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

Original signal

Initial value

Linear trend

Empirical mode decomposition

Variational mode decomposition
Intrinsic Mode Functions

IMF requirements:
1. Number of extrema = number of zero crossings ±1
2. Mean value of maxima and minima envelopes = 0
Power Transfer on a Lossless Line

Voltage at the beginning of the branch: \( \vec{V}_1 = V_1 \angle \theta_1 \)

Voltage at the end of the branch: \( \vec{V}_2 = V_2 \angle \theta_2 \)

Branch current: \( \vec{I} = \frac{\vec{V}_1 - \vec{V}_2}{jX} \)

Complex power: \( \vec{S} = \vec{V}_1 \vec{I}^* \)

\[
\vec{S} = \vec{V}_1 \vec{I}^* = \frac{\vec{V}_1 (\vec{V}_1^* - \vec{V}_2^*)}{-jX} = \frac{j(V_1^2 - \vec{V}_1 \vec{V}_2^*)}{X} = \frac{j(V_1^2 - V_1 V_2 (\cos(\theta_1 - \theta_2) + j\sin(\theta_1 - \theta_2)))}{X}
\]

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

\[
Q = \frac{V_1^2 - V_1 V_2 \cos(\theta_1 - \theta_2)}{X} \approx \frac{V_1 - V_2}{X} V_1
\]
Cross-correlation

\[ P = \frac{V_2}{X}V_1(\theta_1 - \theta_2) \]

\[ Q = \frac{V_1 - V_2}{X}V_1 \]

\( V_1 \) and \( \theta_1 \) are considered to be the inputs; \( P \) and \( Q \) are considered to be the outputs

Output leads input \( \rightarrow \) source of forced oscillation at the beginning of the branch

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

\[ S_{\theta P} = \overline{F\{\theta\}F\{P\}} \quad S_{VP} = \overline{F\{V\}F\{P\}} \quad S_{VQ} = \overline{F\{V\}F\{Q\}} \]
Energy in Increment

Input-output relationship → 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

$$S_{\theta P} = \mathcal{F}\{\theta\}\mathcal{F}\{P\} \rightarrow W_{\theta P} = \int_{\Delta \theta_0}^{\Delta \theta} \Delta P(t)d\Delta \theta(t)$$

$$S_{VQ} = \mathcal{F}\{V\}\mathcal{F}\{Q\} \rightarrow W_{VQ} = \int_{\Delta V_0}^{\Delta V} \Delta Q(t)d\Delta V(t) + \int \Delta Q(t)d(\Delta \ln V(t))$$

$$S_{VP} = \mathcal{F}\{V\}\mathcal{F}\{P\} \rightarrow W_{VP} = \int_{\Delta V_0}^{\Delta V} \Delta P(t)d\Delta V(t)$$

\[\text{Dissipating Energy}\]

$$W_D = \int 2\pi \Delta P(t)\Delta f(t)dt$$
Identification of the oscillation source

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

\[ \max(|S_P|) > \max(|S_Q|) \rightarrow \text{generator governor, cyclic load, sending HVDC terminal} \]

\[ \max(|S_P|) < \max(|S_Q|) \text{ or } \max(|S_P|) \approx \max(|S_Q|) \rightarrow \text{generator excitation system, receiving HVDC terminal} \]

**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
max(|S_p|) = 144 < max(|S_Q|) = 348 → excitation system of generators 2634-C
1. Governor of generator 6533-C, 6533-G, or 6533-H
2. Excitation system of generator 4131-H or 4131-B

Compass plots

- Governor of generator 6533-C, 6533-G, or 6533-H
- Excitation system of generator 4131-H or 4131-B
max(|S_p|) = 267 < max(|S_Q|) = 436 → excitation system of generators 1131-C or 1131-G

CPSD flow

← calculated flow  
← estimated flow  
← likely flow
### Performance Summary

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1 of 3 listed buses was correct

not analyzed, assumed to be a higher order harmonic component

the sending side of HVDC was detected but not submitted as a separate item
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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