Oscillation Source Locating Tool at ISO New England
PMUs have enabled Oscillation monitoring

- Since installation of PMU in ISO-NE system in 2012, multiple instances of poorly damped oscillations with high MW magnitude and frequency from 0.03 Hz to 2 Hz have been detected.
More Examples of Oscillations

- 50 MW, 0.42 Hz
- 90 MW, 0.04 Hz

Time:
- 20 s
- 42 min
Do oscillations impose any threat?

• **Yes**, the sustained oscillations can cause
  
  ✓ Potential uncontrolled *cascading outages*
  
  ✓ Undesirable *mechanical vibrations* in system components, which increases the probability of equipment failure, reduces the lifespan of equipment, and results in increased maintenance requirements
Catastrophic consequences of rotor’s vibration

2009 Sayano–Shushenskaya power station accident, Russia *

Turbine 2 broke apart violently. The turbine hall and engine room were flooded, the ceiling of the turbine hall collapsed, 9 of 10 turbines were damaged or destroyed, and 75 people were killed. The entire plant output, totaling 6,400 MW was lost, leading to a widespread power failure in the local area.

* https://en.wikipedia.org/wiki/2009_Sayan%E2%80%93Shushenskaya_power_station_accident

Before the accident

After the accident
How to mitigate sustained oscillations?

• The majority of the observed oscillations are Forced Oscillations originating from generators. They are caused by the equipment and control systems failures and unplanned operating conditions.

• The mitigation approach is to find the Source and:
  ✓ Disconnect it from the network
  ✓ Reduce MW output
  ✓ Communicate to the power plan - to find out what is going on and to develop remedial actions
  ✓ If the Source is outside of the control area, then communicate to the Operator in the suspected area

• The key step in the mitigating sustained oscillations is to find the Source of oscillations

A number of mitigation measures can be applied depending on situation
What does it mean “Find the Source”?

“I see sustained oscillations!!”

Control Room Operator

Is the Source located in my Control Area?

Yes

Which substation is the suspect?
Which specific unit is the suspect?

Mitigation Actions applied Inside the control area

No

Which of my neighbors is the suspected area?

Actions to find the Source outside of the control area

“Find the Source” means to answer the above questions and provide the Actionable Information to the Operator
Magnitude of oscillations is an unreliable indicator of the Source

- 179-bus WECC system: Generator 4 is the Source of forced oscillations at 0.86Hz creating a resonance with natural mode (case F1*)
- MW Magnitude in other buses is much larger than at the Source
- Magnitude of oscillations cannot be a reliable indicator of the Source location

* http://curent.utk.edu/research/test-cases/
Methods for “finding the Source”

- Variety of methods have been proposed. They are based on different properties of the oscillations:
  - Magnitude
  - Phase angle of the mode shape
  - Propagation speed
  - Statistical signature
  - Damping torque
  - Energy-based method

All these method work well in some situations but do not work in another

- Universally efficient in variety of situations
- Works in resonance conditions

- **Dissipating Energy Flow (DEF) method**
  
  DEF* = Energy-based method** + PMU signal processing


How does the DEF method work?

- PMU Input: $I_{ij}, V_i, f_i$  
  
  $W_{ij}^D(t) = \int \left( \Delta P_{ij} d\Delta \theta_i + \Delta Q_{ij} d\Delta \ln V_i \right)$

  $W_{ij}^D(t) \approx DE_{ij} \cdot t + b_{ij}$

- Output: $DE_{ij}$ coefficient at bus $i$. That is the rate of change of the transient energy

- $DE$ coefficient can be viewed as a regular MW flow in terms of Source-Sink

- The Direction and the value of $DE$ in multiple branches allow tracing the source of oscillations

$DE$ - the source of oscillations is located behind bus $j$

$DE$ - the source of oscillations is located behind bus $i$
How to test a source locating method?

• Sustained oscillations can have many features impacting the performance of the Source locating method (natural, forced, local, inter-area, resonance conditions, multiple sources existing simultaneously, harmonics, etc.)

• Use of actual PMU is the ultimate test, but it is difficult to get a comprehensive set of PMU data covering all possible situations. Actual source of oscillations in real cases could be unknown, which makes the testing difficult

• Rigorous testing should include the following steps
  ✓ Use a set of simulated cases covering a representative set of situations which can be envisioned in actual power systems.
  ✓ Use actual events when the source is known with high confidence level
  ✓ Test as many different type of events as possible
Test case library of sustained oscillations *

- 179 bus, 29 generator equivalent WECC system
- Contains a set of **9 cases of natural** oscillations and **14 cases of forced oscillations**
- The library contains a representative set of cases with sustained oscillations which can be observed in actual power systems
  - Local and Interarea modes
  - Single source – single oscillatory mode
  - Multiple sources – single or multiple modes
  - Resonance and near resonance conditions
  - Forcing signal creating a spectra of forced oscillations

* [http://curent.utk.edu/research/test-cases/](http://curent.utk.edu/research/test-cases/)*
The DEF method Test Results

- Simulated cases - test case library of sustained oscillations

<table>
<thead>
<tr>
<th>Description</th>
<th>Test Results</th>
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</thead>
<tbody>
<tr>
<td>All 9 cases of poorly damped natural oscillations</td>
<td>Pass</td>
</tr>
<tr>
<td>All 14 cases of forced oscillations</td>
<td>Pass</td>
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</table>

- Actual events in ISO-NE and WECC

<table>
<thead>
<tr>
<th>Description</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>More than 30 cases from ISO-NE</td>
<td>Pass</td>
</tr>
<tr>
<td>Two cases from WECC</td>
<td>Pass</td>
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</table>
Online Oscillation Management concept at ISO-NE

- Any oscillation triggered alarm is characterized and reported to the designated personnel.

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Source: Substation XXXXXXX
Unit XXXXXXXX
Online OSL tool

Identification of time interval for analysis $[\text{Tst, Tend}]$

Extract PMU data for $[\text{Tst, Tend}]$

Calculate DE flow in monitored elements

DE pattern recognition: identify source

Visualization

Alarm by PhasorPoint
- Time
- Location
- Frequency

PMU database

Suspect Source
Substation: xxxxxxxx
Unit: xxxxxx

Table: DE, p.u., Line ID

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<thead>
<tr>
<th>DE, p.u.</th>
<th>Line ID</th>
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</table>

Graph: Active power, MW

Source
Forced Oscillations (FO) Originated Outside ISO-NE

- June 17, 2016; oscillations of 0.22-0.28Hz, up to RMS=11MW observed in many locations of ISO-NE during 45 minutes

Time domain data

Results of the DEF method

DE flow in 345kV lines at NE-NY border

DE flow indicates that the source is located outside ISO-NE

Blue color means a substation does not have PMU

Ability to identify whether the Source located Inside or Outside of control area
FO Originated from a Combined Cycle Unit, 0.08Hz

- October 3, 2016; oscillations of 0.08Hz, RMS=7MW observed around a big power plant with Combined Cycle units

**Time domain data**

**Results of the DEF method**

DE flow in 345kV lines around suspect power plant

DE flow indicates G1 as the source
FO Originated from the Excitation Failure

- June 15, 2016; oscillations of 1.32Hz were caused by the failure of the excitation system of one of three units operating at the same conditions.

Time domain data

Active Power

Voltage Magnitude

Results of the DEF method

DE flow in 345kV lines around suspect power plant

DE flow indicates G3 as the source

Ability to identify a specific generator within power plant as the Source
Potentially Enabling New PMU-based Application

• Decentralized, online estimation of the contribution of a power plant/generator into the damping of a specific oscillatory mode

Mode 1, ……, Mode k

Calculation of DE by the DEF method for all Modes

Results of analysis

Mode 1: DE < 0 - positive damping

Mode k: DE > 0 - negative damping

• Analysis based on local data
• At least qualitative analysis on whether generator contributes or deteriorates damping of a specific oscillatory mode
Conclusions

• The DEF method in testing has demonstrated high efficiency in locating the source of oscillations
  ✓ Identification on whether the source is located inside or outside of control area
  ✓ Identification of a suspect substation
  ✓ Identification of a suspect specific generator within power plant

• ISO-NE plans to implement the DEF method in an online version of the Oscillation Source Locating (OSL) tool

• Online OSL is expected to be a significant milestone in the deployment of PMU in the Control Room as delivering an Actionable Information
Questions