WASHINGTON STATE UNIVERSITY

PSERC

Oscillation Monitoring System

Mani V. Venkatasubramanian

Washington State University

PSERC S29 Project Tele-seminar

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Overview of S29 project

- S19 project from June 2002 to May 2005
- S29 project from June 2006 to July 2008
- Detection, Prevention and Mitigation of Cascading Events
- Three tasks:
  - Task I: Detection: Mladen, Texas A&M
    - Advanced warning
  - Task II: Prevention: Mani, Wash. State
    - Wide-area monitoring and controls
  - Task III: Mitigation: Vijay, Iowa State/ASU
    - Adaptive islanding
- S29 Focus on Prototype Implementations

Task II: Mitigation

- Implementation of Wide-area Small-signal Stability controller, Wash. State University
- Two subtasks:
  - Reliable Oscillation detection:
    - Multi-input Prony, Matrix Pencil and HTLS algorithms
    - Rules for real-time analysis of data
    - Noise? Linear versus nonlinear? Switching events?
  - Real-time design of damping controls:
    - Which control to trigger? What design?
    - Not part of the prototype testing

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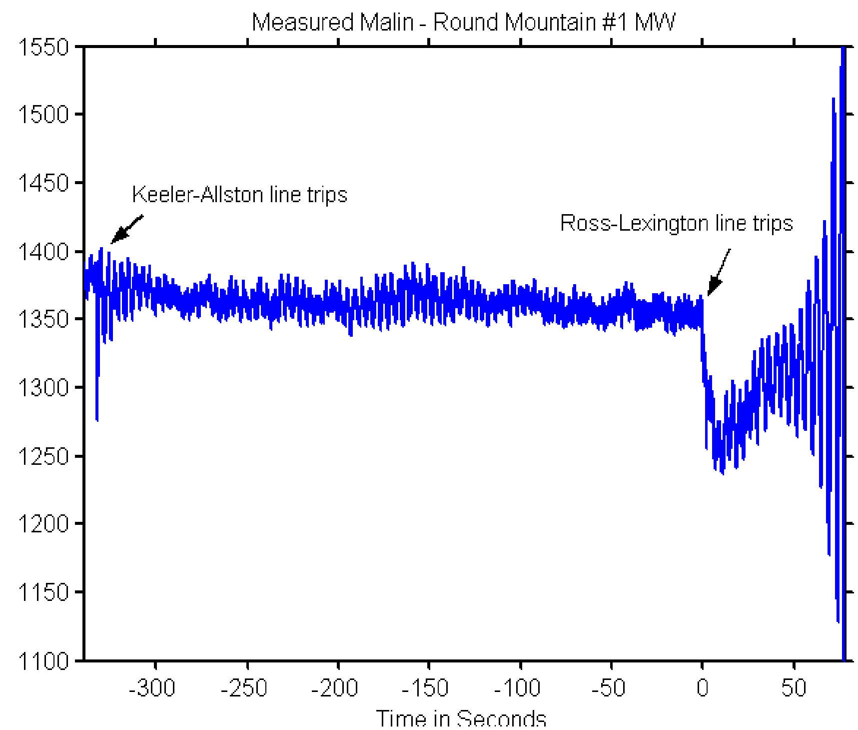
Problem Overview

- Low frequency electromechanical oscillations
  - Local or inter-area oscillations
  - Insufficient damping
  - Example - Aug 10, 1996 WECC blackout
- Detection and control of small signal stability problem in power systems
- Research supported by PSERC, TVA, Entergy, BPA and EPG (CERTS)

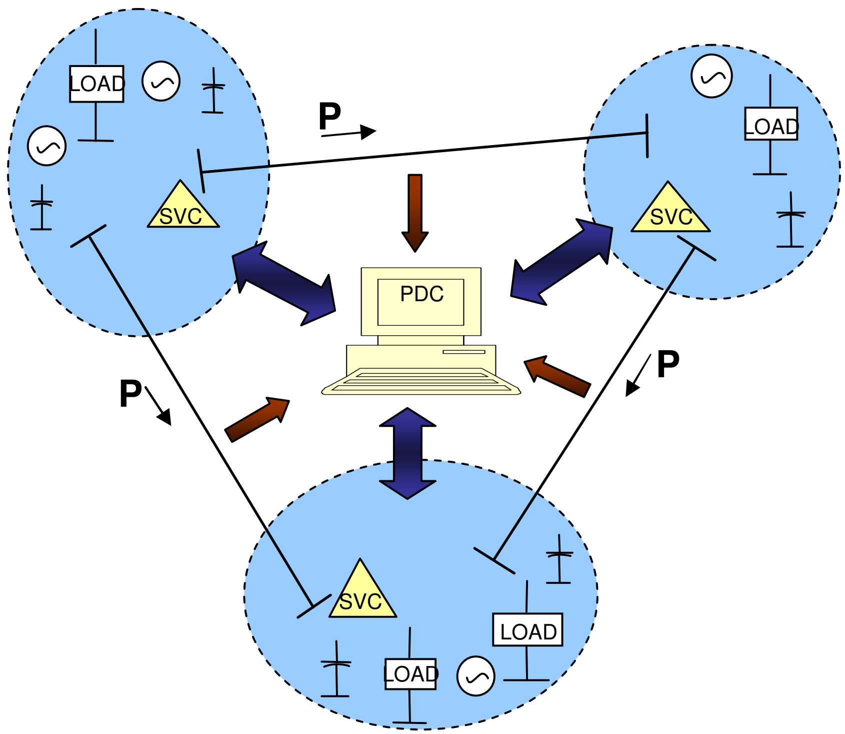


Task II Project Team

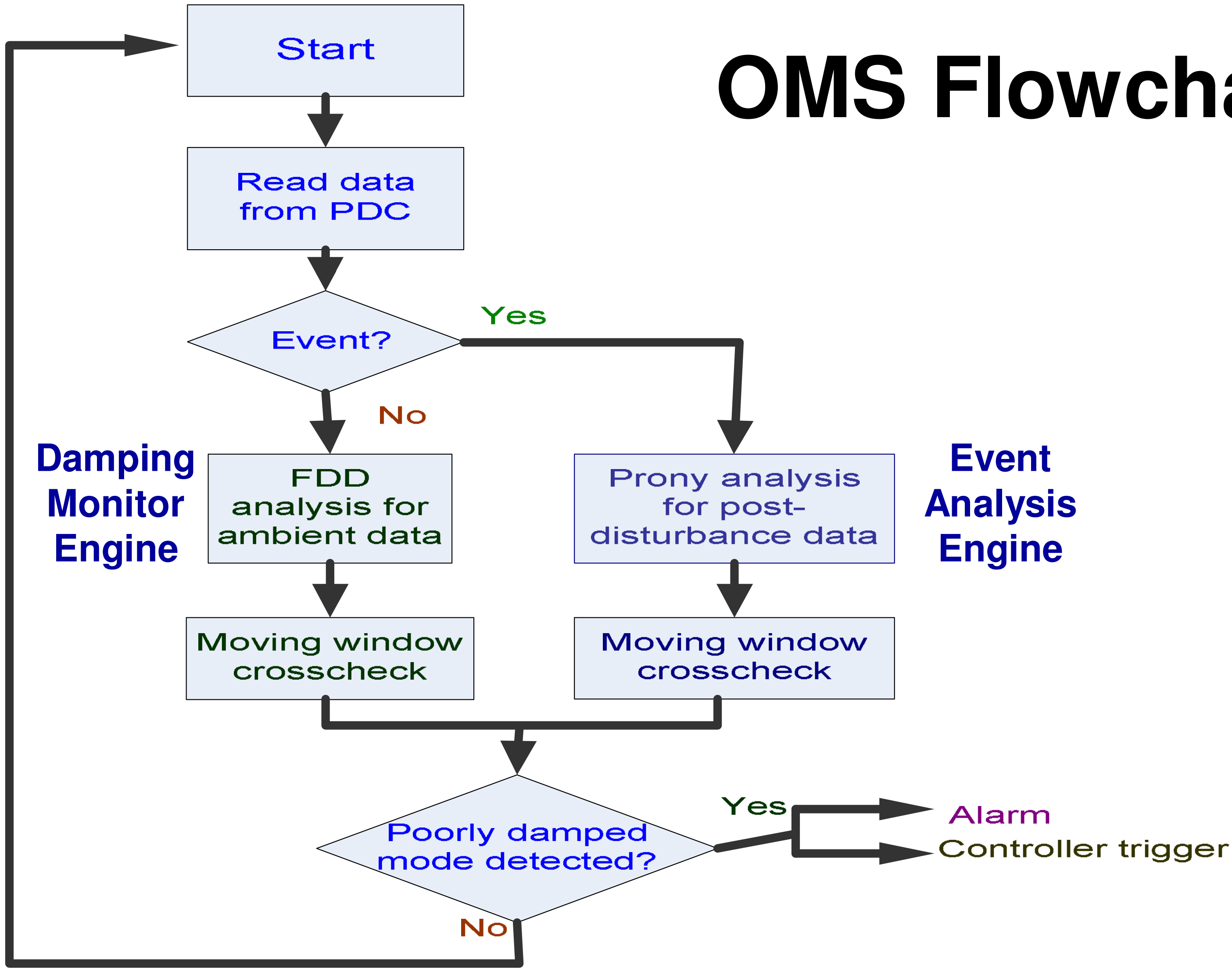
- WSU:
  - Guoping Liu, Qiang Zhang, Jaime Quintero, Mani V. Venkatasubramanian
- TVA:
  - Ritchie Carroll, Gary Kobet, Lisa Beard
- Entergy:
- Floyd Galvan, Sujit Mandal, Sharma Kolluri
- BPA:
  - Bill Mittelstadt, Dmitry Kosterev
- EPG:
  - Manu Parashar

Oscillation Monitoring System (OMS)

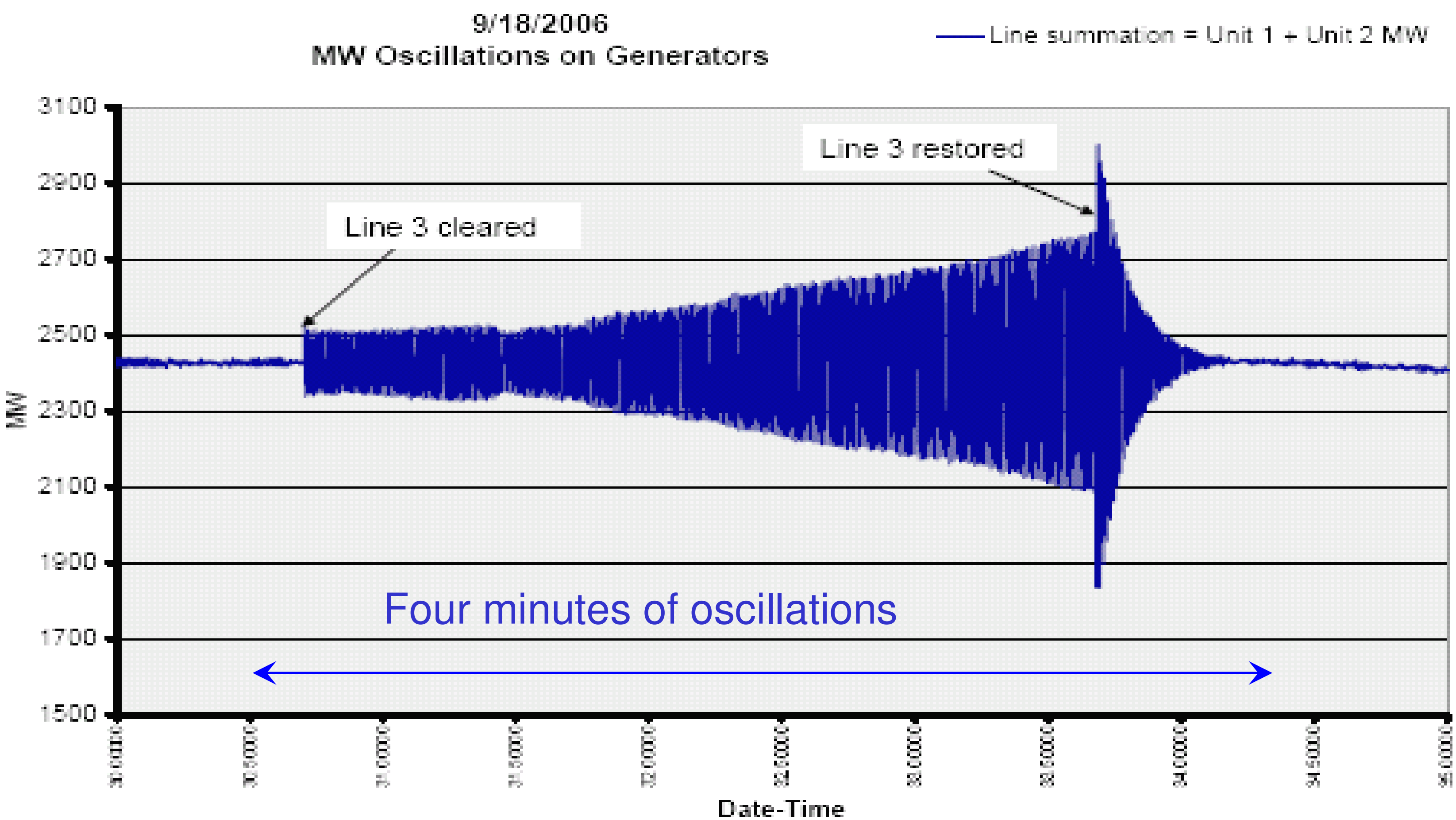
- Goal of Oscillation Monitoring System (OMS)
  - Early detection of poorly damped oscillations as they appear
  - Trigger warning or control signals
- OMS is made possible by Wide Area PMU Measurements
  - Growing numbers of PMUs across the power grid
  - Fast algorithms available for online measurements
  - Rule based automatic analysis of PMU measurements
  - Prototype implementation at TVA



OMS Flowchart



TVA Cumberland event



Source: Gary Kobet/TVA

TVA Cumberland Event

- **Recent oscillatory event at TVA:**
  - Oscillations at Cumberland plant 9/18/2006
  - PMU recordings enabled the analysis
  - Local 1.2 Hz mode changed from +1.5% damping to –0.2% damping and back to +1.5% damping during the event
  - PSS installed at the plant subsequently
  - PMU based real-time alarm coded by TVA into TVA PDC as back-up measure – uses standard deviation thresholds – plant operators to reduce MW output when alarm received.

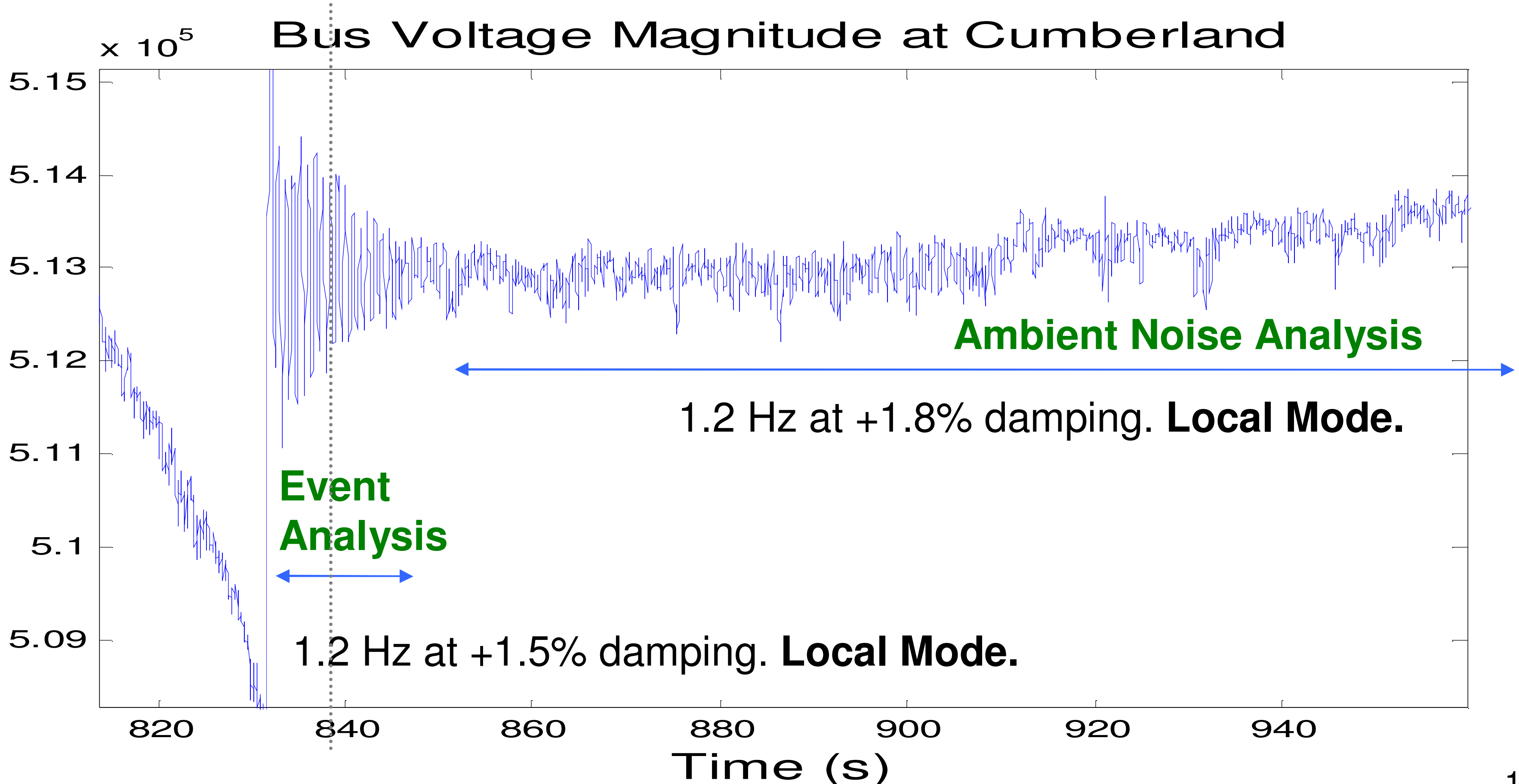
Oscillation Monitoring System

- Software Engines built into TVA PDC
- Real-time streaming data input to the engines
- Fast detection of poorly damped oscillatory modes: mode frequency, damping and mode shape
- Multiple algorithms integrated by expert system like rules
- Focus on Redundancy and Reliability

OMS Engines

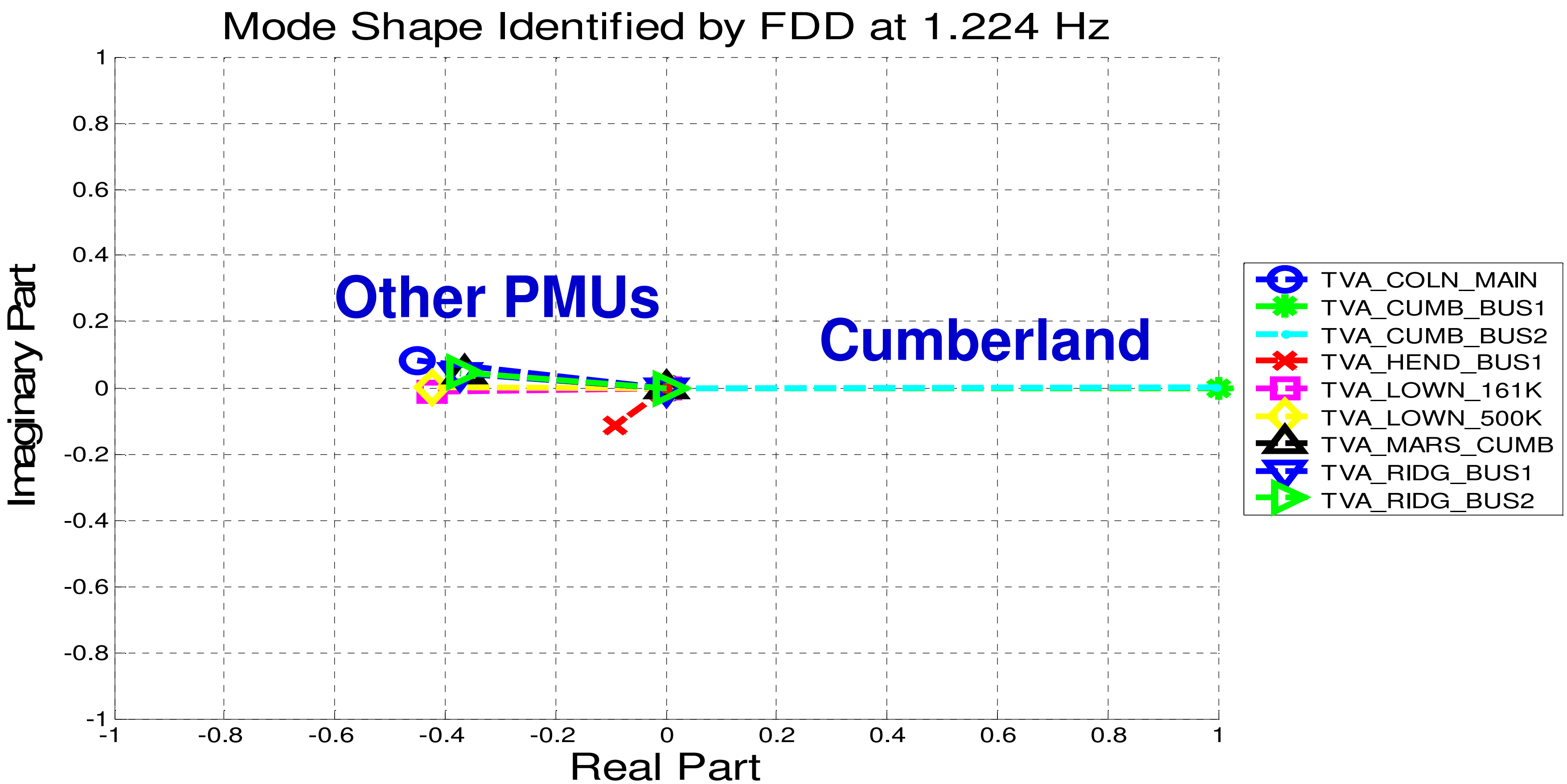
- Event Analysis Engine
  - Automated Prony type analysis of oscillatory ringdown responses
  - *Five seconds* of PMU data analyzed every *one second*
- Damping Monitor Engine
  - Automated analysis of ambient noise data
  - *Three minutes* of PMU data analyzed every *ten seconds*
  - Provisional Patent application filed by WSU

Results from Two Engines



Nov. 29th 2007 TVA event

Mode Shape – Local Mode



Cumberland oscillating against rest of system

Basics of Prony Analysis

$$\dot{x} = A\,x + B\,u$$
$$y = C\,x + D\,u$$

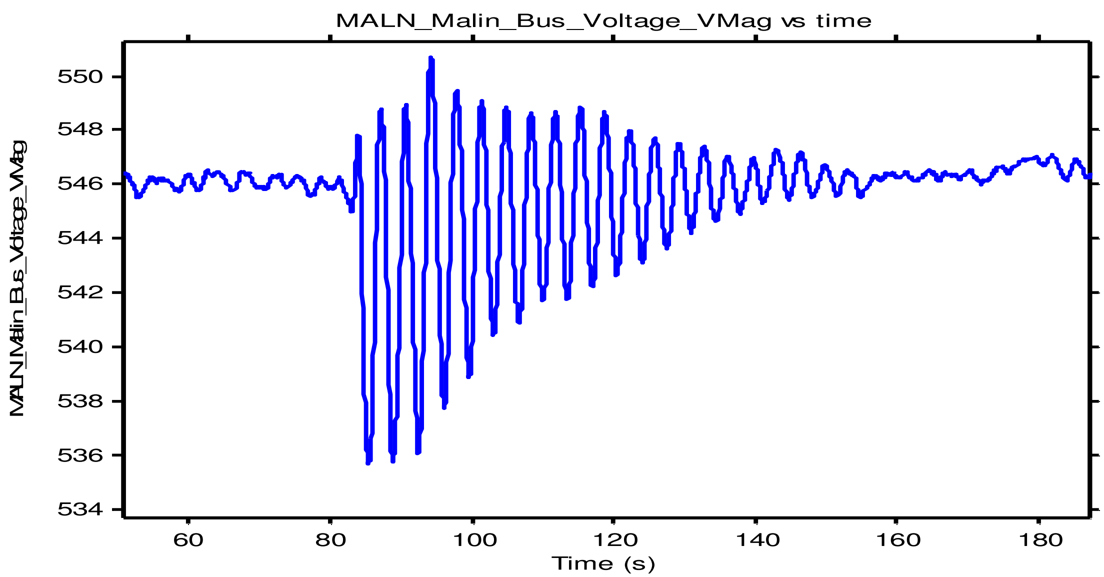
$$y_i(t) = \sum_j c_{ij} e^{-\zeta_j \omega_{nj} t} \cos(\omega_{dj} t - \varphi_j) + \sum_j c_{ij} e^{-a_j t}$$

- Assumptions: Linear Time-Invariant System, Distinct Eigenvalues, Step changes in input, …
- Any output is a linear combination of fundamental modal responses
- Well-suited for Prony type curve fitting methods. Estimate oscillatory frequency, damping ratio and mode shape.
- Estimates should be consistent:
    - **Moving time-windows (Linearity of responses)**
    - **Different groupings of outputs (Superposition)**

Power System Prony Analysis

- Nonlinear Large Scale System
- In theory, Prony Analysis works well for analyzing "Small-disturbance responses"
- Nonlinearity dominant just after large disturbances
- Switching of lines and cap banks in the middle of analysis windows
- Noise effect on results if disturbance "fades away"
- How to get reliable estimation automatically?

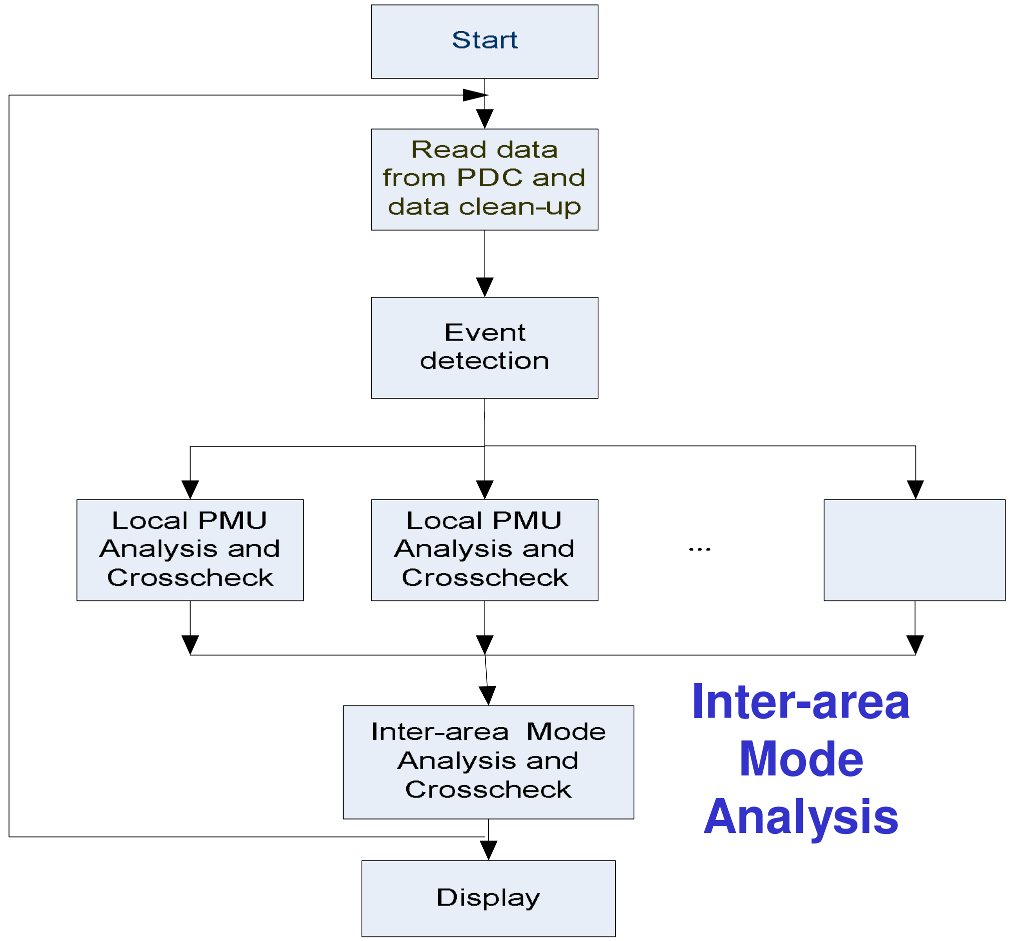
Rules for Real-time Prony Analysis



Three types of Consistency Crosscheck rules

- Different Curve-fitting Methods (Redundancy)
- Different Signal Groups (Superposition)
- Moving Window Analysis (Linearity of Reponses)

Event Analysis Engine



Local PMU Analysis

Inter-area Mode Analysis

Local PMU Analysis

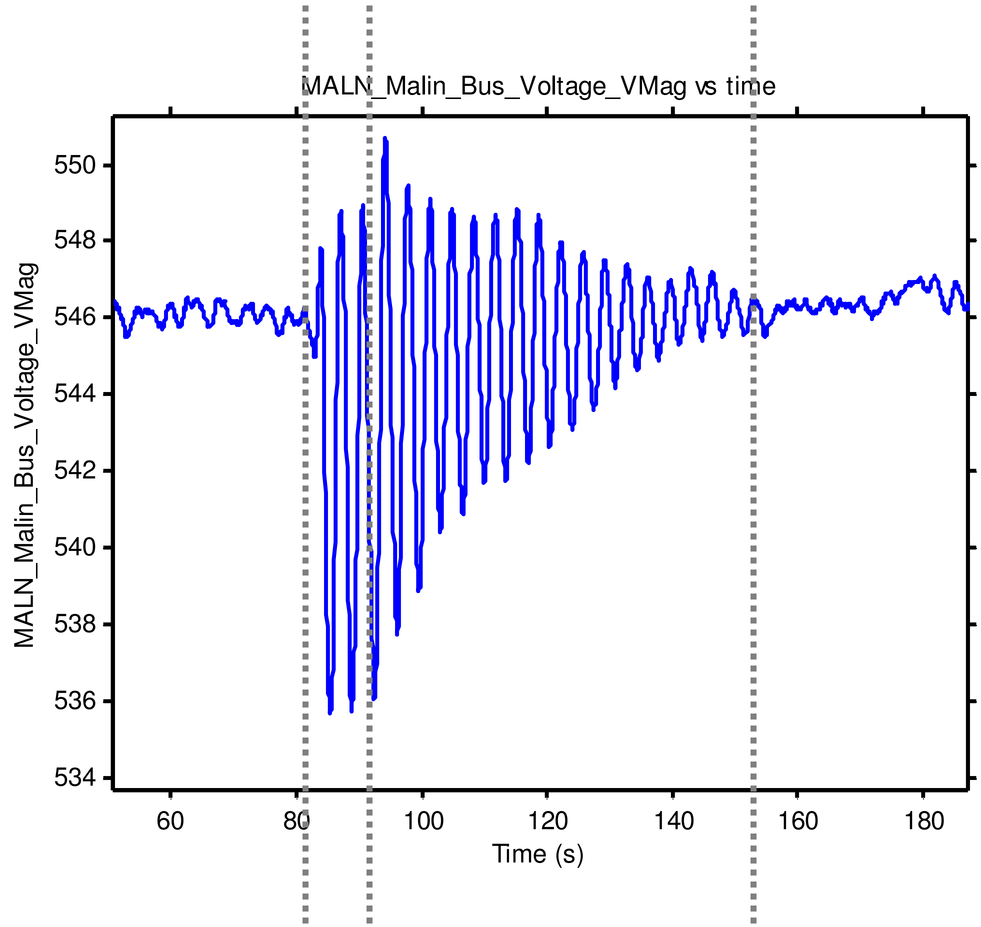
- Signals from one PMU used at a time
- Parallel implementation of multiple PMU analysis
- Parallel implementation for multiple algorithms
- Check for consistency using rules:
  - Crosscheck results from Prony, Matrix Pencil and HTLS
  - Crosscheck results among moving time-windows

Interarea Mode Analysis

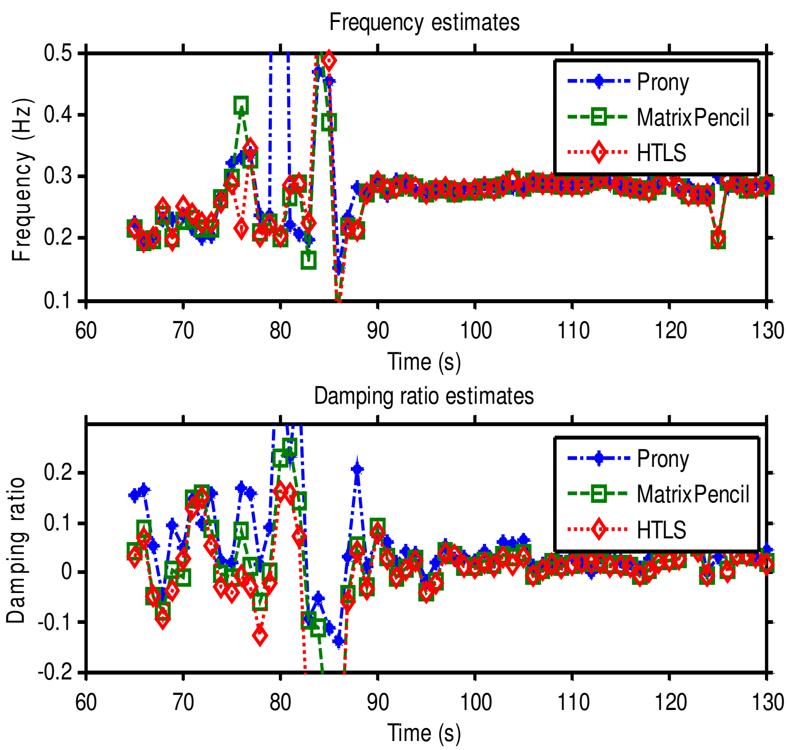
- Identify interarea modes and related PMUs from local analysis
- Grouping of signals from relevant multiple PMUs
- Check for consistency using three sets of rules:
  - Crosscheck results from Prony, Matrix Pencil and HTLS
  - Crosscheck results among moving time-windows
  - Crosscheck results from different groupings
- Parallel implementation for different interarea modes

Event Analysis – Inter-area Example

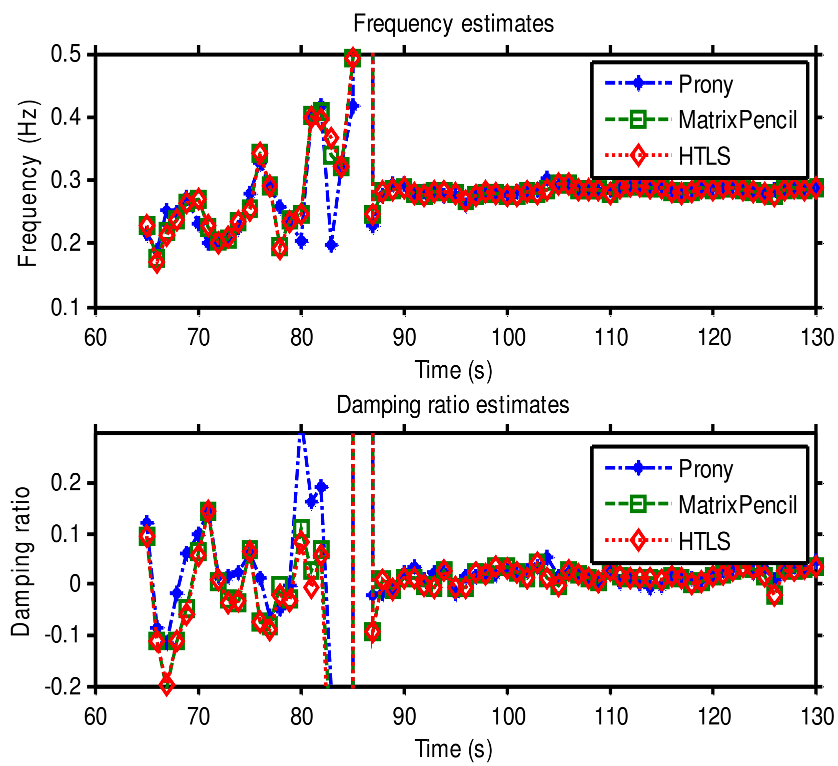
- WECC Aug. 4, 2000
- Alberta system separated at 19:56 GMT
- 0.27 Hz oscillation is poorly damped



Case Study 1 – Local PMU Analysis



Grand Coulee



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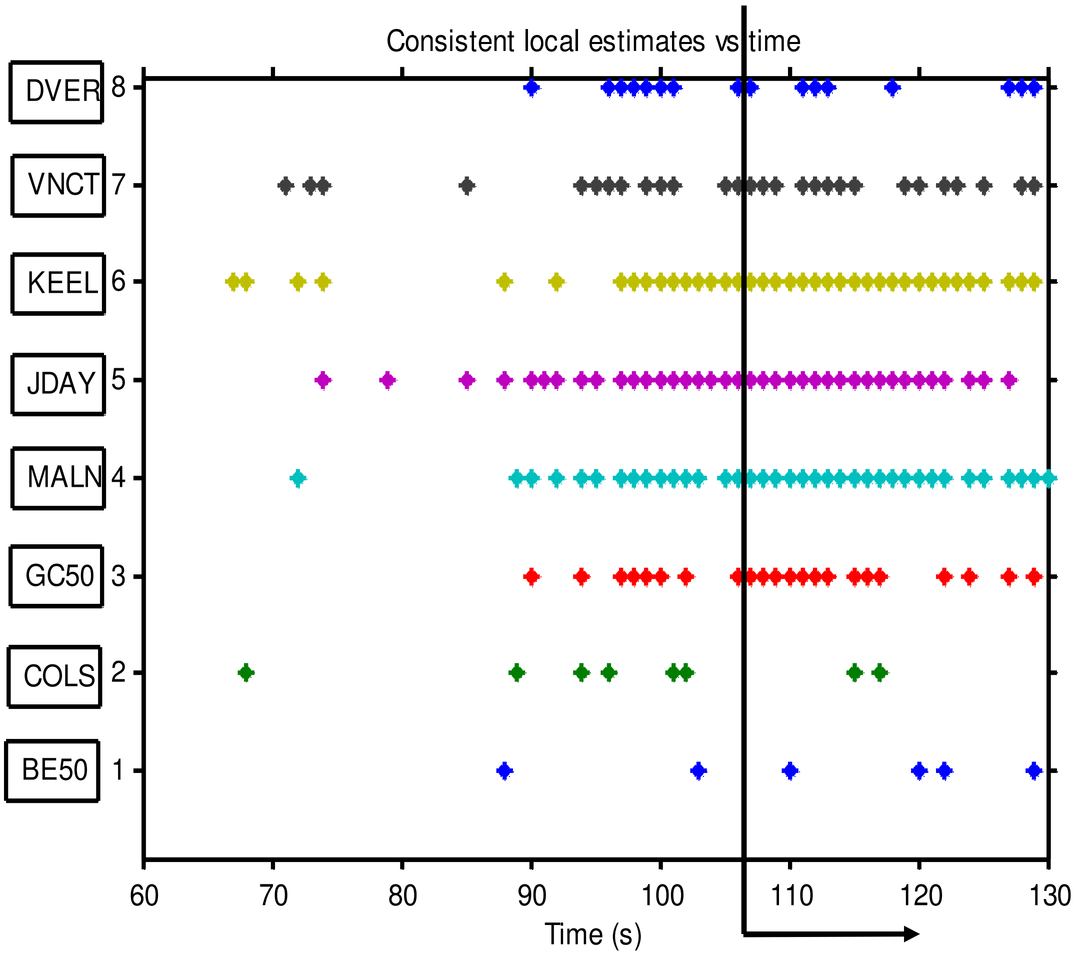
Inter-Area Oscillation Mode

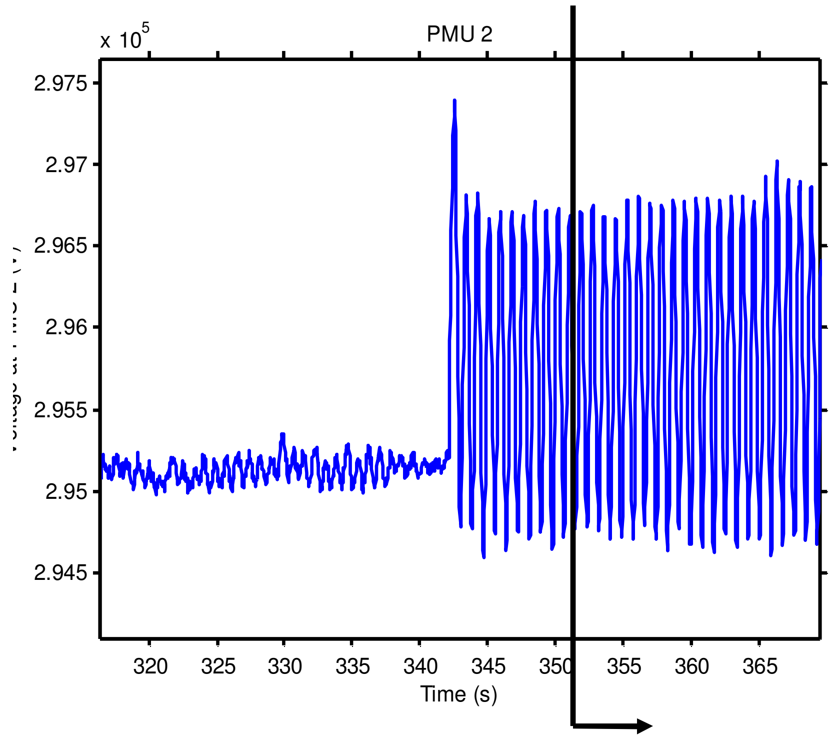


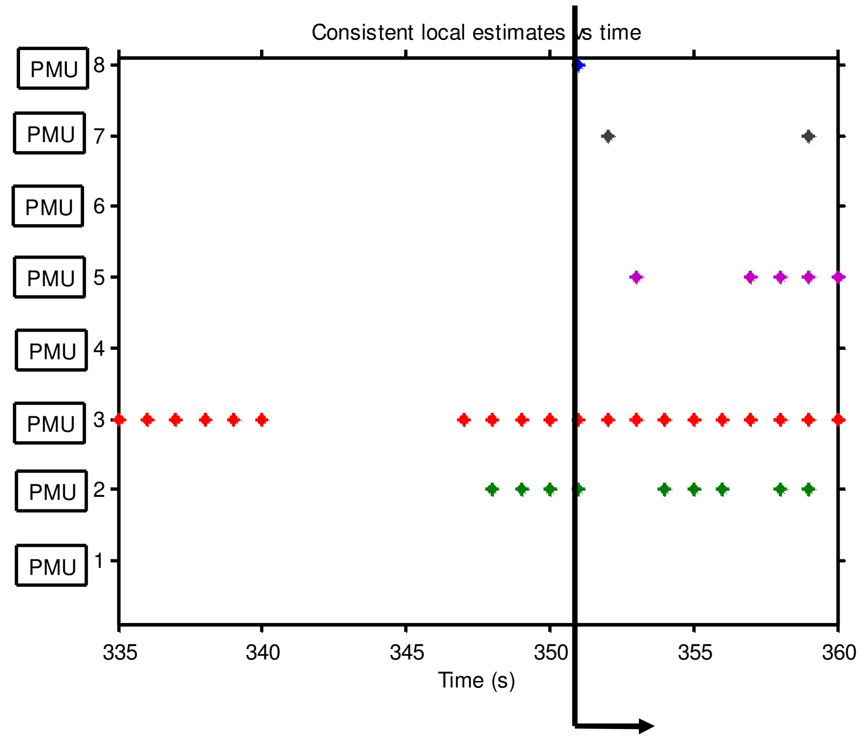
Consistent estimate at 106 sec

Oscillation frequency = 0.286 Hz

Mean damping ratio = +2.77%

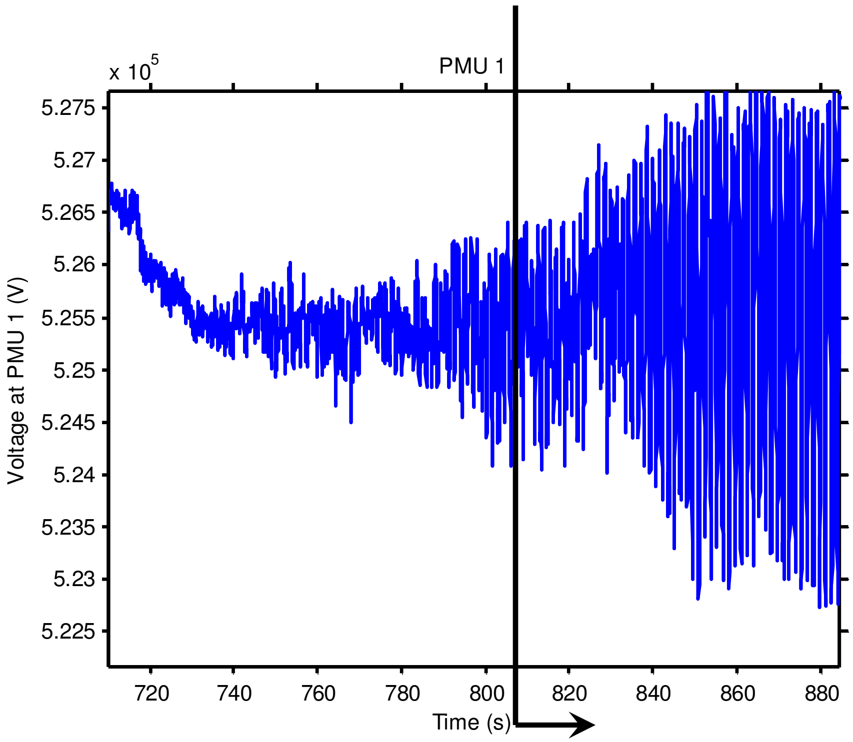
Event Monitor – Local Mode

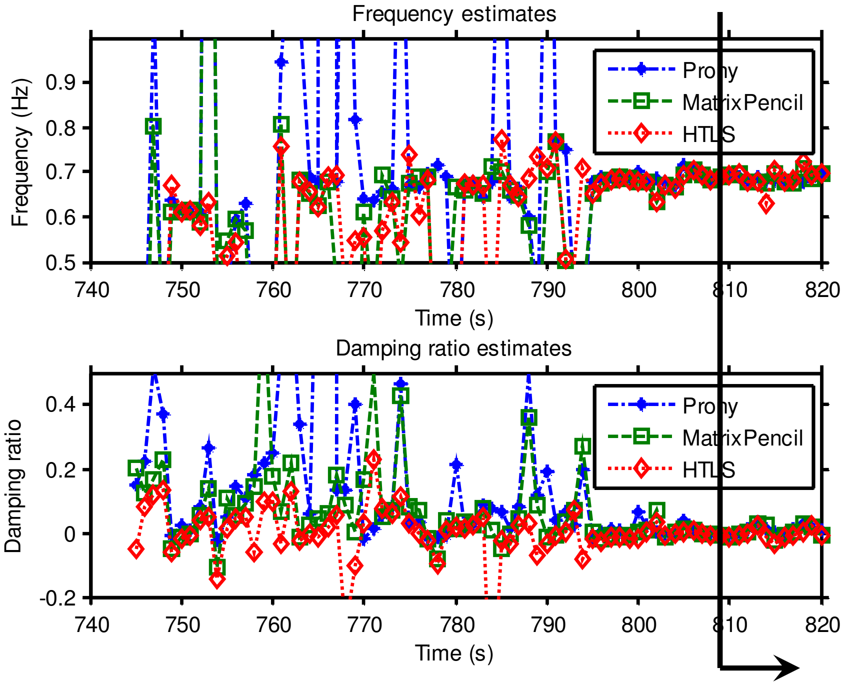




- Consistent estimate at +9 sec
- Frequency = 1.1785 Hz. Damping at 0.04%

Case Study 3 – Growing Oscillations





- Consistent estimate at 809 sec; Local mode.
- Frequency = 0.6930 Hz. Damping ratio = -0. 12%

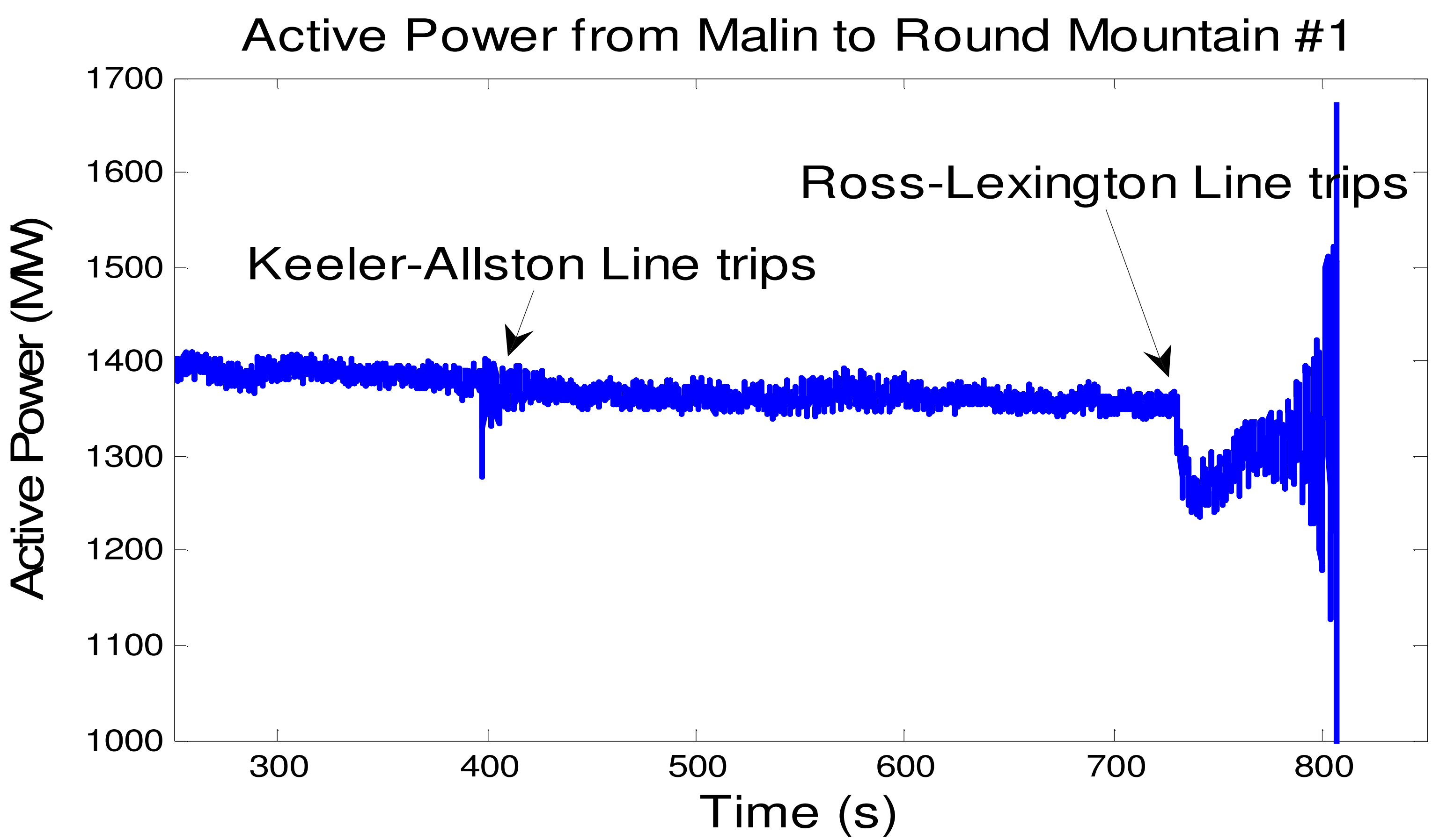
Damping Monitor Engine

- Frequency Domain Decomposition (FDD) algorithm proposed for off-line analysis in other areas
- Extended for real-time PMU analysis by Guoping
- Can detect damping ratio as well as mode shape of poorly damped oscillatory modes using short spans of ambient PMU data
- Mode shape information critical for correctly identifying problematic mode towards control actions
- Excellent results for modes with damping ratio up to +10%

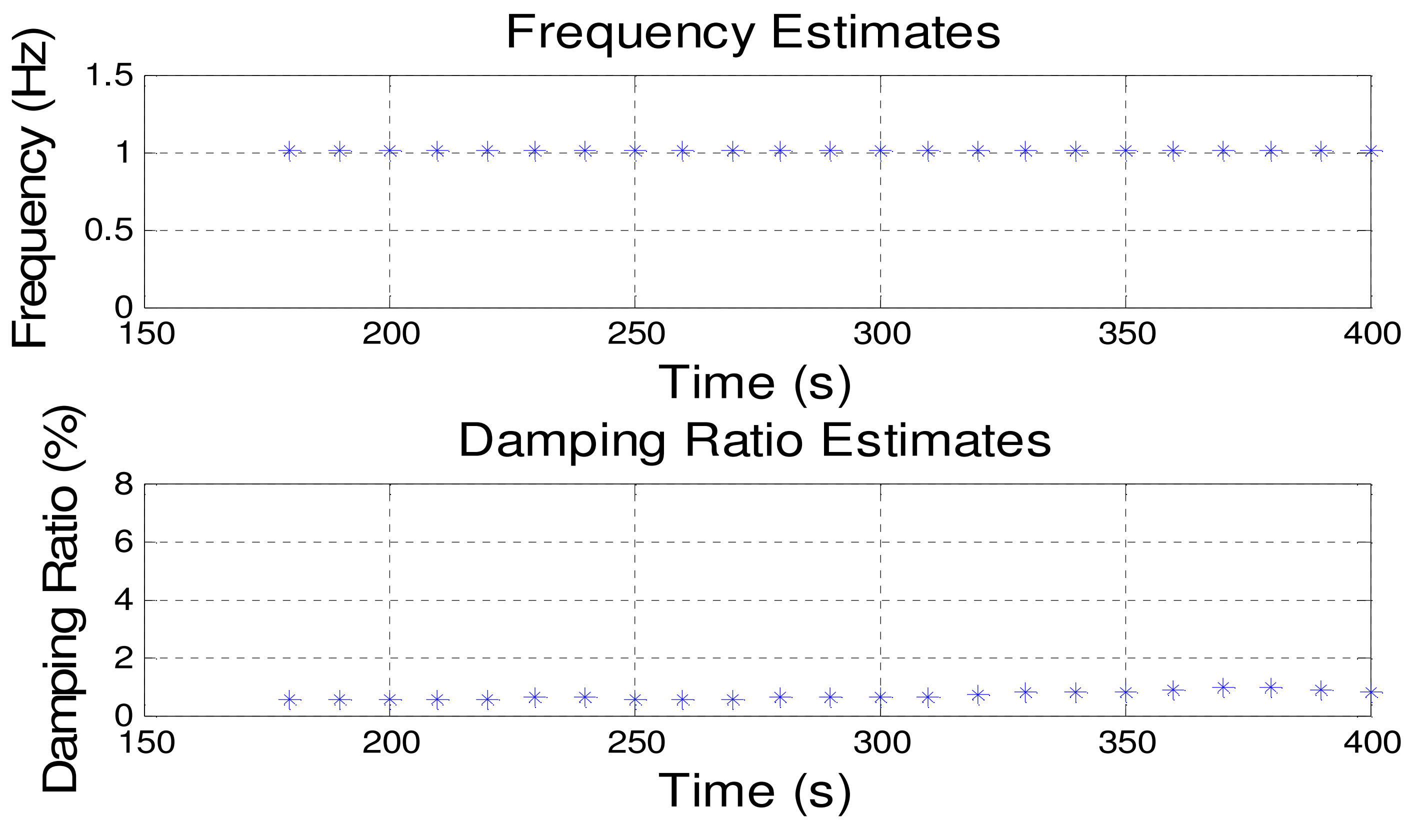
FDD for Ambient Analysis

- FFT and Power Spectra from multiple signals
- Clean up spectra using Singular Value Decomposition procedure near dominant modes
- Prony type damping analysis after Inverse FFT around dominant modes
- ISCAS 2008 paper
- **Simultaneous extraction** of mode damping and mode shape from ambient data

Example of Damping Monitor Engine



Before Keeler-Allston Trip



Dominant mode is McNary **local** mode

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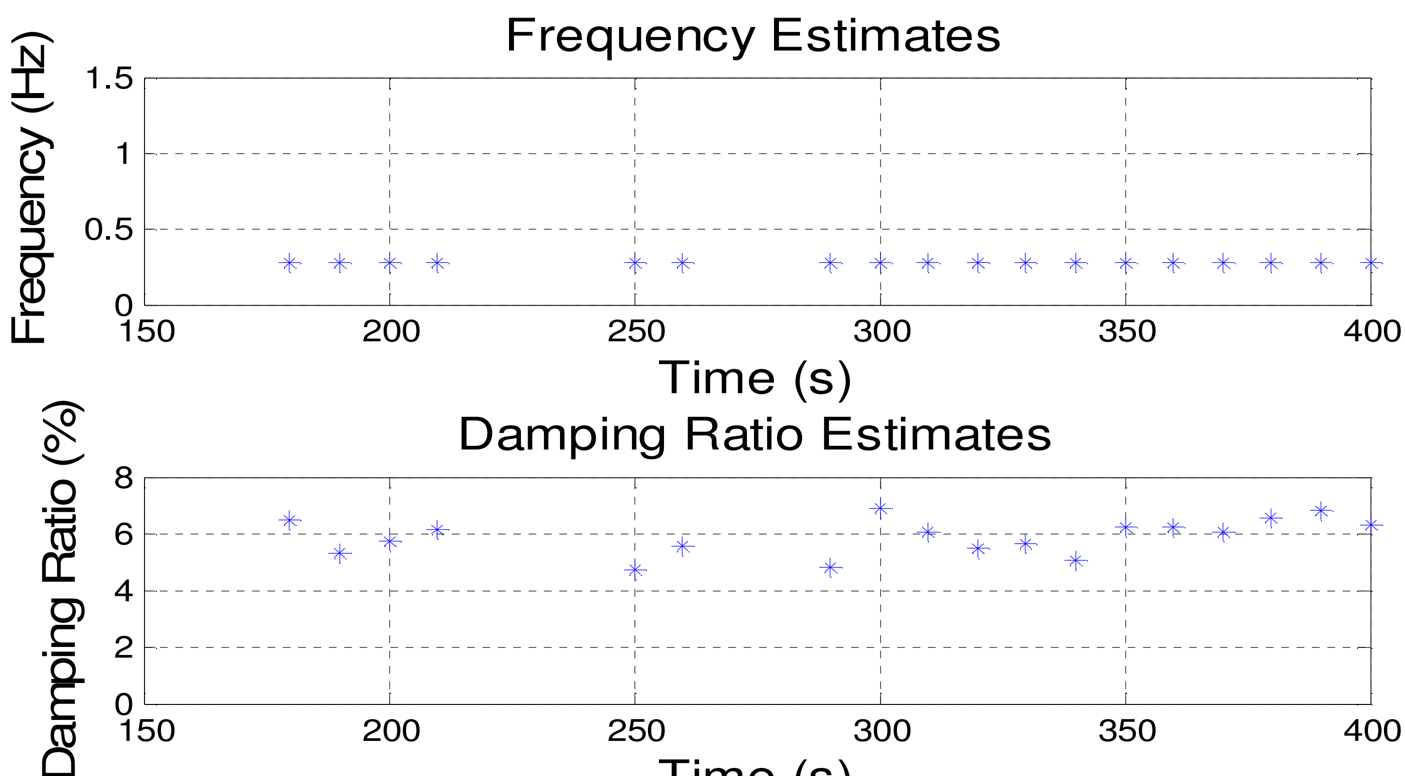
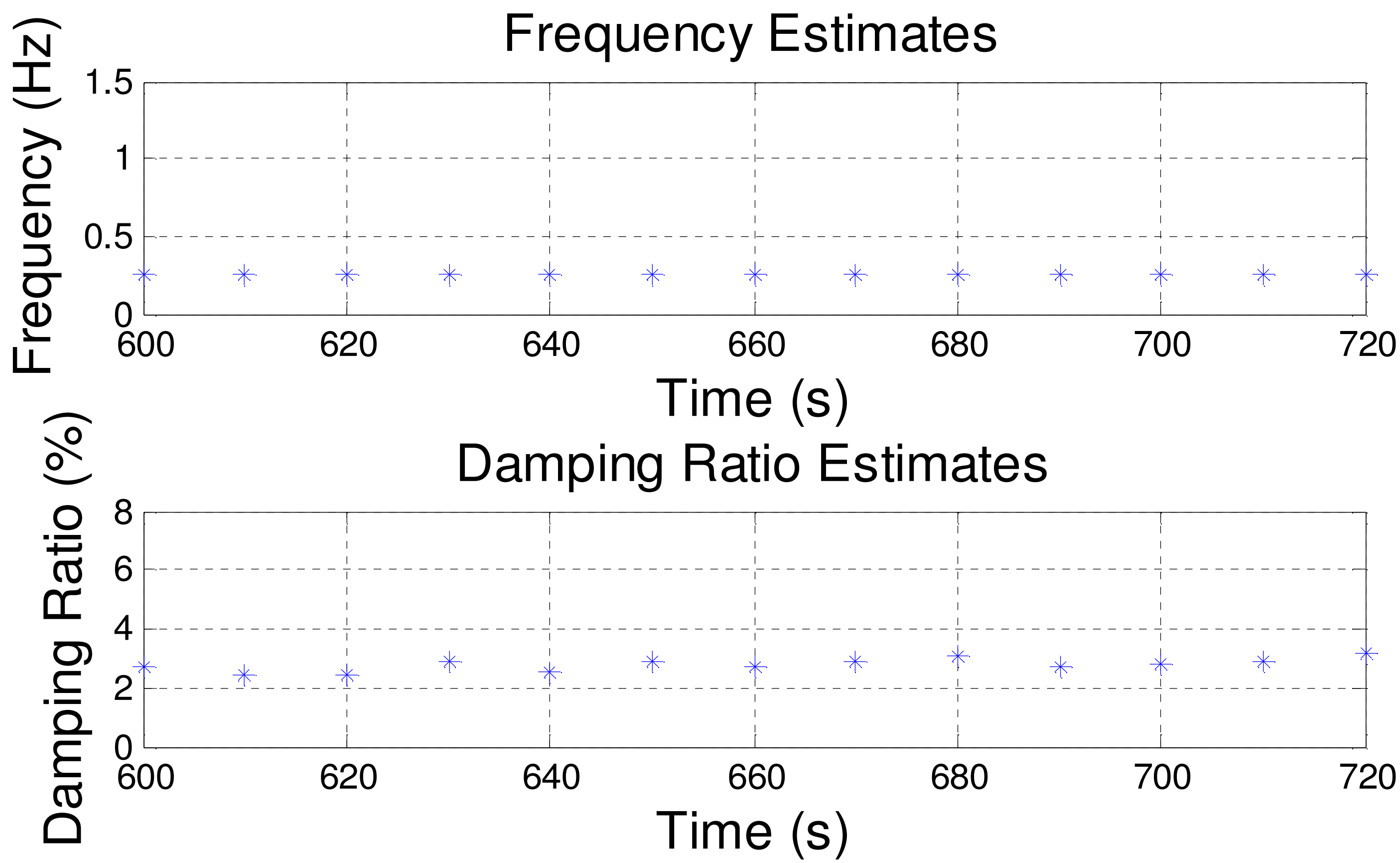
Before Keeler-Allston trip



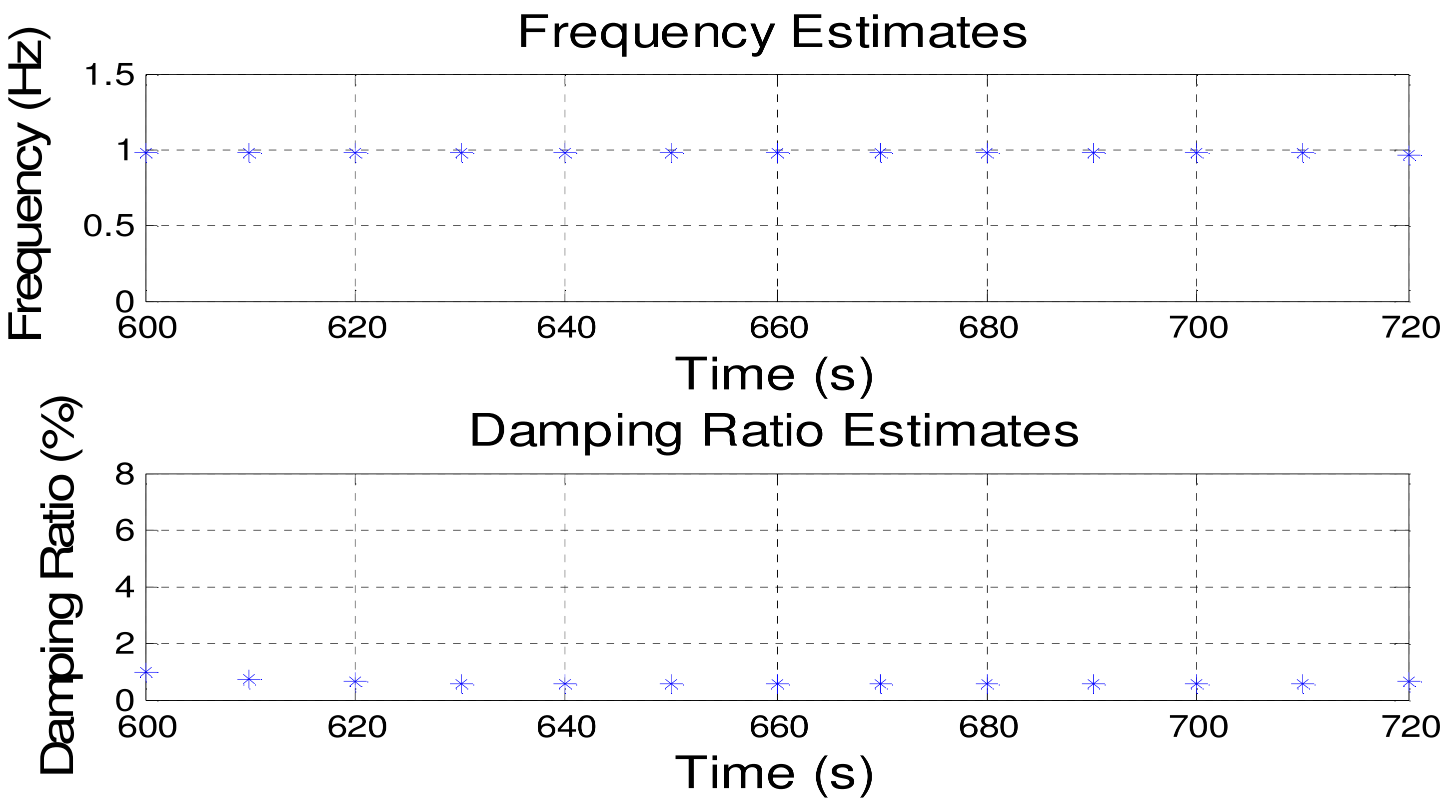
Second Dominant mode is COI **interarea** mode

After Allston-Keeler Trip



Dominant mode is COI **interarea** mode

After Keeler-Allston Trip



Second Dominant mode is McNary **local** mode

Complementary Engines

- Event Analysis Engine
  - Three algorithms: Prony, Matrix Pencil and Hankel Total Least Square. Crosscheck Rules.
  - Aimed at events resulting in sudden changes in damping
- Damping Monitor Engine
  - Ambient noise based. Continuous.
  - Frequency Domain Decomposition Algorithm. (Prony). Crosscheck Rules.
  - Provides early warning on poorly damped modes

Example of results for TVA

Damping history of 1.2 Hz mode	Event Analysis	Damping Monitor	PSS Status
Sept. 18, 2006	+1.7%	+1.7%	No PSS **(2U)**
Dec. 16, 2006	+7.2%	No data	PSS installed **(1U)**
Nov. 29, 2007	+1.5%	+1.8%	PSS offline **(2U)**
Feb. 5, 2008	+4.0%	+3.0%	PSS offline **(1U)**

PSS status and effectiveness from the damping level of the local mode. *PSS not effective for two units in service*. **PSS hardware problem detected and fixed (June 2008).**

Eastern System Interarea Mode

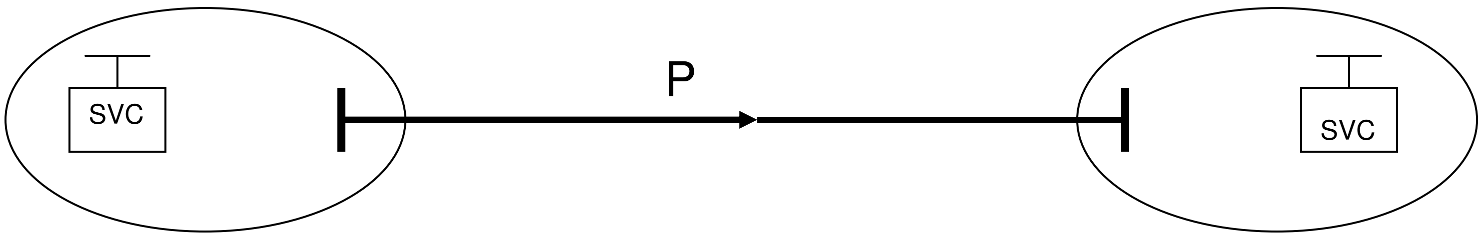
- Interarea mode frequency varies between 0.4 Hz to 0.5 Hz depending on season.
- Damping Monitor (ambient noise) showed the mode to be poorly damped around +3% to +5% seasonally.
- 0.47 Hz Interarea mode clearly visible in Event Analysis of Feb. 26th 2008 Florida blackout event.
- Mode involves many eastern control areas
- Frequency ~ 0.47 Hz, damping ~ +7%, on Feb. 26th 2008
- Likely not related to the blackout. Mode damping at +7% is comparable to the interarea modes in the western system.

Possible Control Actions

- Operator Actions
  - Reduce Critical Tie-line Transfers
  - Switch Damping Enhancement Controls at Specific Thyristor Devices – SVC, HVDC
- Automatic Control Actions
  - Switching of Damping Controls: Series Capacitors, Shunt Capacitors, Thyristor Devices
  - Generation Rescheduling

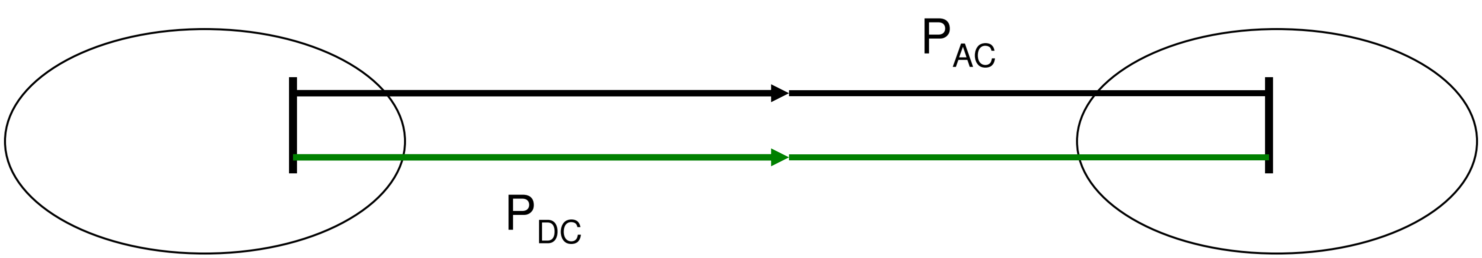
SVC Damping Control

- Stressed Operating Condition
- Near-by tie line active power-flow used as control input
- Sending end => Phase Lag Compensator
- Receiving end => Phase Lead Compensator



HVDC Damping Control

- Stressed Operating Condition
- Phase Angle Difference used as Control Input
- Phase Lead Compensator for HVDC Modulation
- Effective Improvement in Damping of Interarea Mode for Diverse Levels of AC Power Transfer



OMS Summary

- Successful implementation of real-time code into TVA PDC
- Advanced signal processing algorithms for oscillation analysis of events and ambient noise
- Automatic detection of poorly damped electromechanical modes and their mode shape
- Operator alerts, Operator alarms, Control actions, …
- Provides early warning on emerging oscillatory problems
- Can validate effectiveness and status of PSS at generators when PMU near generator

Future Work

- Testing and tuning at TVA
  - Conversion of OMS code to 64 bit architecture
  - New dedicated eight processor machine with 32 GB dynamic memory at TVA
  - OMS Engines for Eastern Grid?
  - Operator Alerts and Alarms? Operator Actions?
- Implementation and testing at BPA and California ISO in collaboration with EPG, Operator Actions?
- Implementation at Entergy