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Oscillation Source Locating Tool at ISO New England

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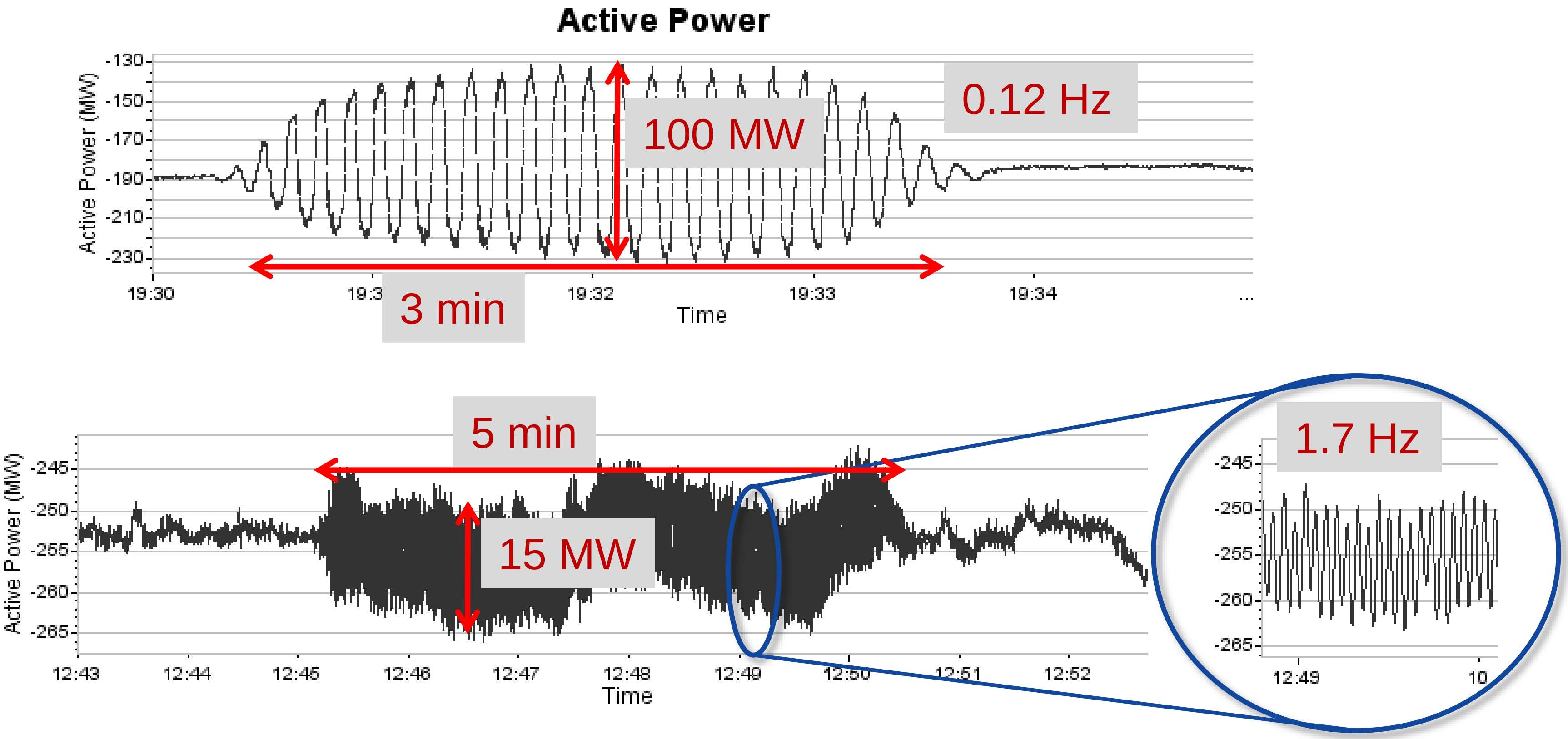
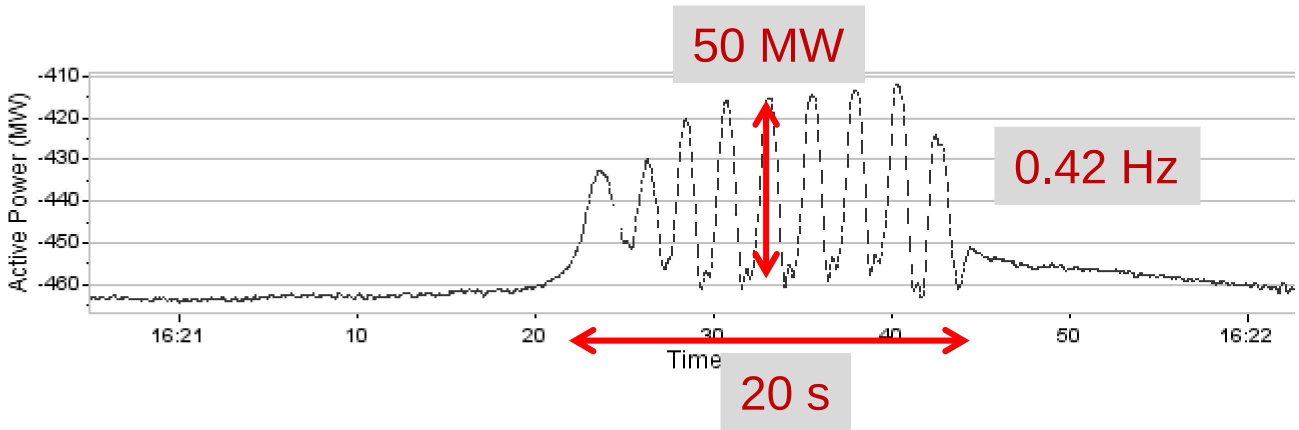
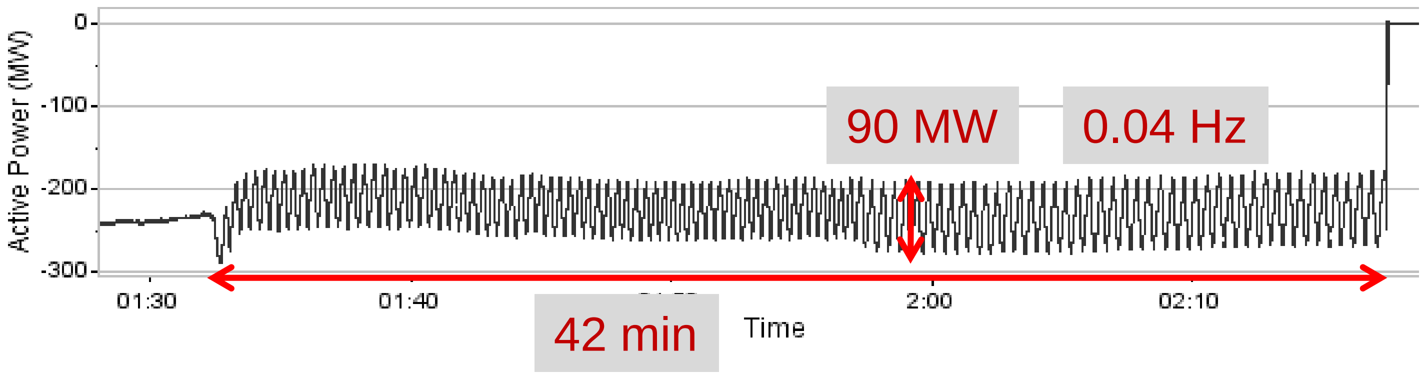
PMUs have enabled Oscillation monitoring

- 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





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.

Before the accident

After the accident

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

A number of mitigation measures can be applied depending on situation

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

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

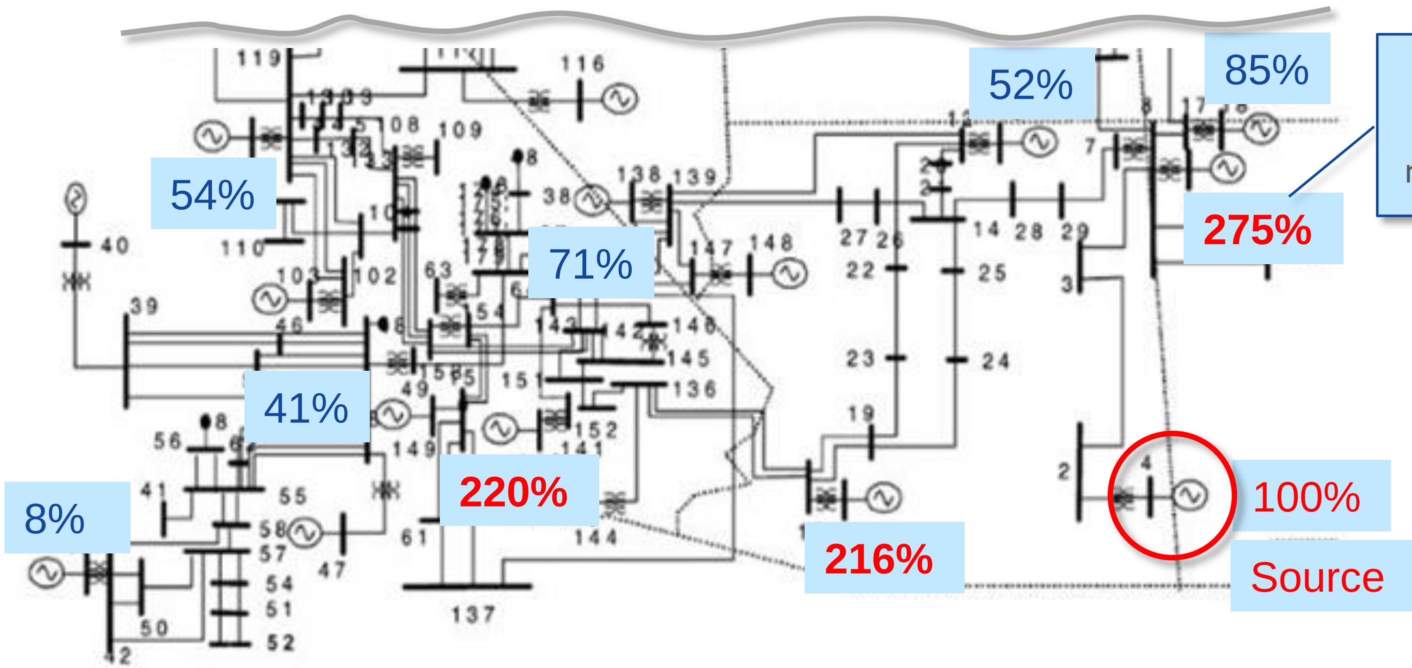
Which of my neighbors is the suspected area?

Actions to find the Source outside of the control area

“Find the Source” means to answer the above questions and provide the **<u>Actionable Information</u>** 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



Magnitude of MW oscillations as % of magnitude at Source

* 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

[*] Slava Maslennikov, Bin Wang, Eugene Litvinov “Dissipating Energy Flow Method for Locating the Source of Sustained Oscillations”, to appear Electrical Power and Energy Systems, Issue 88, 2017, pp.55-62

[**] L Chen, Y Min, W Hu, “An energy-based method for location of power system oscillation source,” *IEEE Transaction on Power Systems*, 28(2):828-836, 2013

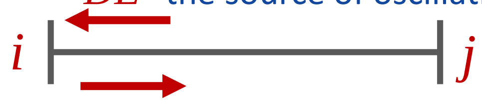
How does the DEF method work?

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

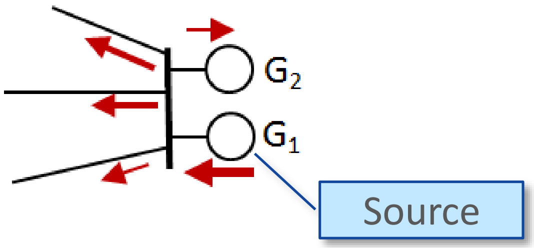
$$W_{ij}{}^{D}(t) \approx DE_{ij} \cdot t + b_{ij}$$

- 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

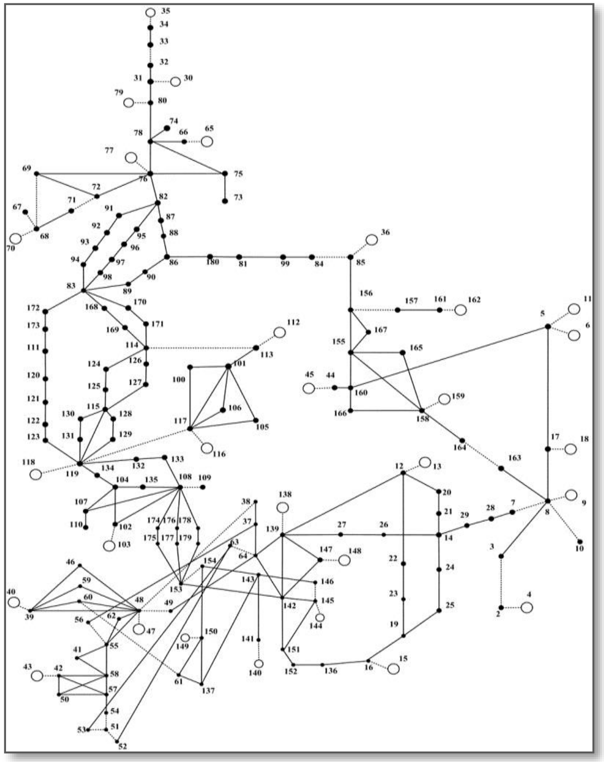
Qualification test to verify the idea

  - ✓ 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

Real test for entire process

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/

The DEF method Test Results

- Simulated cases - test case library of sustained oscillations

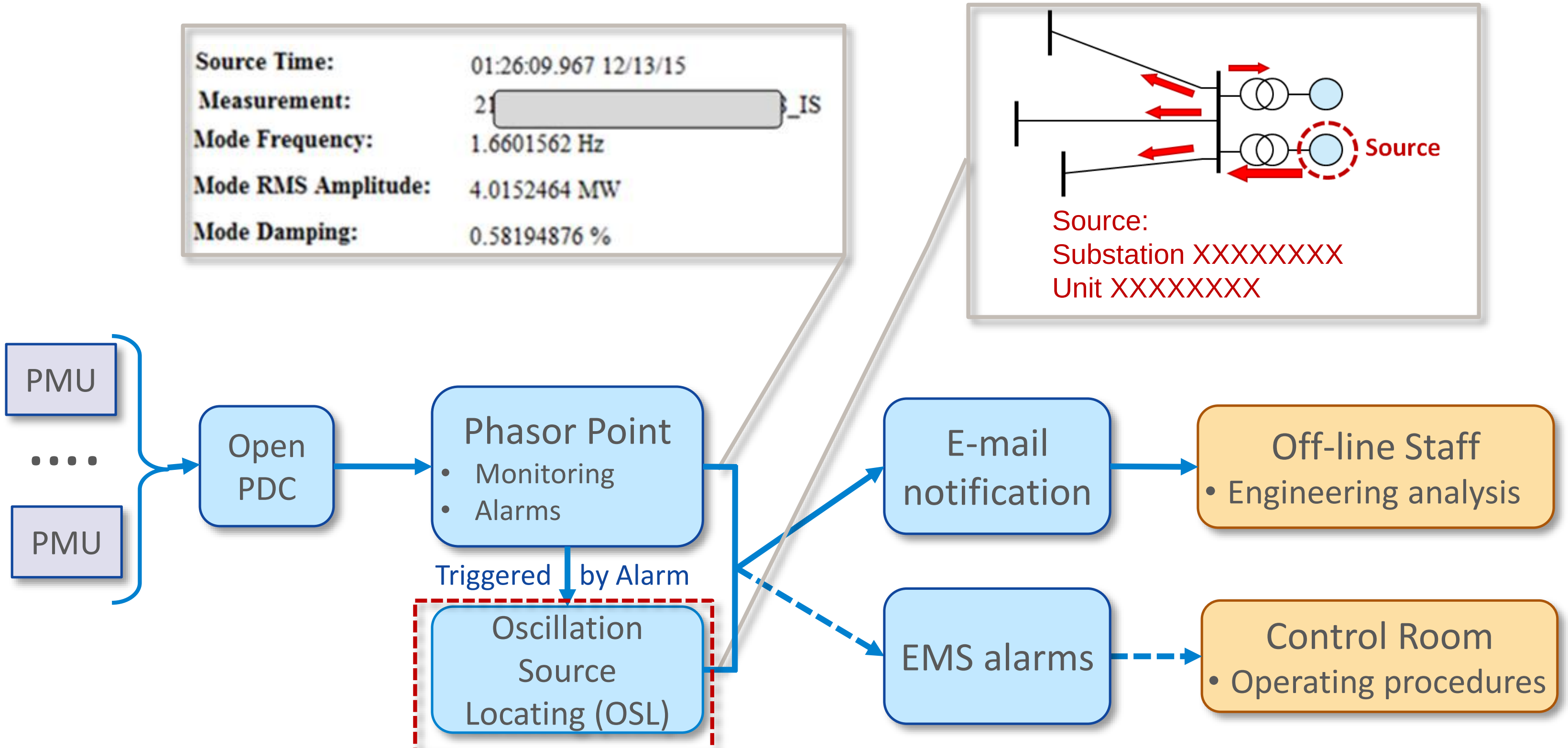
Description	Test Results
All 9 cases of poorly damped natural oscillations	Pass ✓
All 14 cases of forced oscillations	Pass ✓

- Actual events in ISO-NE and WECC

Description	Test Results
More than 30 cases from ISO-NE	Pass ✓
Two cases from WECC	Pass ✓

Online Oscillation Management concept at ISO-NE

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



Online OSL tool

Alarm by PhasorPoint
- Time
- Location
- Frequency

PMU database

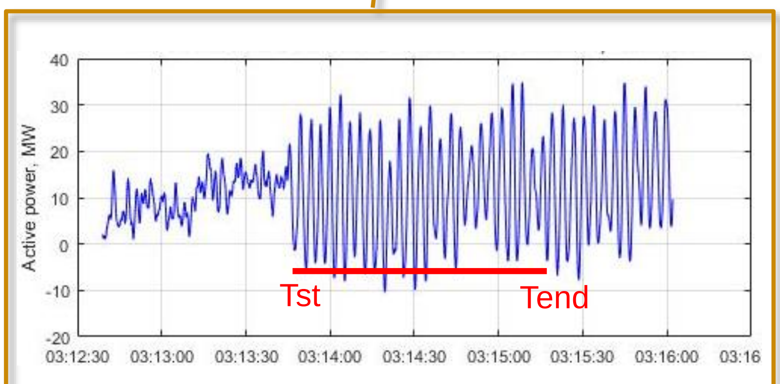
Identification of time interval for analysis [Tst Tend]

Extract PMU data for [Tst Tend]

Calculate DE flow in monitored elements

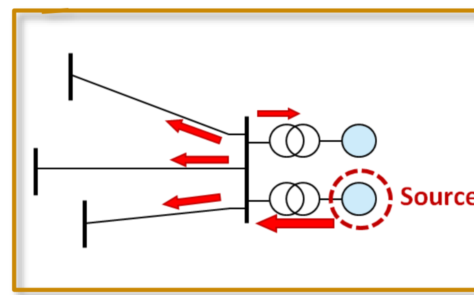
DE pattern recognition: identify source

Suspect Source
Substation: xxxxxxxx
Unit: xxxxxx



DE, p.u.	LineID
-1.00	3533@
0.50	376@
-0.39	t1x@
-0.38	3424@
0.36	3041@
-0.31	3041@
0.26	3827@
-0.24	362@
0.21	398@
-0.18	3619@
0.18	329@
-0.18	3165@

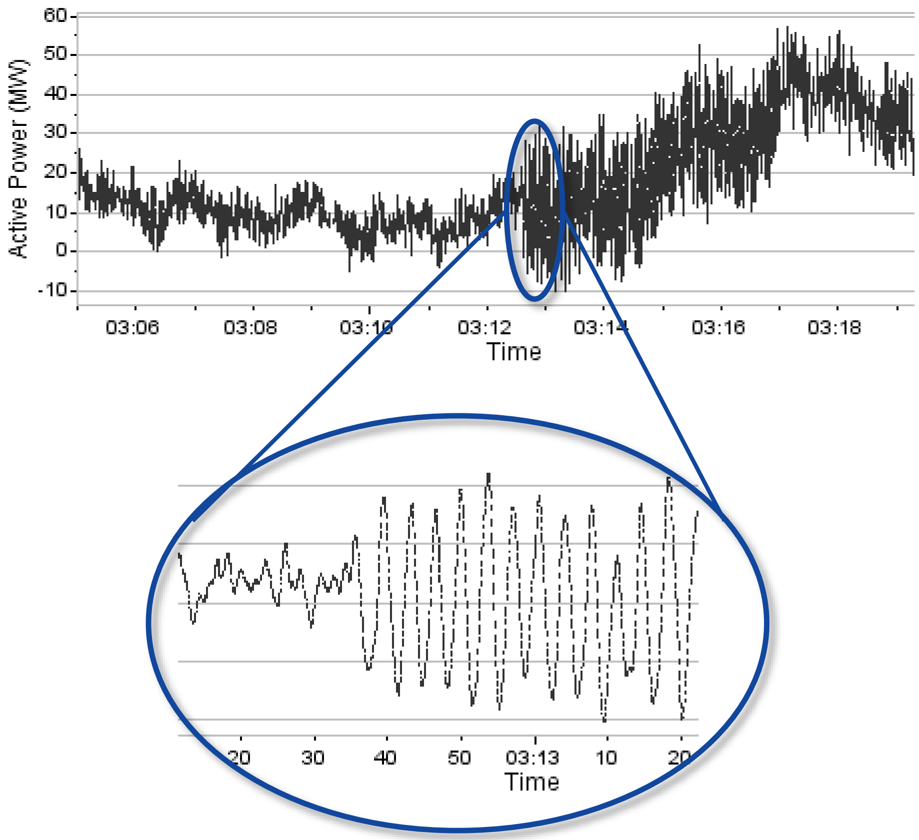
Visualization



Forced Oscillations (FO) Originated Outside ISO-NE

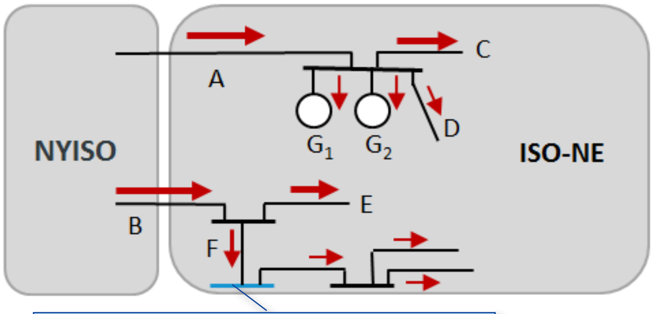
- June 17,2016; oscillations of 0.22-0.28Hz, up to RMS=11MW observed in many locations of ISO-NE during 45 minutes

Time domain data



Results of the DEF method

DE flow in 345kV lines at NE-NY border



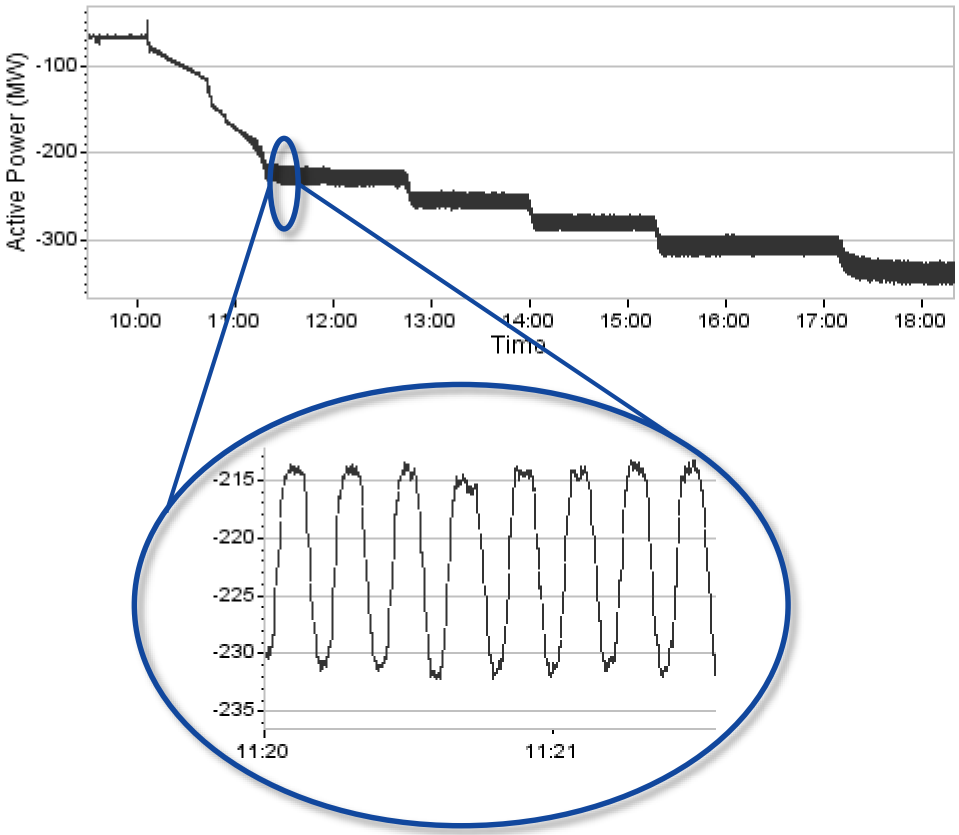
DE flow indicates that the source is located outside ISO-NE

Ability to identify whether the Source located Inside or Outside of control area

FO Originated from a Combined Cycle Unit, 0.08Hz

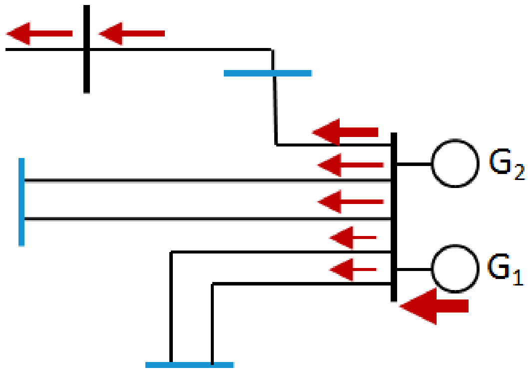
- October 3, 2016; oscillations of 0.08Hz, RMS=7MW observed around a big power plant with Combined Cycle units

Time domain data



Results of the DEF method

DE flow in 345kV lines around suspect power plant

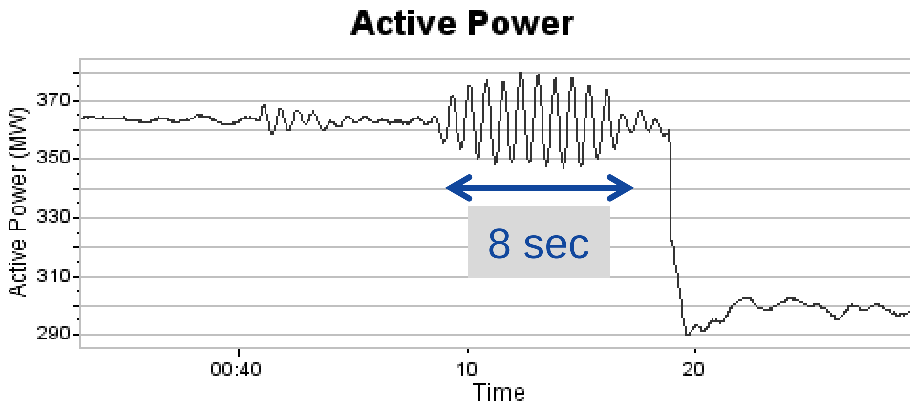


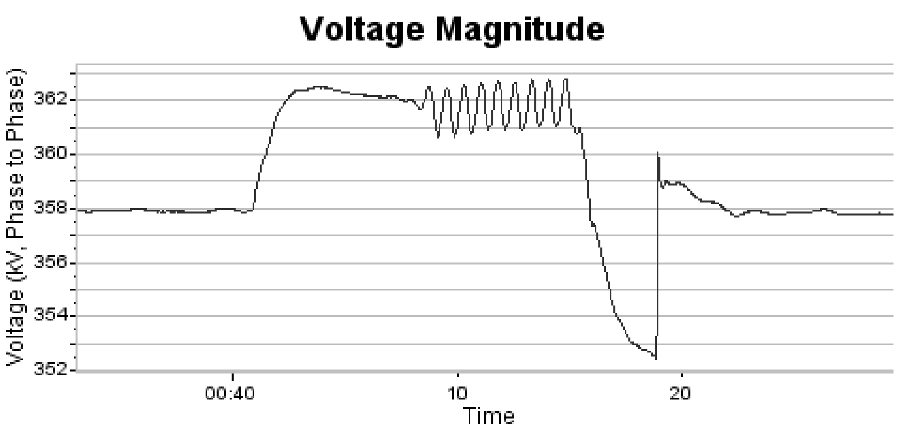
DE flow indicates G1 as the source

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





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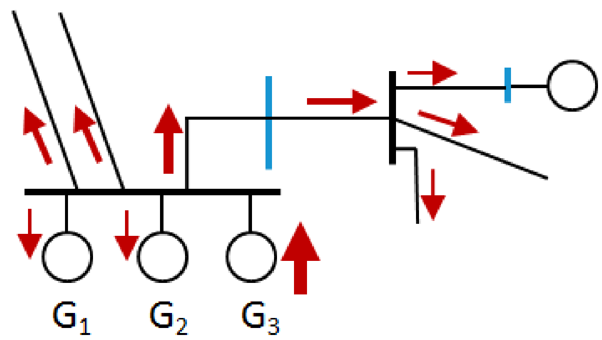
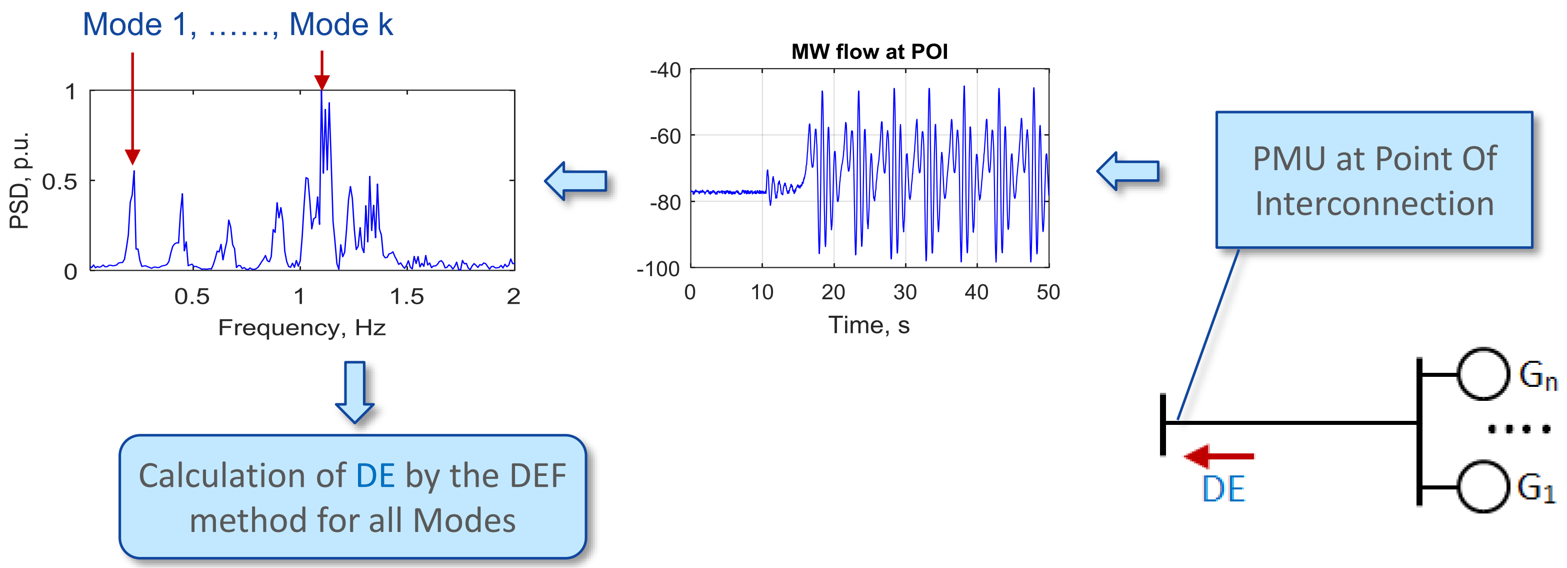


DE flow indicates G3 as the source

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



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