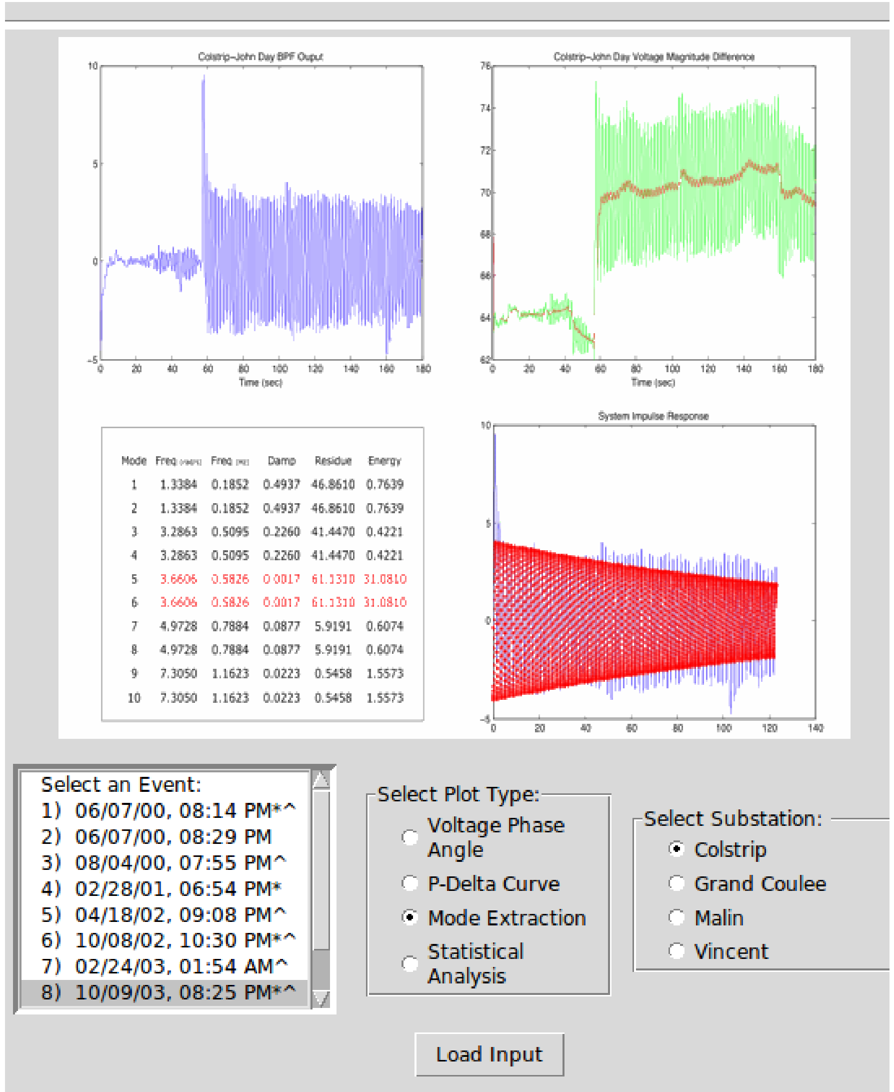
P-Delta Curves





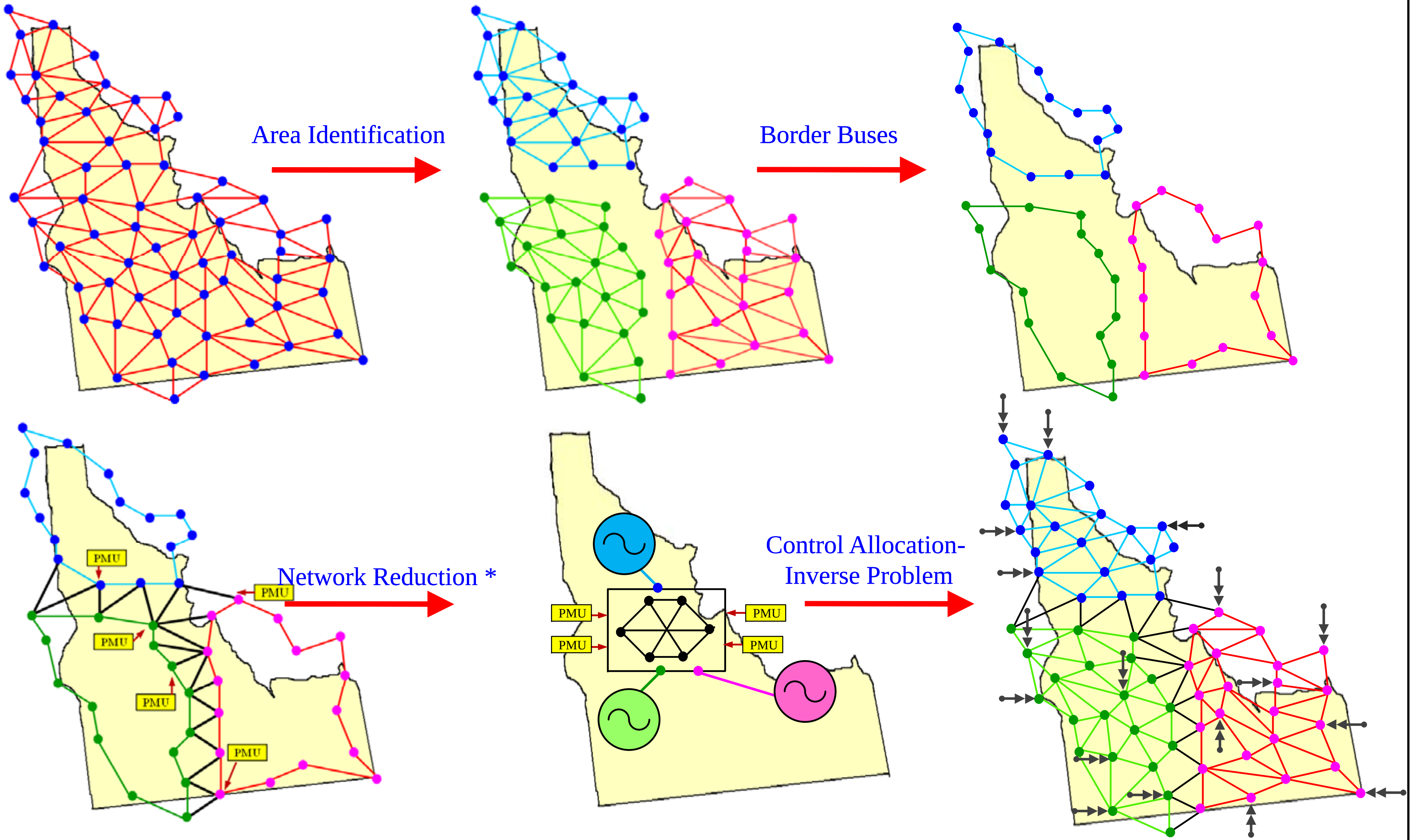
Mode Extraction Information





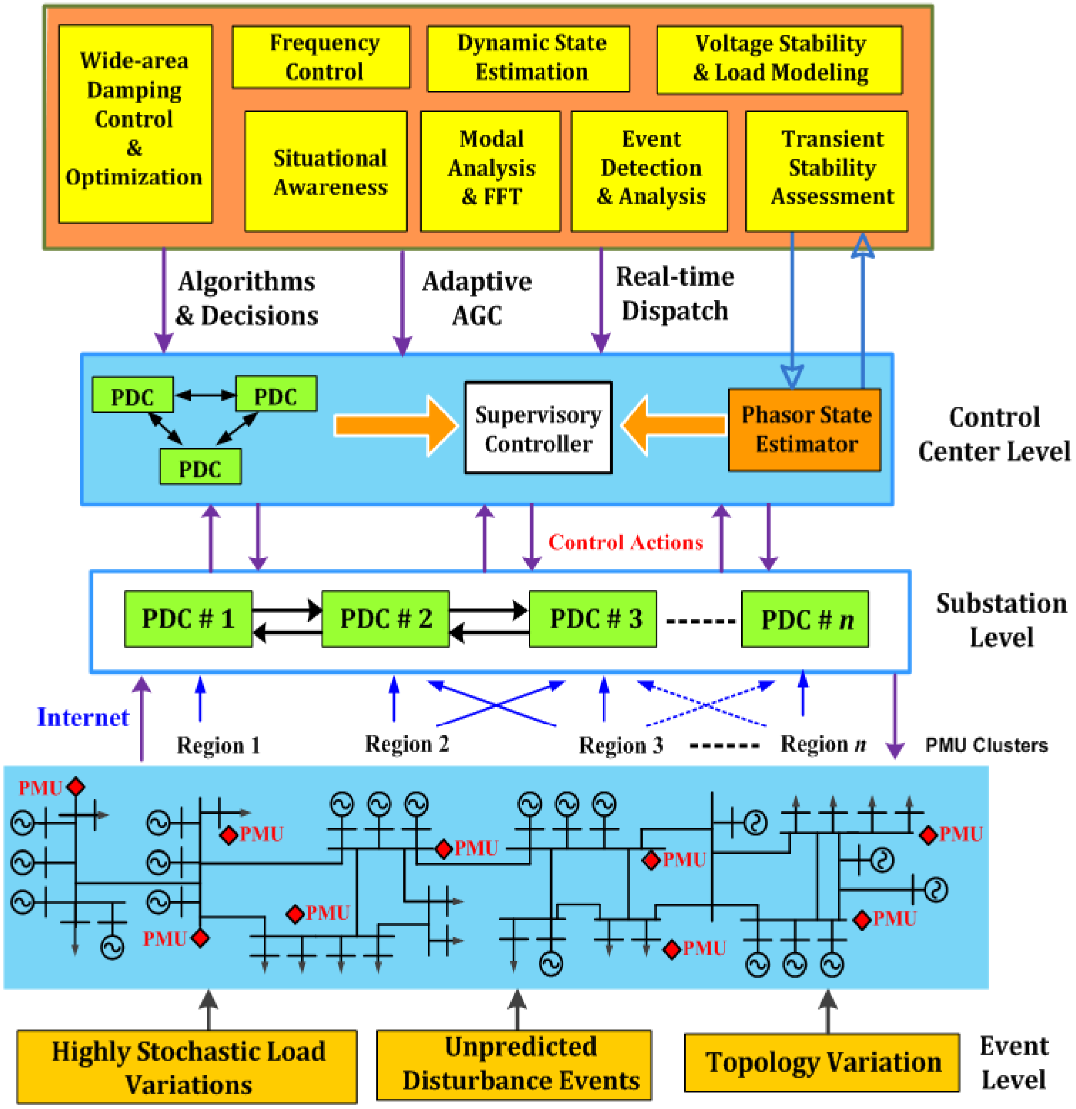
The Wide-area Damping Control

• Computational complexity sharply increases with number of areas

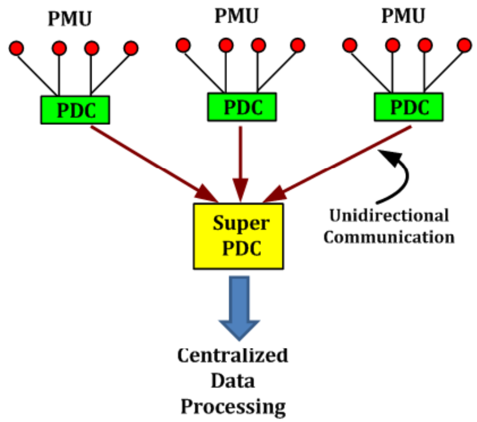


• Please see CDC 2011, ACC 2012 papers by *Chakrabortty* on model-reference control (MRC) approach,

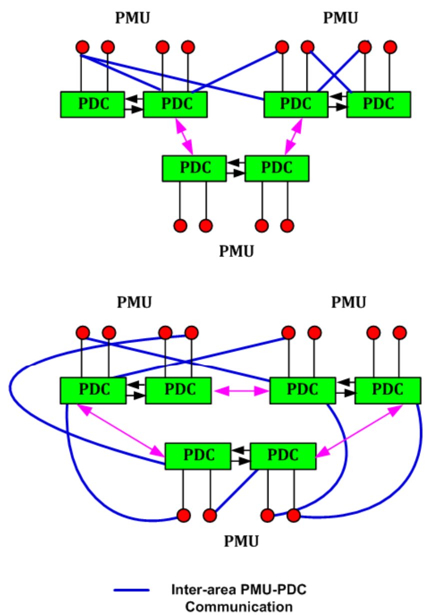
Distributed Architecture for PMU Applications



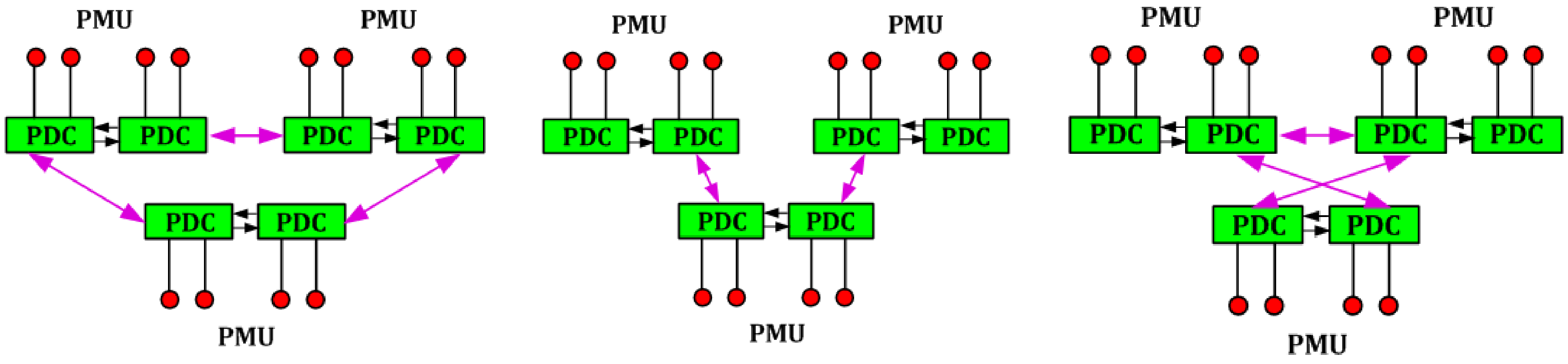
Chakrabortty, Michailidis and Xin, CDC 2012



State-of-art Centralized Processing



Distributed PMU Networks

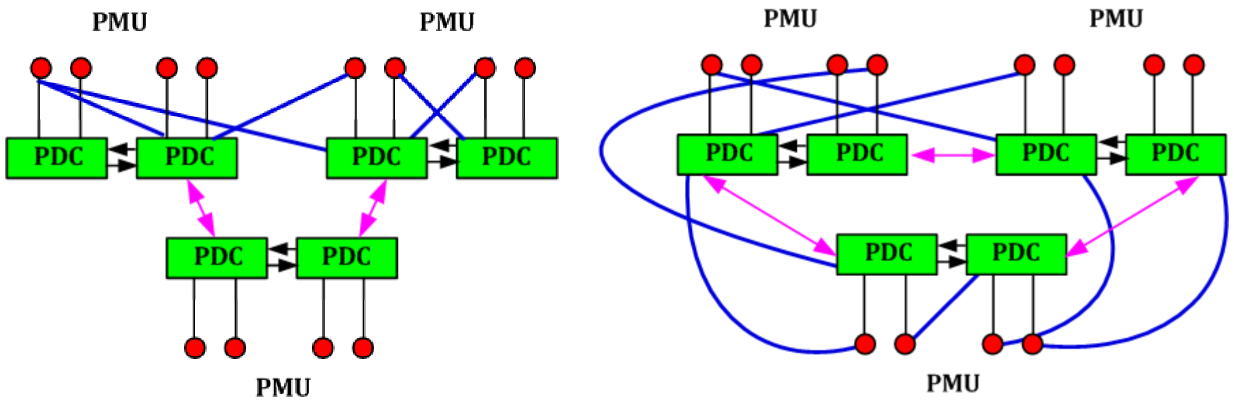


Optimization variables: Data exporting rates of PMUs or virtual PMUs
Information update rate between PDCs – local and inter-area
Network bandwidth

Constraints: Network delays, Processing delays, Congestion, Dynamic routing

- Define an execution metric *M* for each application of the PMU-net
- Minimize the error between distributed M_d and corresponding centralized M_c

Dynamic Rate Control Problem (DRCP)

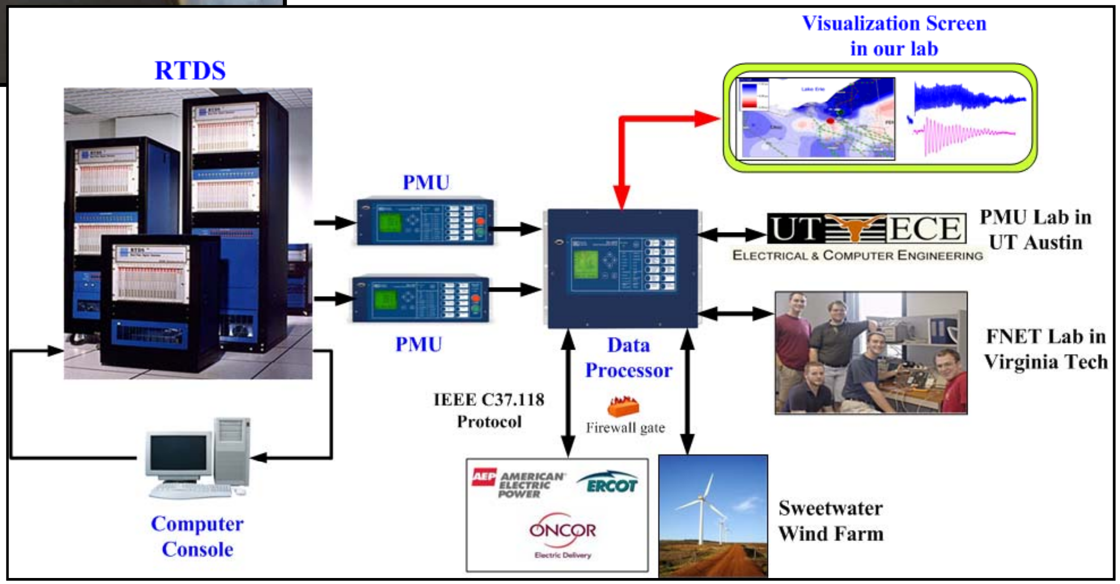


Dynamic Link Assignment Problem (DLAP)

Phasor Lab

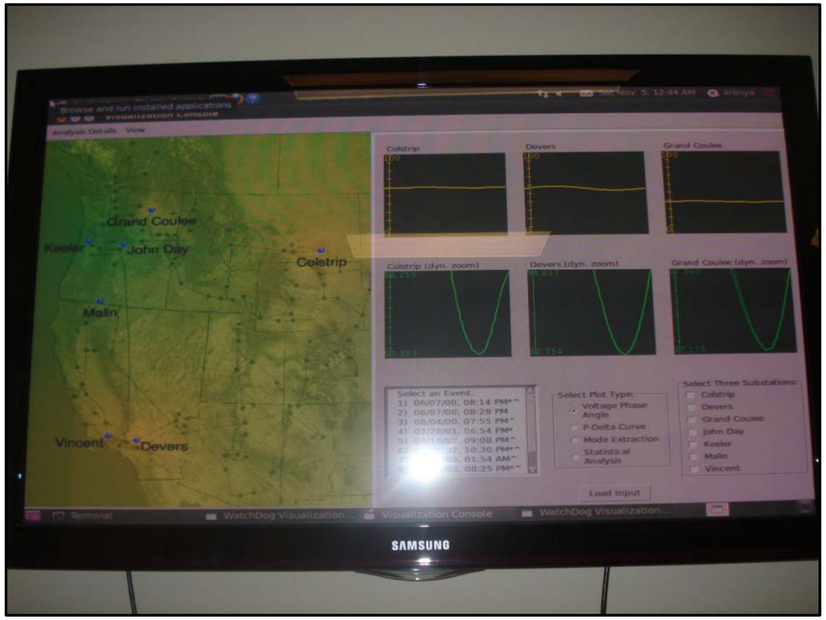
1. Real PMU Data from WECC (NASPI data)
2. RTDS-PMU Data (Schweitzer PhasorLab)
3. FACTS-TNA with NI CRIO PMUs

→ We can provide all three data via our new PMU and RTDS facilities at the FREEDM center

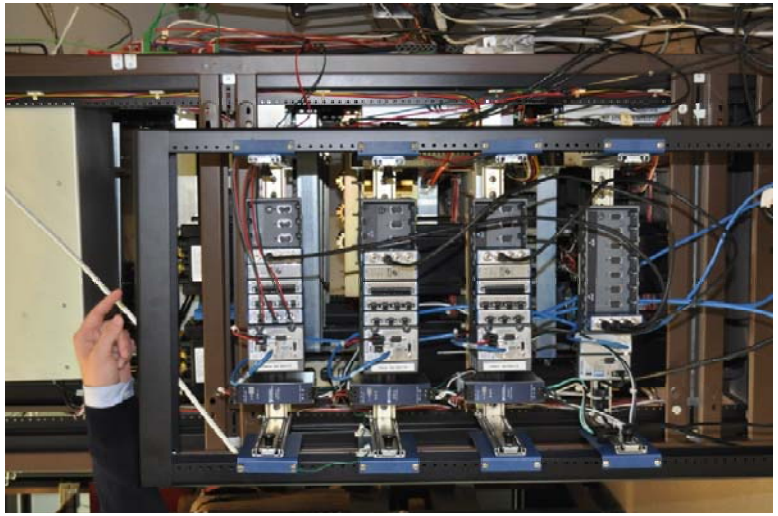


How about setting up an intra-campus local PMU communication network with RENCI/UNC and Duke Univ.?

Real Time Digital Simulators



PMU Data Visualization



NI PMU Rack

SEL/ABB PMU Rack with PDC

Conclusions

1. WAMS is a tremendously promising technology for smart grid researchers
2. Communications and Computing must merge with power engineering
3. Plenty of new research problems – EE, Applied Math, Computer Science
4. Cyber-security is essential
5. Right time to think mathematically – Network theory is imperative
6. Right time to pay attention to the bigger picture of the electric grid
7. Needs participation of young researchers!
8. Promises to create jobs and provide impetus to the ARRA

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