Test Cases Library and Real-life Oscillation Examples

Kai Sun[1], Bin Wang[2], Slava Maslennikov[3]

1- University of Tennessee, 2- Texas A&M University, 3- ISO New England

Paper No. 18PESGM0563

2018 IEEE PES General Meeting, Portland, OR

Power & Energy Society®

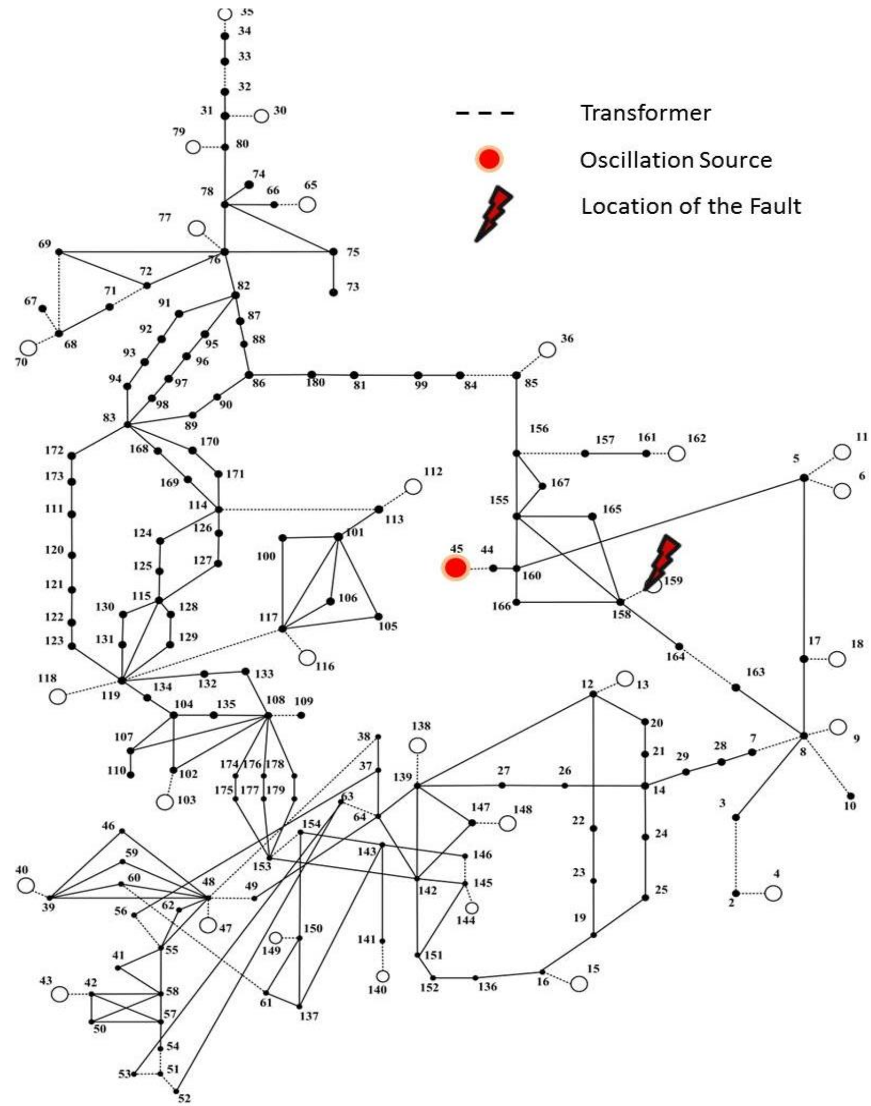
Test Cases Library of Sustained Oscillations

- Website: http://curent.utk.edu/research/test-cases/ or http://web.eecs.utk.edu/~kaisun/Oscillation/
  - Fall 2016: initiated at ISO New England and launched with 23 simulated cases on both natural and forced oscillations
  - Winter 2017: Added 4 more simulated cases to enrich forced oscillation cases
  - Spring 2018: Added 5 actual oscillatory events
  - 4000+ visits in past two years
- Objective: Facilitating the development and testing of methods and tools for identifying the source of poorly damped or forced power system oscillation.
- Test Cases
  - **Simulated oscillation cases** on a WECC 179-bus system model in PSS/E V30
  - **Actual oscillatory events** recorded by PMUs on multiple locations
- White paper:

[1] S Maslennikov, B Wang, Q Zhang, F Ma, X Luo, K Sun, E Litvinov, "A test cases library for methods locating the sources of sustained oscillations" 2016 IEEE PES General Meeting

Simulated Cases

- WECC 179-bus system model
  - 179 buses
  - 29 generators
  - 263 branches, including lines and transformers
  - 28 oscillatory modes: 0.26 to 1.88 Hz
- 27 oscillation cases:
  - 9 natural oscillations (poorly damped or undamped)
  - 18 forced oscillations driven by injected periodical signals

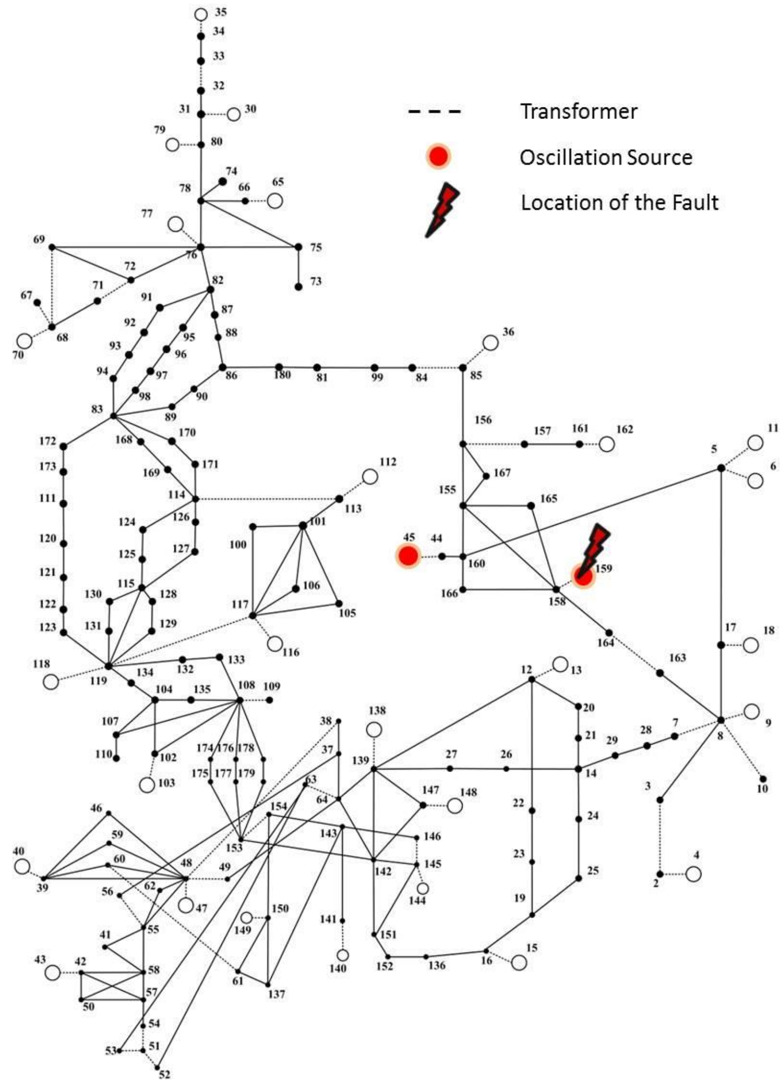


Natural Oscillation Cases

Case #	D	Frequency/Hz	Damping	Source location	Fault location	Description
ND_1	D45=-2 D159=1	1.41	0.01%	45	159	Single source - single local mode
ND_2	D35=0.5 D65=-1.5	0.37	0.02%	65	79	Single source - single inter-area mode
ND_3	D6=2 D11=-6	0.46 0.70 1.63	2.22% 1.15% -0.54%	11	30	Single source - one unstable local mode and two poorly damped inter-area modes
ND_4	D6=5 D11=-9	0.46 0.70 1.63	0.68% -0.58% 0.54%	11	6	Single source - one unstable inter-area mode and two poorly damped local and inter-area modes
ND_5	D6=3 D11=-8	0.46 0.70 1.63	0.69% -0.19% -0.48%	11	30	Single source - two unstable local and inter-area modes, and one poorly damped inter-area mode
ND_6	D45=-2 D159=-0.5	1.41	-0.93%	45&159	159	Two sources with comparable contribution into a single unstable local mode
ND_7	D45=-0.5 D159=-0.5	1.41	-0.40%	45&159	159	Two sources with different contributions into a single unstable local mode
ND_8	D45=-2.5 D159=1 D36=-1	1.27 1.41	-1.06% -0.22%	45&36	159	Two sources - two unstable local modes
ND_9	D11=-10	0.46 0.69 1.63	-0.86% -1.81% -0.40%	11	79	Single source - three unstable modes

Example: Natural Oscillation ND_6

- **System model:**
  - All generators in GENCLS model.
  - All loads in constant MVA model.
  - D= -2 and -0.5 for generators 45 & 159.
  - D=4 for all other generators.
- **Disturbance:**
  - Small 3-phase fault on bus 159 cleared after 0.01s.
- **Oscillation Sources:**
  - Generators 45 & 159 with comparable contributions into an unstable local mode (1.41Hz with a negative damping ratio of -0.93%).



Forced Oscillation Cases

Periodical signals injected into generators' exciters or governors

- Sinusoidal or non-sinusoidal signals
- With or without resonance

- **Forced signal is injected into the excitation system of a generator**

Case #	Type of injected signal	Frequency of first harmonic/Hz	Source location	Description
F_1	Sinusoidal	0.86	4	Resonance with local 0.86Hz mode
F_2	Sinusoidal	0.86	79	Resonance with local 0.86Hz mode
F_3	Sinusoidal	0.37	77	Resonance with inter-area 0.37Hz mode
F_4_1	Sinusoidal	0.81	79	Forcing frequency is below natural 0.84Hz mode
F_4_2	Sinusoidal	0.85	79	Forcing frequency is between natural 0.84Hz and 0.86Hz modes
F_4_3	Sinusoidal	0.89	79	Forcing frequency is higher than natural 0.86Hz mode
F_5_1	Sinusoidal	0.42	79	Forcing frequency is below natural 0.44Hz inter-area mode
F_5_2	Sinusoidal	0.46	79	Forcing frequency is between natural 0.44Hz and 0.47Hz inter-area modes
F_5_3	Sinusoidal	0.50	79	Forcing frequency is higher than natural 0.47Hz inter-area mode
F_6_1	Periodic, rectangular	0.1	79	Spectra of forced harmonics consist of 0.1Hz, 0.3Hz, 0.5Hz, 0.7Hz, etc modes
F_6_2	Periodic, rectangular	0.2	79	Spectra of forced harmonics consist of 0.2Hz, 0.6Hz, 1Hz, 1.4Hz, etc modes
F_6_3	Periodic, rectangular	0.4	79	Spectra of forced harmonics consist of 0.4Hz, 1.2Hz, 2Hz, etc modes
F_7_1	Sinusoidal	0.65 0.43	79 118	Two sources of forced signals creating resonance with two different modes, respectively
F_7_2	Sinusoidal	0.43	70 118	Two sources of forced signals creating resonance with the same mode

- **Forced signal is injected into the governor of a generator**

Case #	Type of injected signal	Frequency of first harmonic/Hz	Source location	Description
FM_1	Sinusoidal	0.86	4	Resonance with local 0.86Hz mode
FM_3	Sinusoidal	0.37	77	Resonance with inter-area 0.37Hz mode
FM_6_2	Periodic, rectangular	0.2	79	Spectra of forced harmonics consist of 0.2Hz, 0.6Hz, 1Hz, 1.4Hz, etc modes
FM_7_1	Sinusoidal	0.65 0.43	79 118	Two sources of forced signals creating resonance with two different modes, respectively

Example 1: Forced Oscillation F_1

In this forced oscillation case, the source of oscillations is at generator 4.

System model:

- Generator 4 is in GENROU model.
- All other generators are in GENCLS model.
- Parameter D for all generators equals 4, except for generator 4 whose D equals 0.
- All loads are in constant MVA model.

Small signal analysis:

- All natural modes have reasonably good damping.
- The system has a natural mode at 0.86Hz.

Sinusoidal signal injected into an exciter to cause resonance

External force:

- Forced oscillation is injected into excitation system as a sinusoidal signal at generator 4 with a frequency 0.86Hz to cause resonance.
- The gain of the external force is tuned such that the largest peak-to-peak value among all generators' active power outputs is about 157MW.

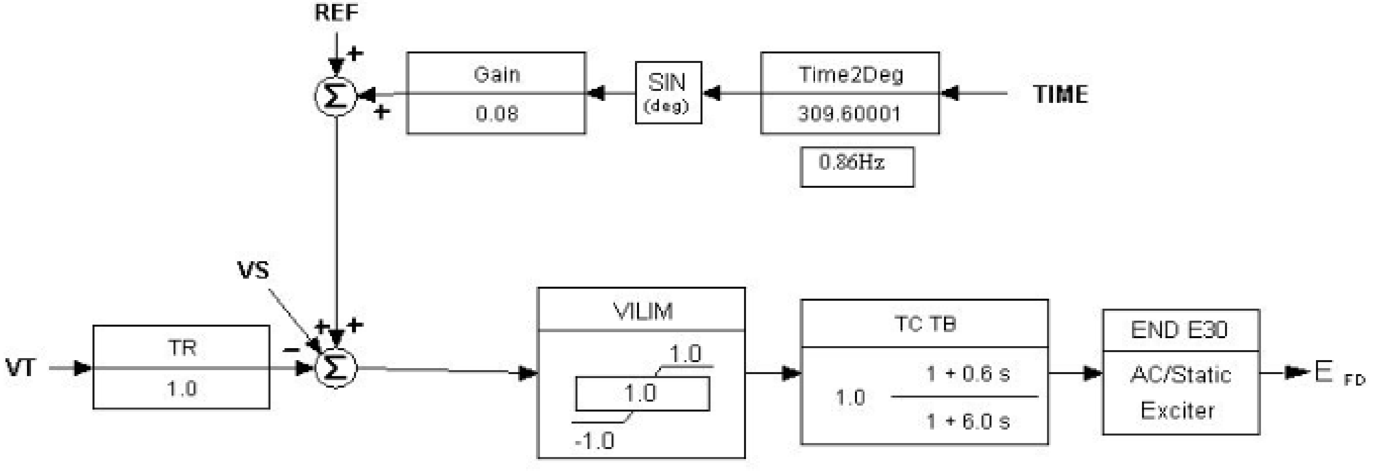


Figure 1. Block diagram of the external force

Example 2: Forced Oscillation FM_1

In this forced oscillation case, the source of oscillations is at the governor of generator 4.

System model:

- All the generators are in GENCLS model.
- Parameter D for all generators equals 4.
- All loads are in constant MVA model.

Small signal analysis:

- All natural modes have reasonably good damping.
- The system has a natural mode at 0.86Hz.

Sinusoidal signal injected into a governor to cause resonance

External force:

- Forced oscillation is injected into the governor of generator 4 as a sinusoidal signal at frequency 0.86Hz to cause resonance.
- The gain of the external force is 0.3 p.u.
- Due to resonance, MW oscillations of generator 9 (which is not the source) is much larger than in generator 4 (source).

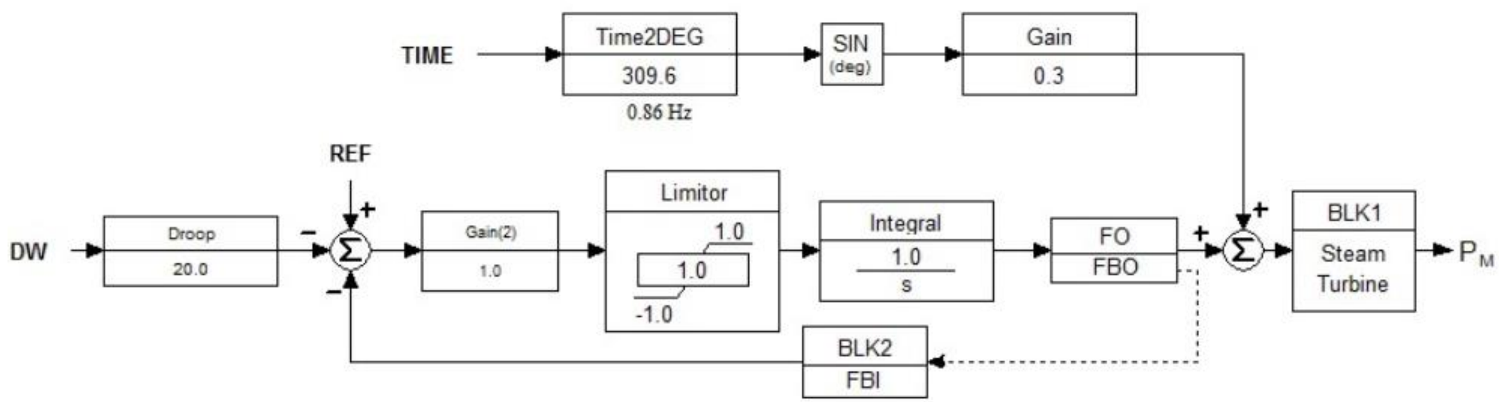


Figure 1. Block diagram of the external force

Illustrations of three existing source locating methods on simulated cases

Existing methods [2]	Assumption on the source
Damping torque	**The generator with a negative damping torque coefficient**
Mode shape	**Largest magnitude or most leading phase in mode shape**
Energy-based method	**The device producing dissipation energy**
Equivalent circuit	The source of an equivalent circuit
Hybrid	Measurement has the largest difference from simulation
Traveling wave	The starting point of the electromechanical wave
Machine learning	Located using a decision tree trained by offline simulation

[2] Bin Wang, Kai Sun, "Location Methods of Oscillation Sources in Power Systems: A Survey," Journal of Modern Power Systems and Clean Energy, 2016

Damping Torque Method [3]

- Estimate the damping torque for each generator about the dominant mode
- Generator with a negative damping torque coefficient is the source
- Data requirement: P_G, f_t and θ_t

- Case ND_1
  - Actual source: Bus 45
  - Identified source: Bus 45
- Case F_1
  - Actual source: Bus 4
  - No source identified

Case #	(Generator, K_{md})
ND_1	(G45, - 1.81) (G*, 0.91 to 7.89)
F_1	(All generators, 1.88 to 3.98)

G* represents all generators in the system except for G45.

[3] Li Y, Huang Y, Liu J, et al, "Power system oscillation source location based on damping torque analysis." Power System Protection and Control, 43(14):84-91, 2015

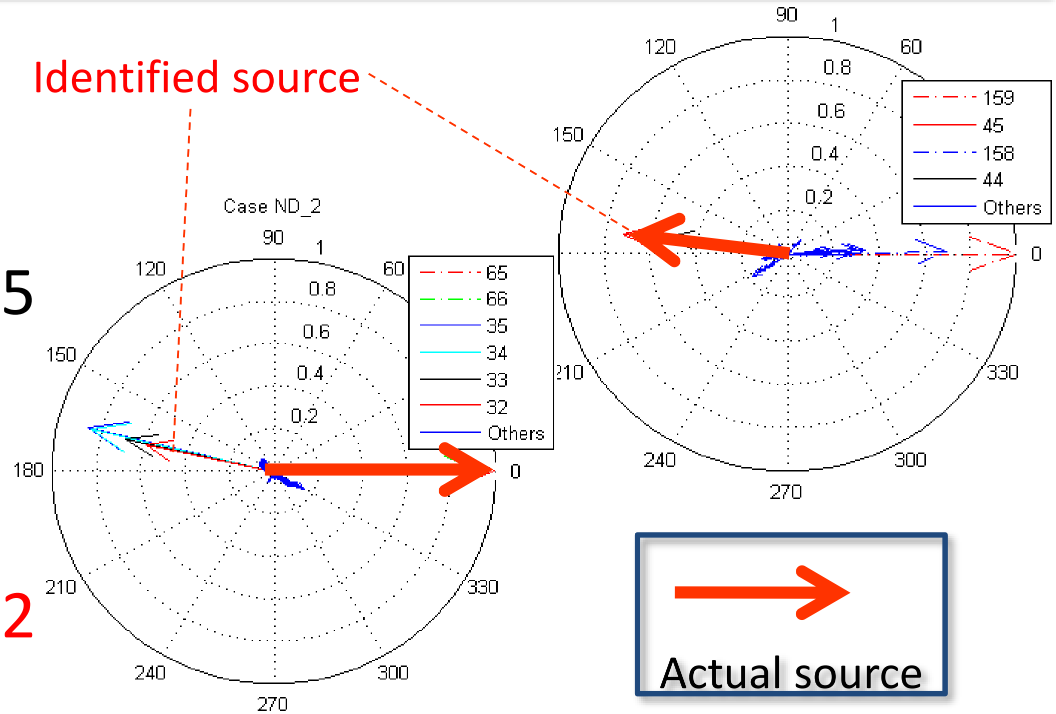
IEEE PES Power & Energy Society®

IEEE

Mode Shape Method [4]

- Calculate mode shape phase and amplitude using PMU data
- Identify two opposing groups oscillating against each other
- The leading phase in the leading group is the source

- Case ND_1
  - Actual source: Bus 45
  - Identified source: Bus 45
- Case ND_2
  - Actual source: Bus 65
  - Identified source: Bus 32



[4] N Ashwal, D Wilson, M Parashar, "Identifying sources of oscillations using wide area measurements," Grid of the Future Symposium, CIGRE US National Committee, 2014

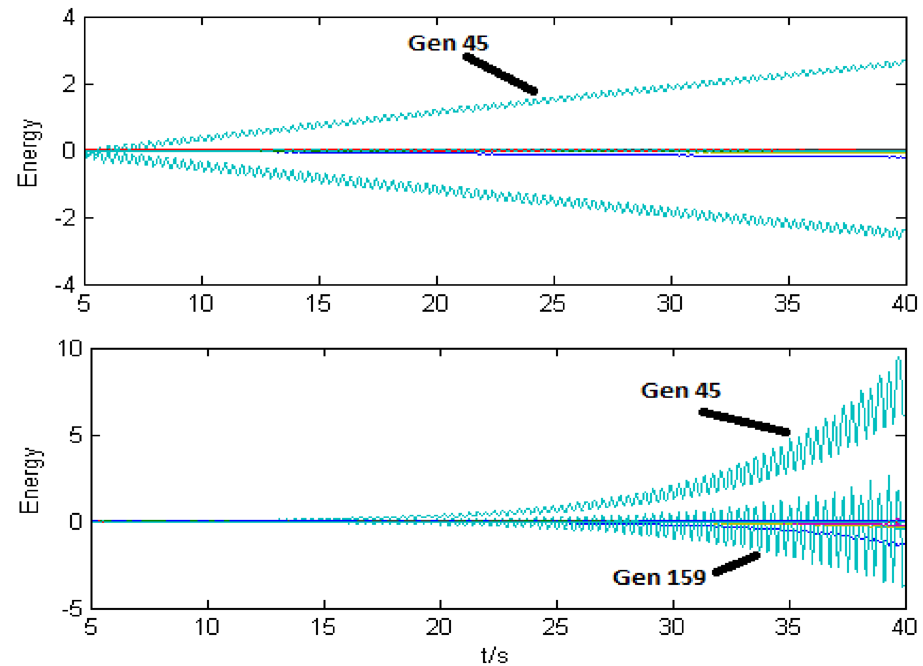
IEEE PES Power & Energy Society®

IEEE

Energy-based Method [5]

- Calculate dissipation energy (DE) on the terminal of each generator
- Generator with increasing DE is the source
- Data requirement: P_G, Q_G, V_t and θ_t

- Case ND_1
  - Actual source: Bus 45
  - Identified source: Bus 45
- Case ND_6
  - Actual sources: Buses 45&159
  - Identified source: Bus 45



[5] 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

Actual Oscillatory Events

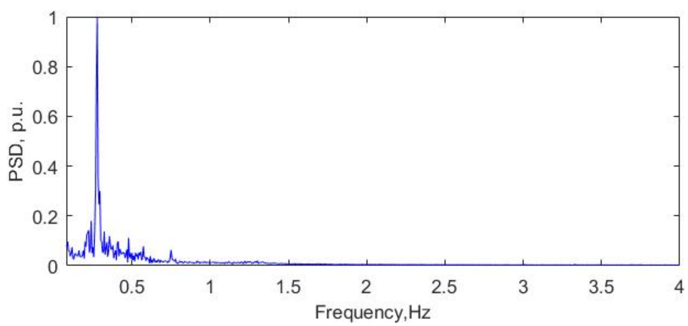
- Using the data format suggested by IEEE PES Oscillation Source Location Taskforce (the effort was led by Slava Maslennikov)
- Five Eastern Interconnection events recorded by ISO-NE PMUs are available now.

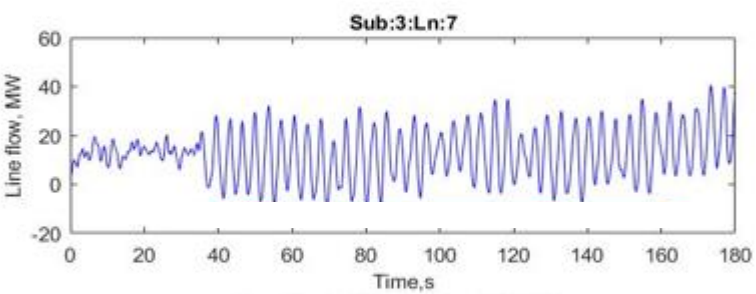
Cases #	Case name	Data of event	Power system - source of PMU	Type of oscillations	Frequency/Hz	Peak to peak magnitude	Source and location	Confidence level on the source location	Duration of sample set	Comments
1	ISO-NE case 1	Jun.17, 2016	ISO-NE	System-wide mode	0.27	Up to 27 MW	Generator outside of ISO-NE in Area 2.	100%	3 min	Near-resonance conditions with system-wide natural oscillatory mode caused by a large generator located in Area 2. Area map: ISO-NE_map.pdf.
2	ISO-NE case 2	Oct.3, 2017	ISO-NE	Multi-frequency, wide-spread	Dominant modes: 0.08 0.15 0.31	Up to 130 MW	Generator outside of ISO-NE in Area 3.	100%	6 min	Multi-frequency process with growing magnitude caused by a generator located outside of ISO-NE in Area 3. Oscillations with significat MW magnitude were observed in multiple locations. Area map: ISO-NE_map.pdf.
3	ISO-NE case 3	Jul.20, 2017	ISO-NE	Regional	1.13	Up to 115 MW	Generator located East from Sub:2. Lines Ln:2 and Ln:4 lead to the area, where the source generator resides.	100%	3 min	Equipment issue in a large generator has created 1.13Hz oscillations with growing magnitude during 40 seconds.
4	ISO-NE case 4	Feb.14, 2018	ISO-NE	Wide-spread	0.25	Up to 10 MW	Presumably outside of ISO-NE.	Low	5 min	Sustained oscillations with variable magnitude and observed in multiple locations.
5	ISO-NE case 5	Jan.29, 2018	ISO-NE	Local	1.57	Up to 15 MW	Generator Gen2 at Sub:7.	100%	4 min	Local oscillations caused by a large generator. Area map: ISO-NE_map.pdf.

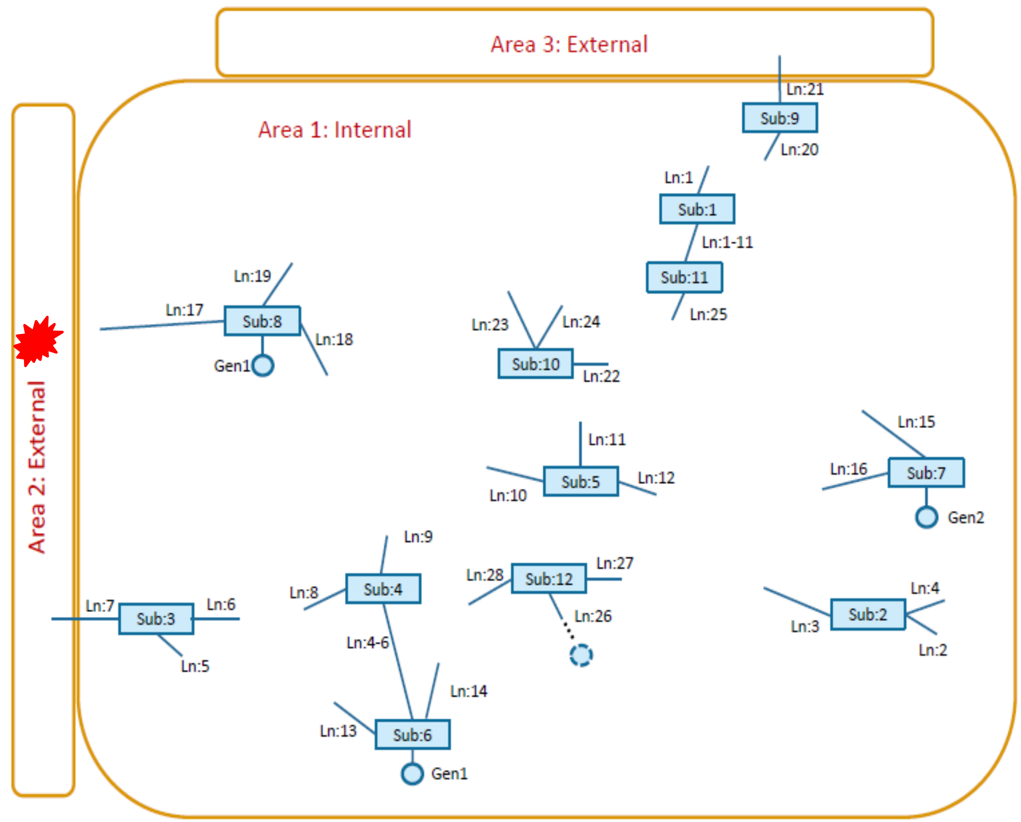
Example 1: June 17, 2016 Event

- Near-resonance condition with system-wide natural oscillation caused by a large unit in Area 2.

Case name	Date	Source of PMUs	Type of oscillation	Freq./Hz	Peak to peak magnitude	Source and location	Confidence level on the location	Duration
ISO-NE case 1	Jun.17, 2016	ISO-NE	System-wide mode	0.27	Up to 27 MW	Generator outside of ISO-NE in Area 2.	100%	3 min



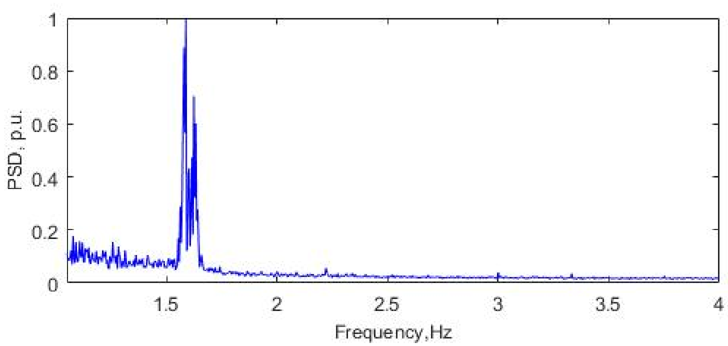


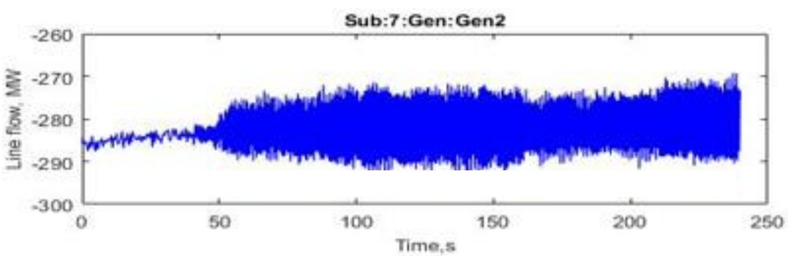


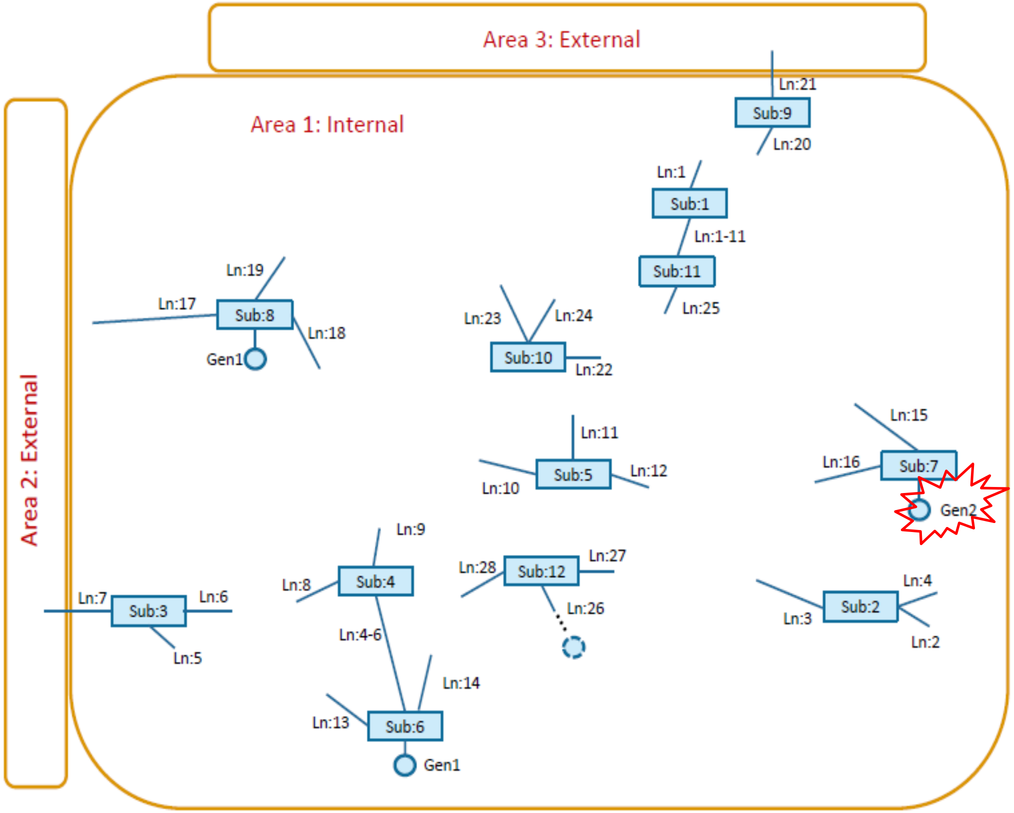
Example 2: Jan 29, 2018 Event

- Local oscillations caused by a large internal unit.

Case name	Date	Source of PMUs	Type of oscillation	Freq./Hz	Peak to peak magnitude	Source and location	Confidence level on the location	Duration
ISO-NE case 5	Jan.29 2018	ISO-NE	Local	1.57	Up to 15 MW	Generator 2 at Sub: 7	100%	4 min







Next Steps

- Encouraging more uses of the library
- Looking for more real oscillation events
- More comparison tests on existing methods using the simulated/real cases
- Adding cases caused by renewables

Q&A

- Contact Information:

Kai Sun (University of Tennessee)
kaisun@utk.edu

Slava Maslennikov (ISO New England)
smaslennikov@iso-ne.com