Fast Stability Monitoring Algorithms for Large Sets of PMU Signals

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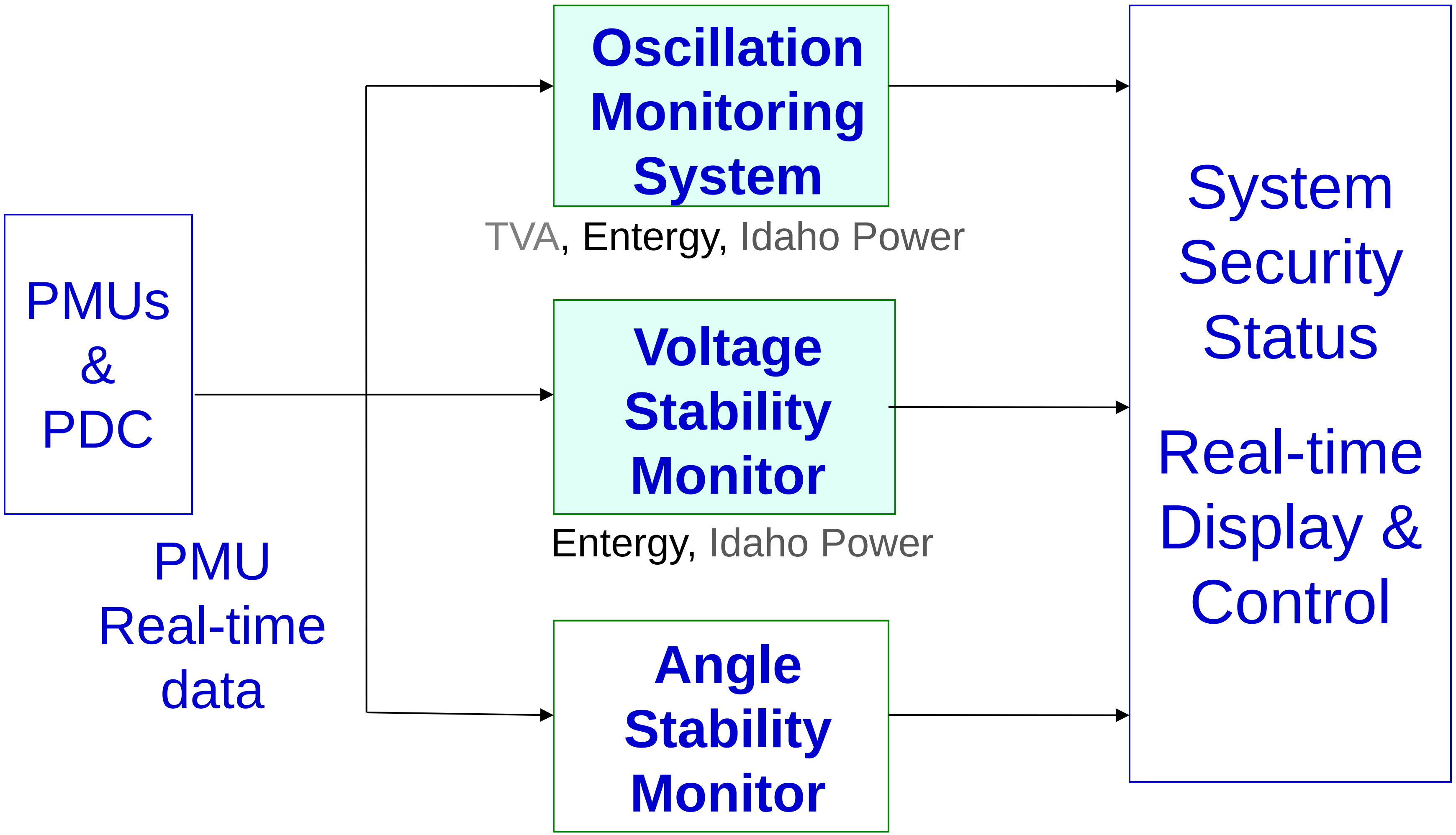
World Class. Face to Face.

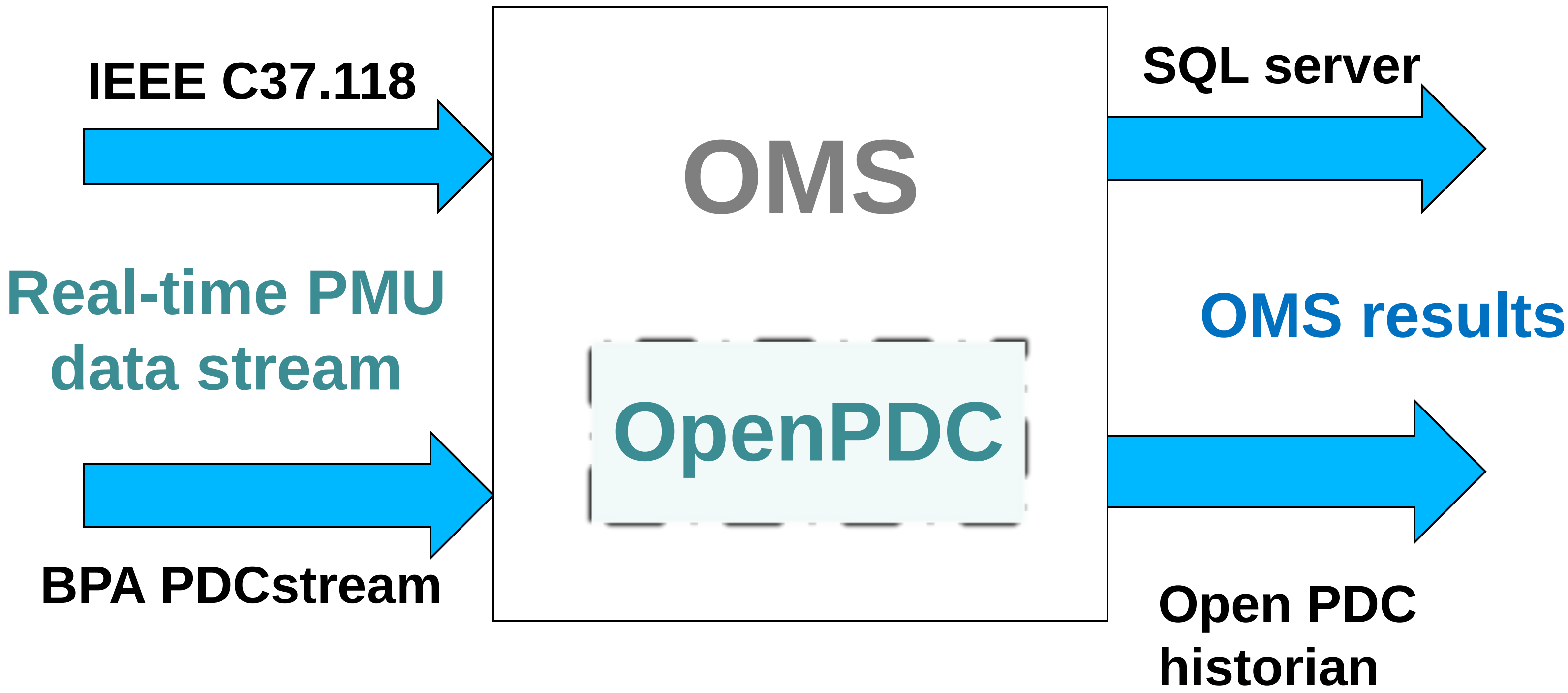
Real-time security monitors @ WSU



Oscillation Monitoring Objectives

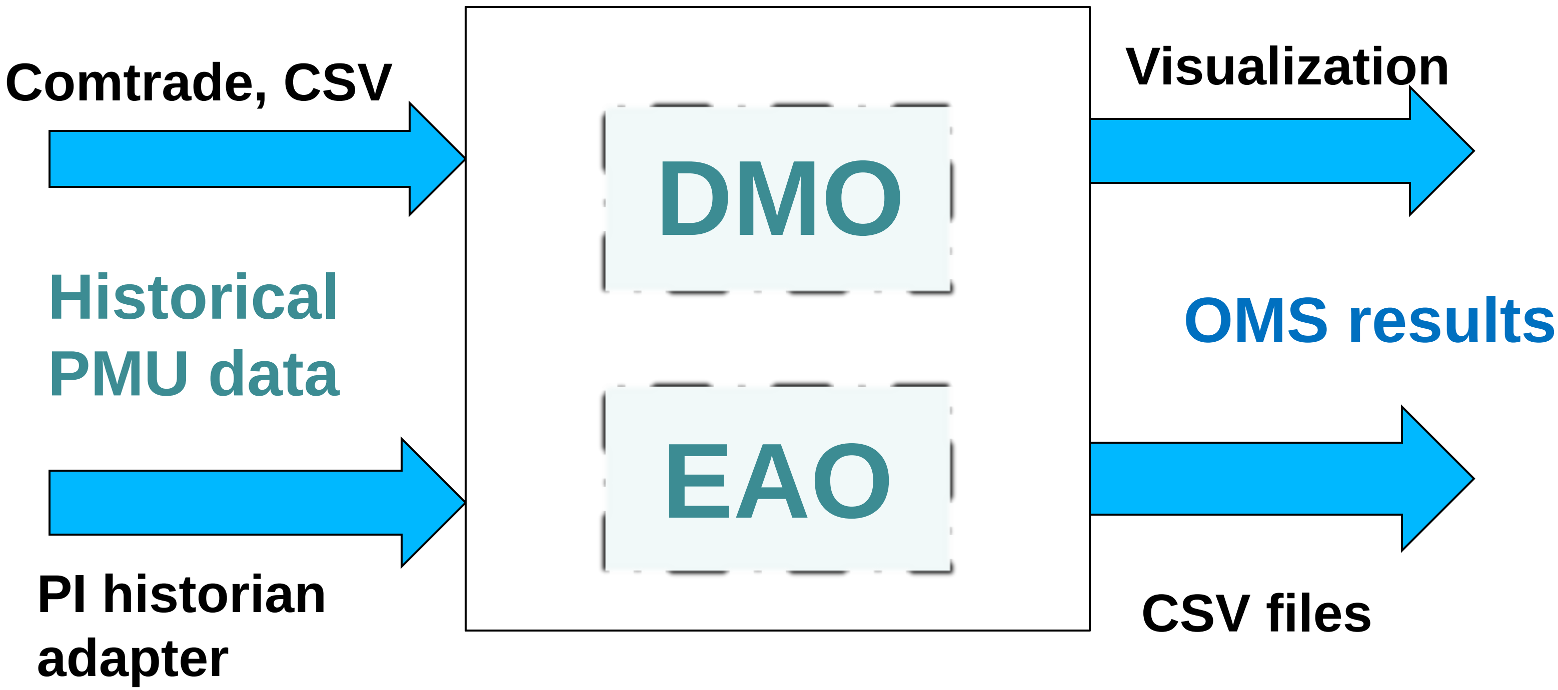
- Oscillation Monitoring System for WECC and Entergy
- Monitoring hundreds of PMUs simultaneously
  - Automatic detection of oscillations
  - Helps pinpoint likely source of oscillations
- Damping Monitor Engine – ambient data analysis
- Event Analysis Engine – detection and analysis of ringdowns and oscillations
- Online engines and off-line engines

Oscillation Monitoring System



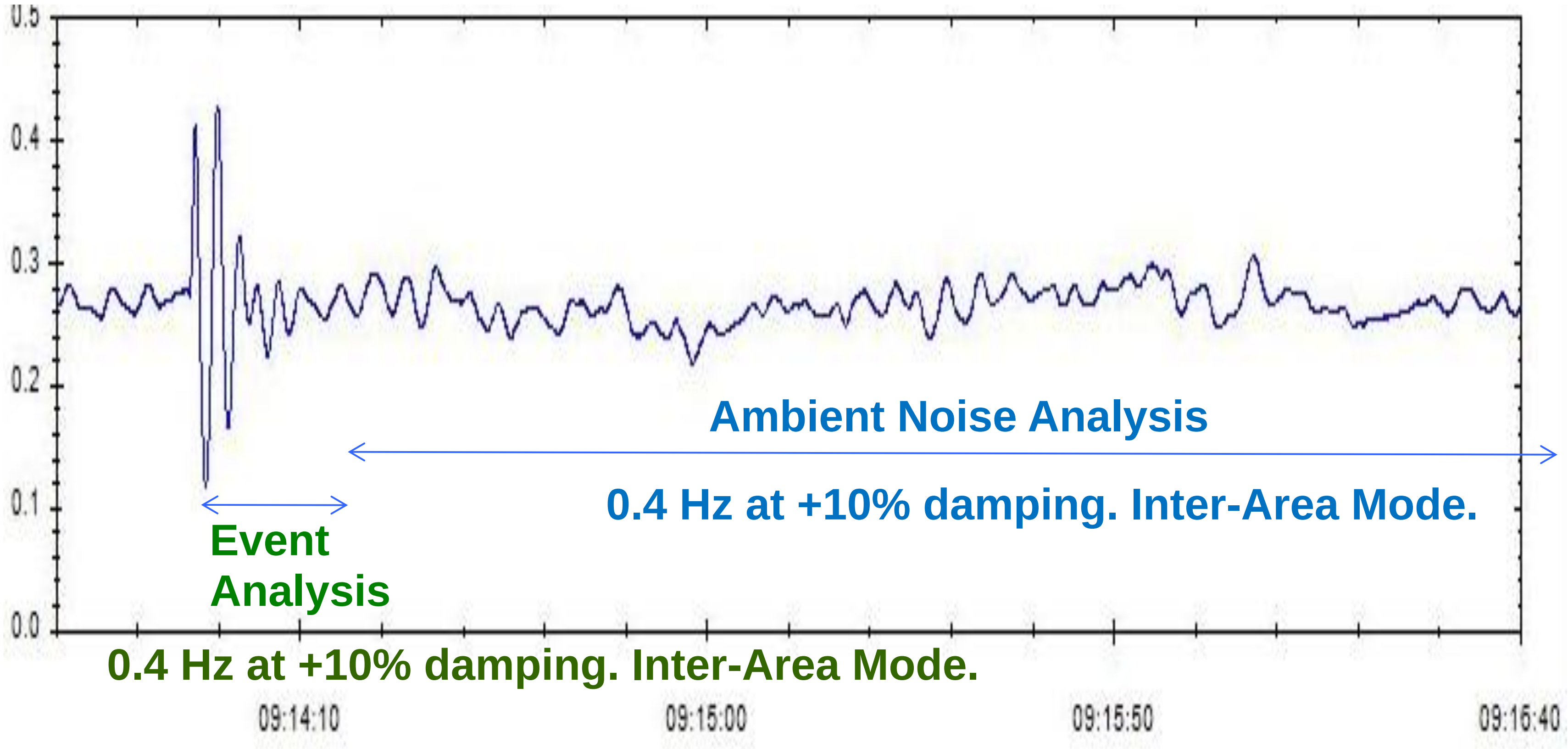
OMS action adapter built into OpenPDC 64 bit version 2.1.

Oscillation Monitoring Off-line



Stand alone oscillation analysis programs for analyzing historical PMU data.

Results from Two Engines



Complementary Engines

- Event Analysis Engine (EAE)
  - Multiple algorithms
  - Prony, Matrix Pencil, HTLS, ERA, MFRA, METRA.
  - Aimed at events resulting in sudden changes in damping
- Damping Monitor Engine (DME)
  - Ambient noise based. Continuous. Provides early warning on poorly damped modes.
  - Several algorithms
  - Fast Frequency Domain Decomposition (FFDD), DFDO, Recursive Adaptive Stochastic Subspace Identification (RASSI), DFDD, RFDD, DRSSI, FSSI.

Frequency Domain Decomposition

- Collect and preprocess signals from PMUs
- Power spectrum matrix estimation by Multi-Taper Method
- Apply SVD on the power spectrum matrix
- Apply inverse FFT on largest singular values
- Extract pole frequency and damping ratio from exponential form by ringdown analysis
- Can process 100 signals simultaneously in real-time (fast)

Fast Frequency Domain Decomposition (FFDD)

- Collect and preprocess signals from PMUs
- Power spectrum estimation by FFT and Multi-Taper Method
- Apply SVD on the power spectrum
  - Approximate the largest singular value by the trace of the power spectrum matrix (**Fast FDD**)
- Apply inverse FFT on largest singular values
- Extract pole frequency and damping ratio from exponential form by ringdown analysis
- Can process 1000+ signals simultaneously.

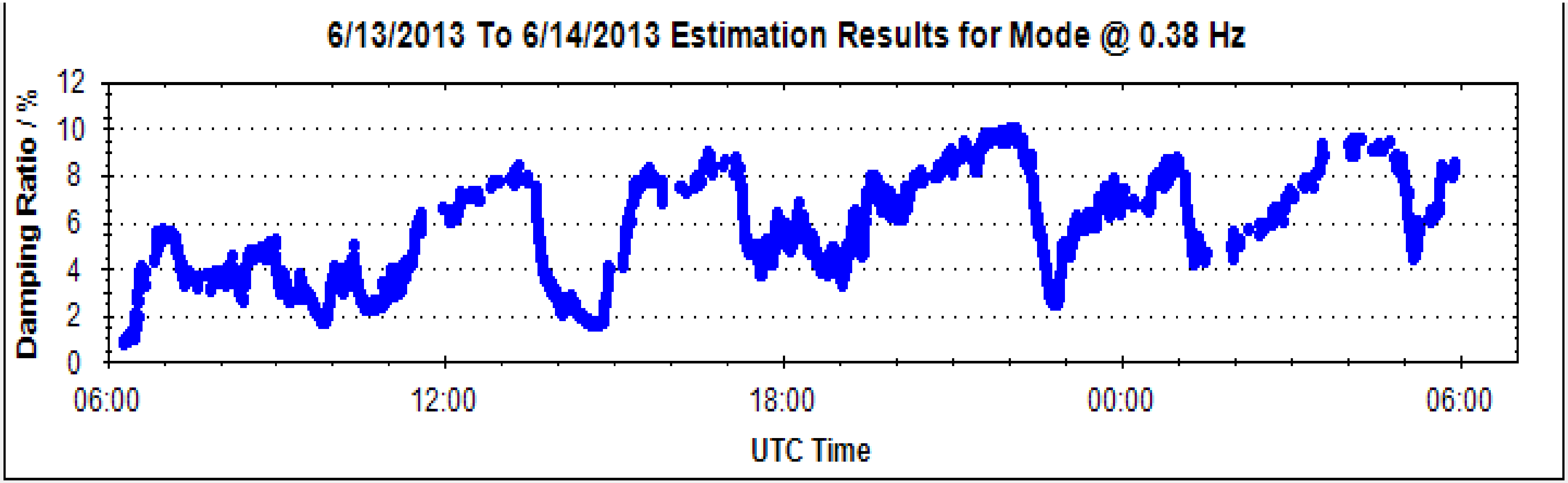
Turbo Oscillation Monitoring

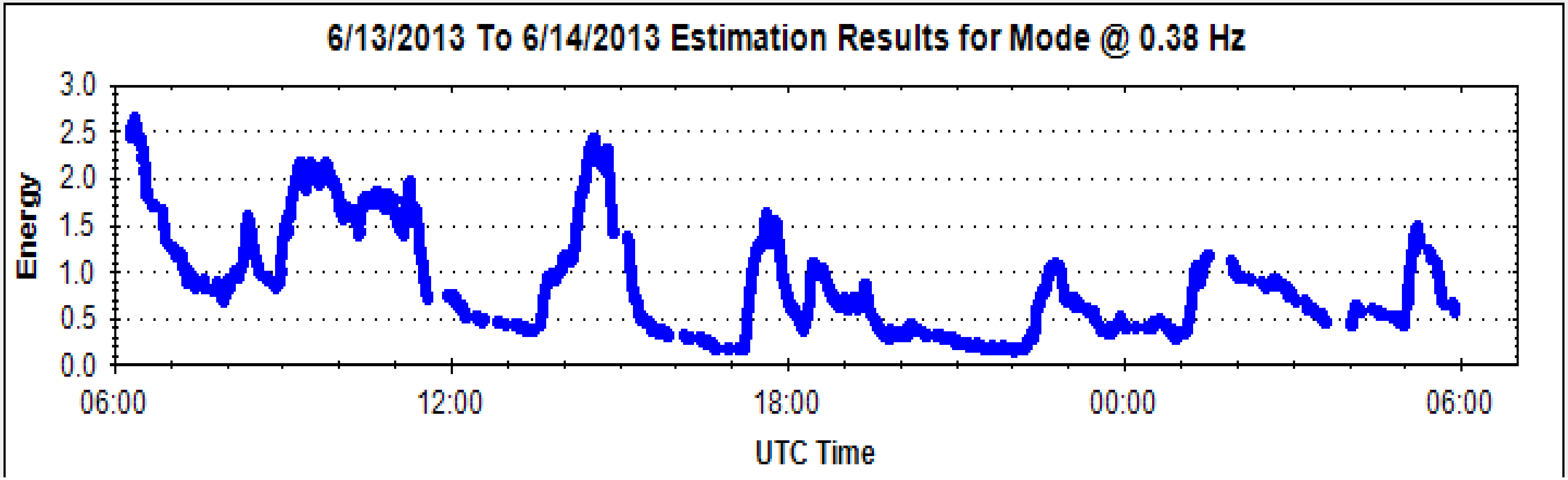
- Can process truly large number of signals 1000+ simultaneously in real-time: needed for reliable estimation and source location.
- Offline mode: Can get a quick overview of system modal properties by fast analysis of historical data. Can study mode trends.
- An hour of data from 200 PMU signals can be analyzed in less than 2 minutes on a desktop
- Implemented in C# using Intel Math library. Multi-threaded. Scalable solutions offered.

FFDD Estimation Results

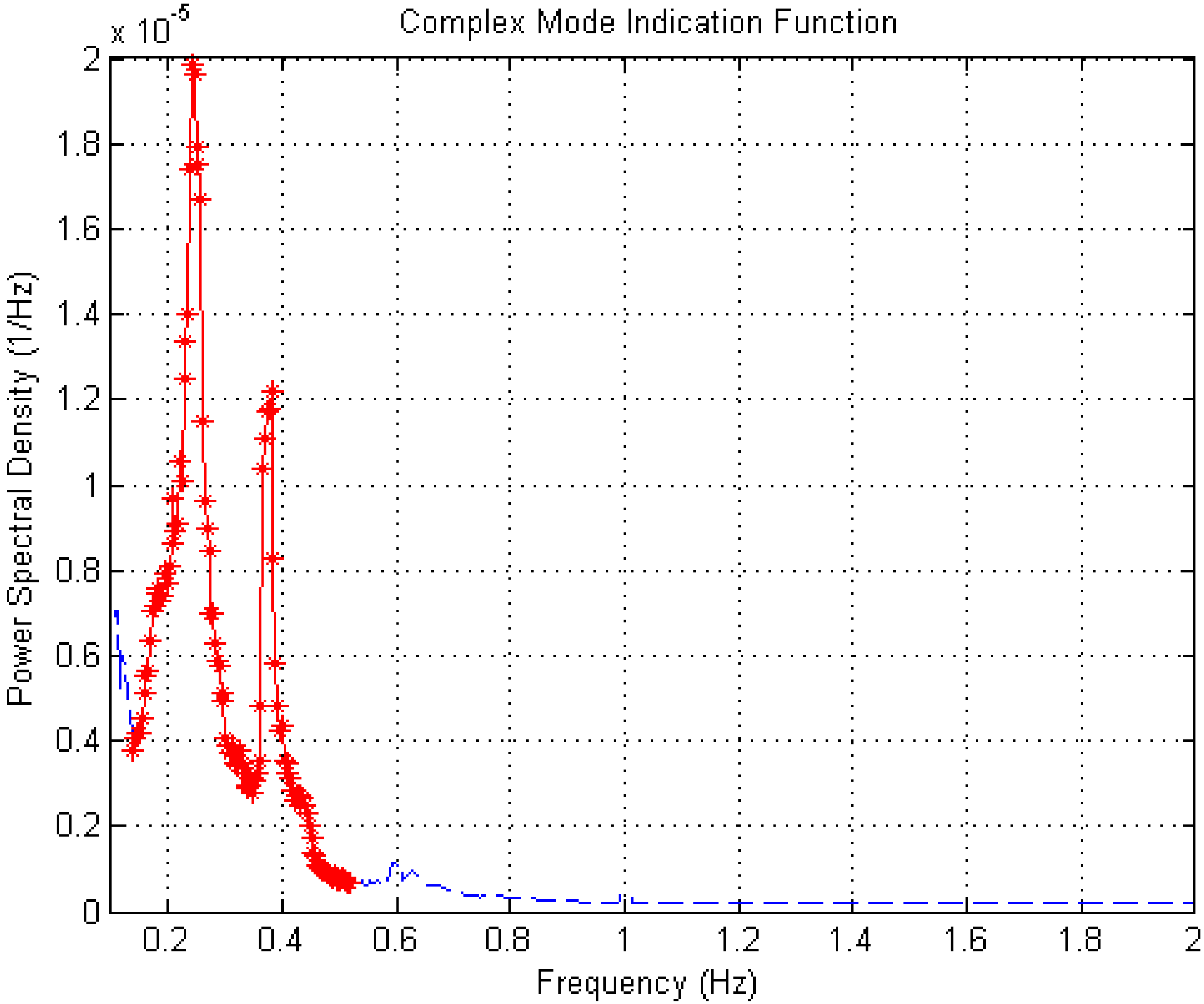
- Dominant modes are analyzed for each data set – four minutes of data updated every ten seconds
- For each mode:
  - Mode frequency
  - Mode damping ratio
  - Mode energy
  - Mode shape
  - Estimation confidence level

WECC Mode Estimation Results

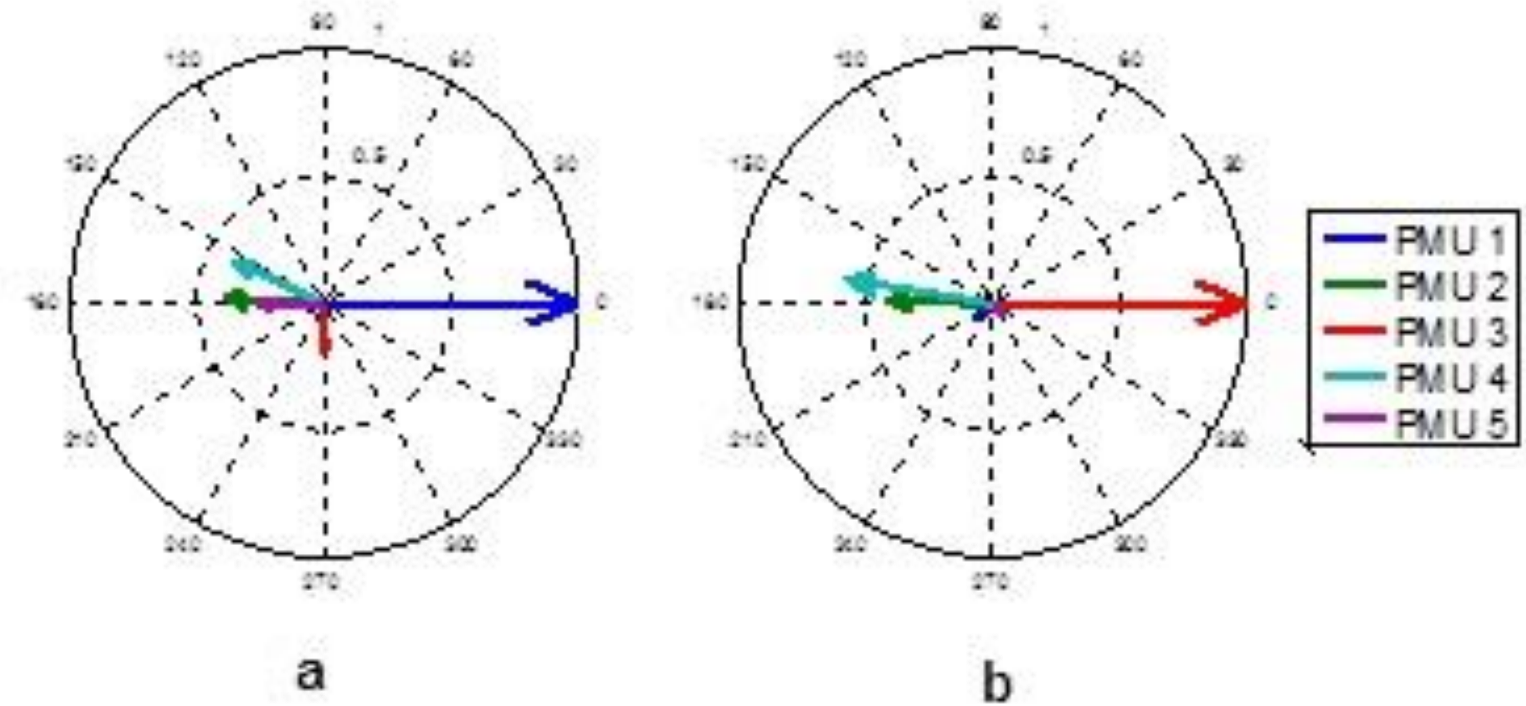




June 13th WECC Power Spectrum Density Plot



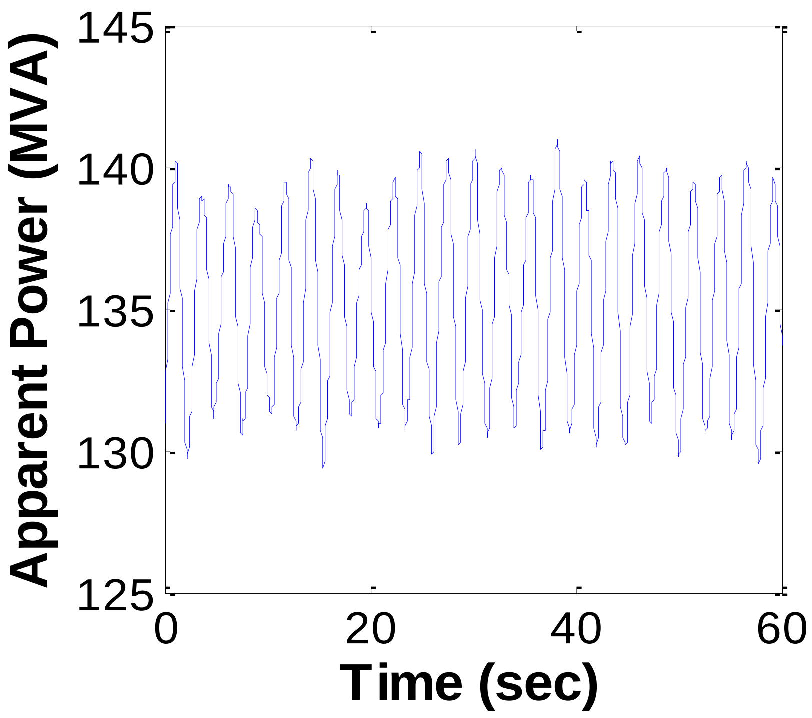
FDD Mode Shapes on June 13, 2013

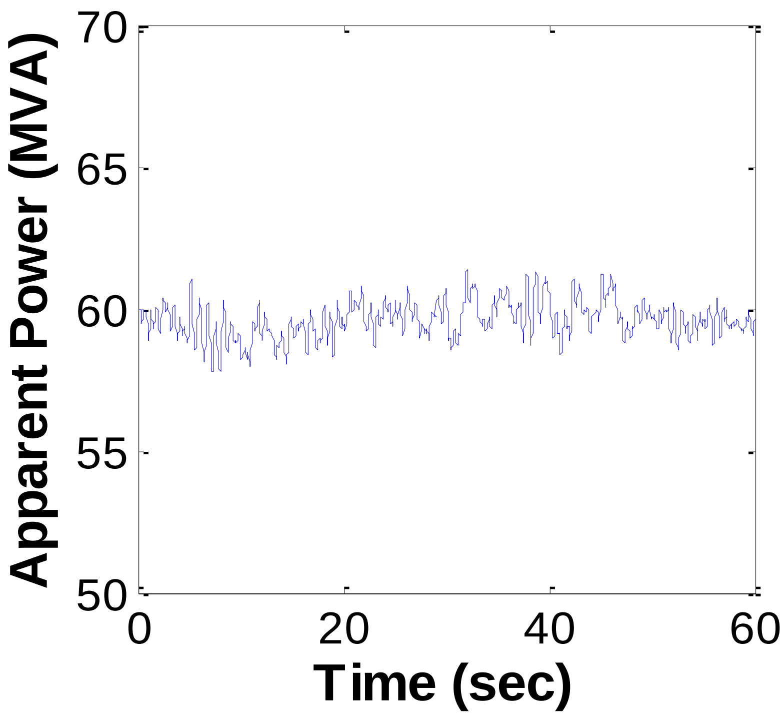


<u>Case 1</u>
0.38 Hz at
0.6% Damping Ratio

<u>Case 2</u>
0.38 Hz at
12% Damping Ratio

PMU Apparent Power Signals on PMU 1

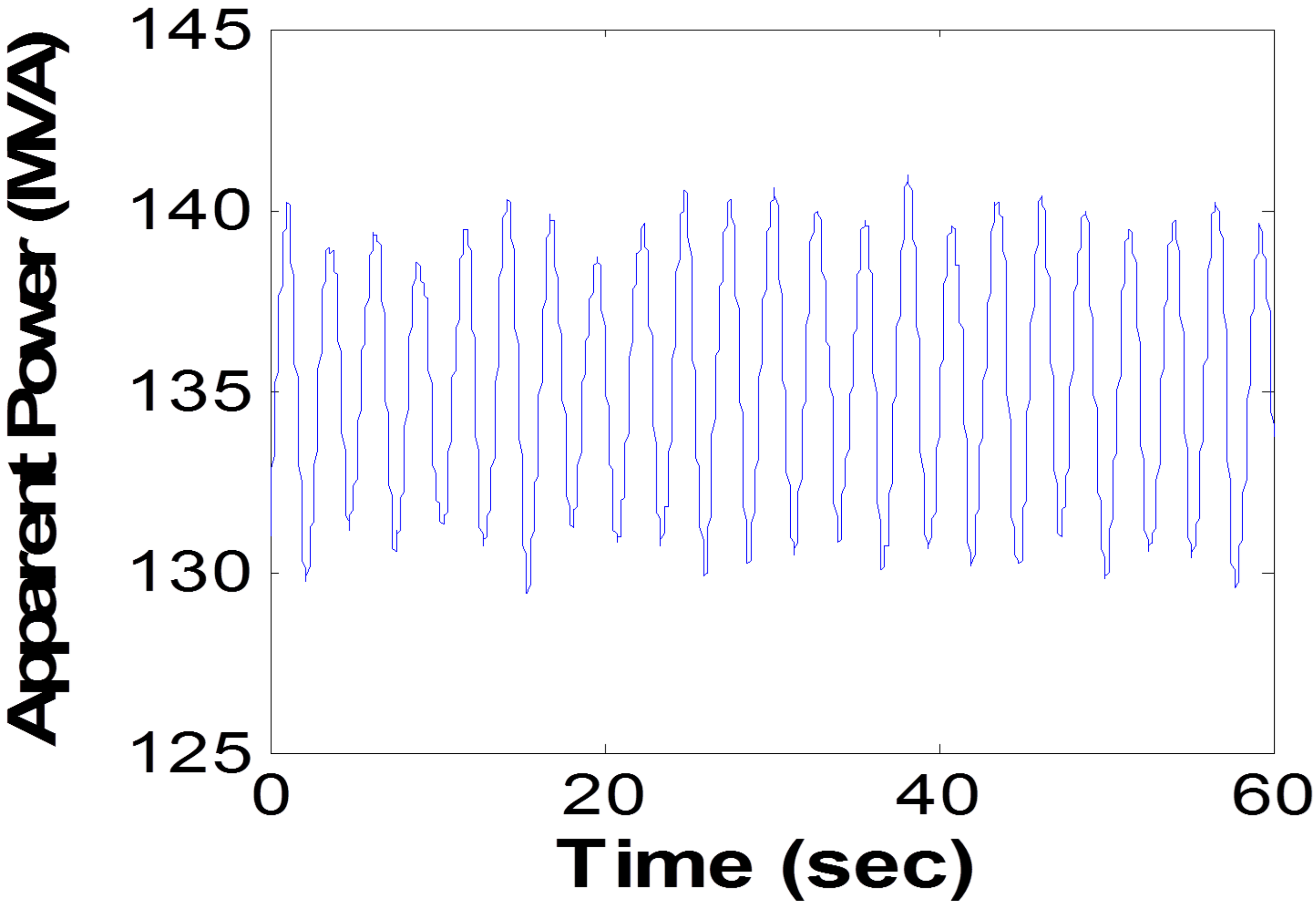




Case 1
0.37 Hz at
0.6% Damping Ratio

Case 2
0.4 Hz at
Near 8% Damping Ratio

0.37 Hz oscillations at Generator for Case 1



10 MW 0.37 Hz Sustained Oscillations

Generator MW Oscillations

- Hydro unit operated in rough zone when wind power output high.
- Vortex effect in Francis turbine for low water flow
- Air compressor to keep oscillations low to nil
- **5 to 25 MW oscillations observed at 0.37 Hz**
- Forced oscillations: mechanical oscillations on turbine shaft onto power grid
- False alarm from ambient mode engines
- Multi-dimensional mode shape analysis critical
- **Resonance possible** from interactions with system modes at nearby frequencies