Measurement Based Stability Assessment

Dan Trudnowski, Montana Tech
dtrudnowski@mtech.edu

John Pierre, U of Wyoming
pierre@uwyo.edu

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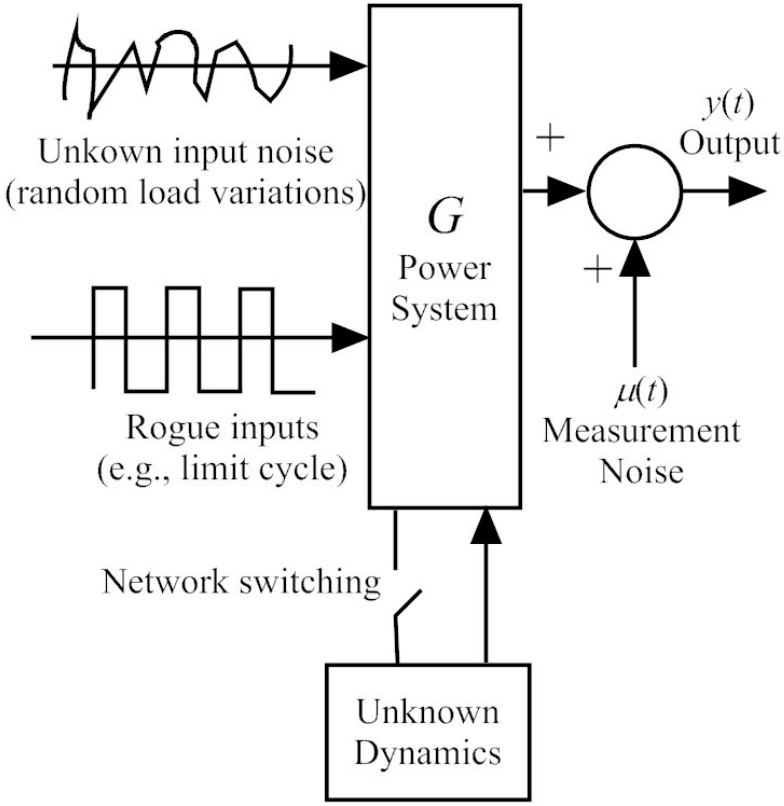
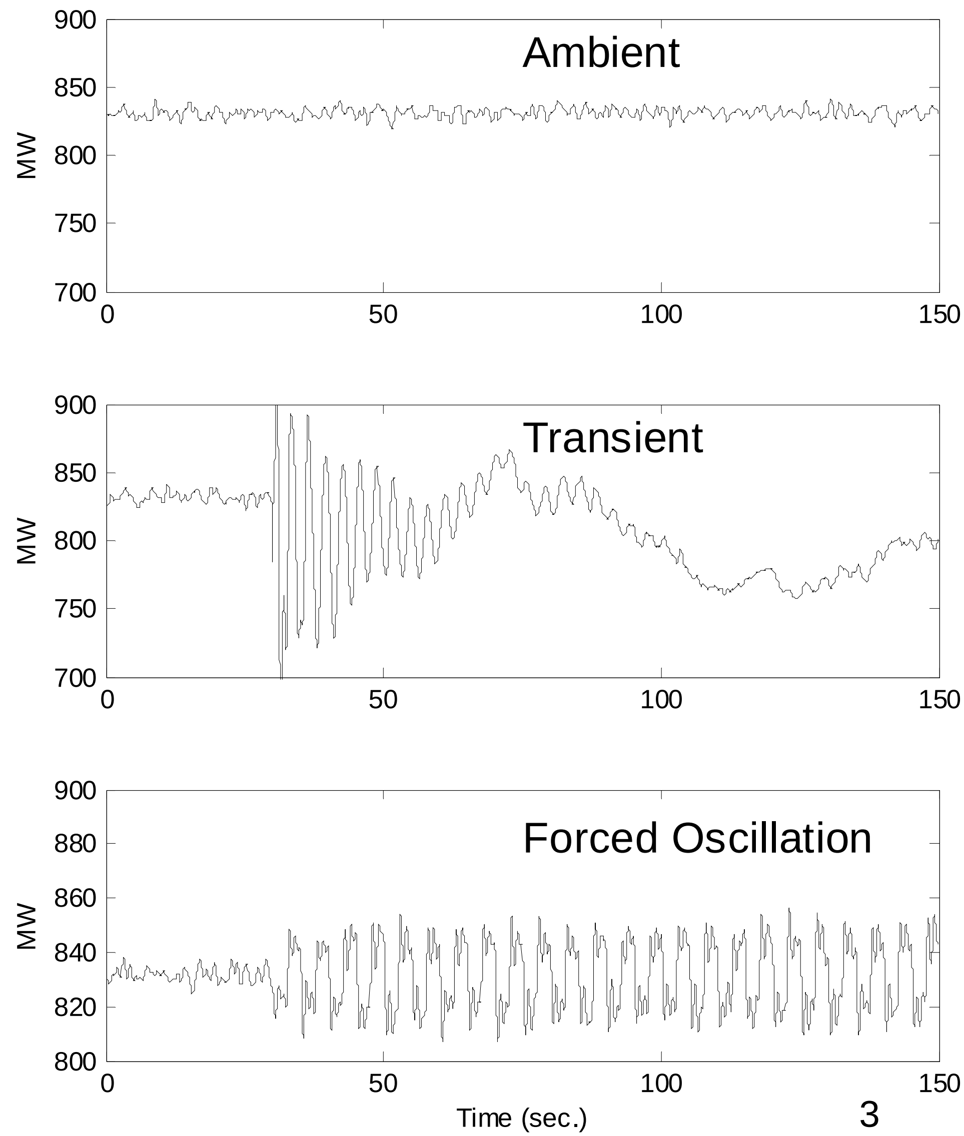
Project Overview

- Objective: Develop, test, and refine algorithms to automatically estimate and quantify oscillations from PMUs in real time.
- Application
  - Real-Time Situational Awareness based upon actual system observations
- Time line:
  - April 2006 thru April 2015
- Participants:
  - Dan Trudnowski, Montana Tech
  - John Pierre, University of Wyoming
  - Louis Scharf, Colorado State University (Retired)
  - Lots of graduate students
- Collaborators:
  - Ning Zhou, Binghampton University (formely at PNNL)
  - Bonneville Power Administration
- Advisors
  - John Hauer, PNNL (Retired)
  - Bill Mittelstadt, BPA (Retired)

Dynamic Response Types

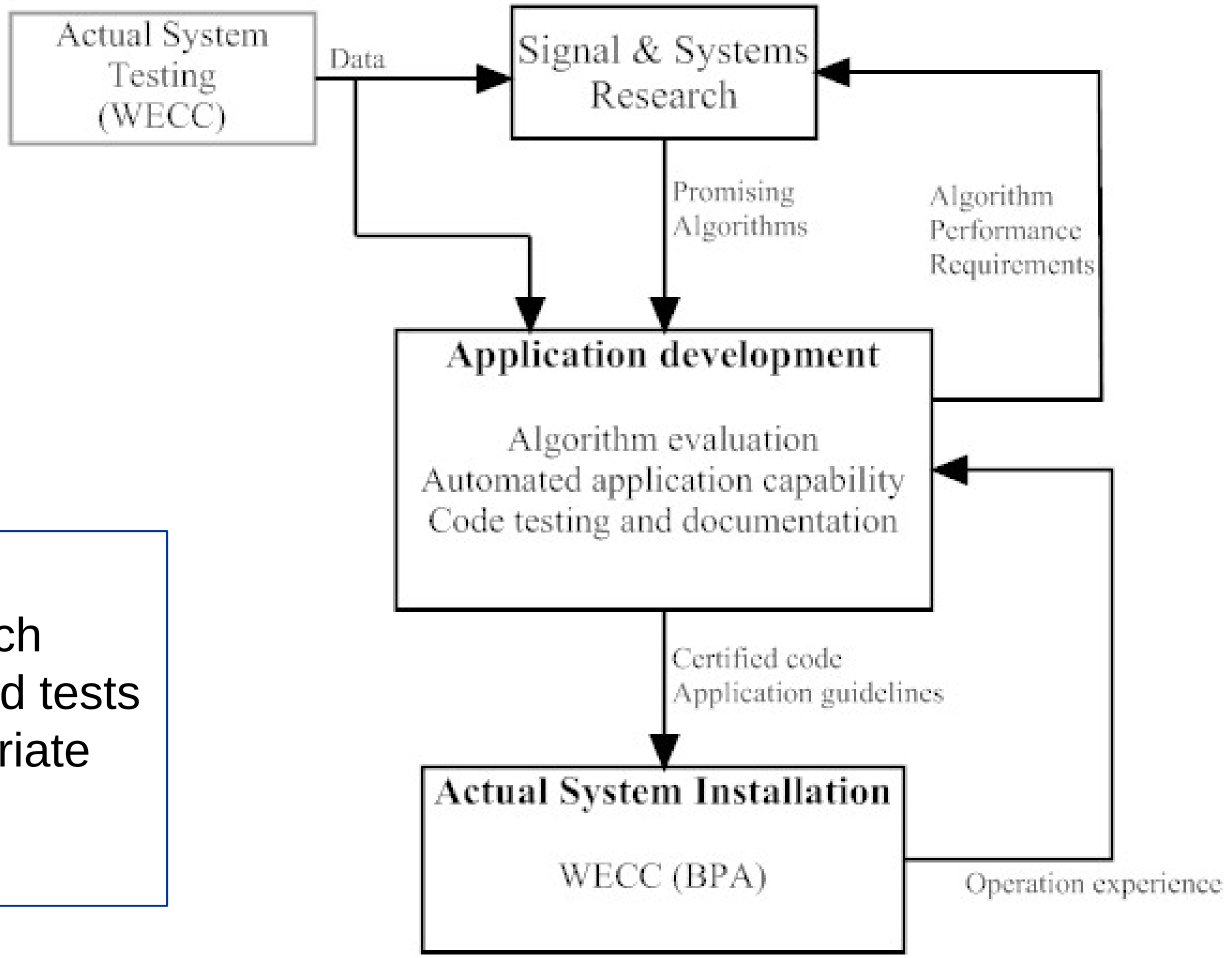




Algorithm Classes

- Oscillation Detector (OD): Immediately tells one that an oscillation is occurring with minimal quantification.
  - Very fast and robust
  - Distinguishes between forced oscillation and transient
  - If it is a FO, tells location of FO.
  - Operations and Engineering tool.
- Mode Meter (MM): Estimates a mode’s frequency, damping, and shape.
  - Operates automatically
  - Ambient conditions (minutes)
  - Transient conditions (seconds)
  - Operations and Engineering tool
- Spectral Estimator (SE): Estimate the spectra of a signal.
  - Requires minutes of data for averaged spectra
  - Requires seconds of data for single window fft
  - Very robust
  - Operations and Engineering (Lots of data management and visualization)
- Ringdown Estimator (RE): Estimates a mode’s frequency, damping, and shape.
  - Only works on transient data, requires seconds of data.
  - Not robust. Easy to fool (e.g., multiple switchings)
  - Engineering tool

Research Approach



Tasks:
1. Signal & systems research
2. Conduct and analyze field tests
3. Develop and test appropriate automated code

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Accomplishments to Date
Signal & Systems Research

Red = Current or past year

- Mode-meter algorithms
  - YW = Yule Walker, YWS = Yule Walker Spectral, N4SID =Sub-space ID, R3LS = Regularized Robust Recursive Least Squares
  - Mode energy calculations for automated application
  - Tested Frequency Domain methods
  - Simultaneous mode and forced oscillation methods; R3ML = Regularized Robust Recursive Maximum Likelihood; MTF = Multi-Channel Transfer Func. – simultaneous mode and shape,
- Performance and Validation Indices
  - Confidence bound estimation (Bootstrapping) for YW, YWS, and N4SID.
  - Direct Confidence bounds from RML
  - Whiteness testing

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Accomplishments to Date

Signal & Systems Research

Red = Current or past year

- Ringdown Estimators
  - Compared BPA/PNNL Prony analysis with Matlab-based Prony
  - Algorithms to automatically detect a ringdown (Zhou)
- Mode Shape
  - Fundamental calculations for extracting mode-shape information.
  - 3 algorithms for estimating the mode-shapes.
- Forced Oscillations
  - Fundamental characteristics of forced oscillations.
  - Simultaneous mode and forced oscillation methods.
  - Effect of forced oscillations on mode-shape estimation algorithms
- Oscillation Detection
  - RMS Energy filtering. Currently updating Band 4 filters to extend to Nyquist.
  - Modified classical detection including Probability of Detection and False alarm
  - Self Coherency
- Spectral Estimation
  - Magnitude and Phase Response Estimates Standard Deviation
  - Fast recursive methods for estimating spectrum

Accomplishments to Date

Application Development & WECC Tests

Red = Current or past year

- Expert System for automated application of mode meter (Patent pending).
- Supported EPG's code implementation
- Installed and operated prototype tools at BPA 2010-13
- Modal Analysis Software (MAS) support (BPA and WECC).
- Update Band 4 filter in MAS-ODM to extend to Nyquist.
- WECC System Tests
  - Designed methodology to construct multi-sine optimized PDCI probing signals
  - Supported and analyzed Aug. 2006, Aug. 2008 tests, 2009 season tests (14 tests), 2011 season tests (16 tests). 2012 season tests (26 tests), 2013 season tests (30 tests)
  - Currently conducting 2014 season tests
  - Design high frequency test signals for controller design (28 Hz bandwidth)
  - Analyze high frequency PMU and PPMS test data

Accomplishments to Date

Publications (49) - Red = Current or past year

L. Dosiek, J.W. Pierre, J. Follum, “A Recursive Maximum Likelihood Estimator for the Online Estimation of Electromechanical Modes with Error Bounds,” *IEEE Trans. on Power Systems*, vol. 28, no. 1, pp. 441-451, February 2013.

L. Dosiek, N. Zhou, J.W. Pierre, Z. Huang, and D.J. Trudnowski, “Mode Shape Estimation Algorithms Under Ambient Conditions: A Comparative Review,” *IEEE Trans. on Power Systems*, vol. 28, no. 2, pp. 779-787, May 2013.

L. Dosiek and J.W. Pierre, “Estimating Electromechanical Modes and Mode Shapes using the Multichannel ARMAX Model,” *IEEE Trans on Power Systems*, vol. 28, no. 2, pp. 1950-1959, May 2013 (special section on synchrophasor applications in power systems).

Ryan Myers and Dan Trudnowski, “Effects of Forced Oscillations on Mode Shape Estimation,” *Proceedings of the IEEE Power Engineering Society General Meeting*, Vancouver BC, July 2013.

N. Zhou, J. Pierre, and D. Trudnowski, “Some Considerations in Using Prony Analysis to Estimate Electromechanical Modes,” *Proceedings of the IEEE Power & Energy Society General Meeting*, July 2013.

Z. Cao, J.W. Pierre, “Electromechanical Mode Estimation Validation Using Recursive Residual Whiteness Testing,” *Proceedings of the North American Power Symposium*, Manhattan, Kansas, September, 2013.

J. Follum, J.W. Pierre, “Initial Results in the Detection and Estimation of Forced Oscillations in Power Systems,” *Proceedings of the North American Power Symposium*, Manhattan, Kansas, September, 2013.

G. Pai and J.W. Pierre, “A Real-time Scheme for Validation of an Auto-regressive Time Series Model for Power System Ambient Inter-area Mode Estimation,” *Proceedings of HICSS-47*, Waikoloa, Hawaii, January 2014.

Forced Oscillations (FOs)

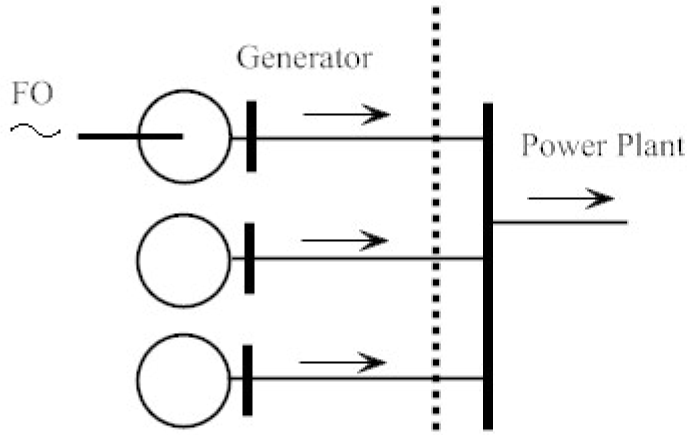
- Many causes, e.g.:
  - Generator rogue controller in limit cycle
  - Pulsing loads
  - NOT A SYSTEM INSTABILITY
- FOs very common
- Can be very severe: November 30, 2005
- Fundamental Goals: Develop signal processing algorithms that
  - Identify forced oscillations and distinguish them from system modes.
  - Identify the root location and cause of the forced oscillation.

FO Properties

- Research Questions
  - What are the fundamental causes?
    - Generator controls and loads.
    - Real power vs reactive power.
    - Pole slipping.
  - How do FOs propagate thru the system?
    - Voltage vs current.
    - Speed vs power.
  - What are the impacts of FOs on MM and Mode Shape algorithms?
- Study approach
  - Fundamental systems analysis.
  - miniWECC simulation and analysis.
- FOs are typically harmonic.

FO Properties

Propagation of real-power non-harmonic FOs



- If FO is not near a system mode, the real-power and current oscillations are largest at the FO power-plant. Easy to find
- If FO is near a system mode, power-plant measurements DO NOT provide info on FO location.
  - FO tends to follow mode shape.
  - No pattern for voltage vs. current at the power plant.
  - Intra-plant measurements can reveal the location of the FO.
  - May require shaft angle or speed measurement.

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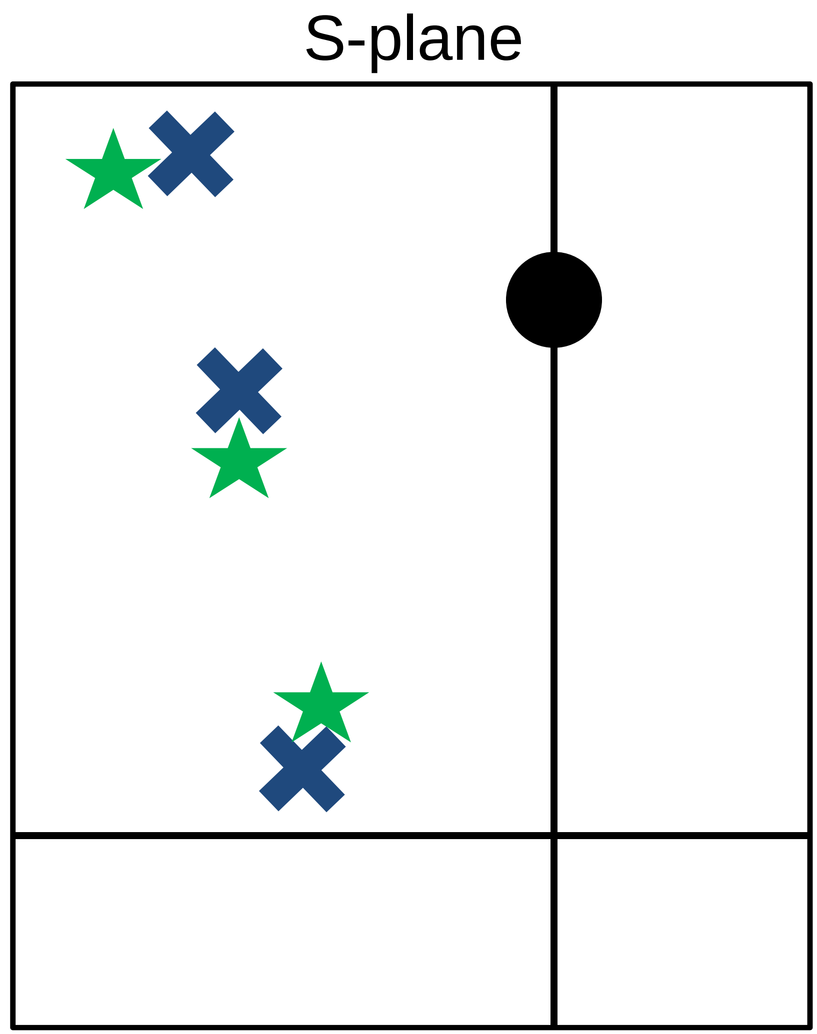
Impact of FO on Standard Mode Meters

- Green Stars – True Modes
- Blue X's estimated modes under ambient conditions
- What if a sinusoidal FO is present in the data?
- The estimated mode can be biased toward the forced oscillation!



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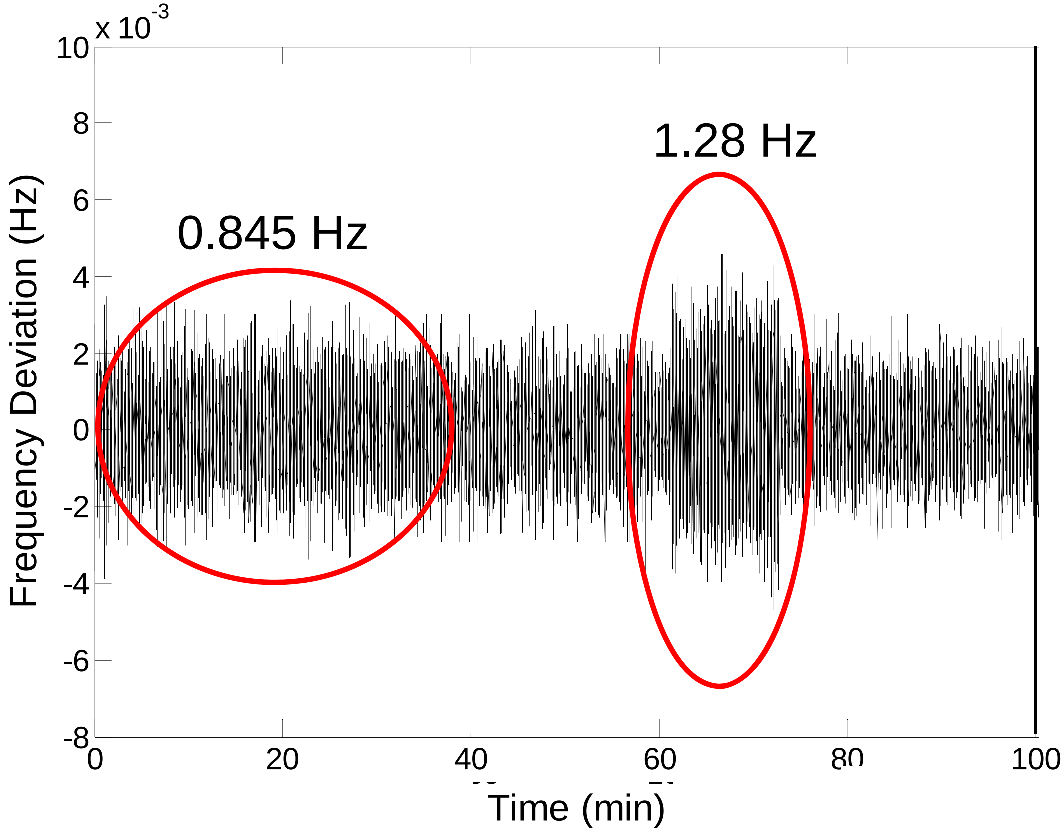
Real World Example: BPA Data - October 2010



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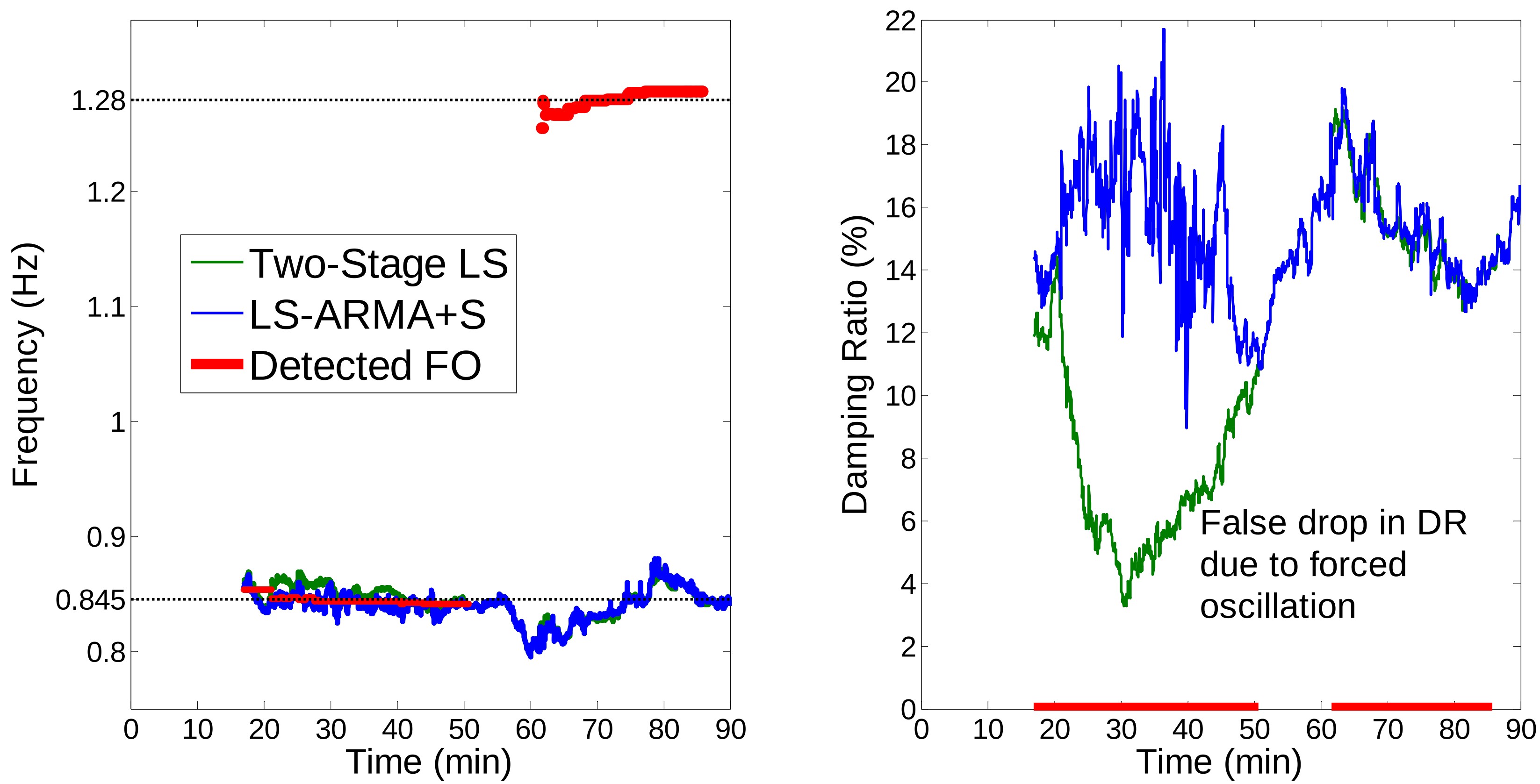
Mode Estimation Results – for Standard Mode Meter versus Modified Mode Meter



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RD&D Stage

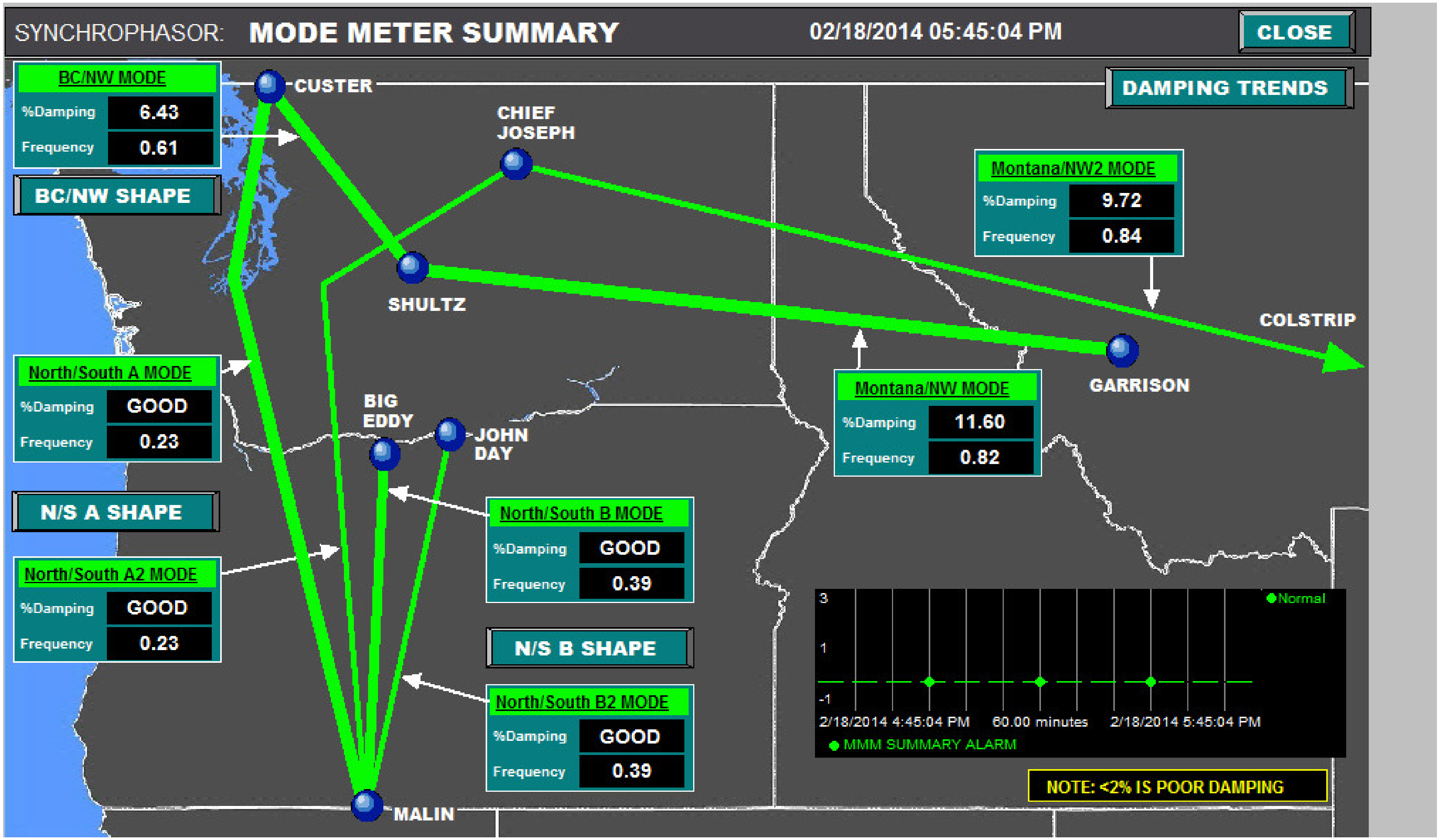
Components ranging from Theoretical Study to Pre-commercial.

- Theoretical Study:
  - Signal & systems research.
  - Forced oscillations research.
- Field Testing:
  - WECC system tests.
- Pre-commercial
  - MAS Software – Production-grade software engine for modal analysis in operations and control environment. (Initial R&D funding from this program, full deployment funding through WISP)
    - YW, R3LS, Mode-Meter Expert System
    - Auto-spectrum Estimation
    - Oscillation Detection via RMS Energy
  - Becoming operational at
    - BPA – Custom EMS software design.
    - WECC – Integrated into Alstom Grid application
    - CaISO – Integrated into RTDMS

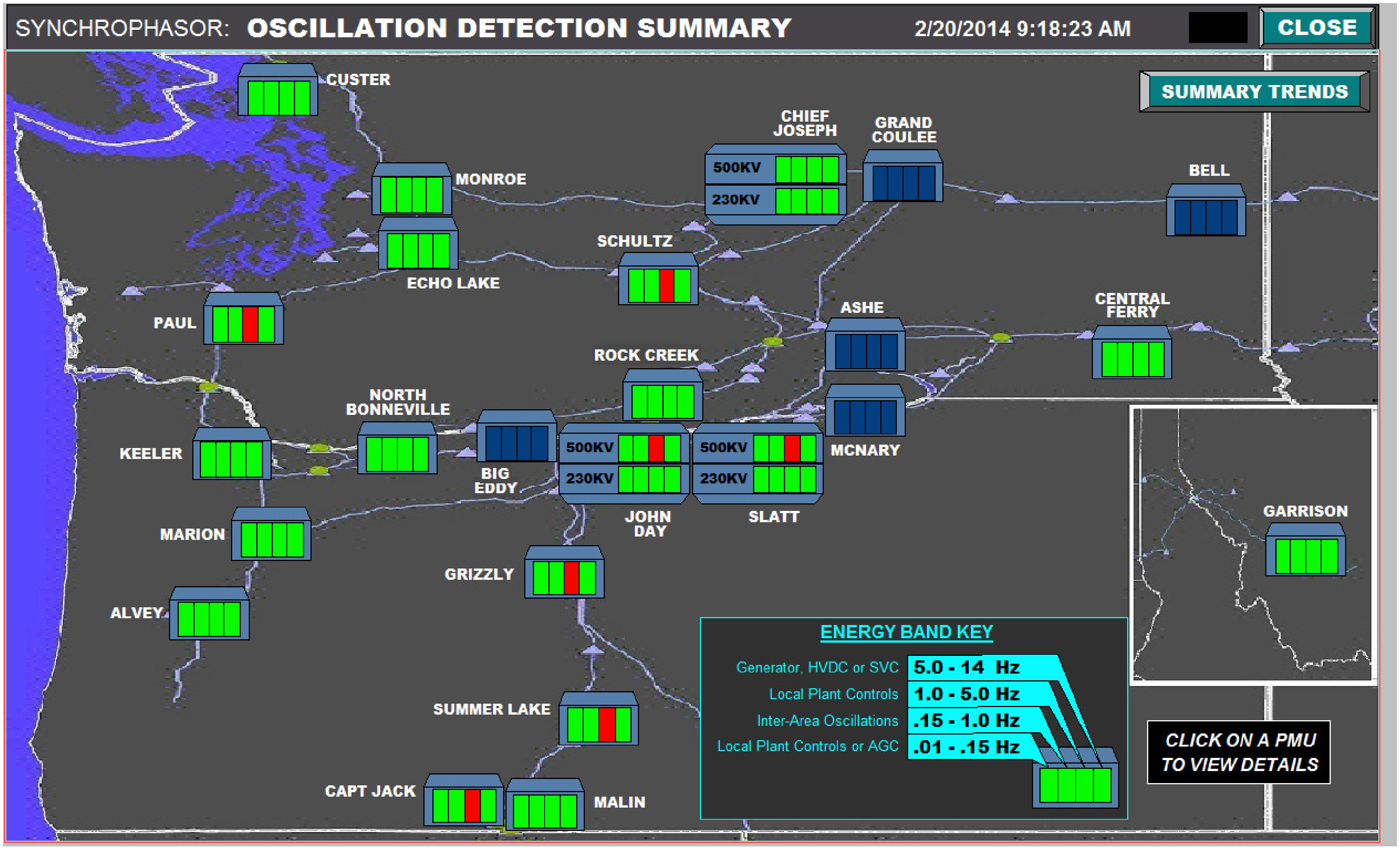
FY14/15 Plans

- Overall objective: Develop, test, and refine algorithms to automatically estimate and quantify oscillations from PMUs in real time.
- Continue fundamental signal & systems research
  - Continue mode-meter and mode-shape research
    - Improved accuracy
    - Impacts of forced oscillations
    - Simultaneous mode and forced oscillation estimation
  - Fundamental nature of forced oscillations
  - Continue developing oscillation detection methods
    - Automated with little tuning
    - Distinguish between transients and forced oscillations
    - Identify root causes
- Continue to support WECC probing tests
- Integrate minor proven enhancements into MAS & support MAS users

Screen Capture of BPA's Mode Meter



Screen Capture of BPA's Oscillation Detector



Testimonials

- ~49 publications in peer-reviewed journals and proceedings.
- Two patents pending.
- Helped organize/conduct IEEE Task Force (special publication).
- MAS production-grade software engine.
- MAS being used at WECC, BPA, and CalSO control centers

- **Questions?**

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