Oscillation Detection, Monitoring & Analysis

Oscillations Analysis Work Group (OAWG)
February 20, 2018
Outline

- Introduction
- Oscillation Detection
- Mode Meter
- On-Demand Oscillation Reports
- Oscillation Event Mining
- Offline Oscillation Analysis
- Summary
EPG provides several different applications for oscillation analysis, monitoring, detection and reporting

- **Oscillation Detection in Real-time (RTDMS)**
  > MAS Version 2.0 ODM, Developed by Montana Tech (Trudnowski et al.)
  > Licensed by T&D Consulting Engineers (TDCE) LLC

- **Oscillation Monitoring - Mode Metering in Real-time (RTDMS)**
  > MAS version 2.0 MMM Developed by Montana Tech (Trudnowski et al.)
  > Licensed by T&D Consulting Engineers (TDCE) LLC

- **On-Demand Oscillation Reports using GridSmarts**

- **Offline Oscillation Analysis - Phasor Grid Dynamics Analyzer (PGDA)**

- **Oscillation Event Mining – Automated Event Mining (AEM)**
Oscillation Detection in RTDMS
Oscillation Detection Module (ODM)

- Runs continuously all the time - Does not require triggers
- Detection based on 4 oscillatory frequency bands
- Result gives signal RMS energy for each band
  - Band 1: 0.01 – 0.15 Hz (Speed Governor)
  - Band 2: 0.15 – 1 Hz (Interarea or local area)
  - Band 3: 1- 5 Hz (Local Controller)
  - Band 4: > 5 Hz (Torsional Dynamics and Fast Acting Controllers)
- Inverse Time Alarming Capability
- Spectral analysis – Frequency & Oscillation Shape
New Oscillation Detection Map View

- Quickly Identify
  - Location of Severe Oscillations
  - Frequency Band in which there are alarms – Likely spread and cause of oscillations
  - Severity of Oscillations based on energy levels

- Added as layer on geospatial map display – user selects signals they want to show

- One Icon per PMU – shows multiple signal alarms on the same icon

- Configurable alarm colors based on energy limits

- For Aggregated Signals such as Angle differences of Power flow Paths - Average of latitude and longitude
Frequency Band – Important Indicator of Cause of Oscillation

<table>
<thead>
<tr>
<th>Oscillation Frequency</th>
<th>Typical Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 – 0.15 Hz</td>
<td>Speed Governor</td>
</tr>
<tr>
<td>0.15 – 1.00 Hz</td>
<td>Inter - Area</td>
</tr>
<tr>
<td>1.00 – 5.00 Hz</td>
<td>Local Controller</td>
</tr>
<tr>
<td>5.00 – 14.0 Hz</td>
<td>HVDC / FACTS Controller</td>
</tr>
</tbody>
</table>

Source: NASPI Technical Report, Diagnosing Equipment Health and Mis-operations with PMU Data
New Oscillation Detection Alarm Popup

- Drill Down Display showing
  - Trend for the alarmed signal
  - OD 4 band results chart for top 10 signals sorted in the order of highest energy
  - Spectral Shape for the top 10 signals
- Scroll bar for event analyzer function to scroll forward or backward in time
Oscillation Detection Trend Chart
Oscillations in PJM
Oscillation Event Popup

Oscillation Detection Trend Chart

Band 1, 0.01Hz to 0.15Hz Speed Governor
Band 2, 0.15Hz to 1Hz InterArea
Band 3, 1Hz to 8Hz Local Control System
Band 4, 8Hz to 14Hz TorsionalDynamics

Oscillation Spectral Results

Highest Magnitude
ERCOT Oscillation Example

Source: NASPI September 2017
ERCOT Oscillation Example

Source: NASPI September 2017
Oscillation Detection Alarms

A0 = Initial Alert Level
A1 = Inverse time Curve Alarm Level
A2 = Definite time Curve Alarm level
TD0 = Alert time corresponding to A0 (seconds)
TD1 = Alarm time corresponding to A1 (seconds)
TD2 = Alarm time corresponding to A2 (seconds)

Note: Set A1 = NaN if Inverse time curve is not to be used.

Alarm levels can be specified for each individual signal and for each band.
- Input several key synchrophasor signals. Best applied to generator output and key intertie MW signals, and key voltage signals.
- Estimate RMS energy in 4 frequency bands.
- Spectral Analysis
  - Frequency
  - Shape

RMS Energy 1 = 0.01 Hz to 0.15 Hz, 200 sec. response time.
RMS Energy 2 = 0.15 Hz to 1.00 Hz, 12 sec. response time.
RMS Energy 3 = 1.00 Hz to 5.00 Hz, 6 sec. response time.
RMS Energy 4 = 5.00 Hz to 14.0 Hz, 3 sec. response time.
Mode Meter in RTDMS
Mode Meter in RTDMS

- Mode Meter Results Include:
  - Frequency
  - Damping
  - Energy (RMS value in unit of selected signal)
  - Mode Shape

- Alarming option based on
  - Energy
  - Damping
  - Combination of Energy And Damping

- Allows different signal types – Voltage Magnitude, Voltage Angle Derivative, Angle Difference Derivative, Real & Reactive power flows and paths

- Data Quality Indicators – Incomplete Data Buffer etc.
Mode Meter – Alarming on Damping & Energy
New Mode Meter Map View

- Mode shape shown in geo-location, Location of icon
  - Individual signal location
  - Aggregated signal: average of angle difference, or power PMU location
- Size of circle represents shape amplitude
- Arrow in circle represents shape phase, arrow length is twice the radius of circle
- Color of circle is green, use alarm color scheme of damping
# Mode Meter Alarm Displays

<table>
<thead>
<tr>
<th>Metric Name</th>
<th>Central</th>
<th>South</th>
<th>North</th>
<th>West</th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Angle &amp; Magnitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle Difference</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MW</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MVAR</td>
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</tr>
<tr>
<td>Damping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Alarms

- **Display Name**: Simulated Test Mode
- **SignalType Name**: Mode
- **Start Time**: 08/24/2017 05:37:15 AM
- **Alarm Type**: L4 Damping Alarm

![Diagram](image-url)
ERCOT RTDMS Display

Source: NASPI September 2017
- Allows multiple signals for each mode
- Estimate mode several times using different algorithms and data window lengths.
- Select “best” estimate by choosing result meeting specified accuracy with minimal data.
- Results include frequency, damping and energy.
- Using “best” mode estimate, calculate mode shape from voltage angles at many locations.
On-Demand Oscillation Reports

- GridSmarts
On-demand Event Report in GridSmarts

- GridSmarts – Reporting module in RTDMS
  - Daily, Monthly, On-Demand Reports
  - PMU Performance and Quality
  - Statistical Reports, Comparison of Performance – Prior day vs Today etc.
  - Alarm and Event Summary Reports
  - Near real-time Dashboard

- On-demand Oscillations Report
  - Event driven – Generated when user make a request for an event captured
  - Template based – Template based on the type of event captured
  - A Semi-completed report – Including placeholder for engineers to write event details and summary, analysis plots, statistical table based on other data source
  - Centrally located – Report saved in the central location where can be shared accessed by multiple users
  - File format – In MS Word format for further editing by user to publish as complete report
- Event Summary
- Participating Signals – Frequency, Real and Reactive power, Currents, Voltages, Angles
- Energy levels in each band
- Modal Analysis for Identified frequency – Frequency, Energy and Damping
Oscillation Event Mining

Automated Event Mining (AEM)
Automated Event Miner (AEM) Overview

- AEM is designed to mine through archived data (Days to Years) to identify events based on user defined mining parameters.
- AEM can be used for oscillations, low voltage, high phase angle difference and frequency signatures.
- Data Sources – Databases (MySQL, MSSQL, PI, OH), Flat Files (*.csv, COMTRADE)
- Data Types – Simulated and PMU
- AEM provides GUIs to setup mining parameters, select mining engines, visualize mining results and generate mining report
- Mined events are reported by location, severity, duration and count to provide engineers an event library to select significant events for analysis.
Oscillation Event Mining Methodology – 3 Steps

Parameter Selection - Engine for Event Detection - Generate Reports

Mining Parameters

- Duration – Hours to Years
- Footprint
- Filters – Energy, Modal Frequency & Duration

Mining Approach

- Engine – Oscillation Detection Module (ODM)
- Oscillations are categorized by root cause using 4 bands

Oscillation Report

- Count of Events
- Location of Events
- Event Timing
- Dominant Modes
- High Energy Events
Oscillation Event Mining Report – ERCOT Example

Using 2 weeks of Historical PMU data

- **Need** – Oscillation Event Mining Tool

- **Automated Event Miner (AEM)** – Add-on application to Phasor Grid Dynamics Analyzer (PGDA) for mining power system events

- **Mining Parameters** – Energy Filters

- **Mining Summary** – Report by Band

- **Mining Report** – AEM Oscillations

**Mining Parameters**

<table>
<thead>
<tr>
<th>Signal Type</th>
<th>69kV</th>
<th>138kV</th>
<th>345kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Power (MW)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Reactive Power (MVar)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>Voltage Magnitude (kV)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Current Magnitude (Amps)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Angle Pairs (deg)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Mining Summary**

<table>
<thead>
<tr>
<th>Band</th>
<th>Root Cause</th>
<th>Mode Range (Hz)</th>
<th>Count of PMU Locations</th>
<th>Count of Events</th>
<th>Count of Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Speed Governor</td>
<td>0.01 to 0.15</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Inter-area or Local Oscillations</td>
<td>0.16 to 1.0</td>
<td>13</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>Local Plant Control Systems</td>
<td>1.1 to 5.0</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Controllers</td>
<td>5.1 to 15</td>
<td>3</td>
<td>15</td>
<td>4</td>
</tr>
</tbody>
</table>
### Oscillation Event Mining Report

#### Count of Events, Mode and Location by Root Cause

<table>
<thead>
<tr>
<th>Band</th>
<th>Root Cause</th>
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<th>Count of Events</th>
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</tr>
</tbody>
</table>

### Count of Events & Dominant Mode – PMU 2

<table>
<thead>
<tr>
<th>PMU Locations</th>
<th>Counts of Events by PMU Location</th>
<th>Count of Events by Mode</th>
<th>Mode (Hz)</th>
<th>Peak-to-Peak Magnitude of Oscillation by Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMU2</td>
<td>9</td>
<td>3</td>
<td>0.6</td>
<td>77.3 Amps</td>
</tr>
<tr>
<td>PMU2</td>
<td>9</td>
<td>3</td>
<td>0.7</td>
<td>88.7 Amps</td>
</tr>
<tr>
<td>PMU2</td>
<td>9</td>
<td>1</td>
<td>0.3</td>
<td>10.6 Amps</td>
</tr>
<tr>
<td>PMU2</td>
<td>9</td>
<td>1</td>
<td>0.6</td>
<td>1.1 kV</td>
</tr>
</tbody>
</table>

#### Signal Name | Signal Type | Event Start Time | Event End Time | Mode (Hz) | Peak-to-Peak Magnitude
--- | --- | --- | --- | --- | ---
PMU2.I1.IM | IM | 3/18/2017 21:45 | 3/18/2017 21:49 | 0.3 | 10.62
PMU2.I1.IM | IM | 3/22/2017 0:35 | 3/22/2017 0:43 | 0.65 | 38.04
PMU2.I1.IM | IM | 3/22/2017 9:08 | 3/22/2017 9:13 | 0.7 | 88.73
PMU2.I1.IM | IM | 3/22/2017 9:30 | 3/22/2017 9:37 | 0.7 | 73.96
PMU2.I1.IM | IM | 3/25/2017 18:08 | 3/25/2017 18:13 | 0.6 | 77.25
PMU2.V1.VM | VM | 3/25/2017 18:08 | 3/25/2017 18:13 | 0.6 | 1.06
PMU2.I1.IM | IM | 3/25/2017 18:14 | 3/25/2017 18:18 | 0.7 | 67.36
PMU2.I1.IM | IM | 3/25/2017 18:20 | 3/25/2017 18:26 | 0.65 | 76.00
PMU2.I1.IM | IM | 3/27/2017 14:29 | 3/27/2017 14:36 | 0.4 | 39.52
PMU2.I1.IM | IM | 3/27/2017 14:37 | 3/27/2017 14:43 | 0.7 | 61.79
PMU2.I1.IM | IM | 3/27/2017 14:44 | 3/27/2017 14:49 | 0.6 | 73.72

**Oscillation Events at PMU 2 Location**
ERCOT Experience with Oscillations and Event Mining

- **2010 – 2014 = Center for the Commercialization of Electric Technologies (CCET) Discovery Across Texas (DAT) project under Department of Energy (DOE) Award**
  - **Event Analysis**
    - Inter-area oscillations (e.g. 0.6Hz N-S mode etc)
  - **Operations**
    - Wind Farm oscillations (e.g. 3.33Hz Band 3 mode)
    - Hydro Unit oscillations (e.g. 1.8Hz Band 3 mode)
    - Conventional Unit oscillations (e.g. 0.13Hz Band 1 mode)
  - **Oscillation Data Mining Activity**
    - Wind Production related (e.g. 0.9Hz Band 2 mode)
    - Wind Turbine Design related (e.g. 5-6Hz Band 3 mode)
    - Control Systems Settings related (e.g. 2Hz Band 3 mode)
    - Local Oscillations topology related (e.g. 0.6Hz Band 2 mode)
Offline Oscillation Analysis

Phasor Grid Dynamics Analyzer (PGDA)
PGDA – The Tool and its Uses

PGDA is used for:

- **Disturbance Analysis and Root Cause Assessment**
  Quick and detailed analysis of power system events like generation trips, line trips, generation-load imbalances, and other dynamic events

- **Baseline Daily Performance & Establish Safe Operating Ranges**
  Examine Daily System Performance and establish reliable ranges for voltage, frequency, and other system metrics for real time monitoring systems

- **Oscillation Detection**
  Identify the presence of event-driven and ambient oscillatory modes in power system and determine conditions (Location/s, Significant Modes, Energy, Frequency) for additional monitoring of significant modes.

- **Generator Frequency Response Analysis**
  Calculate the Primary/Inertial Frequency Response of a system following a generation loss.

- **Model Validation**
  Verify and improve dynamic models used in power system simulations to aid in planning and engineering studies

- **Comparative Analysis**
  Verify & Validate SCADA & State Estimation results with phasor data to identify differences & deviations

- **Stability Assessment**
  Identify & Locate substations approaching instability issues and quantify sensitivity limits for real time monitoring
PGDA Features and Capabilities

Data Engine
- Data Merging
- Data Handling – Multiple Data Sources
- Pseudo Signal creation
- Save and Re-produce analysis
- Event Templates
- Advanced Data Conditioning Filters

Data Sources
- Databases
- Data Files

Statistical Analysis
- Baseline Daily Performance Ranges
- Identify & Locate hidden events

Sensitivity Analysis
- Quantify Variation of one metric over another (kV/100MW)
- Identify stressed locations

Plot Analysis
- Plot metrics over time
- Signal manipulation i.e. Normalize voltage by basekV
- Variability of the grid metrics across time intervals measured at different locations

Ringdown Analysis
- Oscillation Detection Tool under system dynamic conditions
- Provides Modal Frequency & Damping
- Provides Magnitude of Modes and Nature of Oscillations

Spectral Analysis
- Significant peaks signify oscillatory modes
- Identify & group location with similar oscillation patterns
- Identify Nature of Oscillations

Ambient Modal Analysis
- Sustained Oscillation Detection Tool
- Provides Modal Frequency
- Provides Damping
- Provides Energy

PGDA Report
- Automated Report Generator
- Word, PDF

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- Word, PDF
### PGDA Spectral Analysis

<table>
<thead>
<tr>
<th>Why</th>
<th>When (Data Duration)</th>
<th>How (Key Analysis Parameter)</th>
</tr>
</thead>
</table>
| • Study of Oscillation frequency (Both Natural and Forced Oscillations)  
• Affected locations and their degree of participation | • > 5 minutes  
• During Ambient and Event conditions | • Frequency Range – Expand till half sampling rate (e.g. 15 Hz for 30 samples/second).  
• Calculation Reference Signal – Set an input signal as reference to calculate coherency and cross spectral density for other input signals relative to reference signal. Use the signal with highest power spectral density at a particular frequency of oscillation as reference.  
• Oscillation with PSD (dB) > 0 is dominant and has relatively high peak to peak magnitude of oscillation |
Using Spectral Analysis

The relatively higher pinnacles or peaks in this metric are useful to identify dominant frequency of oscillation reported in the x-axis.

A higher correlation (> 0.7) confirms participation of another or multiple signals in frequency of oscillation reported on the x-axis.

This is useful to identify signals participating in the frequency of oscillation in phase (close to 0 deg) and out of phase (close to 180 deg or -180 deg).
## PGDA Modal Analysis

<table>
<thead>
<tr>
<th>Why</th>
<th>When (Data Duration)</th>
<th>How (Key Analysis Parameter)</th>
</tr>
</thead>
</table>
| • Establish frequency bands, damping %, energy limits and appropriate signals for real time oscillation monitoring  
• Oscillation frequency with low damping and high energy critical for operations | • > 5 minutes  
• During Ambient and Event conditions | • Frequency Range – Expand till half sampling rate (e.g. 15 Hz for 30 samples/second). Or Tune around a specific frequency of oscillation to establish configuration for real time oscillation monitoring.  
• Energy Min – Specify the relative energy minimum (0 to 1). Only those modal estimates with relative energy levels greater than this value are displayed (the rest are discarded).  
• Damping Max - Specify the damping maximum. Only those modal estimates with damping levels less than this number are displayed (the rest are discarded). |
Using Modal Analysis

- Frequency of Oscillation (Hz):
  Trend of each mode reported over time.

- Damping (%):
  Trend of damping calculated for each mode calculated and reported over time.

- Energy:
  Trend of amplitude or energy for each mode calculated reported over time.
# PGDA Ringdown Analysis

<table>
<thead>
<tr>
<th>Why</th>
<th>When (Data Duration)</th>
<th>How (Key Analysis Parameter)</th>
</tr>
</thead>
</table>
| • Oscillation frequency, damping % and mode shape (Magnitude and Phase) | • < 1 minute  
• During transient response  
• Use Time reference signal window to select data for analysis | • Frequency Range – Expand till half sampling rate (e.g. 15 Hz for 30 samples/second). Or Tune around a specific frequency of oscillation to establish configuration for real time oscillation monitoring.  
• Energy Min – Specify the relative energy minimum (0 to 1). Only those modal estimates with relative energy levels greater than this value are displayed (the rest are discarded).  
• Damping Max - Specify the damping maximum. Only those modal estimates with damping levels less than this number are displayed (the rest are discarded). |
| • Study of Natural modes (e.g. inter area modes) |                                                            |                              |
Using Ringdown Analysis

Forensics:
- a) 0.6Hz Inter-area mode
- b) 180 deg indicates two locations are oscillating against each other
- c) Well Damped
- d) Energy of Mode in Signal 1 is Stronger

- Mode Shape
- Signal 2 Energy = 1.0
- 180 Deg
- Signal 1 Energy = 1.2
- Mode Estimate
- Signal 2 - 0.59Hz, 11%
- Signal 1 - 0.58Hz, 8%
RTDMS provides Oscillation Detection and Monitoring applications for detecting unknown oscillations and monitoring known oscillations in real-time.

GridSmarts can be used to generate oscillation reports from alarms and events detected by RTDMS.

Automated Event Miner (AEM) can be used to identify oscillations in the system by mining long term data sets – Months, Years.

Phasor Grid Dynamics Analyzer (PGDA) is used to perform offline oscillation analysis using tools such as spectral, modal and ringdown analysis.
Thank You

251 S. Lake Ave., Suite 300
Pasadena, CA 91101
626-685-2015
www.electricpowergroup.com