Measurement Based Stability Assessment

DOE/CERTS Transmission Reliability R&D Internal Program Review Meeting

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Washington DC

Presenter: Dan Trudnowski, Montana Tech

Participants:

Dan Trudnowski

John Pierre, U of Wyoming

Ning Zhou, PNNL

Louis Scharf, Consultant

Project Objective and Application

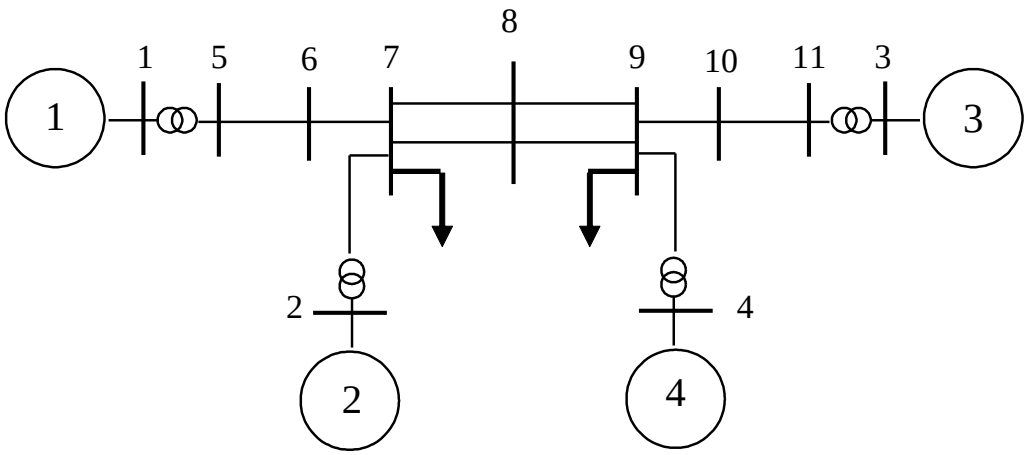
- Objective: Develop, test, and refine algorithms to automatically estimate oscillations from PMUs in real time.
  - estimate modal frequency, damping, and shape
  - estimate mode-estimation performance and validation indices (e.g., error bounds)
  - detect forced oscillations and identify the cause(s) of such oscillations
  - collaborate with power-industry partners to test potential algorithms
  - assist in the WECC system tests

- Application
  - Real-Time Situational Awareness based upon actual system observations

Project Overview

- Time line:
  - April 2006 thru April 2013
- Participants:
  - Dan Trudnowski, Montana Tech
  - John Pierre, University of Wyoming
  - Louis Scharf, Colorado State University (Retired)
  - Ning Zhou, PNNL (funded independently)
  - Lots of graduate students
- Collaborators:
  - Bonneville Power Administration
- Advisors
  - John Hauer, PNNL (Retired)
  - Bill Mittelstadt, BPA (Retired), WECC

Background



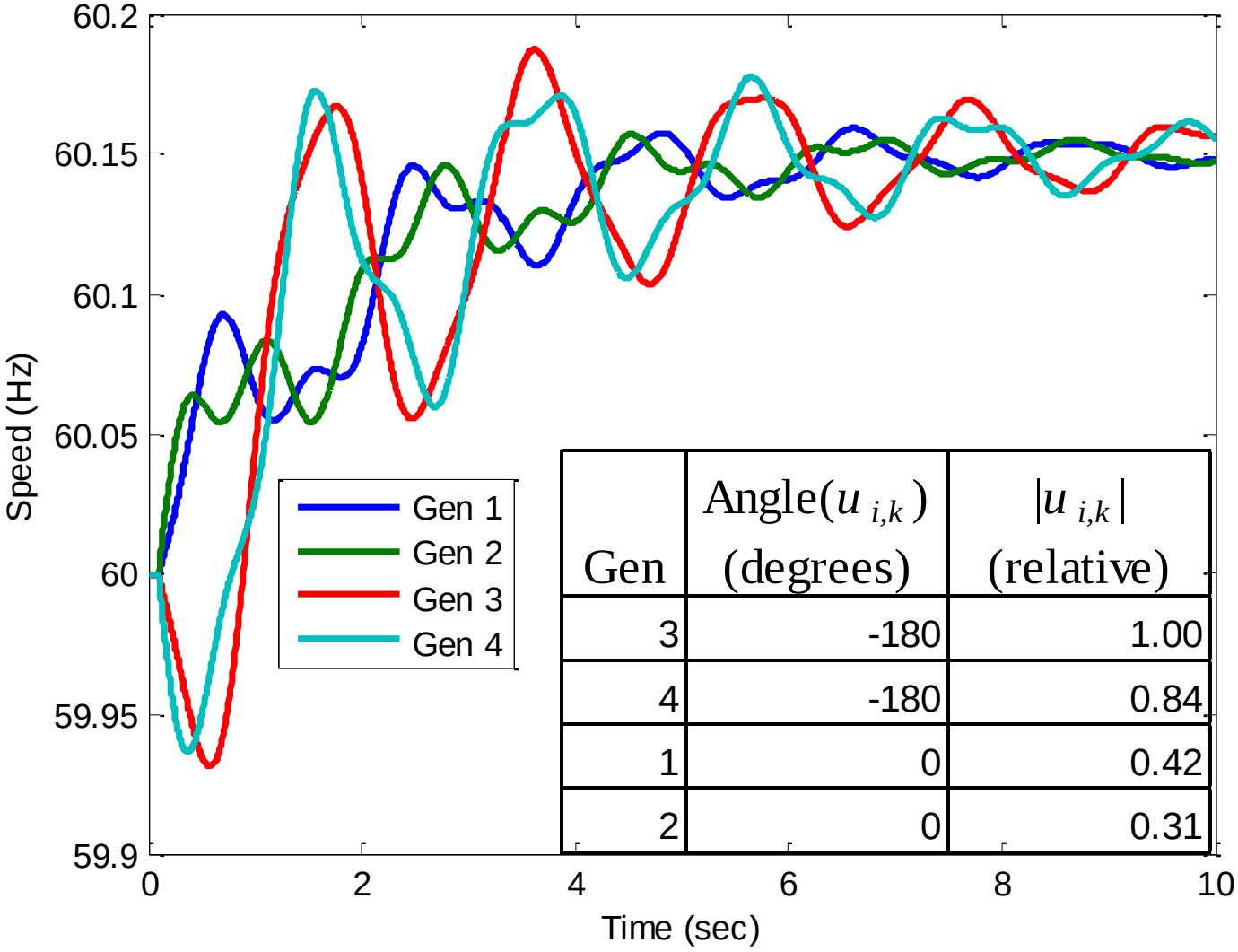
Modes

Mode	Frequency (Hz)	Damping (%)
1	0.51	7.80
2	1.19	3.40
3	1.22	3.30

0.51-Hz Mode Shape

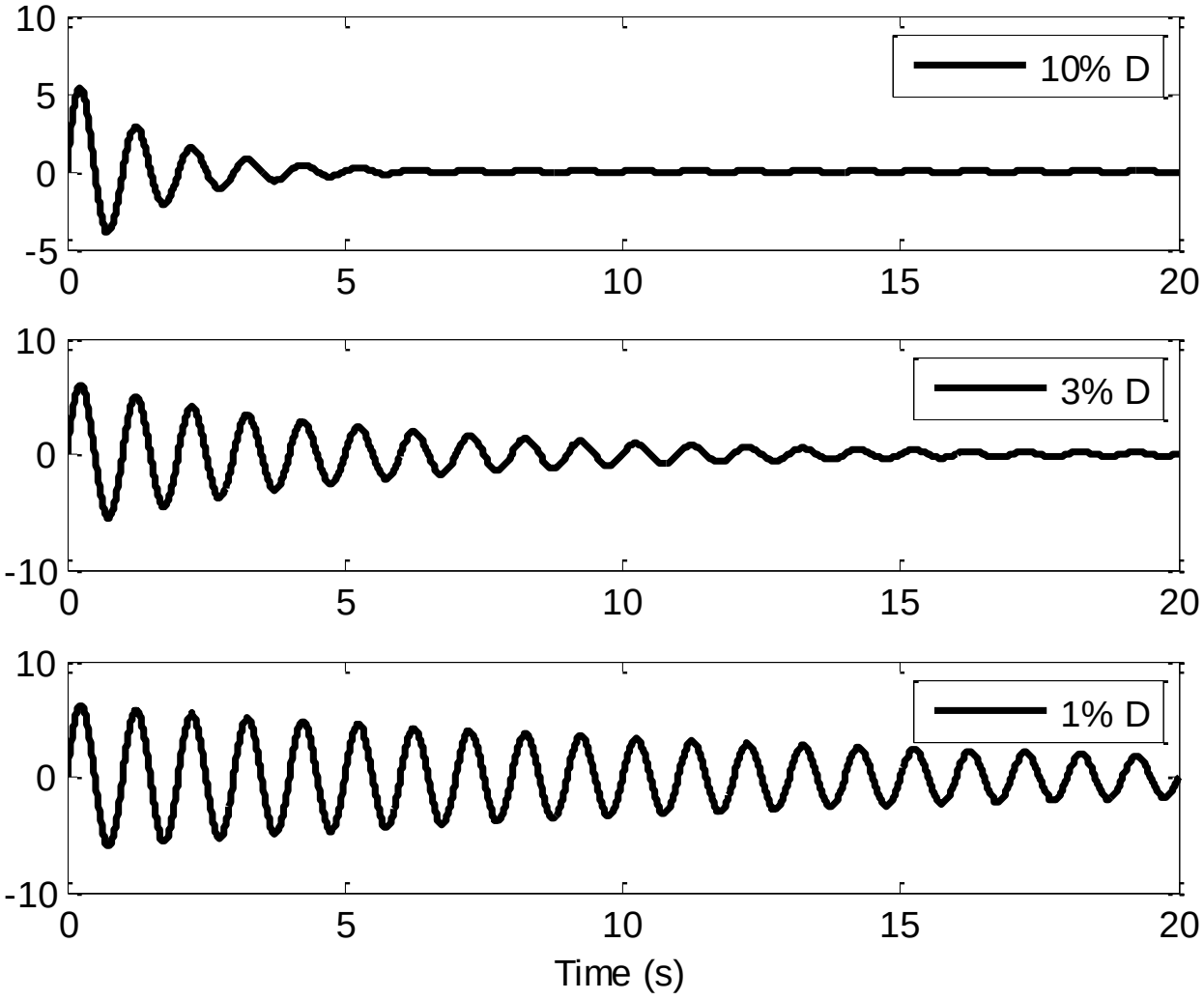
Gen	Angle($u_{i,k}$) (degrees)	Amplitude $\lvert u_{i,k} \rvert$
3	-180	1.00
4	-180	0.84
1	0	0.42
2	0	0.31

Background – cont.

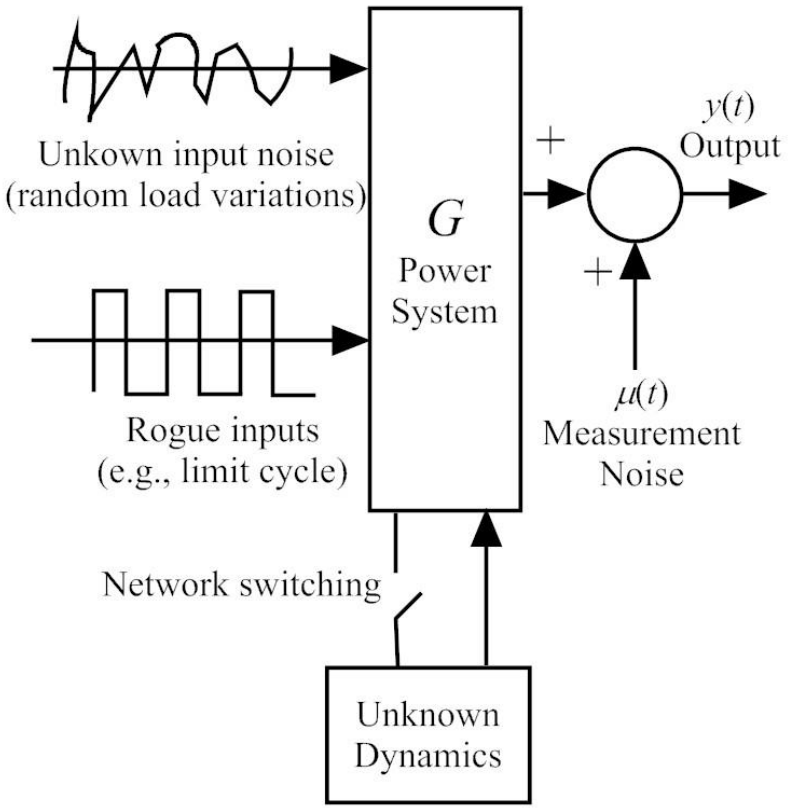


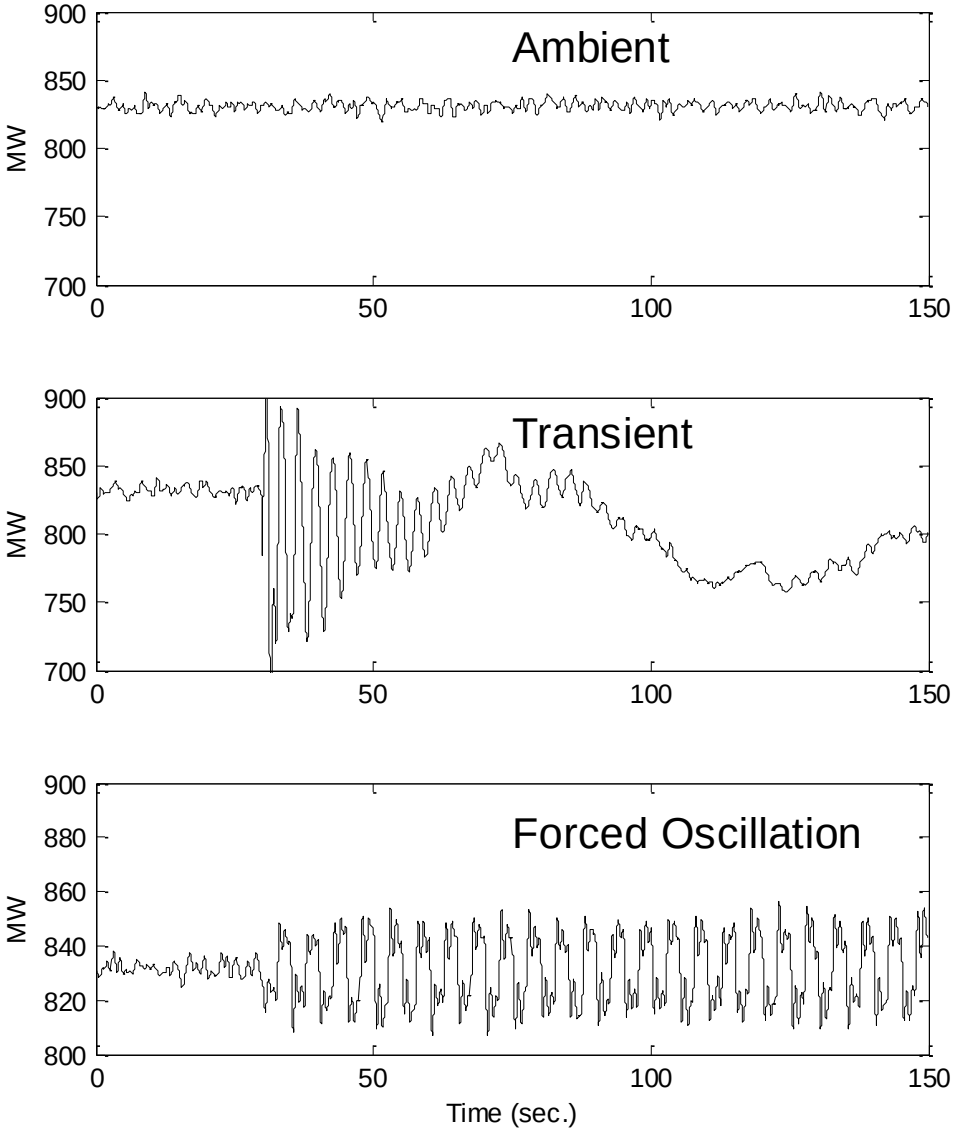
Gen	Angle($u_{i,k}$) (degrees)	$\lvert u_{i,k} \rvert$ (relative)
3	-180	1.00
4	-180	0.84
1	0	0.42
2	0	0.31

Background - Damping



Dynamic Response Types



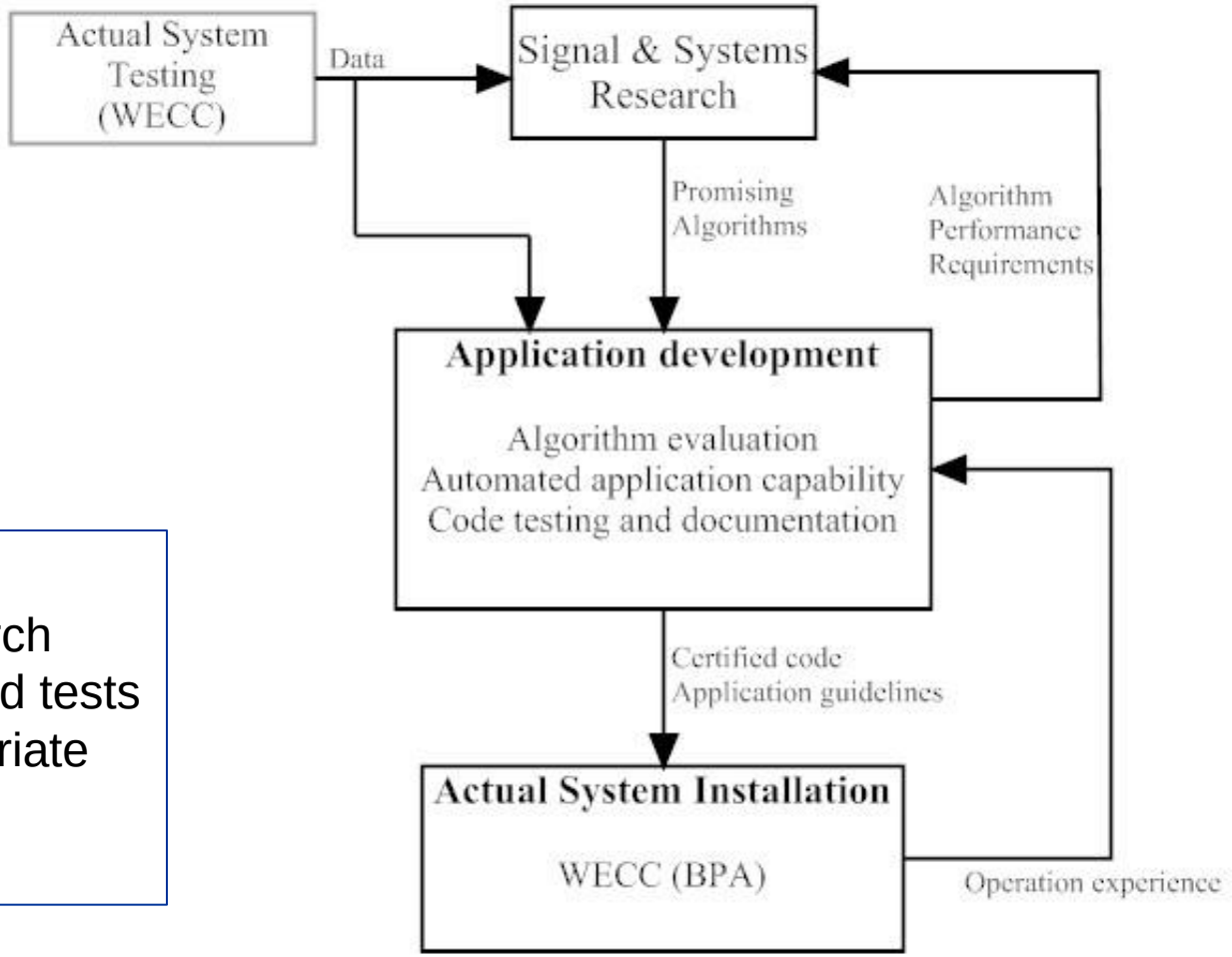


Algorithm Classes

- Oscillation Detector (OD): Estimates RMS Energy in specified frequency band.
  - Very fast
  - Very robust
  - Operations and Engineering tool
- Mode Meter (MM): Estimates a mode's frequency, damping, and shape. [1].
  - Requires minutes of data under ambient conditions
  - Requires seconds of data under transient
  - Robust
  - 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. [1].
  - Only works on transient data, requires seconds of data.
  - Not robust. Easy to fool (e.g., multiple switchings)
  - Engineering tool

[1] IEEE/PES Task Force on Electromechanical Mode Estimation

Research Approach



Tasks:

1. Signal processing research
2. Conduct and analyze field tests
3. Develop and test appropriate automated code

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 (SYSFIT) methods for estimating modes
  - Evaluated “FFT” algorithms
  - R3ML = Regularized Robust Recursive Maximum Likelihood
  - MTF = Multi-Channel Transfer Func. – simultaneous mode and shape
  - Simultaneous mode and forced oscillation methods
- Performance and Validation Indices
  - Confidence bound estimation (Bootstrapping) for YW, YWS, and N4SID.
  - Direct Confidence bounds from RML
  - Whiteness testing

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.
- Other
  - Magnitude and Phase Response Estimates Standard Deviation
  - RMS Energy filtering

Accomplishments to Date
Application Development
Red = Current or past

- Expert system applications (patent pending)
  - Developed expert system frameworks
  - Conducted study to map bootstrapping to confidence estimates of modes.
  - “Results Selection” algorithm for selecting from multiple mode-meter solutions
  - Pseudo signals to improve Mode Meter accuracy
  - Determined under what conditions each algorithm provides the best results (Monte Carlo and 2009 probing tests).
    - To be expanded to 2011 and 2012 probing tests.

Accomplishments to Date

Application Development

Red = Current or past year

- Supported EPG's code implementation
- Installed prototype mode-meter at BPA for 2010-12 operating season
- Installed prototype Ringdown estimator at BPA for 2011-12 operating season

Accomplishments to Date
WECC Probing Tests

Red = Current or past year

- Goal: evaluate and test algorithms and concepts on real-life data
  - Designed methodology to construct multi-sine optimized PDCI probing signals
  - Supported and analyzed Aug. 2006, Aug. 2008 tests
  - Supported and analyzed 2009 season tests (14 tests)
  - Supported and analyzed 2011 season tests (16 tests)
  - Analyzed effects of probing on mode-meter performance
  - Currently conducting 2012 season tests

Forced Oscillations

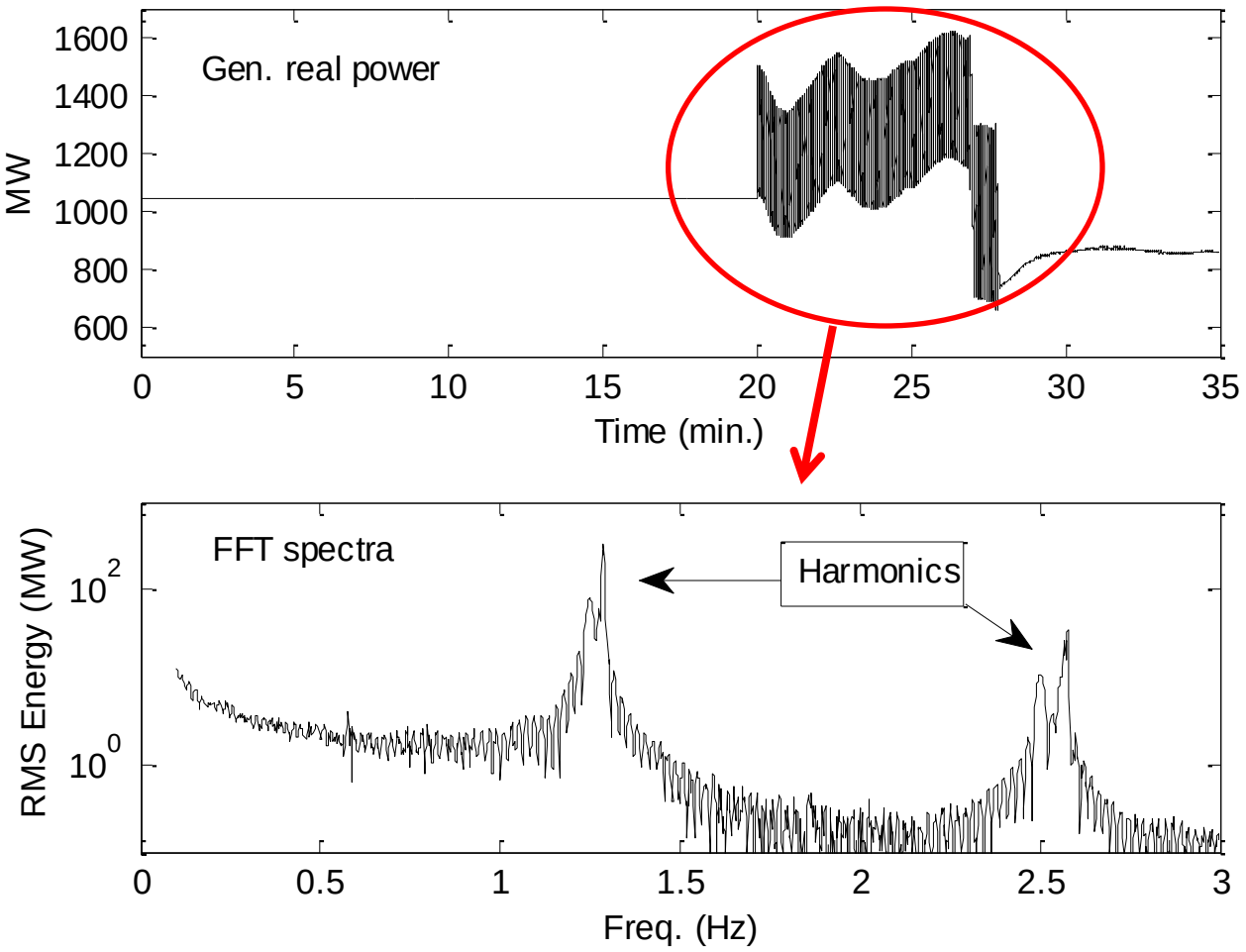
- Many causes, e.g.:
  - Generator rogue controller in limit cycle
  - Pulsing loads
- NOT A SYSTEM INSTABILITY
- Forced oscillations very common
- Can be very severe: November 30, 2005
- Fundamental Goals: Develop signal processing algorithms that
  - Identify forced oscillations and distinguish them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

Forced Oscillations (FOs)

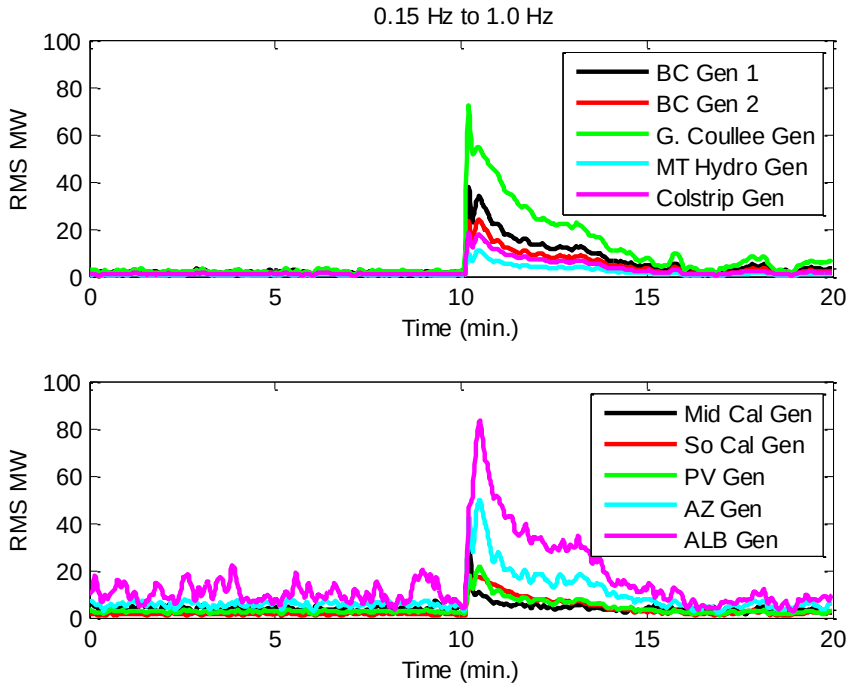
Fundamental Knowledge (On-going research)

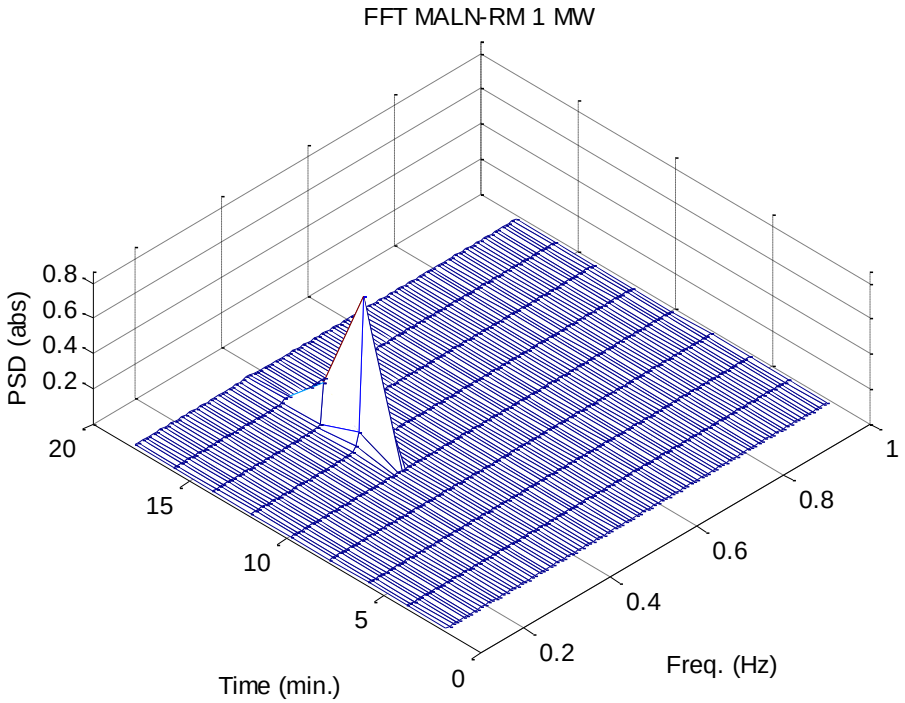
- Research Questions
  - What are the fundamental causes?
    - Generator controls and loads.
    - Real power vs reactive power.
    - Pole slipping.
  - How do FOs propagate thru the system?
    - Voltage vs Current.
- Study approach
  - Fundamental systems analysis.
  - miniWECC simulation and analysis.
- What we're learning
  - FOs typically are harmonic with common shape.
  - FO magnitude points to source.
  - Voltage/Current points to source.

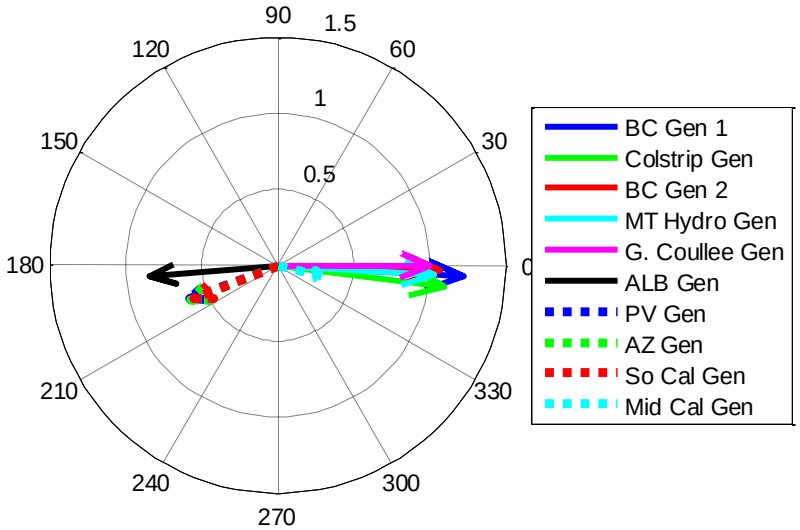
2010 WECC Example



Example System Event



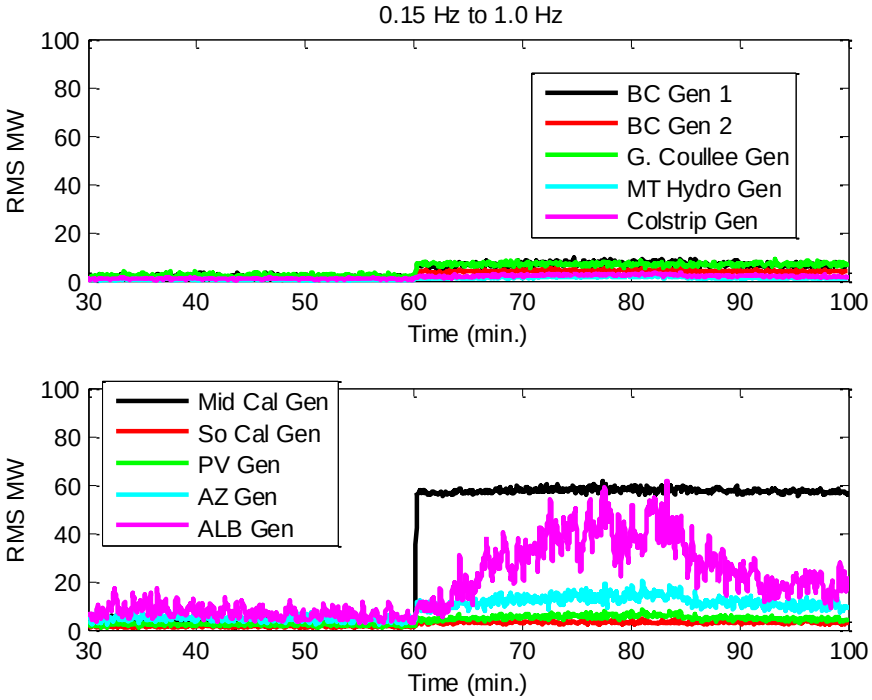


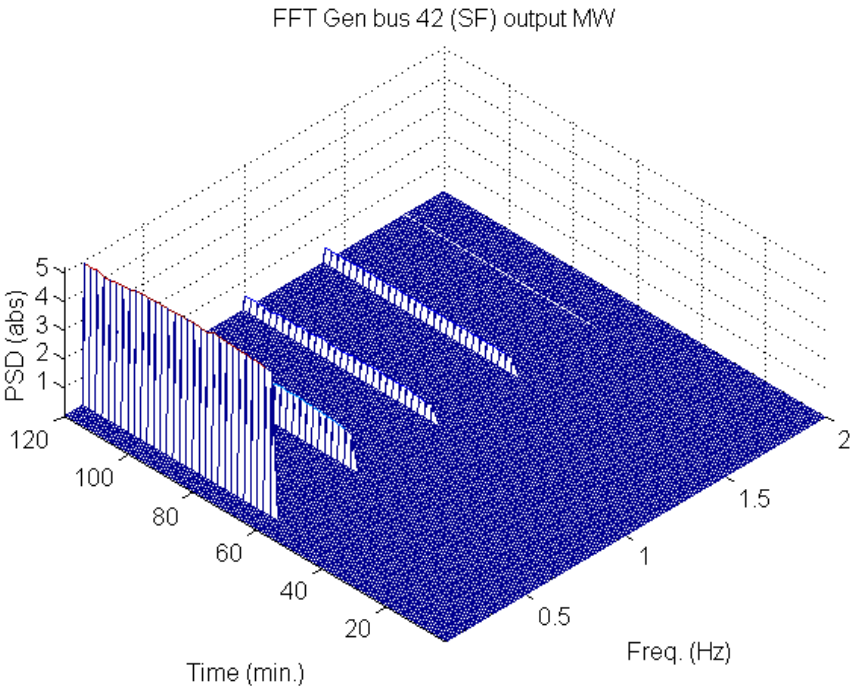


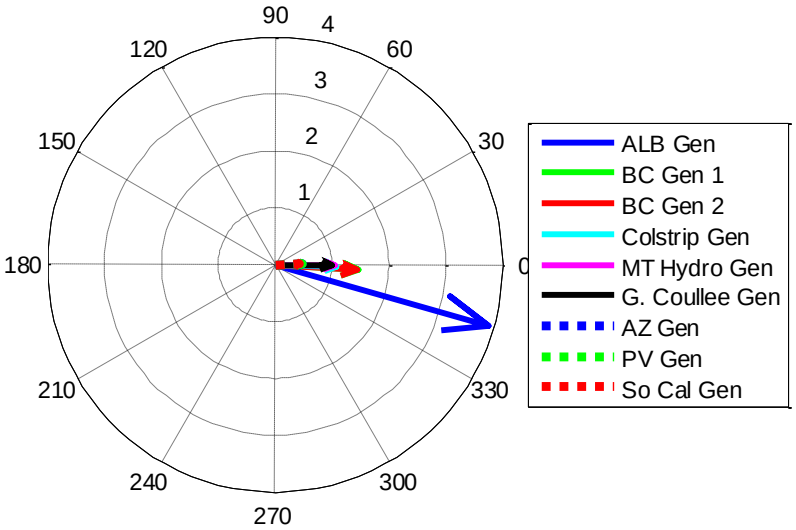
Observations

- OD and SE indicates wide-spread oscillation matching a known system mode.
- Shape matches mode baseline.

Example Forced Oscillation







Observation

- SE contains harmonics
- OD and SE dominated by one generator site indicating FO source
- Shape is unique to a FO

Simultaneous Mode and FO Estimation

- Traditional Mode Meters greatly underestimate the mode damping and do not estimate the forced oscillation.
- New Mode Meter algorithm more accurately estimates the mode and forced oscillation simultaneously (patent pending).

Example Simulation

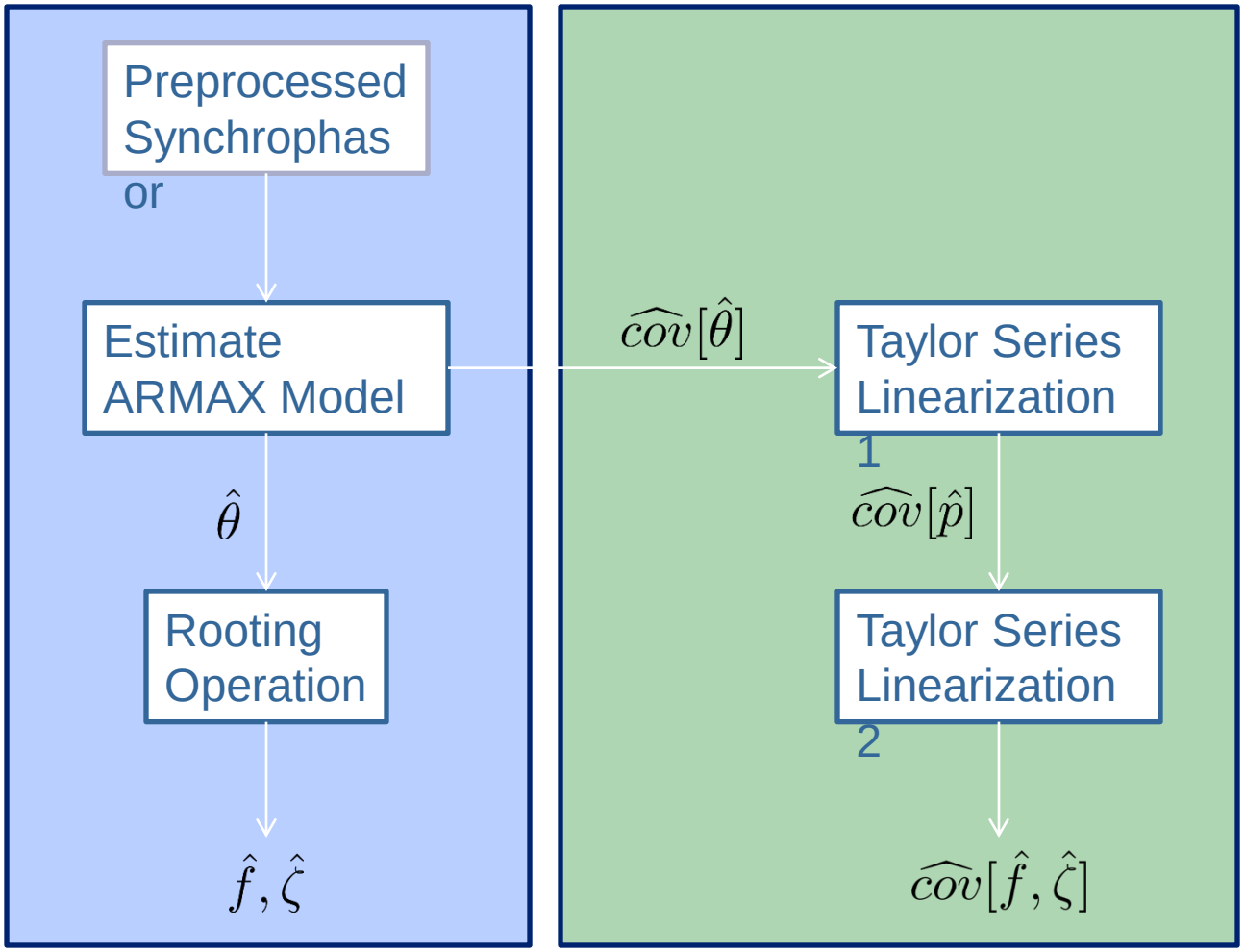
- Alberta Mode: 0.372 Hz, 4.67%
- Forced oscillation via generator limit-cycle (0.37 Hz, 0.2 MW)

	Frequency	Damping Ratio
True Mode	0.372 Hz	4.67 %
Traditional Mode Meter	0.370 Hz	0.83 %
New Mode Meter	0.373 Hz	4.19 %

Recursive Maximum Likelihood (RML) with Error Bounds

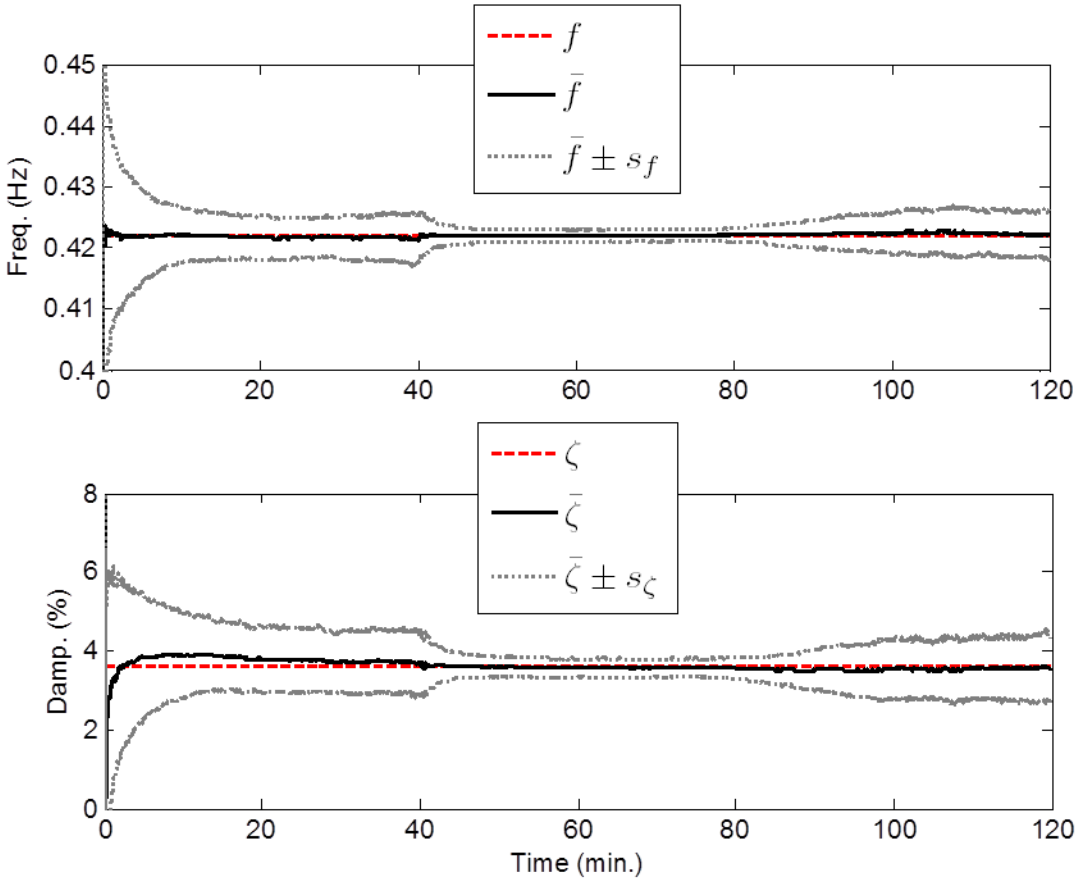
- Algorithm that
  - estimates mode frequency and damping
  - directly estimates mode variance
- Present to operator a near real-time estimate of mode with error bounds
  - Estimate of confidence in the mode estimates
- Note on Speed! Designed to replace bootstrapping for use in online real-time environment

RML with Error Bounds



RML with Error Bounds – Simulation Results

- 500 Monte Carlo Trials
- Probing from 40 to 70 minutes
- True values in RED
- Mean and region of one standard deviation given
- Mean lines up with true
- Standard deviation is low



RD&D Stage

Project has components ranging from Theoretical Study to Pre-commercial. For example:

- Theoretical Study:
  - Signal processing research.
  - Forced oscillations research.
- Prototype/Field Demonstration
  - Real-time testing at BPA for Mode Meter and Ringdown Estimation
- Pre-commercial
  - WISP project – Developing production-grade software to be integrated with commercial vendors and installed in control centers in WECC.
    - YW, R3LS, Mode-Meter Expert System
    - Spectral Estimation
    - Oscillation Detection

FY12/13 Plans

- Continue fundamental signal processing research
  - Continue focus on fundamental understanding of forced oscillations
  - Continue testing methods for forced oscillation ID
  - Continue focus on performance and validation indices
- Continue to support WECC probing tests
- Continue application development
  - Automated expert system use

Testimonials since 2006

- ~40 publications in peer-reviewed journals and proceedings.
  - 2009 *IEEE PES Power System Dynamic Performance Committee's* prize paper.
- Two patents pending.
- Helped organize/conduct IEEE Task Force (special publication).
- WISP development project.

Questions?