Locating the Source of Sustained Oscillation

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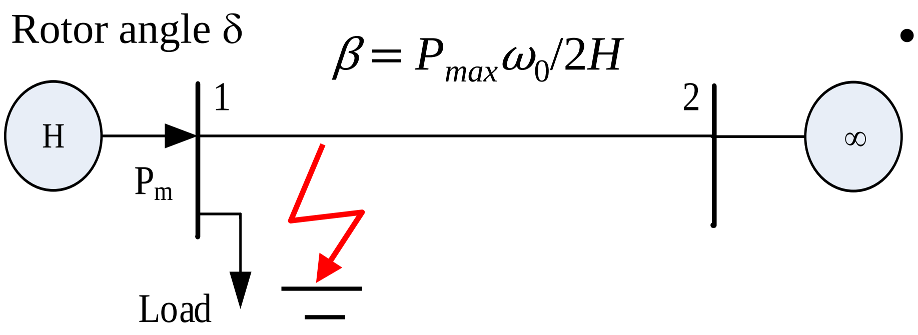
Content

- Electromechanical oscillation vs. forced oscillation
- Methods for locating the source of oscillations
- Tests on NASPI forced oscillation data
- Conclusions

Characteristics of electromechanical oscillation



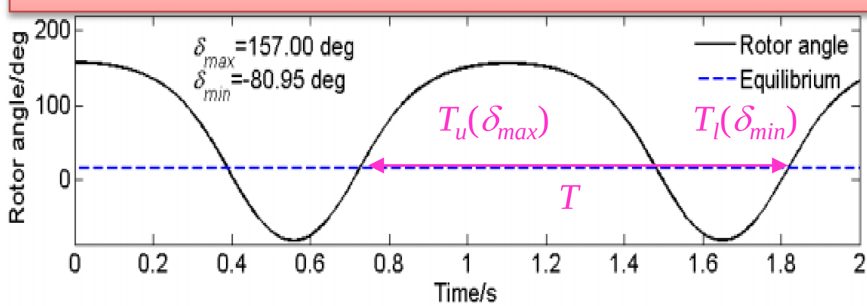
- These nonlinearities can be observed
  - Asymmetry
  - Frequency-amplitude dependency

$$\ddot{\delta} + \alpha\dot{\delta} + \beta\frac{\sin(\delta/2)}{\delta/2}\cos(\delta_s + \delta/2)\delta = 0$$

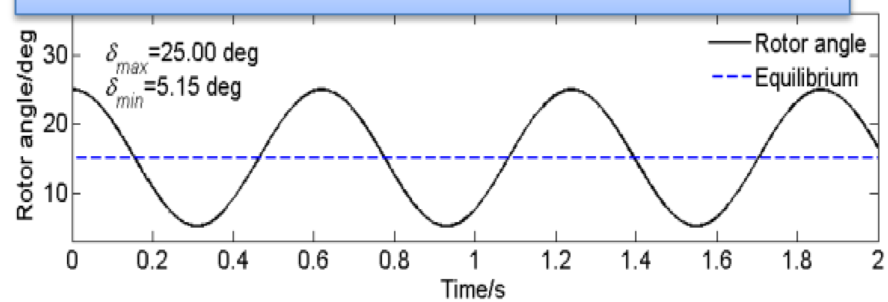
$|\delta| \approx 0$ ⇒

$$\ddot{\delta} + \alpha\dot{\delta} + \beta\cos\delta_s\delta = 0$$

Large amplitude (marginally stable)

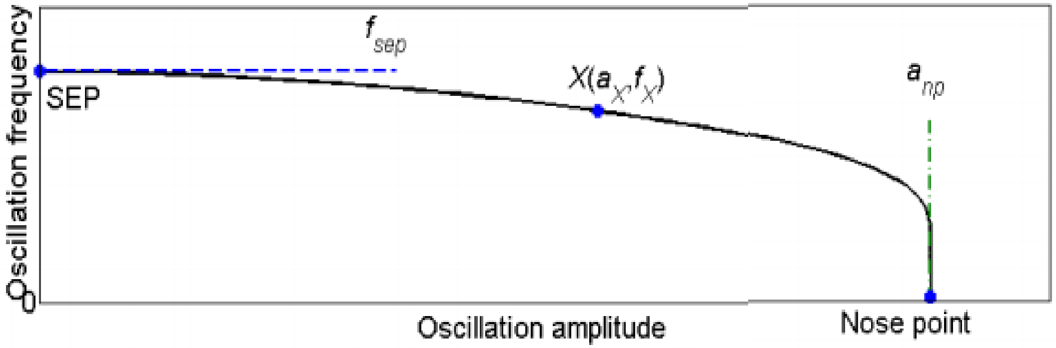


Small amplitude (very stable)

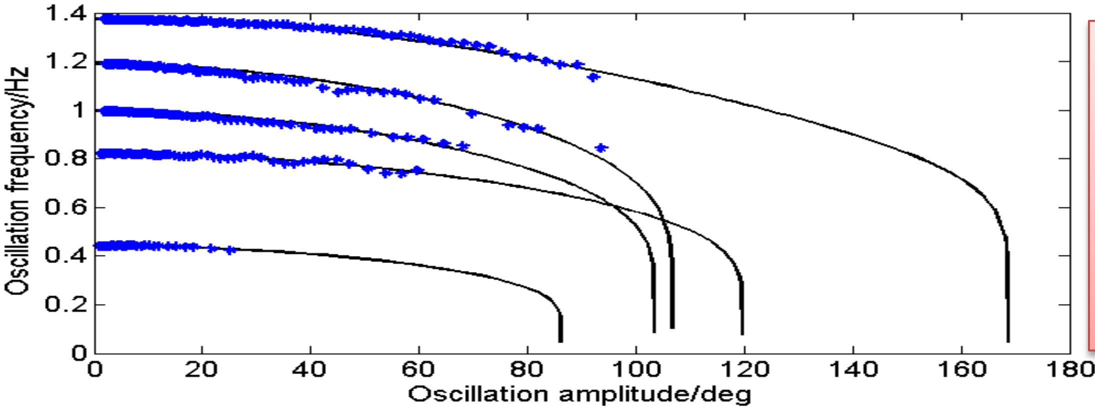


Frequency-amplitude (F-A) curve [1][2]

$$f(\delta_{max},\delta_{min}) = \frac{1}{T_u(\delta_{max})+T_l(\delta_{min})} \approx \frac{\sqrt{\beta}}{\sqrt{2\pi}}\left(\frac{\sin(\delta_{max}/2)}{m(\delta_{max})}+\frac{\sin(-\delta_{min}/2)}{m(\delta_{min})}\right)^{-1} \quad \text{where } m(x)=\sqrt{\cos\delta_s-\cos(\delta_s+x)-x\sin\delta_s}$$



F-A curve on the only mode of a single machine infinite bus system



F-A curves estimated for some electromechanical modes of the WECC system: each star represents a system state seen from the mode, whose distance to the nose-point tells the real-time angular stability margin

[1] B. Wang, K. Sun, "Formulation and Characterization of Power System Electromechanical Oscillations," IEEE Trans. Power Systems, 2016

[2] B. Wang, X. Su, K. Sun, "Properties of the Frequency-Amplitude Curve," IEEE Trans. Power Systems, 2016

System response under an external force

- Linearization of the system under external force

$$\dot{\mathbf{Y}} = \mathbf{AY} + \mathbf{F} \qquad (1)$$

where $\mathbf{F} = \mathbf{K}\boldsymbol{e}^{j\omega t}$ is the forcing function.

- The system response

$$y(m) = c_m \boldsymbol{e}^{j\omega t} \qquad (2)$$

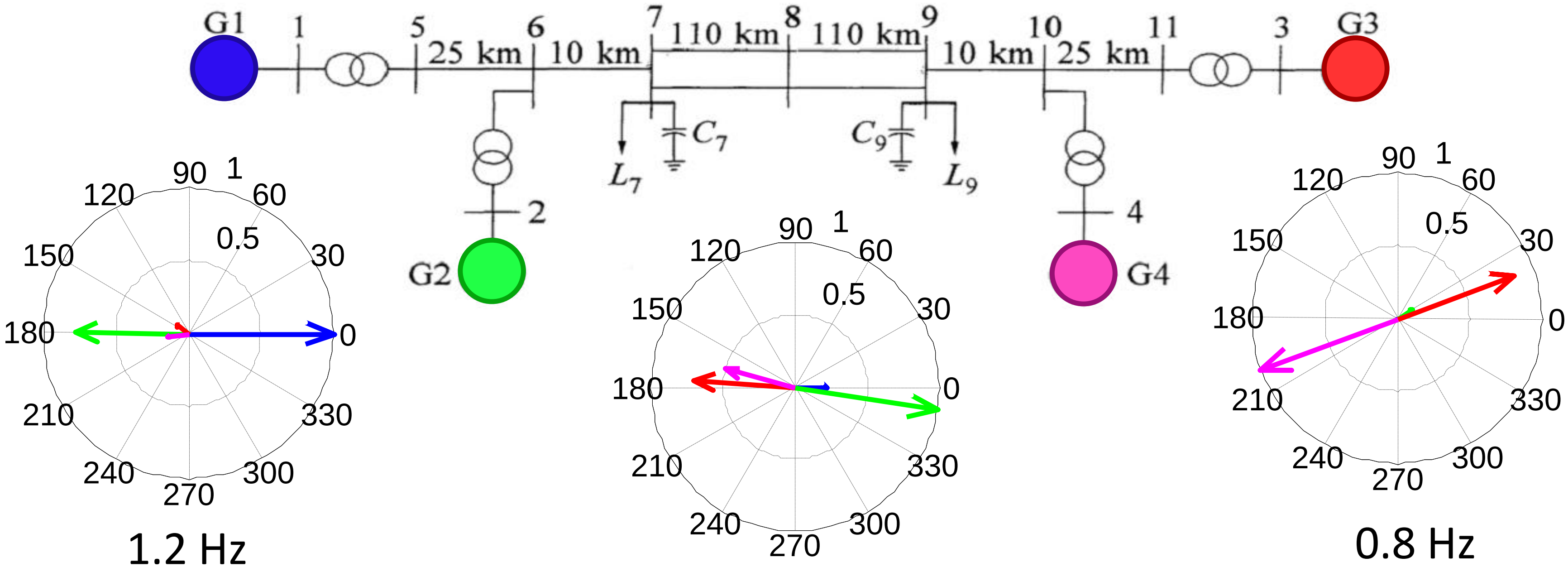
$$c_m = r_m \boldsymbol{e}^{j\boldsymbol{\theta}_m} = \sum_{p=1}^{M} k_p \sum_{i=1}^{M} \frac{x_{im} v_{ip}}{(j\omega - \lambda_i)} \qquad (3)$$

where λ_i and v_{ip} are eigenvalues and eigenvectors of matrix A and r_m and θ_m are the amplitude and phase shift introduced by the forcing function.

[3] J. E. Van Ness, "Response of Large Power Systems to Cyclic Load Variations," in IEEE Trans. Power Apparatus and Systems, vol. PAS-85, no. 7, pp. 723-727, July 1966.

Test on a two-area system

- Mode shape of each electromechanical mode:

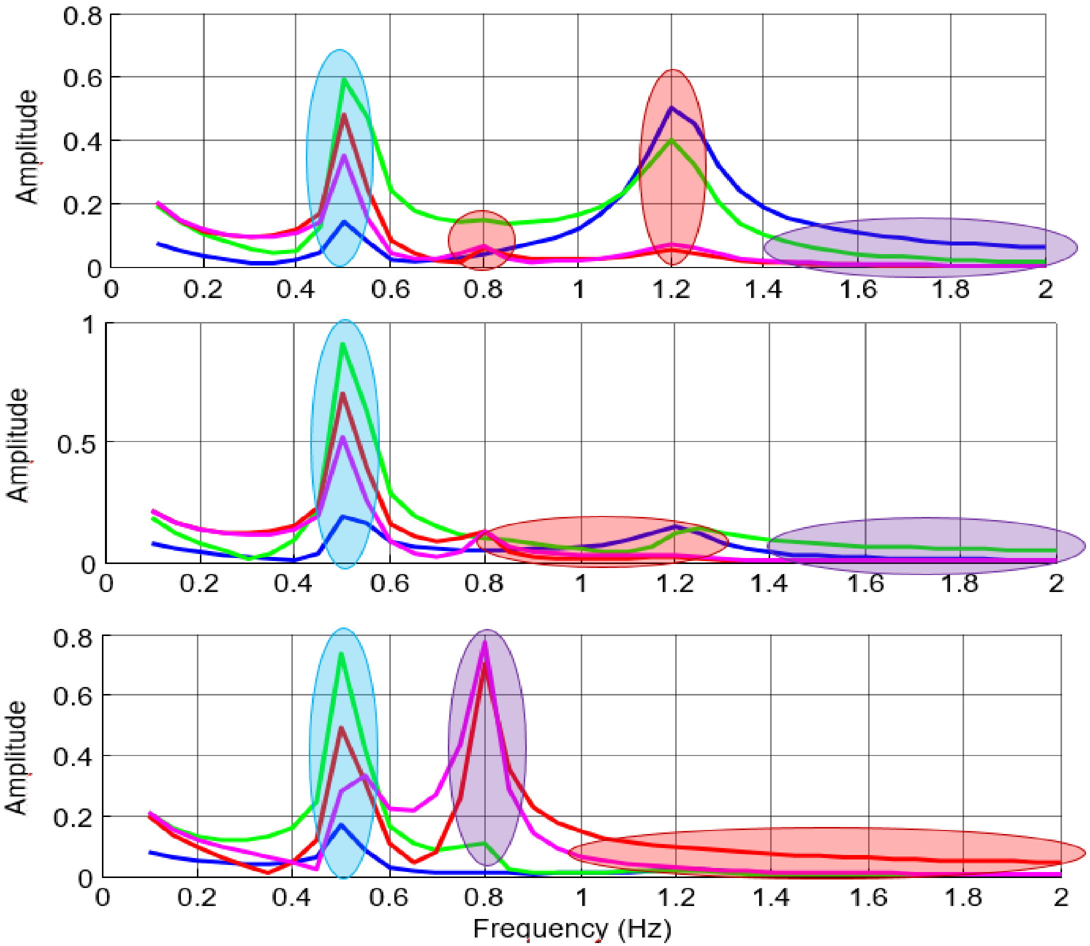


1.2 Hz 0.5 Hz 0.8 Hz

- Periodic disturbance (f=0.1-2.0Hz) is added to one generator.

Can the oscillation amplitude tell the source?

- Source at **G1**
- Source at **G2**
- Source at **G3**



Yes, if the forced oscillation has a different frequency than electromechanical modes

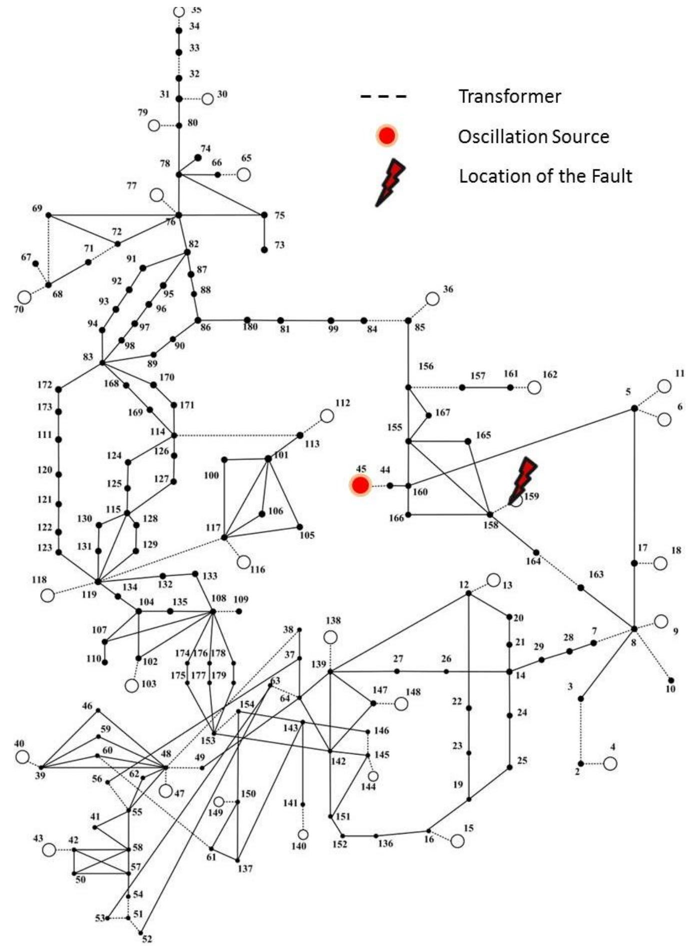
Some existing methods (by 2015) for locating the oscillation source

Category	Key Idea	Cons
Damping torque	The generator with a negative damping torque coefficient is the source	Possible unavailability of rotor angle and speed data. Possible failures under forced oscillation cases.
Mode shape	Largest magnitude, most leading phase of the mode shape or their combinations may indicate the source	Lack of a theoretical foundation. Possible failures for cases having weakly damped/undamped oscillation together with forced oscillation.
Energy	The device producing dissipation energy is the source	Strong assumption in modeling loads and network. Lack of theoretical proofs for multi-mode cases.
Equivalent circuit	The source of the equivalent circuit is the source of the oscillation	Possible failures when the phasor concept cannot be applied, e.g. non-sinusoidal oscillations. Lack of theoretical proofs for multi-mode oscillation cases.
Hybrid	A larger difference between simulations and measurements indicates the source	Possible unavailability of the accurate model of the entire system.
Traveling wave	The closer to the source, the earlier the location will exhibit oscillation	Inaccurate and unreliable detection of the oscillation arrival time. Unavailability of the wave speed map in real-time. Lack of investigations on multi-mode cases.
Machine learning	An offline trained decision tree from model-based simulations to locate the source using online measurements	Possible unavailability of the accurate model of the entire system. Can be only applied to forced oscillation cases.

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

Test cases library

- WECC 179-bus system
  - 179 buses
  - 29 generators
  - 263 branches, including transformers
  - 28 oscillatory modes, 0.26~1.88Hz
- 23 oscillation cases
  - 9 Natural oscillation cases
  - 14 Forced oscillation cases
- Coverage
  - Linear/non-linear
  - Resonance/non-resonance
  - Sinusoidal/non-sinusoidal



[5] http://curent.utk.edu/research/test-cases/

[6] 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” IEEE PES General Meeting, 2016

Method 1: Damping torque based OSL

- 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*, 0.91~7.89)
F_1	(All generators, 1.88~3.98)

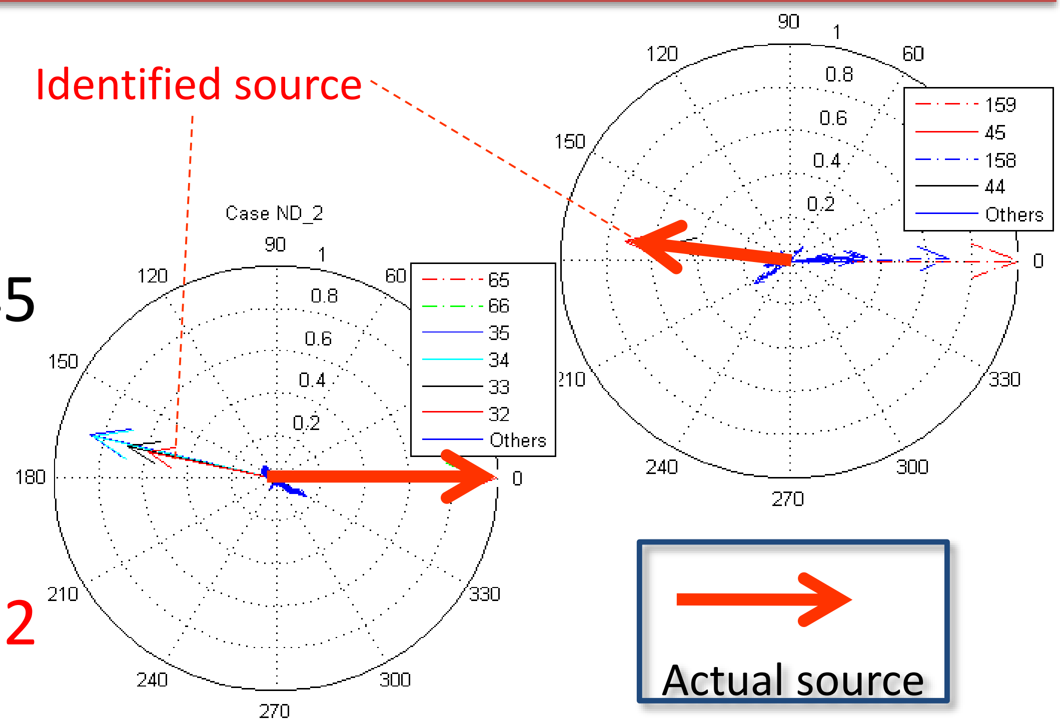
G* represents all generators in the system except for G45.

[7] 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

Method 2: Estimated mode shape based OSL

- 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

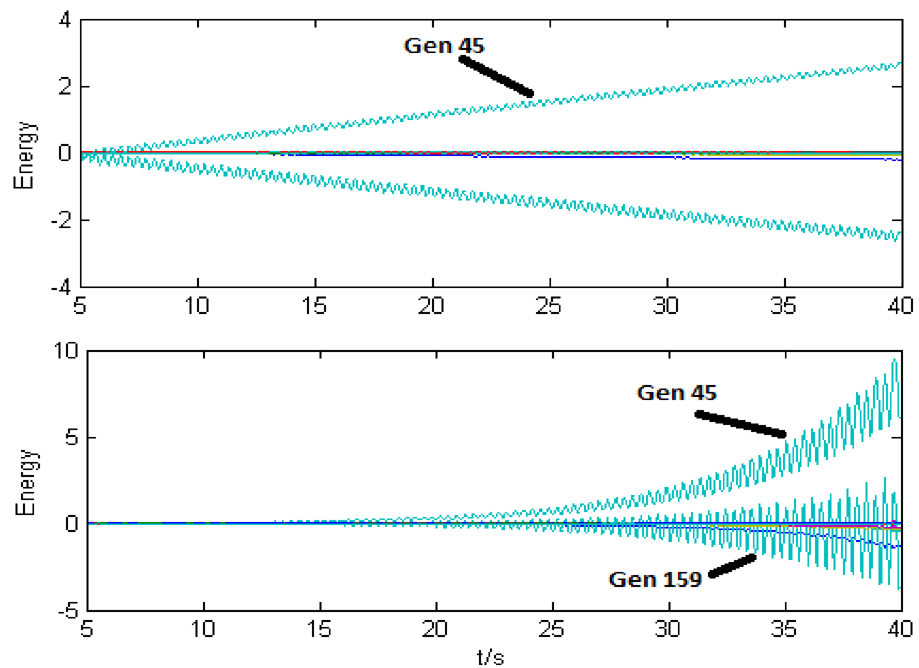


[8] N Ashwal, D Wilson, M Parashar, "Identifying sources of oscillations using wide area measurements," Grid of the Future Symposium, CIGRE US National Committee, 2014

Method 3: Energy based OSL

- 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

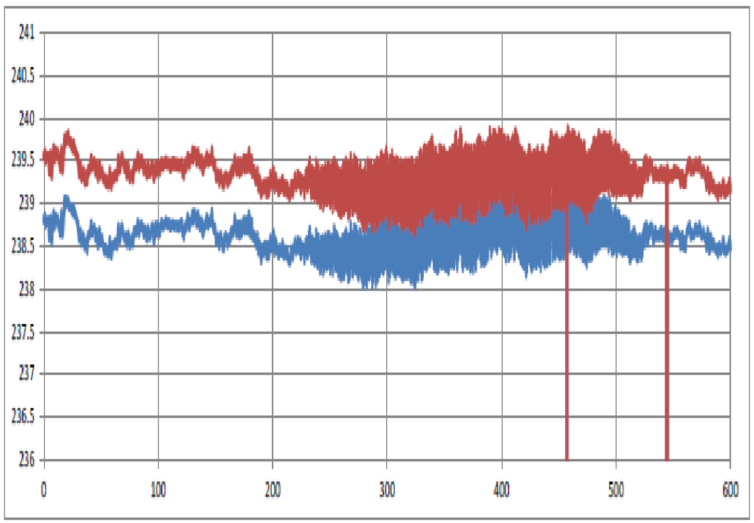
- Case ND_1
  - Actual source: Bus 45
  - Identified source: Bus 45
- Case ND_6
  - Actual source: Bus 45&159
  - Identified source: Bus 45

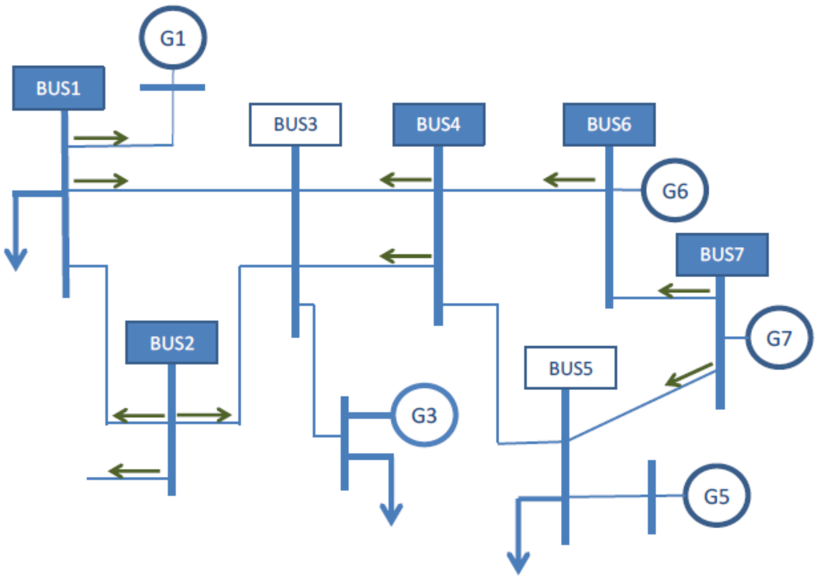


[9] L Chen, Y Min, W Hu, "An energy-based method for location of power system oscillation source," IEEE Transaction on Power Systems, 28(2):828-836, 2013

Tests on NASPI forced oscillation case

- **Objective:** The objective of this test is to demonstrate how Oscillation Detection applications can detect forced power system oscillations, display the information to the system dispatchers, and to indicate the source of forced oscillations.
- **Provided:**10-min data record and a one-line-diagram with PMU locations





[10] https://www.naspi.org/site/Module/Meeting/Forms/General.aspx?m__ID=MEETING&meetingid=347

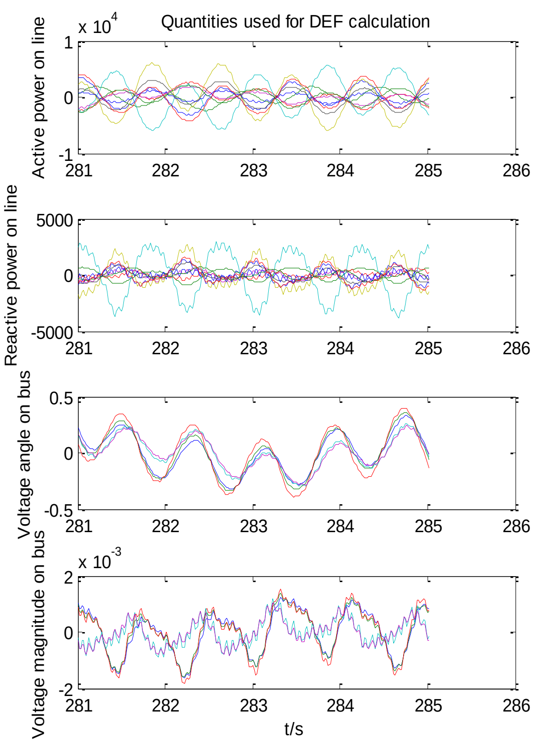
Tests on NASPI forced oscillation case

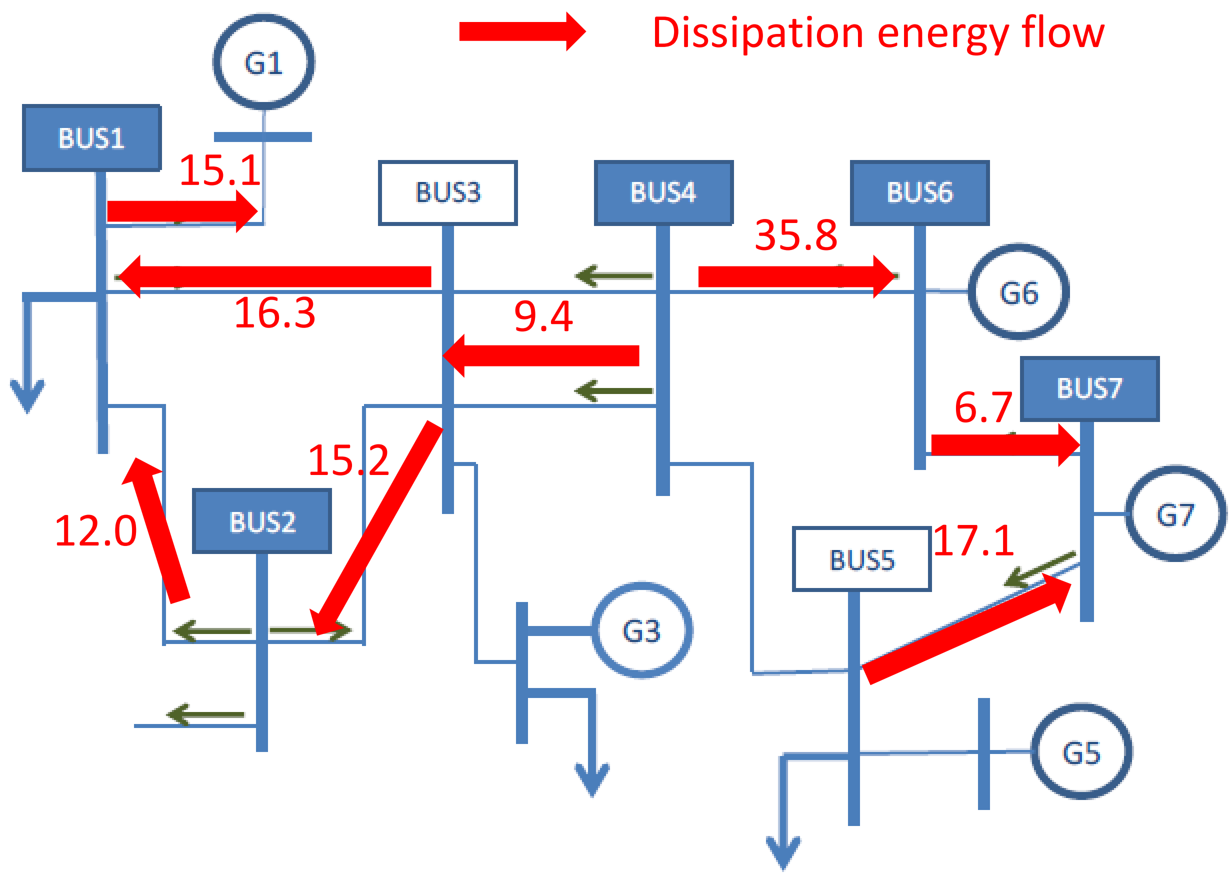
- **Results from five vendors:**

	Vendor 1	Vendor 2	Vendor 3	Vendor 4	Vendor 5
Source of Oscillation (Generator)	Generator 1	Not provided by tool	Generator 1	Generator 6	Generator 6
Time When Oscillation Detected [s]	230	234	232	248 s	10
Signals Used	Gen 1 Real Power	Angle differences, Reference - Bus 1	Voltage Magnitudes	Generator Real Powers	Bus Frequency, Line MW
Forced Oscillation Mode Frequency	1.263 Hz	1.3 Hz	1.25 Hz	1.25 Hz	1.25 Hz
Forced Oscillation Mode Damping Ratio	0.103 %	Near 0	-1% < DR < 2% throughout event	0.05 %	0.24 %
Algorithm Used	Total Least Squares	Kalman Filtering, subspace identification	STI Oscillation Detection Algorithm	Mode Meter	Alstom Phasor Dynamics eXtraction (PDX)

Test on the energy based OSL method

- Calculation is based on data within 281s-285s

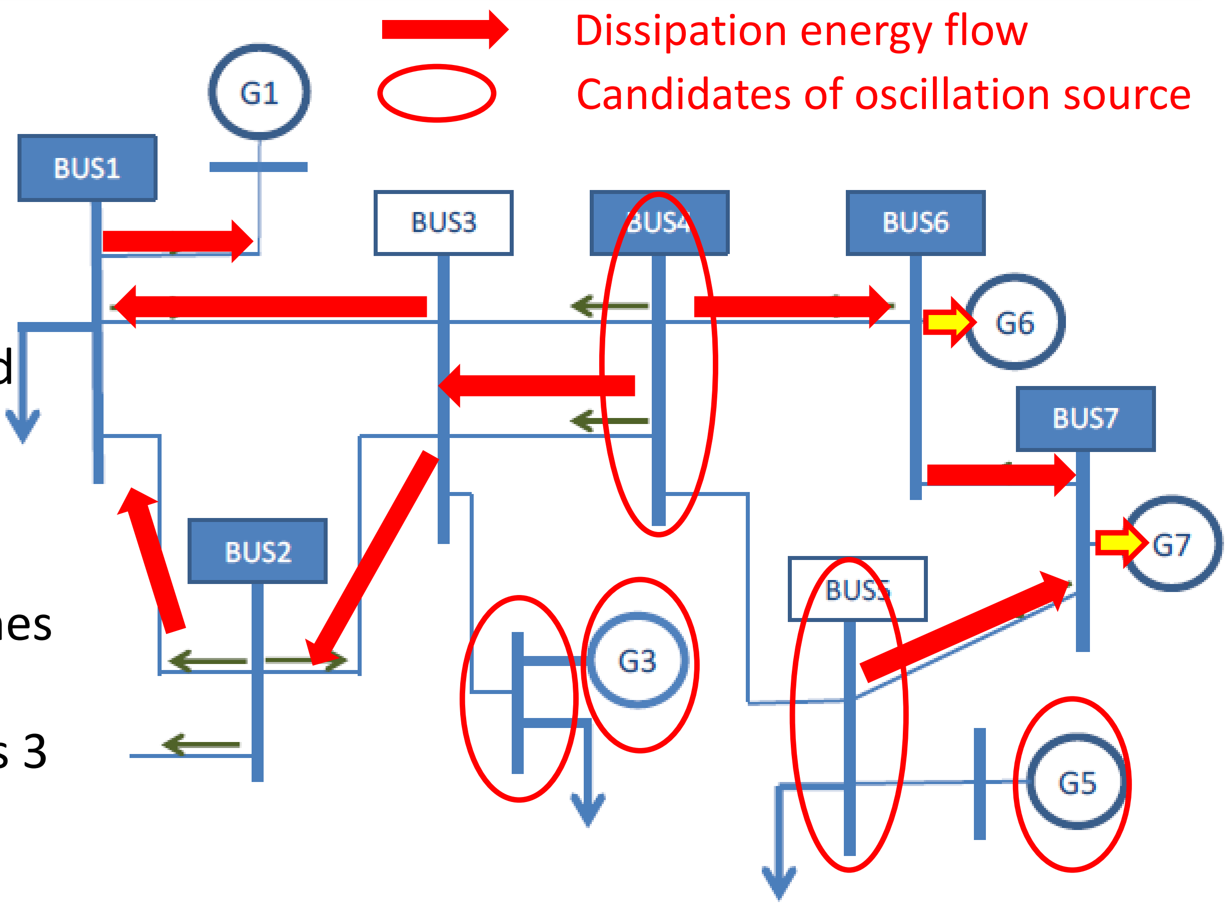




Test results

- Several source candidates can be found, see red circles
- Need more measurements to further locate the source

- Since non-constant-power loads can significantly influence the directions of DEFs, the DEF method cannot make sure to locate the oscillation source based on DEFs in the network.
- To locate the source more accurately, additional measurement data from lines Bus3-Gen3, Bus4-Bus5, terminal lines of generators 3 and 5 are required.



Conclusions

- Synchrophasors have been widely used in the oscillation source location problem
- Largest oscillation amplitude does not always indicate the location of the source because the amplitude is influenced by both modal parameters and the source location
- Energy based location method shows the most promising performance