Detection the Source of Forced Oscillations

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Forced Oscillations (FO) Can be Dangerous

- Potential uncontrolled cascading outages
  - ✓ Tripping by protection relays at normal and false operation
- Undesirable mechanical vibrations in system components
  - ✓ Increased the probability of equipment failure
  - ✓ Reduced the lifespan of equipment
  - ✓ Increased maintenance requirements

Catastrophic event of rotor's vibration at Sayano–Shushenskaya hydro power station in 2009*

Before the accident

After the accident

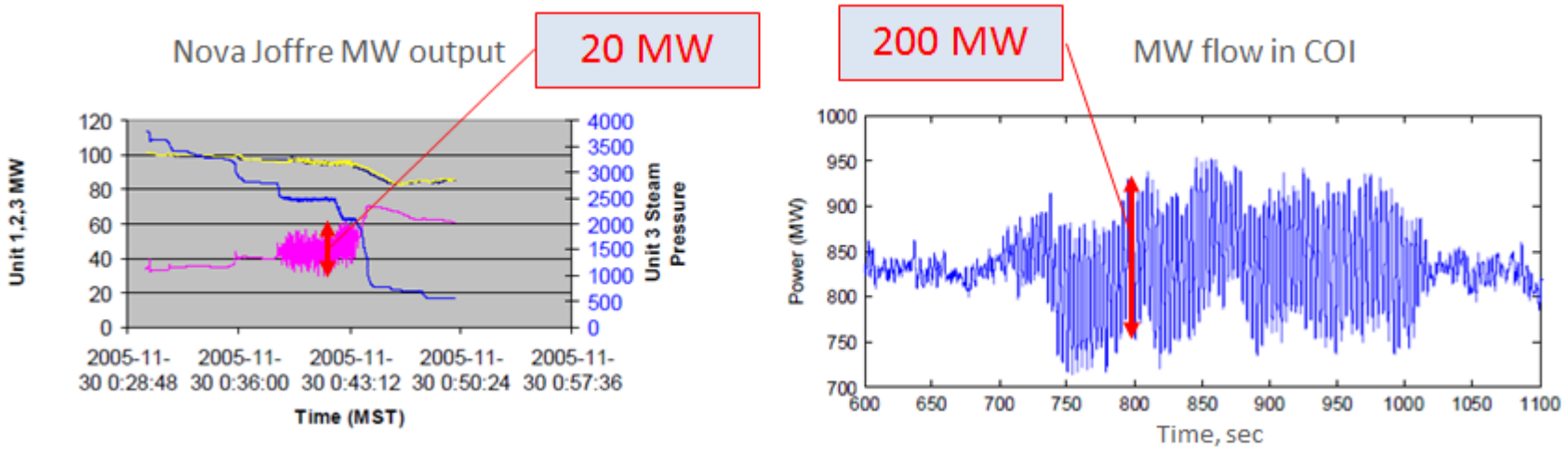
* https://en.wikipedia.org/wiki/2009_Sayano%E2%80%93Shushenskaya_power_station_accident

Mitigation of FO

- Forced Oscillations exist as long as the Source of forced signal exist
  - ✓ Equipment or control system failure
  - ✓ Wrong settings of control systems
  - ✓ Unplanned operating conditions; Cycling load
  - ✓ Unintended interaction of control systems
- The only efficient measure is to eliminate the Source of forced signal
  - ✓ Disconnect the source from the network
  - ✓ Change operating conditions /control mode
- The pre-requisite for the mitigating of FO is to find the Source
  - ✓ Ability to identify the Source online is a must feature to implement mitigation by the Control Room
  - ✓ Ability to identify the Source offline is helpful for preventing the occurrence of similar events in the future
    - ❖ Offline engineering analysis and measures for preventing the conditions for forced signal
- Practically important is to find a generator – source of oscillations

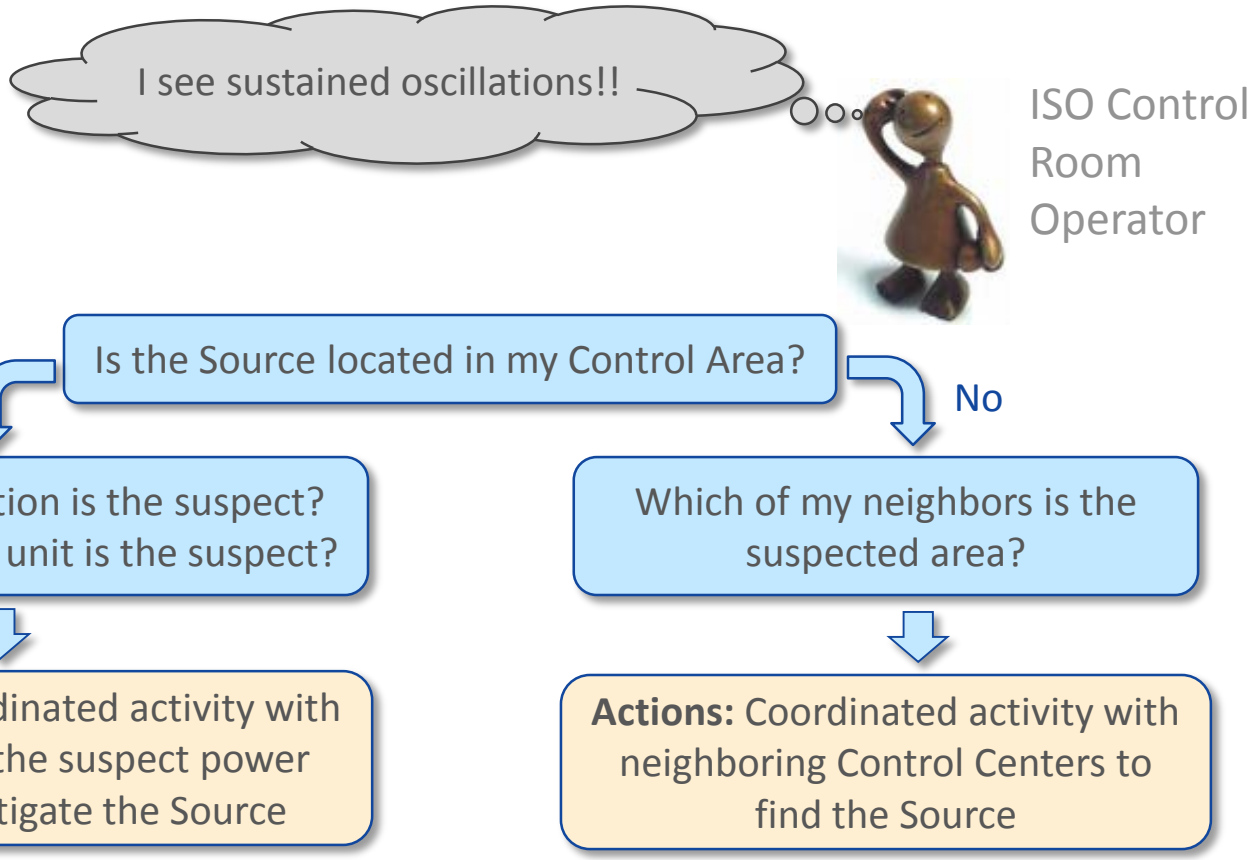
Finding the Source is Not Trivial

- November 29, 2005 : 200 MW oscillations on California-Oregon Interface (COI) were caused by 20 MW oscillations at the Nova Joffre generating plant in Alberta, Canada, 1100 miles away due to malfunctioning steam extractor control valve
  - ✓ Resonance conditions for 0.27 Hz interarea mode



(Source: BPA)

What Does it Mean “Find the Source”?



“Find the Source” for the Control Room Operator means to find the specific power plan/generator causing oscillations

Requirements for Practically Meaningful Source Locating Methods/Tools

- Efficiency for variety of practical situations
  - ✓ Locating the source **regardless of nature** of actual "forcing" signal
  - ✓ **Resonance conditions** for FO
  - ✓ Ability to distinguish location of the Source **inside/outside** of control area
  - ✓ Robustness for variable topology and operating conditions
- Ability to work online without false alarms
- Measurements-based only; do not depend on model
  - ✓ Robustness against noise, "bad" or partially missed data
- Ability to provide useful information even at partial system observability

Source Locating Principles

- Multiple research paper explore different principles, features and attributes of oscillations for locating the Source of FO
  - ✓ Magnitude
  - ✓ Energy
  - ✓ Mode shape estimation
  - ✓ Traveling wave
  - ✓ Damping torque
  - ✓ Other methods

Used in available practical tools

Magnitude– Based Method

- Idea: Location with the largest magnitude of FO not creating resonance conditions is at the Source.
- Pros:
  - ✓ Works well for FO not creating resonance conditions
  - ✓ Easy to implement
  - ✓ SCADA data can be used additionally to PMU to enlarge system observability
- Cons:
  - ✓ Does not work for resonance conditions
  - ✓ Cannot identify that the Source is located outside of control area by using data only from inside of control area

Energy– Based Method

- Idea: Estimate the flow of dissipating energy (DE) of a mode in any transmission element monitored by PMU. Dissipating energy flows from Source to Sink. Tracing DE flow in network allows to identify the Source
- Pros:
  - ✓ Efficient for variety of practical situations
  - ✓ Works in resonance conditions
  - ✓ Ability to distinguish location of the Source inside and outside of control area
  - ✓ Extensively tested with simulated and actual PMU data
- Cons:
  - ✓ Constant resistance load and network resistance can impact accuracy of DE calculation in network. Nevertheless, tracing DE values of only generators allows detecting generator- source

Mode Shape Estimation– Based Method

- Idea: Estimate mode shape of oscillations. “Leading” in phase generator in “leading” group is the Source
- Pros:
  - ✓ Works well in two-machine system
  - ✓ Potentially efficient for significant system observability by PMUs
  - ✓ Supported by GE with a plan to be a feature of the PhasorPoint application
- Cons:
  - ✓ No rigorous theoretical justification for multi-machine system
  - ✓ Can potentially provide false alarms and particularly in resonance conditions
  - ✓ Relies of accurate estimation of mode shape and ability to identify a “leading” group of generators

Traveling Wave – Based Method

- Idea: Electromagnetic wave starts from the Source and has a constant speed. Metering time of arrival (or phase) of a wave in multiple locations at the beginning of FO allows to pinpoint the Source
- Pros:
  - ✓ Works well for ideal accuracy of measurements
  - ✓ Fast response
- Cons:
  - ✓ Not robust for actual accuracy of PMU data
  - ✓ Needs to have clear inception of FO
  - ✓ Sensitive to topology and non-constant wave speed throughout network

Damping Torque– Based Method

- Idea: The generator with negative damping torque coefficient is the Source
- Pros:
  - ✓ Could be promising for locating the source- generator which has negative damping
  - ✓ Allows distributed implementation
- Cons:
  - ✓ Not robust for forced oscillations
  - ✓ Requires generator's rotor angle and speed measurements additionally to terminal voltage and current

Other Methods

- Statistical signature of FO differs from natural oscillations. Location with maximal kurtosis can be helpful to indicate the Source
- Fitting measurement data into a generalized linear based model
- Artificial Intelligence based method by offline training the decision tree
- Hybrid based method analyzes the difference between model and actual measurements

- All above methods have not been demonstrated as satisfying the requirements for practically meaningful Source locating methods

Source Locating Tools

Available tools

- Peak-RC: Forced Oscillation Detection and Source Locating (FODSL) tool
- ISO-NE: Oscillation Source Locating (OSL) tool

Tool with a feature to trace the Source

- BPA: Oscillation Detection (OD) application

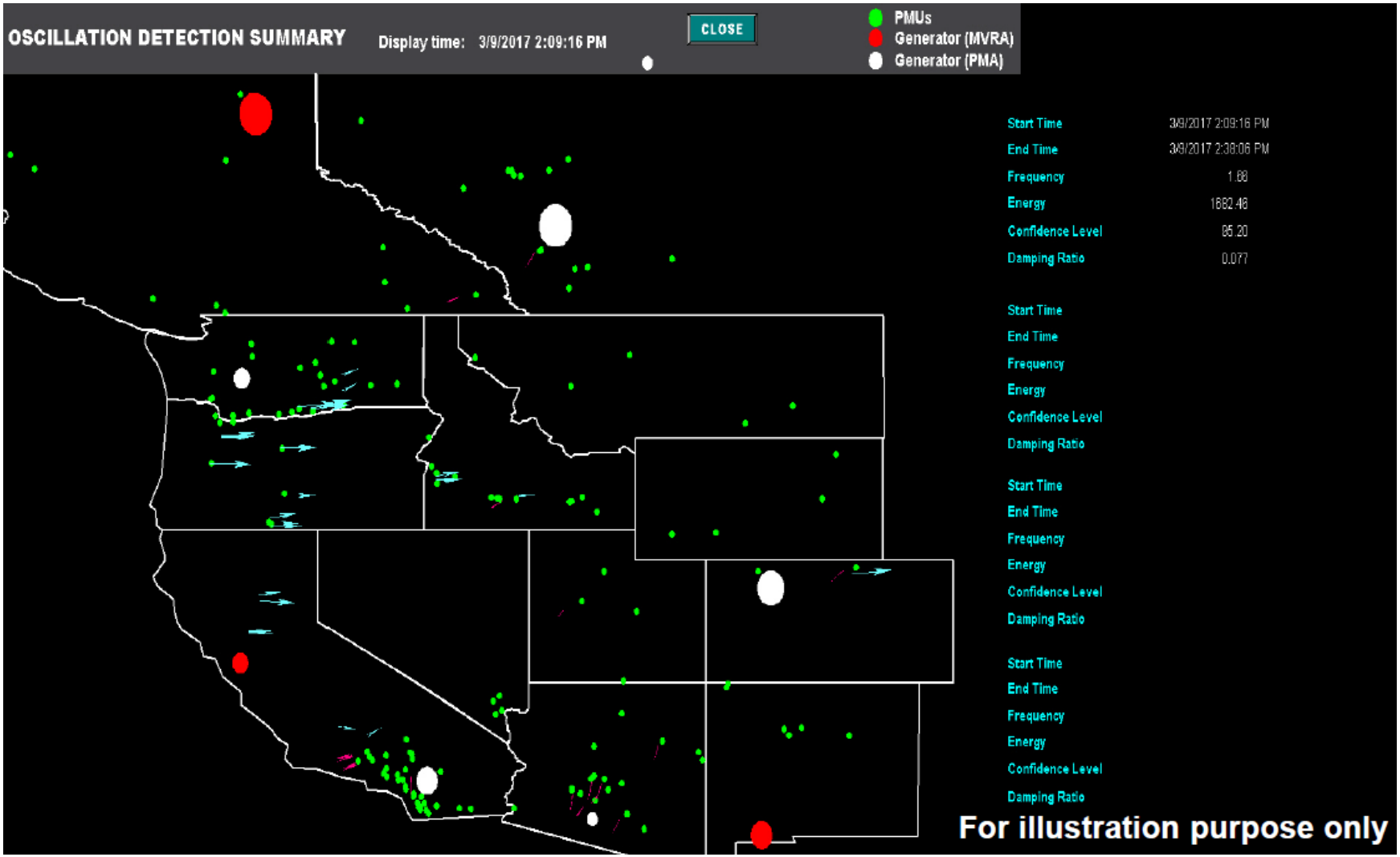
Announced for release

- GE: Feature in the PhasorPoint application

Forced Oscillation Detection and Source Locating (FODSL) tool

- Vendor/Developer: Peak-RC and Washington State University
- Principle for Source locating: Magnitude of oscillations by using SCADA
- Status of development: - Offline version is available;
  - Online version (RT-FODSL) under development
- How the Source is reported: List of ranked suspect-sources
- Pros: Observability of practically all generators
- Cons: - Inefficient for resonance conditions
  - Can be effective only for SCADA collected for entire interconnection
  - Requires to know start and end time of oscillations
  - Inefficient for short (< 1-2 min) and long (continuous) oscillations

Mockup of Expected FODSL User Interface



Oscillation Source Locating (OSL) tool

- Vendor/Developer: ISO-NE
- Principle for Source locating: Energy- based method
- Status of development: Prototype online version is deployed; 09/2017
- How the Source is reported: Exact area/substation/generator
- Pros: - Efficient for majority of practical situations including resonance conditions
  - Fully automated online version; run is triggered by PhasorPoint's Alarm
  - Detects the Source outside of control area
  - Useful results even for partial PMU availability
- Cons: - Resolution of results is limited to the system observability by PMU

Example of email with online OSL Results

WARNING - PhasorPoint Alarms Notification

DoNotReply@iso-ne.com

Sent: Tue 9/12/2017 6:14 AM

To:

Message | DE20170912_060339.csv (438 B) | P_DE20170912_060339.jpg (15 KB) | DE20170912_060339.jpg (770 KB)

*** This message has been automatically generated - DO NOT REPLY ***

Computer: [redacted]; PhasorPoint has issued 1 oscillation Alerts/Alarms for the 30 seconds interval.

Time interval: [2017-09-12 06:03:36 - 2017-09-12 06:04:06]

---------- Alarm ----------

Signal Used: [P]

Frequency Band: [1.13-4.0 Hz]

Message: [PDX1-3 event status alarm]

Mode Frequency: [1.138 Hz]

Mode RMS Amplitude: [17.2 MW]

Mode Damping Ratio: [1.5 %]

Parameters of oscillations

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Oscillation Source Location (OSL) detection summary:

Source: [redacted]

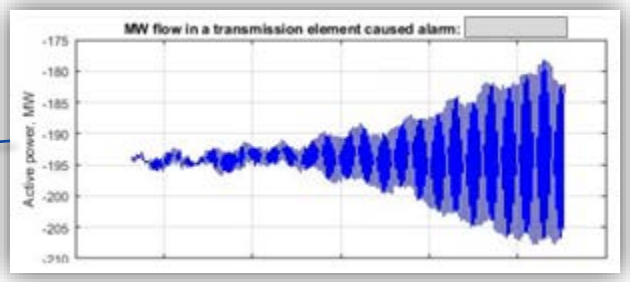
Sufficient time interval for the DEF method was identified

PMU data can be used for the DEF method

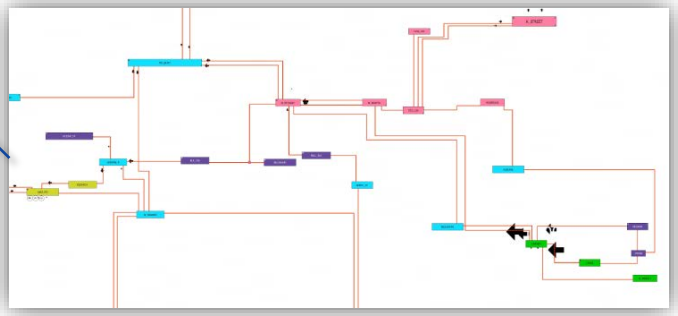
No tripping was detected

Results of DE pattern recognition

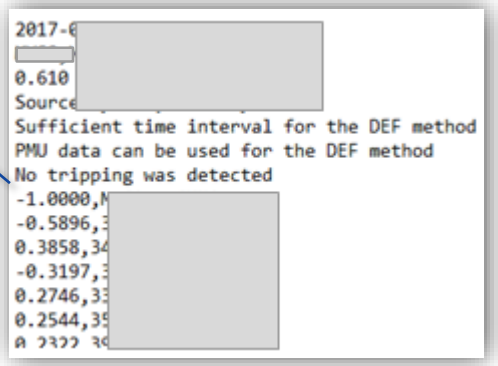
MW flow in line causing Alarm



DE visualization



DE pattern and identified source



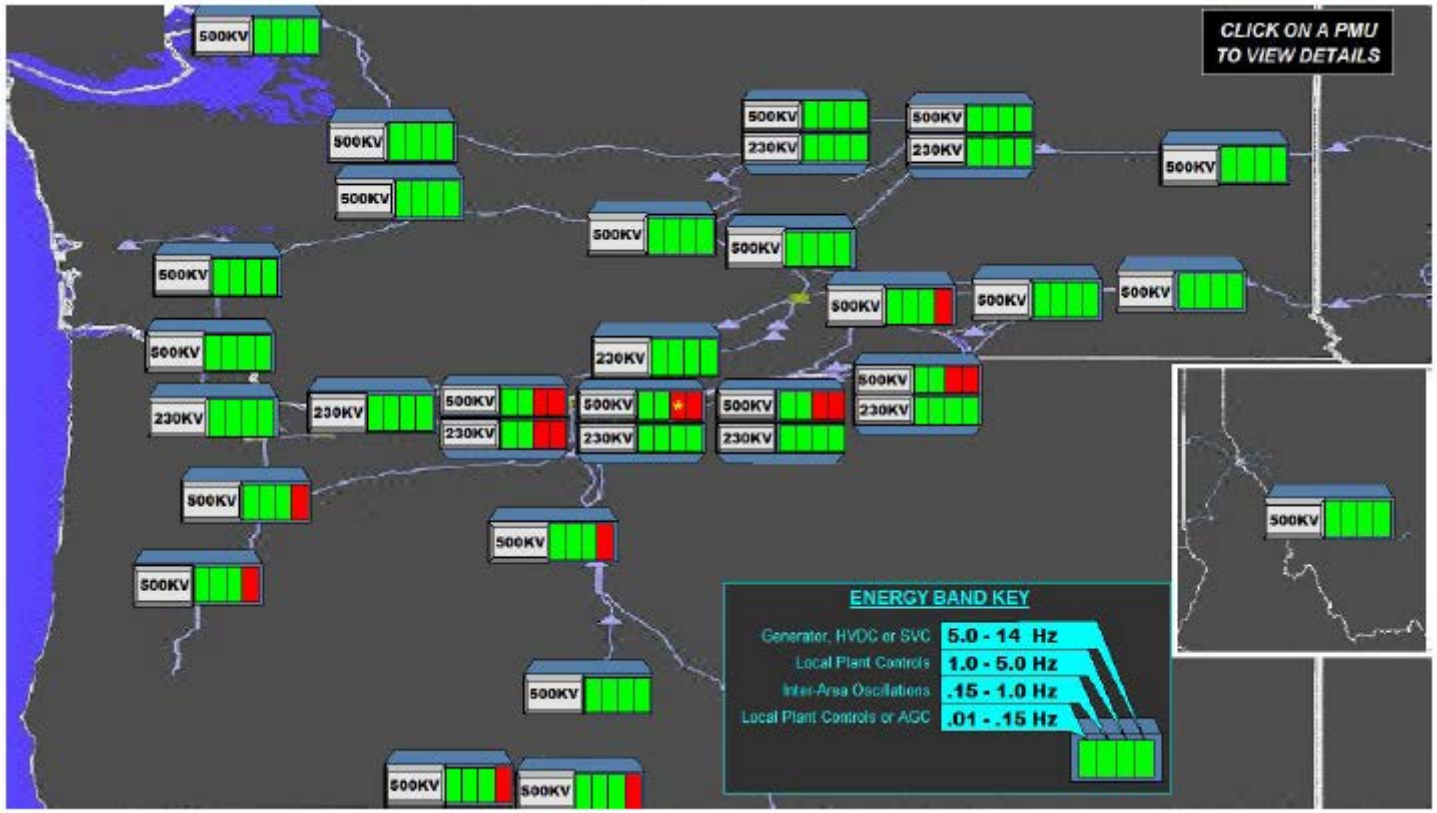
Oscillation Detection(OD) application

- Vendor/Developer: BPA and Montana Tech
- Principle for Source locating: Magnitude of oscillations
- Status of development: Online version is deployed; 06/2016
- How the Source is reported: Suspect Source at a location with the highest energy of oscillations
- Pros: - Efficient for non-resonance conditions

  - Online version with Operating Procedures is in place
- Cons: - Could be misleading for resonance conditions

  - Cannot detect the Source outside of control area

Example of OD results



Feature in PhasorPoint Application

- Vendor/Developer: GE
- Principle for Source locating: Mode shape estimation
- Status of development: Announced for release
- How the Source is reported: no information
- Pros: no information
- Cons: no information

Questions

Statement: The largest magnitude of FO is observed at the Source if there is no resonance conditions* with natural modes

Can Magnitude of Oscillations be Efficient in Finding the Source?

- Yes, if there is no resonance conditions
  - ✓ That is a majority of practically observed situations
- No, if there is resonance conditions and particularly with inter-area modes

Even resonance conditions are infrequent, the risk of making wrong operational decision in real-time is too high. So, the use of the largest magnitude of oscillations as indicator of the Source is unreliable in online environment

* The main resonance condition: Frequency of forced signal is close to frequency of natural mode

Assumption: If I know frequencies of natural modes, then I am able to identify FO not creating resonance conditions as oscillations with frequency different from the frequencies of natural modes

Can FO not creating resonance be reliably identified by looking at the spectra of oscillations?

- No, that is not trivial. Frequencies of natural modes fluctuate with operating conditions and topology

Histogram of oscillations in ISO-NE system during 24 hours. The spectra was estimated every 5 seconds