U.S. DEPARTMENT OF ENERGY
Electricity Delivery & Energy Reliability

Advanced Grid Modeling 2014 Peer Review

High-Performance Hybrid Simulation/Measurement-Based Tools For Proactive Operator Decision-Support

Lawrence Livermore National Laboratory

ALSTOM GRID

THE UNIVERSITY of TENNESSEE KNOXVILLE

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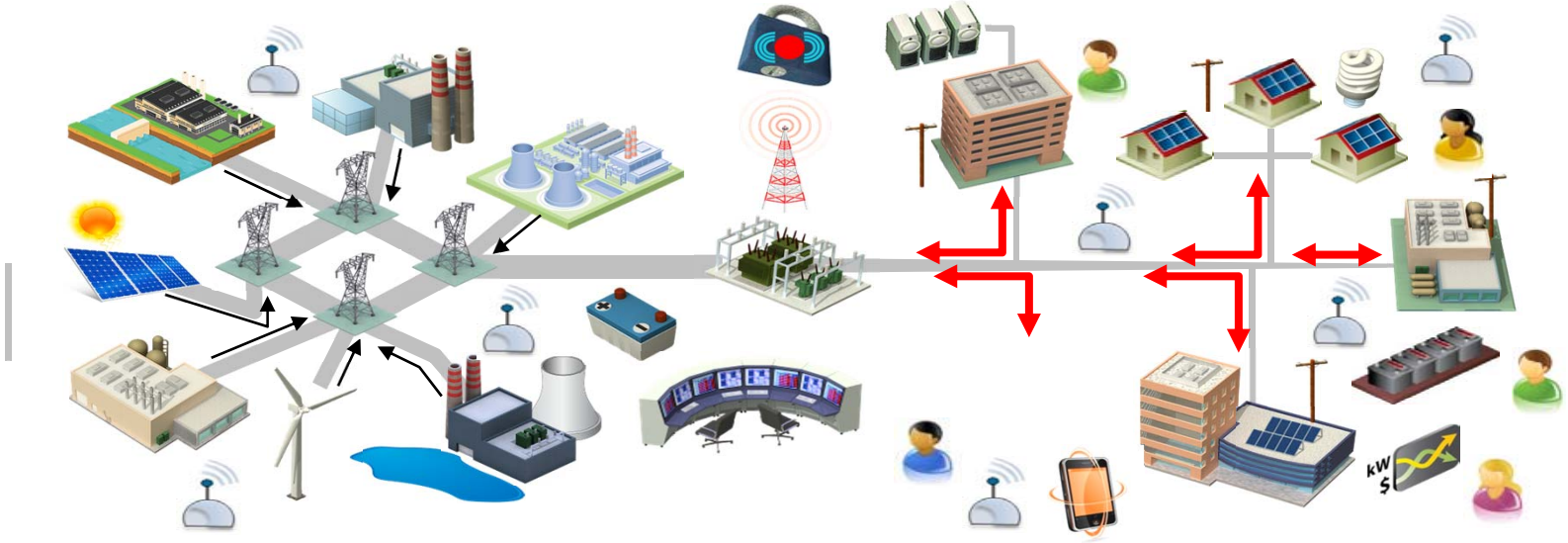
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Dr. Alberto Del Rosso, EPRI

June 17, 2014

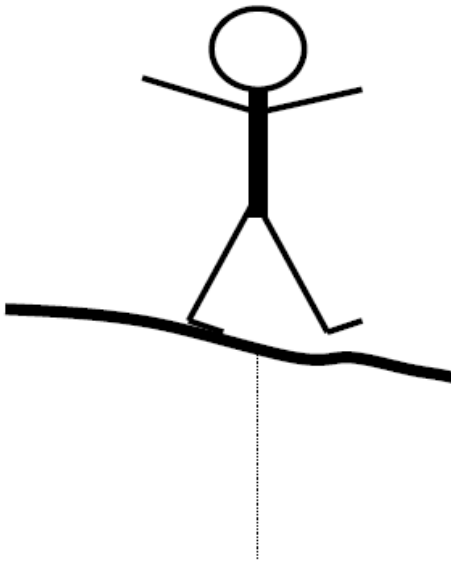
Roadmap Starts with a Vision



Power System that is Highly Flexible, Resilient, Highly Interconnected and Optimizes Energy Resources

Better software tools to support transmission operators' situational awareness and decision making are needed

Wide-area situational awareness



Courtesy of Mahendra Patel

Measurements give us current system states:

For true situation awareness we need to know;

- Where the edge is
- How close to the edge we can safely (reliably) operate
- Where would the states be during & after the next contingency

Decision support tool should provide:

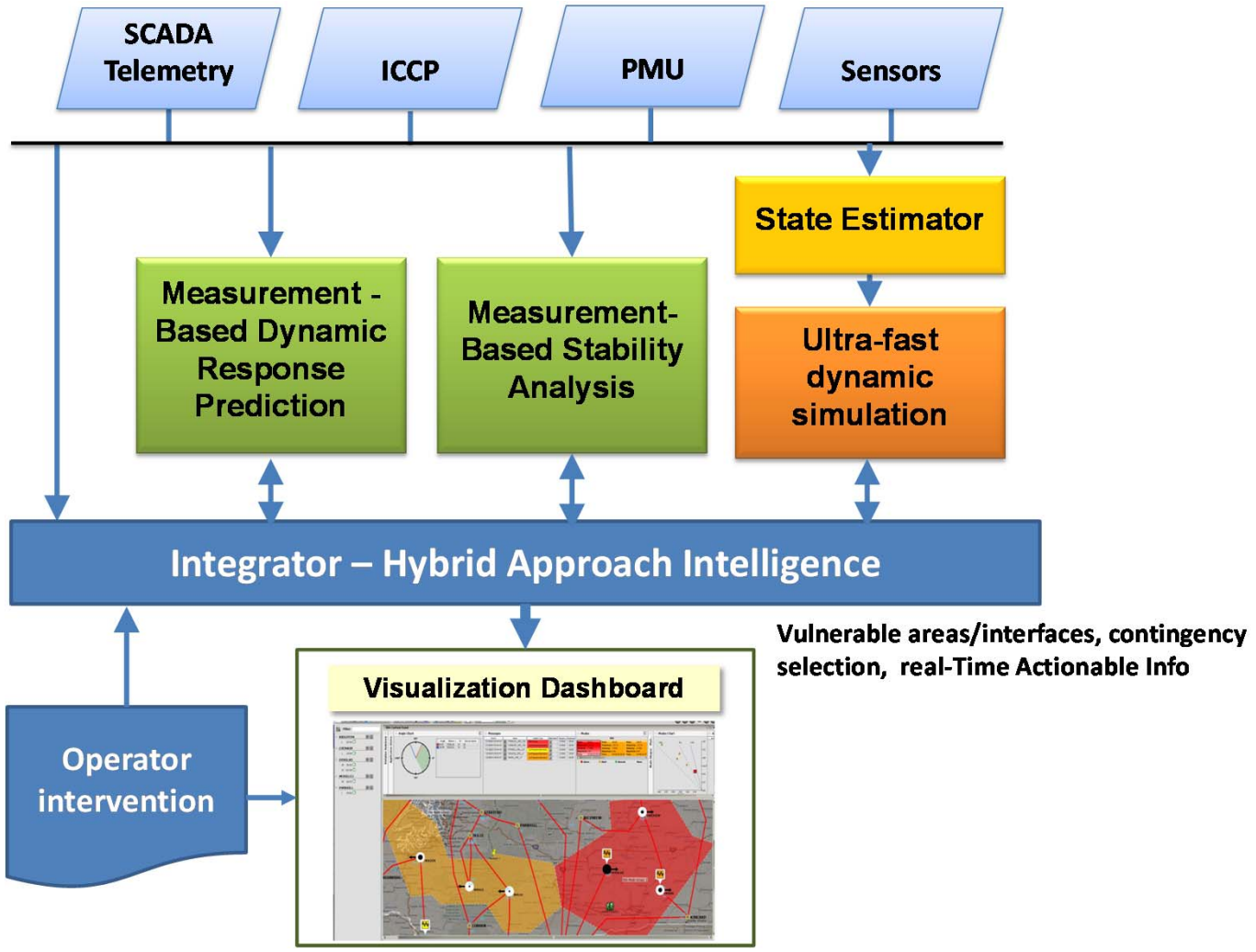
- A succinct view of the current status of the power system
- "look-ahead" capability based on "what-if" scenarios

Project Objective and Outcome

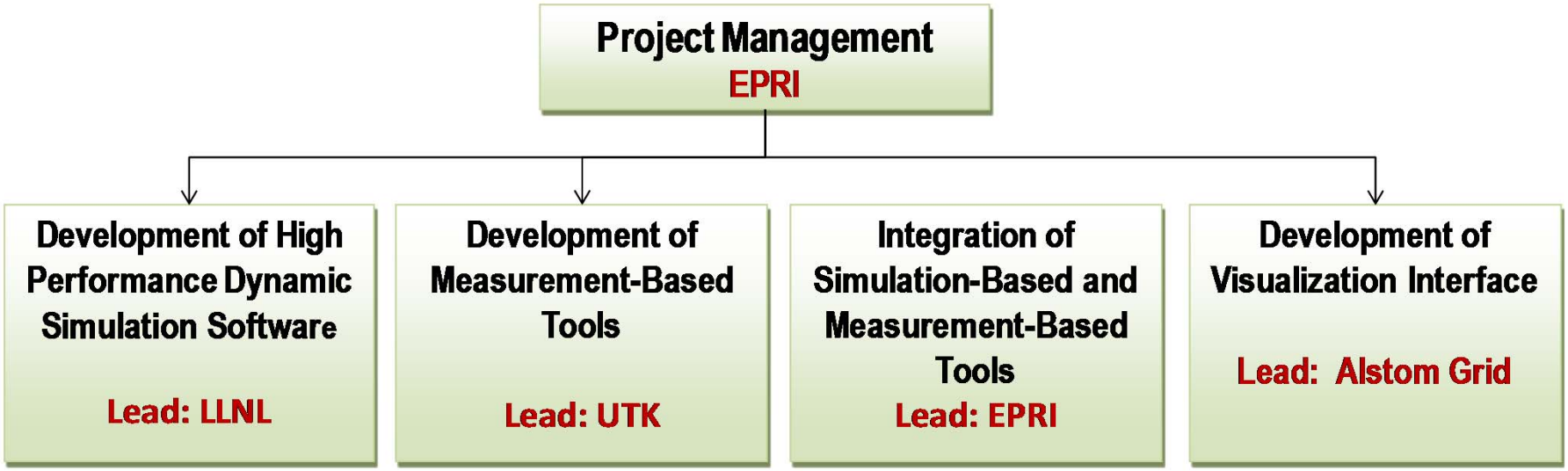
- Develop a set of new algorithms and computational approaches for improving situational awareness and support operator decision making by means of:
  - **real-time assessment of system dynamic performance**
  - **operational security risk**
- Outcomes:
  - Computational approach for ultra-fast power-system dynamic simulation
  - Mathematical algorithms for synchrophasor-based and hybrid DSA
  - Specification for advanced visualization software

Outcomes are expected to set a foundation for a new generation of real-time Dynamic Security Assessment tools

Technical Approach



Project Team and Participants



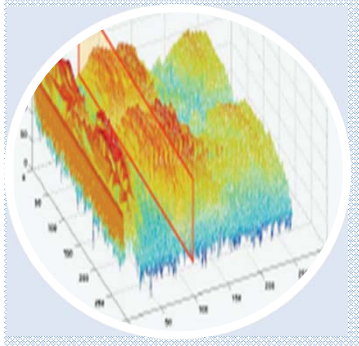
Utility/ISO Participants

Southern Company
American Electric Power (AEP)
PJM Interconnection
Tennessee Valley Authority (TVA)

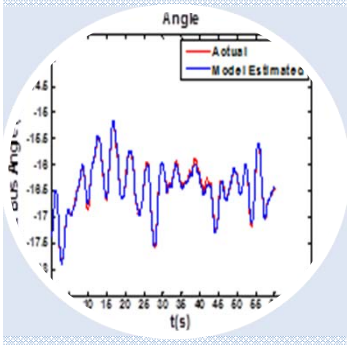
EPRI: Electric Power Research Institute
LLNL: Lawrence Livermore National Laboratory
UTK: University of Tennessee Knoxville

Areas of Development

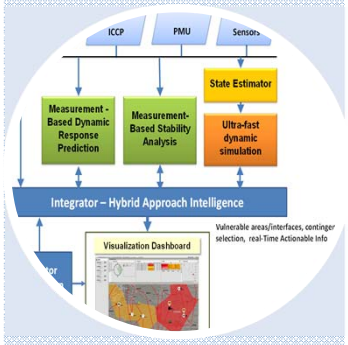
High performance dynamic simulation software



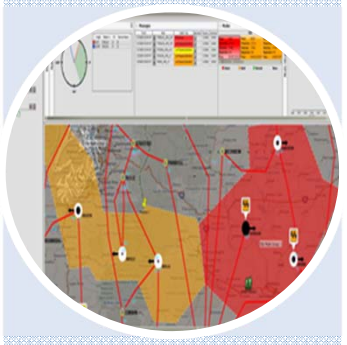
Measurement-based Voltage and Angular Stability Analysis



Measurement Based Dynamic Response Prediction

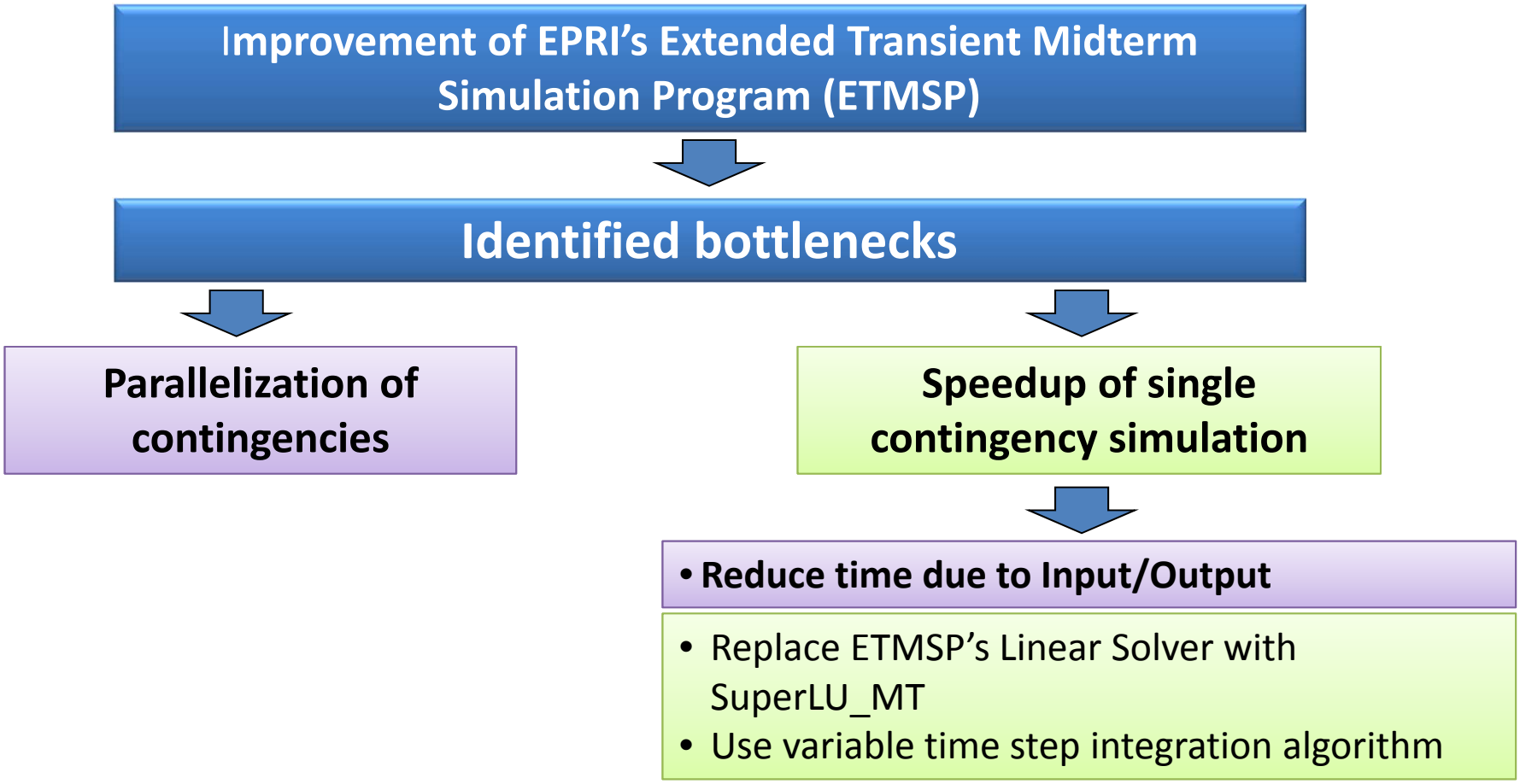


Hybrid Approach Intelligence



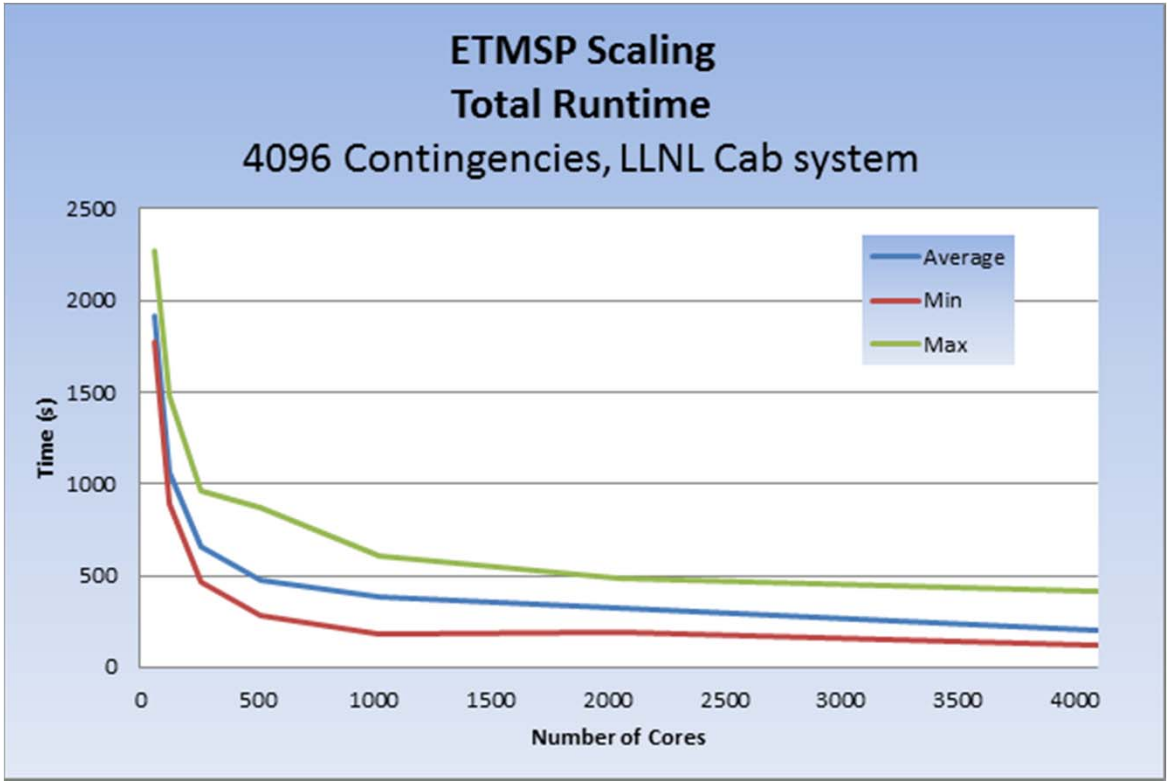
Advanced Visualization

High Performance Dynamic Simulation Software



Parallel Contingency Analysis

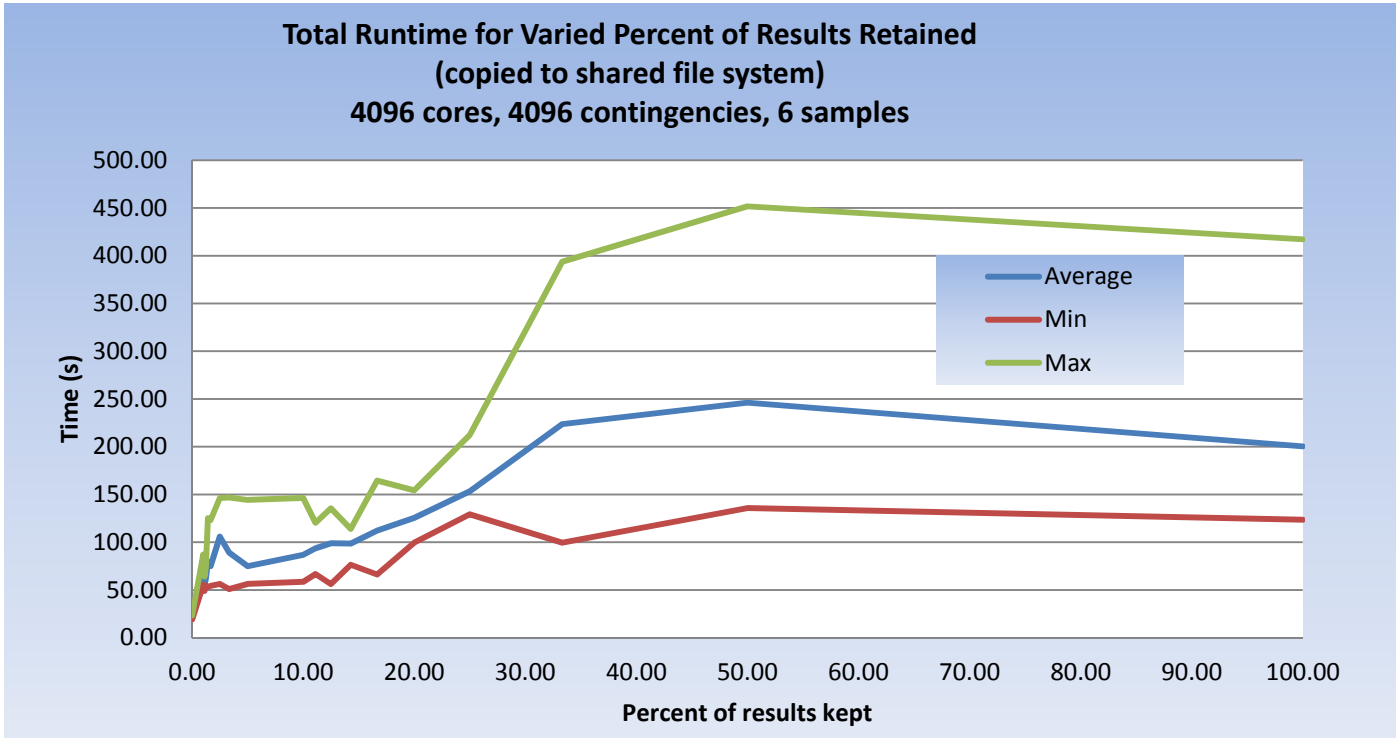
	Total Runtime (s)			
Number of Cores	Average	Min	Max	StdDev
64	1915	1774	2275	184
128	1062	891	1480	211
256	658	469	960	189
512	477	286	869	187
1024	384	183	610	129
2048	324	193	490	96
4096	200	123	417	105



Would take ~20.4 hours on sequential machine

Reducing I/O Bottleneck

- I/O reduction by keeping only results of interest
- Experiments with different % of output results
- Would need to output <30% for this strategy to have a significant impact on performance



Variable Time Step Integrator

- Applied Adams-Bashforth-Moulton predictor-corrector control for differential variables
- Step sizes chosen to minimize truncation error for differential variables

Speedup 59% for 10s simulation on the 25,000 bus test case

Step Size Scheme	Time (s)
Fixed Step	21.0
Variable Step	8.8

Thread-parallelization of Sparse Linear Solver

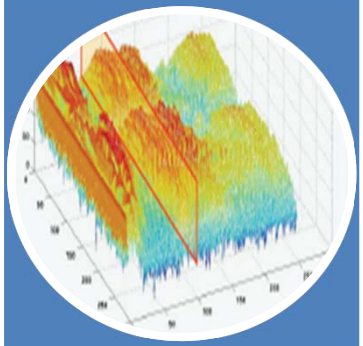
- Test results on 25,000 bus system

Number of Monitored Buses	Original Solver (sec)	SuperLU_MT with 4 Threads (sec)
200	0.8	9.66
2000	4.32	9.69
20,000	10.23	9.71

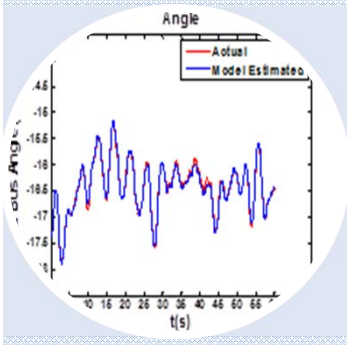
- **No advantage when limited number of buses is monitored**
- Reason: SuperLU_MT does full backward substitution. ETMSP does only partial backward substitution
- Linear solver takes only 10% of overall CPU time

Areas of Development

High performance dynamic simulation software



Measurement-based Voltage and Angular Stability Analysis



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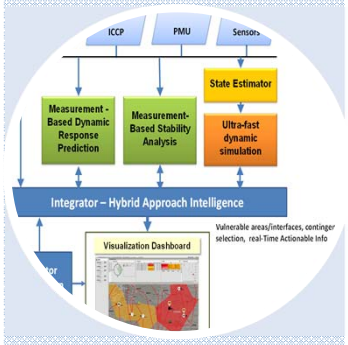

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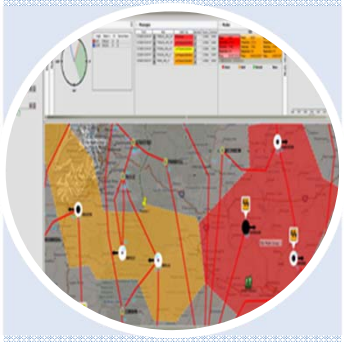
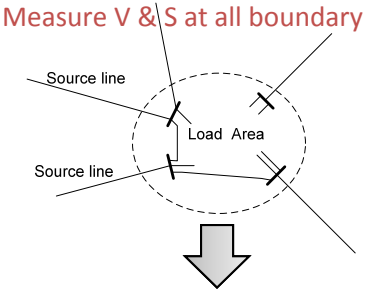


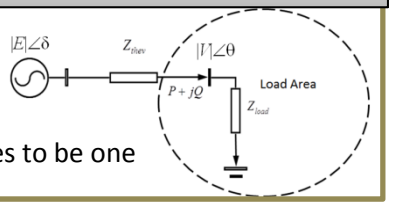
Advanced Visualization

Measurement-based Voltage Stability Assessment

1. Measure V & S at all boundary buses



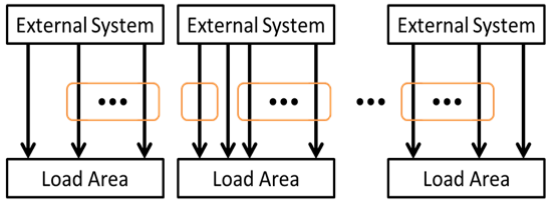
Thevenin equivalent (1+1 buses)



Merge all lines to be one

New multi-terminal network equivalent (N+M buses)

2. Equivalent with details on different transfer paths

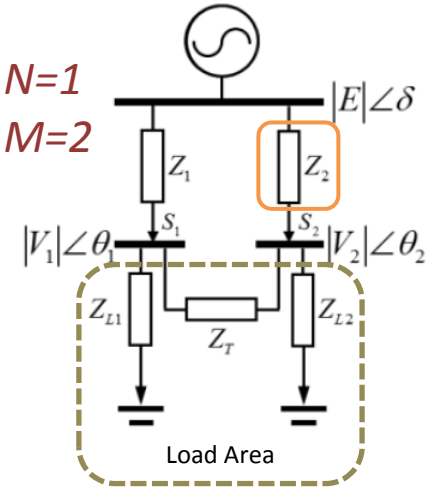


3. Real time estimation for E and Z's

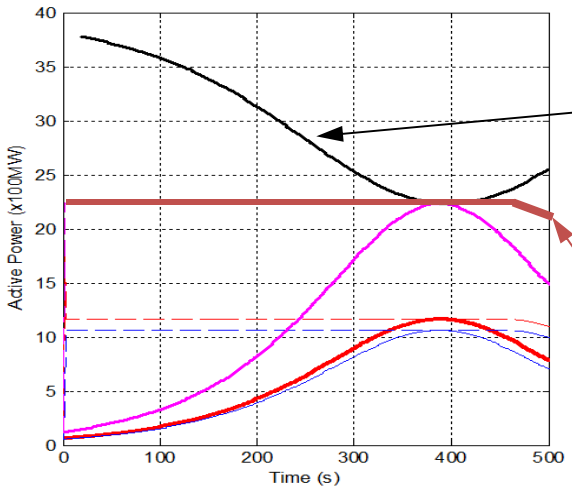
4. Direct transfer limit calculation for each path

$$P_{1\max} = f_1(E, Z_1, Z_2, Z_{L1}, Z_{L2}, Z_T)$$

$$P_{2\max} = f_2(E, Z_1, Z_2, Z_{L1}, Z_{L2}, Z_T)$$



Tight coupling between tie lines (small |ZT|)

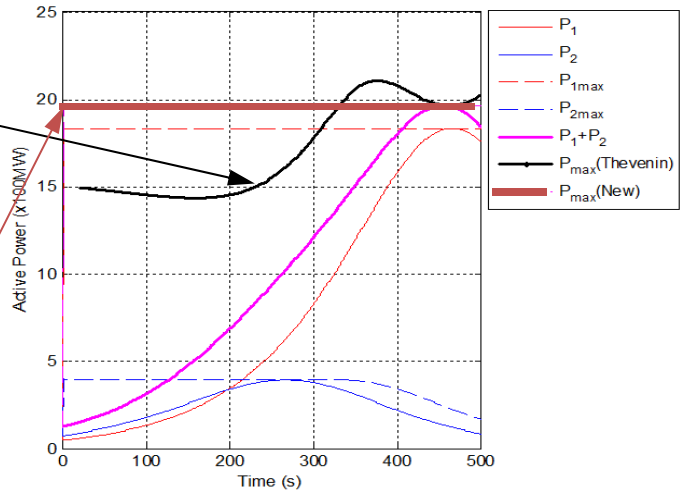


Comparison

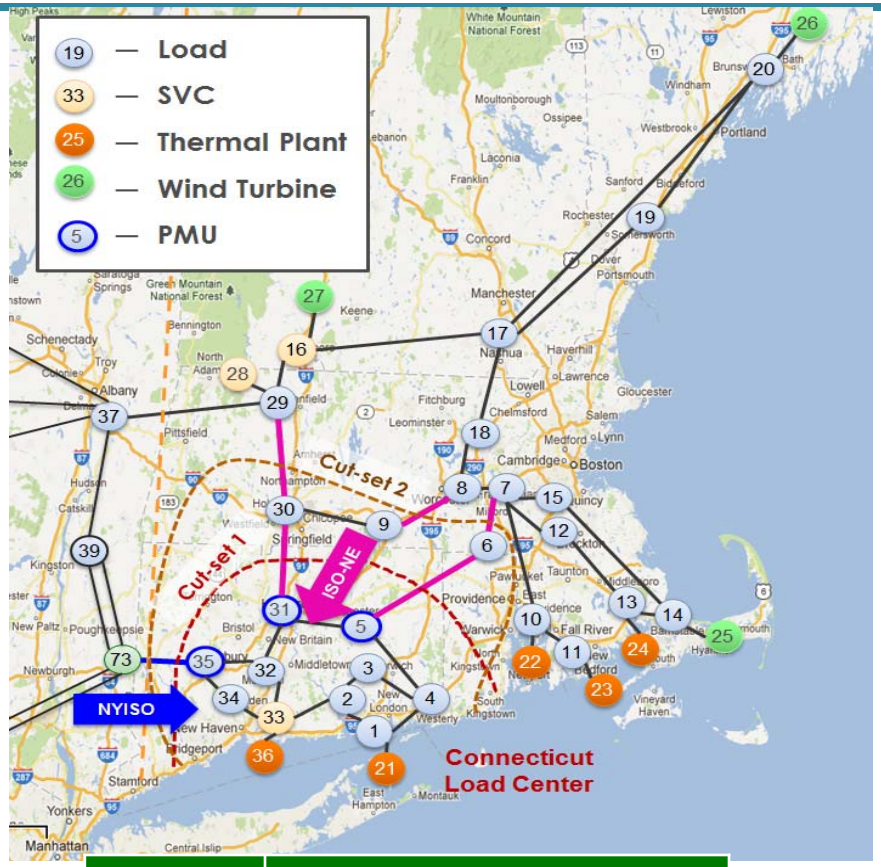
Thevenin approach:
- Inaccurate due to merging all tie lines

New approach:
- accurate total limit
- estimates the limit for each line

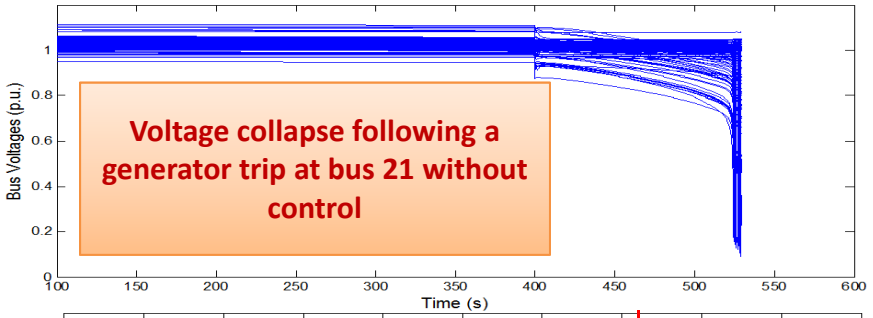
Weak coupling between tie lines (large $|Z_T|$)

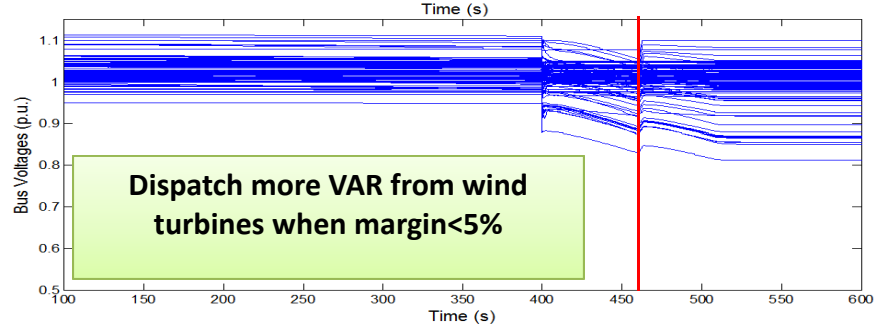


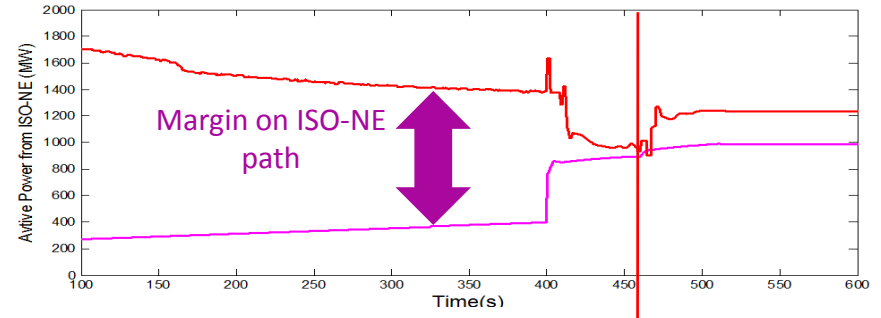
Demonstration on CURENT NPCC 140-bus Testbed

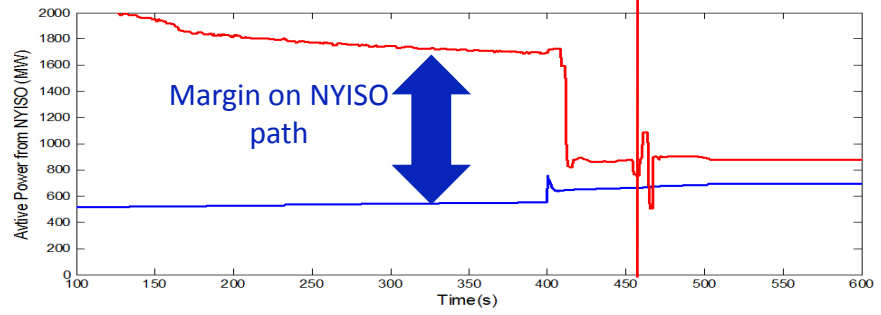


Time (s)	Tie lines ranked by MBVSA
Before generator trip	Line 30-31, Line 6-5
	Line 29-30, Line 8-9, Line 7-6
	Line 73-35
After generator trip	Line 29-30, Line 8-9, Line 7-6
	Line 30-31, Line 6-5
	Line 73-35





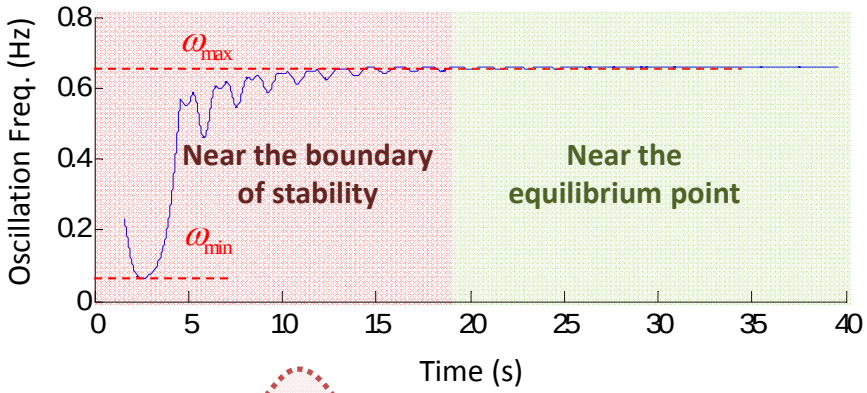




Measurement-based Angular Stability Assessment

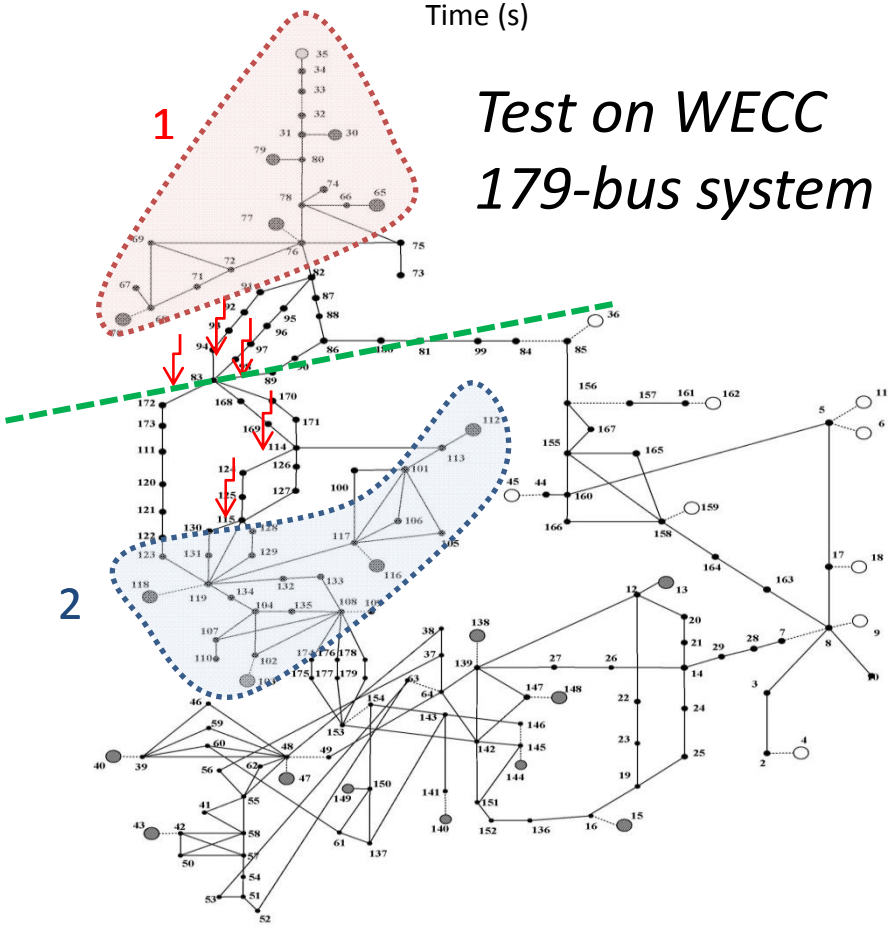
- Using PMU data to identify critical network interfaces or generators vulnerable to angular oscillation and instability
- Estimating stability margin only from PMU data
- Can suggest locations for contingency simulations
- Can also help rank contingencies by simulated trajectories

Approach

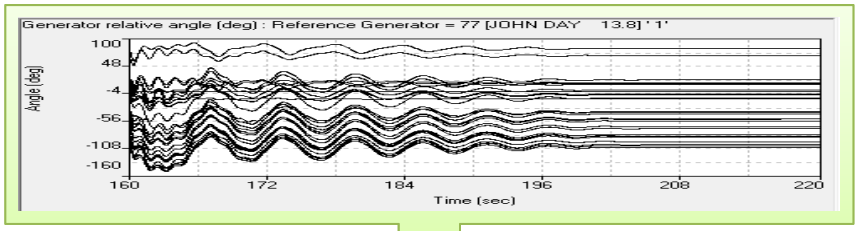


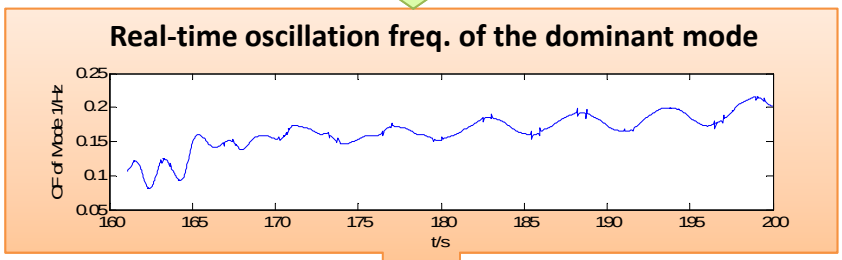
Stability margin index based on fluctuation of the oscillation frequency about a dominant mode

$$SMI = \frac{\omega_{\min}}{\omega_{\max}} \times 100\%$$

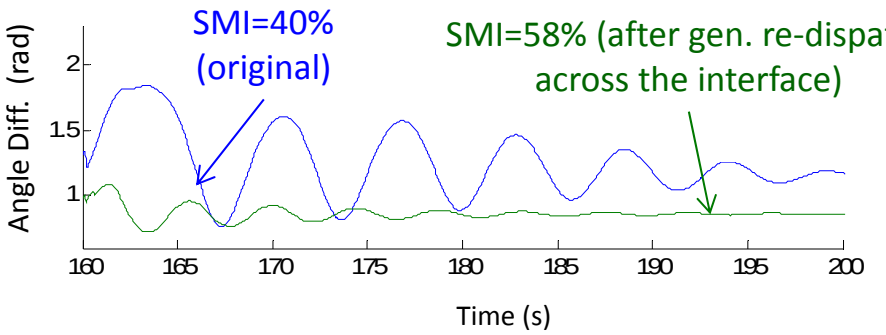


Test on WECC 179-bus system



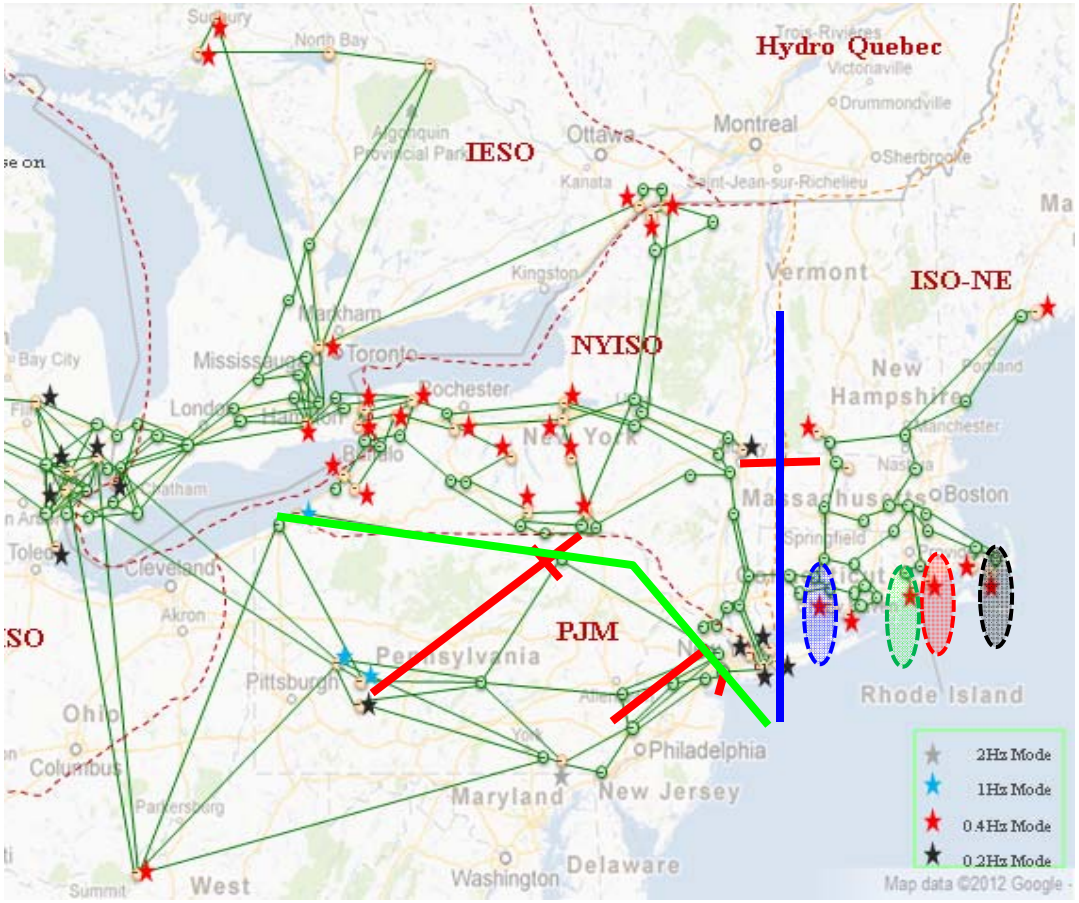


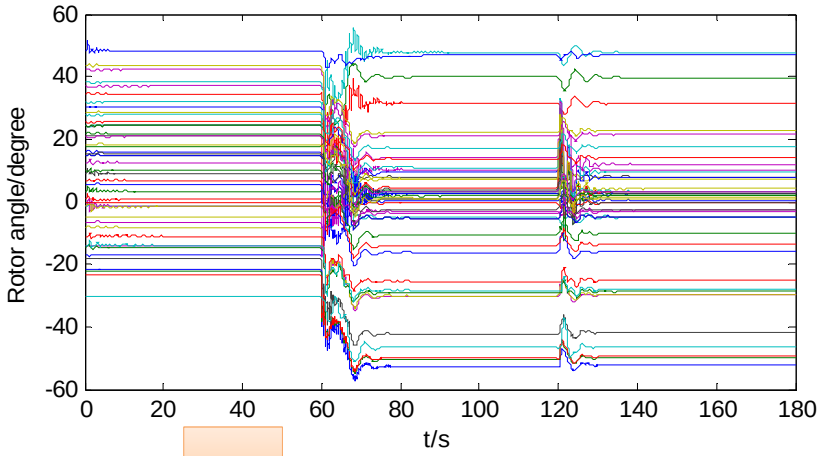
SMI=40%

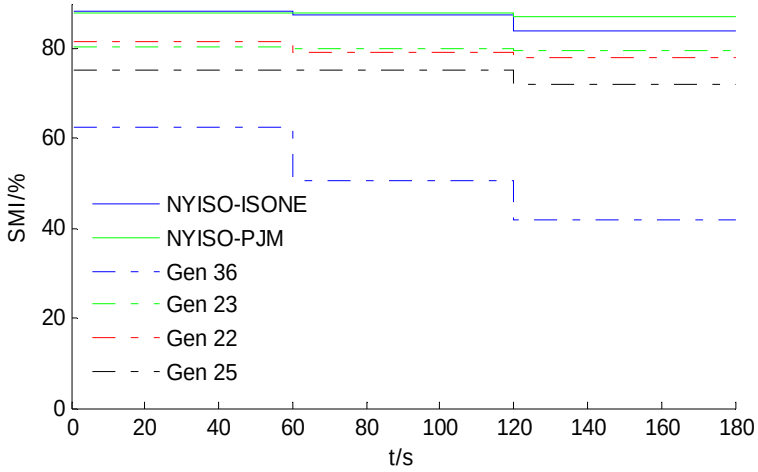


Test on NPCC 140-bus testbed: Suggesting locations for contingency simulations

- Three events from the 8/14/2003 blackout
- Calculate SMI for NYISO-ISONE and NYISO-PJM interfaces and key generators following each event



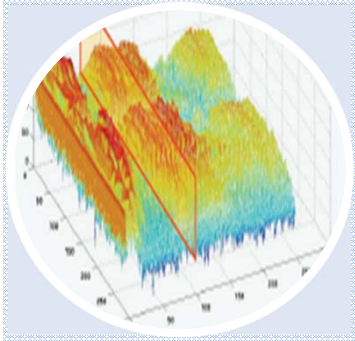




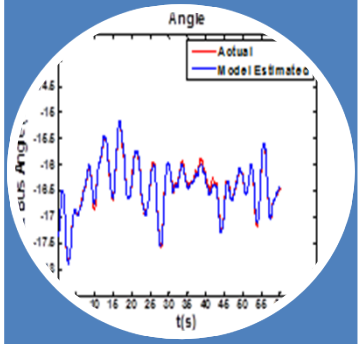
- NYISO-ISONE interface and the generators near that interface are more vulnerable.

Areas of Development

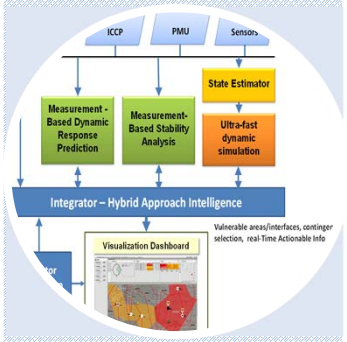
High performance dynamic simulation software



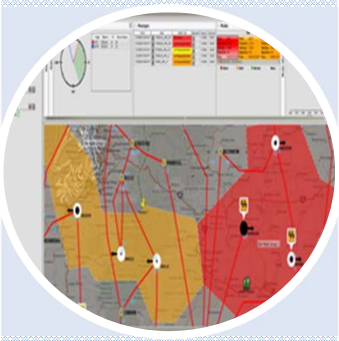
Measurement-based Voltage and Angular Stability Analysis



Measurement Based Dynamic Response Prediction

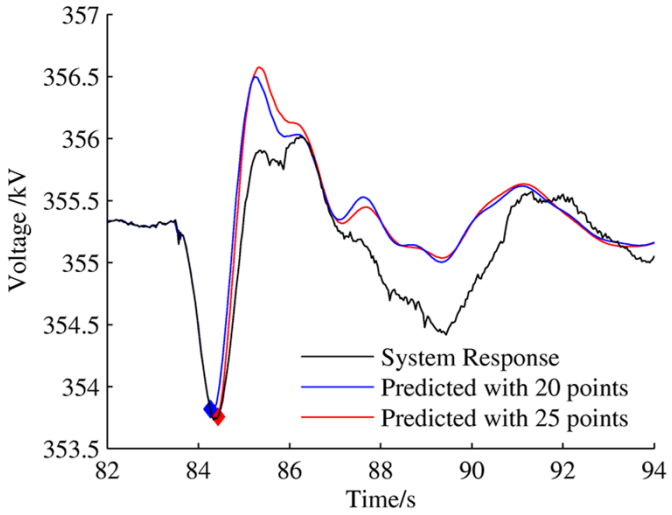


Hybrid Approach Intelligence

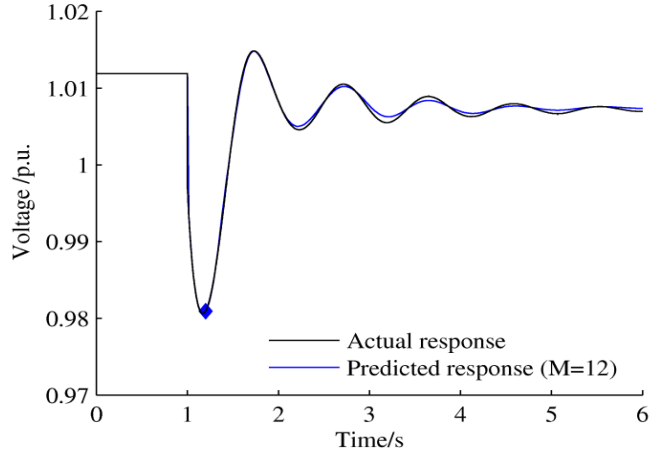


Advanced Visualization

Dynamics Prediction using Measurement Based Transfer Functions



- PMU data from ISO New England

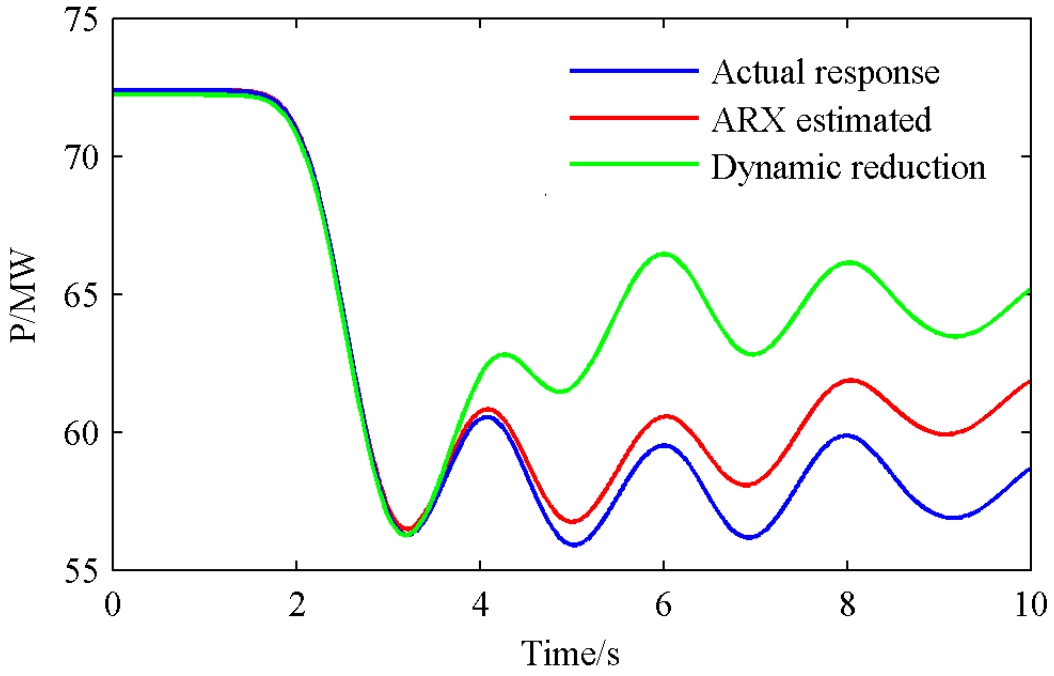


- Simulation on 23-bus system

- Multivariate Auto-Regressive Model (ARX)
- Predict system dynamics with:
  - ➢ transfer functions derived from wide-area phasor measurement data, and
  - ➢ first few data points of an event
- Overcome the challenges of circuit models
- System reduction to speed up simulation in very large system models

System Reduction Using Transfer Function Model to Speedup Simulation

- Reduce simulation time by simplifying representation of external system:
  - Reduction using transfer function models derived from measurements (Red).
  - Traditional dynamic reduction approach (green)



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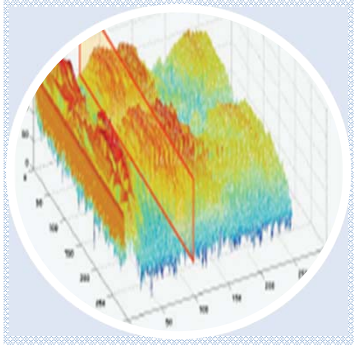

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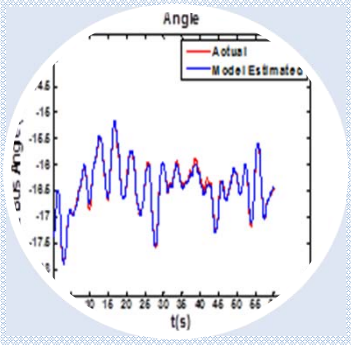

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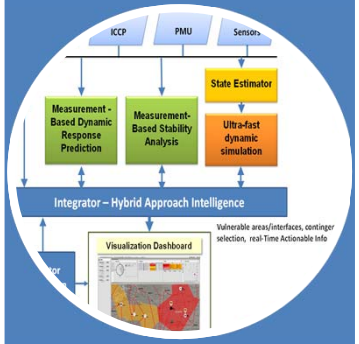

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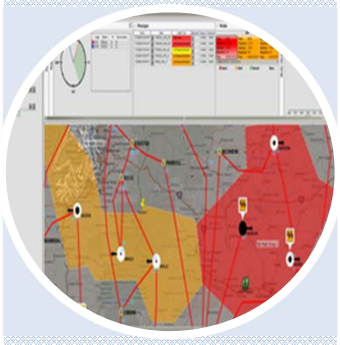


Advanced Visualization

Hybrid Approach Intelligence

Measurement Based Analysis

- Identifies criticality of the system when simulation results are not available
- Identifies vulnerable regions and critical grid components
- Triggers emergency control actions
- Model reduction

Simulation Based Analysis

- "What-if" analysis. Identifies potential N-1 violations
- Preventive control actions recommendations
- HPC enabled faster than real-time performance

Hybrid Approach Intelligence

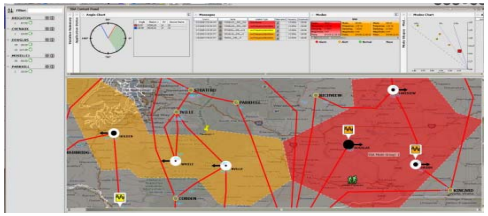
- Combines strengths of both approaches
- Analyzes, manages, coordinates, and post-processes results from the different modules to generate actionable information
- Information and visualizations with focus on the operator needs &perspective

Real-time Stability Margins

Real-Time Alerts

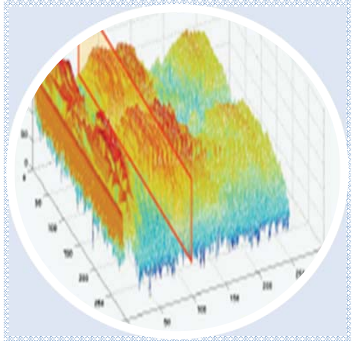
Emergency Automated Actions

Recommendations on Preventive Actions

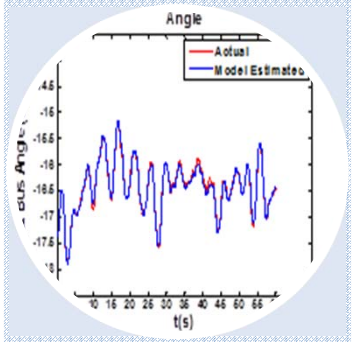


Areas of Development

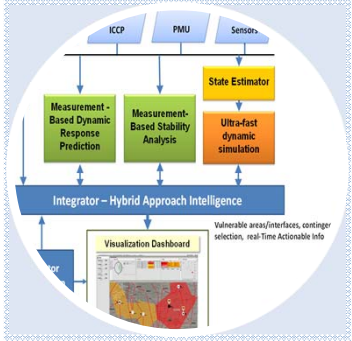
High performance dynamic simulation software



Measurement-based Voltage and Angular Stability Analysis



Measurement Based Dynamic Response Prediction



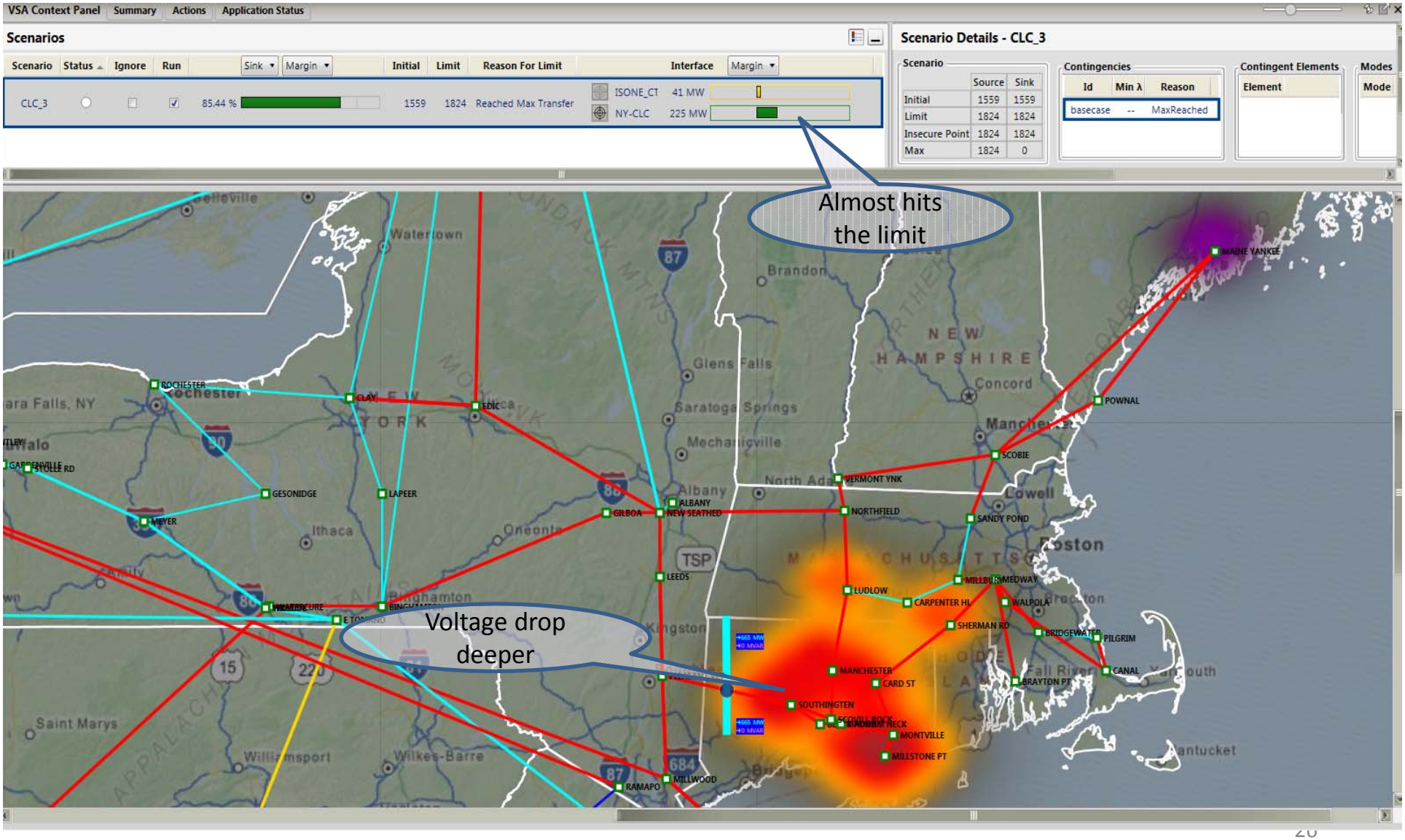
Hybrid Approach Intelligence

Advanced Visualization

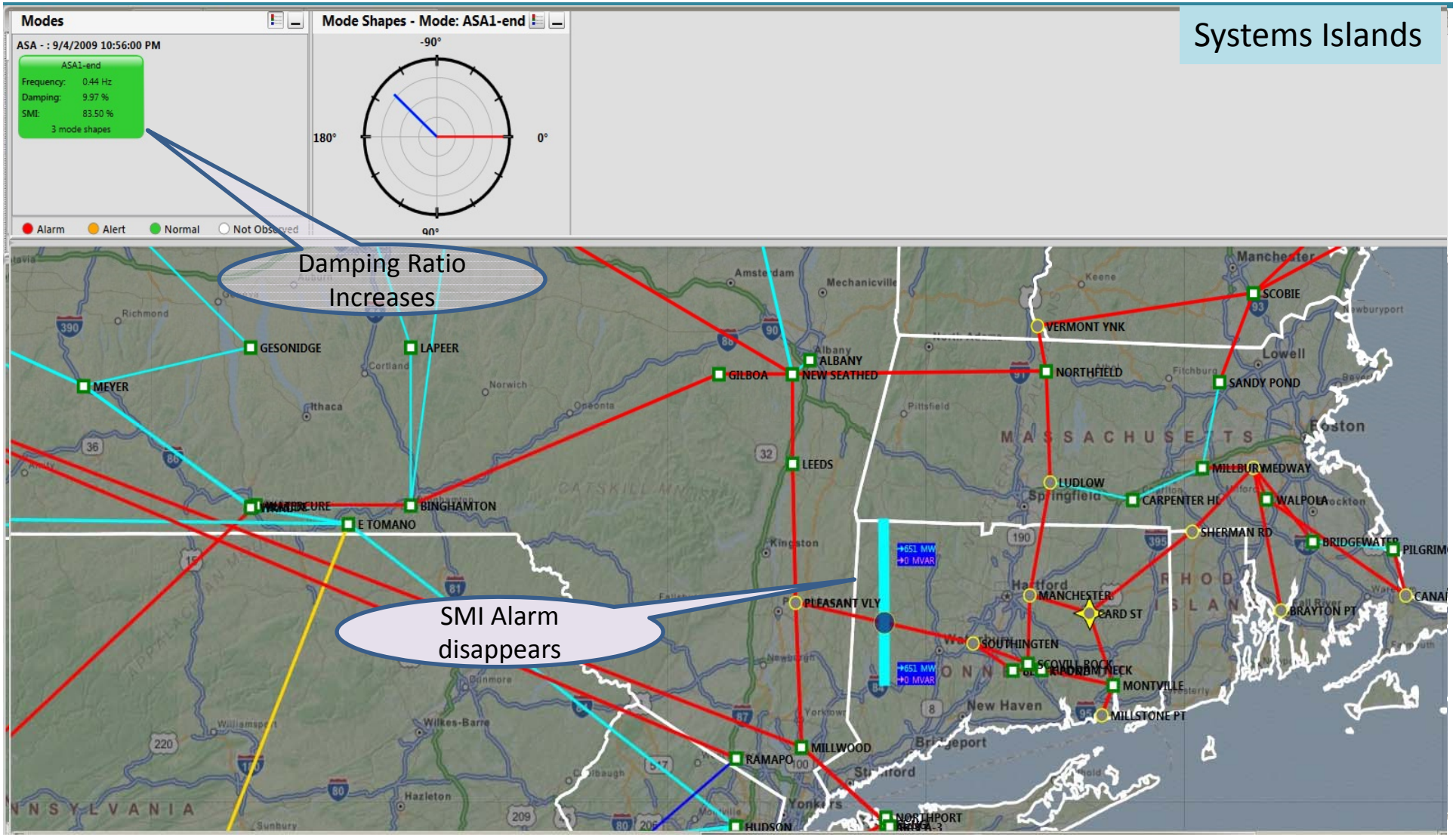
Advanced Visualization

- Essential to improve situational awareness
- Relevant characteristics:
  - provide concise and actionable information to operators
  - ability to navigate and drill-down for additional information
  - Present cause-effect relationship
- Document visualization concepts and interface requirements
- Test in Alstom's e-terravision platform

Visualization of Voltage Stability Assessment based on **e-terra***vision*



Visualization of Angular Stability Analysis based on **e-terra***vision*



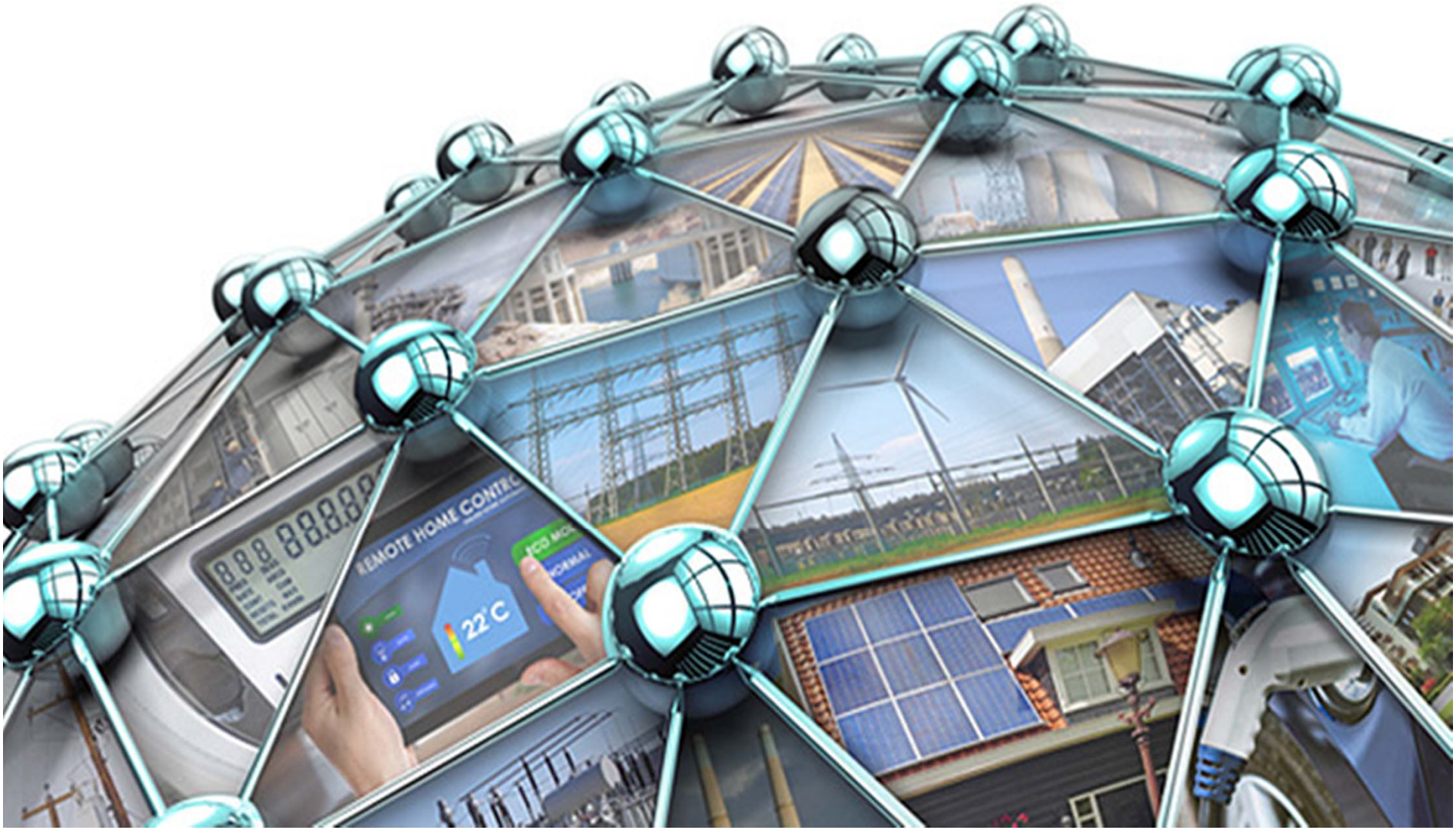
Concluding Remarks

- Need for tools to improve situational awareness and operator support decision making
- Existing DSA tools:
  - Mainly based on simulations
  - Not capable to fully respond to operators needs
- High-performance computing technology is accessible
- Improved synchrophasor-based algorithms developed
- A sound approach:

  $\Rightarrow$ **combine measurement-based algorithms with simulation-based tools and advanced visualization**

Opportunities for Future Work

- Develop the software platform to integrate the developed tools in a common data and model framework
- Conduct a full pilot demonstration at utility or ISO/RTO
- Develop a roadmap for production-grade deployment in real-time operations.
- Support utilities and ISOs/ RTOs in their efforts to implement the roadmap


REMOTE HOME CONTRO
22°C

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Back-Up Slides (if Necessary)