NASPI meeting, February 20, 2013

Real-time Monitoring of Power Oscillations and Modal Damping in the European ENTSO-E System
Recent Advances and Experience with Power System Oscillation Monitoring and Control using Wide-area Phasor Measurements

Motivation

- Power oscillations are a growing concern among power system operators worldwide
  - Increased penetration of renewables
  - Increased transmission asset utilization
- Phasor measurement units (PMUs) are becoming commonplace in the grids worldwide
- Phasor measurements are ideal sensor to monitoring of local as well as inter-area oscillations
Increasing demand for power

Transmission networks get bigger by aggregation (island ➔ interconnected)

Distance between generation and load changes
  - Laws, regulations & politics often impede building power plants where they are needed
  - Introduction of distributed energy resources e.g. wind
  ➔ Load flow becomes volatile

Modern supervision and tools are needed
  ➔ Increase the utilization of new technologies e.g. WAMS to allow the networks to operate closer to its capacity while maintaining system security
Wide Area Monitoring Systems
Challenges and solutions

1) Integration of renewables
- Remote grid operation with distributed generation (wind/solar farms)
- Increase grid capacity and stability
- Balance load to supply

2) Integration of electric vehicles
- Charging / billing
- Energy storage
- Load management

3) Demand response
- Real time pricing / tariffs
- Home automation / load management
- Distributed generation / storage

4) Reliability and efficiency
- Cyber security
- Customer outage information
- Emergency / peak power

Applications and technologies
- Gateways with bi-directional communication for consumer interaction
- Smart meters, Internet/mobile telecom, smart houses
- Customer service systems including billing
- Fault detection, isolation and restoration; voltage optimization
- FACTS, HVDC,
- WAMS → WAMPACS
Wide Area Monitoring Systems
Basic idea

- Synchronous sampling by PMUs locally in substations
- Periodic (10-50Hz) transmission of measurements to central location
- Processing and monitoring/control applications at central location
Wide Area Monitoring Systems

Positioning

- WAMS: Coordinated measures based on dynamic view for monitoring, protection and control of power systems
- SCADA / EMS: Monitoring at SCADA/EMS cycle rates actions initiated by long-term phenomena
- Object Protection: Direct local actions by on-line status information
Power Oscillation Monitoring
Ambient vs. Transient Oscillations

- POM detecting transient oscillations
- PDM determining modes and characteristics based on ambient variations
Wide Area Monitoring Systems
Power Oscillations Monitoring (POM)

- Real-time detection of power swings
- Algorithm is fed with selected voltage and current phasors
- Detection of various swing (power oscillation) modes
- Quickly identifies amplitude and frequency of oscillations (in order of seconds)
- First generation of oscillation damping monitoring: accurate estimate of transient oscillations
- In service since 2005
- Field experience in Switzerland, Croatia, Thailand, Finland, Norway, Austria

<table>
<thead>
<tr>
<th>Bus Voltage</th>
<th>Mode Frequency, Hz</th>
<th>Damping, %</th>
<th>Mode Amplitude, V</th>
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Wide Area Monitoring Systems
Power Oscillations Monitoring (POM)

Use Cases

- From 2005 Swissgrid uses POM to continually track the both the north-south and the east-west modes
- POM is used as event detector to detect low-damping situations
- Statistical post-processing has revealed key factors:
  - low damping – low load conditions
  - certain generation dispatch patterns (different Power System Stabilizers, PSSs for different generation units)
- Action has been to retune PSSs in Greece and Spain
- Occurrence of low-damping situations now much less frequent
- Low damping condition implies that the damping estimate stays low for a certain amount of time, and that the oscillations were excited
Wide Area Monitoring Systems

Power Damping Monitoring (PDM)

- In 2010 ABB Corporate Research developed second generation of oscillations monitoring and damping, called Power Damping Monitoring, PDM
  - Accurate determination of damping levels for ambient oscillations
  - Mode shape determination
  - Use of multiple input signals: frequency, angle and power differences can be used
  - Simultaneous detection of multiple modes

- Verified against other algorithms in collaboration with University
- Verified using data captured in the field from Fingrid WAMS (uses 4 frequency measurements)
- Implemented in Swissgrid WAMS in December 2010 (uses 7 frequency measurements)
- A system with PDM under is development for CORPOELEC in Venezuela
Wide Area Monitoring Systems
Power Damping Monitoring (PDM)

- Real-time detection and visualization of multiple oscillation modes to truly understand the system behavior
- Monitor damping and modal activity of most dangerous modes in the power system from ambient data (before large excitations happen)
- Quickly identify the participants and sources of inter-area oscillations using online visualization of modal shapes

Early warning of poorly damped lines allows operators to react before an event triggers an inter-area oscillation
Power Damping Monitoring (PDM)

Principle

- Sliding window of 10-15 minutes in length
- Estimate Multiple Inputs Multiple Output (MIMO) state space model

\[
x(k + 1) = Ax(k) + Bu(k) + Ke(k)
\]
\[
y(k) = Cx(k) + Du(k) + e(k)
\]

- \(e(k)\) – background power system load variations
- \(u(k)\) – probing signals (optional)
- \(y(k)\) – angle difference measurements
- Carry out modal analysis
  - Damping & frequency of critical modes
  - Visibility in different measurements (mode shape)
  - Activity in each mode
European ENTSO-E System

- Consists of Nordic, UK and Continental European Systems, coordinated from Brussels
- 22 PMUs in 9 countries in Continental European System
- Communication over secure Inter-TSO Network, multi-vendor interoperability through IEEE C37.118
- 3 ABB PSGuard Systems: Switzerland, Austria and Croatia, super PDC in Switzerland
- PMU data exchange between utilities in real-time, using IEEE1344-1995 and IEEE C37.118 protocols
- PDM functionality implemented in Swissgrid in 2010. It was added to POM functionality in operation from 2005.
PDM Modal Observability Map
Identification of participants in inter-area oscillations

Power Damping Monitoring
- Determines in real-time ambient oscillations
- Detects up to 2Hz oscillation, requires at least 10 measurements per second
- Modal frequencies and damping
- Simultaneous monitoring of multiple modes (2 modes tracked for Swissgrid, no theoretical limit)
- Phase in each measurement signal
- Modal activity
- In operation at Swissgrid since December 2010

Oscillatory behavior dominated by 3 modes
- East-west mode - ~0.13 Hz
- North-south mode - ~0.25 Hz
- Former east-west mode - ~0.17 Hz
At 14.59, a busbar fault causes a hydro power plant in Turkey to trip off the grid.

- 1300 MW generation loss, registered by PDM
- 270 MW of load is tripped by system protection scheme (load shedding)
- A well-damped oscillation in the east-west direction follows
- Prior to the event PDM reported a damping of 60% (magnitude ratio)
Analysis of Raw Data

Oscillation Damping

![Graph showing frequency deviation over time with key data points and calculations]

- Upper Extremes
  - Damping = \((1 - \frac{21}{78}) = 73\%

- Lower Extremes
  - Damping = \((1 - \frac{24}{74}) = 68\%

- Average: \(~70\%\)

- ~Time-domain damping ~ 70 %
Analysis of Raw Data
Oscillation Frequency

Frequency \( \approx 0.14 \text{ Hz} \)

Average:
\[
\frac{2}{7+7.4} = 0.14\text{Hz}
\]
PDM Output
Before event (red) and After Event (blue)

- Trip of plant appears to have reduced damping of the old east-west mode with around 10%
- PDM reported around 60% damping of new east-west mode before disturbance
Conclusions

- Recent developments are changing power utility networks from radial to distributed, with loads and generations being dispersed, making achieving system reliability requirements much more challenging.
- Wide-area monitoring provides a handy toolbox for managing existing and emerging system challenges.
- PDM extends the capability of POM with mode shape estimation and the ability to characterize the damping under ambient conditions.
- The capability of newer PDM application, in Swissgrid registered oscillations damping at 60% prior to a disturbance event in Turkey, which happened shortly after and was also captured by PDM.
- POM and PDM applications are continuously monitoring and analyzing transient and ambient oscillations in ENTSO-E system, particularly the dominant oscillations of East-West and North-South.