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Locating Forced Oscillations Sources

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Power System Forced Oscillations

Forced oscillations are sustained oscillations initiated by an external or unintended periodic input to the power system

Causes:

- Steam valve malfunction at a thermal plant
  - November 29, 2005 Western Interconnection event
  - September 5, 2015 Western Interconnection event
  - June 17, 2016 Eastern Interconnection event
  - January 11, 2019 Eastern Interconnection event
- Cyclic loads
- Excitation system loose contacts
- Water vortices at a hydro plant

Forced Oscillations Features

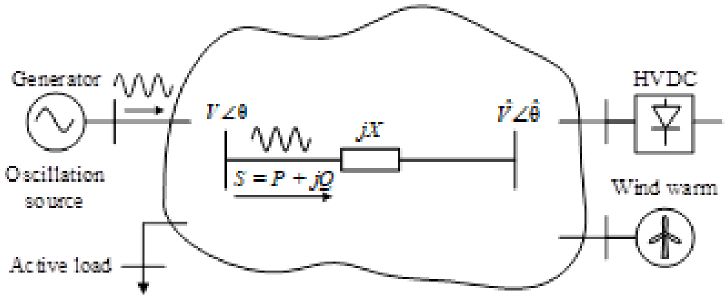
- More often exhibit intermittent behavior
- Can go from having low energy to having high energy and vice versa
- Can have any frequency, which can be non-stationary
- Often have harmonics as the cyclic forced input is not sinusoidal
- Have zero damping
- Can create resonance condition:
    - Frequency close to a natural mode frequency
    - High participation factors in the excited natural mode
    - Low damping of the excited natural mode

Factors Influencing Oscillation Source Identification

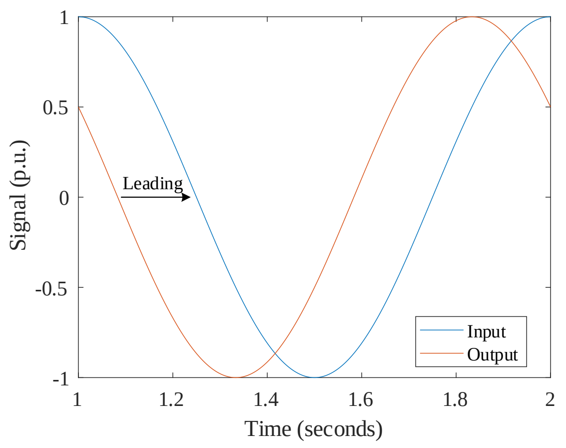
- **Load characteristics**: dependence of active power consumed by a load on voltage magnitude
- **Cause of oscillation**: due to maloperation in either reactive or active power control equipment
- **Observability**: is oscillation present in measured signals and how close to the source the available measurements are
- **Resonance condition**: frequency of a forced oscillation is close to the frequency of a natural mode

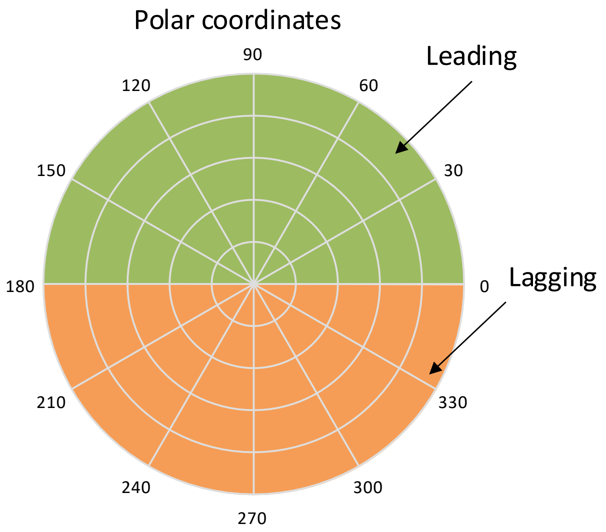
Cross-power Spectral Density for Source Identification

Power transfer on a lossless branch: $P = \frac{V_2}{X} V_1(\theta_1 - \theta_2)$ $Q = \frac{V_1 - V_2}{X} V_1$



V_1 and θ_1 are considered as inputs; P and Q are considered as outputs
Output leads input → source of forced oscillation at the beginning of the branch
Input-output relationship → input-output cross-correlation → input-output cross-power spectral density (CPSD): $S_{\theta P} = \overline{\mathcal{F}\{\theta\}} \circ \mathcal{F}\{P\}$ $S_{VP} = \overline{\mathcal{F}\{V\}} \circ \mathcal{F}\{P\}$ $S_{VQ} = \overline{\mathcal{F}\{V\}} \circ \mathcal{F}\{Q\}$
where $\mathcal{F}\{\}$: Fourier transform, $\circ$: element-wise product, $^{-}$: conjugate.





Source location: the branch with the largest *imaginary part* of CPSD:
- radial topology: source is identified
- ring or meshed topology: bus with the largest total Imag(CPSD) outflow is the source

D. Osipov, S. Konstantinopoulos, and J. H. Chow, "A Cross-Power Spectral Density Method for Locating Oscillation Sources using Synchrophasor Measurements," *IEEE Transactions on Power Systems, 2022*

Incremental Energy

Input-output relationship $\rightarrow$ energy function:

$$E = \int_{u_0}^{u} y(t)du(t)$$

Incremental energy:

$$W = \int_{\Delta u_0}^{\Delta u} \Delta y(t)d\Delta u(t)$$

where $\Delta y = y - y_s$, $\Delta u = u - u_s$, y_s and u_s are the output and input trajectories corresponding to quasi-steady state.

CPSD		Incremental energy	Dissipating Energy
$S_{\theta P} = \overline{\mathcal{F}\{\theta\}}\mathcal{F}\{P\}$	$\rightarrow$	$W_{\theta P} = \int_{\Delta\theta_0}^{\Delta\theta} \Delta P(t)d\Delta\theta(t)$	$W_D = \int 2\pi\Delta P(t)\Delta f(t)dt$
$S_{VQ} = \overline{\mathcal{F}\{V\}}\mathcal{F}\{Q\}$	$\rightarrow$	$W_{VQ} = \int_{\Delta V_0}^{\Delta V} \Delta Q(t)d\Delta V(t)$	$+\int \Delta Q(t)d(\Delta \ln V(t))$
$S_{VP} = \overline{\mathcal{F}\{V\}}\mathcal{F}\{P\}$	$\rightarrow$	$W_{VP} = \int_{\Delta V_0}^{\Delta V} \Delta P(t)d\Delta V(t)$	

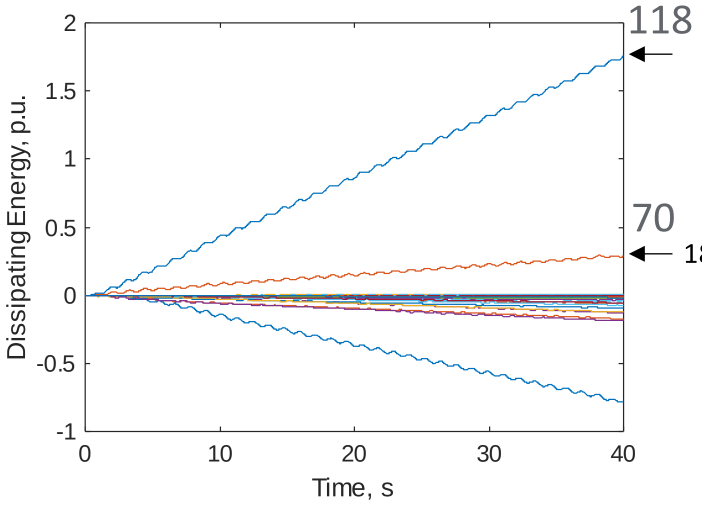
S_{VP} CPSD addresses the issue of misidentification reported in: Y. Zhi and V. Venkatasubramanian, "Analysis of energy flow method for oscillation source location," *IEEE Trans. Power Syst*, vol. 36, no. 2, pp. 1338-1349, Mar. 2021

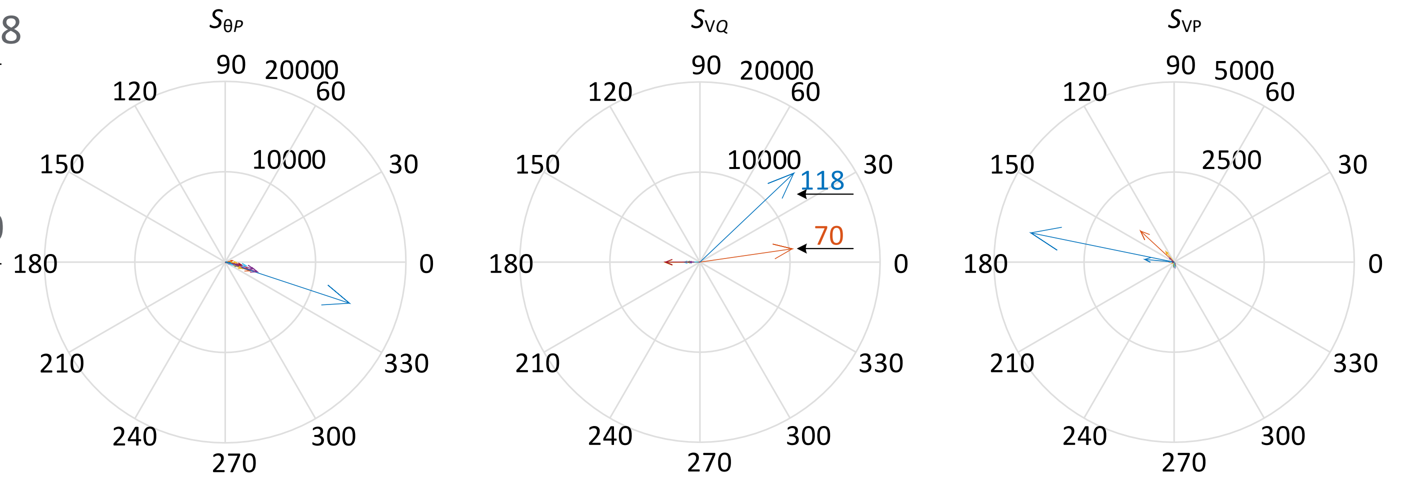
Load Model Test in the 179-bus WECC System

A test case from the Test Cases Library for Methods Locating the Sources of Sustained Oscillations.

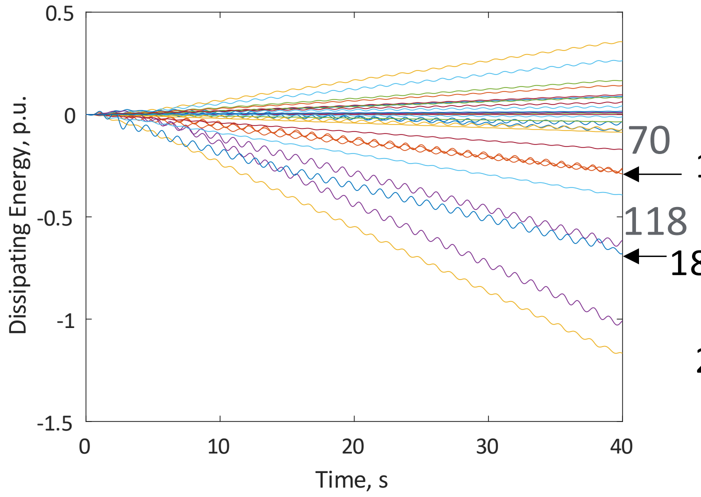
Case F_7_2: Forced signal of 0.43 Hz is injected into the excitation system of Generators 70 and 118

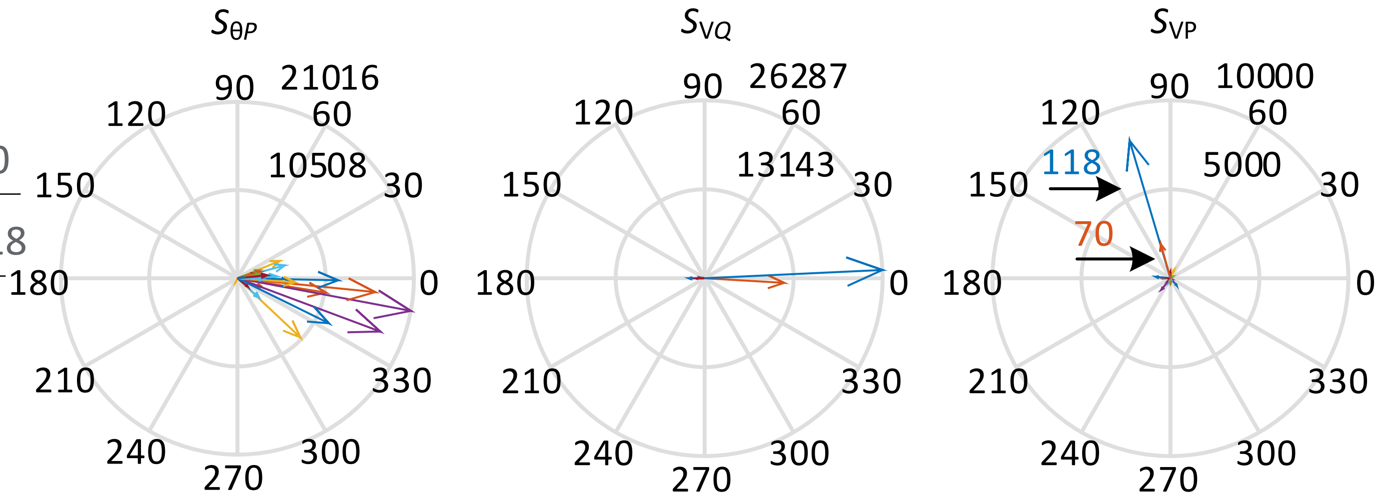
Constant *Power* Load Model





Constant *Impedance* Load Model





Oscillation Source Type Identification

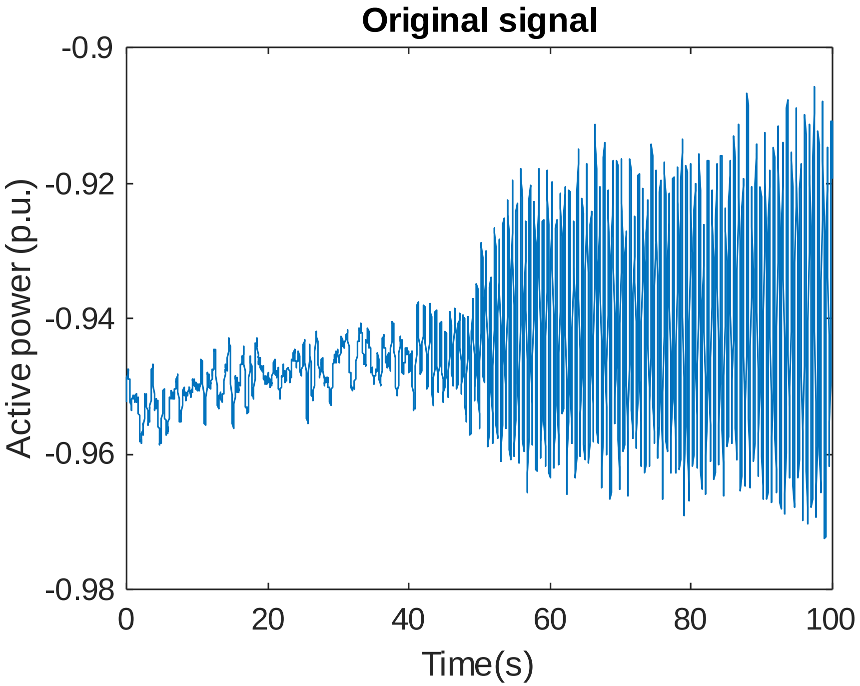
- **Type of source**: compare power spectral density of active power $S_P = \mathcal{F}\{P\}$ and reactive power $S_Q = \mathcal{F}\{Q\}$

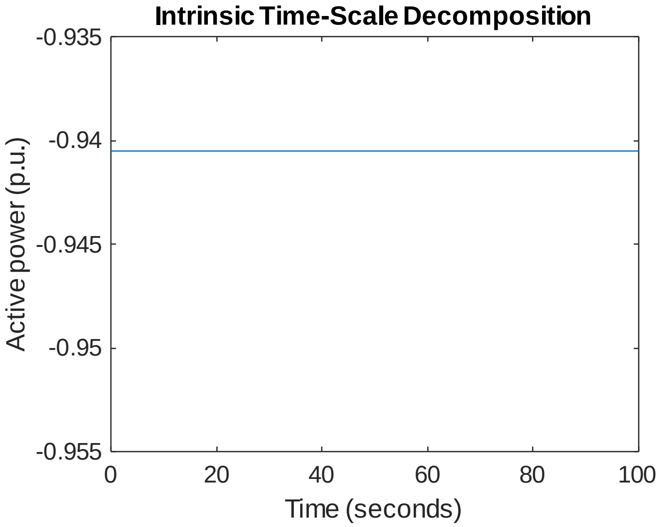
- $\max(|S_P|) > \max(|S_Q|) \rightarrow$ P-type: generator governor, cyclic load, sending-end HVDC terminal

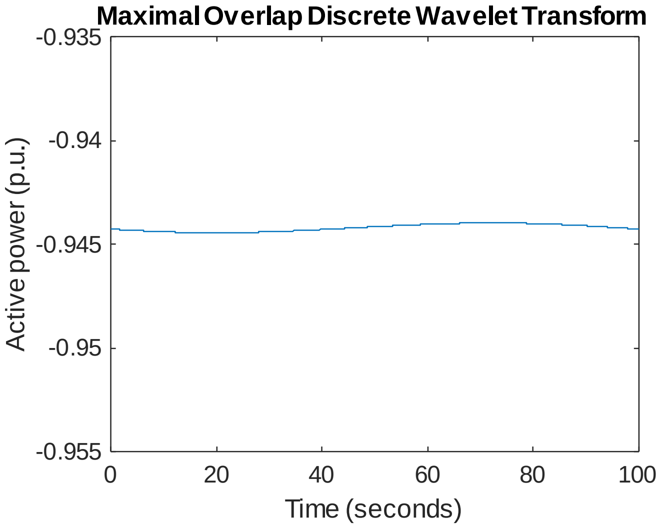
- $\max(|S_P|) < \max(|S_Q|) \rightarrow$ Q-type: generator excitation system, receiving-end HVDC terminal

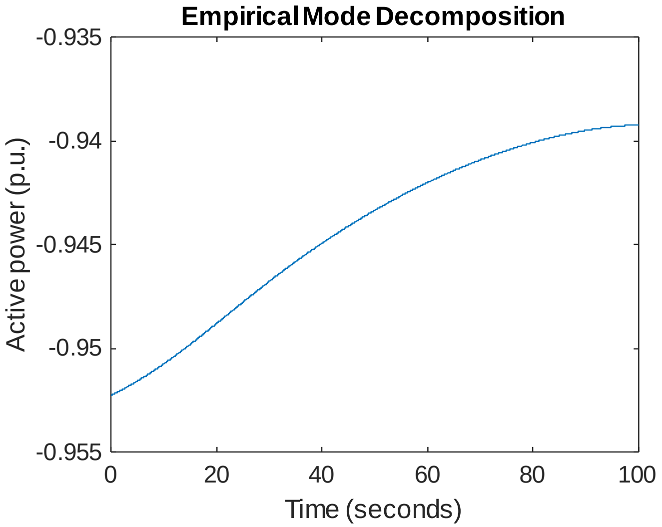
- For a Q-type, the oscillation is observed in both the active and reactive power signals: $\max(|S_P|) \cong \max(|S_Q|) \rightarrow$ Q-type

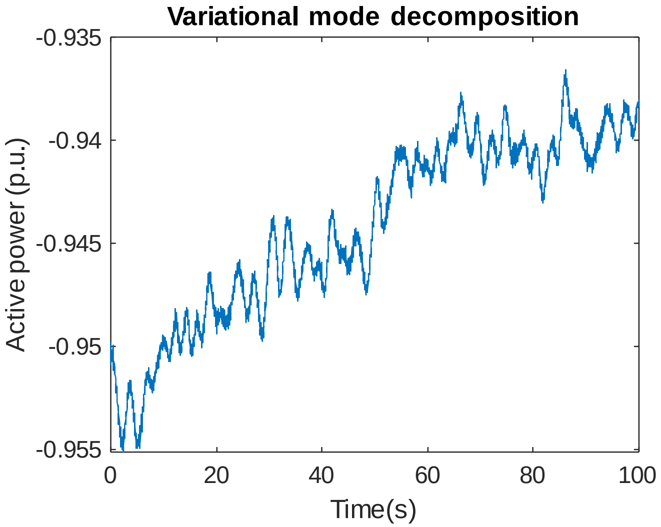
Dynamic Component Extraction



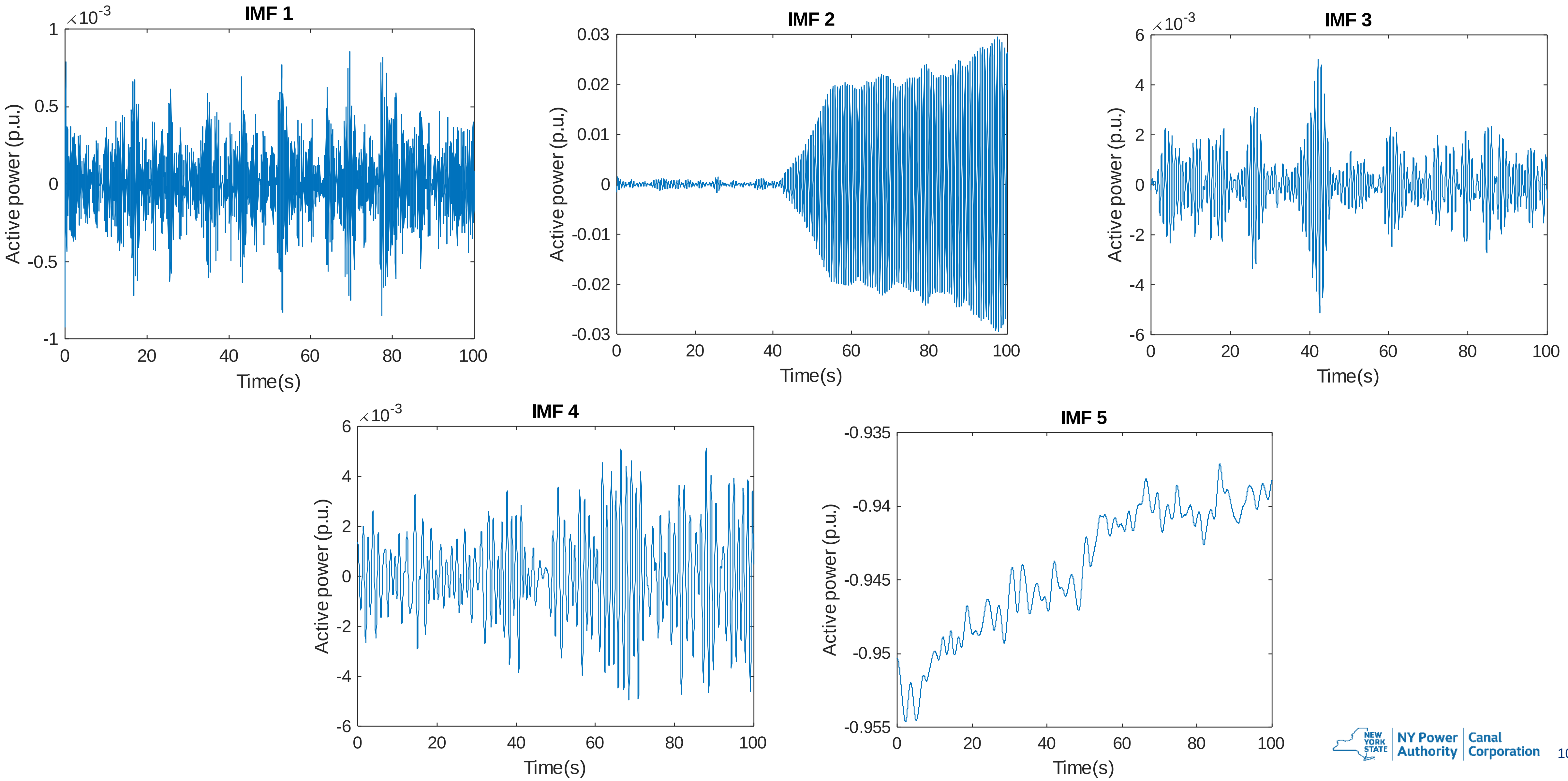








Intrinsic Mode Functions

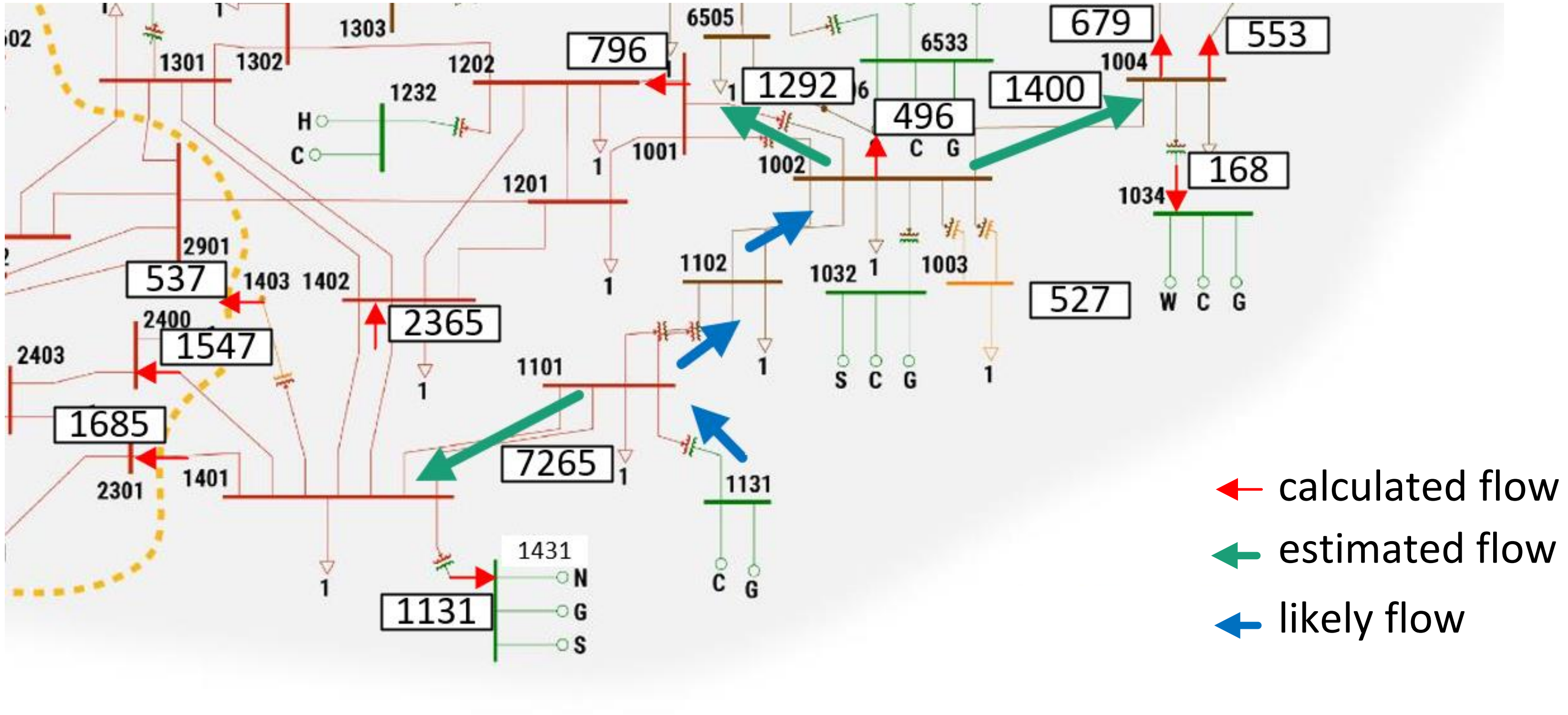


Source Type Identification in 240-bus WECC System

Simulated cases for 2021 IEEE-NASPI Oscillation Source Location Contest. (In Test Cases Library now.)
Case 3: Forced oscillation signal of 0.379 Hz is injected into the excitation system of a generator at Bus 1131.

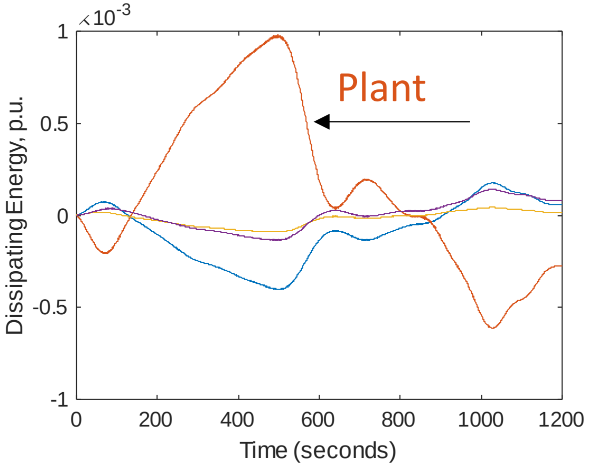
$\max(|S_P|) = 267 < \max(|S_Q|) = 436 \rightarrow$ *excitation system*

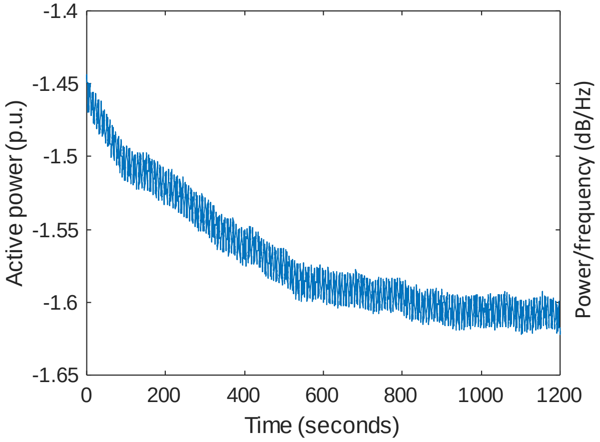
CPSD flow

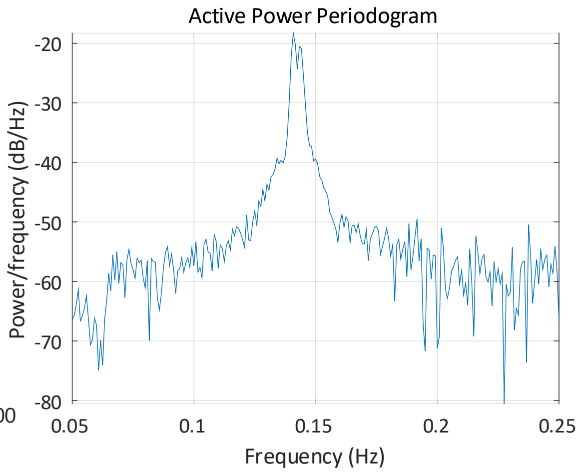


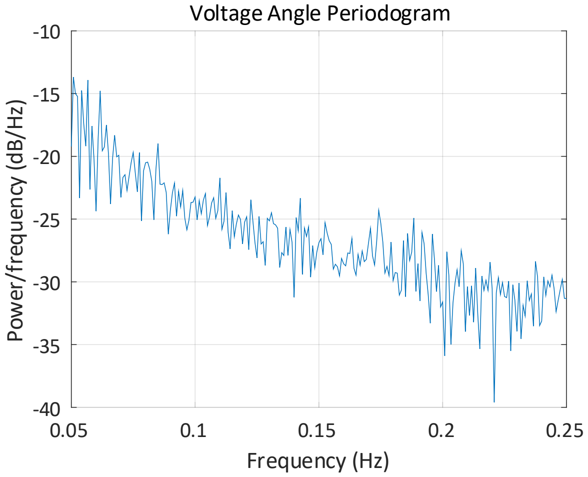
Actual Oscillatory Event In ISO New England

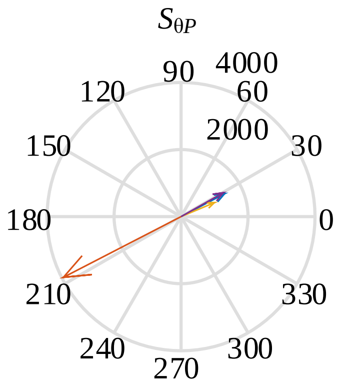
A test case from the Test Cases Library for Methods Locating the Sources of Sustained Oscillations.
Cases of actual oscillatory events (source unknown, although governor suspected)
Case 6: Forced oscillation of 0.14 Hz at a power plant measured at the receiving end of a line (substation with 4 lines)

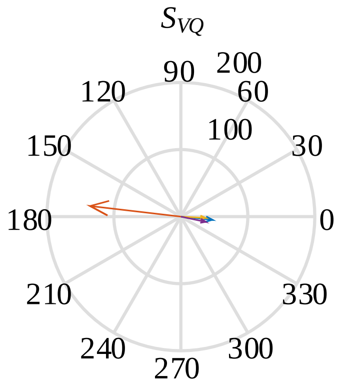


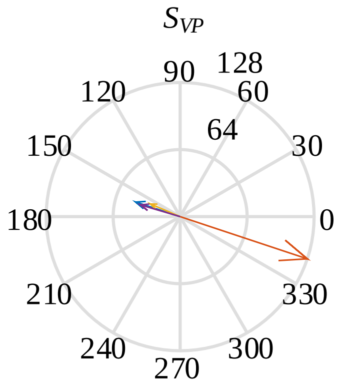












- Dissipating energy and the phase of $S_{\theta P}$ both cannot be trusted because the amplitude of oscillation was very small.
- This is not a resonant case → source can be identified by $|S_{\theta P}|$

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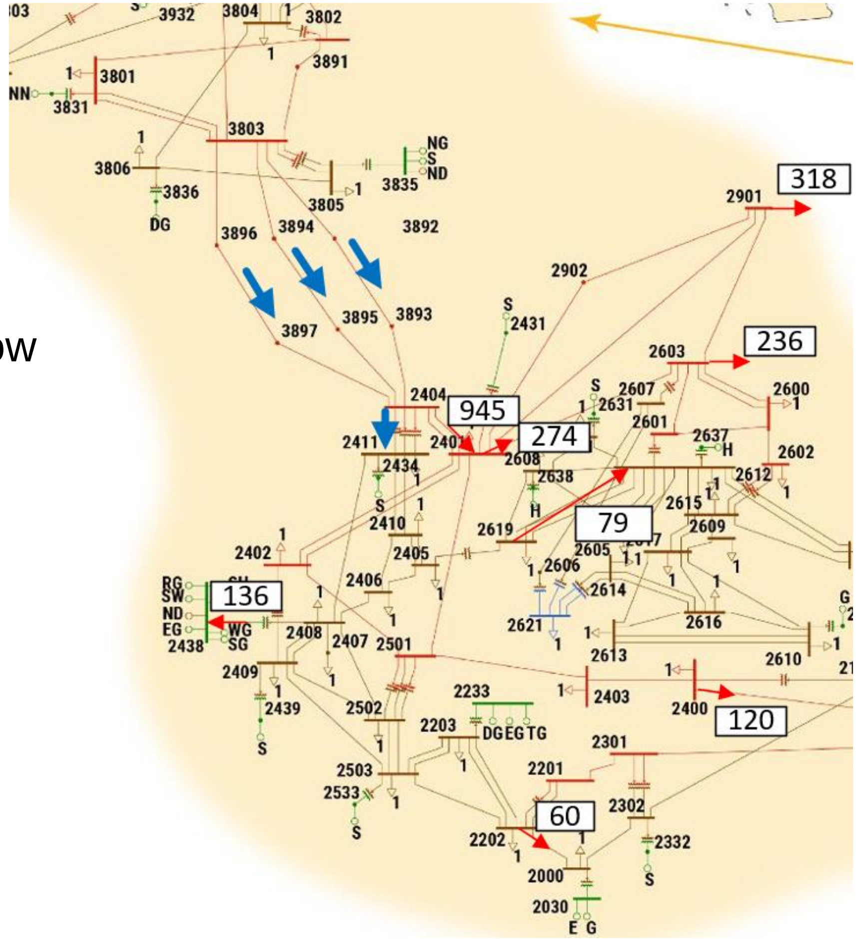
Source location identification in 240-bus WECC System

Simulated cases for 2021 IEEE-NASPI Oscillation Source Location Contest. (In Test Cases Library now.)
Case 4: Forced signal of 0.379 Hz is injected into the governor of a generator at Bus 3831

CPSD flow



Conclusions

Advantages of the CPSD approach:

- Does not require band-pass filtering
- Requires only topological information
- Can accurately identify the type of the source
- Performs well when active power consumed by loads depends on voltage magnitude

Limitation of the CPSD approach:

- Long window of data is required for good frequency resolution

Future directions:

- Adapt the CPSD approach for point-on-wave data and use it to identify oscillations originating from inverter-based resources