NASPI MARCH 23, 2016

A Test Cases Library for methods locating the sources of sustained oscillations

KAI SUN & BIN WANG

UNIVERSITY OF TENNESSEE

SLAVA MASLENNIKOV,

FRANKIE ZHANG & XIAOCHUAN LUO

ISO NEW ENGLAND

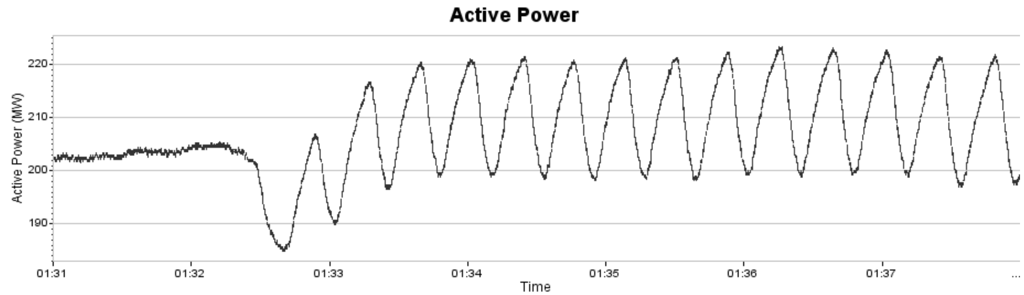
Outline

- Motivation
- Test system
- Process of creating test cases and simulated PMU
- Covered situations – natural and forced oscillations
- Examples of using library
- Future plans

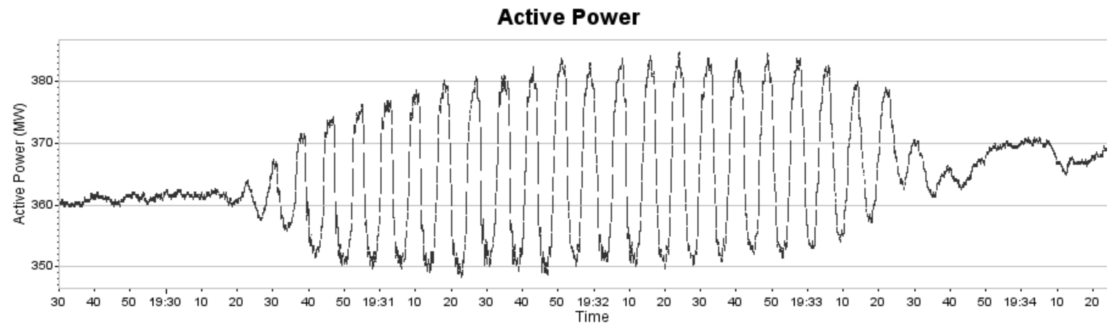
Motivation

- PMU measurements detect instances of sudden occurrence of poorly damped oscillations with high MW magnitude and frequency from 0.02 Hz to 5-20 Hz

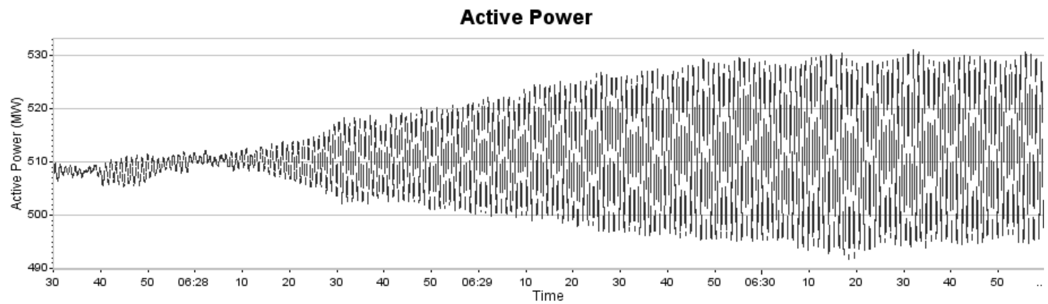
- 0.04 Hz



- 0.12 Hz



- 0.93 Hz



Motivation, cont.

- The Source of initiation of oscillations remains often unknown. Oscillations cannot typically be replicated by the model.
- Finding the Source of “bad damping”/“forced oscillations” has to rely on PMU measurements
- Best mitigation approach is to find the Source and fix it
- Need methods that can locate the Source of sustained oscillations regardless of the nature of oscillations - forced or natural poor damped
- Source locating algorithms must be first verified with simulated data where the answer is known

Natural vs. Forced oscillations

Natural

- Inherent dynamic property of power systems
- Poor damping is typically caused by bad tuning of control systems or/and by stressed operating conditions
- Can be reproduced by modeling

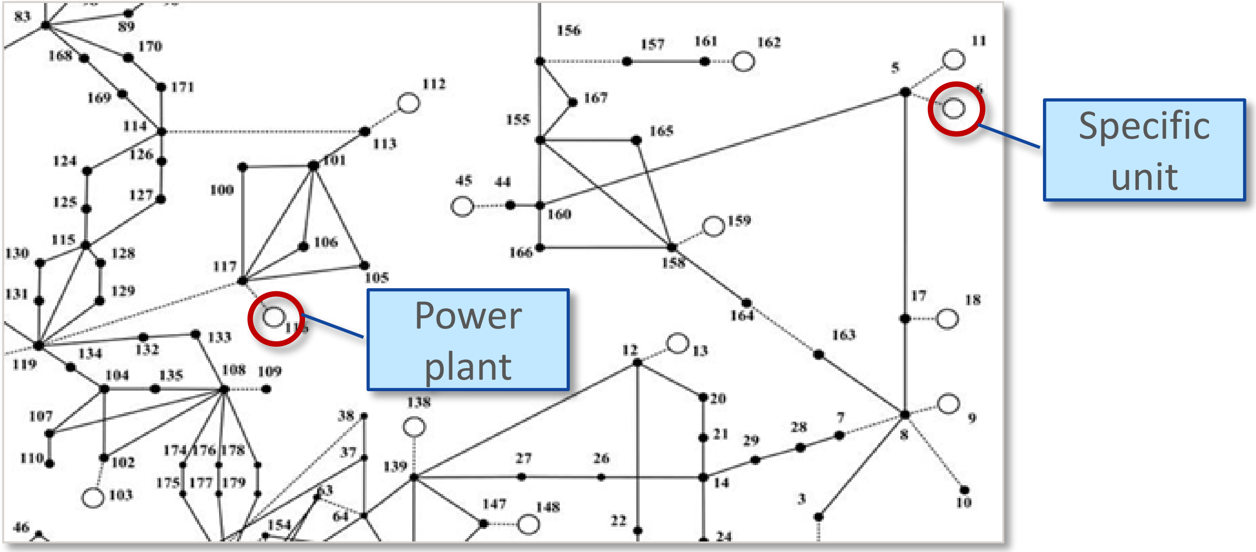
Forced

- Caused by periodic disturbance in power system (failure of equipment or control systems)
- Always poorly damped and can exist at any operating conditions
- Typically cannot be reproduced by modeling

I don’t care whether these beasts are Natural or Forced… I just want to track them down and kill them!!

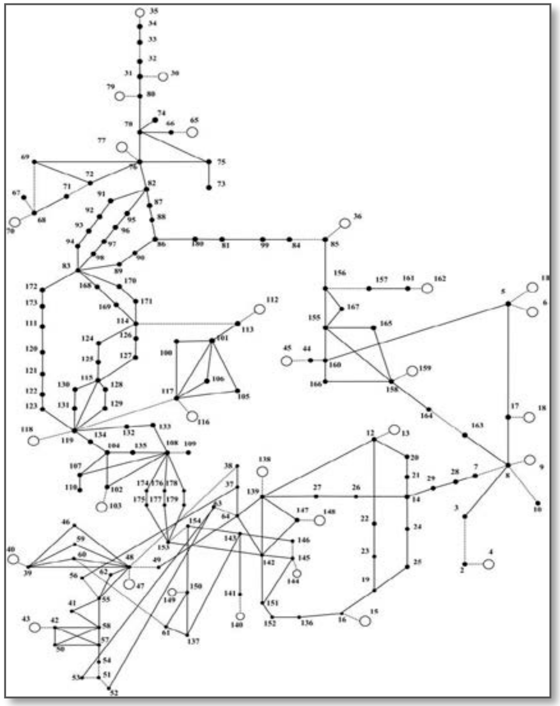
Source identification objective

- Identification method targets to localize the source in the system to a power plant or to a unit level if proper PMU measurements are available
- Identification of the source to a specific hardware/control system component is beyond the scope
- Identification method should use PMU measurements and work for both “forced” and “natural” oscillations



Test system

- 179 bus, 29 generator equivalent WECC system
- Classical model of generator with damping parameter D; model GENCLS
- Source of oscillation:

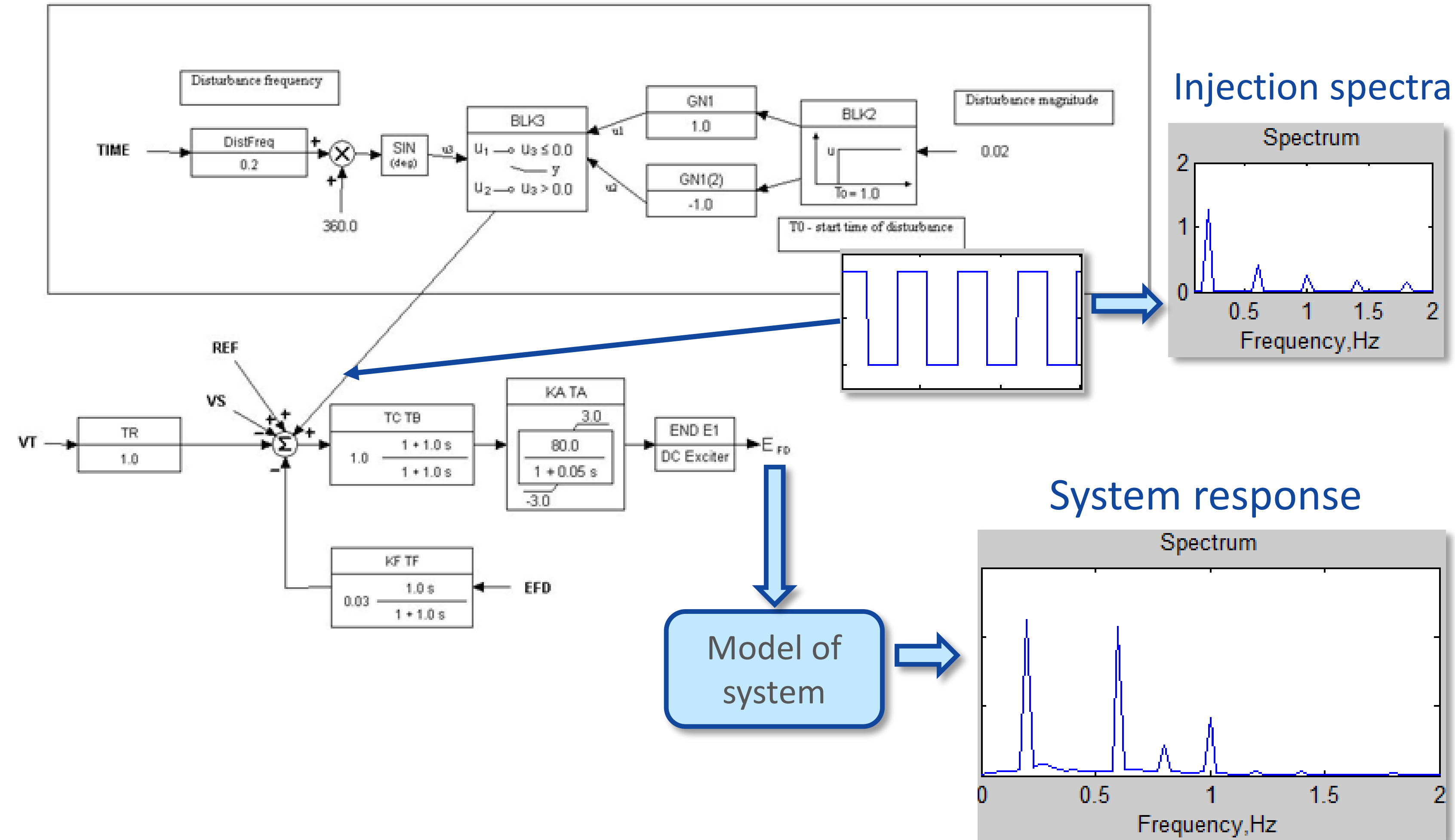


Type of Source	How a Source is created	Disturbance
Bad natural damping	Negative D for specific generator	3-phase short circuit for 0.03-0.05 s
Forced oscillations	Injection of periodic input in excitation system of a specific generator*	No

* Such a generator is modeled with excitation system; model GENROU

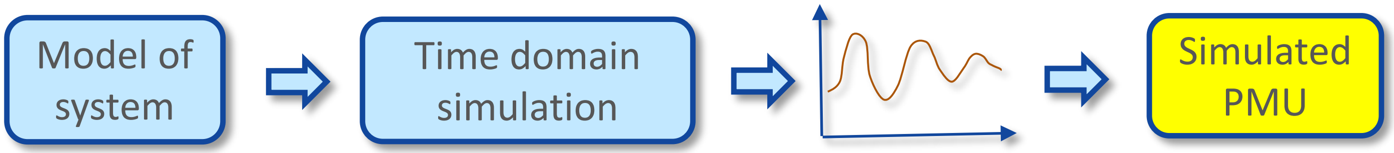
Forced oscillations modeling

Excitation system with injected rectangular-wave disturbance



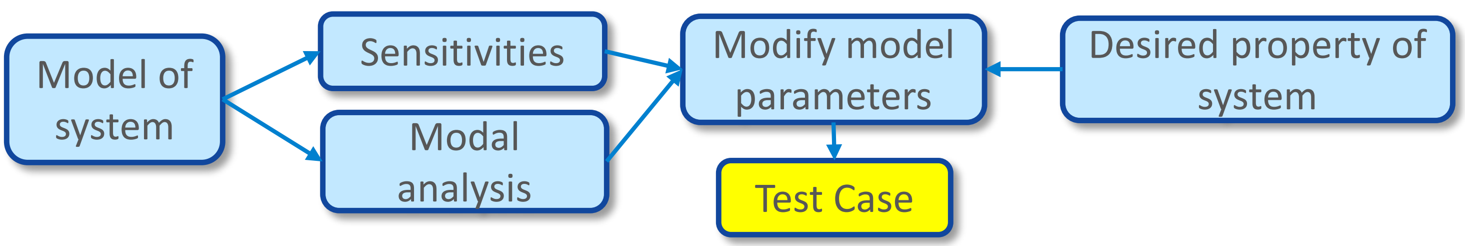
Approach to create simulated PMU data

- Run time domain simulation for 40 seconds by TSAT software
- Output at 30 samples per second:
  - All bus voltages, magnitude and angle; 179 buses
  - All line currents, magnitude and angle from both sides; 263 lines
  - All generator speeds; 29 generators
  - All rotor angles; 29 generators
- This output mimics full network observability by PMU and PMU measurements of rotor speed and angle for all generators



Approach for generation of scenarios

- SSAT software was used for modal analysis
  - Eigenvalues (damping and frequency)
  - Right and Left eigenvectors (observability and excitability of modes)
  - Sensitivity of real parts of eigenvalues to D parameter (damping control) $\frac{\partial \alpha_i}{\partial D_k}$
- Linear analysis by SSAT was used to create desirable properties of system
  - Tune D values to create desirable damping $\Delta \alpha_i = \frac{\partial \alpha_i}{\partial D_k} \Delta D_k$
  - Allocation of the “Source” to make it not trivial to locate
  - Allocation of disturbance to excite modes of interest with significant magnitude
- Good correlation of linear modal analysis with time domain simulation



Scenarios

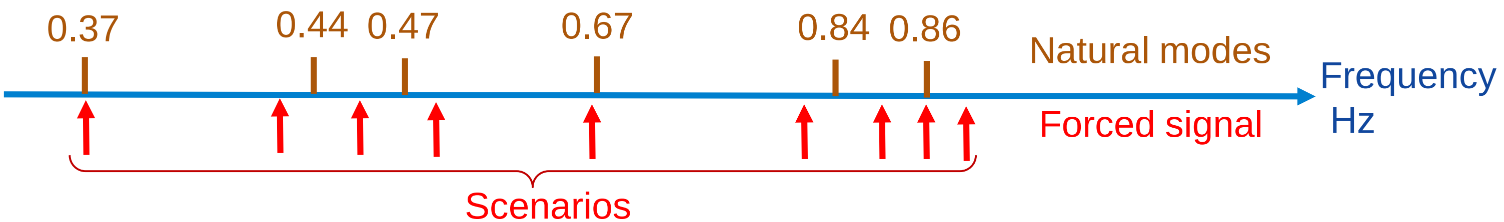
- Forced oscillations
  - Exact resonance with inter-area and local modes
  - Near resonance forced oscillations with frequency below and above the frequency of natural inter-area and local modes
  - Sinusoidal and rectangular injection of signal
  - Two simultaneous sources
- Undamped natural oscillations
  - One source creating one undamped inter-area or local mode
  - One source impacting two inter-area and one local modes; different combination of undamped and low damped modes
  - Two sources contributing the same low damped local mode
  - Two sources creating two low damped local modes

Cases with poorly damped natural oscillation

Case #	D	Freq (Hz)	Damping	Source bus	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 0.7 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 0.7 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 0.7 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

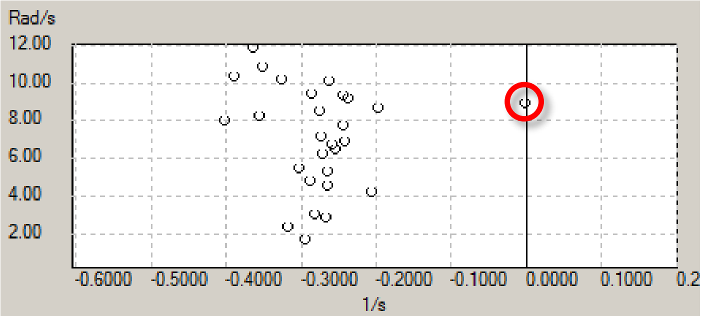
Forced oscillation cases

Case #	Type of injected signal	Frequency of 1st 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	0.5	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

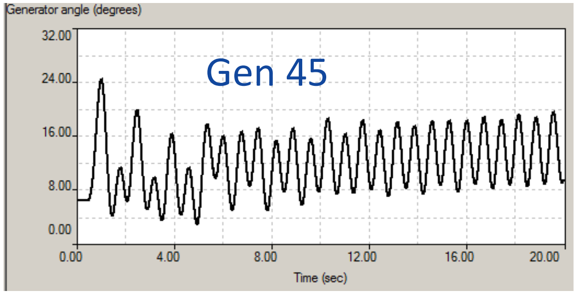


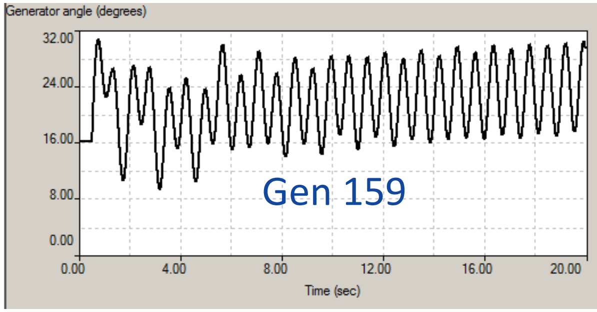
Example: one Source – one Local mode, Case 1

Oscillation spectra



Time domain





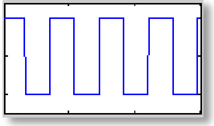
- 1.4 Hz local mode has damping = 0.01%
- Source of poor damping is Gen 45; $D_{45} = -2$
- Specifics: Gen 159 is not the Source but has magnitude of oscillations larger than Source (Gen 45)

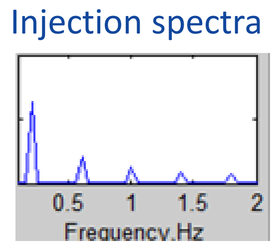
Amplitudes of oscillations

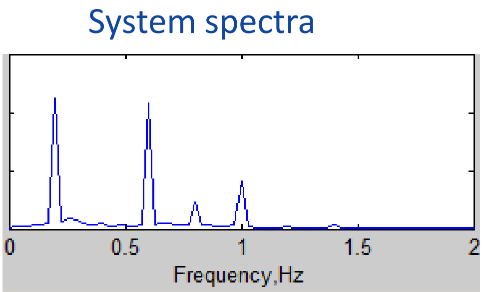
Generator	Angle, degrees	P, MW
45 (Source)	5.5	411
159	7.3	488

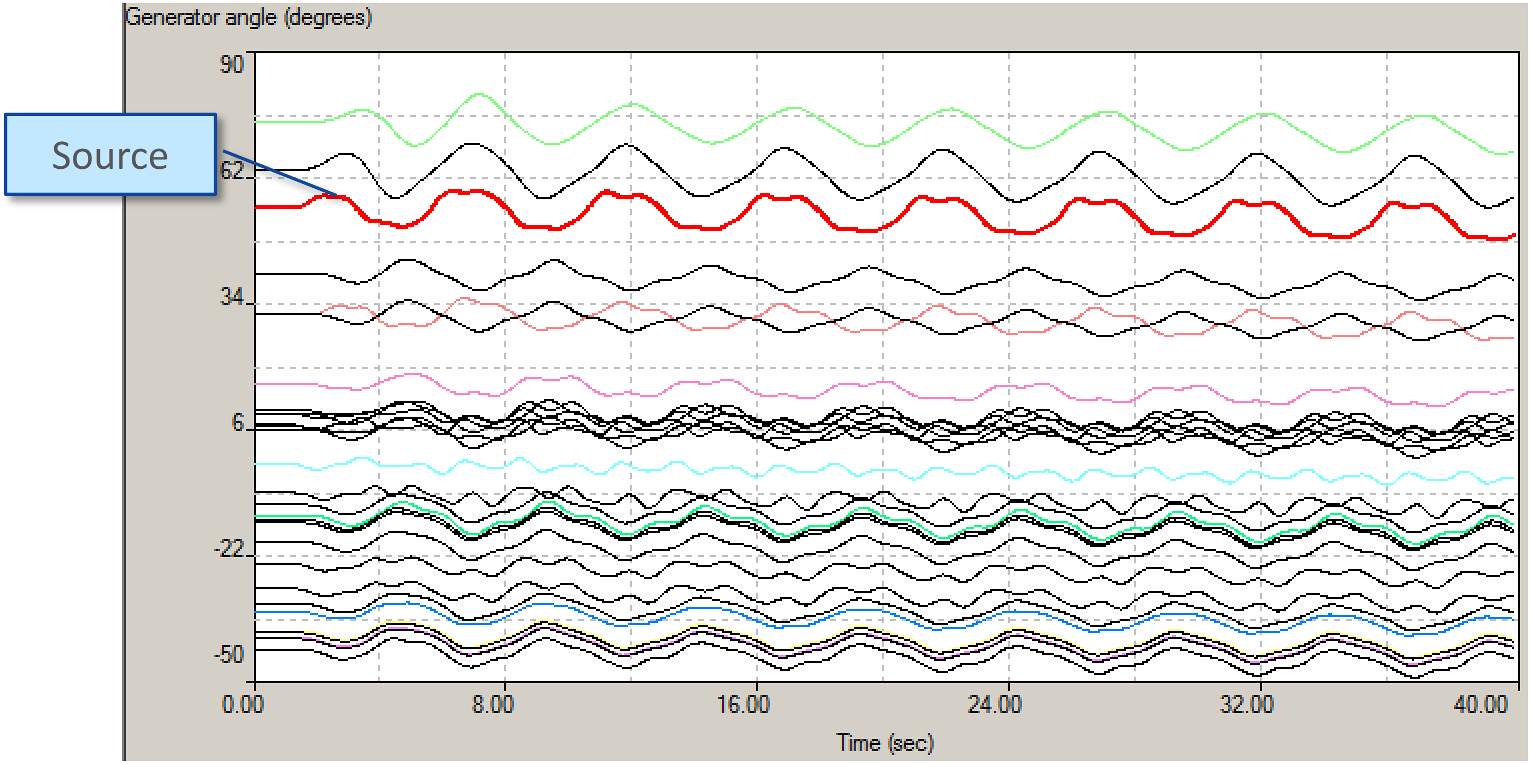
Example: Forced oscillations Case 6-2

Rectangular periodic injection into generator 79









Use of library: example

- Three location methods under test:
  - Damping torque based method [1]
  - Estimated mode shape based method [2]
  - Energy-based method [3]

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

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

[3] 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

Damping torque based method

- Damping torque is estimated for each generator for the dominant mode
- Principle: generator with a negative damping torque coefficient is the source
- Data requirements: P_e, ω and δ

$$\begin{cases} \Delta P_e = P_e - P_{e0} \\ \Delta \omega = \omega - \omega_0 \\ \Delta \delta = \delta - \delta_0 \end{cases} \Rightarrow \Delta P_{e,\lambda}(t) \quad \Delta \delta_\lambda(t) \quad \Delta \omega_\lambda(t) \Rightarrow \Delta P_{e,\lambda} = K_{s,\lambda} \Delta \delta_\lambda + \boxed{K_{d,\lambda}} \Delta \omega_\lambda$$

Dominant mode λ

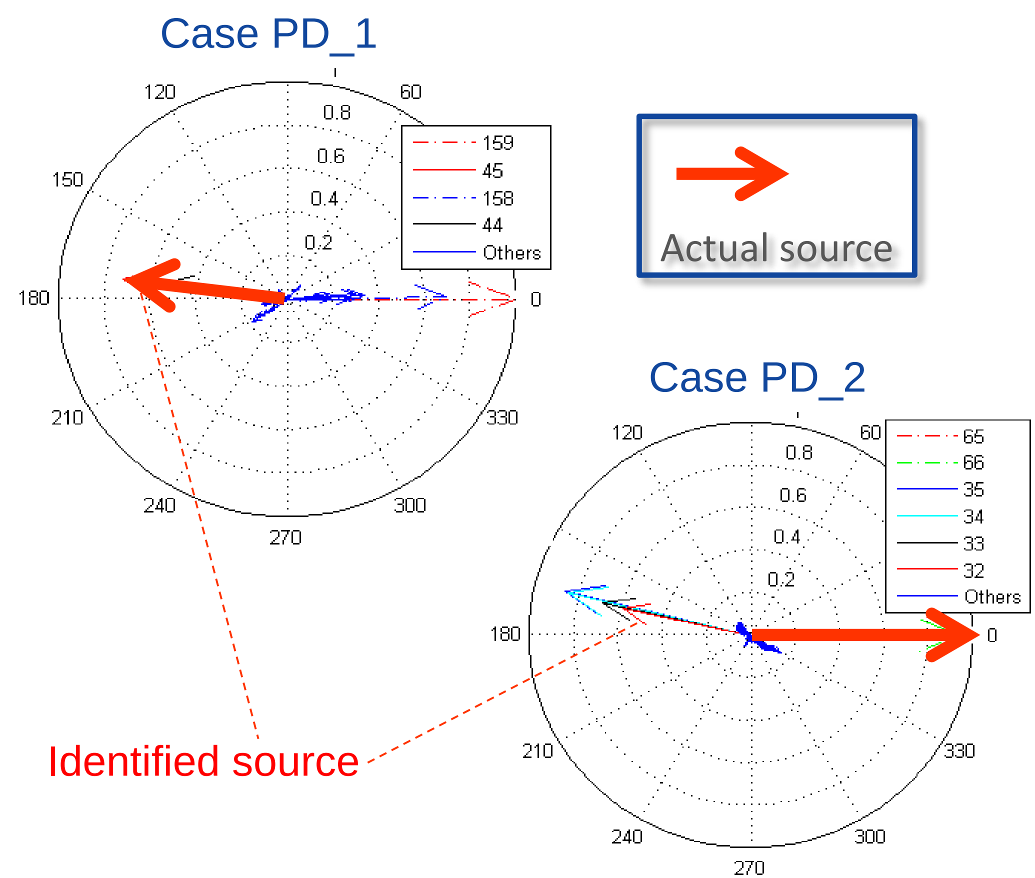
Cases from the library	Actual source bus	Identified source bus	Estimated damping torque coefficients
PD_1	45	45	**K_d(G45) = – 1.81** K_d(else) = 0.91~7.89
F_1	4	No source found	K_d(all) = 1.88~3.98

Estimated mode shape based method

- Mode shape is estimated using measurements from different locations
- Principle: the most leading generator in the pre-specified leading group is the source
- Data requirements: ω or δ

Cases from the library	Actual source bus	Identified source bus
PD_1	45	45
PD_2	65	32

Wrong



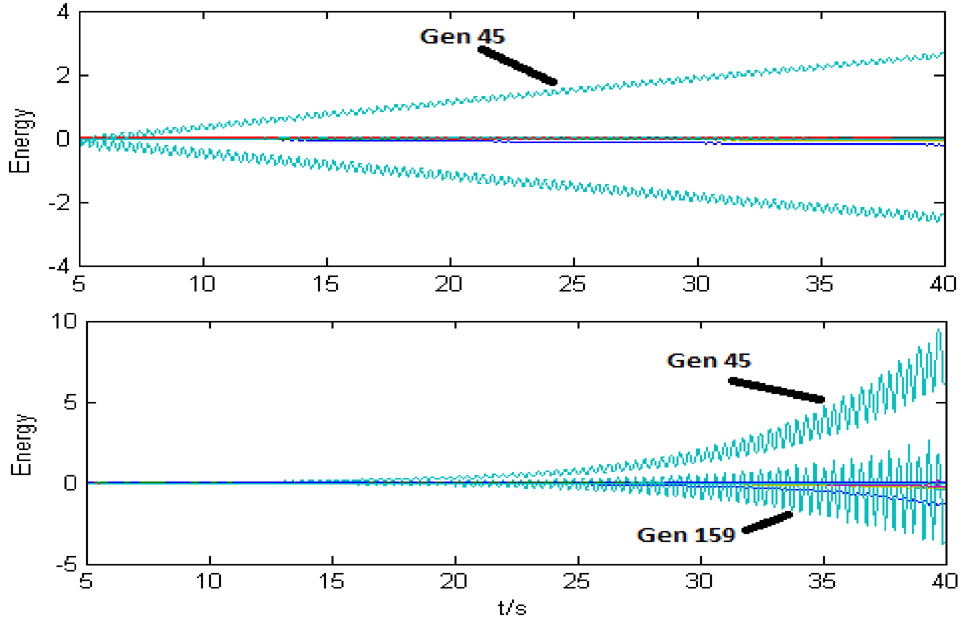
Energy-based method

- Dissipating energy flow is calculated for each generator terminal branch
- Principle: the generator producing dissipating energy is the source
- Data requirements: P_e, Q_e, V_t, and θ_t

$$W^D = \int \left(\Delta P_e \mathrm{d}\Delta\theta_t + \Delta Q_e \mathrm{d}\Delta \ln V \right)$$

The monotonically increasing component in W^D indicates the source

Cases from the library	Actual source bus	Identified source bus
PD_1	45	45
PD_6	45&159	45



Test case library

- Publicly available here:

  http://curent.utk.edu/research/test-cases/

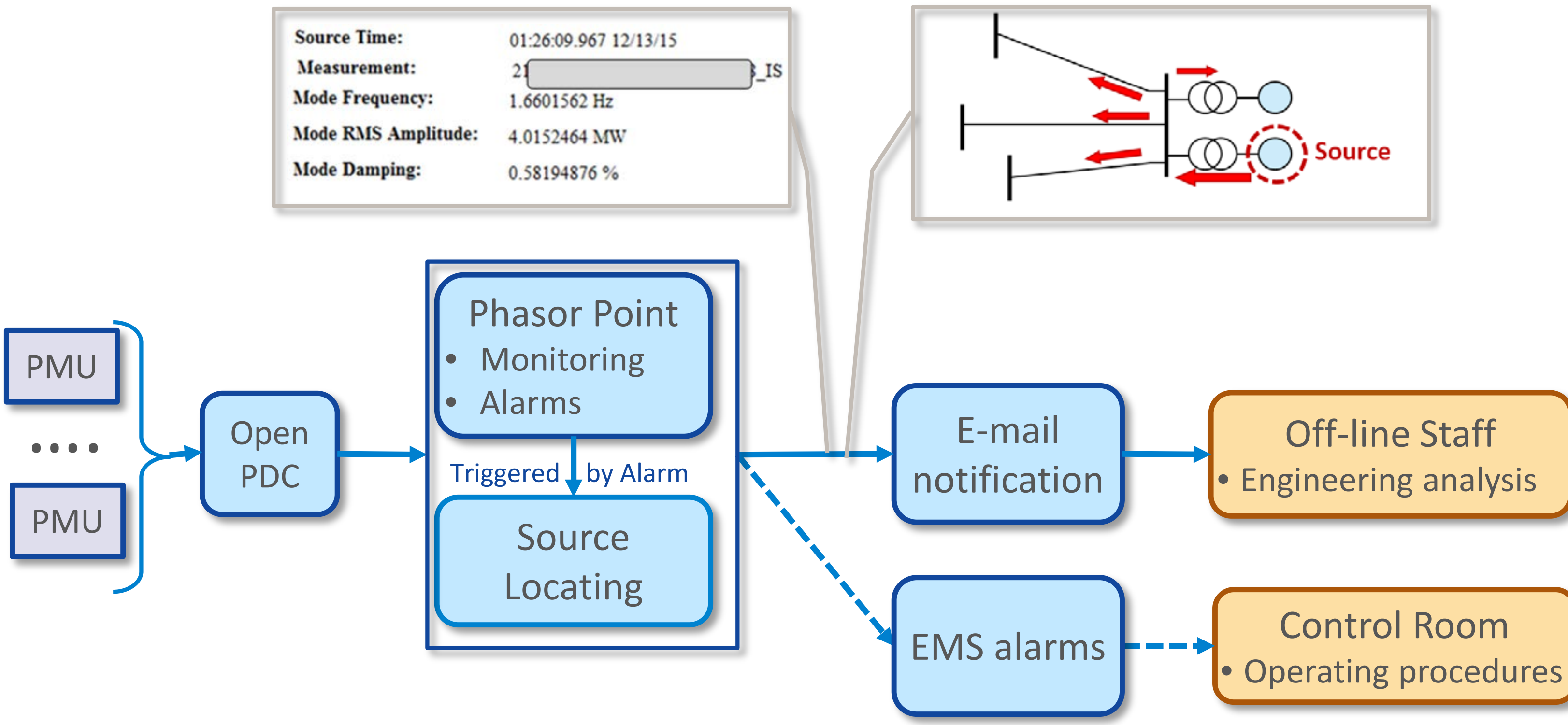
- Library contains
  - Detailed description
  - Simulated PMU
  - Model in PSSE/30 format and User Defined Model for TSAT
  - Matlab code to load simulated PMU in Workspace
- Contact information
  - Kai Sun, kaisun@utk.edu
  - Bin Wang bwang@utk.edu
  - Slava Maslennikov, smaslennikov@iso-ne.com

What is next?

- Test case library has been used to validate several candidate methods locating the source of oscillations
- Energy based method based [3] works for all test cases and this method demonstrates the best results so far
- Modified by ISO-NE version named Dissipating Energy Flow (DEF) method works well with actual PMU data
- ISO New England is enhancing DEF method to make it a robust and automated tool

Online Oscillation Management concept at ISO-NE

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



Questions