Testing and Implementation of a Source Locating method at ISO New England

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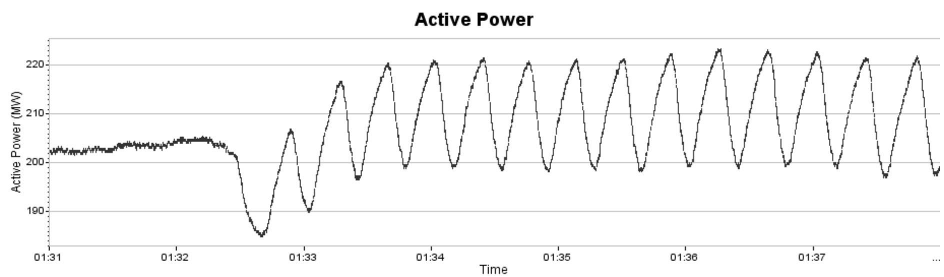
Outline

- Motivation
- Library of simulated test cases
- Specifics of actual PMU
- Dissipating Energy Flow (DEF) method
- Testing of the DEF method
- Oscillation Management at ISO-NE

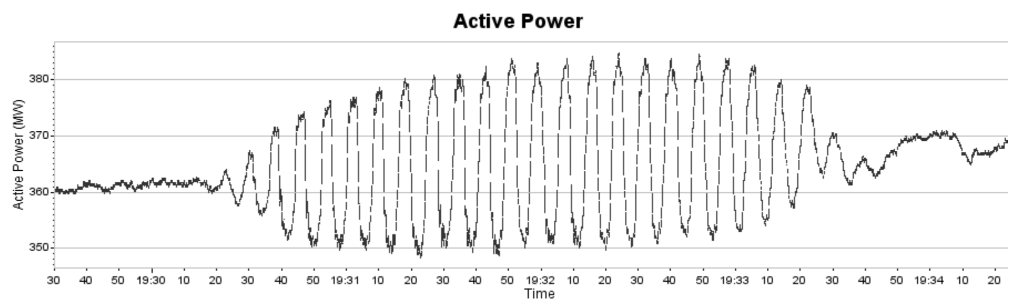
Motivation

- In ISO-NE system, PMU measurements detect instances of poorly damped oscillations with high MW magnitude and frequency from 0.03 Hz to 2 Hz

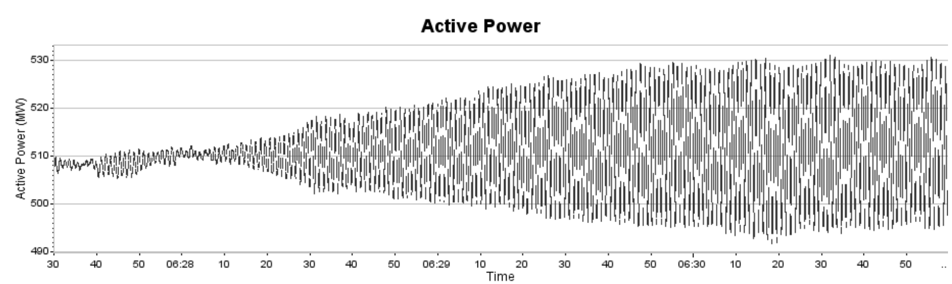
  - 0.04 Hz



  - 0.12 Hz



  - 0.93 Hz



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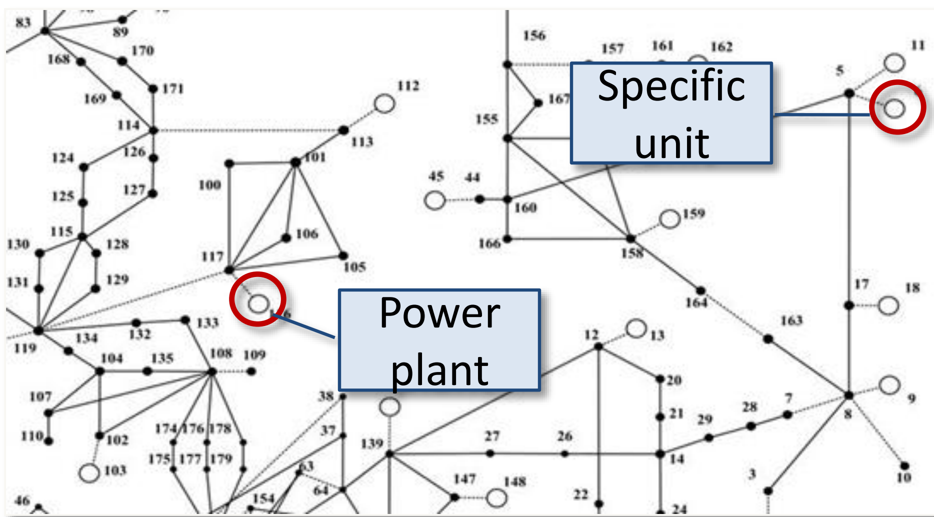
Motivation, cont.

- Sustained oscillations with large magnitude create risk of uncontrolled outages and risk for equipment due to vibrations
- Finding the Source of “bad damping”/“forced oscillations” has to rely on PMU measurements because oscillations cannot be typically replicated by the model
- 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

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



How to test a source locating method?

- Sustained oscillations can have many features impacting the performance of 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 testing difficult
- Need to have a set of representative simulated test cases with known answers. That is just a qualification test…
- Next testing step is the use of actual PMU data when the source is known with high confidence level
- Test as many different type of events as possible

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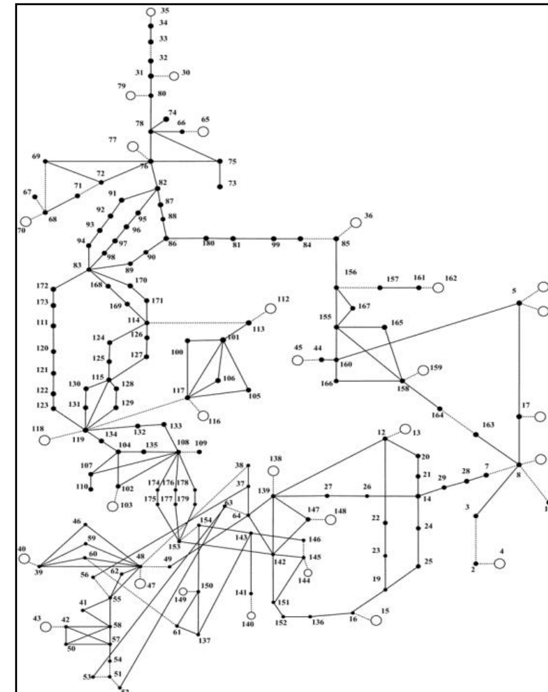
Test system for sustained oscillations

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

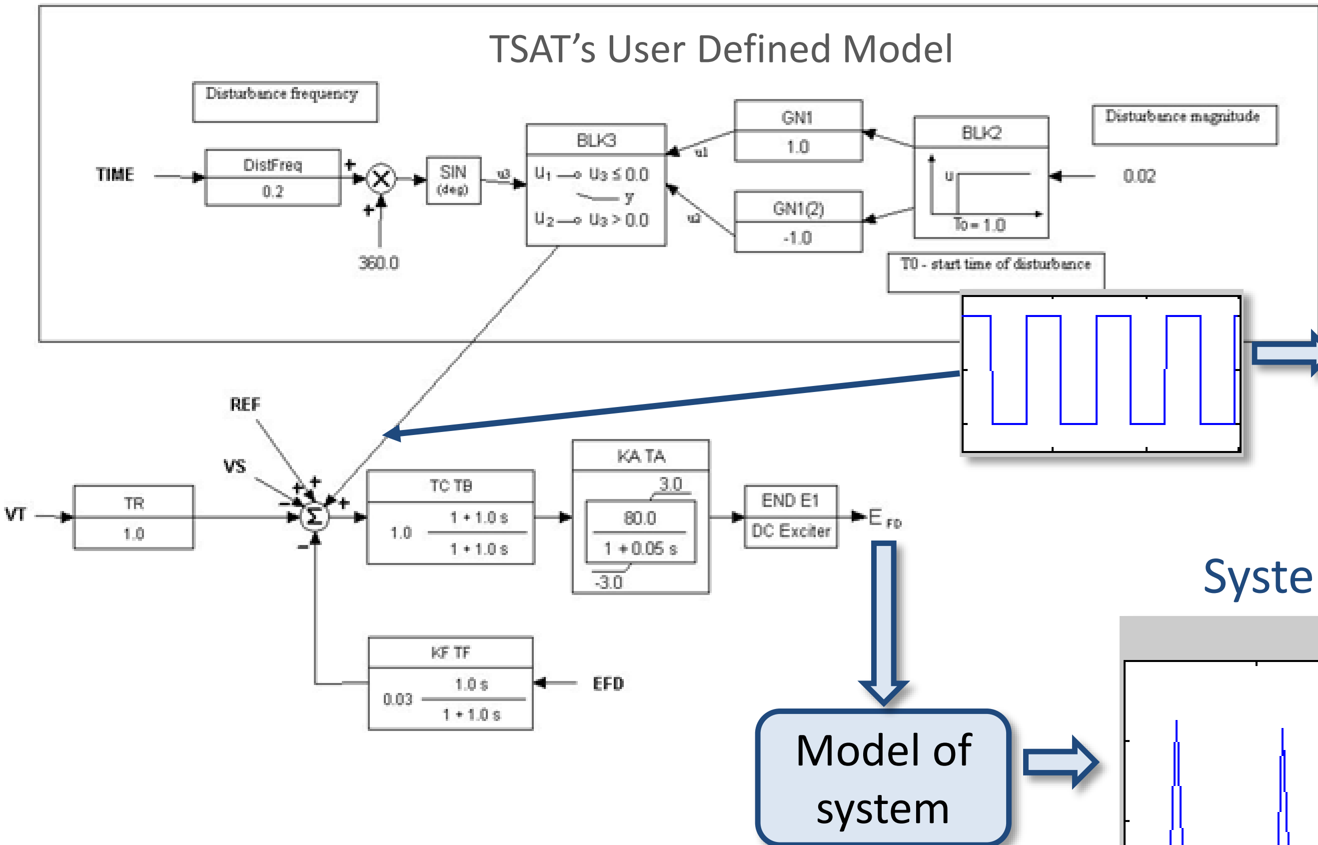


Type of Source	How a Source is created	Disturbance
Bad natural damping	Negative D for specific generator	3-phase short circuit for 0.03-0.05 s
Forced oscillations	Injection of periodic input in excitation system of a specific generator*	No

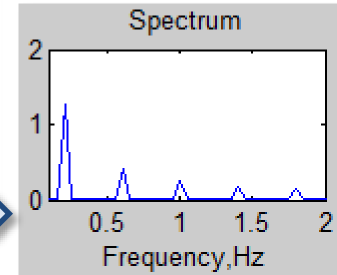
* Such a generator is modeled with excitation system; model GENROU

Forced oscillations modeling

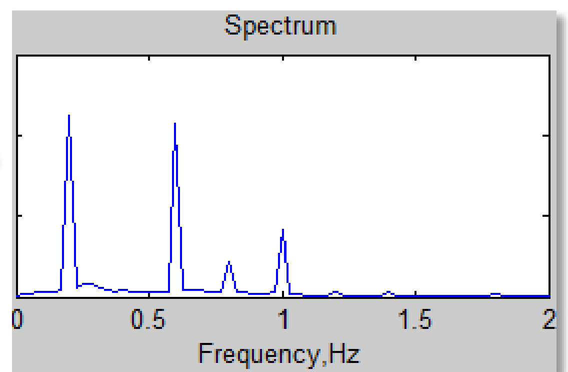
Example: Excitation system with injected rectangular-wave disturbance



Injection spectra

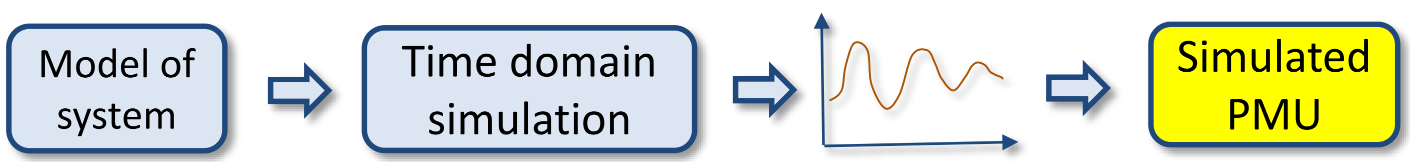


System response



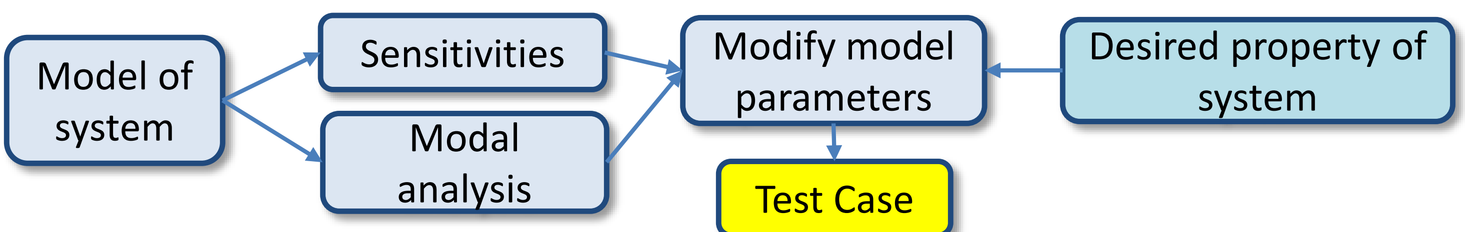
Approach to create simulated PMU data

- Run time domain simulation for 40 seconds by TSAT software
- Output at 30 samples per second:
  - ✓ All bus voltages, magnitudes and angles; 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

- Systematic approach to generate cases with desirable properties
- 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)
- Linear analysis by SSAT was used to create desirable properties of system
  - Tune D values to create desirable damping
  - 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



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Scenarios

- Forced oscillations (12 cases)
  - 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

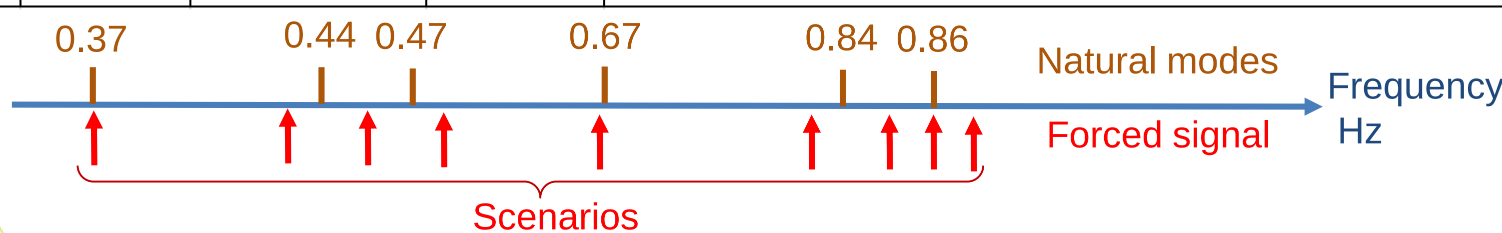
- Undamped natural oscillations (9 cases)
  - One source creating one undamped inter-area or local mode
  - One source impacting two inter-area and one local modes; different combination of undamped and low damped modes
  - Two sources contributing the same low damped local mode
  - Two sources creating 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

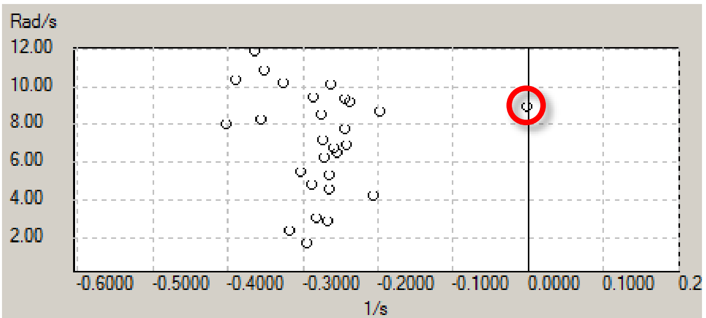
Forced oscillation cases

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

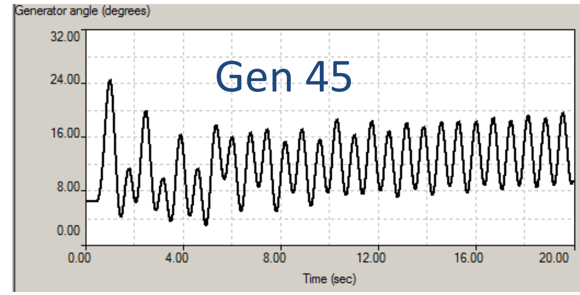


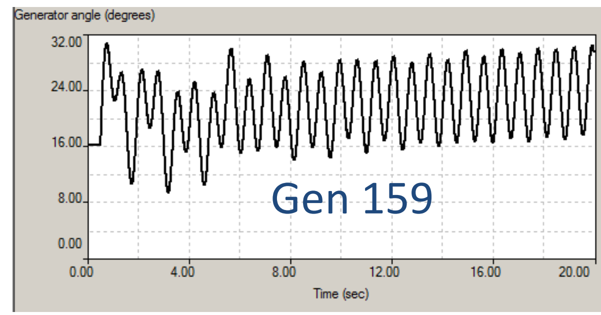
Example: ND 1, one Source – one Local mode

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

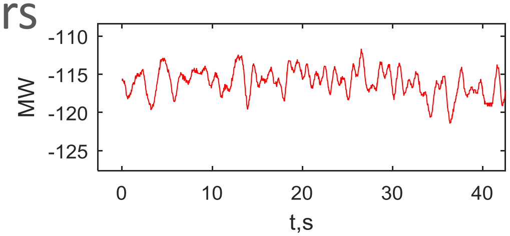
Generator	Angle, degrees	P, MW
45 (Source)	5.5	411
159	7.3	488

Test case library

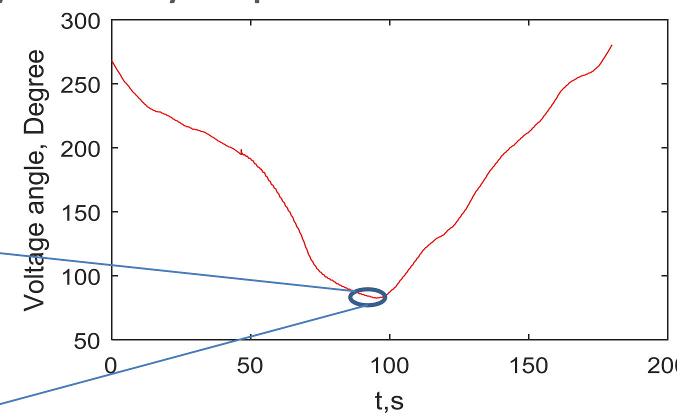
- Publicly available here:
  http://curent.utk.edu/research/test-cases/
- Library contains
  - Detailed description
  - Simulated PMU
  - Model in PSSE/30 format and User Defined Model for TSAT
  - Matlab code to load simulated PMU in Workspace
- Contact information
  - Kai Sun, kaisun@utk.edu
  - Bin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

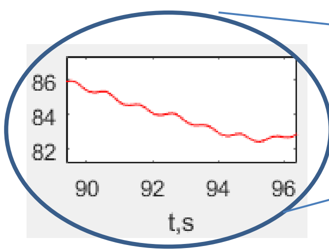
Specifics of actual PMU not covered by simulated cases

- “Bad” PMU data: missing samples, outliers
- Constantly observed multi-frequency “colored” random noise



- PMU inaccuracies coming from PTs, CTs, settings in digital processing
- Complex nature of load dynamics; non-symmetry in phases
- Steady-state does not exist.
  Significant trends of all parameters and particularly angles over time





- Source locating method must be robust in the presence of all above factors

Energy-based method

- Energy-based source locating method* was selected as the most promising
- Idea: use PMU measurements to calculate a flow of dissipating energy in any *ij* branch of network
- Principle: the generator producing dissipating energy is the source

$$W_{ij}^{D} = \int \left(\Delta P_{ij} \mathrm{d} \Delta \theta_{i} + \Delta Q_{ij} \mathrm{d} \Delta \ln V_{i} \right)$$

Δ means deviation from steady-state value

- For a single mode oscillations with frequency ω and constant magnitude

$$W_{ij}^{D} \approx DEF_{ij} \cdot t + A \cdot \sin(\omega t + \varphi_{\theta}) + B \cdot \sin(2\omega t + \varphi_{v})$$

The monotonically increasing over time component

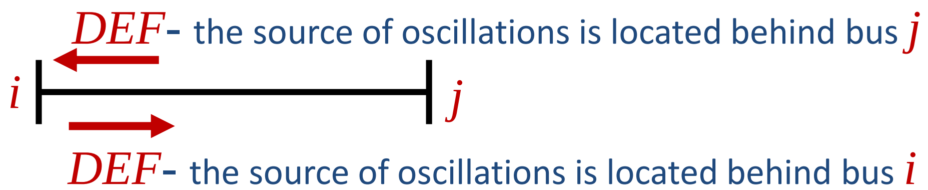
[*] L Chen, Y Min, W Hu, "An energy-based method for location of power system oscillation source," *IEEE Transaction on Power Systems*, 28(2):828-836, 2013

Dissipating Energy Flow (DEF) method

- Deficiencies of original energy-based method
  - Assumption on single oscillatory mode process
  - The requirement to know steady-state values for all variables (I, V, f, angle)
- That makes the use of energy-based method with actual PMU data not sufficiently robust to be used as reliable and automated tool
- ISO-NE have developed a modification named the DEF method for use with actual PMU
- The key addition to energy-based method is the filtering and processing of PMU data
- The DEF method has good chances to be used as automated and robust Production tool for detecting the source of sustained oscillations on-line and off-line

How the DEF method works

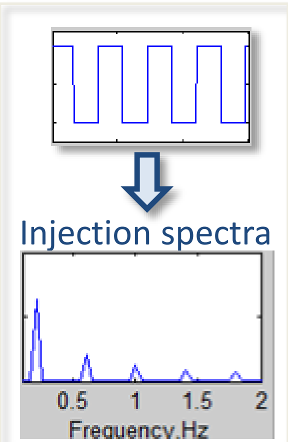
- Input:
  - Current phasor for branch *ij*;
  - Voltage phasor for bus *i*
  - Frequency or voltage angle for bus *i*
- Output: *DEFij* coefficient at bus *i*.
  - *DEFij>0 means dissipating energy flows from the bus i*
  - *DEFij<0 means dissipating energy flows into the bus i*
  - *Abs(DEFij) indicates how big is the flow*
- DEF coefficient can be viewed as a regular MW flow. Direction and value of DEF in multiple branches allow to trace the source of dissipating energy.

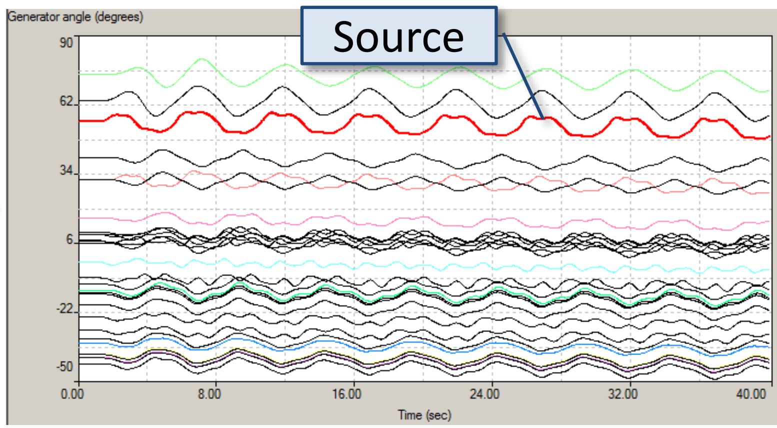


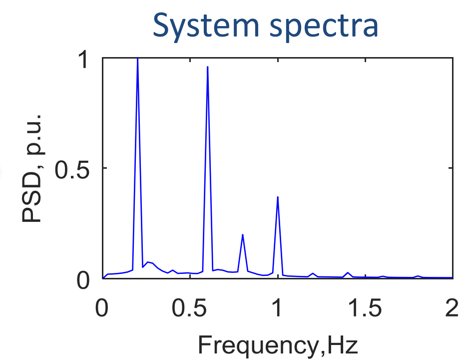
- DEF concept works equally well for Forced and undamped Natural modes
  - Accuracy is insensitive to a resonance of forced and natural modes
  - Is capable to identify generator-source if output of generator is metered by PMU

The DEF method testing: Simulated Cases

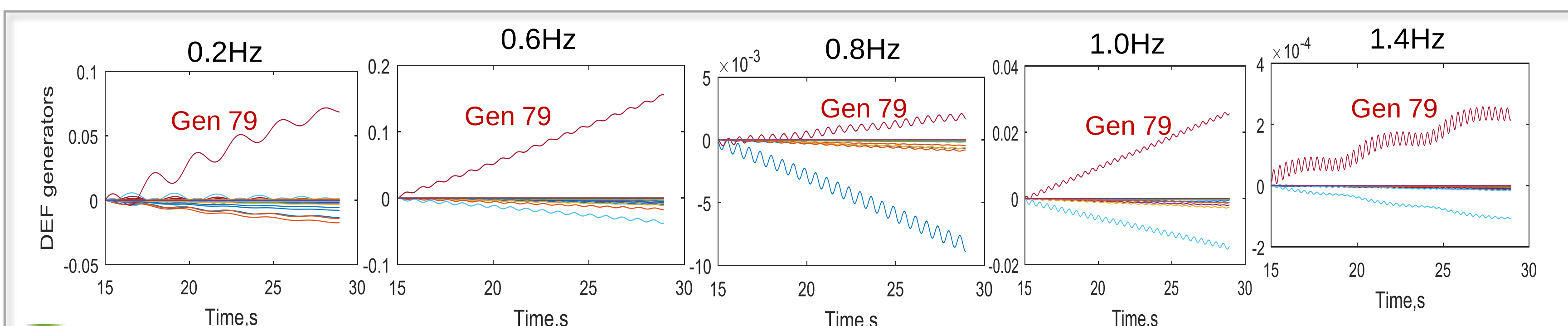
- 100% success rate for all Forced and Natural oscillation Cases
- Example: Case F_6_2 - rectangular periodic injection into generator 79





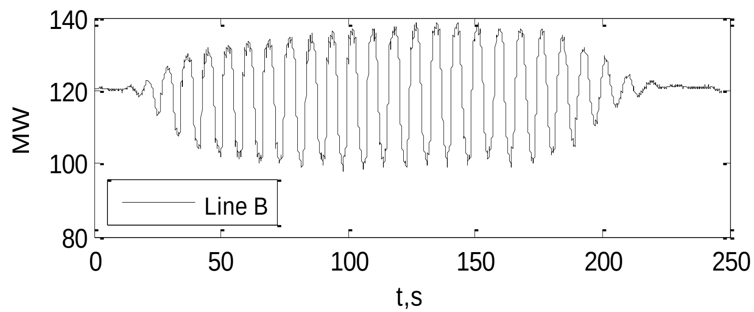


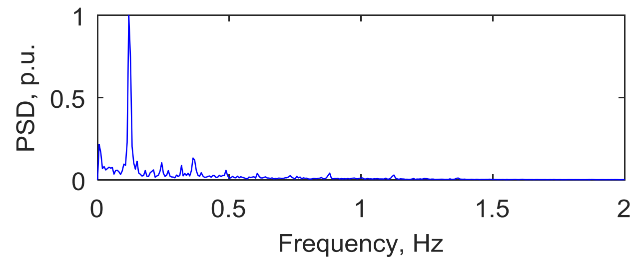
DEF results for all excited modes

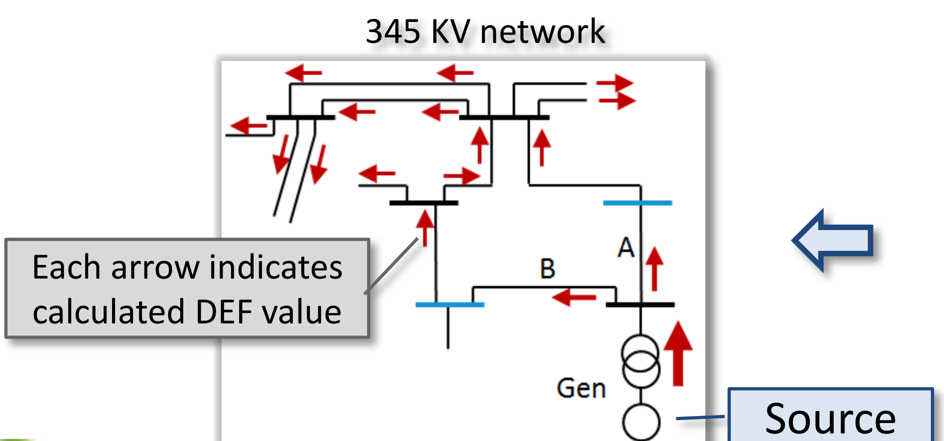


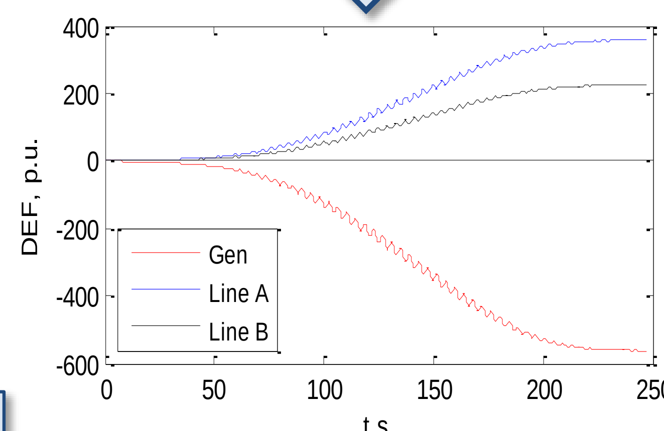
The DEF method testing: ISO-NE actual events

- High efficiency for tested 20+ events for oscillations 0.04… 1.7Hz
- PMU from 24 locations, 102 metered branches
- April 5, 2013 event: 0.12Hz up to 100 MW oscillations



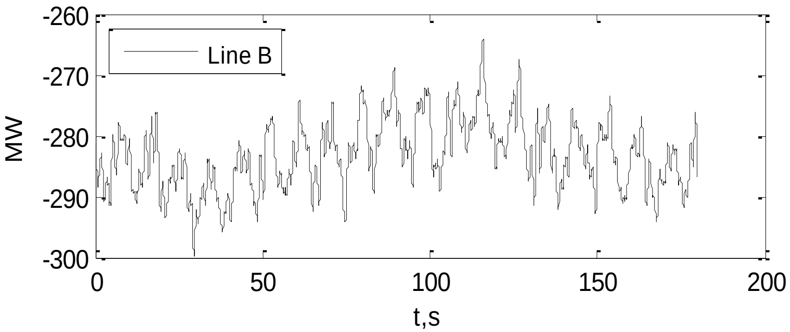




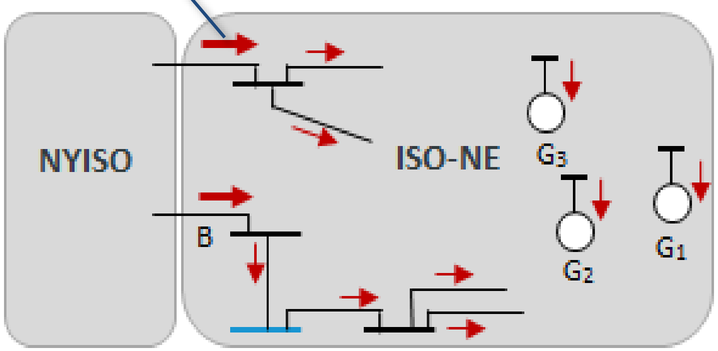


The DEF method testing: ISO-NE actual events

- February 4, 2014 event: 0.14Hz up to 10-20 MW oscillations observed across the system.
- PMU from ISO-NE footprint only are available
- All generators oscillate in phase suggesting that PMU cover only a part of oscillating system



DEF flow suggests that the Source of oscillations is in NYISO



The DEF method testing: WECC actual events

- BPA has kindly provided PMU data for two events in WECC:
  - ✓ 1.48Hz oscillations, March 2015
  - ✓ 1.17 Hz oscillations, November 2015
- 55 locations, 271 metered branches
- The DEF method correctly identified the source of forced oscillation as confirmed by BPA personnel

Additional benefits of the DEF method

- Potentially the DEF method can enable new type of PMU applications: *online estimation of damping contribution of system components (generators, HVDC lines, FACTS) into damping of a specific mode of oscillations*
- Similar functionality could be used in simulations
- Possible limitations of this capability related to the DEF assumptions and PMU data processing need to be investigated

Example of simulated case

- Low damped interarea mode due to negative damping from Gen 65 (D_{35}=1, D_{65}=-1, D_{77}=0.2) $\lambda = -0.034 \pm j0.37Hz$
- Damping contribution of generator i : $\Delta\alpha = D_i \cdot \partial\alpha / \partial D_i$

Damping contribution of generators into 0.37Hz mode

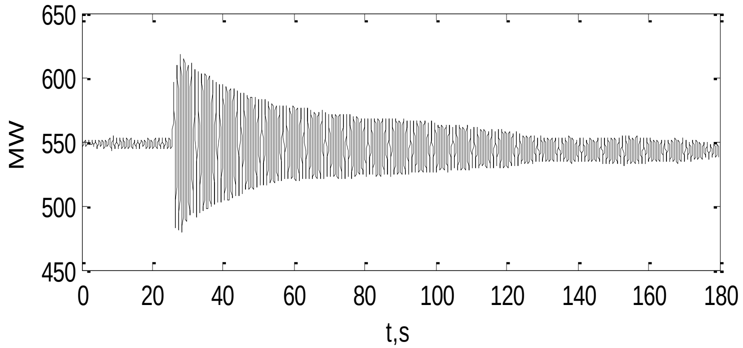
Gen	D	$\partial\alpha / \partial D$	$\Delta\alpha$	DEF	Rank
35	1	-0.0386	-0.039	-1	1
79	4	-0.0038	-0.015	-0.307	2
140	4	-0.0011	-0.004	-0.023	3
9	4	-0.001	-0.004	-0.018	4
77	0.2	-0.0108	-0.002	-0.005	5
65	-1	-0.0294	0.029	0.956	Source

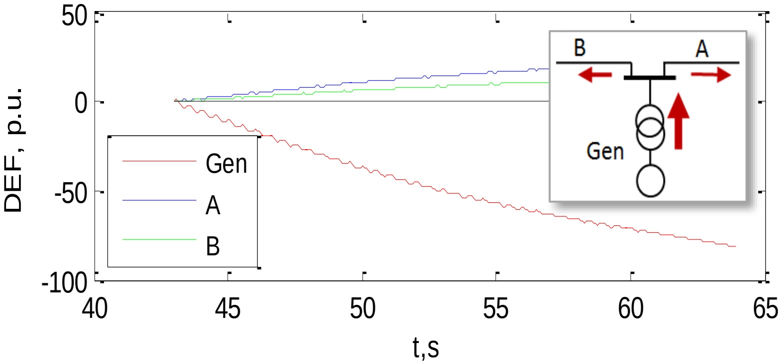
- The DEF method provides correct ranking for damping contribution of generators

Example of ISO-NE event

- January 25, 2016: trip of large generator has excited very low damped 0.98Hz oscillations observed in a part of system

Output of suspect – source generator





- The DEF method has identified the suspect-source generator as the source of sustained oscillations

Online Oscillation Management concept at ISO-NE

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