Advanced PMU Data Processing for Oscillation Detection and Identification

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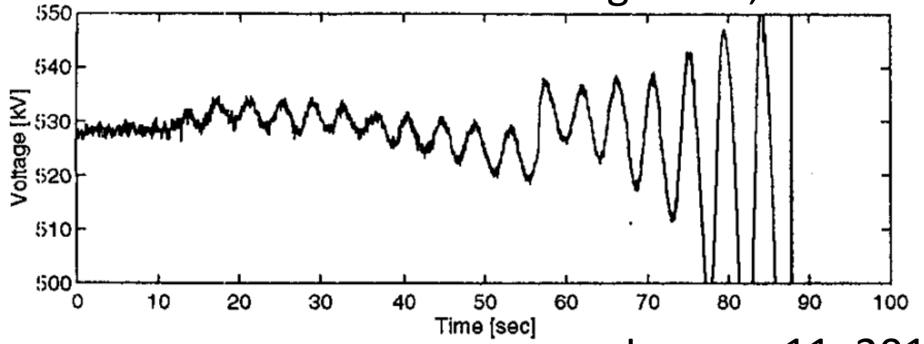
Introduction

Oscillation is a periodic variation of power system quantities (voltages, currents)

Sources of the oscillations in a power system:

- Improper tuning of power system stabilizers which reduces damping of a natural mode
- Maloperation of cyclic nature in the mechanical or electrical control systems of a power plant which causes a forced oscillation in the system

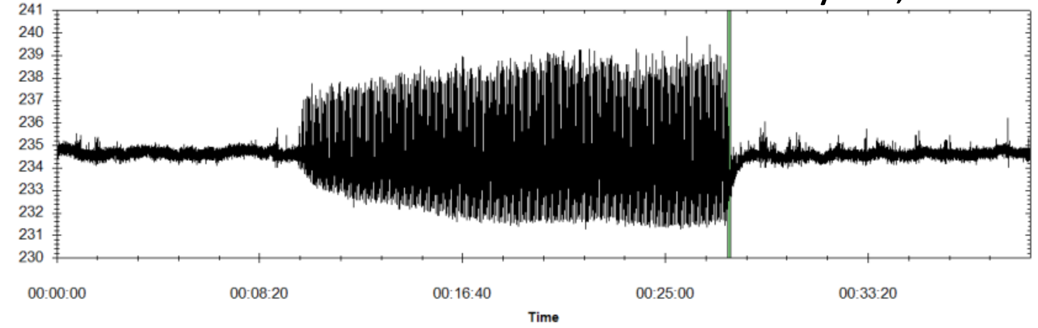
August 10, 1996



Consequences of unmitigated oscillations:

- Equipment damage
- Power outage

January 11, 2019



Examples of natural and forced oscillations:

- August 10, 1996 WSCC System Outage
- January 11, 2019 EI Forced Oscillation Event

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 frequency of a natural mode

Cross-Power Spectral Density

Cross-power Spectral Density for Source Identification

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

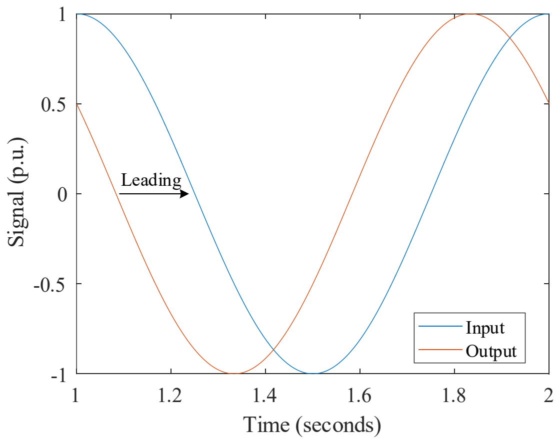
V_1 and θ_1 are considered to be the inputs; P and Q are considered to be the outputs

Output leads input → source of forced oscillation at the beginning of the branch

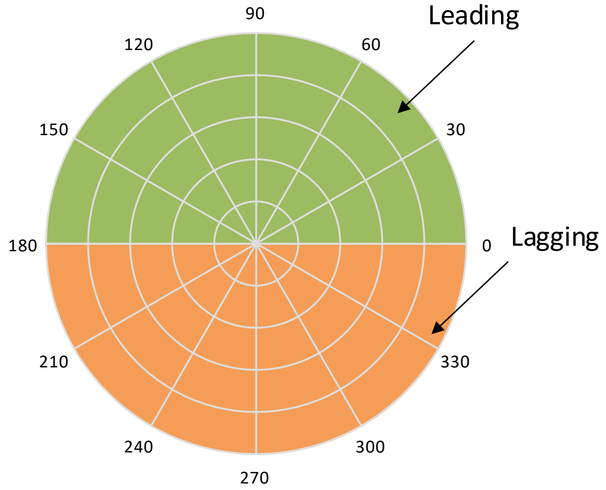
Input-output relationship → input-output cross-correlation → input-output cross-power spectral density (CPSD):

$$S_{\theta P} = \overline{\mathcal{F}\{\theta\}} \circ \mathcal{F}\{P\} \qquad S_{VP} = \overline{\mathcal{F}\{V\}} \circ \mathcal{F}\{P\} \qquad S_{VQ} = \overline{\mathcal{F}\{V\}} \circ \mathcal{F}\{Q\}$$

where $\mathcal{F}\{\}$ denotes the Fourier transform, $\circ$ denotes the element-wise product, $\bar{}$ denotes the conjugate.



Polar coordinates



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 Im(CPSD) outflow is the source

Incremental Energy

Input-output relationship → 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 Characteristics

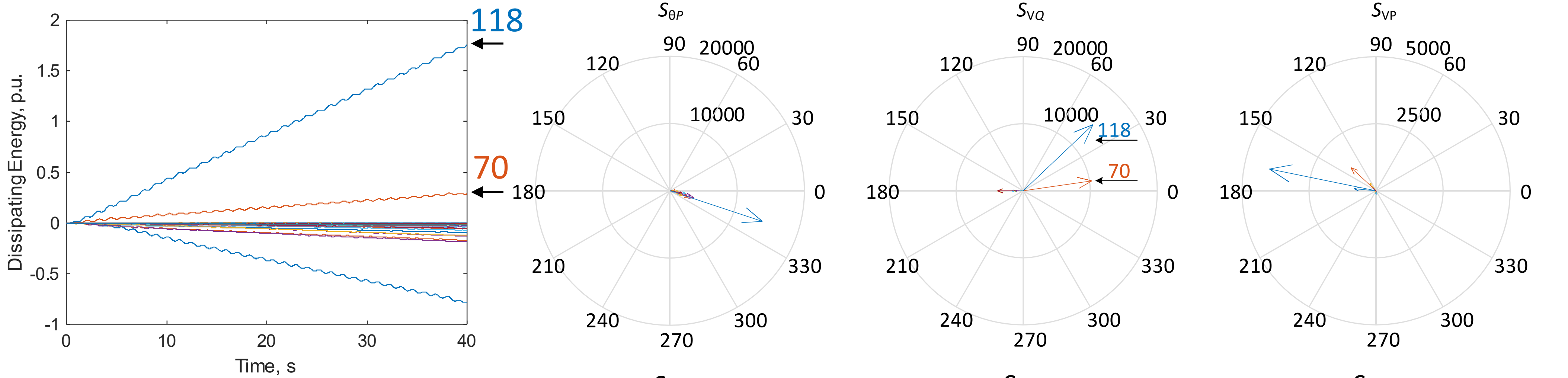
Load Model test in the 179-bus WECC System

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

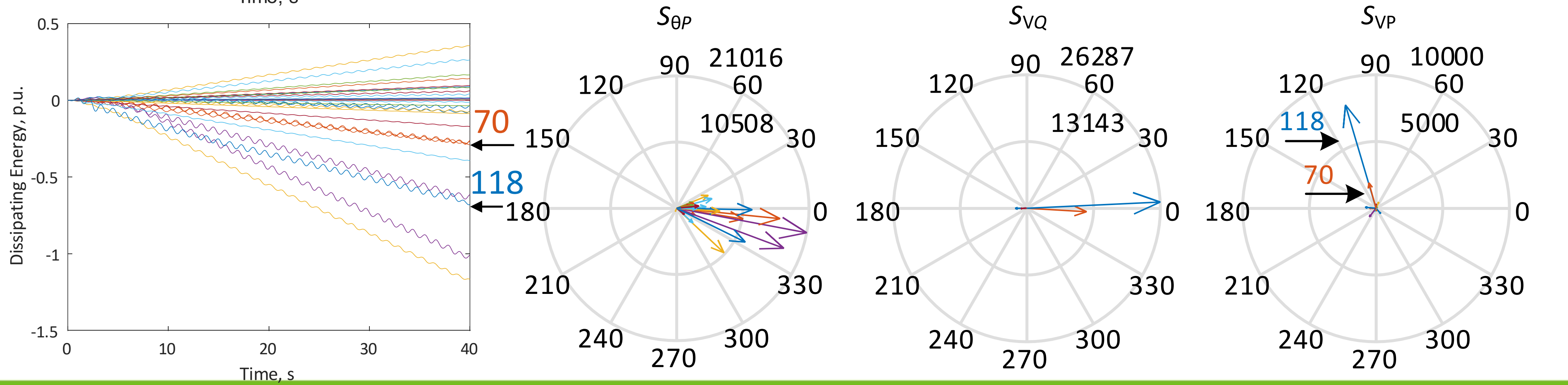
Case F_7_2: Forced signal of 0.43 Hz is injected into the excitation system of Generators 70 and 118

It becomes a difficult case when constant impedance load model is used, effecting the dissipating energies

Constant *Power* Load Model



Constant *Impedance* Load Model



Oscillation Cause Identification

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 HVDC terminal

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

Source type identification in the 240-bus WECC System

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

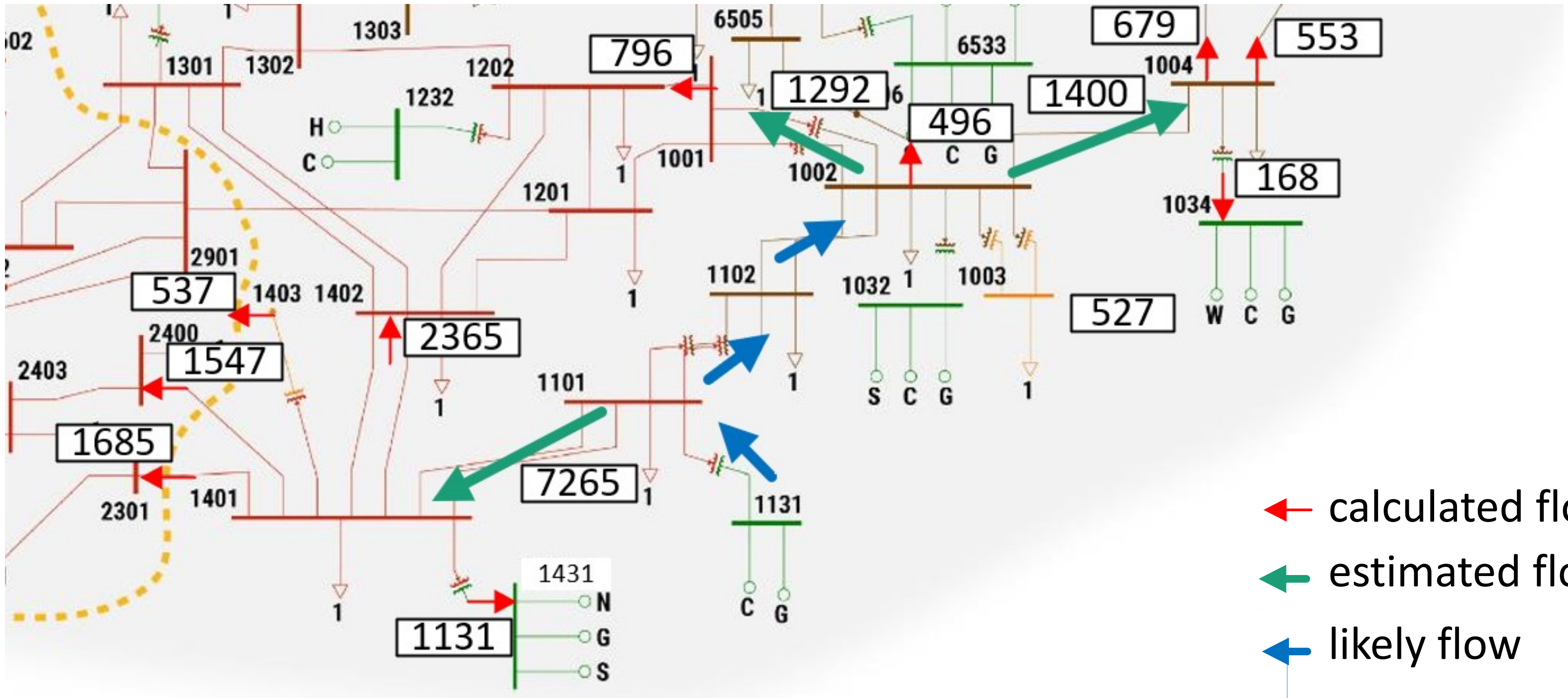
Simulated cases for 2021 IEEE-NASPI Oscillation Source Location Contest.

Case 3: Forced oscillation signal of 0.379 Hz is injected into the excitation system of a generator at Bus 1131.

Source of potential confusion – the bus with the oscillation source is not monitored; large CPSD flows occur at branches connected to Bus 1401 (lower left corner)

$$\max(|S_P|) = 267 < \max(|S_Q|) = 436 \rightarrow \textit{excitation system}$$

CPSD flow



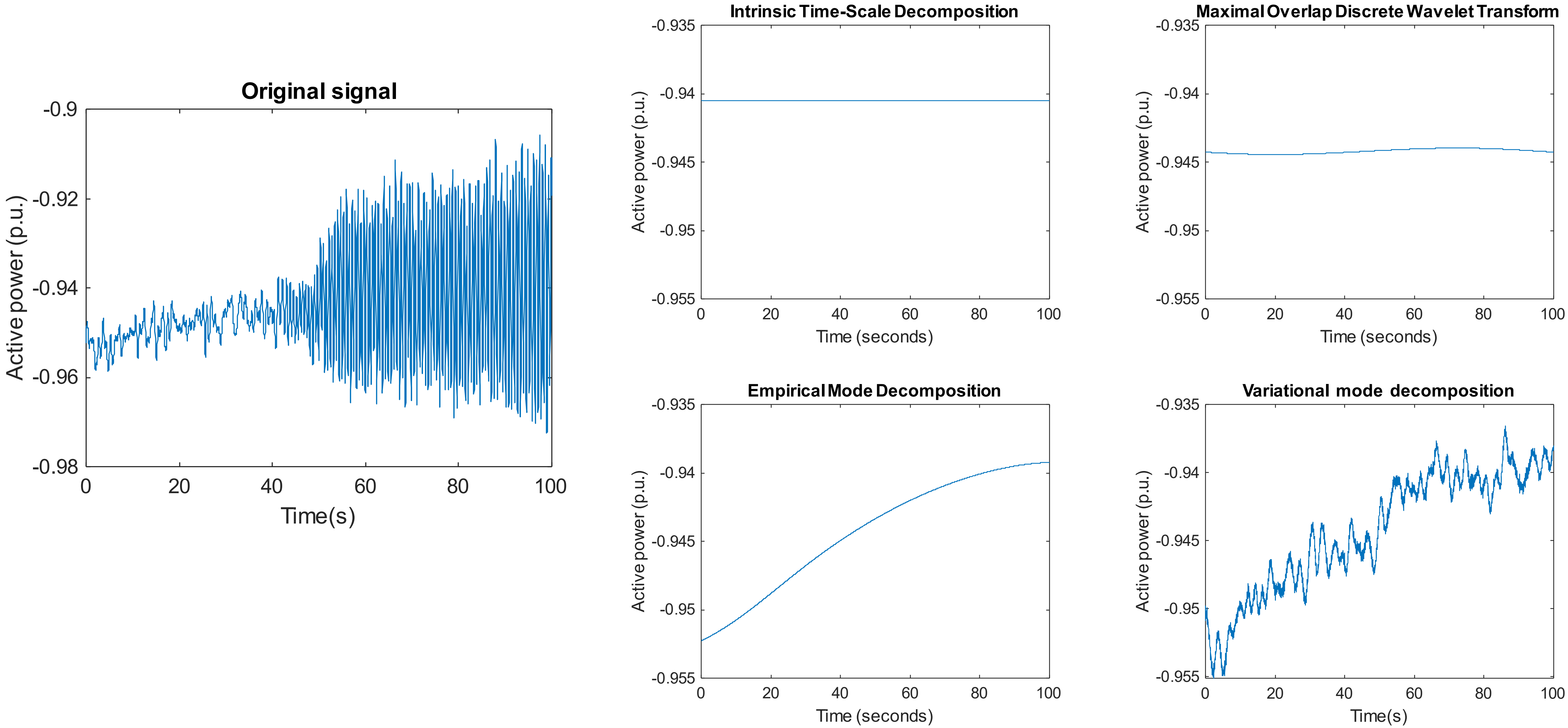
calculated flow

estimated flow

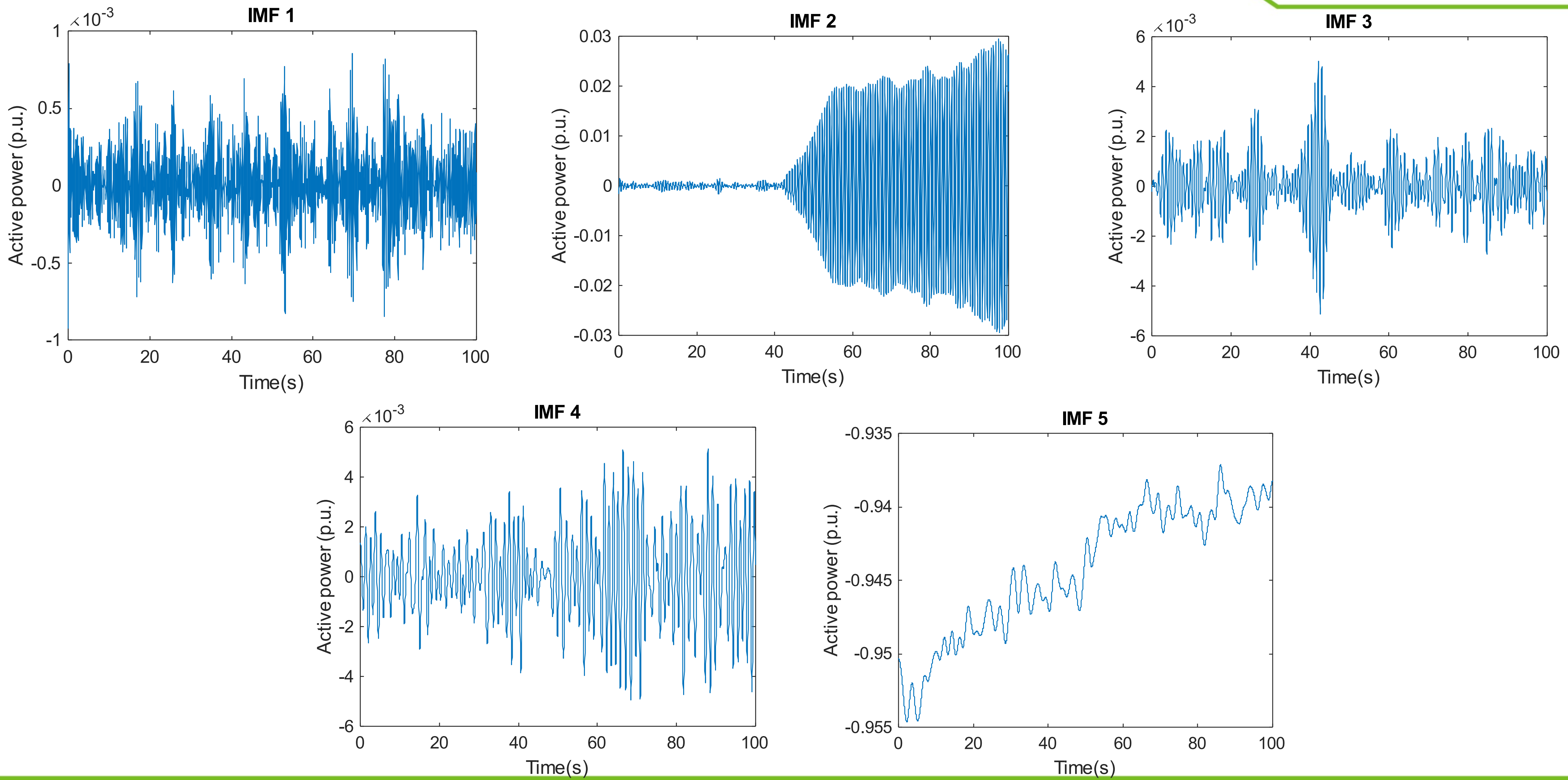
likely flow

Dynamic Component Extraction

Dynamic Component Extraction by Quasi-steady State Removal



Intrinsic Mode Functions



Observability

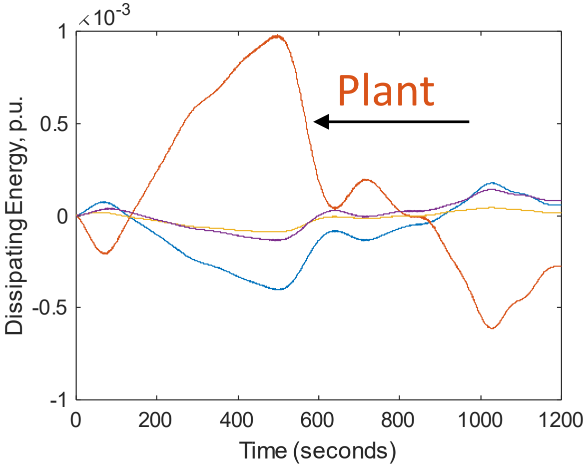
Actual Oscillatory Event In ISO New England

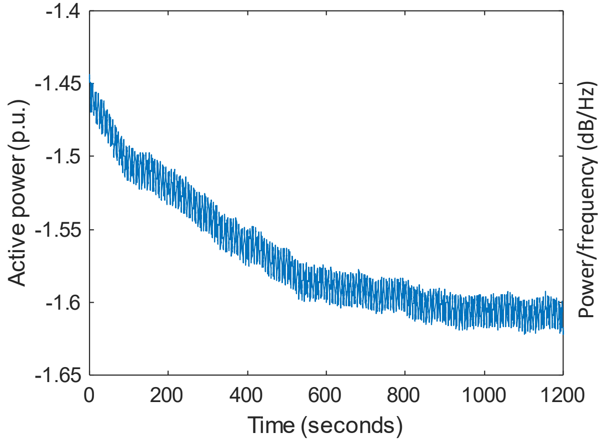
A test case from the Test Cases Library for Methods Locating the Sources of Sustained Oscillations.

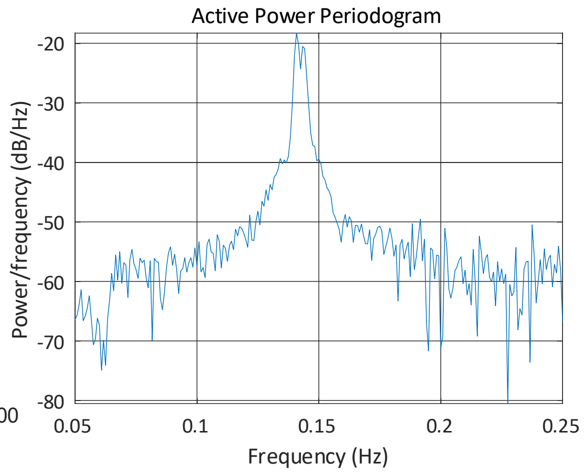
Cases of actual oscillatory events

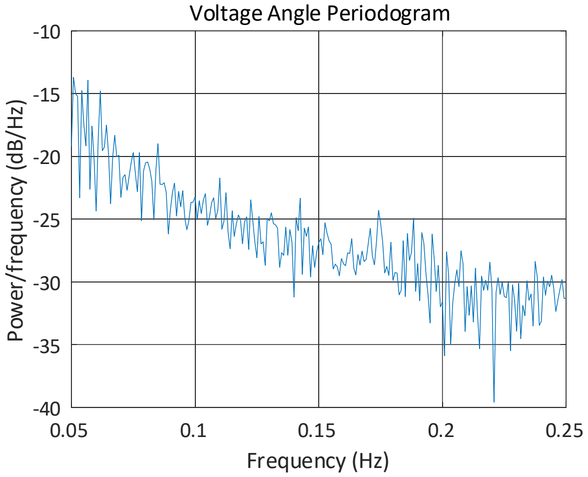
Case 6: Forced oscillation of 0.14 Hz at a power plant measured at the receiving end of a line

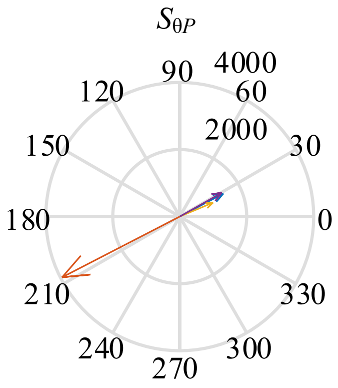
Dissipating energy changes direction due to *absence* of the oscillation in the voltage angle signal

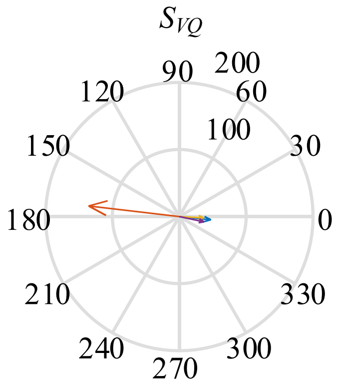


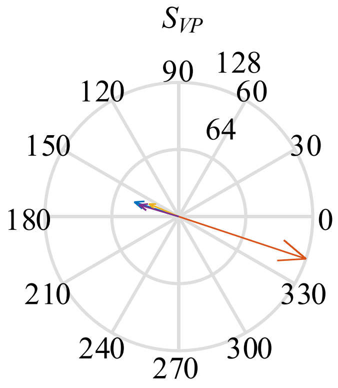










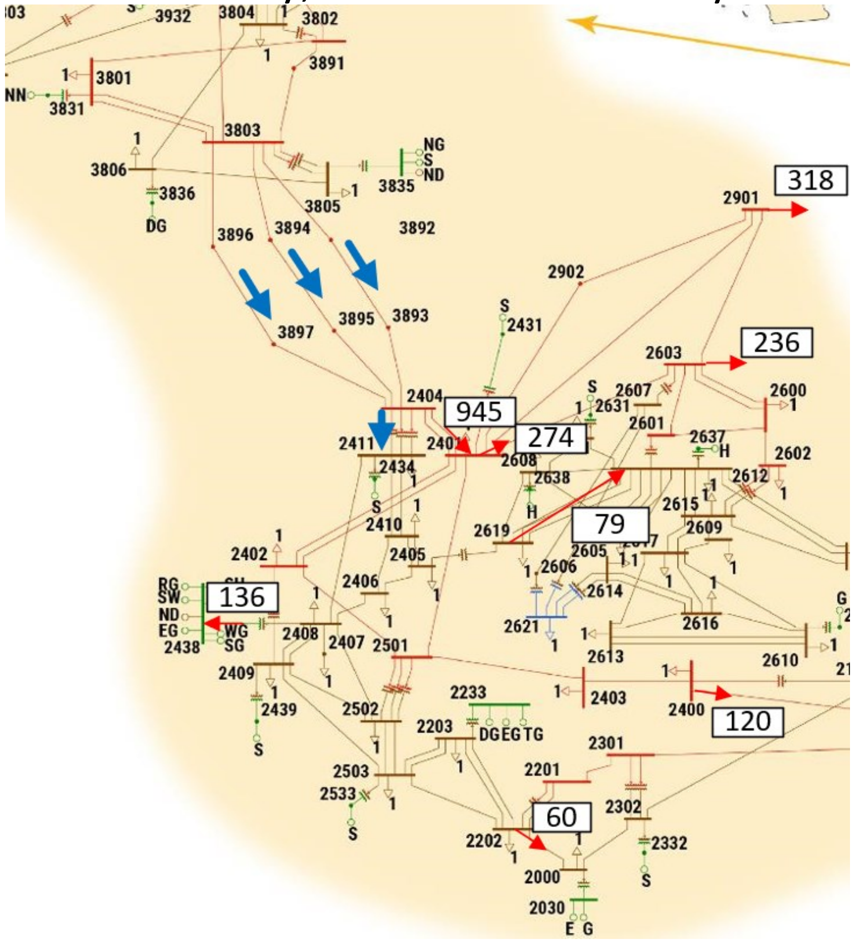


- Dissipating energy and the phase of $S_{\theta P}$ both cannot be trusted because the amplitude of oscillation was very small.
- This is not a resonant case → source can be identified by $|S_{\theta P}|$

Source location identification in the 240-bus WECC System

A test case from the Test Cases Library for Methods Locating the Sources of Sustained Oscillations.
Simulated cases for 2021 IEEE-NASPI Oscillation Source Location Contest.
Case 4: Forced signal of 0.379 Hz is injected into the governor of a generator at Bus 3831
This case is difficult because of limited observability; our method can only identify a zone with several possible buses

CPSD flow



Conclusions

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:

- Adoption of measurement devices with improved accuracy of voltage angle/frequency measurements