Prevention and Mitigation of Cascading Outages in Power Grids Using Synchrophasor-based Wide-Area Measurements

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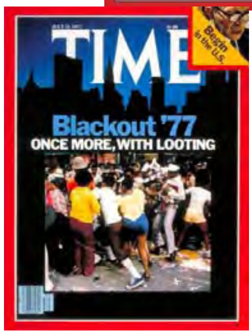
Content

- Cascading outages (impacts, causes, new challenges and solutions)
- Intelligent system separation utilizing synchrophasors
- Situational awareness utilizing wide-area measurements (DOE demonstration project)
- Conclusions

Blackouts of Power Grids

Date	Area	Impacts	Duration
Nov 9, 1965	**North America (NE)**	**20,000+MW, 30M people**	**13 hrs**
Jul 13, 1977	**North America (NY)**	**6,000MW, 9M people**	**26 hrs**
Dec 22, 1982	North America (W)	12, 350 MW, 5M people	
Jul 2-3, 1996	North America (W)	11,850 MW, 2M people	13 hrs
Aug 10, 1996	**North America (W)**	**28,000+MW, 7.5M people**	**9 hrs**
Jun 25, 1998	North America (N-C)	950 MW, 0.15MK people	19 hrs
Mar 11, 1999	Brazil	90M people	hrs
Aug 14, 2003	**North America (N-E)**	**61,800MW, 50M people**	**2+ days**
Sep 13, 2003	Italy	57M people	5-9 hrs
Sep 23, 2003	Sweden & Denmark	5M people	5 hrs
Nov 4, 2006	Europe	15M households	2 hrs
Nov 10, 2009	Brazil & Paraguay	17,000MW, 80M people, 18 states	7hrs
Feb 4, 2011	Brazil	53M people, 8 states	
Sep 8, 2011	**US & Mexico (S-W)**	**4,300MW, 5M people**	**12hrs**



Causes of a blackout

Blackout event in Aug. 1996

1. Initial events (15:42:03):

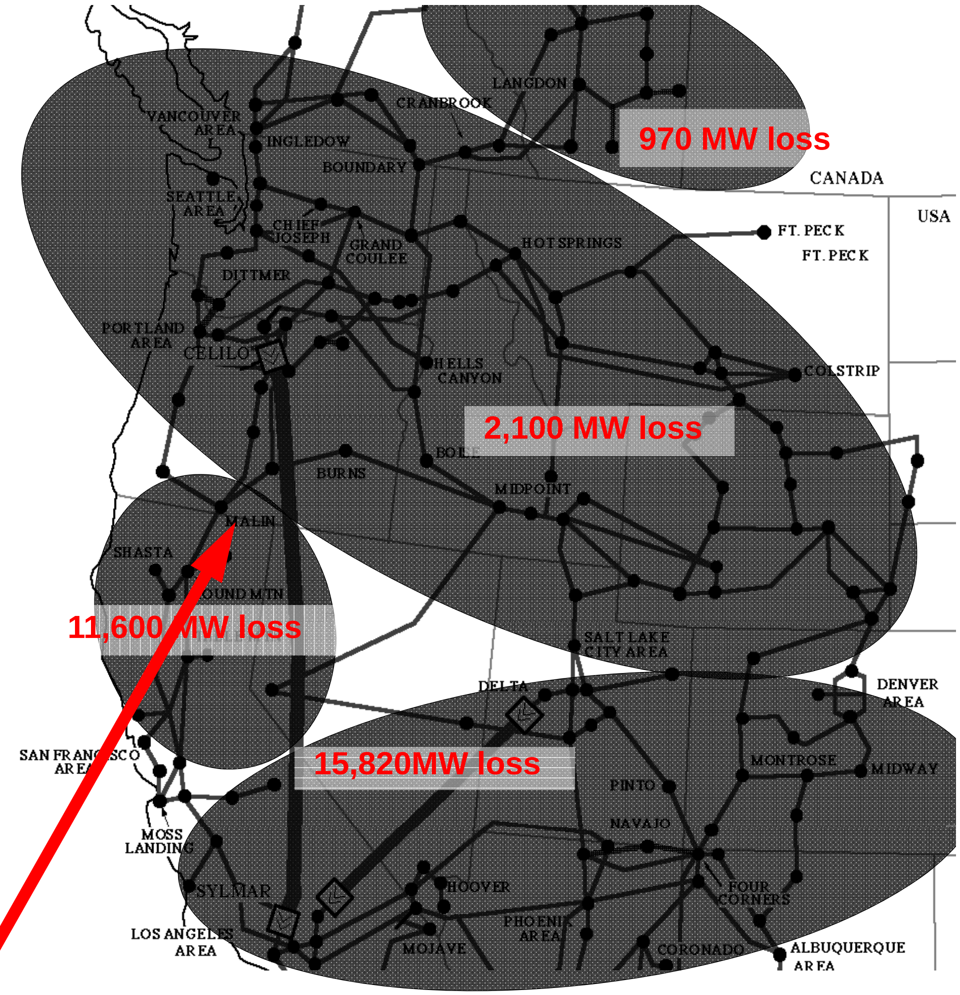
Short circuit due to tree contact ->
Outages of 6 transformers and lines

2. Vulnerable conditions (minutes)

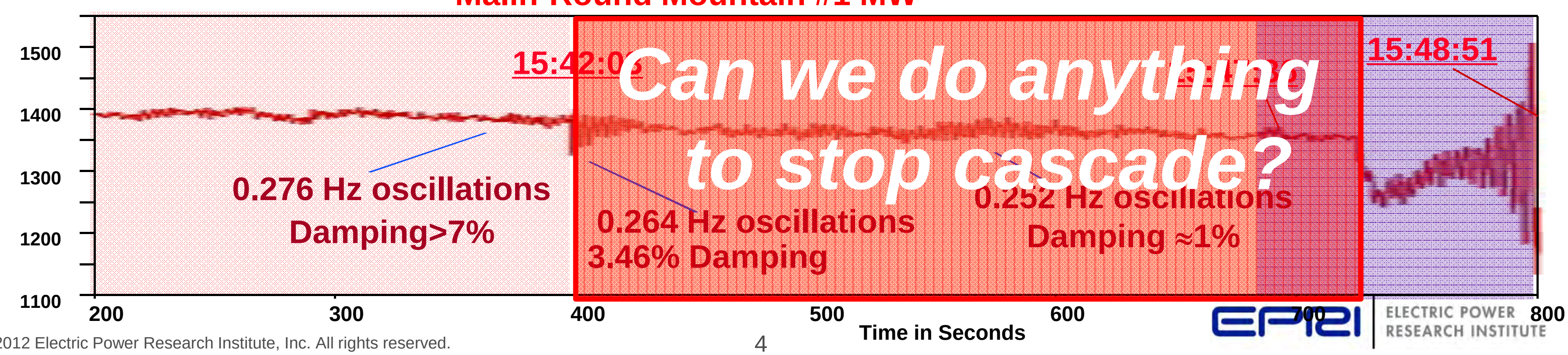
Low-damped oscillations->
Outages of generators and tie-lines

3. Blackouts (seconds)

Grid separated into islands ->
Loss of 24% load



Malin-Round Mountain #1 MW



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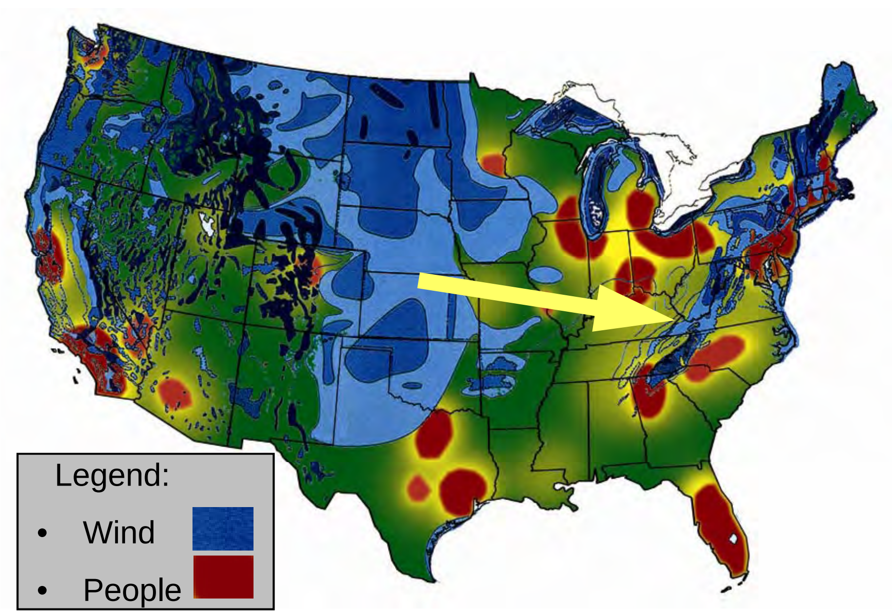
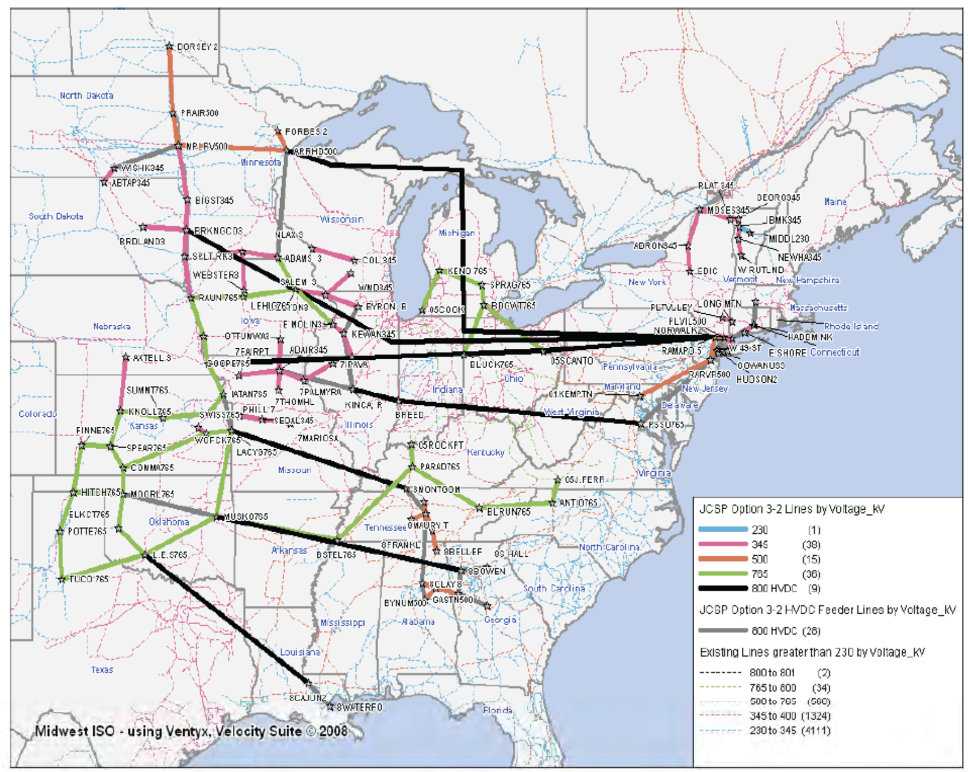
New Challenges from Integration of Renewables

1. Reliability and congestion issues with long-distance power transmission

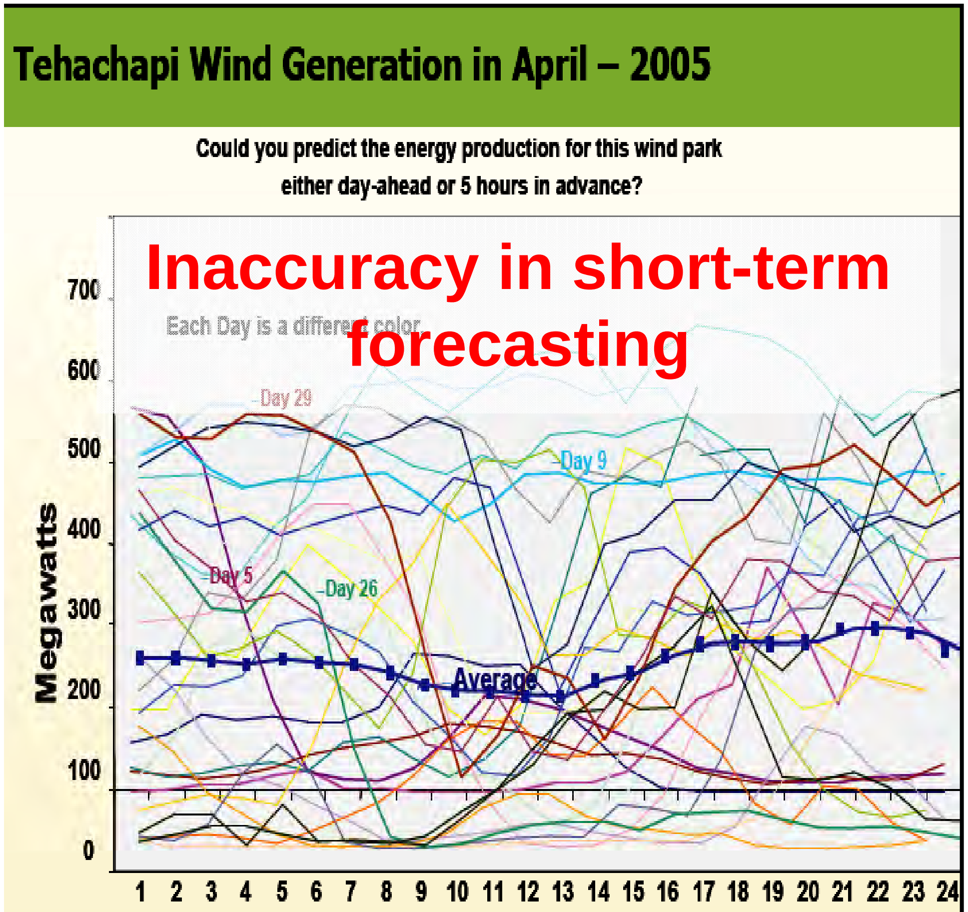




Source: JCSP

New Challenges from Integration of Renewables (cont')

2. More uncertainties in real-time operation



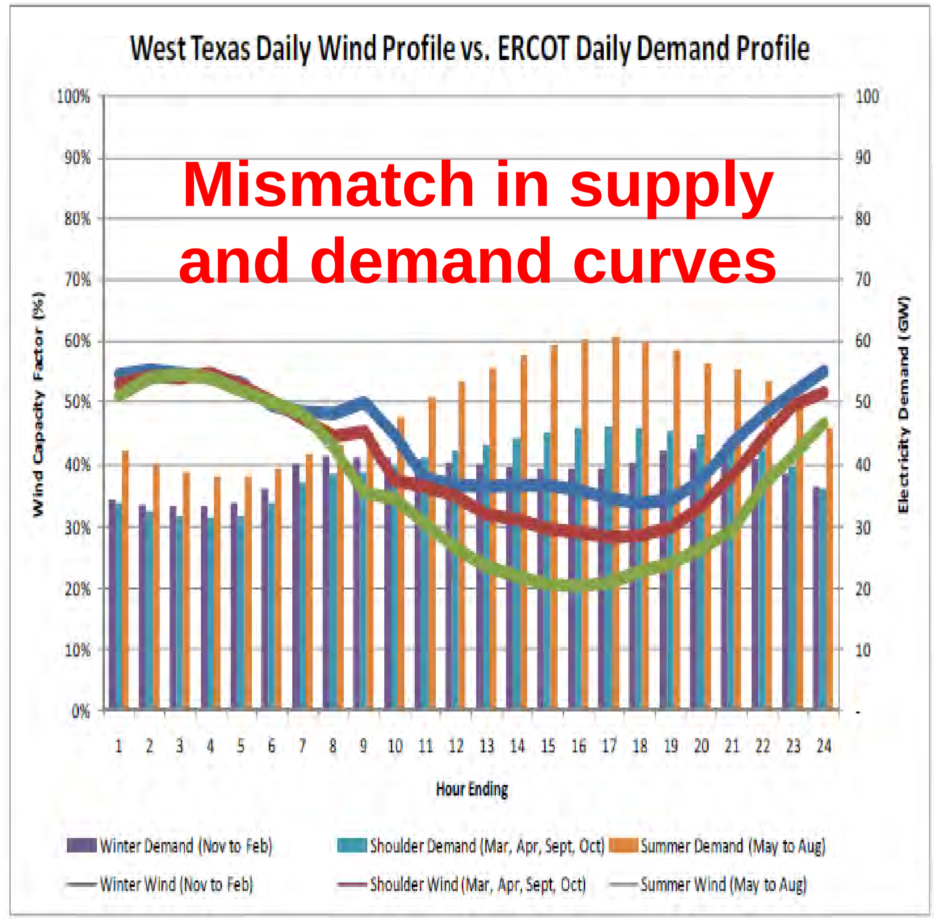


Image Source: LCG Consulting

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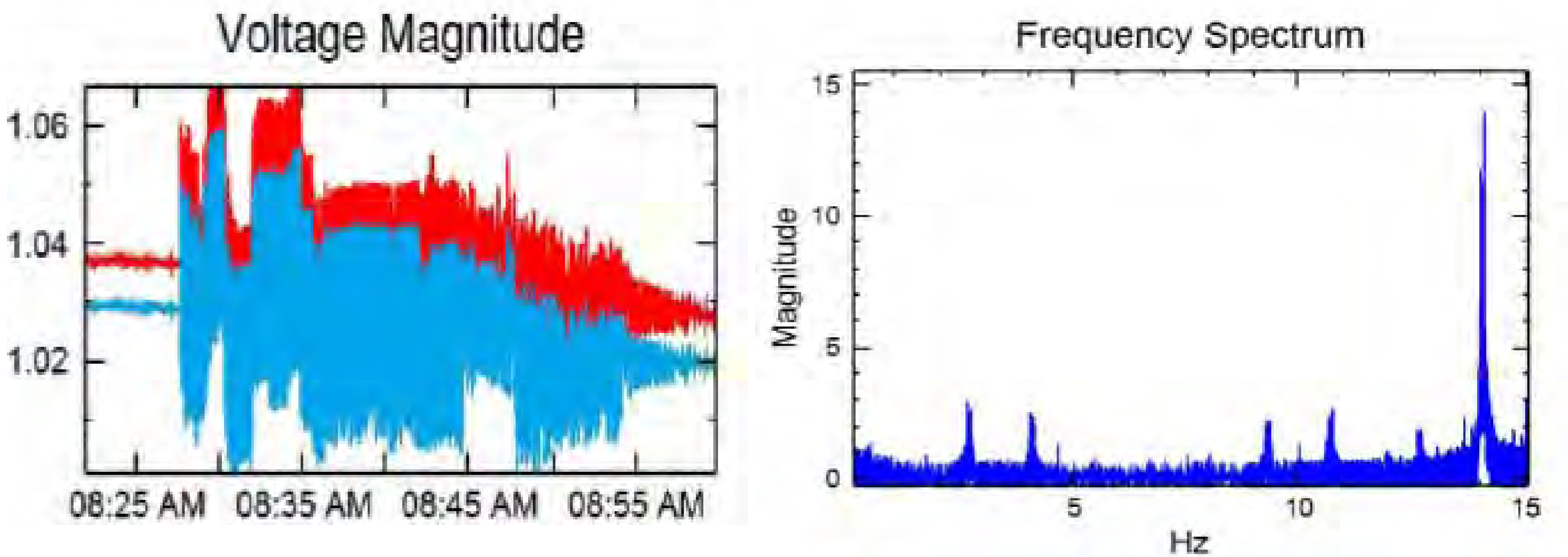
New Challenges from Integration of Renewables (cont')

3. Changing the grid's dynamics



From OG&E synchrophasor presentation

Better monitoring applications are needed at the control room for real-time situational awareness

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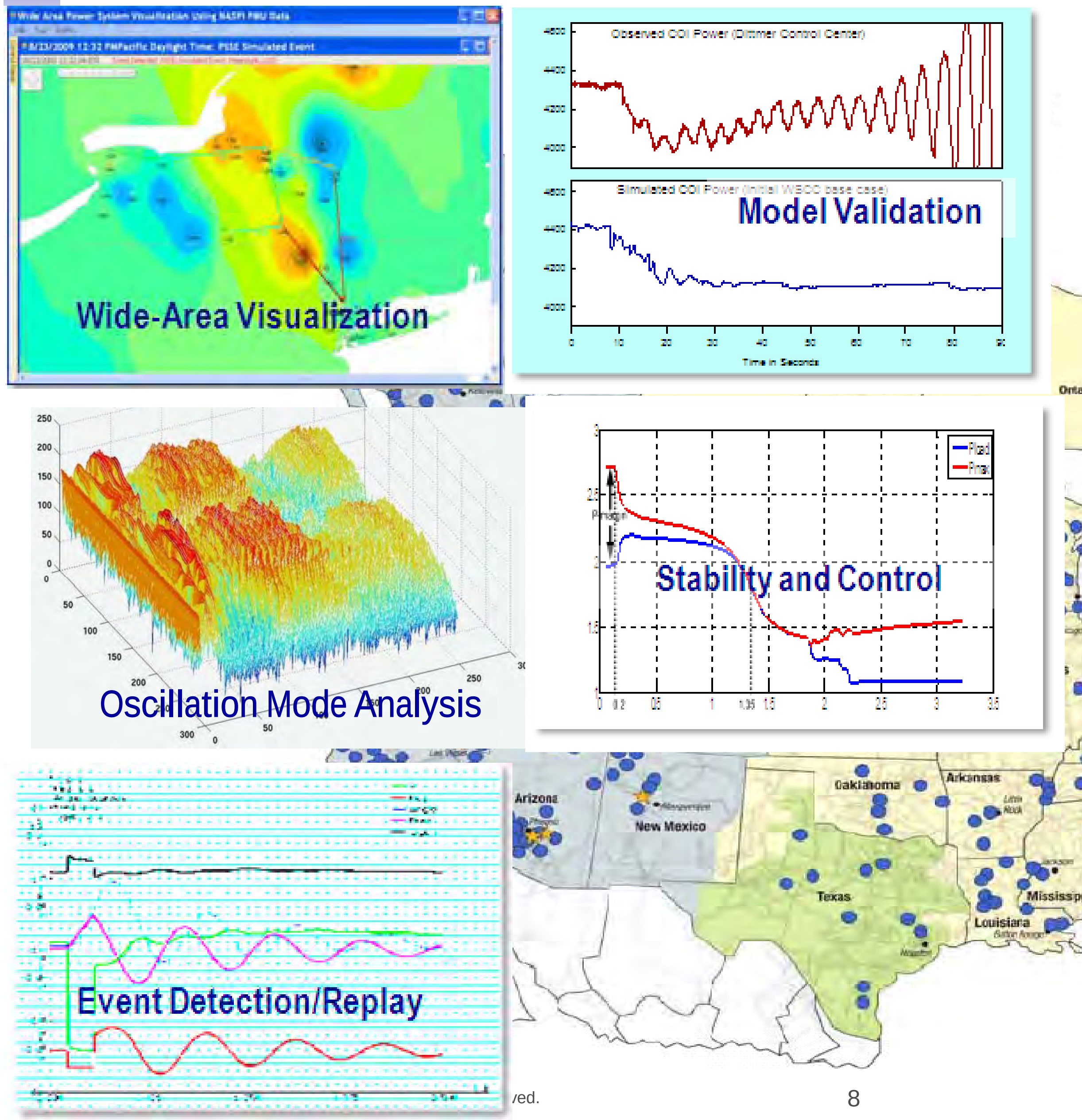
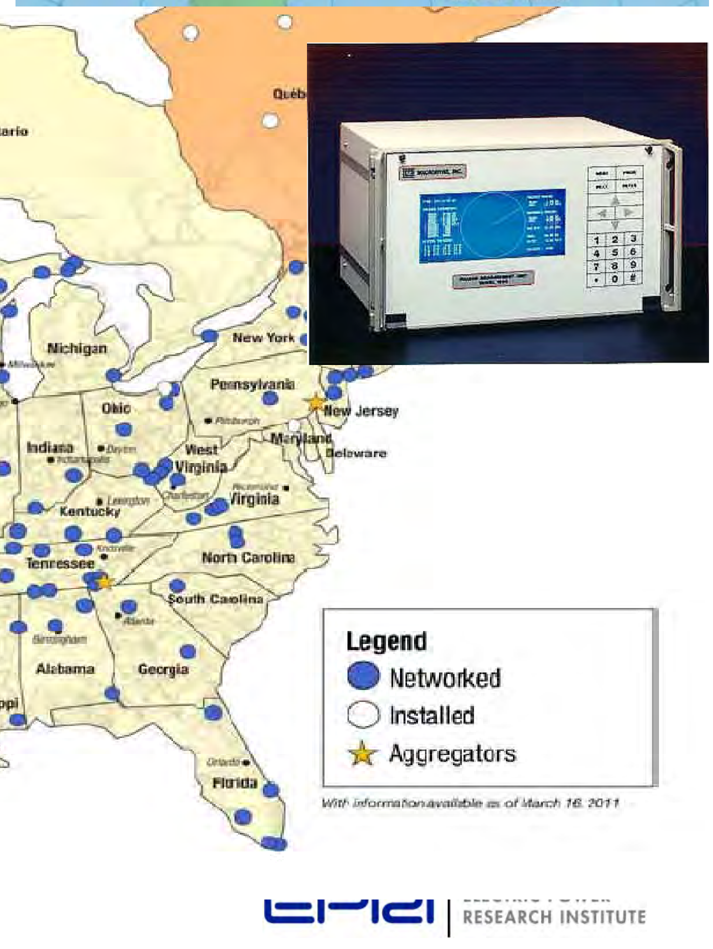
Synchrophasor based Wide-Area Measurement System (WAMS)





Prevention of Cascading Outages

- Power System Stability Assessment:

Offline probabilistic analysis on system vulnerabilities and potential cascading outages

Simulation-based contingency analysis

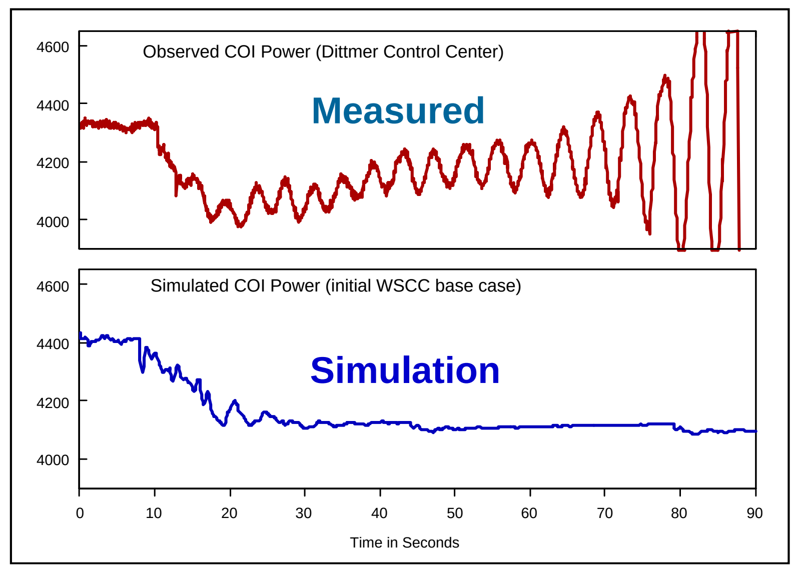
Real-time stability analysis using wide-area measurements

- Limitations:
  - Too many system conditions
  - Combinatorial explosion of N-k contingencies
  - Inaccuracy in simulation models

Simulation-based approach

+

Measurement-based approach



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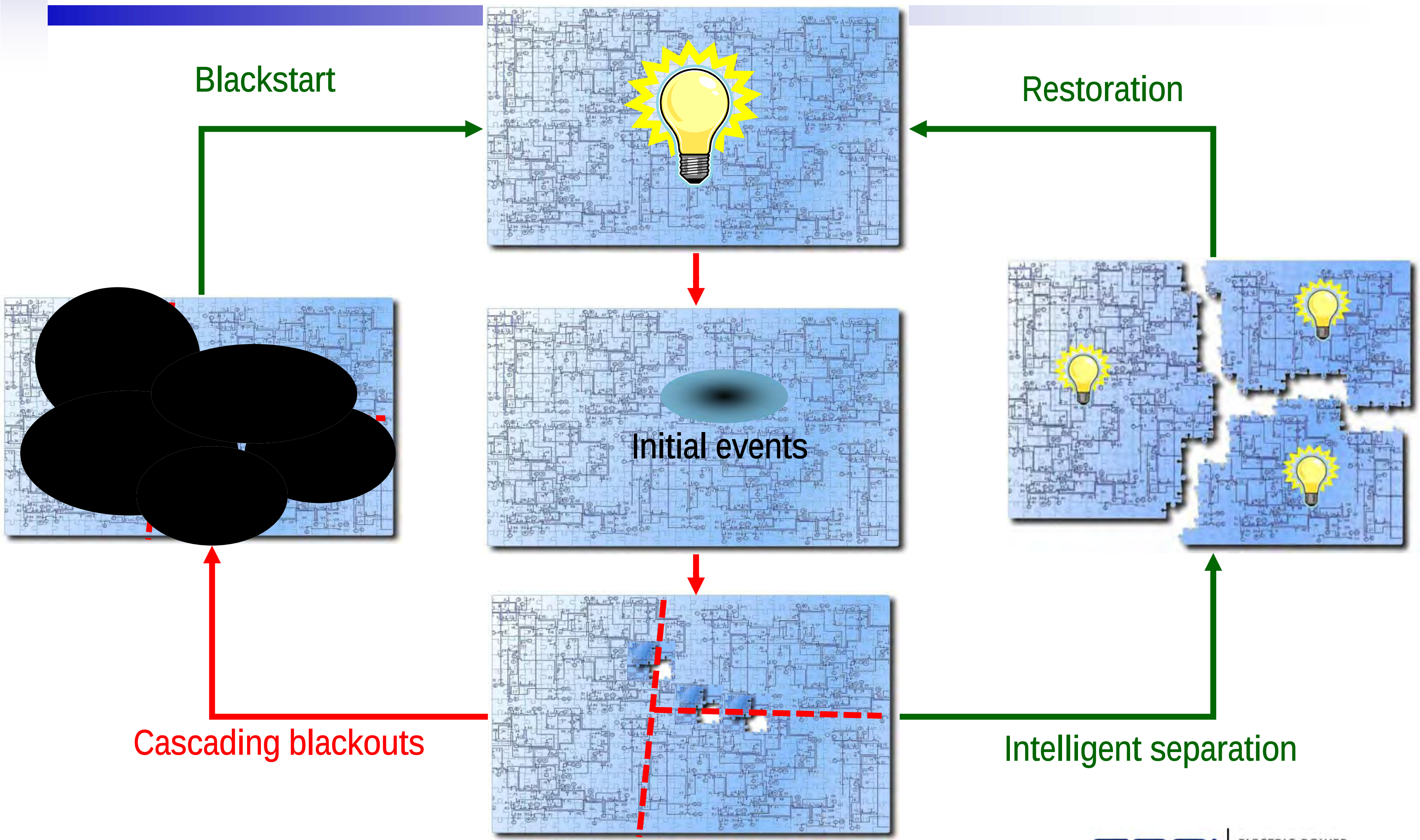
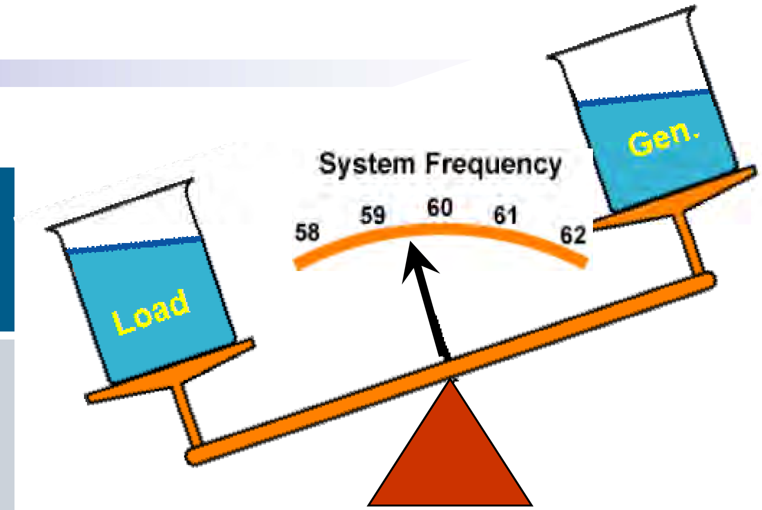
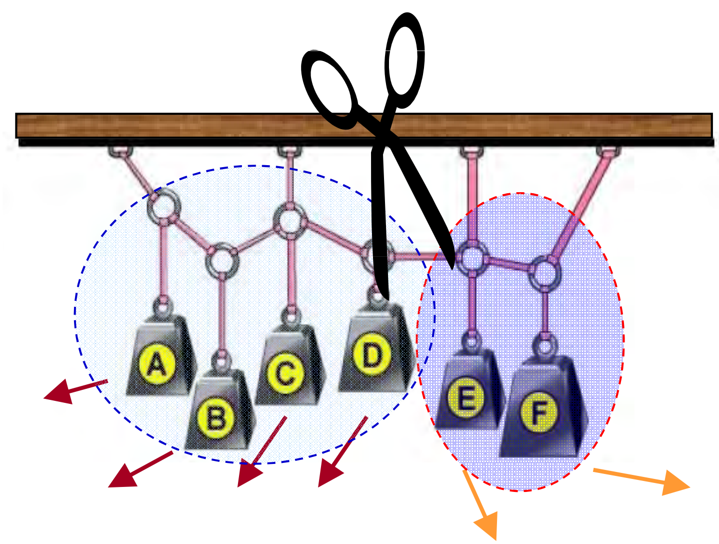
Intelligent System Separation



Key Questions on System Separation

Question	Nature
WHERE (locations)	Network optimization
WHEN (timing)	Nonlinear system stability
HOW (control)	Implementation of control strategies





Three-Step Approach

Offline procedure →

- **Offline Studies** (*daily ~ yearly*)
  - Synchrophasors siting (near generators)
  - Separation point optimization
  - Validation of a control-strategy table

Where

How

Online software →

- **Online Monitoring** (*every second*)
  - Identify most vulnerable grid interface based on the shape of the dominant oscillation mode
  - Predict the timing of instability on the interface

Where

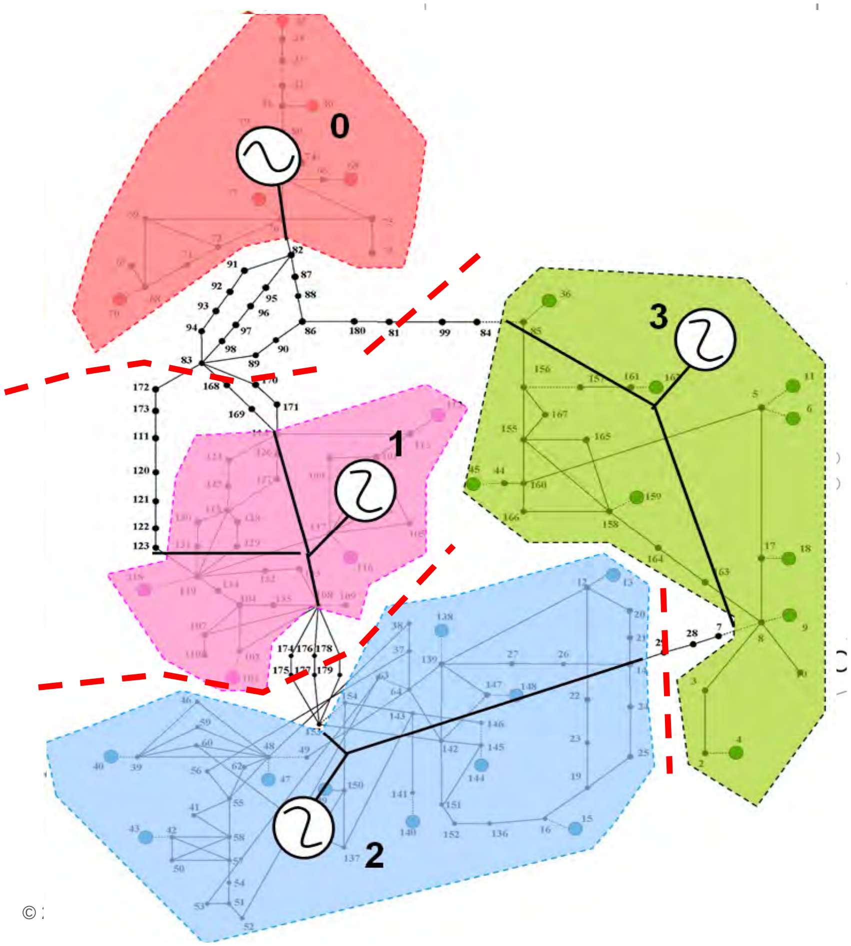
When

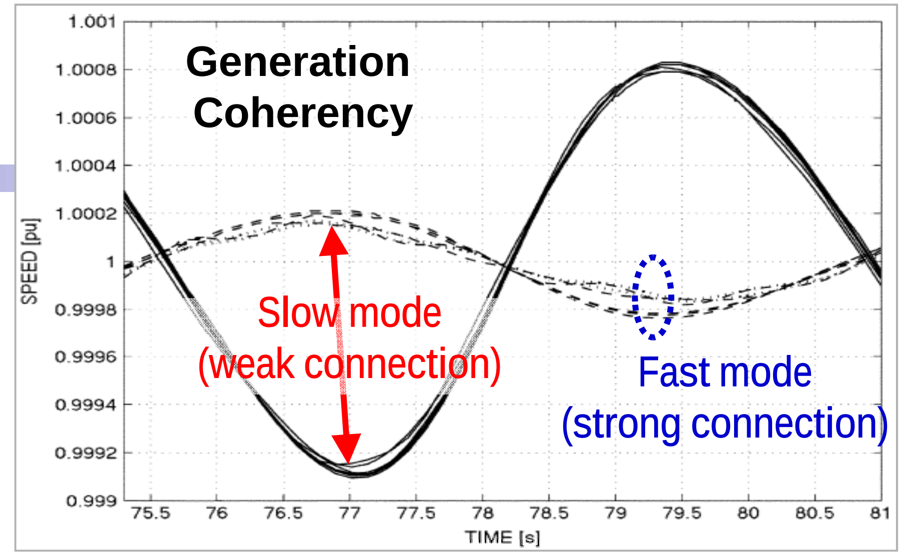
- **Real-Time Control** (*milliseconds*)
  - Perform a control strategy matching the current condition

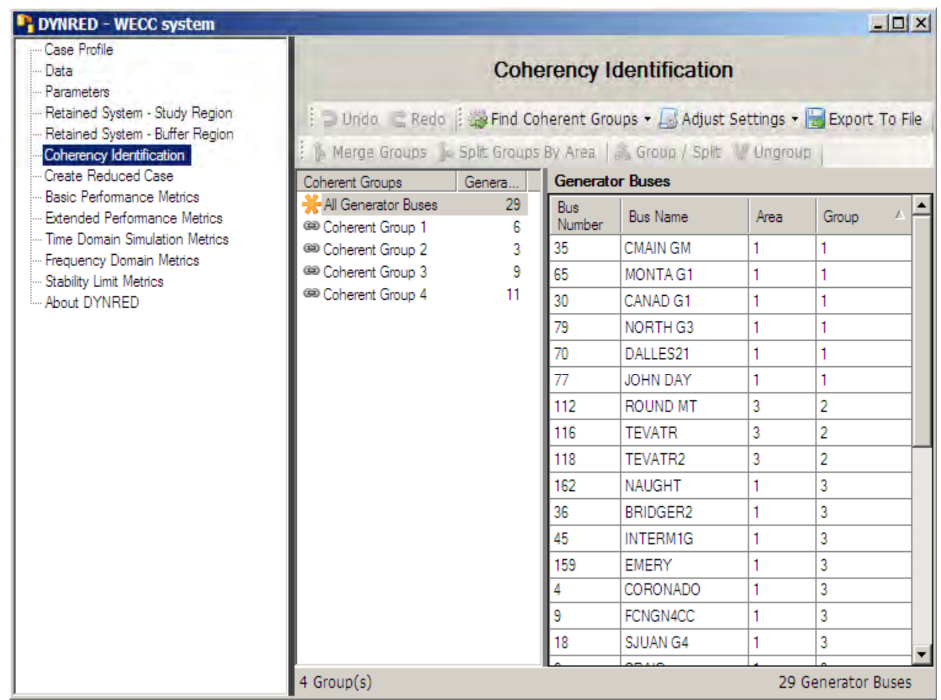
How

WHERE to Separate

1. Cluster generators into coherent groups (by EPRI DYNRED software)
2. Reduce the network by graph theory







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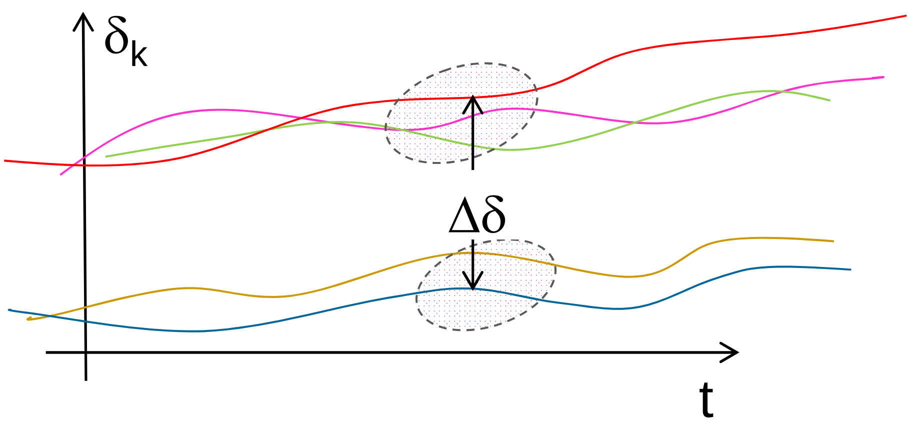
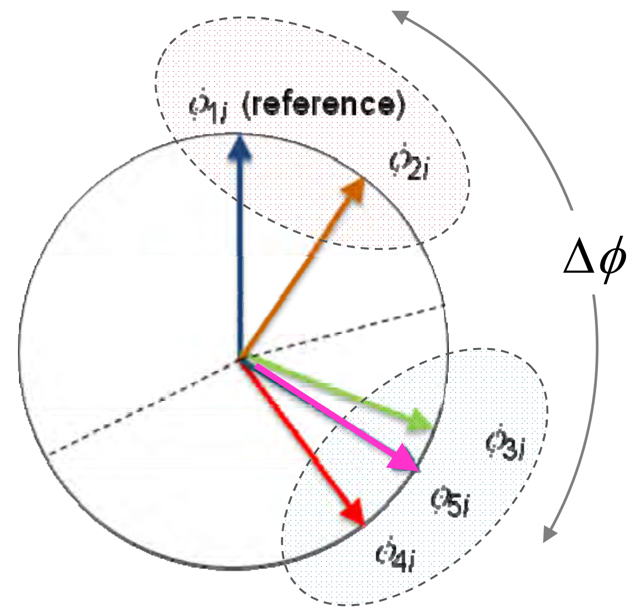
WHEN to Separate

- Modal analysis
  - Identify the dominant oscillation mode by synchrophasors
  - Predict a vulnerable grid interface from the mode’s shape (phasing)



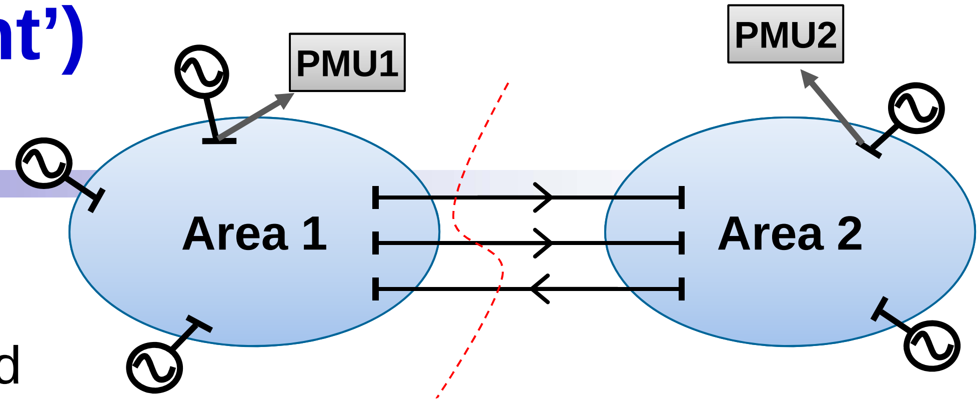
$$\delta_k(t) \approx \delta_{k0} + \sum_{i=1}^{M} A_{ki} e^{\frac{-\zeta_{ki}}{\sqrt{1-\zeta_{ki}^2}}\omega_{ki} t} \cos(\omega_{ki} t + \phi_{ki})$$

Monitored variable | Oscillation frequency | Phasing (mode shape)

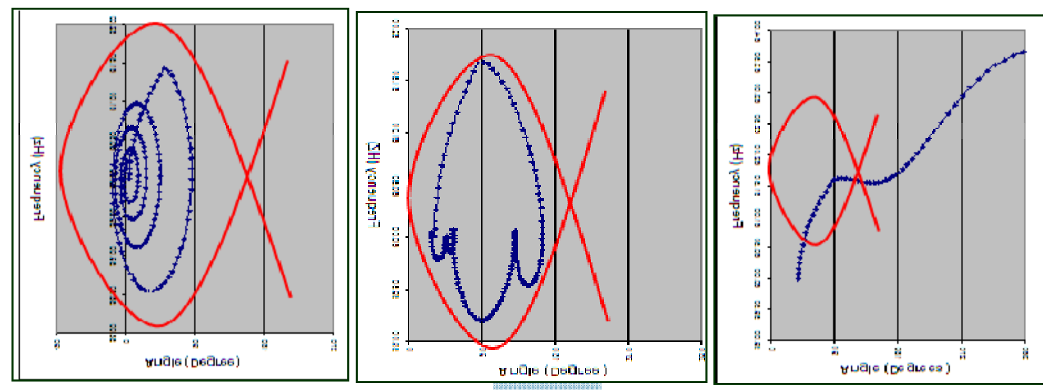


“Phase Clock” on mode *i*

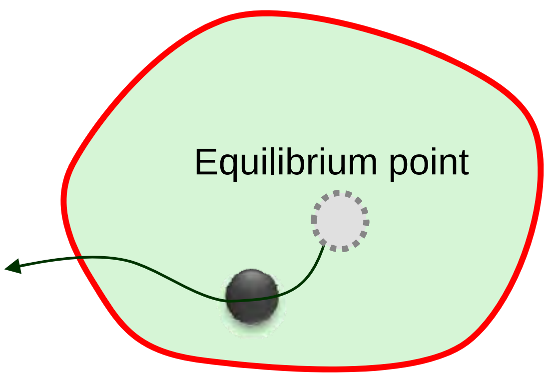
WHEN to Separate (cont')



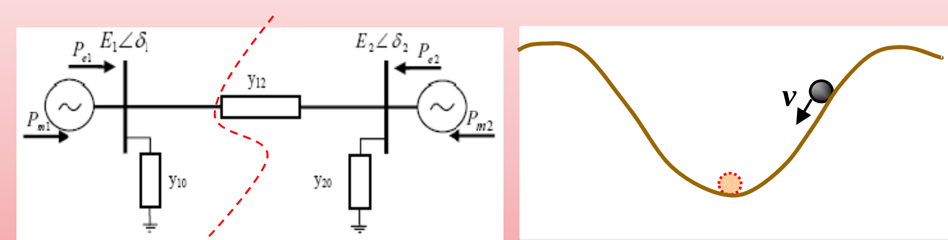
- Stability analysis
  - Estimate the state of a simplified model about the interface
  - Predict instability using the energy function of the model



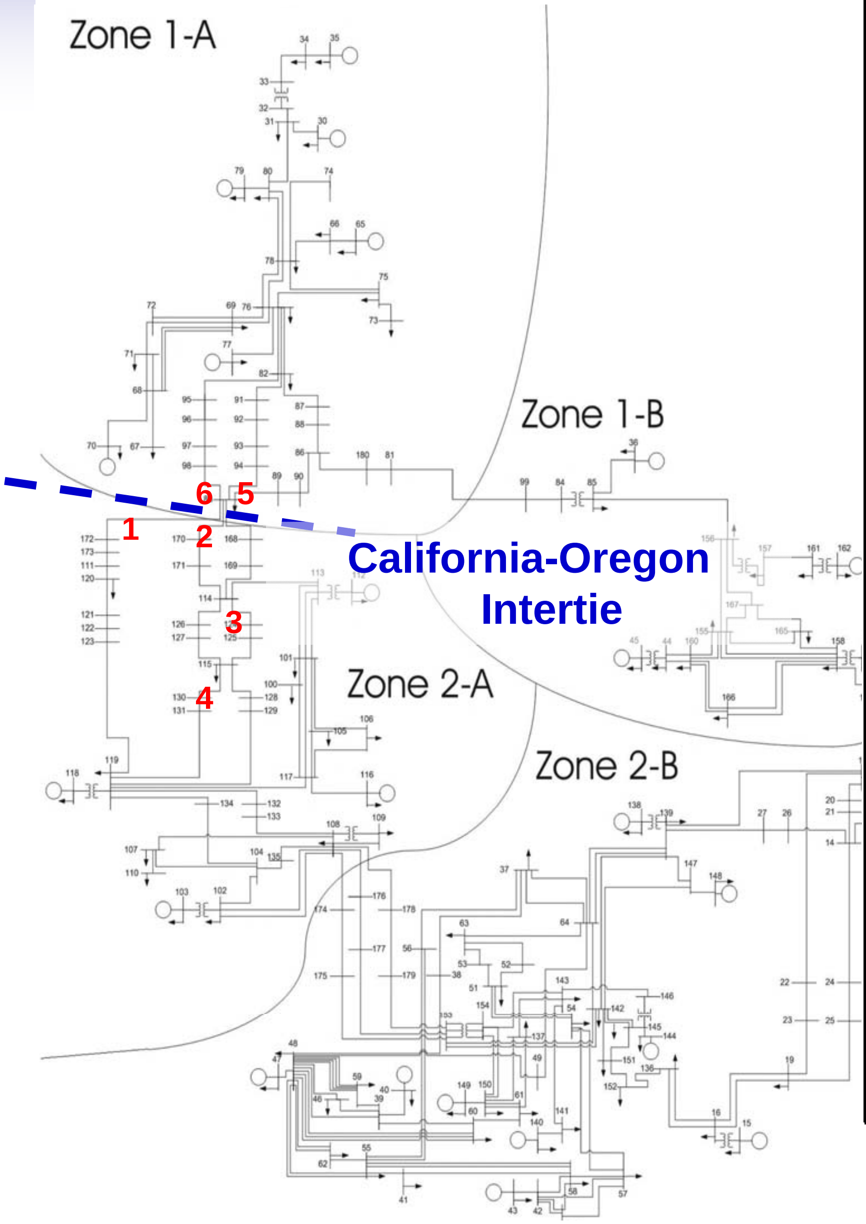
Boundary of Stability

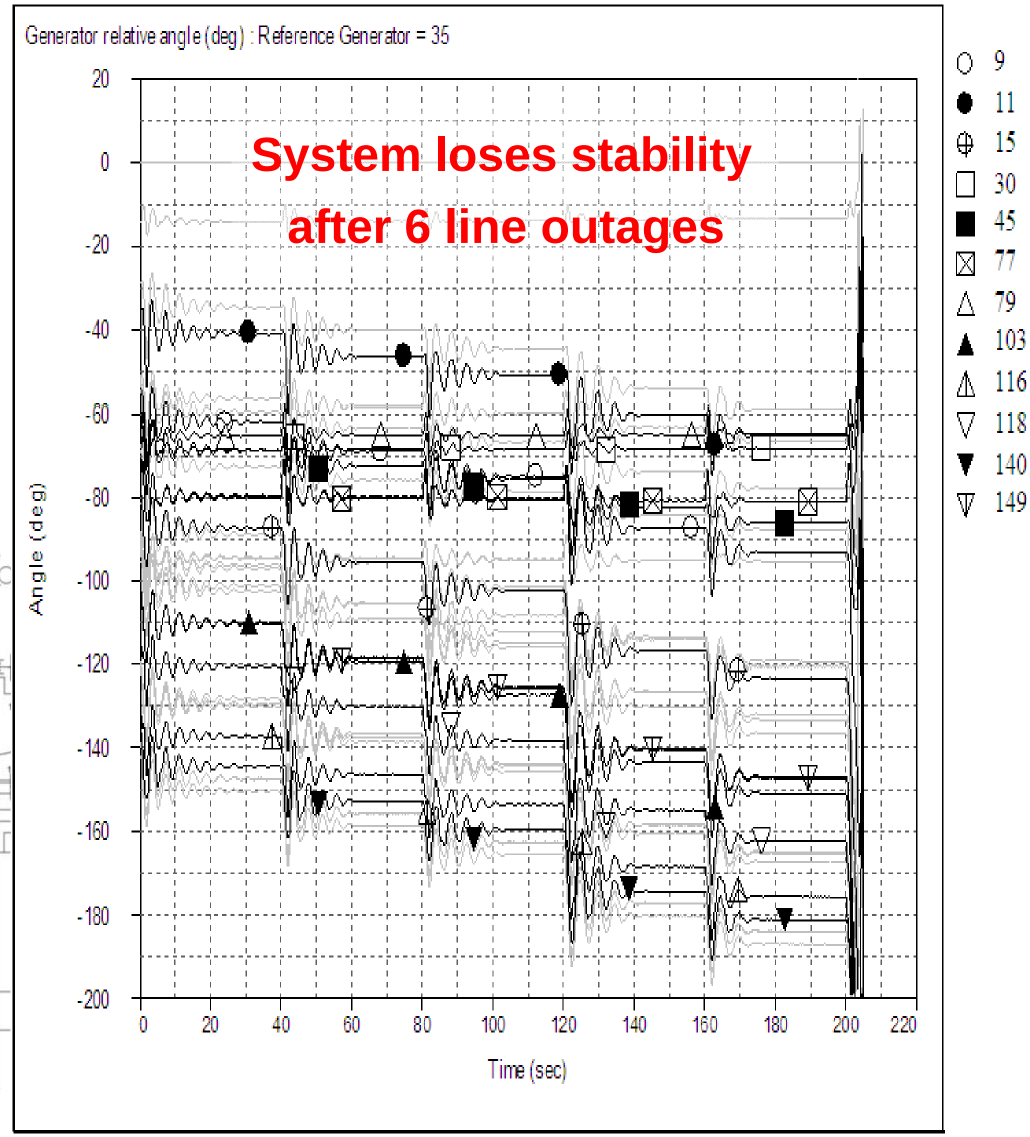


State estimation on a simplified model



Example: 179-bus System





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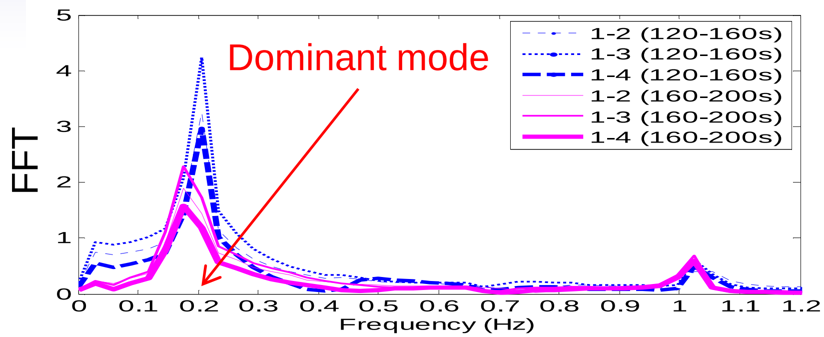
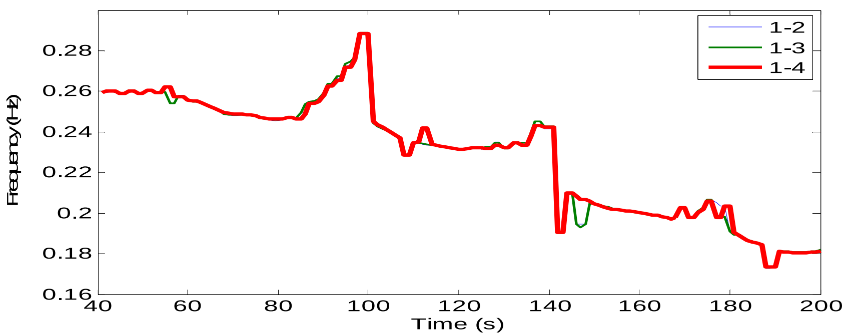
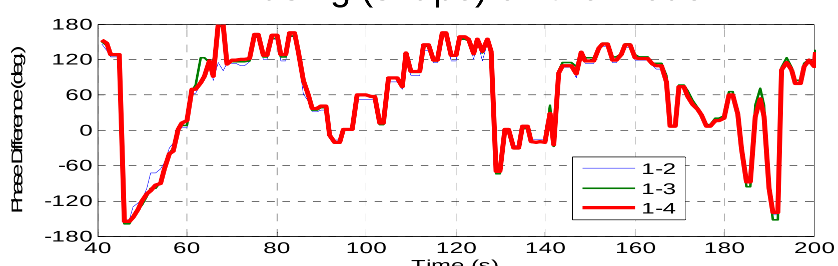
Example: 179-bus System (cont')

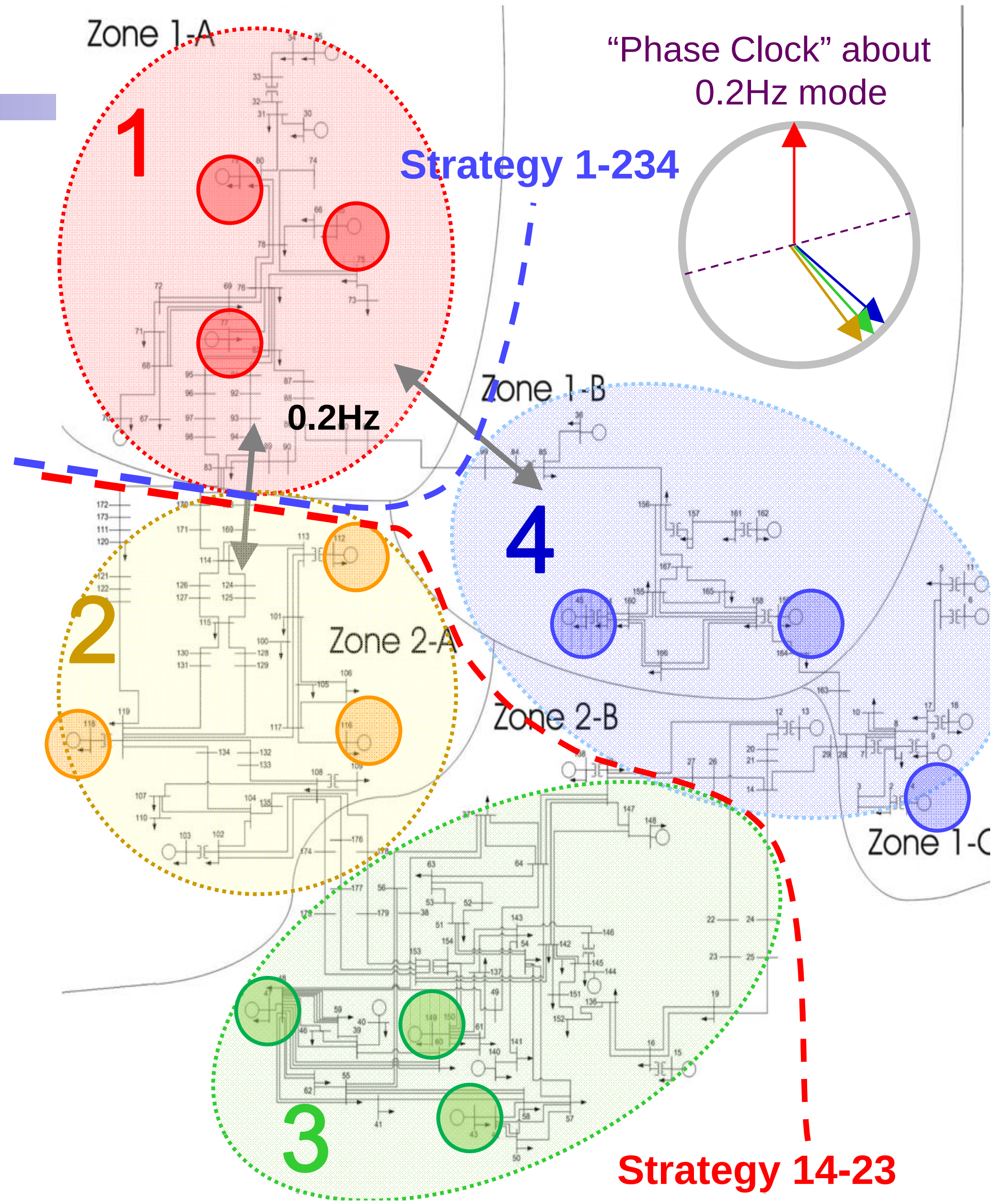


Frequency of the mode

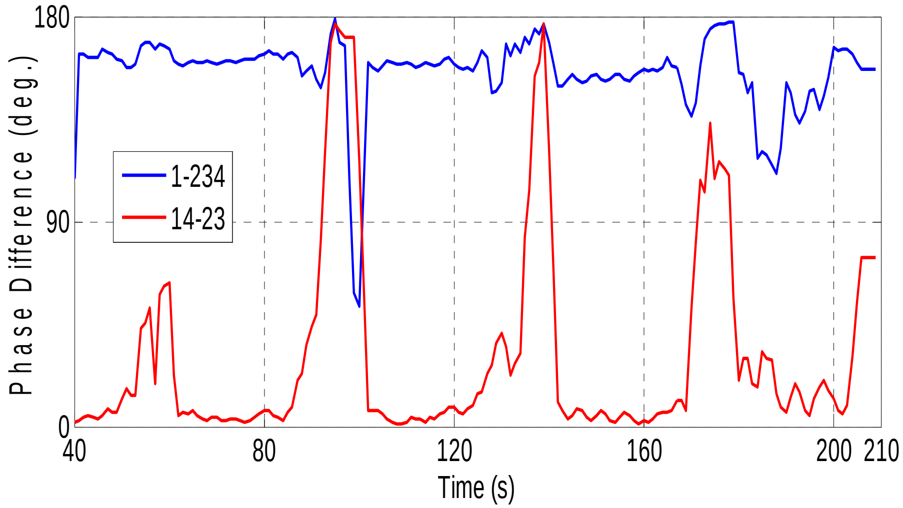


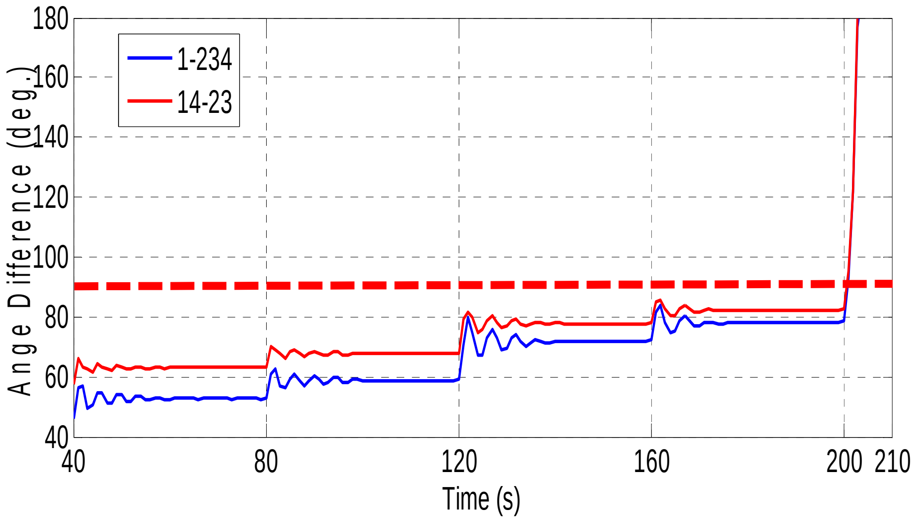
Phasing (shape) on the mode



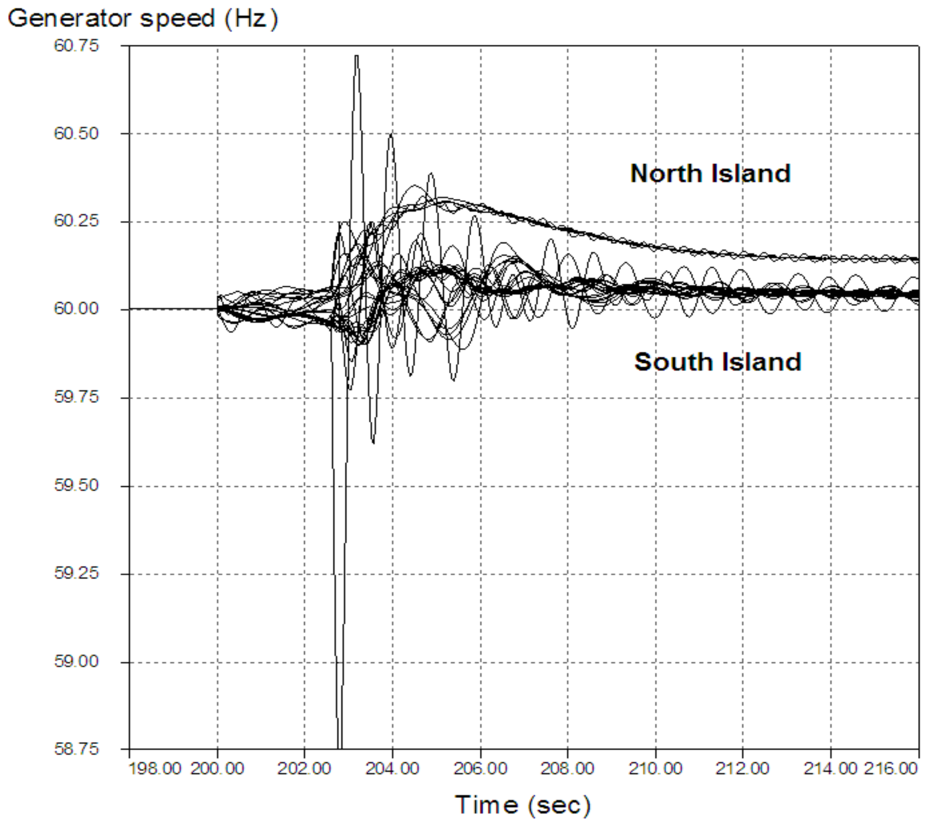


Example: 179-bus System (cont')





- Perform strategy 1-234 once the angle distance exceeds a threshold
- Shed 4.9% system load



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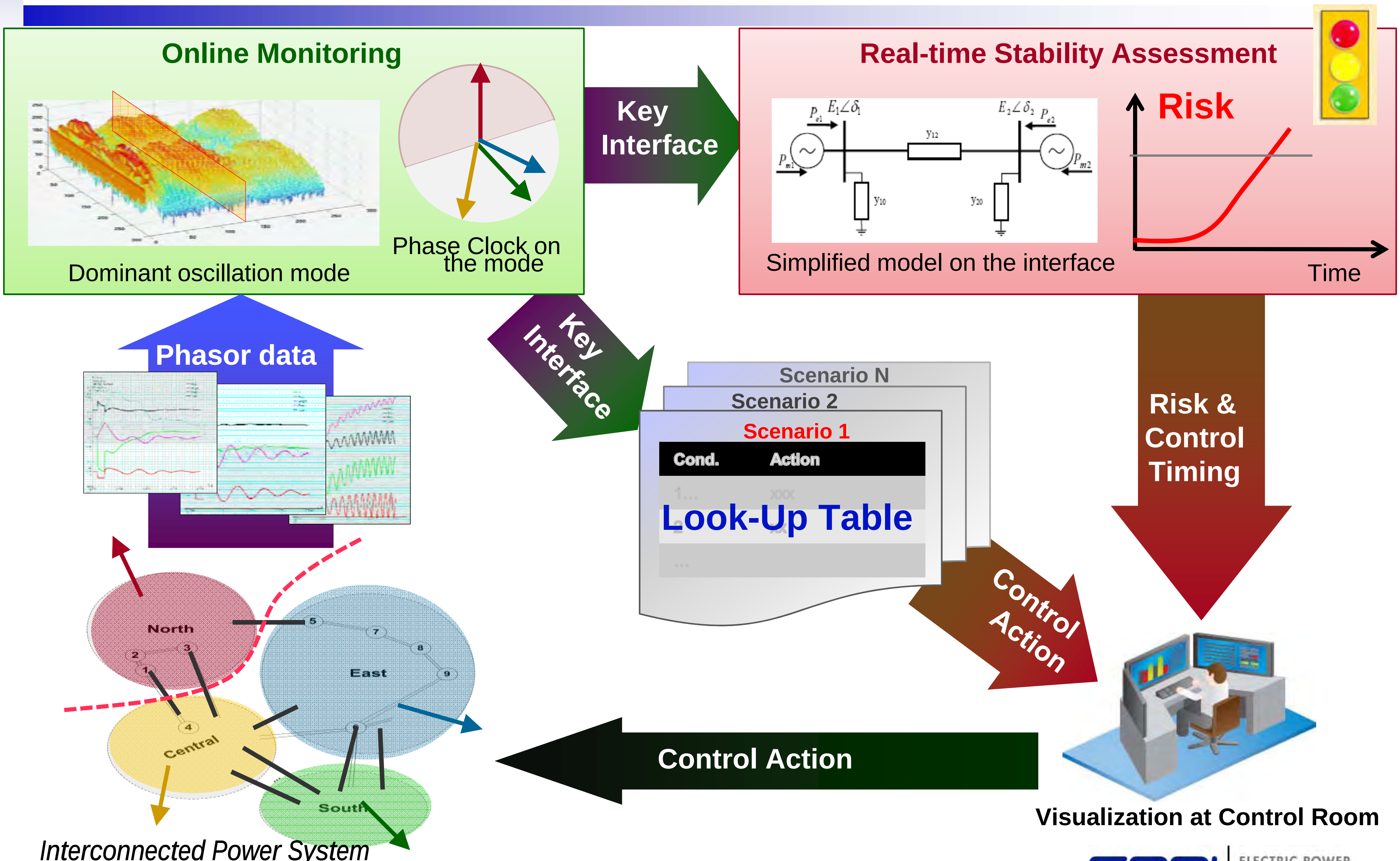
Synchrophasor-based Situational Awareness and Decision Support



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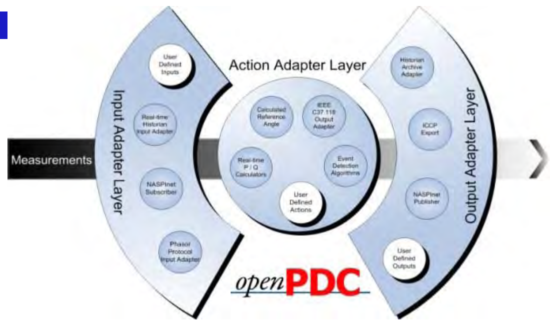
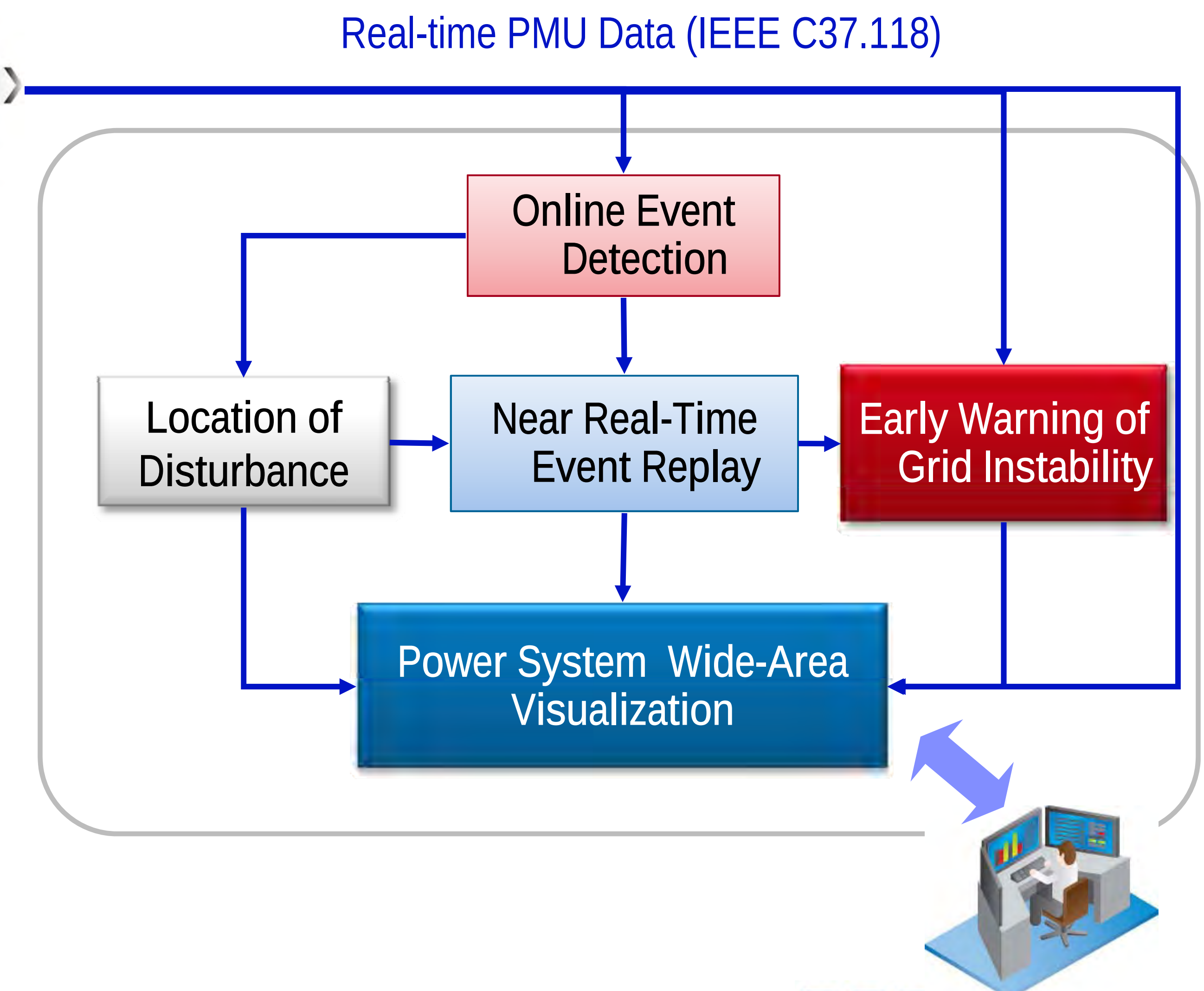
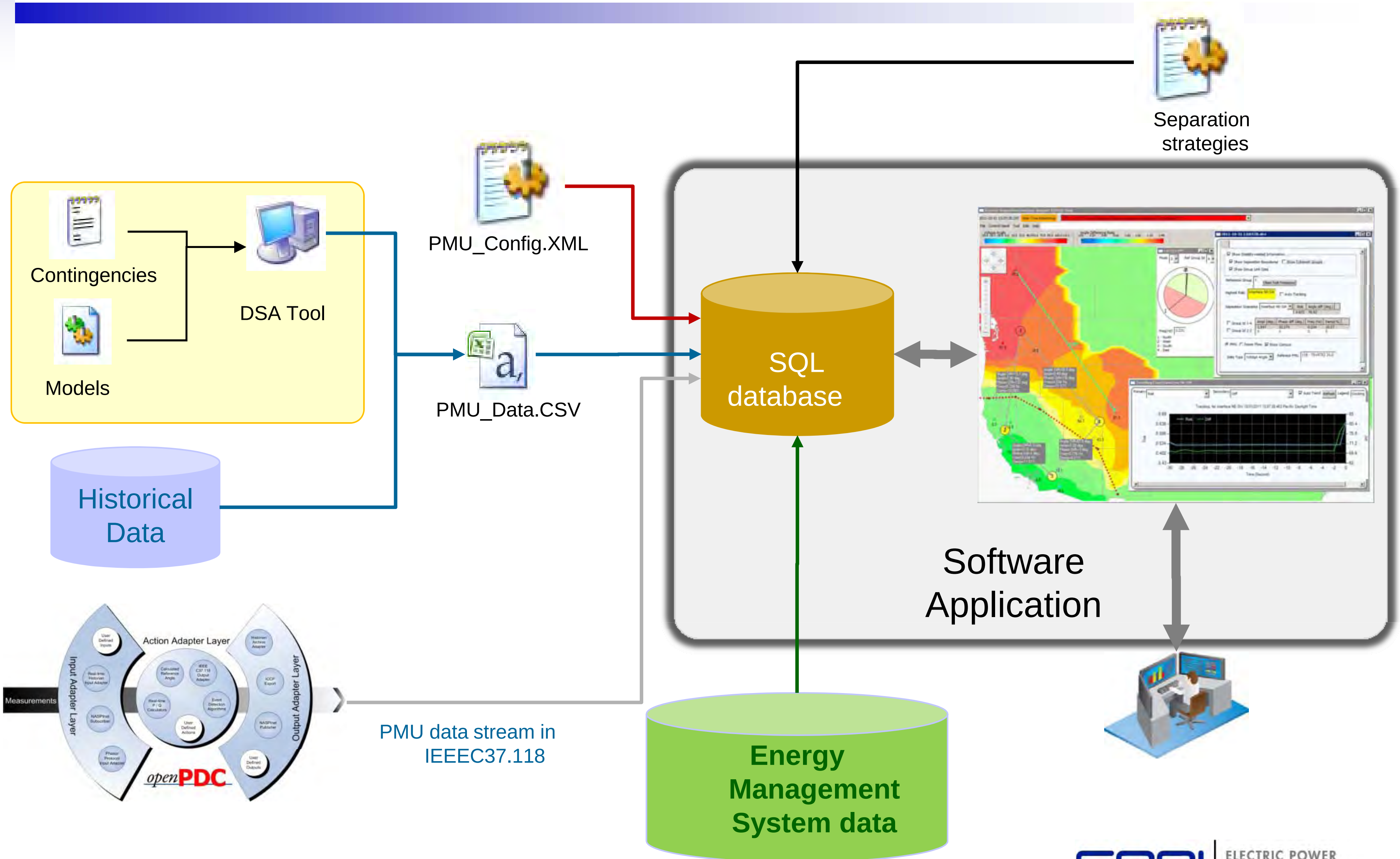
DOE Synchrophasor Demonstration Project (DOE Grant #DE-OE0000128; 2009-2012)



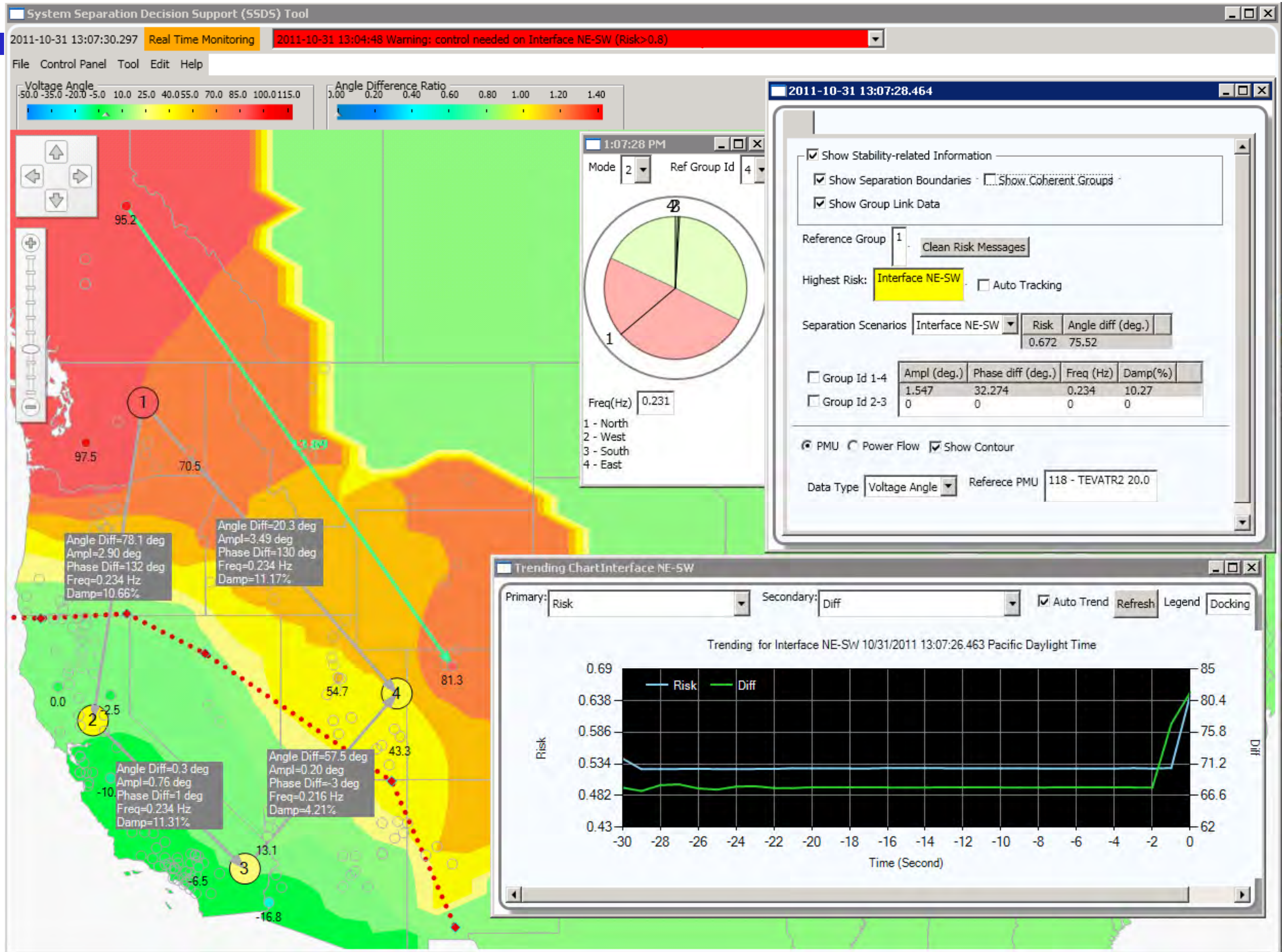
- Phase 1 (research)
- Phase 2 (software development)
- Phase 3 (demonstration at TVA in 2012)



Performance Testing Using Simulated or Real Synchrophasor Data



Tests on Simulated WECC PMUs



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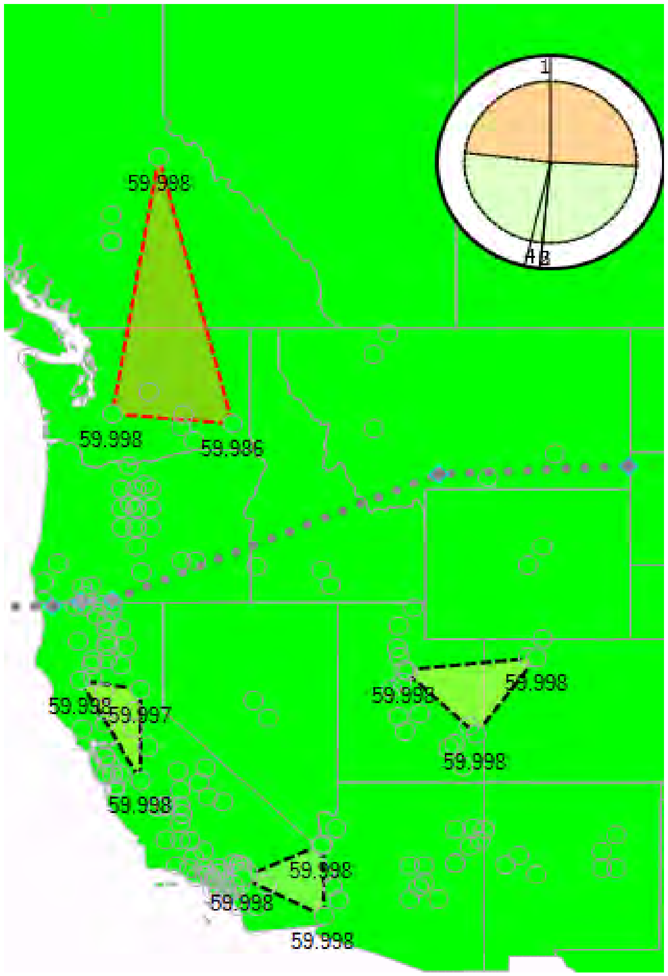
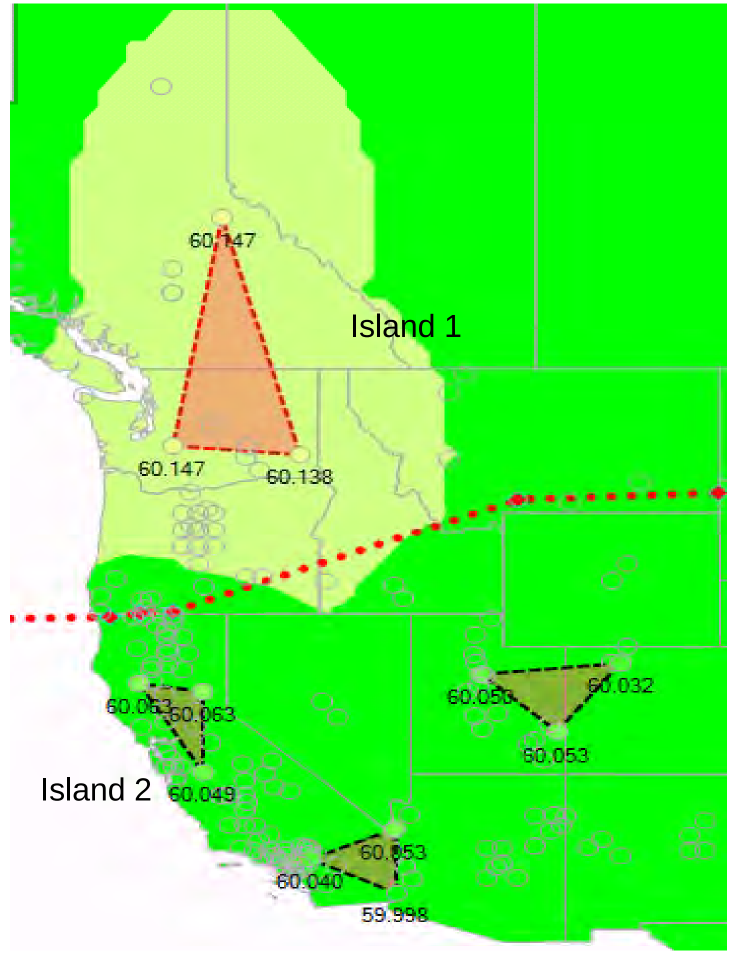
Separating the grid when risk=100%

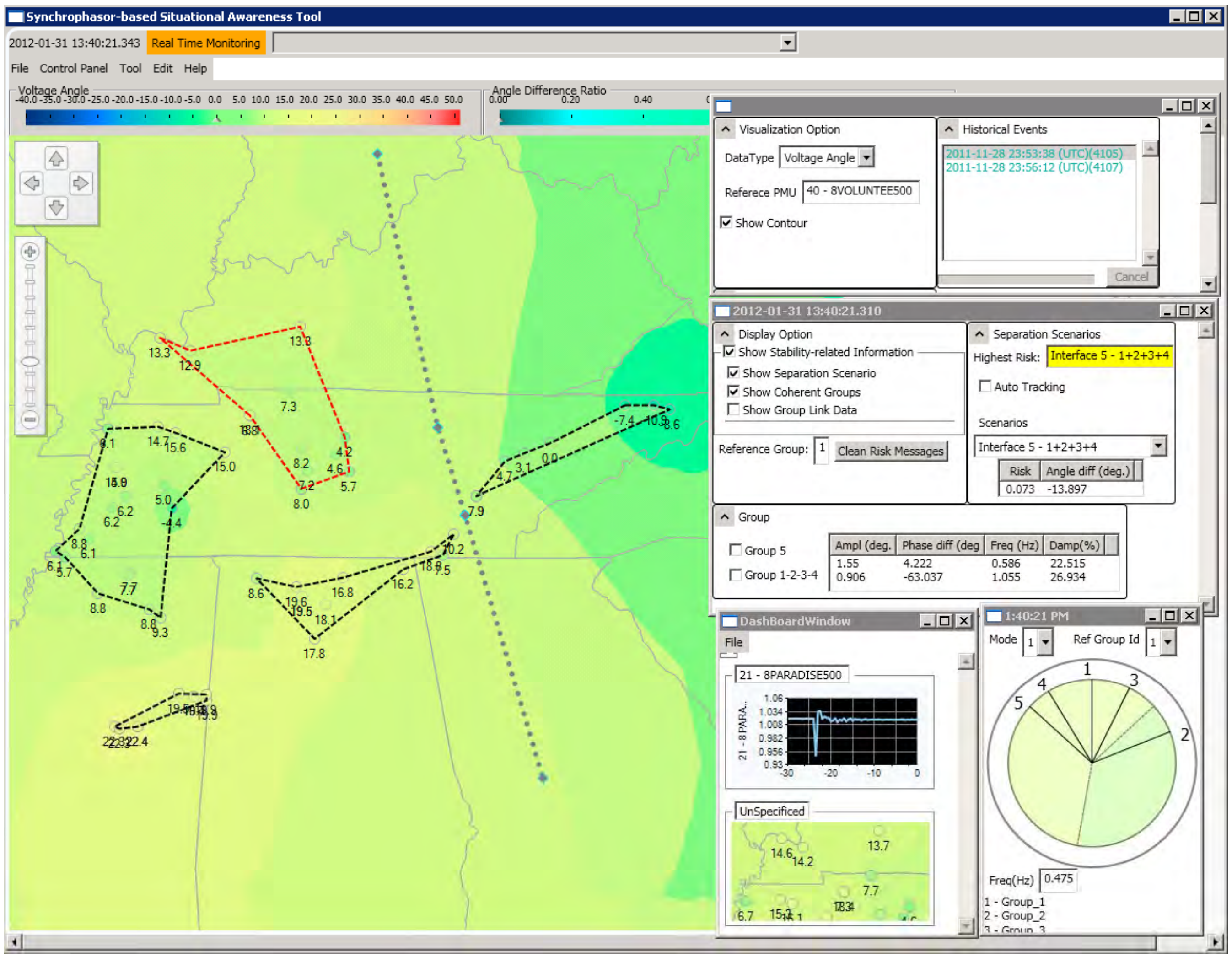


Frequencies before Control



Frequencies after Separation

Tests on Simulated TVA PMU Data



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Conclusions

- Online situational awareness and decision support applications are important for grid operators to prevent or mitigate cascading outages
- Wide-area synchrophasor measurements would enable next-generation grid monitoring applications
- Technologies to help prevent cascading outages are such as
  - System reduction (topological and dynamical)
  - Signal processing
  - Data mining

References

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Q&A

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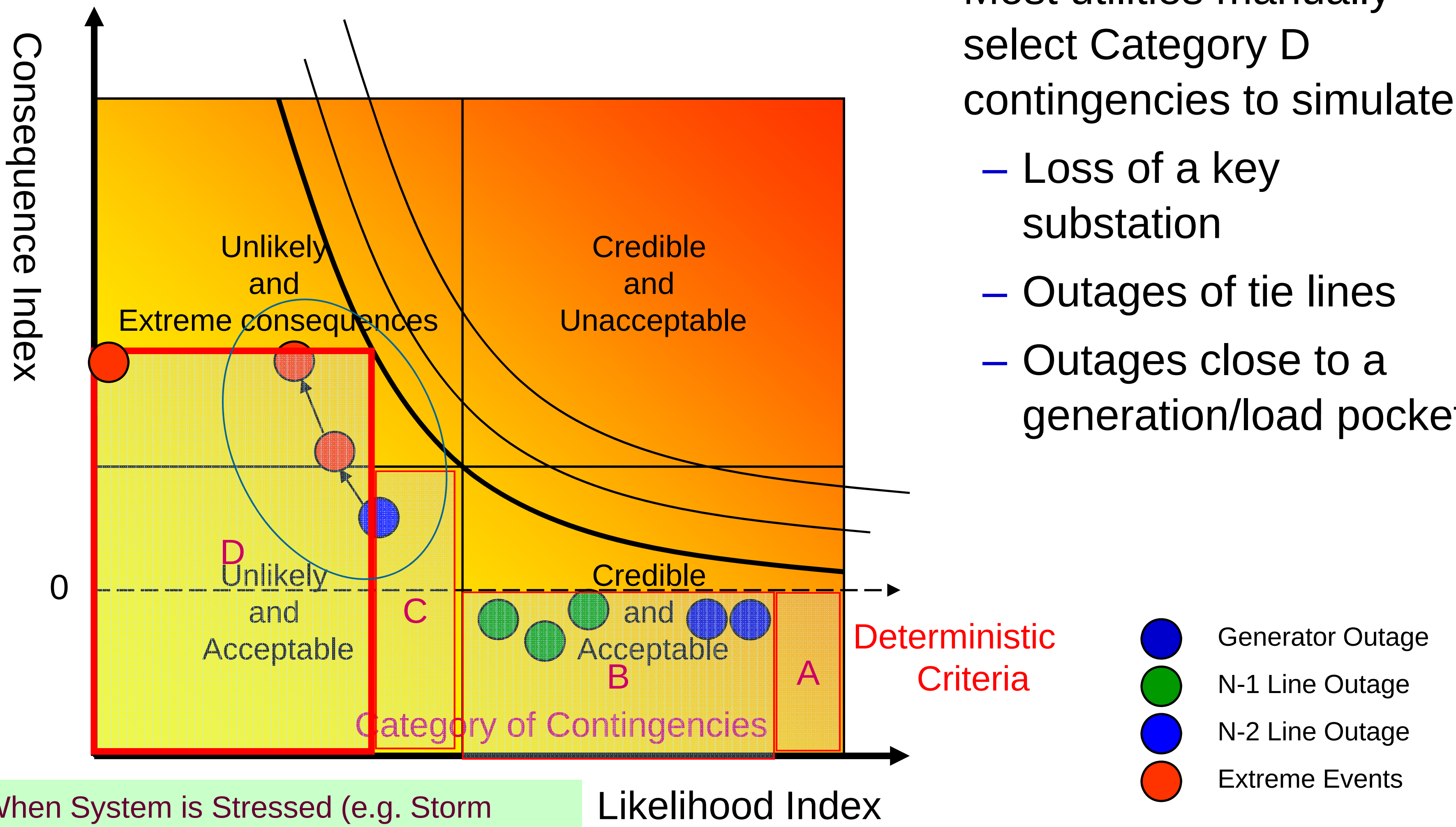
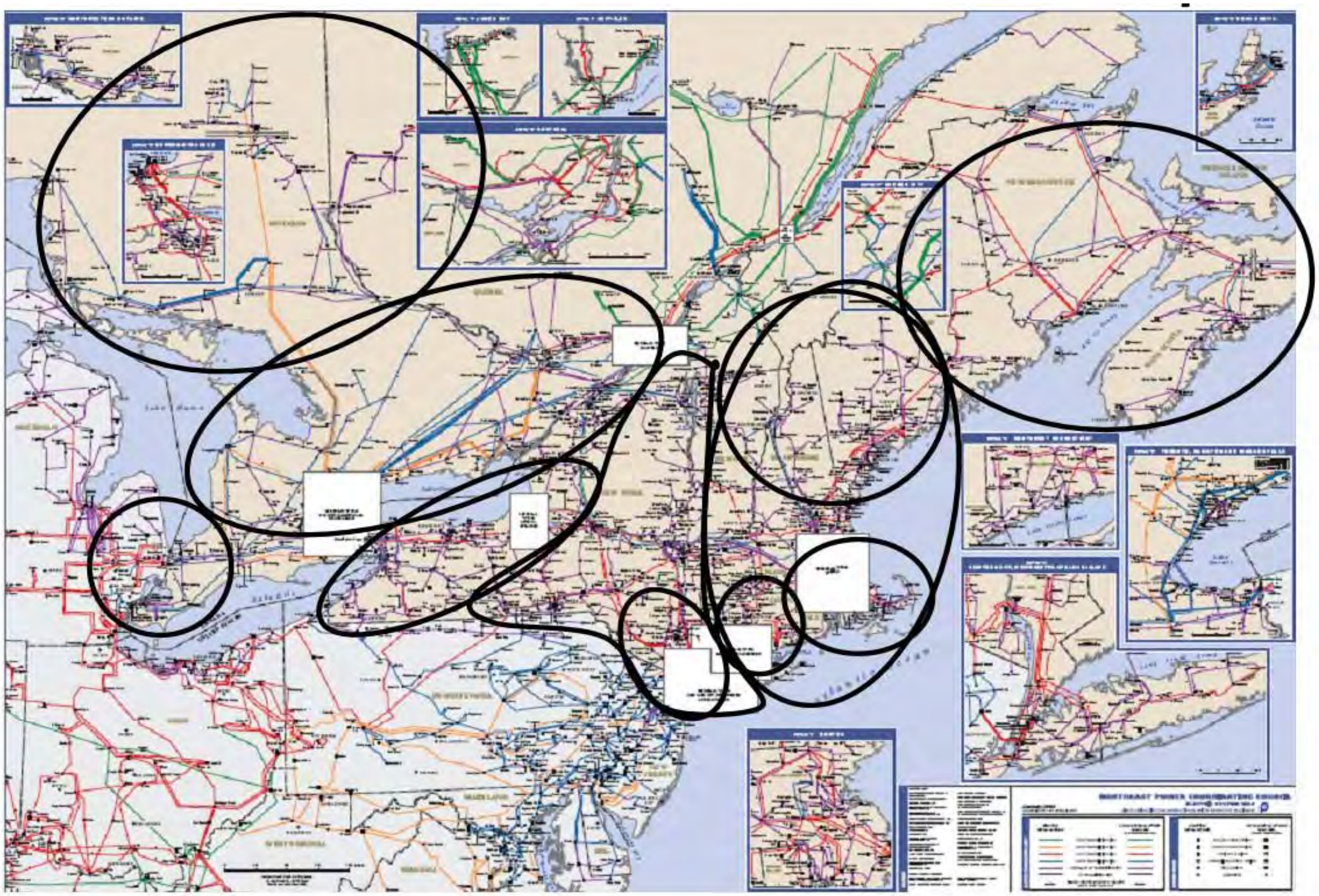
NERC Categories of Contingencies



When System is Stressed (e.g. Storm Approaching), the likelihood may increase

- Most utilities manually select Category D contingencies to simulate:
  - Loss of a key substation
  - Outages of tie lines
  - Outages close to a generation/load pocket

Northeast Coherent Generation Groups



— Approximate Boundaries of Coherent Generation

From NPCC (Northeast Power Coordinating Council) Study Results

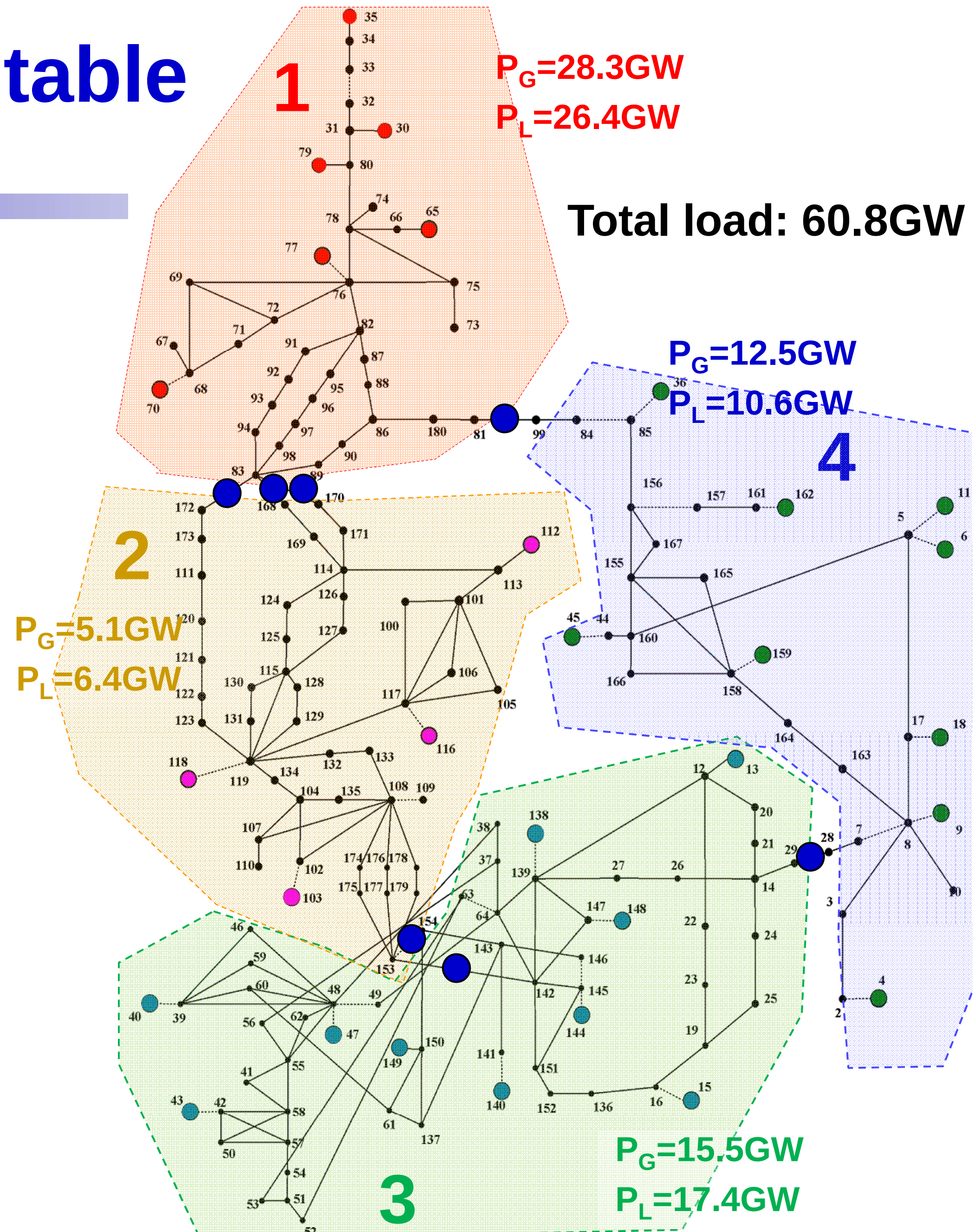
Building a strategy table

- 7 potential separation points
- 6 strategies (2 islands):

  1-234, 2-134, 3-124, 4-123

  12-34, 14-23
- 12 potential islands
- Validate control actions by simulations

Island	Shed Load	Island	Shed Load
1	0	23	7.3%
2	3.6%	34	1.5%
3	3.8%	124	0
4	0	123	4.1%
12	0	234	4.9%
14	0	134	0



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