The Energy Flow Approach for Oscillation Source Location and Damping Evaluation

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Background

• **What is oscillation source?** – cause of oscillation
  – Disturbance source in forced oscillation
  – Generator with negative damping (often caused by wrong parameters) in free/natural oscillation

• **Why should we find oscillation source?**
  – Online location of oscillation source is the key to effective measures for oscillation suppression
  – Remove the disturbance source or adjust the negatively damped generator
Energy Based Idea

- The concept of energy is widely used in oscillation or vibration analysis
  - Oscillations are accompanied by the conversion of energy
    - Kinetic energy, potential energy
  - The amount of energy is consistent with the oscillation amplitude
    - More energy, larger oscillation amplitude
  - The dissipation of energy brings damping effect
    - Friction

The component producing energy is the oscillation source, which maintains or increases the oscillation amplitude
Concept of Energy Flow

• Energy in power system dynamics: Transient energy
  – The construction of energy function is very difficult
  – Not suitable for online application with measurements

• Energy flow
  – Computed with measurements, independent of energy functions
  – The energy dissipation or production can be identified with the energy flow on the network
Energy Flow Computation

• The energy flowing from bus $i$ to branch $L_{ij}$ is [1]

$$W_{ij} = \int (I_{ij,x} \, d\, U_{i,y} - I_{ij,y} \, d\, U_{i,x})$$

$$= \int (P_{ij} \, d\, \theta_{i} + \frac{Q_{ij}}{U_{i}} \, d\, U_{i}) = \int (P_{ij} \, 2\pi \Delta f_{i} \, d\, t + Q_{ij} \, d\, (\ln U_{i}))$$

• Computed with WAMS data and independent of energy functions
• Identical to the transient energy
• The energy flow into an element is composed of two types of terms:
  conservative term (independent of integral path) - transient energy
  non-conservative term (dependent of integral path) - energy dissipation

$$\int \text{Im} \left( (-I_{Gi})^* \, d\, V_{i} \right) = \left( \frac{1}{2} T_{j} \omega_{0} \omega^2 - P_{m} \delta \right)_{x_{0}}^{x} + \int D \omega_{0} \omega^2 \, d\, t$$

Conservative and Non-Conservative Terms

Conservative term - transient energy - oscillating

Non-conservative term - energy dissipation – monotonically changing (rising or descending)

\[
\int \text{Im} \left( (-I_{\omega_i})^* dV_i \right) = \left[ \frac{1}{2} T \omega_i \omega^2 - P_m \delta \right]_{t_0}^{t_f} + \int D \omega_i \omega^2 dt
\]
Energy Dissipation or Production

• The energy dissipation/production can be extracted from the energy flow, which reflects the damping of a component in low frequency oscillation

• Net Energy Flow / Dissipating Energy Flow

\[ W_{ij}^{D} = \int \left( \Delta P_{ij} \, d\Delta \theta_{i} + \Delta Q_{ij} \, d\left( \Delta \ln U_{i} \right) \right) \]
\[ = \int \left( \Delta P_{ij} \, 2\pi f_{i} \, dt + \Delta Q_{ij} \, d\left( \Delta \ln U_{i} \right) \right) \]

– Computed with deviations
– Reserve non-conservative terms but eliminate conservative terms

Energy flow into a generator that dissipates transient energy and has positive damping
**Energy Dissipation Corresponds to Positive Damping**

- **Energy dissipation is consistent with damping torque of a generator**
  - Mathematically proved: in Heffron-Phillips model, actual energy dissipation in a period equals the energy dissipated by the damping torque
    \[ \frac{T_{d0}'}{X_d - X_d'} \int_{t}^{t + \frac{2\pi}{\omega_d}} \left( \dot{E}_{q}' \right)^2 \, dt = K_p \omega_0 \int_{t}^{t + \frac{2\pi}{\omega_d}} \omega^2 \, dt \]
  - Damping torque can be evaluated with energy dissipation

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<th>Case</th>
<th>Oscillation Type</th>
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</table>
Energy Dissipation in Detailed Generator Model

Generator with a field winding and 3 damper windings

\[ \delta = \omega_0 \omega \]
\[ T_f \omega = P_m - P_e - D \omega \]
\[ \psi_{fd} = U_{fd} - R_{fd} I_{fd} \]
\[ \psi_{1d} = -R_{1d} I_{1d} \]
\[ \psi_{1q} = -R_{1q} I_{1q} \]
\[ \psi_{2q} = -R_{2q} I_{2q} \]

Conservative terms

\[ -P_m \delta + \frac{1}{2} T_f \omega_0 \omega^2 \]
\[ + \frac{1}{2} \left( X_d - \frac{X_{ad}^2 (X_{11d} + X_{jmd} - 2X_{ad})}{X_{11d} - X_{ad}^2} \right) I_d^2 \]
\[ + \frac{1}{X_{adm} X_{11d} - X_{ad}^2} \left( \frac{X_{11d} \psi_{1d}^2}{2} + \frac{X_{adm} \psi_{1d}^2}{2} - X_{ad} \psi_{jmd} \psi_{1d} \right) \]
\[ + \frac{1}{2} \left( X_q - \frac{X_{aq}^2 (X_{11q} + X_{22q} - 2X_{aq})}{X_{11q} X_{22q} - X_{aq}^2} \right) I_q^2 \]
\[ + \frac{1}{X_{11q} X_{22q} - X_{aq}^2} \left( \frac{X_{22q} \psi_{1q}^2}{2} + \frac{X_{11q} \psi_{1q}^2}{2} - X_{aq} \psi_{2d} \psi_{2q} \right) \]

Energy dissipations of windings: damping [2]

Energy dissipation coefficients as \( P_m \) changes

Energy Production of Disturbance Source in Forced Oscillation

- The disturbance source in forced oscillation produces

**Periodic disturbance on mechanical power**

\[ P'_m = P_m + P_d \sin (\omega_d t) \]

**Energy production of disturbance**

\[ \int (P_d \sin (\omega_d t) \omega_0 \omega) \, dt \]

**Periodic disturbance on field voltage**

\[ E'_{fd} = E_{fd} + E_d \sin (\omega_d t) \]

**Energy production of disturbance**

\[ \frac{1}{X_d - X_d'} \int \left( E_d \sin (\omega_d t) \dot{E}_q' \right) \, dt \]
Online Oscillation Source Location

• PMU/WAMS based
  – Used data: $P$, $Q$, $U$, $f$

• Steps
  – When the oscillation is detected, compute the energy flow in the network using a short period (often less than 10s) of data with
    \[ W_{ij}^D = \int \left( \Delta P_{ij} 2\pi \Delta f_i dt + \Delta Q_{ij} d \left( \Delta \ln U_i \right) \right) \]
  – Compute the slope of $W_{ij}^D$ using linear fitting, which reflects the power of the energy flow
  – Find the energy source using the direction and the magnitude of the energy flow power, and it is the oscillation source
Pingban plant oscillation - 0.94Hz

- Caused by the trip of one sending line Pingban-Baise
- Negatively damped free oscillation
- The generators in Pingban are producing energy
Actual Oscillation Incidents Analysis

Three gorges station oscillation - 0.82Hz
• Caused by wrong PSS parameters in Youer plant
• Nearly zero damped free oscillation
• The Youer plant is producing energy

Energy flow from different plants to the system
Faer plant oscillation - 0.30Hz
• Caused by governor fault in gen #4 of Faer plant, which induces power oscillation of the generator
• Forced oscillation
• Gen #4 is producing energy
Online System Implementation

- Based on PMU/WAMS in China Southern Grid
- Successfully locate oscillation sources in many incidents since its commissioning in 2013
Online System Implementation

When oscillation detected
Online System Implementation

When oscillation detected
Other Applications

- Also implemented in Center China Grid Company
- Successfully used in China Xinjiang and Xizang Grids for oscillation incident analysis
- Through the energy flow inside the generator, the oscillation source can be further located at exciter or governor, which is helpful for cause analysis and defect correction
Connection with Modal/Eigen Analysis

- The **energy dissipation** is connected with **damping ratio** in modal analysis [3]

\[ \sigma = -\gamma \sum_i K_{EDC,i} \]

\( \sigma \): real-part of eigenvalue  
\( K_{EDC,i} \): energy dissipation coefficient of generator

The damping of the whole system of a mode comes from the total energy dissipations of generators

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Discussions on New Developments

• Physical meaning of oscillation energy flow
  – Connection with the actual electrical power

\[
W_{1d} = \int I_{1d}^2 R_{1d} \, dt
\]
\[
W_{1q} = \int I_{1q}^2 R_{1q} \, dt
\]
\[
W_{2q} = \int I_{2q}^2 R_{2q} \, dt
\]

• Application in transient stability
  – The transient energy injection of a fault can be computed through the energy flow at the fault point with the voltages and the currents
  – Energy function is not needed
  – Transient stability may be studied through the energy flow on the network
Thanks!

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