Overview of Synchrophasor Applications

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Recognition of the Synchrophasor Technology at the World-Wide Stage:

BPA synchrophasor project received 2013 Platt's Global Energy Award for Grid Optimization

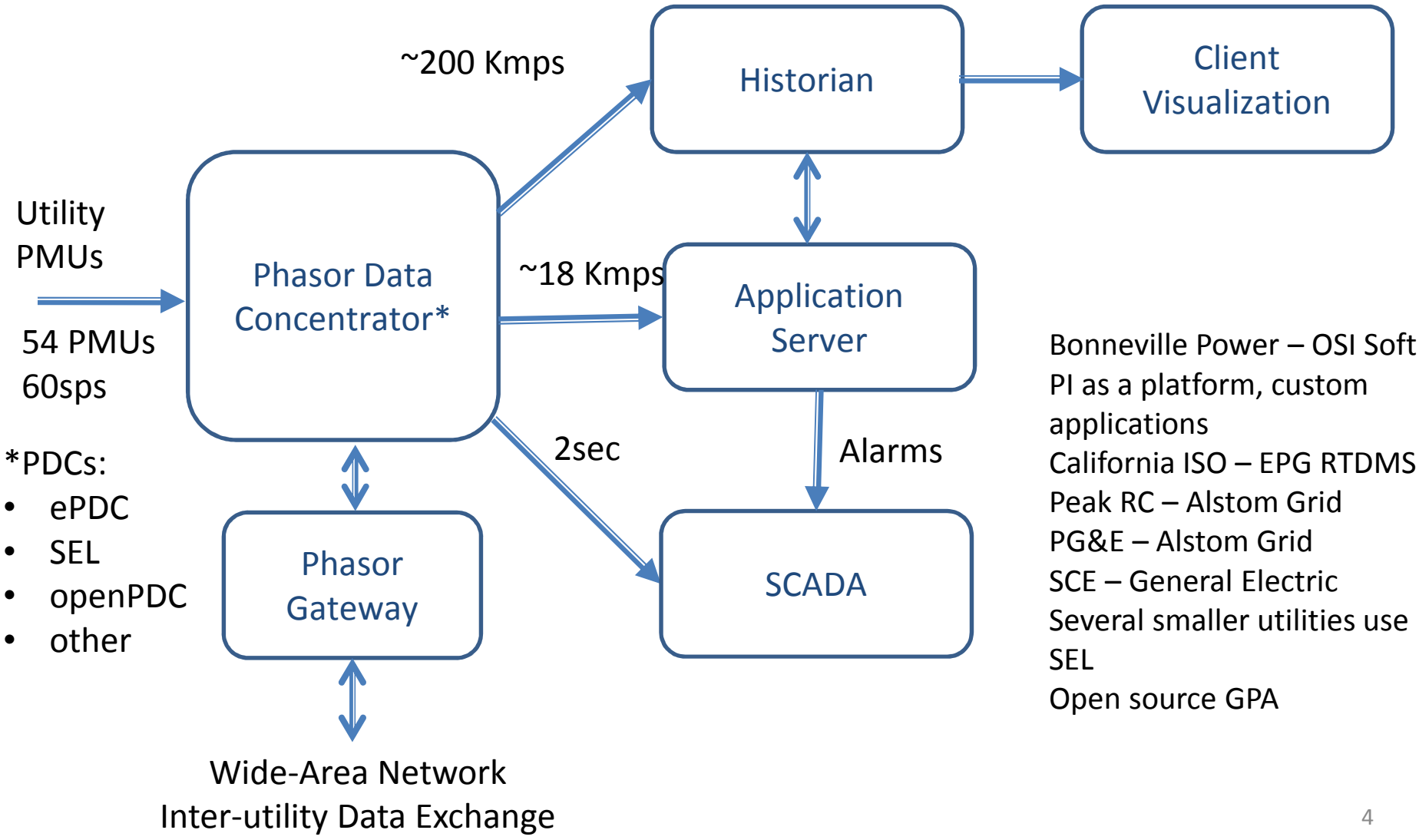
PMU Installations

- PMU installations and system design are driven by requirements of planned applications

- Stand alone or relay upgrade ?
- Redundancy ?
- PMU status monitoring ?
- Critical Cyber Asset ?

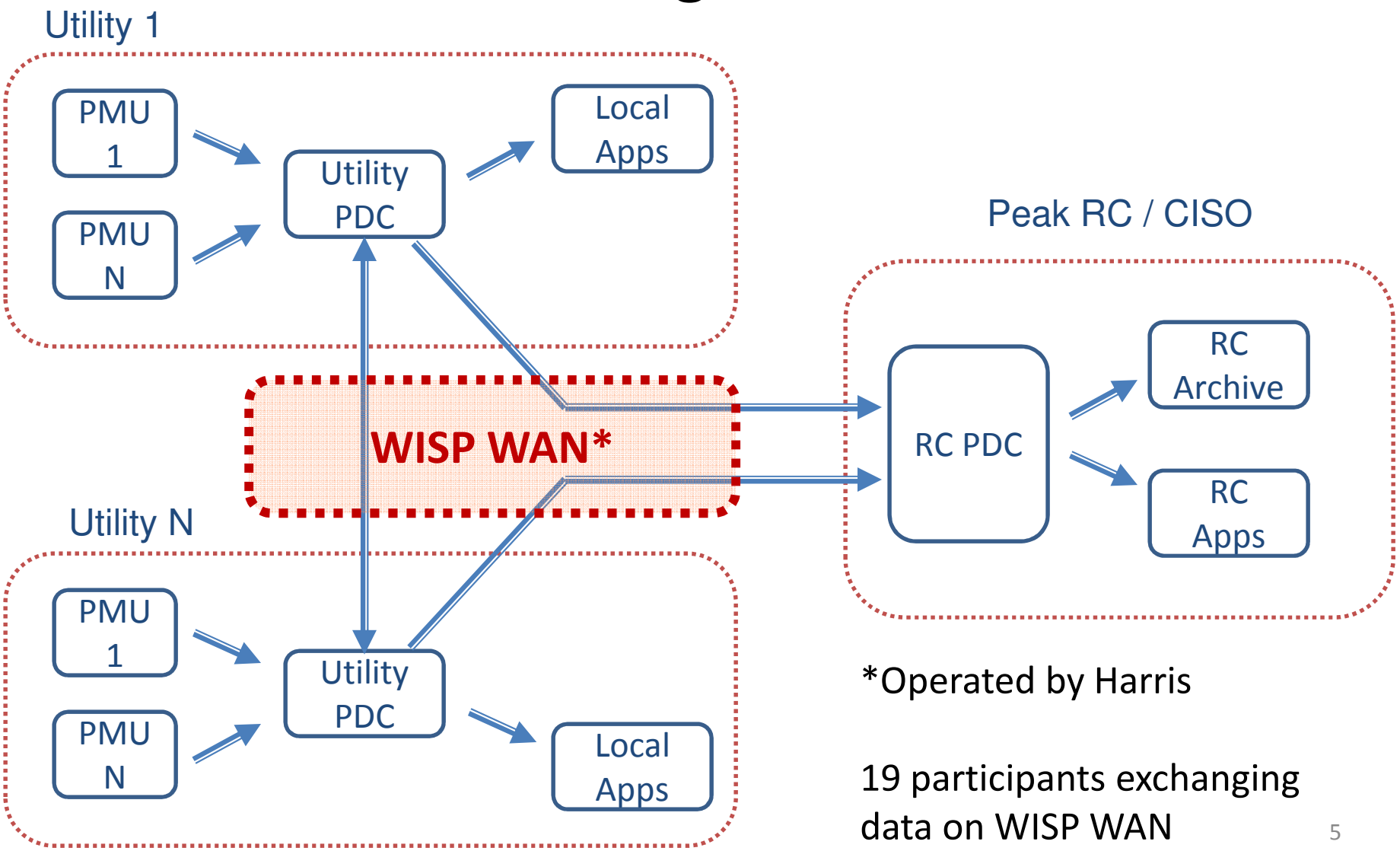
- Measurements: voltage and current phasors, active and reactive power, ABC phase values, digital status

Typical Control Room Architecture



Bonneville Power – OSI Soft PI as a platform, custom applications
California ISO – EPG RTDMS
Peak RC – Alstom Grid
PG&E – Alstom Grid
SCE – General Electric
Several smaller utilities use SEL
Open source GPA

Western Interconnection Sycnhrophasor Program



*Operated by Harris

19 participants exchanging data on WISP WAN

Overview of Applications

- Event Analysis
- Model Validation
- Frequency Response Analysis
- Frequency Disturbance Detection
- Islanding Detection
- Oscillation Detection and Mode Meter
- Voltage Stability
- State Estimation
- Equipment Malfunction
- Development Pipeline

Event Analysis

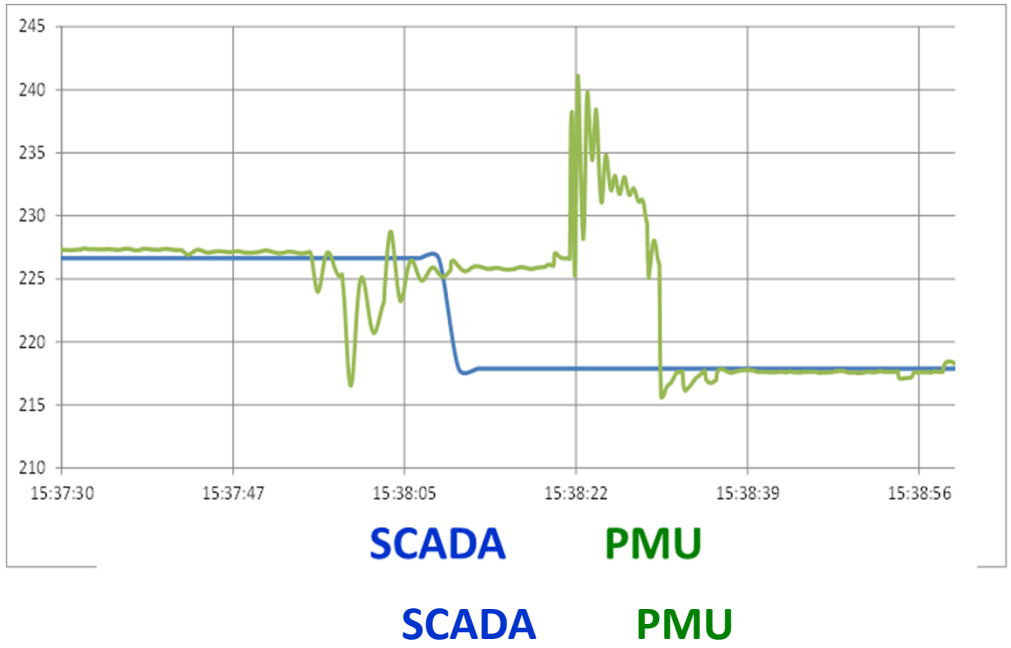
Event Analysis

- **Maturity: 9/10**

- Event Analysis is the most mature application of the synchropahsor technology since mid 1990s
- Synchronized-wide-area PMU data is used to time-align events to correctly determine sequence of events, their causes and effects
- NERC PRC-002 Reliability Standard (out for ballot) sets placement requirements for disturbance monitoring devices
  - Regional entities (e.g. WECC) have their own guidelines in place

September 8, 2011 Pacific Southwest Outage

- Disturbance evolved over about 11 minutes
- There were several phases of multiple switching actions
- Timing of events reported by utilities was different, a few by several minutes



- Time-synchronized data from three PMUs was used to align switching events precisely in about 2 hours versus months
- PMU data was also essential for model validation studies to simulate the event in time sequence power flow and transient stability programs

Trending Real-Time Data

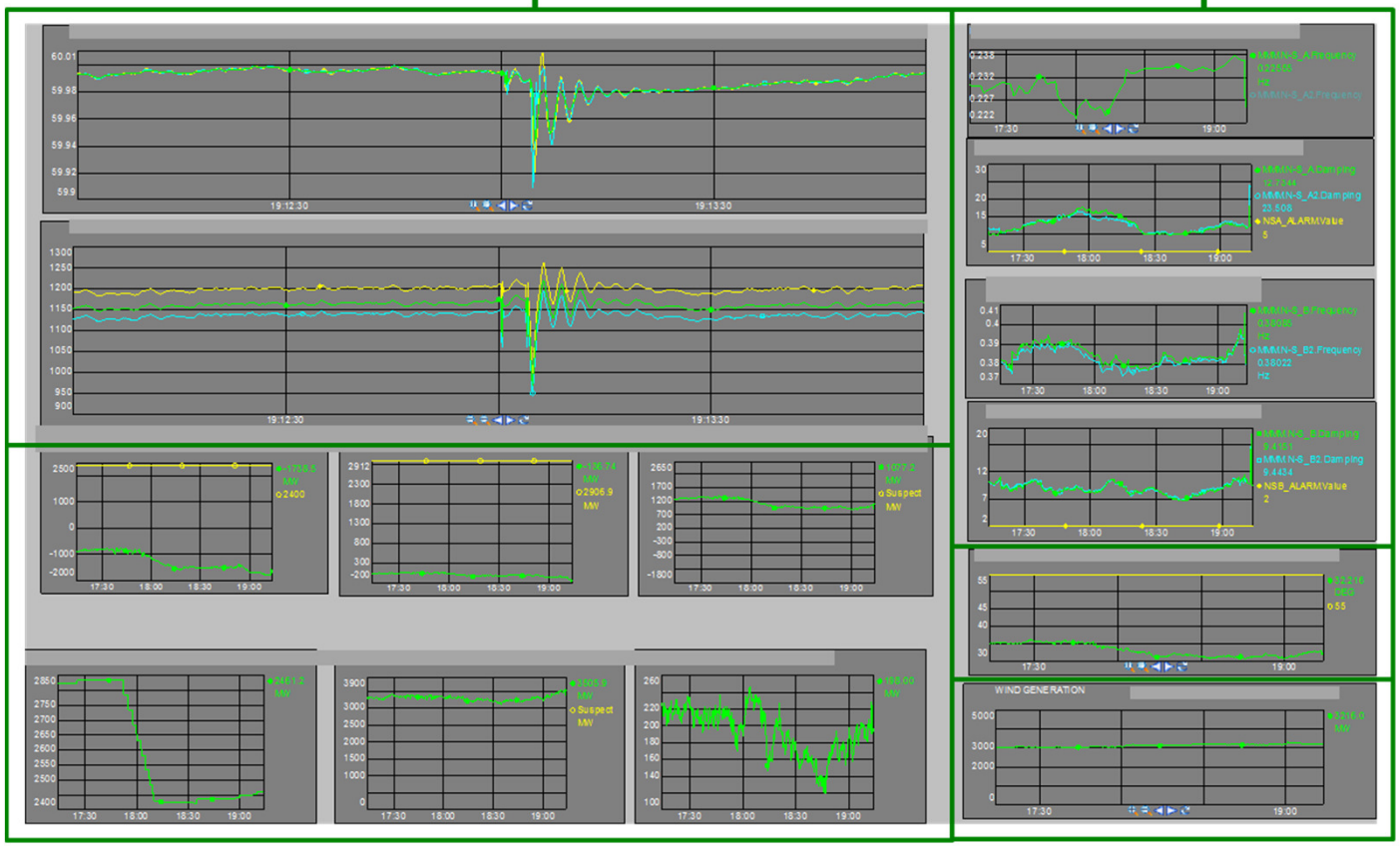
Trend Displays

- “A good trend is your friend”
- Trend displays provide “pulse” on the system state
- A good trend display supports decision-making
  - the goal is to help operate the system, and not to amuse
  - customization is often required to align with operating procedures
- A good trend display needs to include:
  - High-resolution synchrophasor trends
  - Long-term SCADA trends and respective operating limits
  - Results of analytical applications

- An example is on next page…

Synchrophasor trends (2 minute window at 60 samples per second)

Synchrophasor Application Results (Mode Meter) (2 hour window with 5-sec update)



Phase angle trend and limit

Wind generation trend

SCADA data path flows and limits (2 hour window, 2-second update)

OSI Soft PI Process Book display is shown above

SEL Synchrowave, EPG RTDMS, Alstom Phasorpoint, Space Time Insight have trending apps, a number of utilities developed their own displays

Power Plant Model Validation

Power Plant Model Validation

- **Maturity: 8/10**
  - Users: transmission planners, generator owners
  - in use at BPA in various forms since 2000, programmatic since 2009
  - Currently works with GE PSLF
  - PSS®E and TSAT are adding same capabilities

- PPMV Application has been used:
  - compliance with NERC MOD -026/27 Standards
  - determination of power plant operating practices
  - Identifying model inaccuracies even after stage testing was done
  - detection of generator control failures

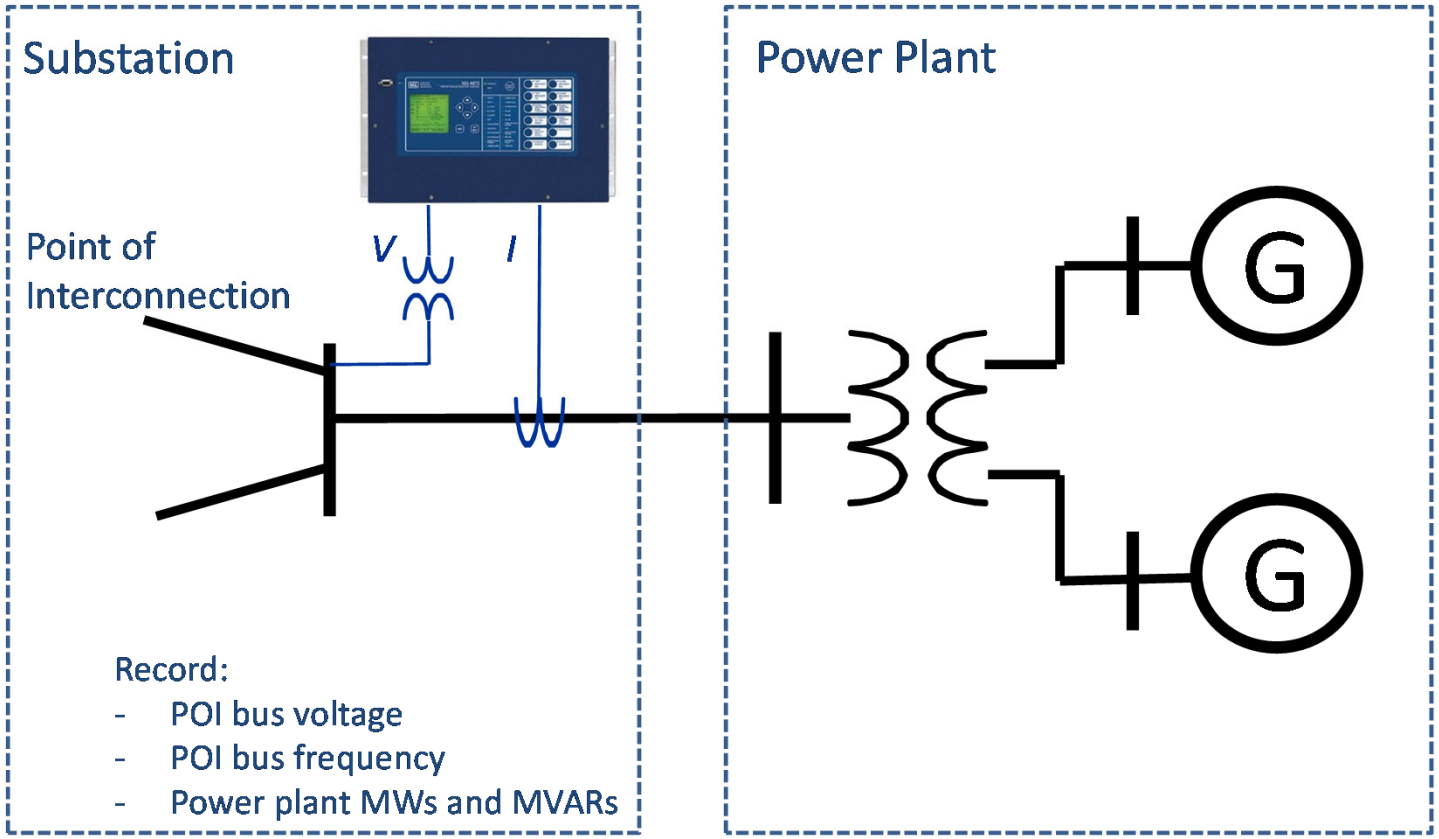
- PPMV can produce disturbance performance reports for the entire generating fleet (monitored by PMUs)

Power Plant Model Validation

- Periodic validation is required by NERC MOD-026,-027 Reliability Standards
- Cost-effective alternative to staged tests (assuming a good baseline model exists)
- PMUs allow more frequent model validation, becomes a clinical tool in detecting control abnormalities

- **Make PMU/DDR installation a part of youe generation interconnection requirements (visit www.naspi.org for typical language)**

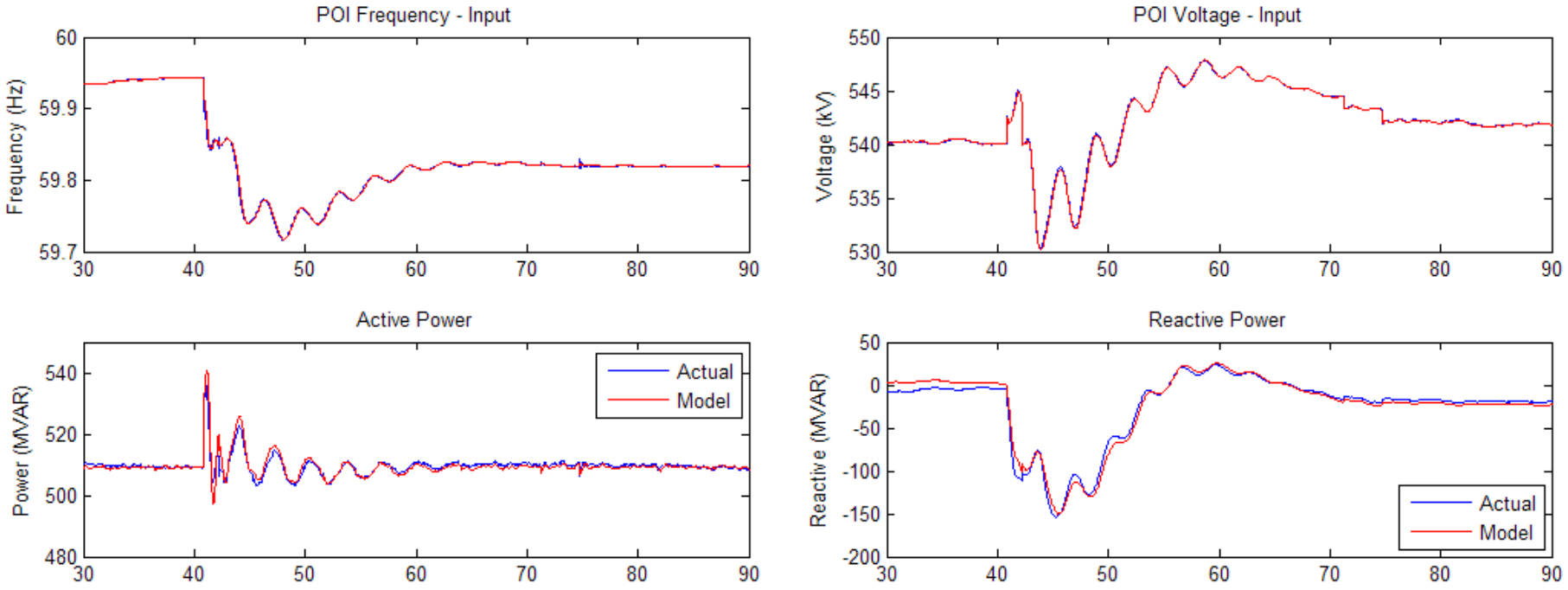
Using PMU Data for Model Validation



Disturbance play-in capabilities are added to GE PSLF in 2001

Power Plant Model Validation

- What a **good** models looks like:



Voltage and frequency are inputs

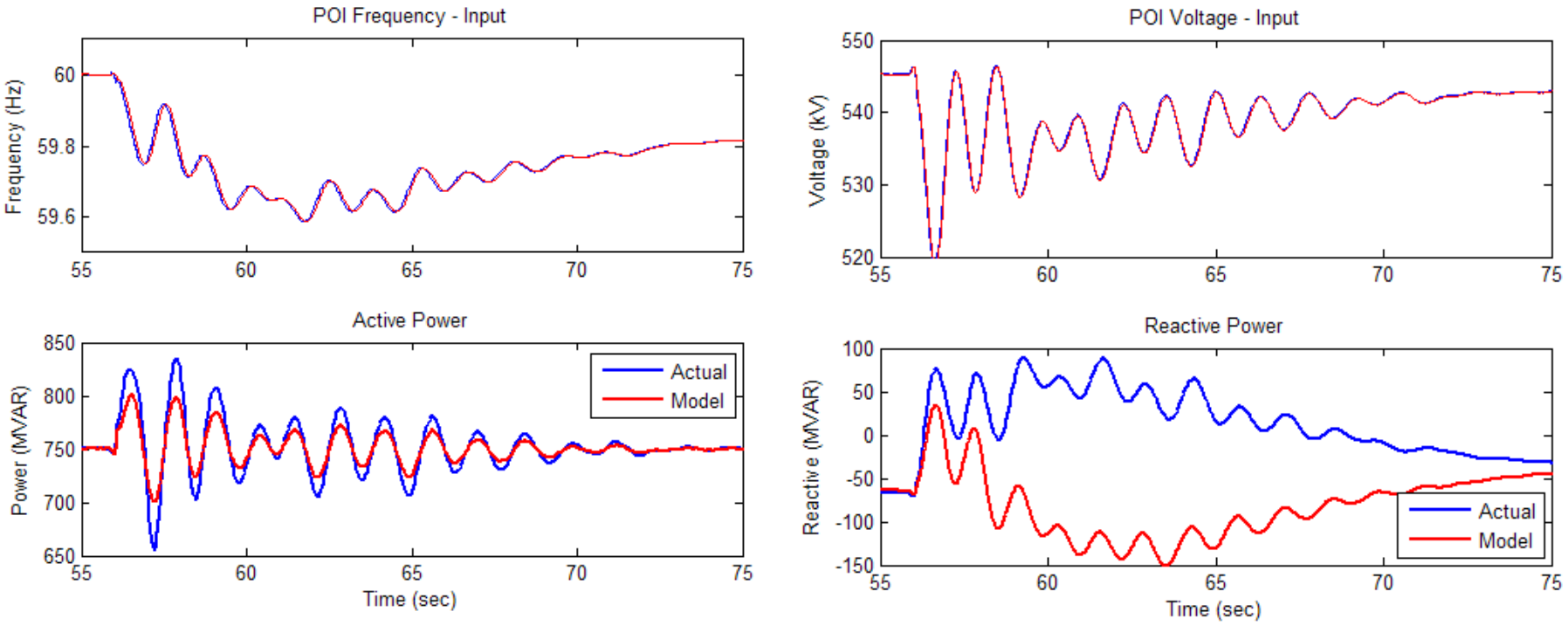
Active and reactive power are “measures of success”

Blue line = actual recording

Red line = model

Power Plant Model Validation

- What a **bad** model looks like:



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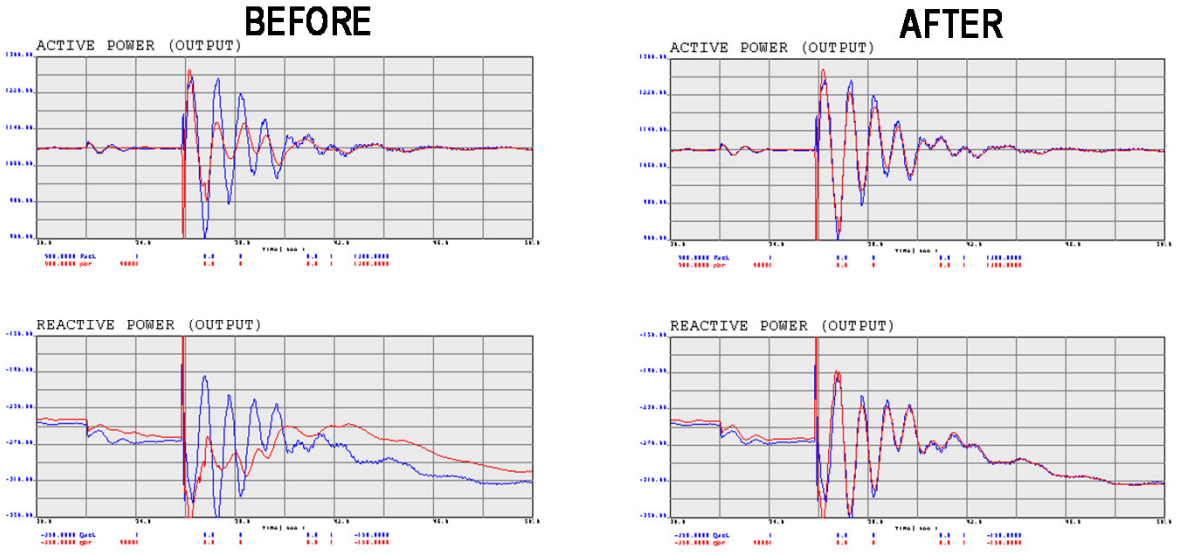
Model Calibration

- Can PMU data be used for model calibration ?



- Yes, PMUs can *complement* model development, there are successful case studies – engineering expertise and knowledge of generator controls is essential
- But, beware of curve fitting exercises

Model Calibration

- EPRI Power Plant Parameter Derivation (PPPD) is most mature, a user group is established including 23 participants
- Bernie Lesieutre @ University of Wisconsin uses a unique approach of pattern matching – which is useful to provide insight in model inaccuracies
- Others:
  - MATLAB
  - University of Texas – Particle Swarm Optimization
  - PNNL – Kalman filter
  - Georgia Tech – super-calibrator
  - Idaho Power developed in-house optimizers

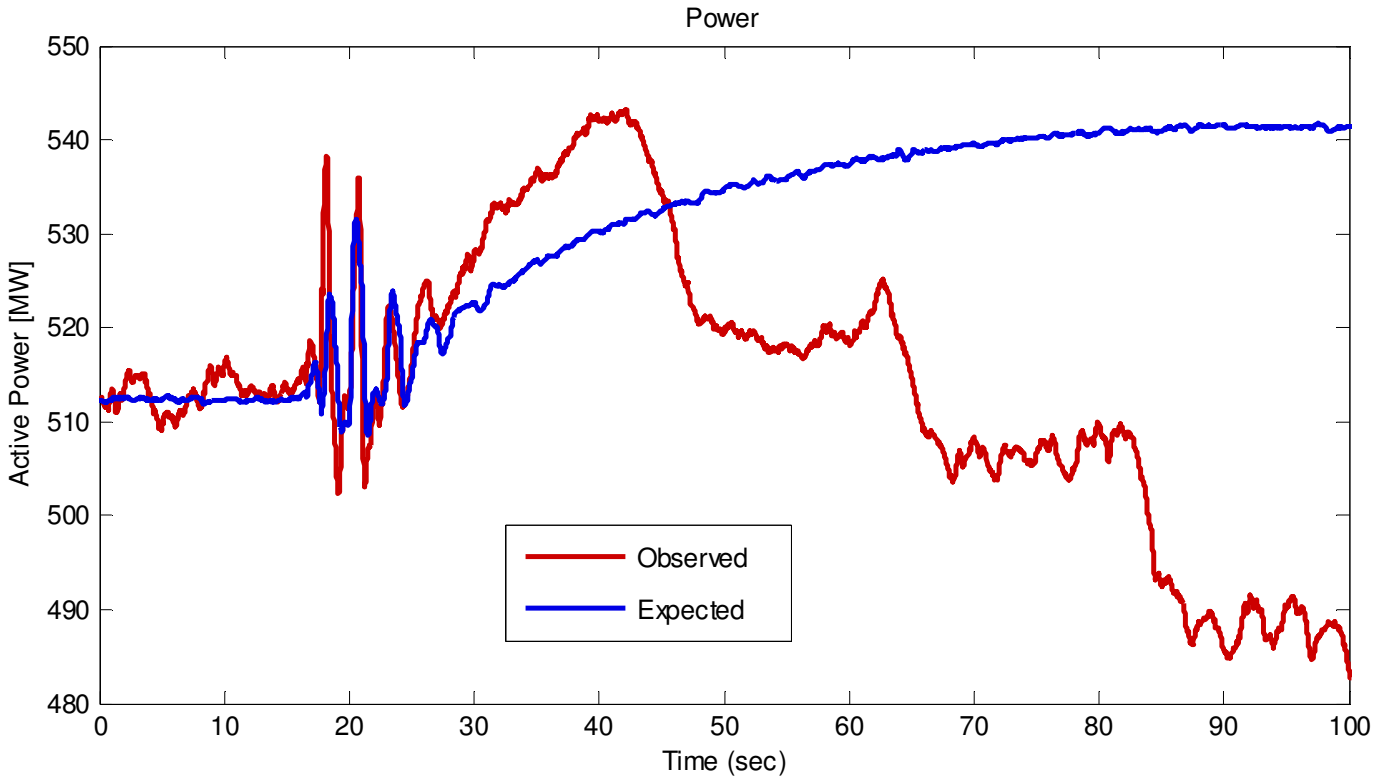
Power Plant Model Validation

- Power Plant Model Validation (PPMV) application
  - works with GE PSLF
  - PTI PSS®E functionality is being added
- Data and model management layer is added as a stand-alone program (PNNL)
- Model validation reports for 20 GW of BPA generating fleet are produced within minutes
- Working on expanding to wind and solar plant validation (need point-on-wave data)

Detecting Abnormal Control Behavior

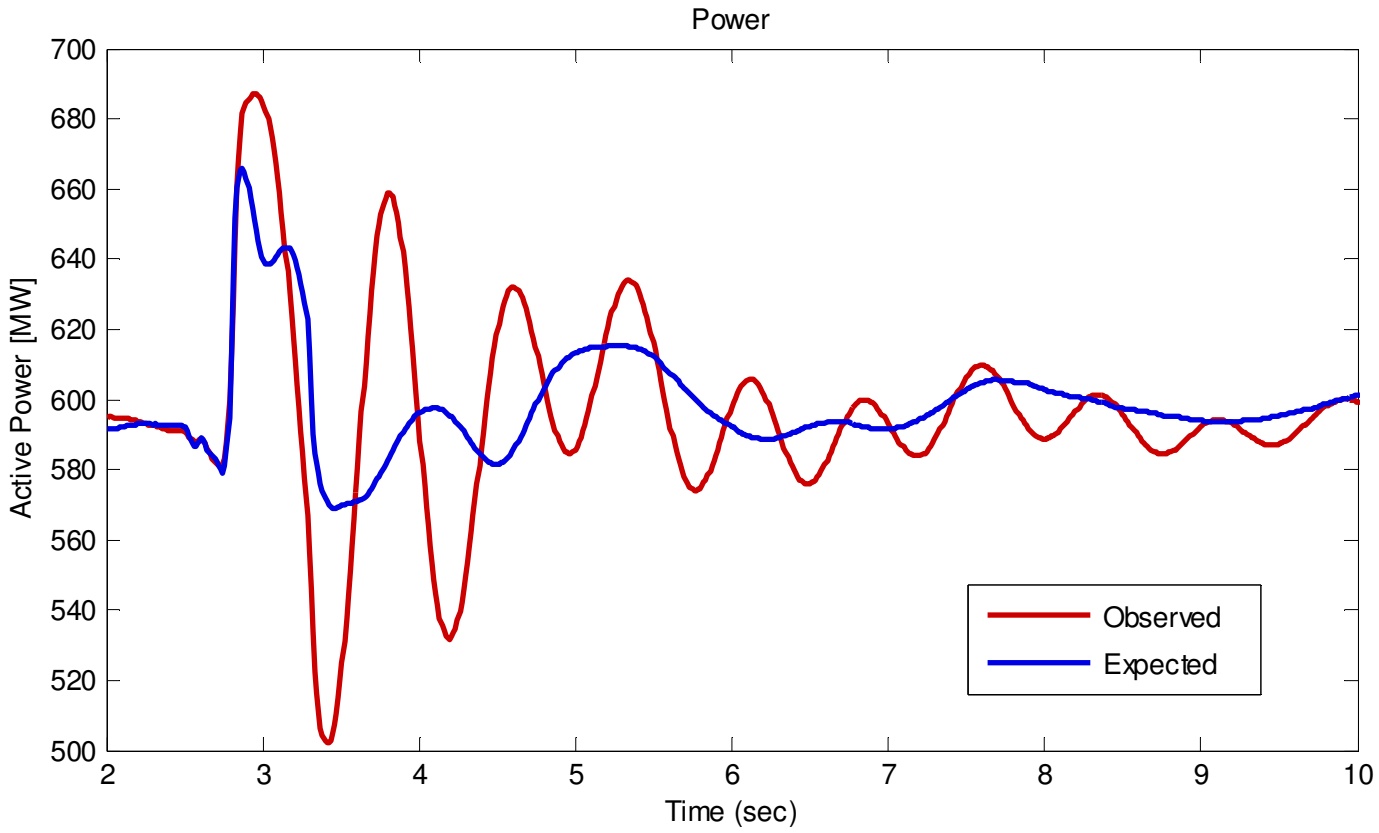
- Once a good model is established,

  PPMV becomes a clinical tool for detecting control abnormalities



Detecting Abnormal Control Behavior

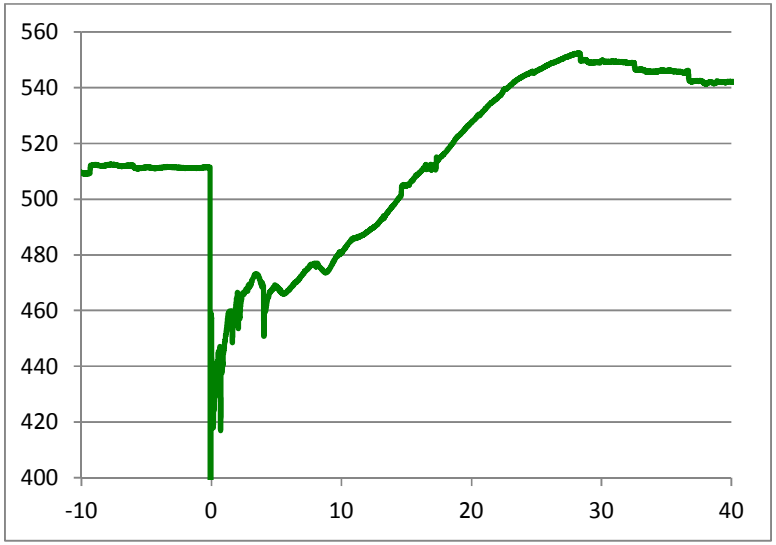
… and control failures



Load Modeling

Load Modeling

- Load plays greater role in system stability
- Load modeling efforts are under way to develop and implement composite load model



- Model validation efforts are essential
- **Positive sequence data is not sufficient, point-on-wave disturbance recordings are needed**
  - Micro-PMU project
  - Extended triggering is feasible at PMU – used by BPA

System Model Validation

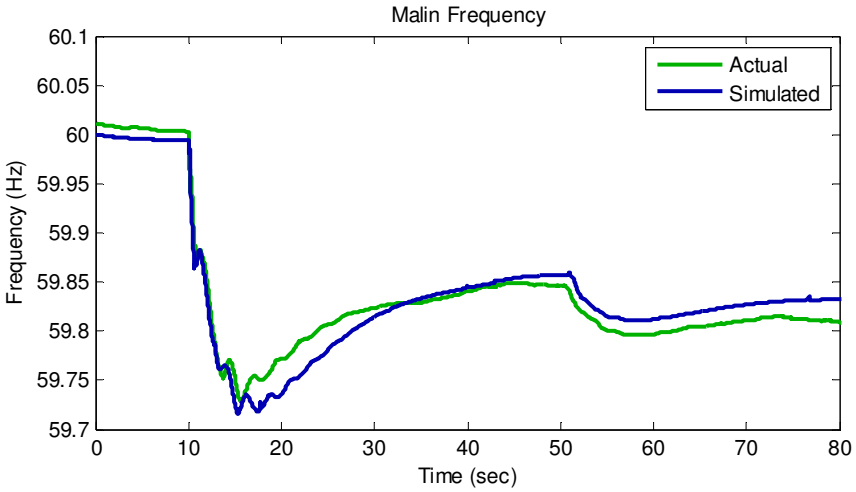
System Model Validation

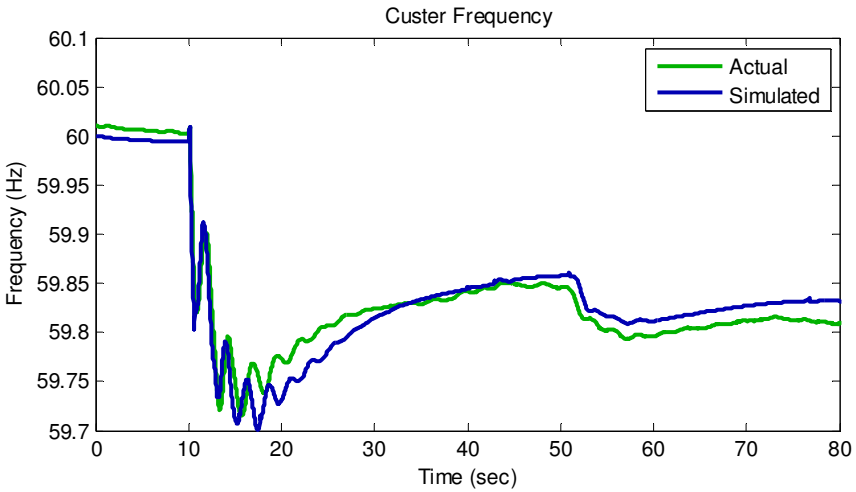
- Periodic verification of system models is required by MOD-033 Reliability Standards
- PMU data of system frequency, voltages, path flows is essential for credible model validation

- In the West, there is a long history of system model validation, on 1 to 2 system model validation studies are done each year

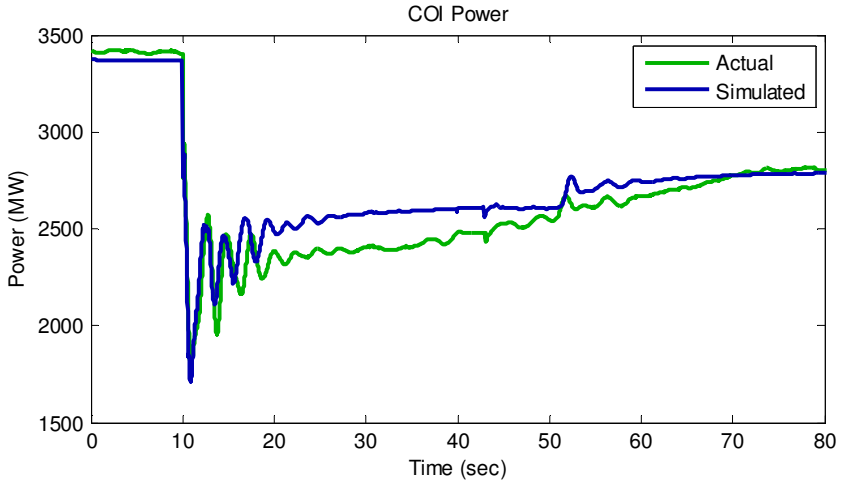
System Model Validation

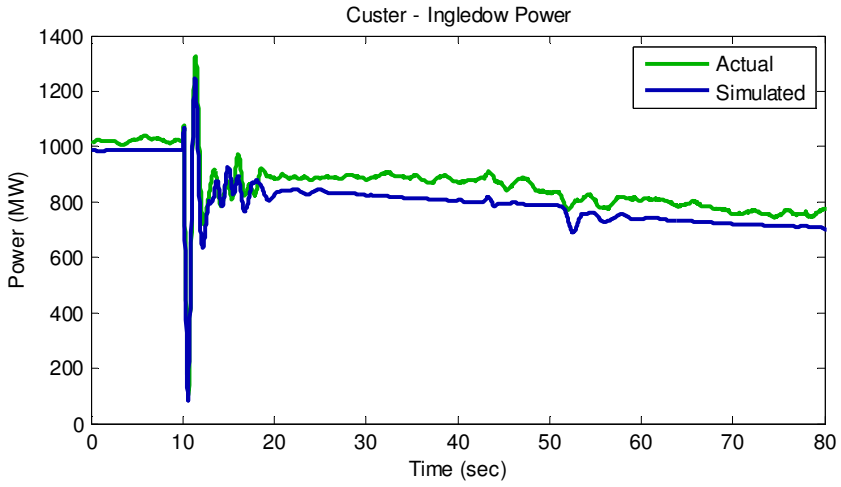
FREQUENCY

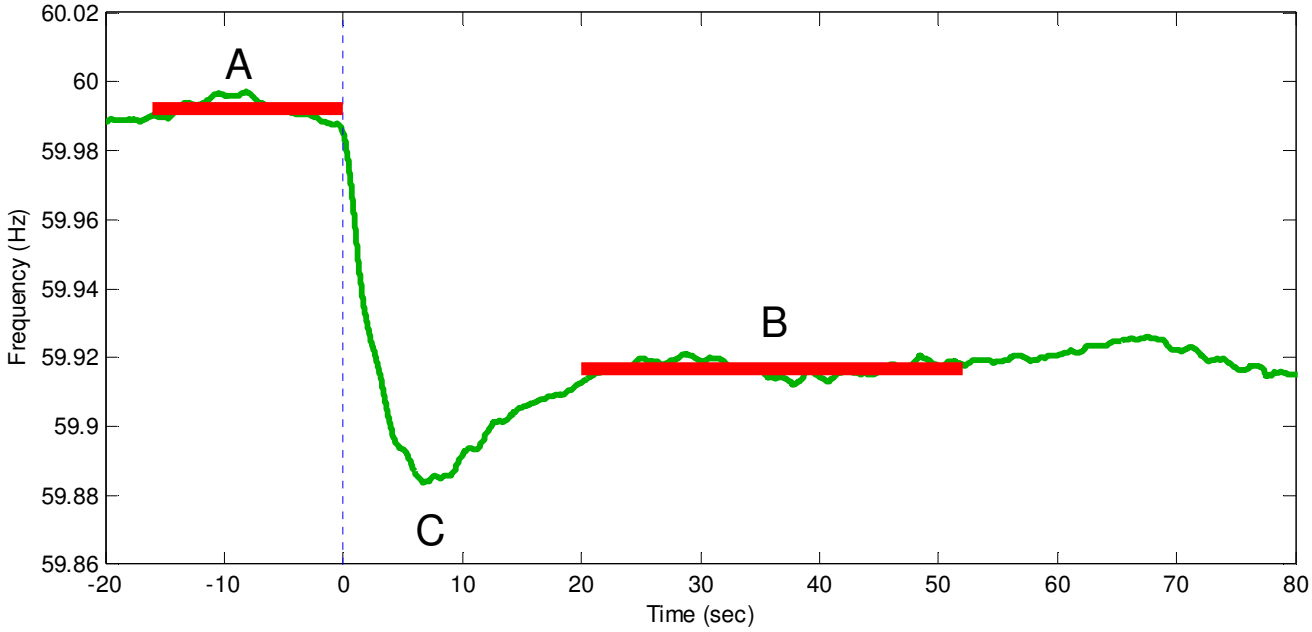




ACTIVE POWER







Frequency Response Analysis

Frequency Response

FERC defines in RM13-11:

"*Frequency response* is a measure of an Interconnection's ability to stabilize frequency immediately following the sudden loss of generation or load, and is a *critical component of the reliable operation* of the Bulk-Power System, particularly during disturbances and recoveries."

Frequency Response

- NERC BAL-003-1 Frequency Response and Frequency Bias Setting Reliability Standard is approved
- No loss of load is permitted for resource contingencies:

Table 11: Recommended Resource Contingency Protection Criteria			
Interconnection	Resource Contingency	Basis	MW
Eastern	Largest Resource Event in Last 10 Years	August 4, 2007 Disturbance	4,500
Western	Largest N-2 Event	2 Palo Verde Units	2,740[46]
ERCOT	Largest N-2 Event	2 South Texas Project Units	2,750[47]

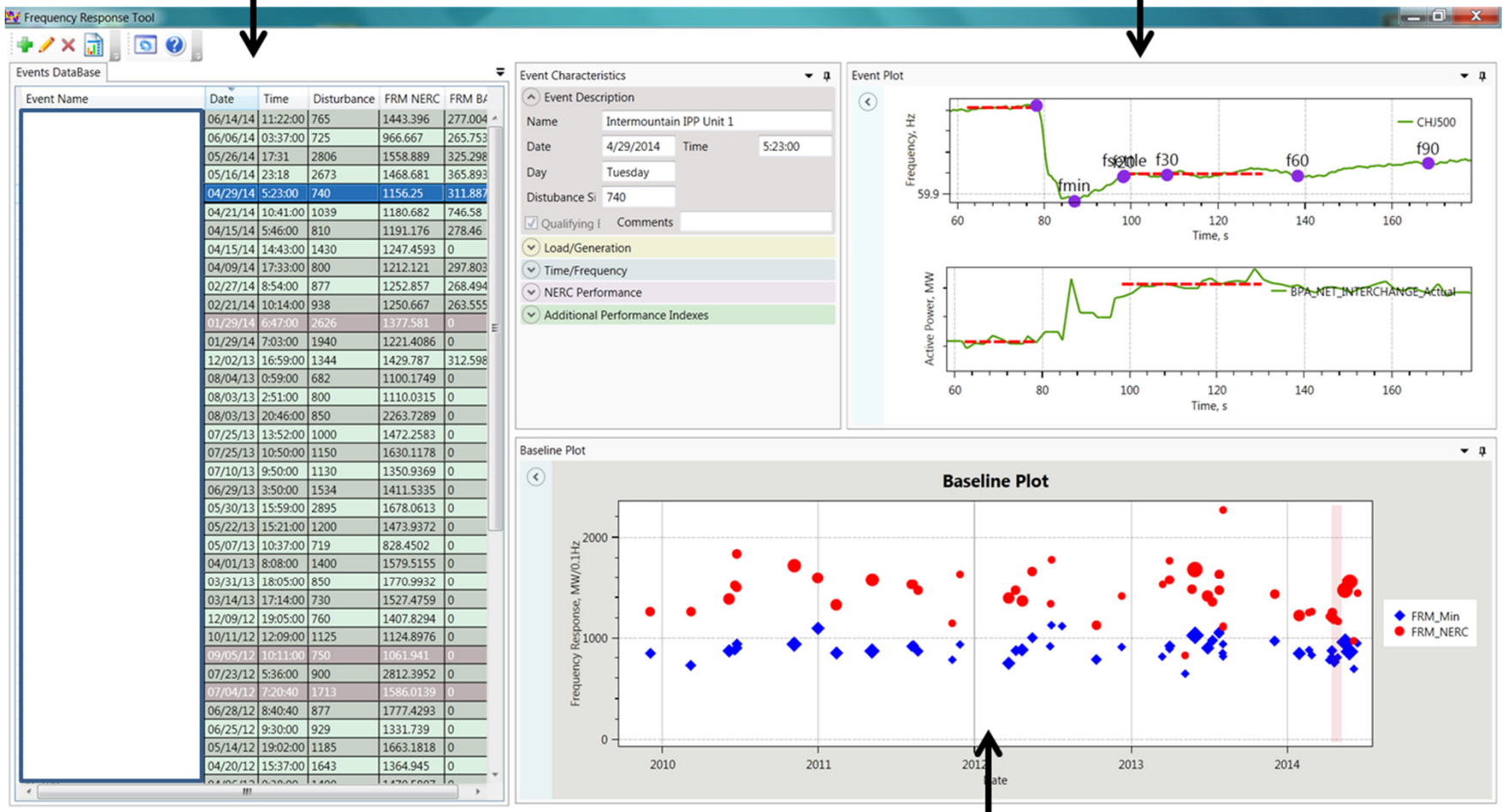
NERC BAL-003-1

- Interconnection Frequency Response Obligation is calculated in MW per 0.1 Hz at settling frequency (point B)
- IFRO is prorated among Balancing Authorities (BAs) based on annual load and generation
- BAs are responsible for providing frequency response,
  - BA FRM is measured as change in BA interchange over the delta frequency between initial and settling values
- Formation of Reserve Sharing Groups is permitted

BPA – PNNL Frequency Response Analysis Application

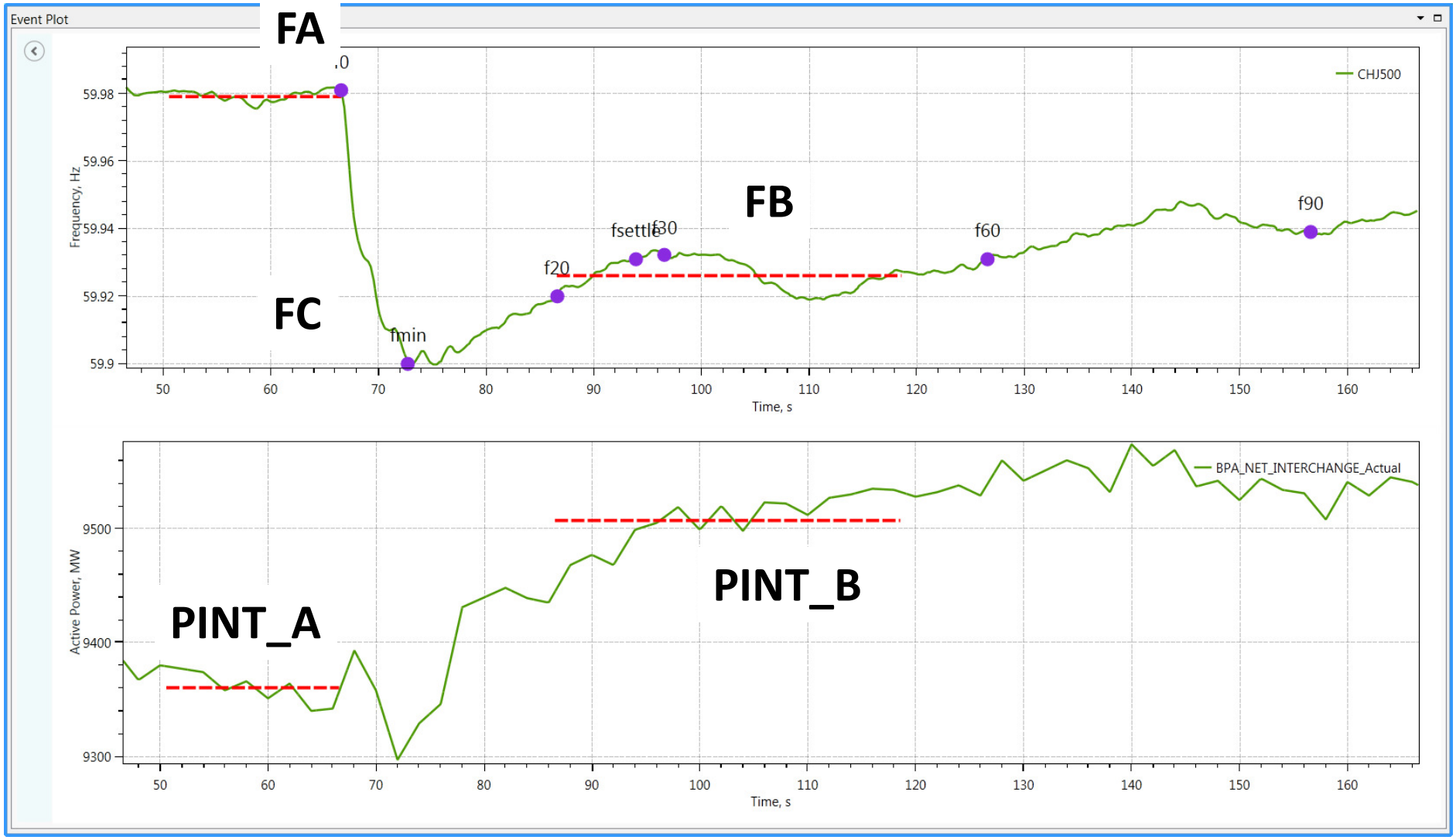
Database of Events

Add / View / Edit Events



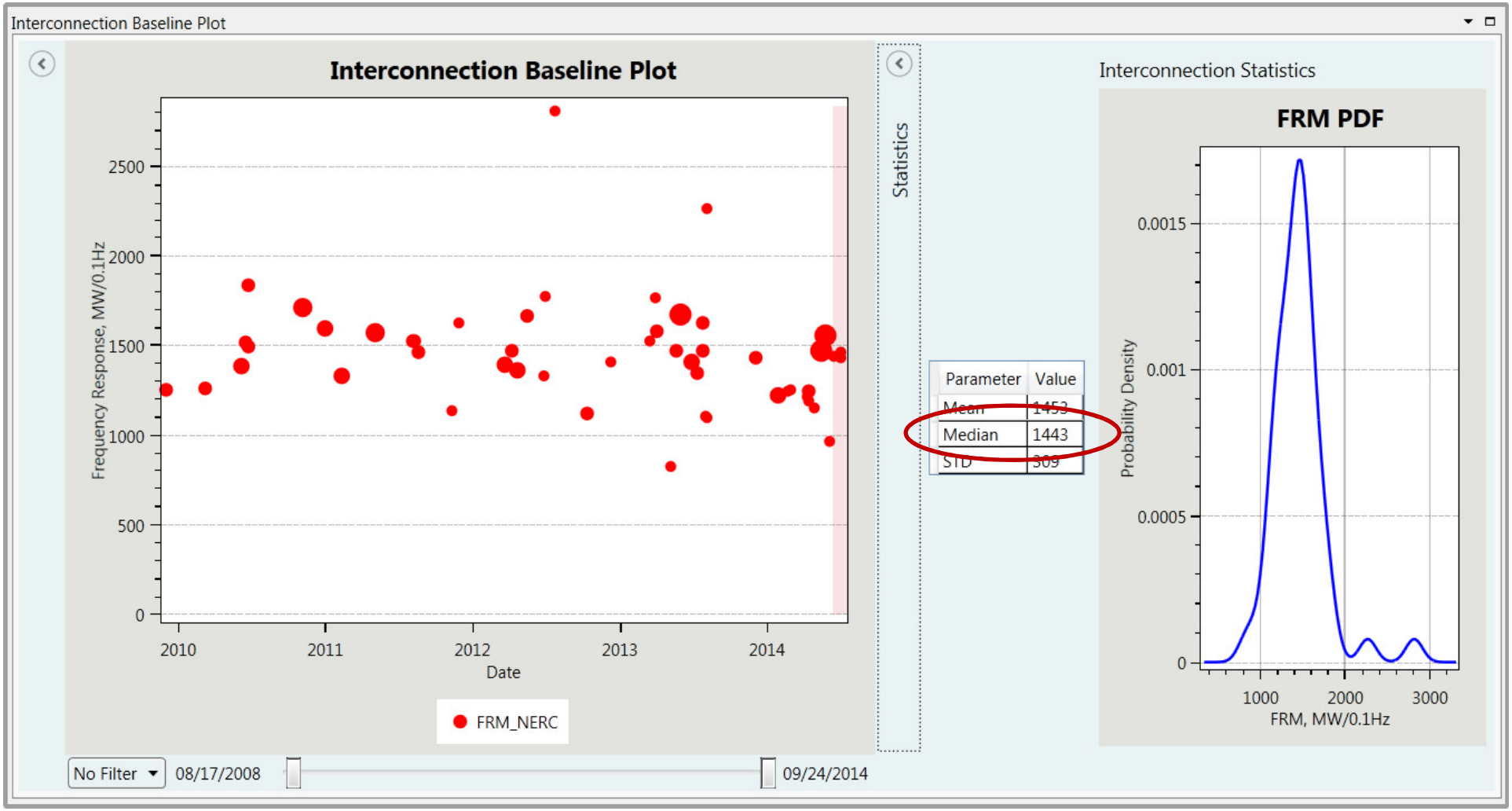
Performance Baseline

BA Frequency Response Measure Calculation



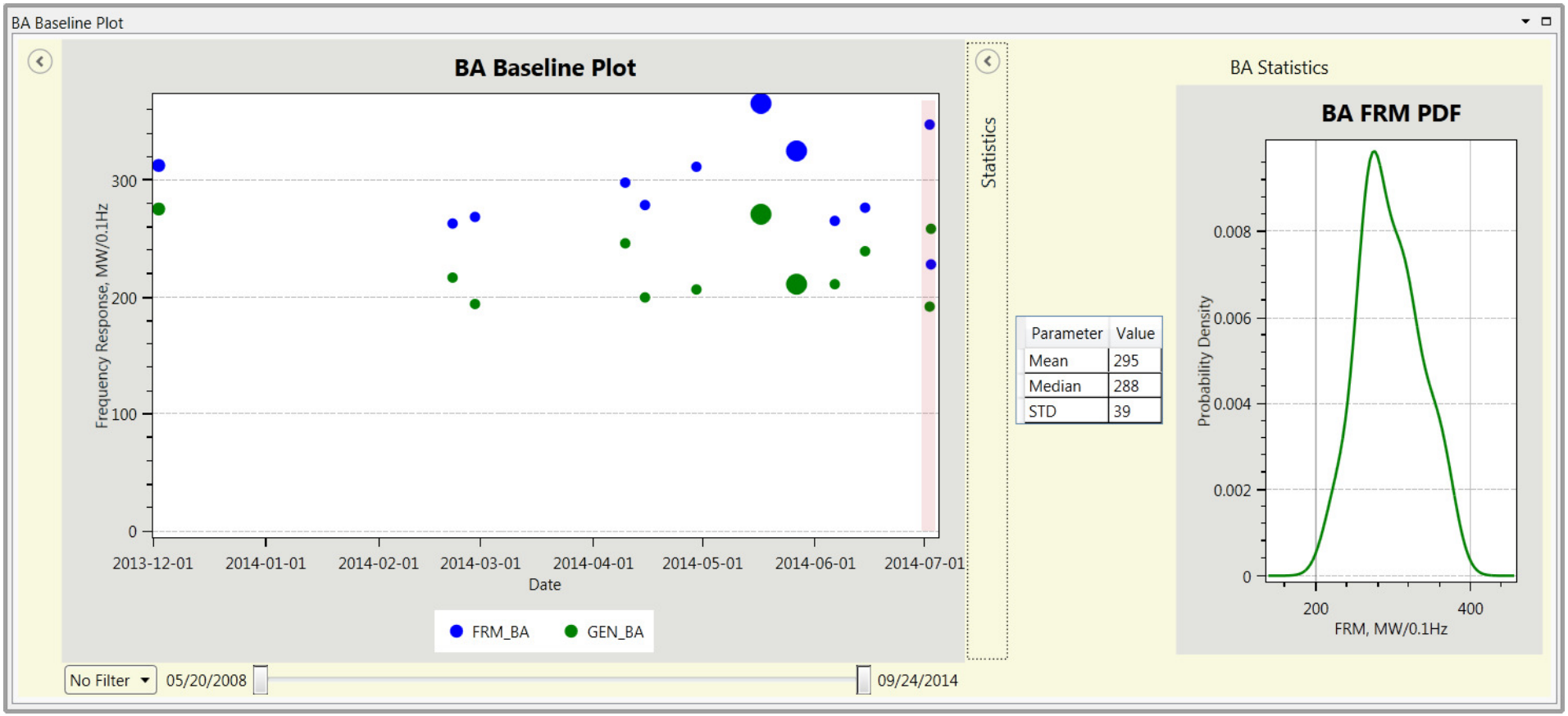
BA FRM = (PINT_B – PINT_A + BA GEN LOSS) / (FA – FB)

Western Interconnection Performance



WECC IFRO is about 950 MW per 0.1 Hz, system performance is about 1,440 MW per 0.1 Hz

Balancing Authority Performance



Interchange response is measured for compliance with NERC BAL-003-1

Generation response is calculated to determine how much frequency response to acquire

Frequency Response Analysis Tool

- Maturity: **6 /10**
  - Users: Balancing Authorities, Reliability Coordinators
- Frequency Response Analysis Tool (FRAT):
- What is does now
  - Has been used in WECC for interconnection-wide frequency response analysis since 2012
  - BA frequency response analysis is added in 2014
- *Work in Progress*
  - *Produce NERC FRS 1 and 2 Forms*
  - *Power plant response analysis is under development*
  - *Power pick-up on transmission paths is under development*

Frequency Event Detection

Basic Frequency Triggers

Frequency Chart

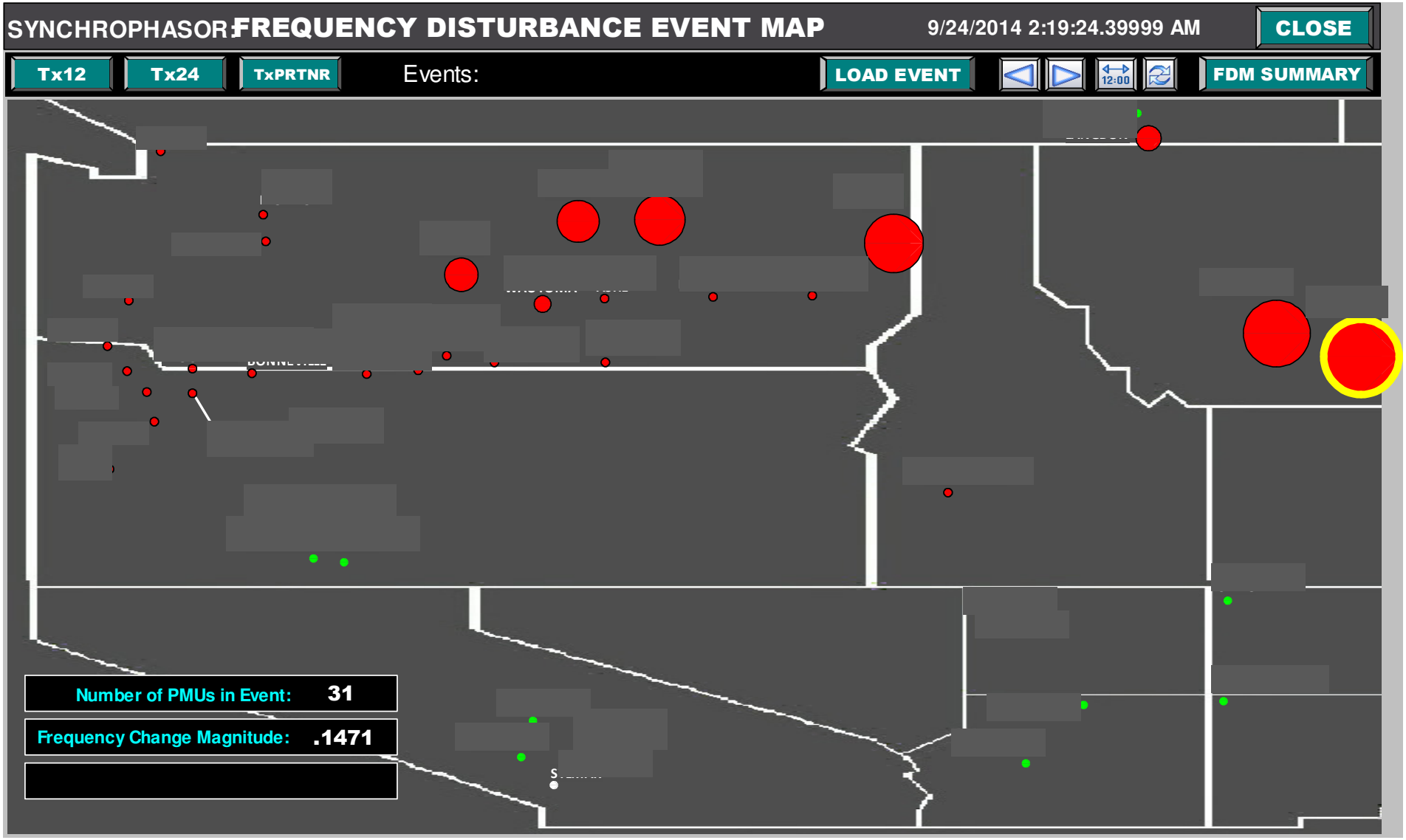
Frequency Alarms

Frequency Event Detection

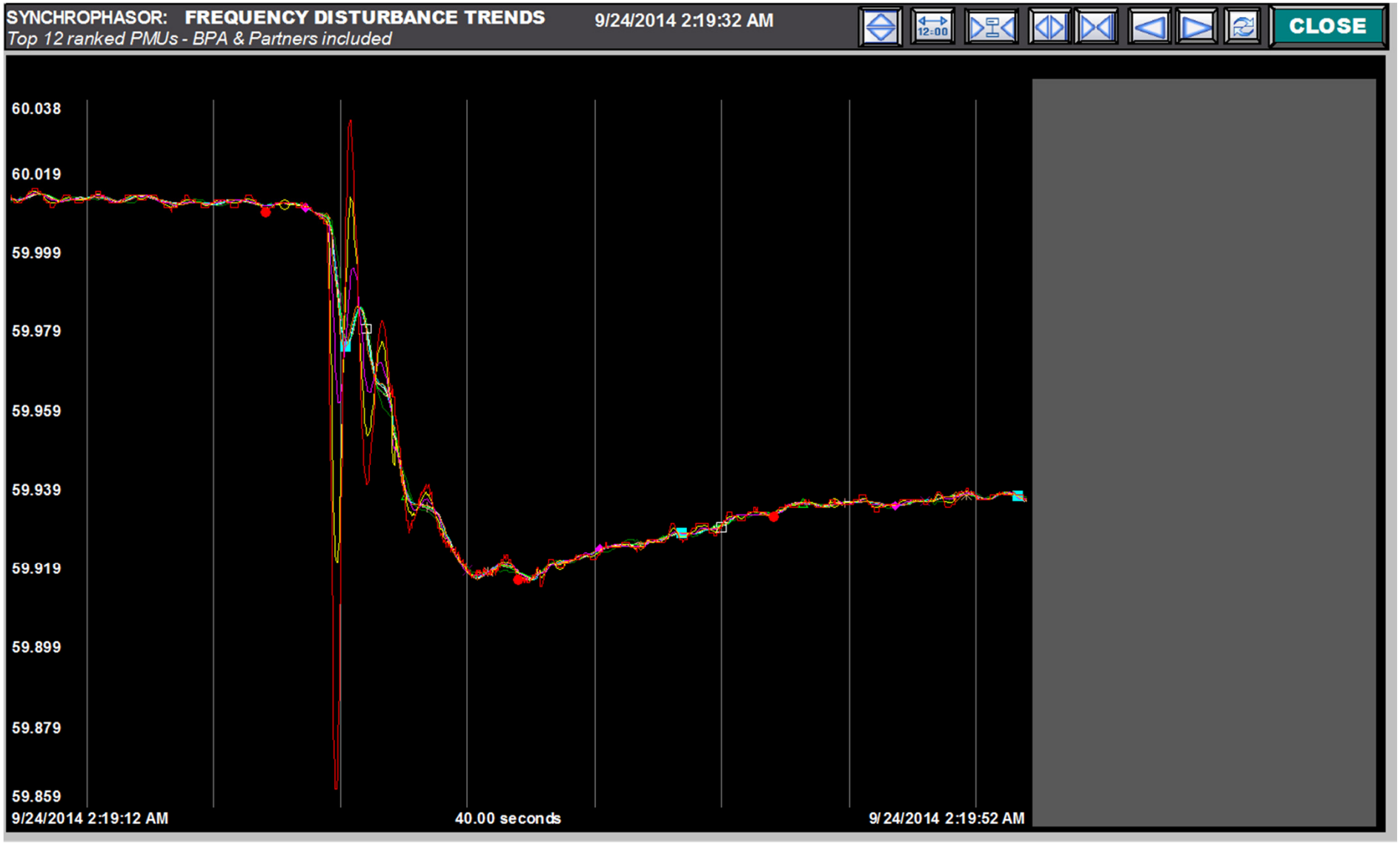
- Maturity: **7/10**
- Users: dispatchers, operating and planning engineers

- FNET
- BPA FDM
  - Identify origin of frequency event by the propagation of “frequency wave”
  - Triggers on frequency deviation, ranks PMUs based on frequency deviation and its rate of change
  - Future development:
    - Add power pick-up on major paths

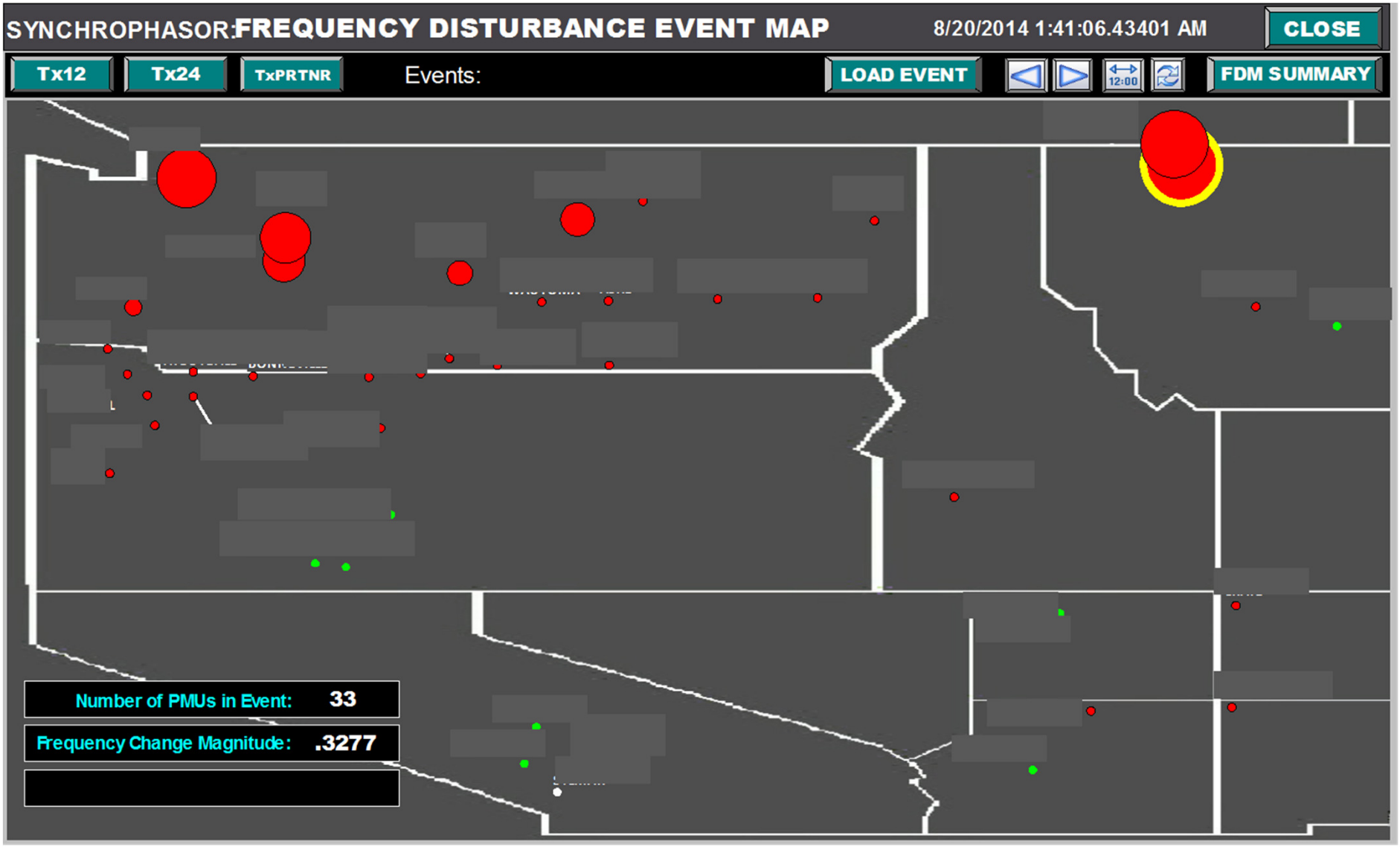
Frequency Event Detection



Frequency Event Detection



Frequency Event Detection

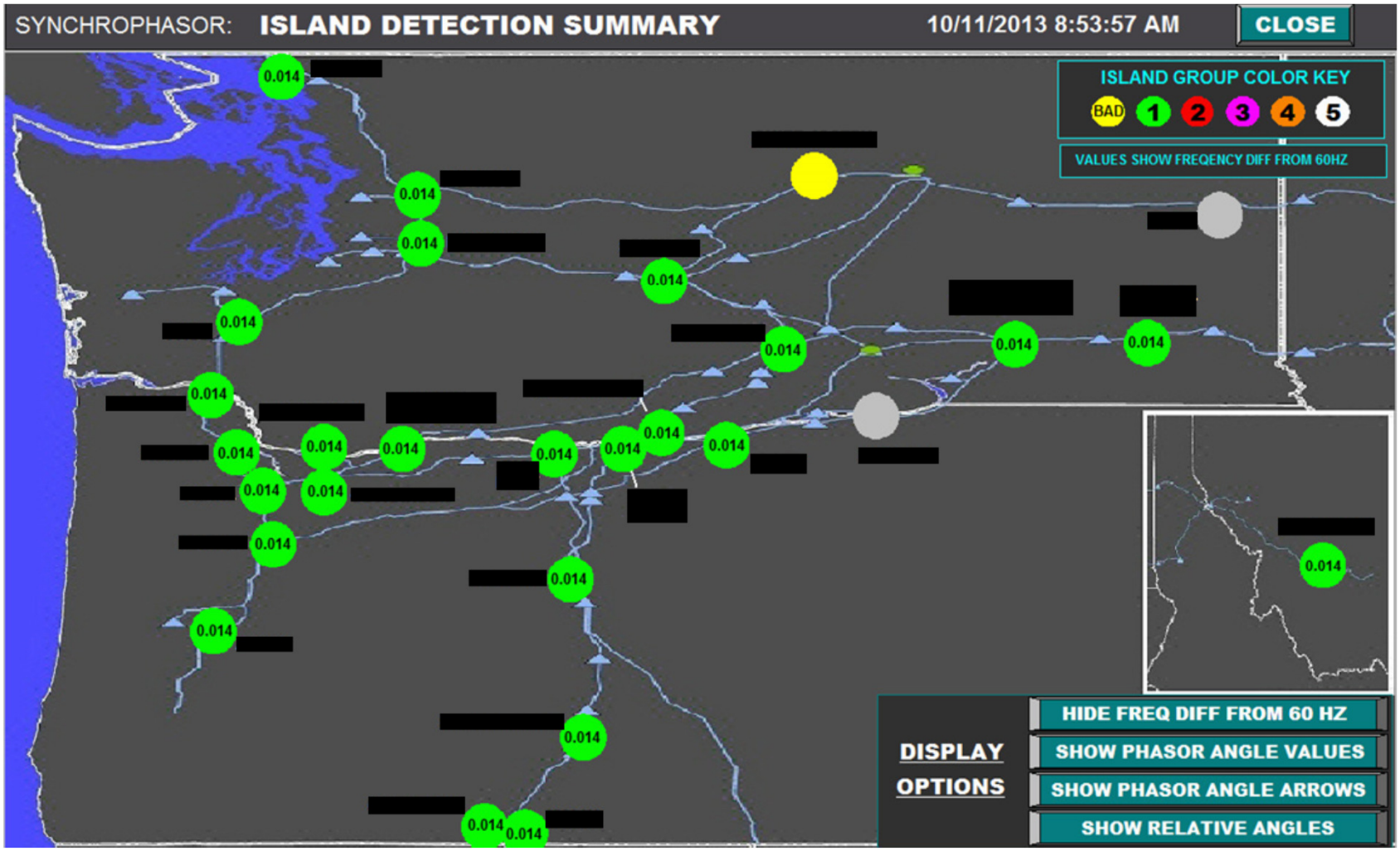


Reconnection of Alberta to WECC

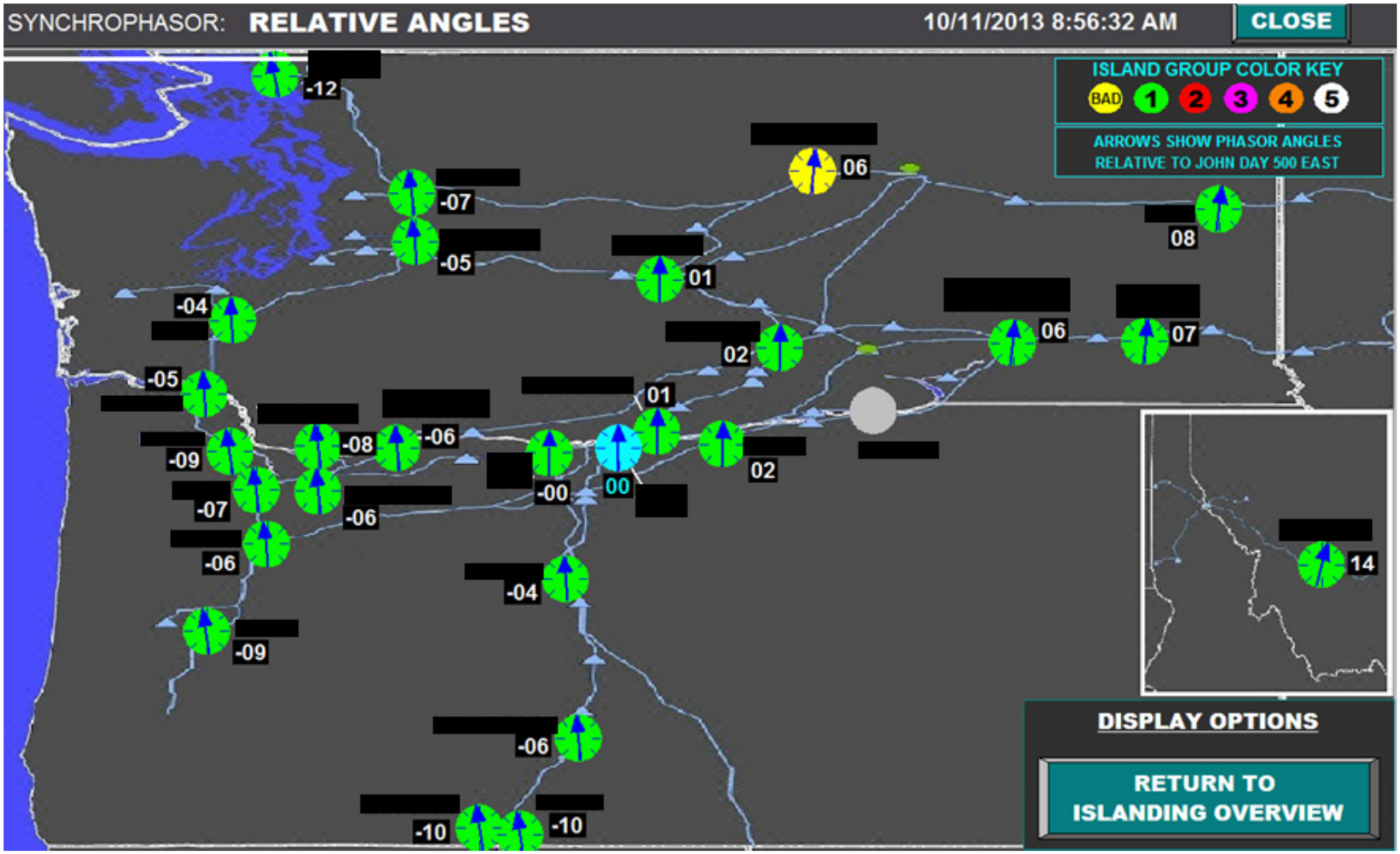
Islanding of Alberta

Islanding Detection

Island Detection



Phase Angle Differences



Islanding Detection

- Maturity: **7/10**
- Users: dispatchers, operating engineers

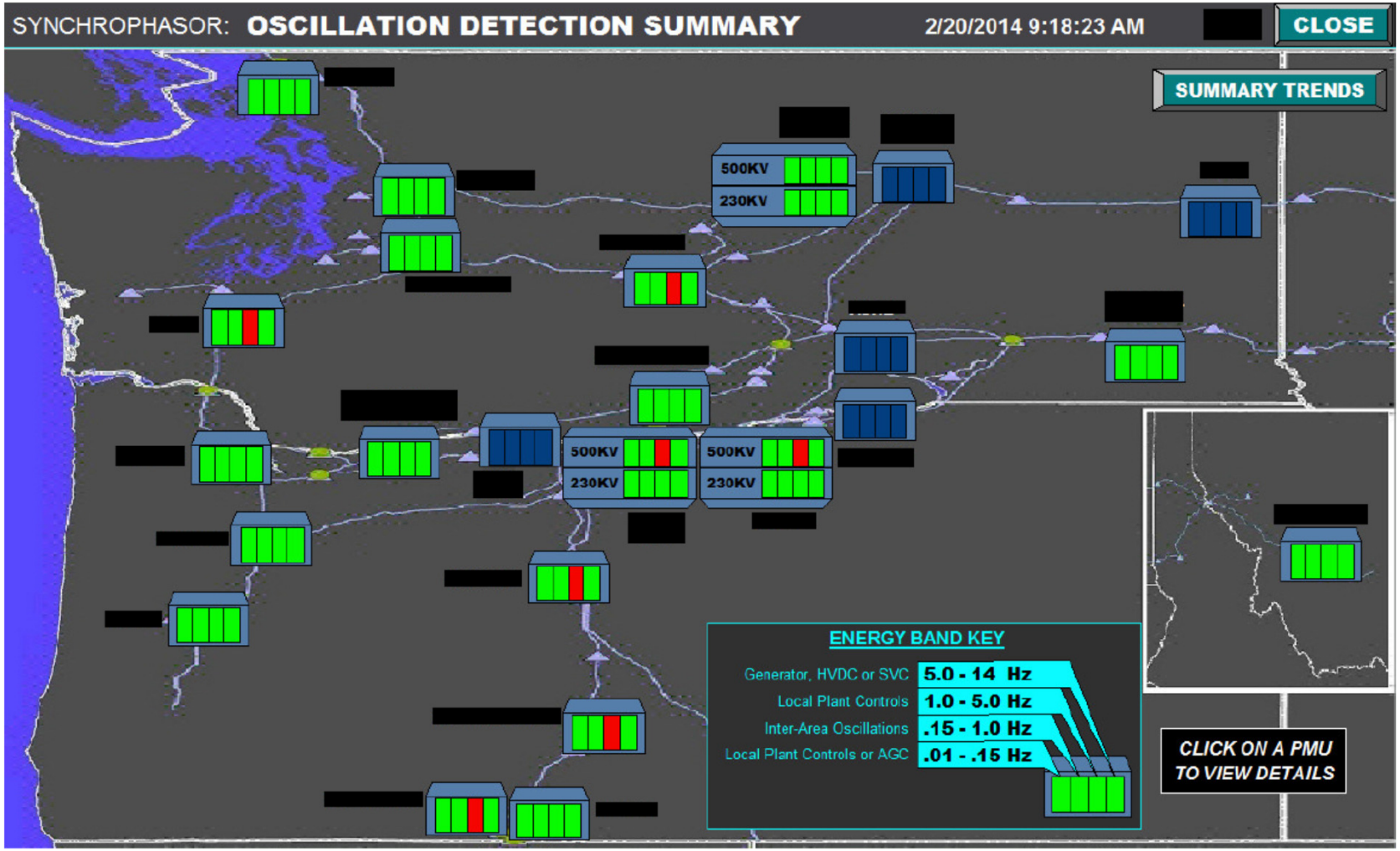
- The application could be very useful during system restoration from outages caused by natural disasters
- The value of using PMUs for island detection during hurricane Katrina is well documented by Floyd Galvin at Entergy

Oscillation Detection

Oscillation Detection

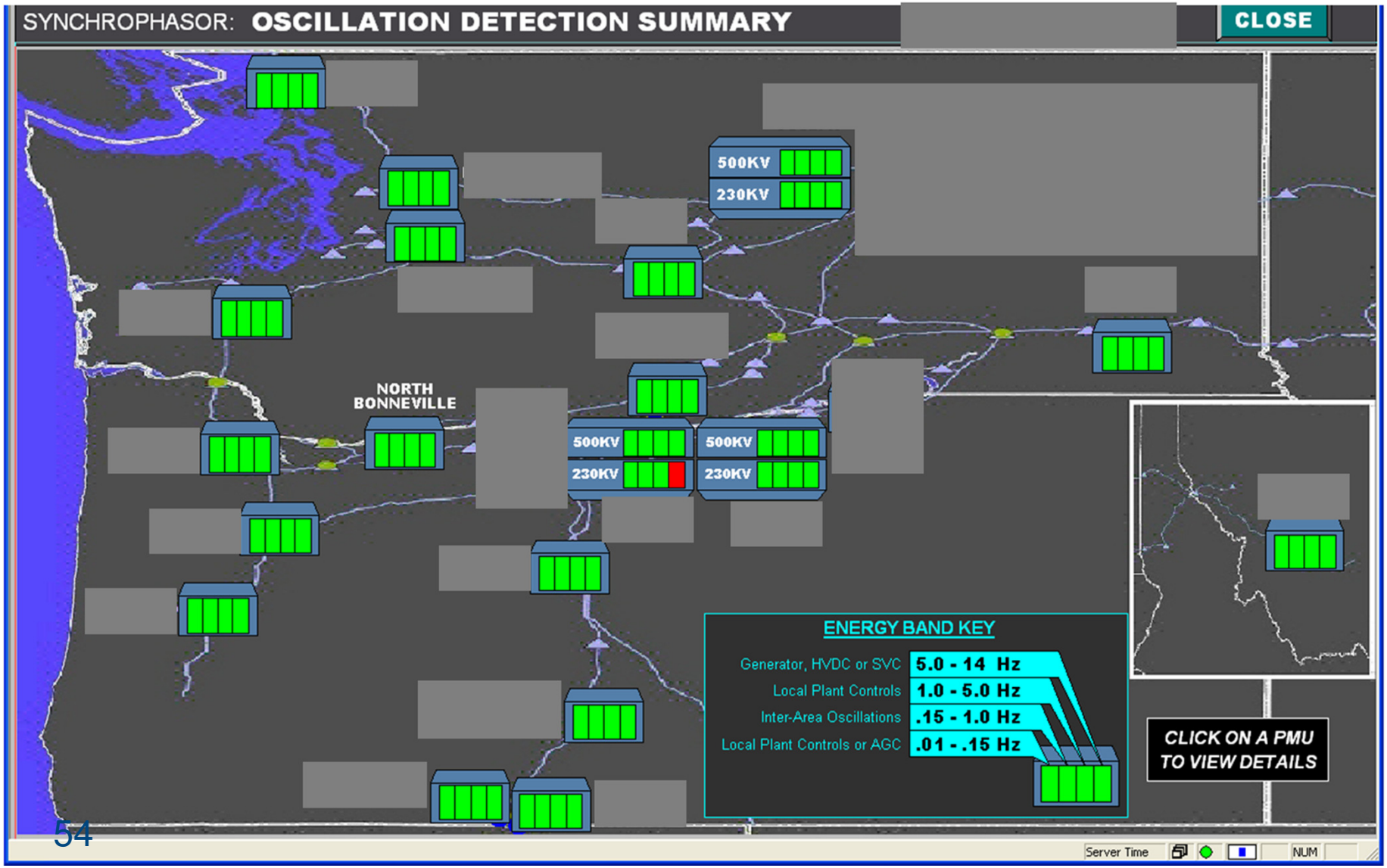
- Maturity: **8/10**
- Users: dispatchers, operating and planning engineers
- Scans power plants, interties, HVDC and SVCs for growing or sustained high energy oscillations
- Developed by Dan Trundowski at Montana Tech
- Operational at BPA since October 1, 2013, alarms dispatchers
- Dispatcher training is performed
- A number of events has been detected

Oscillation Detection



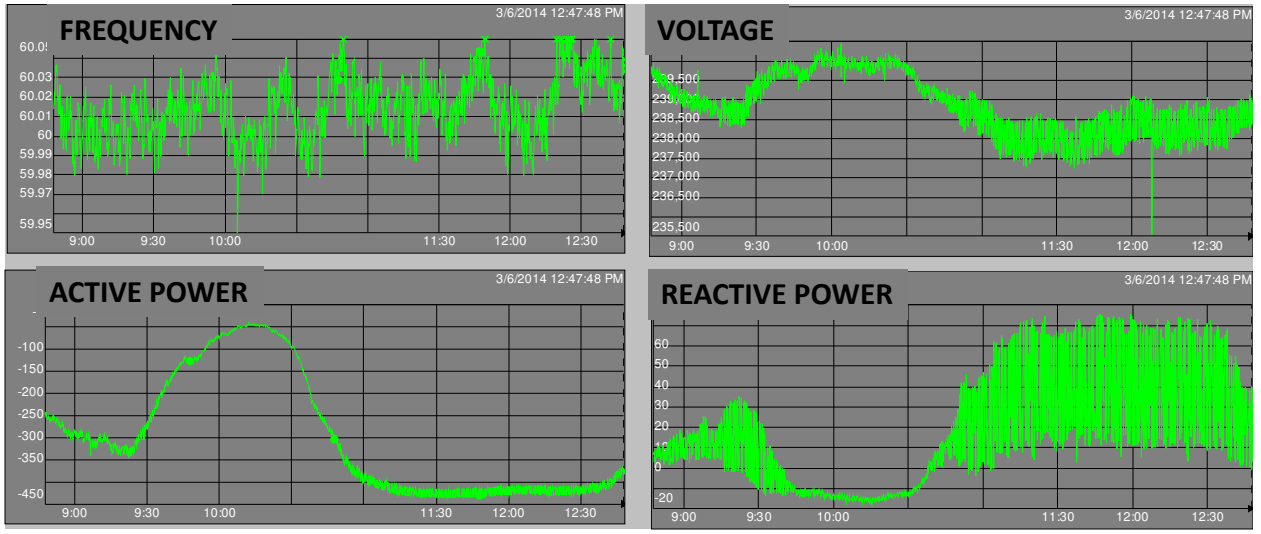
Oscillation Detection

Oscillation Detection – Wind Power Plant

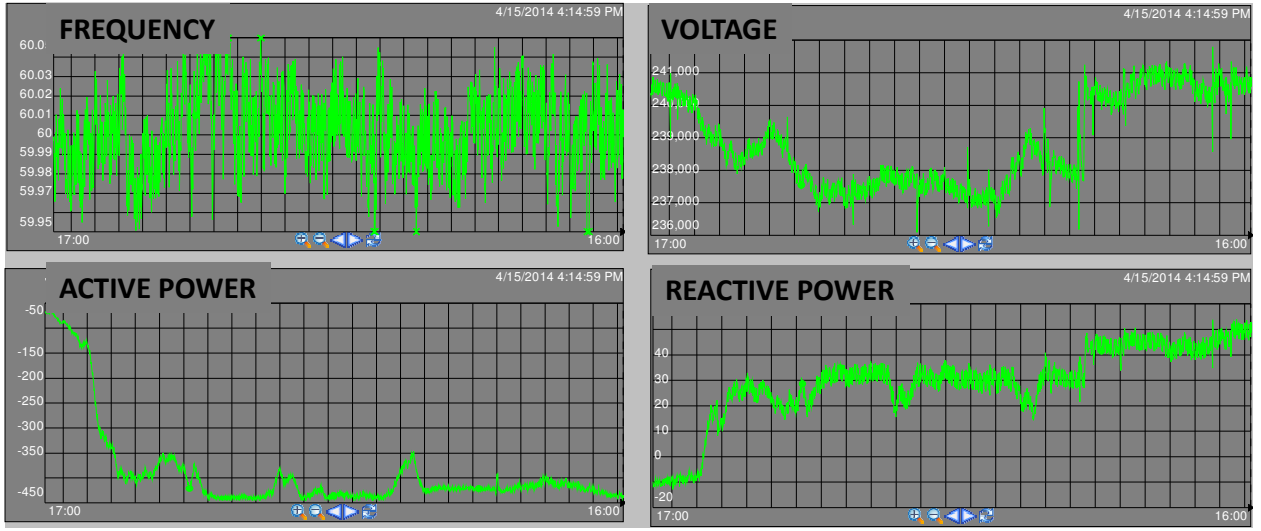


Oscillation Detection – Wind Power Plant

BEFORE



AFTER



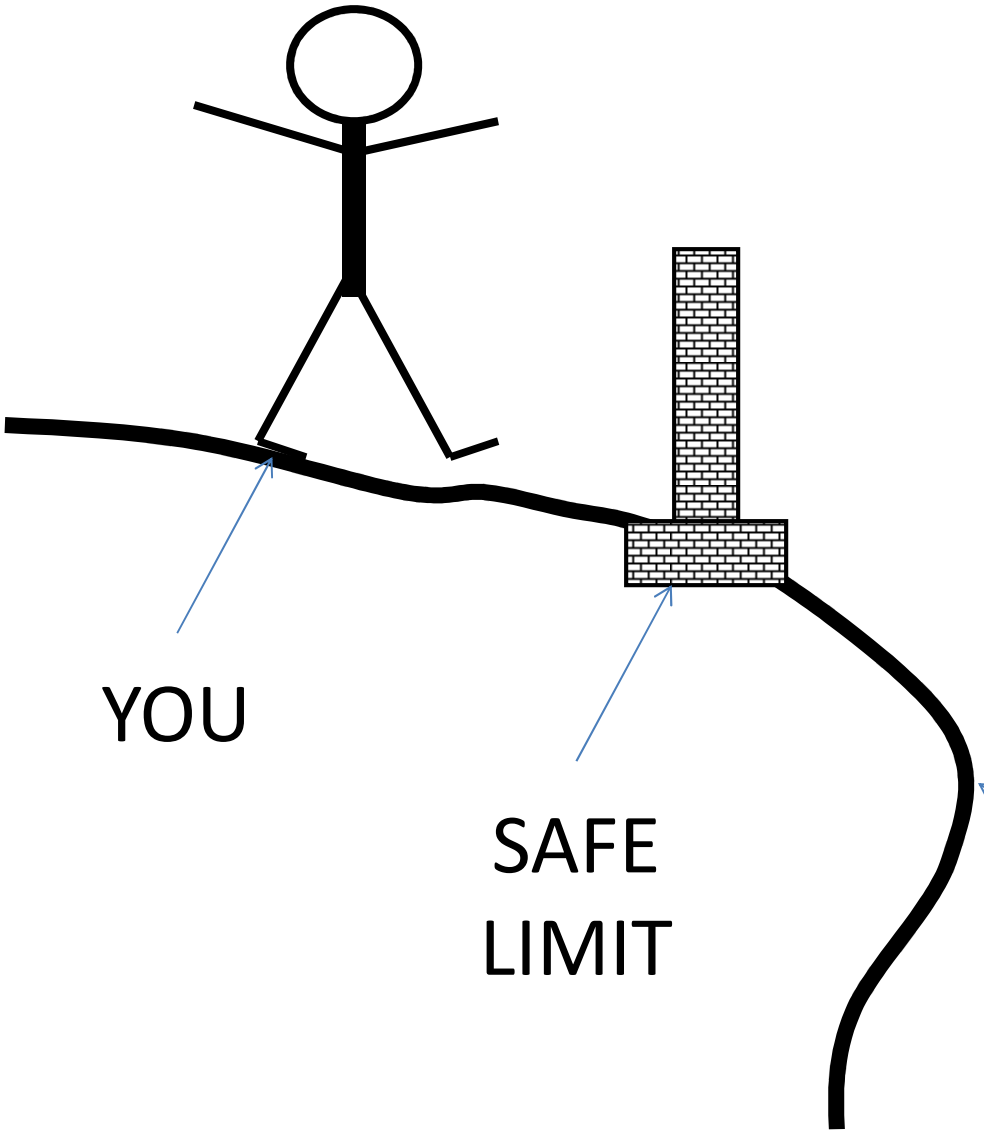
Mode Meter

Mode Meter

- Maturity: **5/10**
- Users: dispatchers, operating and planning engineers
- Pro-active: estimates damping of inter-area power oscillations from ambient data
- Developed by Dan Trundowski at Montana Tech, University of Wyoming, PNNL
- Implemented, under evaluation
- Operating procedures are under development

Voltage Stability

Voltage Stability Situational Awareness



- You need to know where you are
- You need to know where the edge is, and
- You need to know how far from the edge is safe to be – the operating limit

Voltage Stability Situational Awareness

Measurements tell where you are, measurements do not tell you where the edge is

You need a model to estimate where the edge is

- **Full-topology voltage stability solutions (for wide-area voltage stability)**
  - V&R ROSE – uses state estimator model for voltage stability analysis, PMU data is used between snapshots
    - Implemented at New England ISO
    - Evaluated at Peak RC

Voltage Stability Situational Awareness

- Reduced topology voltage stability solutions
  - Renesaller Polytechnic Institute
    - Evaluated at BPA and SCE
- Thevenin Equivalent
  - ABB VIP, EPRI VIP, Quanta/Alstom Grid RVII
    - Application is limited to simple radial systems
- PV-Slope Sensitivity
  - Electric Power Group
    - Lagging indicator
- **Reactive Reserves**

State Estimator

State Estimator

- Leading state estimators can take phasor measurements as inputs
- Peak RC and BPA integrated phasor measurements in Alstom Grid state estimator

- Linear State Estimators
  - Used for line parameter verification at Dominion
  - Used for data calibration
    - WECC-funded work at EPG

Equipment Mis-Opertaion

Equipment Mis-operation and Control Failures

- US DOE Paper on using PMUs for detecting equipment mis-operation and control failures
- Documented cases:
  - Predicting transformer failure
  - Control system failure at generators
  - Control system failure at HVDC line
  - Forced oscillations rock major tie-lines

Data Quality

Data Quality

- Data availability and quality are essential for applications
- DOE CERTS funded development of applications for monitoring data quality and developing best data management practices – competitive solicitation was awarded to EPG
- WECC funded a project on developing an application for PMU data calibration – competitive solicitation was awarded to EPG
- EPG PDVC application is available

Application Pipeline

Application Pipeline

- Research pipeline is very long with advanced applications, a few more mature are noted here
- Data mining
  - PNNL statistical application for finding system abnormalities and close calls
  - EPG data mining application
- Voltage stability controls
  - Synchrophasor-based reactive switching controller is being implemented at BPA
  - Voltage controller is evaluated at SCE
- Oscillation Damping Controls
  - PDCI modulation is evaluated by BPA, SCE and Sandia
- Wide Area Monitoring, Protection and Control (WAMPAC) by PG&E

Questions ?