Oscillation Monitoring System

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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
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

Start

Read data from PDC

Event?

Yes

No

FDD analysis for ambient data

Prony analysis for post-disturbance data

Moving window crosscheck

Moving window crosscheck

Poorly damped mode detected?

Yes

Alarm

Controller trigger

No
TVA Cumberland event

9/18/2006
MW Oscillations on Generators

Line summation = Unit 1 + Unit 2 MW

Line 3 cleared
Line 3 restored

Four minutes of oscillations

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

Bus Voltage Magnitude at Cumberland

- Event Analysis: 1.2 Hz at +1.5% damping. **Local Mode.**
- Ambient Noise Analysis: 1.2 Hz at +1.8% damping. **Local Mode.**

Nov. 29th 2007 TVA event
Mode Shape – Local Mode

Mode Shape Identified by FDD at 1.224 Hz

Cumberland oscillating against rest of system
Basics of Prony Analysis

\[ \dot{x} = A x + B u \]
\[ y = C x + D u \]

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

• 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 Responses)
Event Analysis Engine

Start

Read data from PDC and data clean-up

Event detection

Local PMU Analysis and Crosscheck

Local PMU Analysis and Crosscheck

Inter-area Mode Analysis and Crosscheck

Display

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

Frequency estimates
- Prony
- MatrixPencil
- HTLS

Damping ratio estimates
- Prony
- MatrixPencil
- HTLS

Grand Coulee

Malin
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

Active Power from Malin to Round Mountain #1

Keeler-Allston Line trips

Ross-Lexington Line trips
Before Keeler-Allston Trip

Dominant mode is McNary local mode
Before Keeler-Allston trip

Frequency Estimates

Damping Ratio Estimates

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.
  ▪ Provides early warning on poorly damped modes
### Example of results for TVA

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

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