Cross Power Spectral Density based Approach for Locating Oscillations in Power Systems using Phasor Measurements

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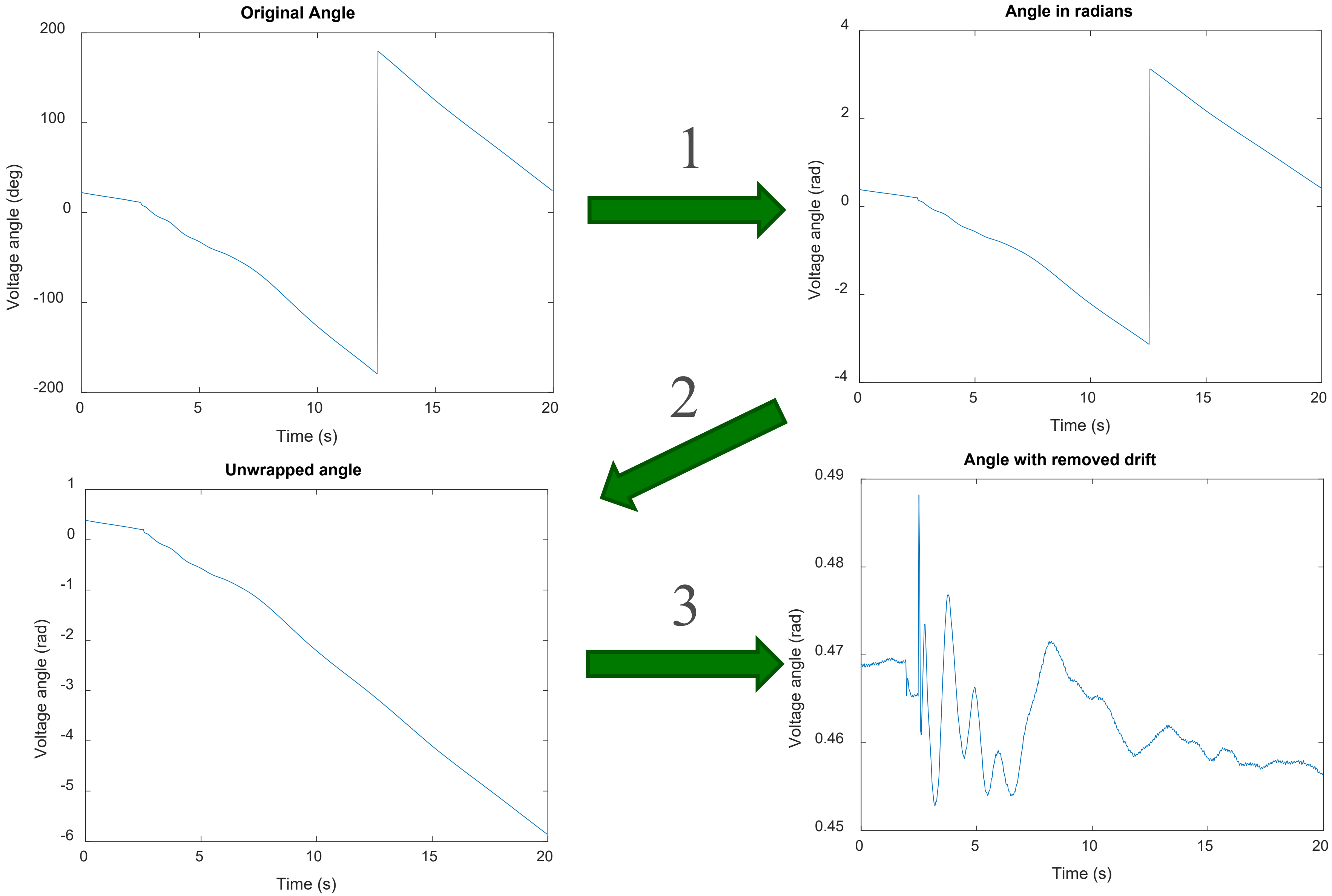
Voltage Angle Preprocessing

Preprocessing steps:

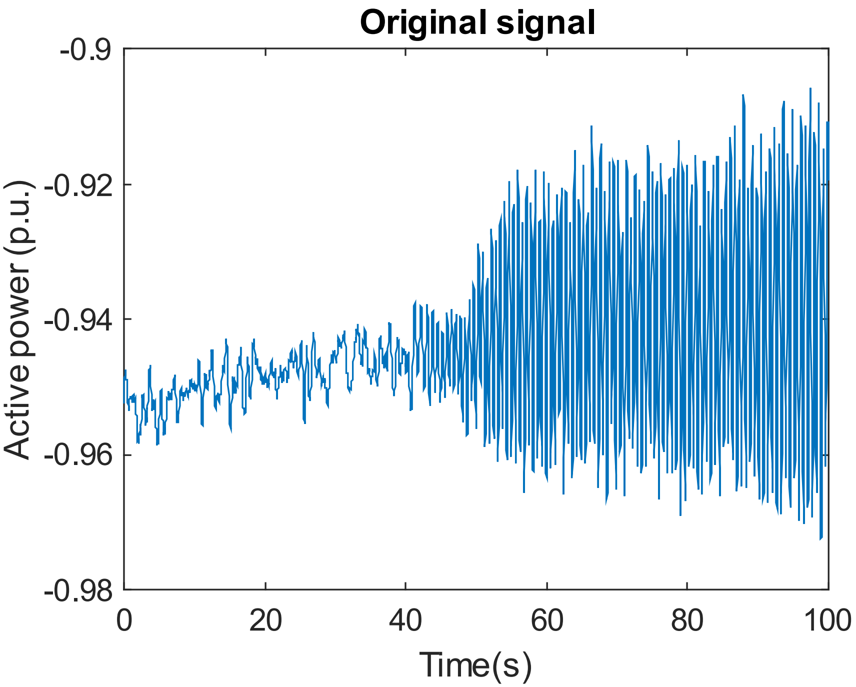
1. Convert degrees to radians

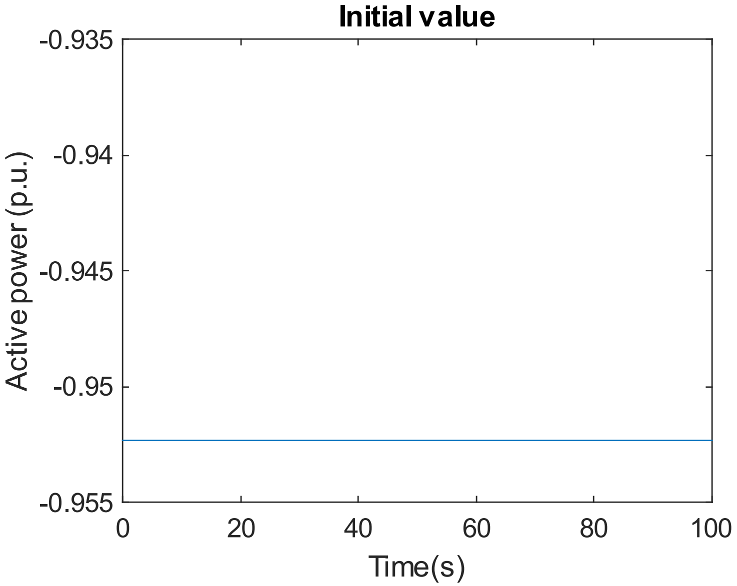
2. Unwrap angle

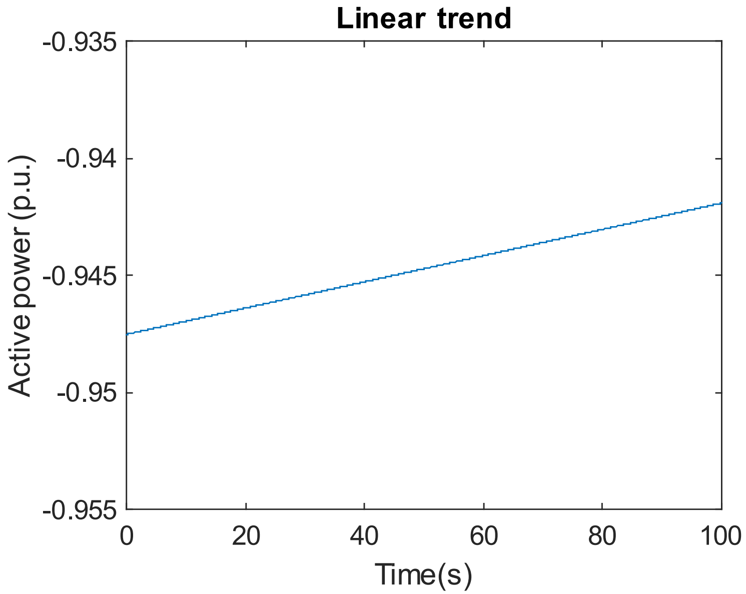
3. Remove angle drift
   (subtract a reference angle)

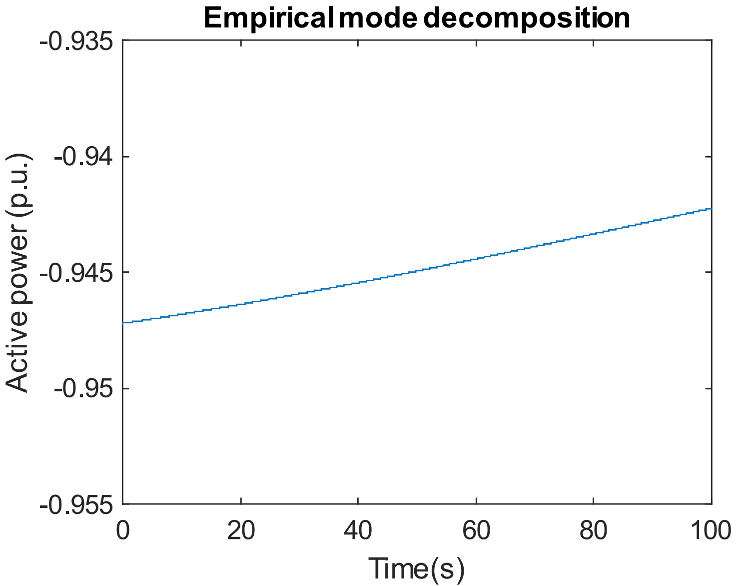


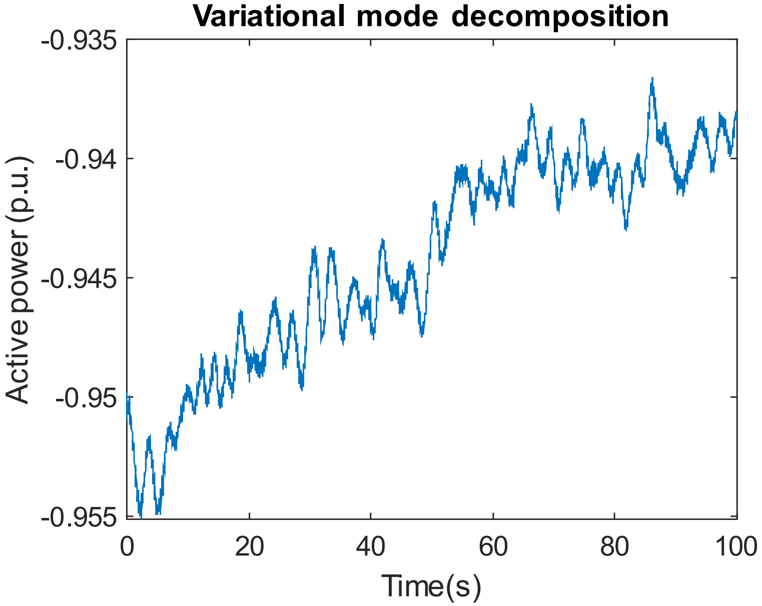
Dynamic Component Extraction by Quasi-steady State Removal











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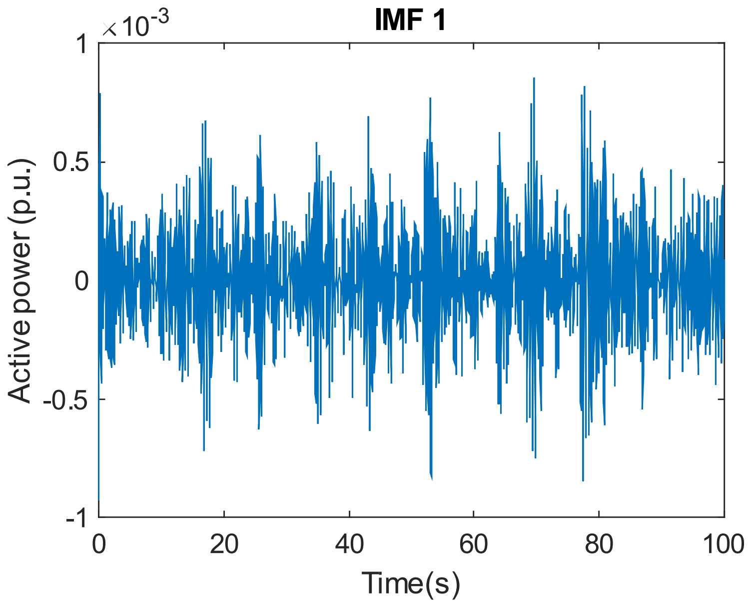
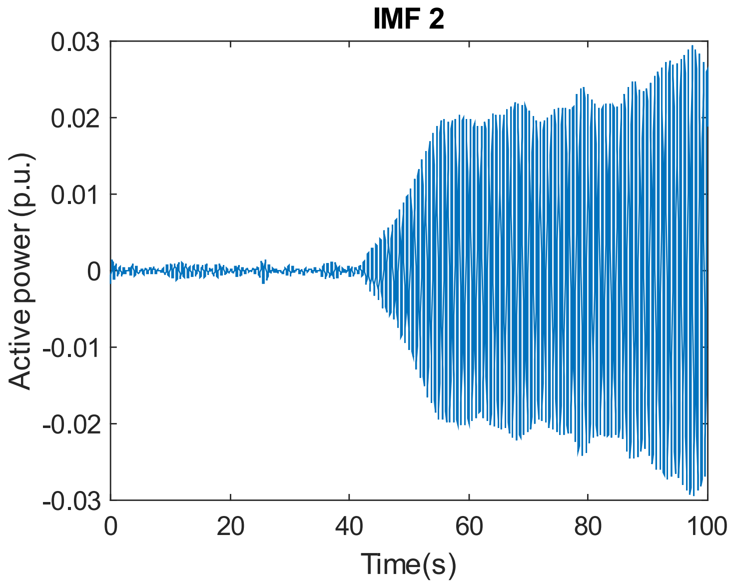
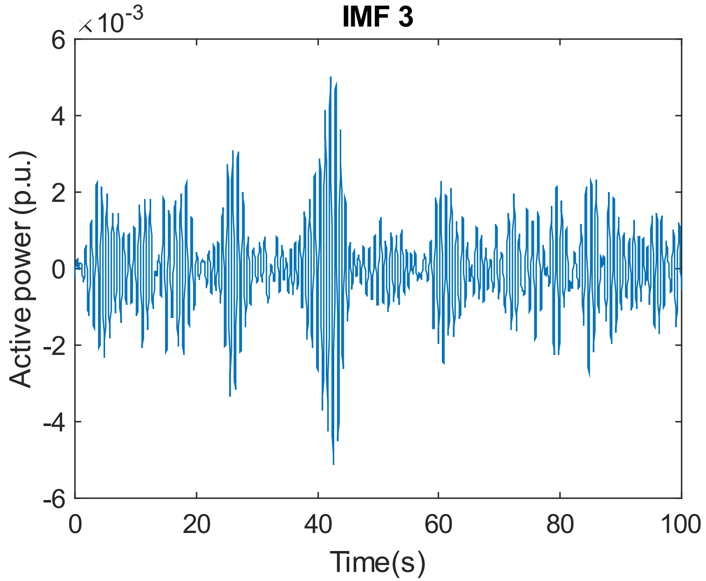
Intrinsic Mode Functions

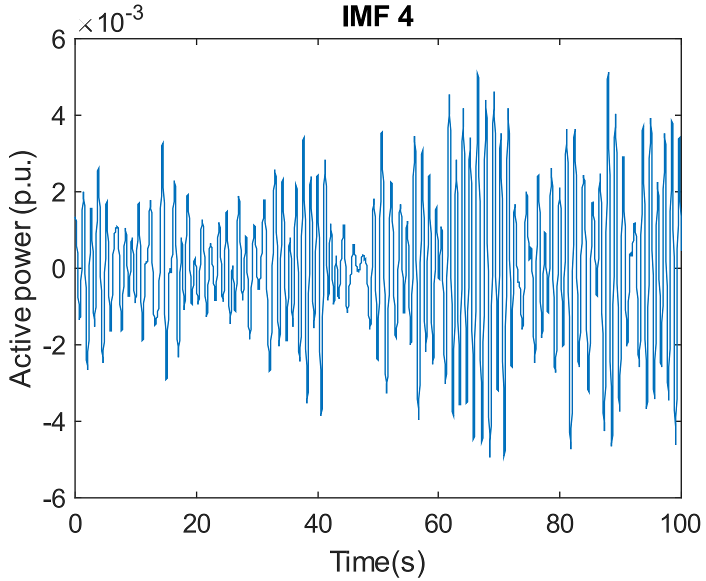


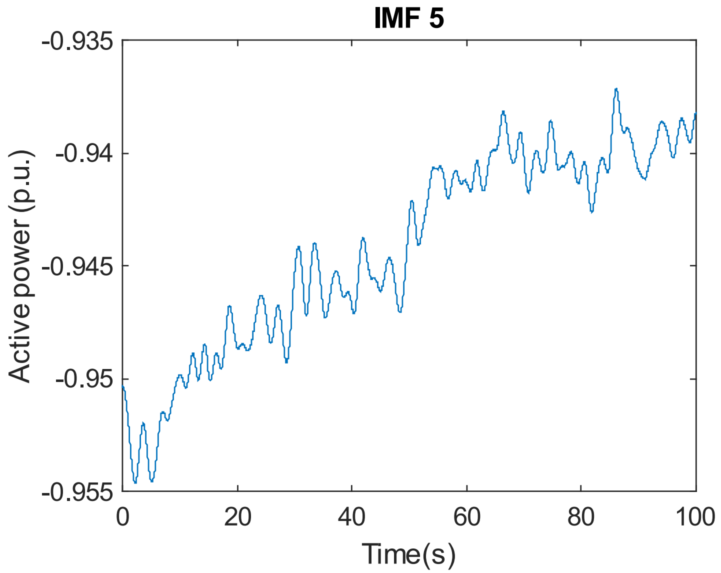




IMF requirements:

1. Number of extrema = number of zero crossings ±1
2. Mean value of maxima and minima envelopes = 0





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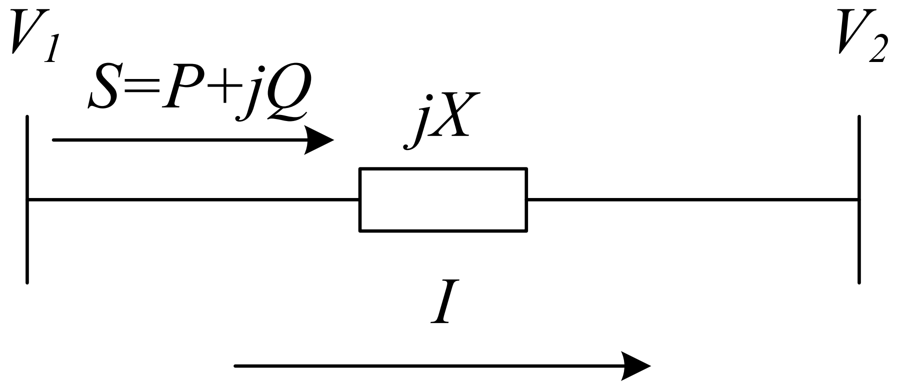
Power Transfer on a Lossless Line

Voltage at the beginning of the branch: $\bar{V}_1 = V_1\angle\theta_1$

Voltage at the end of the branch: $\bar{V}_2 = V_2\angle\theta_2$

Branch current: $\bar{I} = \frac{\bar{V}_1 - \bar{V}_2}{jX}$

Complex power: $\bar{S} = \bar{V}_1\bar{I}^*$



$$\bar{S} = \bar{V}_1\bar{I}^* = \frac{\bar{V}_1(\bar{V}_1^* - \bar{V}_2^*)}{-jX} = \frac{j(V_1^2 - \bar{V}_1\bar{V}_2^*)}{X} = \frac{j\left(V_1^2 - V_1V_2\left(\cos(\theta_1-\theta_2) + j\sin(\theta_1-\theta_2)\right)\right)}{X}$$

$$P = \frac{V_1V_2\sin(\theta_1-\theta_2)}{X} \approx \frac{V_2}{X}V_1(\theta_1-\theta_2)$$

$$Q = \frac{V_1^2 - V_1V_2\cos(\theta_1-\theta_2)}{X} \approx \frac{V_1-V_2}{X}V_1$$

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Cross-correlation

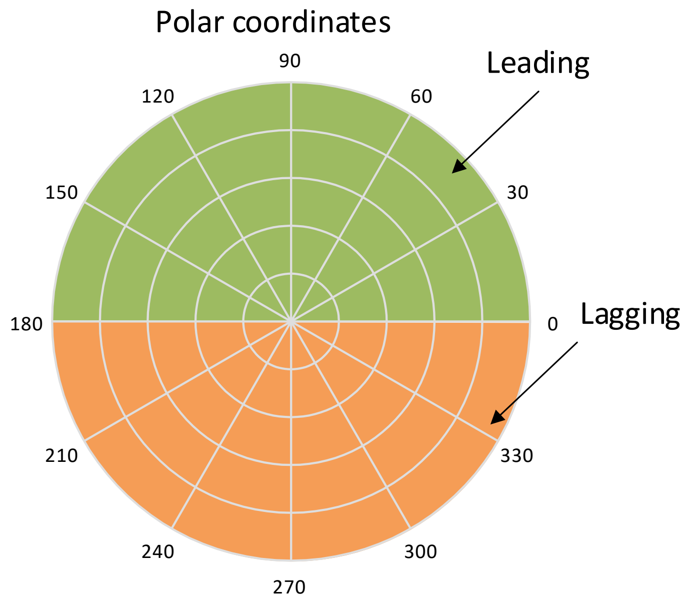
$$P = \frac{V_2}{X} V_1(\theta_1 - \theta_2) \qquad Q = \frac{V_1 - V_2}{X} V_1$$

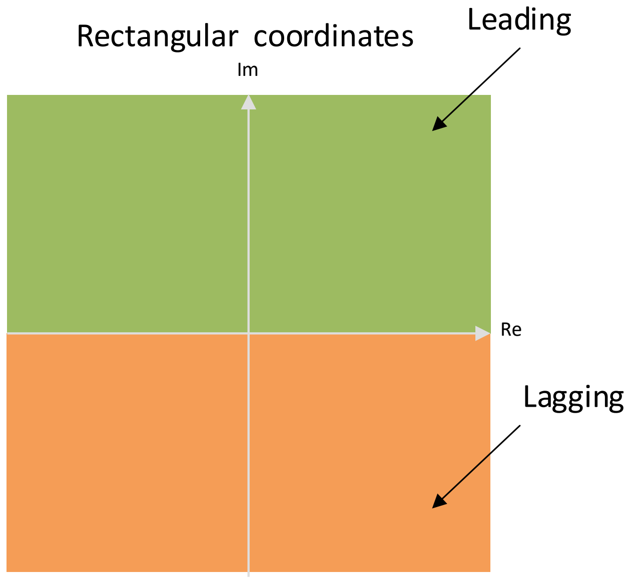
V_1 and θ_1 are considered to be the inputs; P and Q are considered to be the outputs

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):

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





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Energy in Increment

Input-output relationship $\rightarrow$ energy function:

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

Energy in increment:

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

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

Identification of the oscillation source

Type of source: compare power spectral density of active and reactive power

$\max(|S_P|) > \max(|S_Q|) \rightarrow$ generator governor, cyclic load, sending HVDC terminal

$\max(|S_P|) < \max(|S_Q|)$ or $\max(|S_P|) \approx \max(|S_Q|) \rightarrow$ generator excitation system, receiving HVDC terminal

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 CPSD outflow is the source

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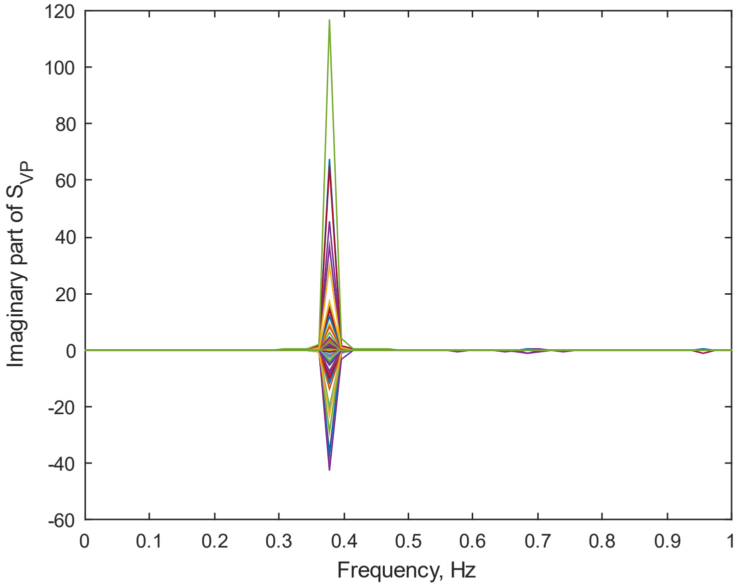
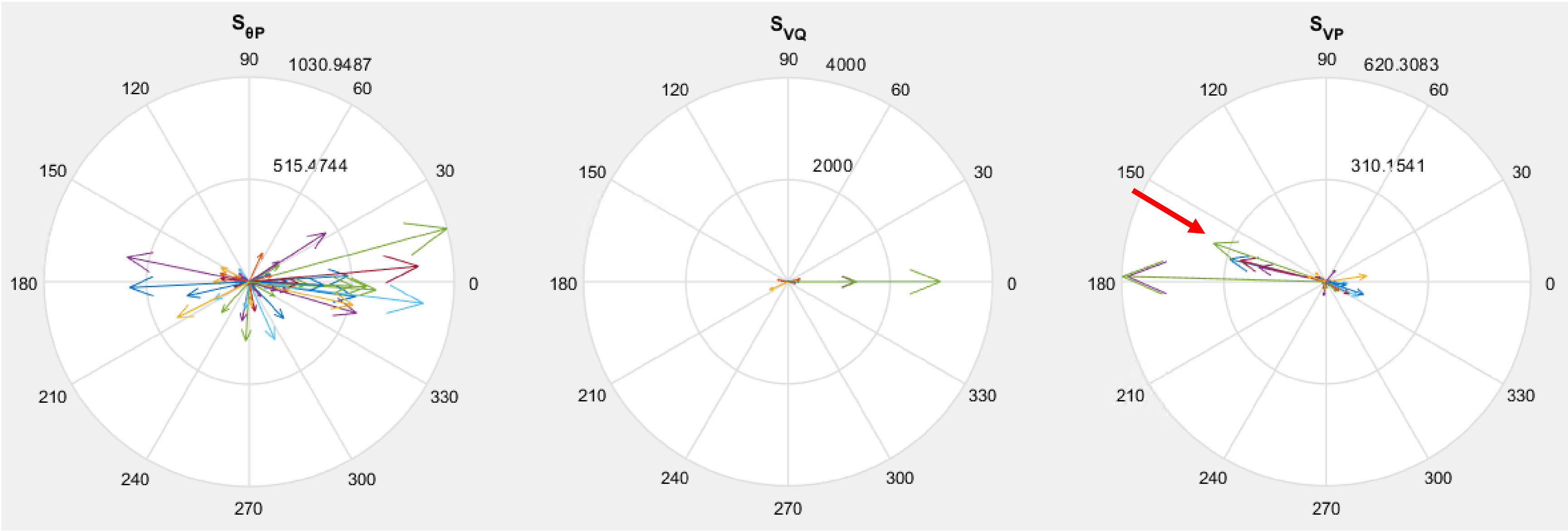
OSL Contest. Case 7

$\max(|S_P|) = 144 < \max(|S_Q|) = 348 \rightarrow$ excitation system of generators 2634-C



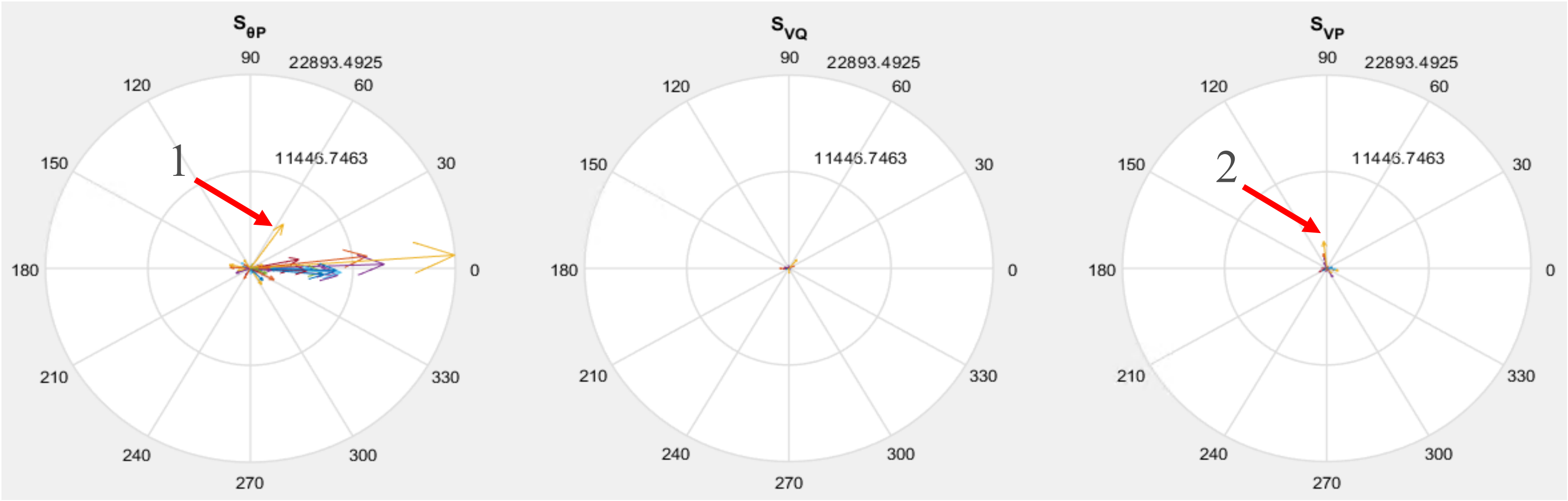
Compass plots

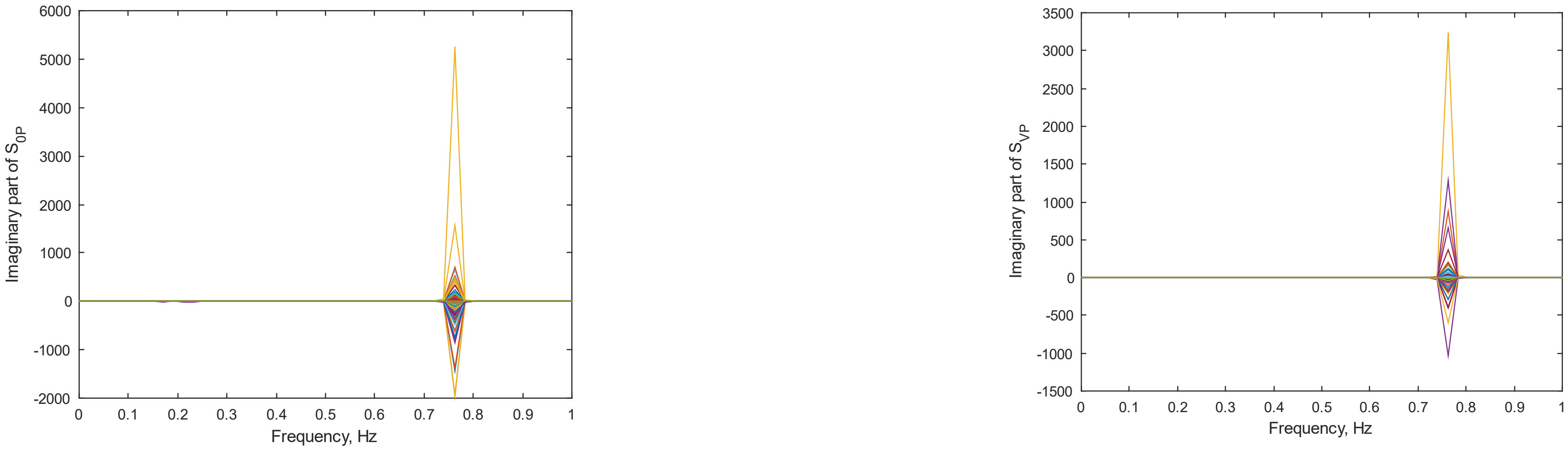


OSL Contest. Case 9

1. Governor of generator 6533-C, 6533-G, or 6533-H
2. Excitation system of generator 4131-H or 4131-B

Compass plots

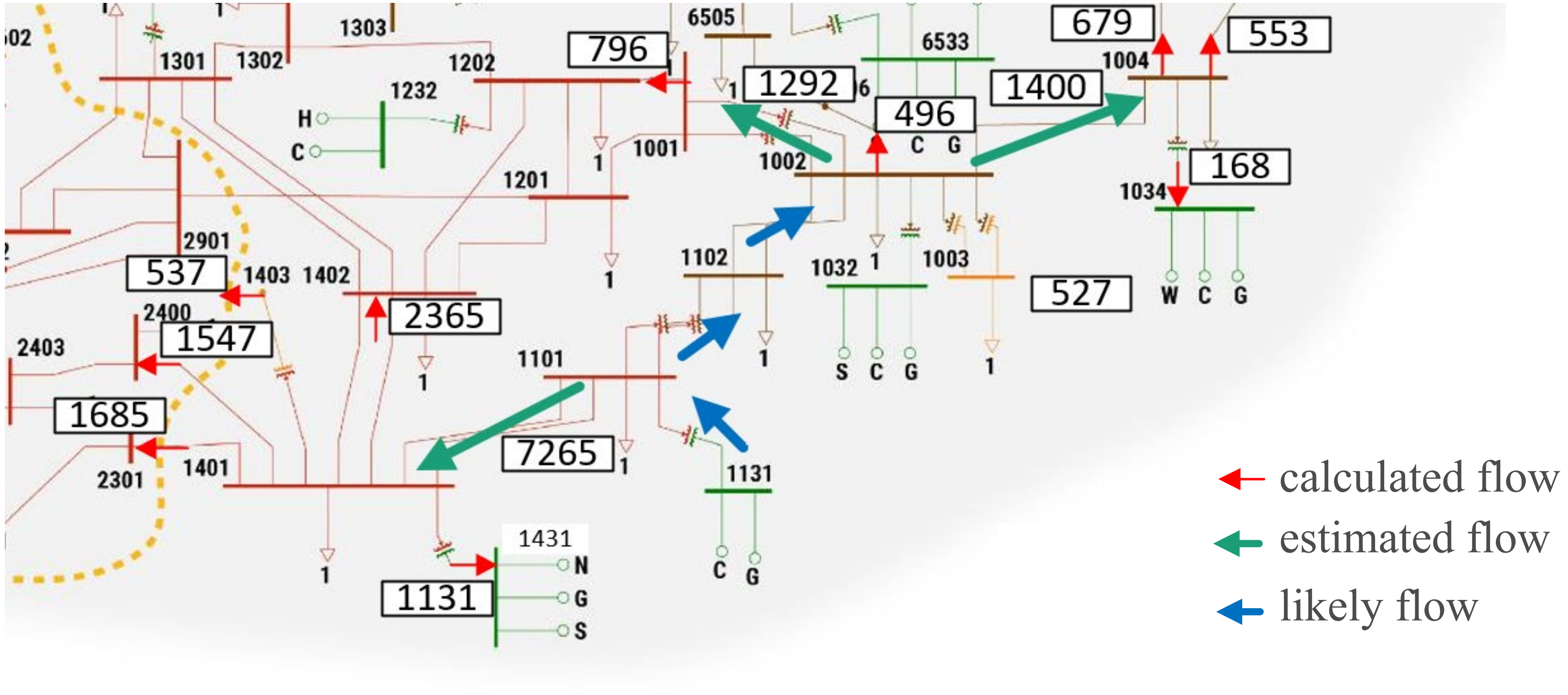




OSL Contest. Case 3

$\max(|S_P|) = 267 < \max(|S_Q|) = 436 \rightarrow$ excitation system of generators 1131-C or 1131-G

CPSD flow



Performance Summary

Case	Frequency	Area	Bus	Asset Type	Controller
1	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓
3	✓	✓	✓	✓	✓
4	✓	✓	✓ 1 of 3 listed buses was correct	✓	✓
5	✓	✓	✓	✓	✓
6	✓	✓	✓	✓	✓
7	✓	✓	✓	✓	✓
8	✓	✓	✓	✓	✓
9	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓
10	not analyzed, assumed to be a higher order harmonic component				
	✓	✓	✓	✓	✓
11	✓	✓	✓	✓	✓
12	✓	✓	✓	✓	✓
13	the sending side of HVDC was detected but not submitted as a separate item				
	✓	✓	✓	✓	✓

Conclusions

Advantages of the approach:

- requires only topological information
- does not require band-pass filtering
- can accurately identify the type of the source
- performs well when active power consumed by loads depends on voltage magnitude
- can identify the location of the source when the frequency of the oscillation is very low

Disadvantages of the approach:

- long window of data is required for good frequency resolution

Acknowledgements

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