The Energy Flow Approach for Oscillation Source Location and Damping Evaluation

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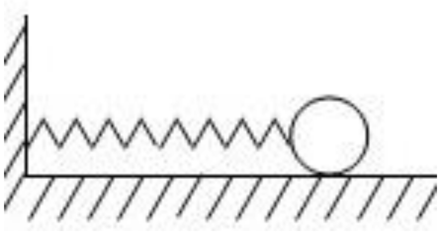
Background

- 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

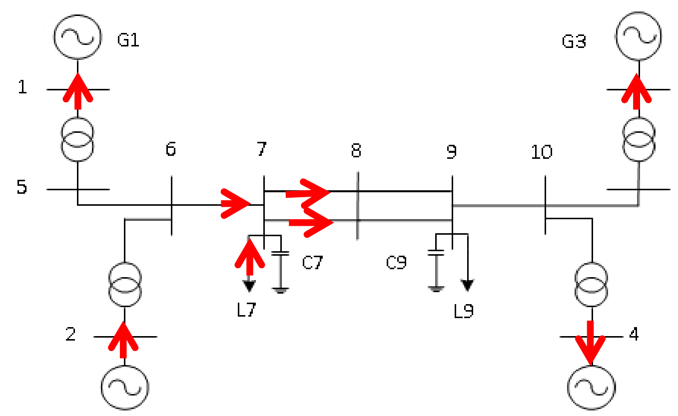


  - Oscillations are accompanied by the conversion of energy
    - Kinetic energy, potential energy
  - The amount of energy is consistent with the oscillation amplitude
    - More energy, larger oscillation amplitude
  - The dissipation of energy brings damping effect
    - Friction

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]

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

$$= \int (P_{ij} \mathrm{d}\theta_i + \frac{Q_{ij}}{U_i} \mathrm{d} U_i) = \int (P_{ij} 2\pi \Delta f_i \mathrm{d} t + Q_{ij} \mathrm{d}(\ln U_i))$$

- 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

$$\int \mathrm{Im}\left((-\boldsymbol{I}_{Gi})^* \mathrm{d} \boldsymbol{V}_i \right) = \left(\frac{1}{2} T_J \omega_0 \omega^2 - P_m \delta \right) \Big|_{x_0}^{x} + \int D \omega_0 \omega^2 \mathrm{d} t$$

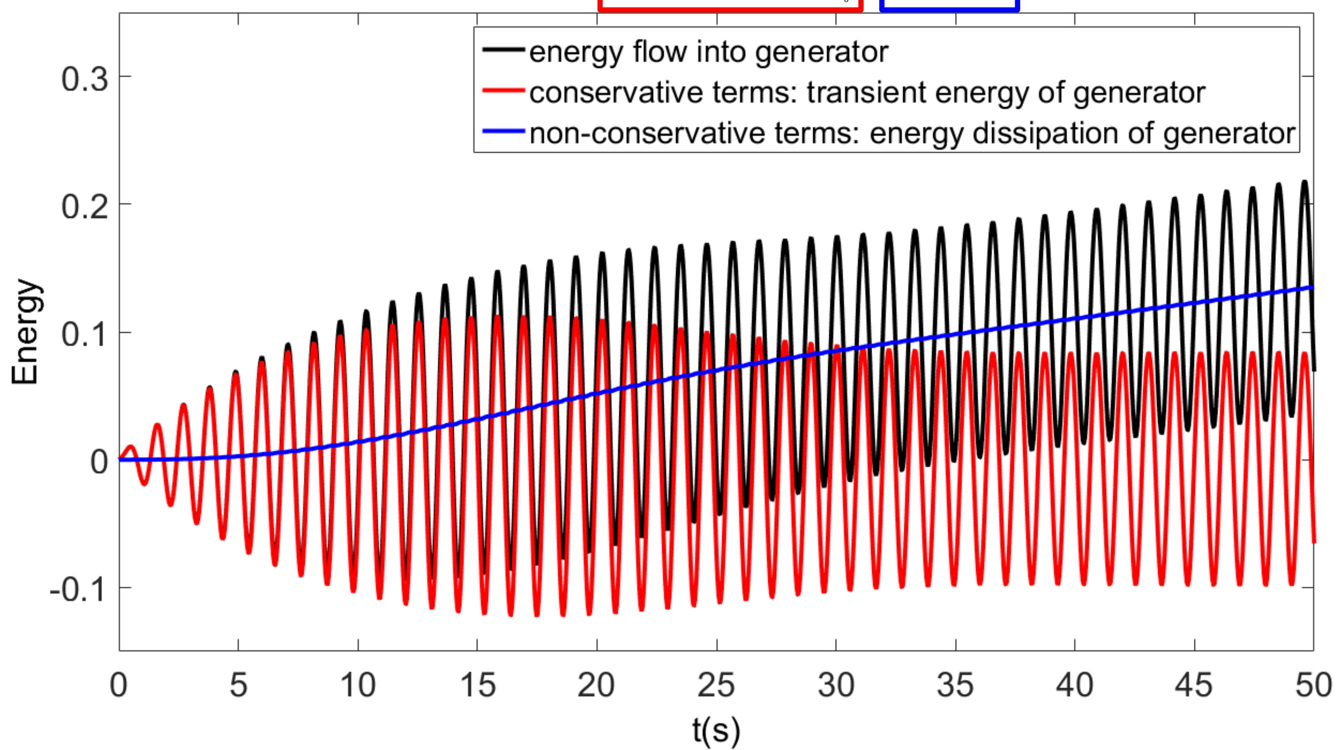
[1] Lei Chen, Yong Min, Wei Hu. An energy-based method for location of power system oscillation source. IEEE Trans Power Syst, 2013, 28(2): 828-836.

Conservative and Non-Conservative Terms

conservative term - transient energy - oscillating

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

$$\int \mathrm{Im}\left(\left(-\boldsymbol{I}_{Gi}\right)^{*} \mathrm{d}\boldsymbol{V}_{i}\right) = \left.\left(\frac{1}{2}T_{J}\omega_{0}\omega^{2} - P_{m}\delta\right)\right|_{x_0}^{x} + \int D\omega_{0}\omega^{2}\mathrm{d}t$$



Energy Dissipation or Production

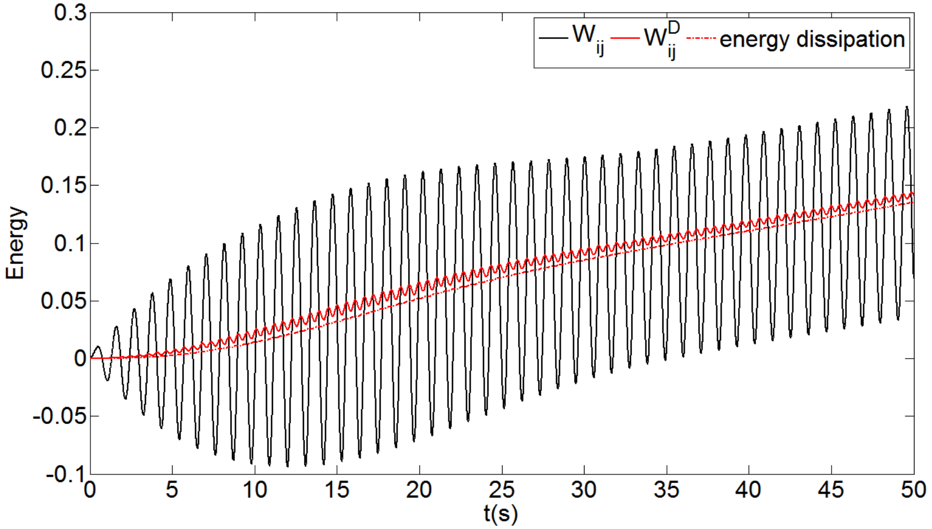
- The energy dissipation/production can be extracted from the energy flow, which reflects the damping of a component in low frequency oscillation

- Net Energy Flow / Dissipating Energy Flow

$$W_{ij}^{D} = \int \left(\Delta P_{ij} \mathrm{d} \Delta \theta_i + \Delta Q_{ij} \mathrm{d} \left(\Delta \ln U_i \right) \right)$$

$$= \int \left(\Delta P_{ij} 2 \pi \Delta f_i \mathrm{d} t + \Delta Q_{ij} \mathrm{d} \left(\Delta \ln U_i \right) \right)$$

  - 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

$$\frac{T_{d0}'}{X_d - X_d'} \int_t^{t+\frac{2\pi}{\omega_d}} (\dot{E}_q')^2 \mathrm{d}t = K_D \omega_0 \int_t^{t+\frac{2\pi}{\omega_d}} \omega^2 \mathrm{d}t$$

  - Damping torque can be evaluated with energy dissipation

Test results

Case	Oscillation Type		DTA	Energy Dissipation	Relative Error(%)
No AVR		Free	1.9037	1.9070	0.17
		Forced	1.9037	1.8990	-0.25
AVR, no PSS	a	Free	1.2446	1.2519	0.59
		Forced	1.2446	1.2333	-0.91
	b	Free	-1.1747	-1.1784	0.31
		Forced	-	-	-
AVR, PSS		Free	1.6989	1.7572	3.43
		Forced	1.6989	1.6218	-4.54

Energy Dissipation in Detailed Generator Model

Generator with a field winding and 3 damper windings

$$\dot{\delta} = \omega_0 \omega$$
$$T_J \dot{\omega} = P_m - P_e - D\omega$$
$$\dot{\psi}_{fd} = U_{fd} - R_{fd} I_{fd}$$
$$\dot{\psi}_{1d} = -R_{1d} I_{1d}$$
$$\dot{\psi}_{1q} = -R_{1q} I_{1q}$$
$$\dot{\psi}_{2q} = -R_{2q} I_{2q}$$

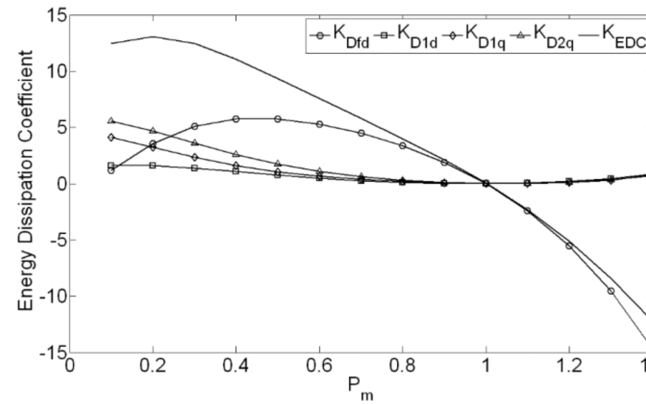
Conservative terms

$$-P_m \delta + \frac{1}{2} T_J \omega_0 \omega^2$$
$$+\frac{1}{2}\left(X_d - \frac{X_{ad}^2 (X_{11d} + X_{ffd} - 2X_{ad})}{X_{ffd} X_{11d} - X_{ad}^2}\right) I_d^2$$
$$+\frac{1}{X_{ffd} X_{11d} - X_{ad}^2}\left(\frac{X_{11d}\psi_{fd}^2}{2} + \frac{X_{ffd}\psi_{1d}^2}{2} - X_{ad}\psi_{fd}\psi_{1d}\right)$$
$$+\frac{1}{2}\left(X_q - \frac{X_{aq}^2 (X_{11q} + X_{22q} - 2X_{aq})}{X_{11q} X_{22q} - X_{aq}^2}\right) I_q^2$$
$$+\frac{1}{X_{11q} X_{22q} - X_{aq}^2}\left(\frac{X_{22q}\psi_{1q}^2}{2} + \frac{X_{11q}\psi_{2q}^2}{2} - X_{aq}\psi_{1q}\psi_{2q}\right)$$

Non-conservative terms

$$W_D = D\omega_0 \int \omega^2 \mathrm{d}t$$
$$W_{fd} = \int -(U_{fd} I_{fd} - I_{fd}^2 R_{fd})\mathrm{d}t$$
$$W_{1d} = \int I_{1d}^2 R_{1d} \mathrm{d}t$$
$$W_{1q} = \int I_{1q}^2 R_{1q} \mathrm{d}t$$
$$W_{2q} = \int I_{2q}^2 R_{2q} \mathrm{d}t$$

Energy dissipations of windings : damping [2]



Energy dissipation coefficients as Pm changes

[2] Lei Chen, Fei Xu, Yong Min, Fang Li. Evaluation of damping of windings in a generator using oscillation energy dissipation. 2014 IEEE Power & Energy Society General Meeting, 27-31 July 2014, National Harbor, Maryland, USA.

Energy Production of Disturbance Source in Forced Oscillation

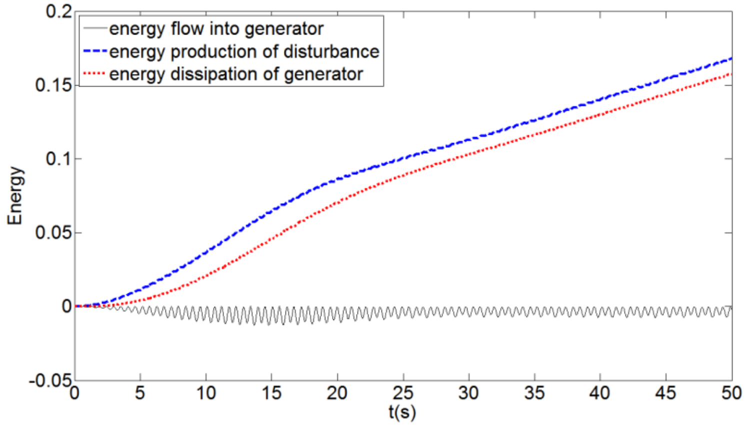
- The disturbance source in forced oscillation produces

Periodic disturbance on mechanical power

$$P_m' = P_m + P_d \sin(\omega_d t)$$

Energy production of disturbance

$$\int \left(P_d \sin(\omega_d t) \omega_0 \omega \right) dt$$

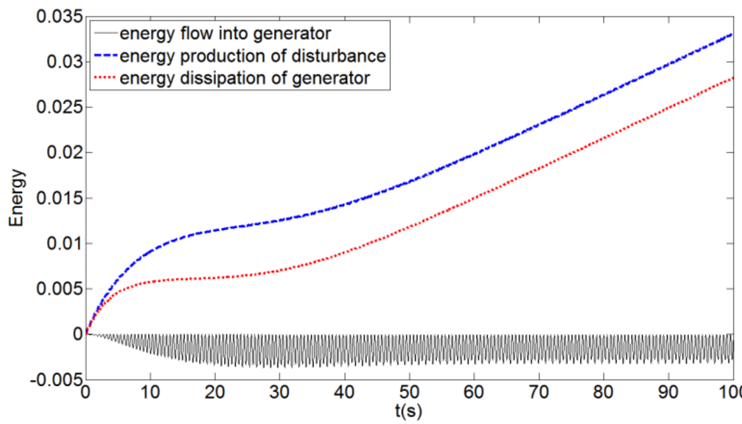


Periodic disturbance on field voltage

$$E_{fd}' = E_{fd} + E_d \sin(\omega_d t)$$

Energy production of disturbance

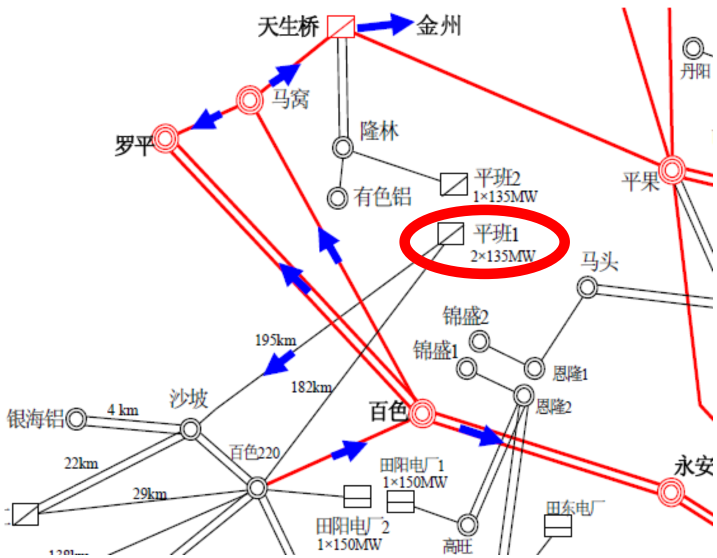
$$\frac{1}{X_d - X_d'} \int \left(E_d \sin(\omega_d t) \dot{E}_q' \right) dt$$



Online Oscillation Source Location

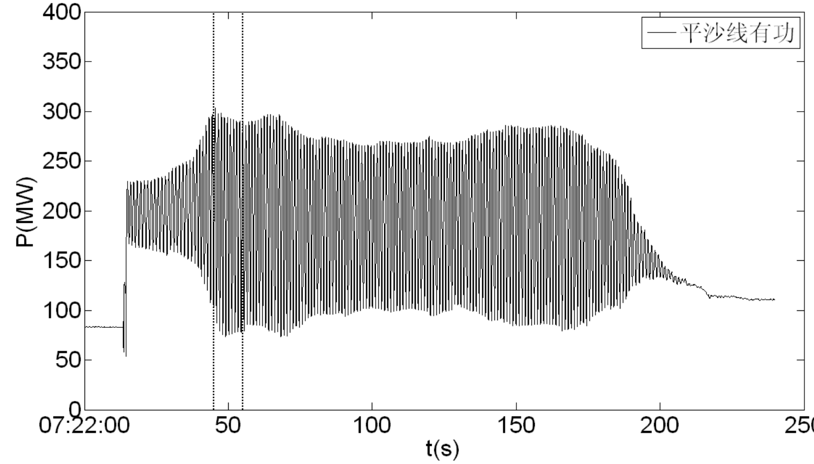
- PMU/WAMS based
  - Used data: P, Q, U, f
- Steps
  - When the oscillation is detected, compute the energy flow in the network using a short period (often less than 10s) of data with $W_{ij}^{D} = \int \left(\Delta P_{ij} 2\pi \Delta f_i \mathrm{d}t + \Delta Q_{ij} \mathrm{d}\left(\Delta \ln U_i \right) \right)$
  - 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

Actual Oscillation Incidents Analysis

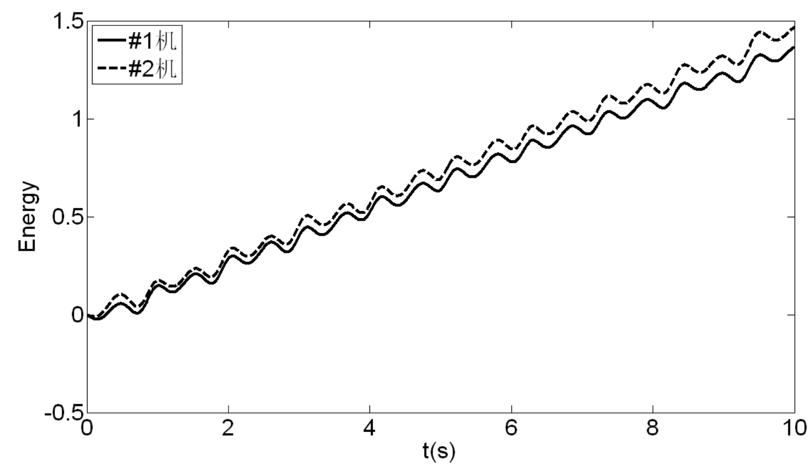


Pingban plant oscillation - 0.94Hz

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



P of line Pingban-Shapo



Energy flow from Pingban generators to the system

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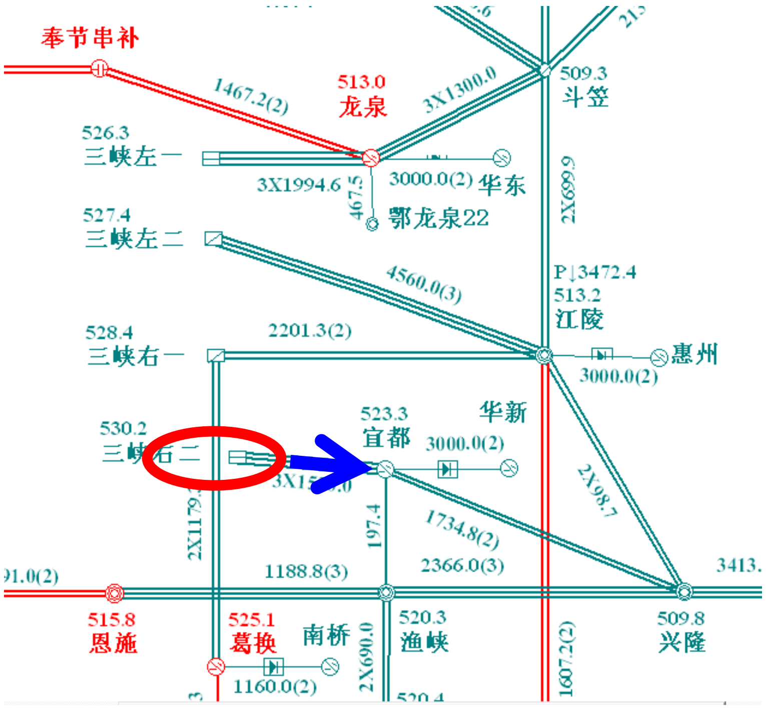
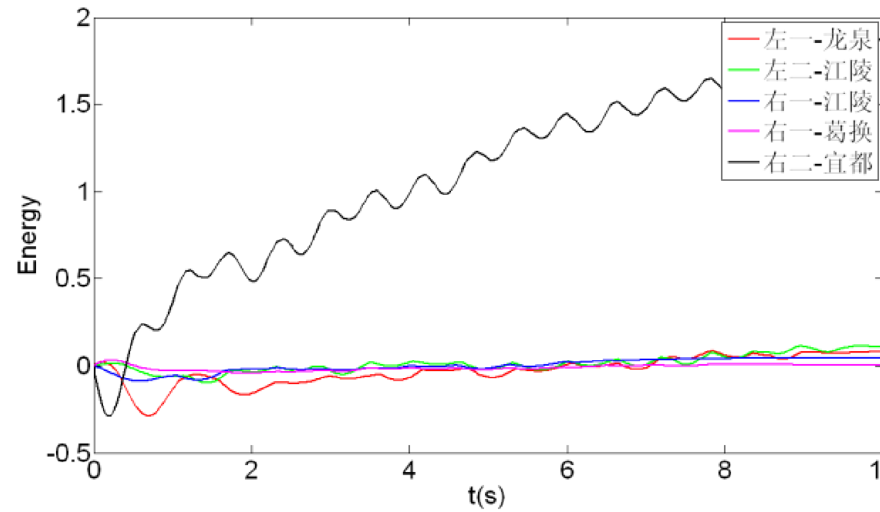
Actual Oscillation Incidents Analysis



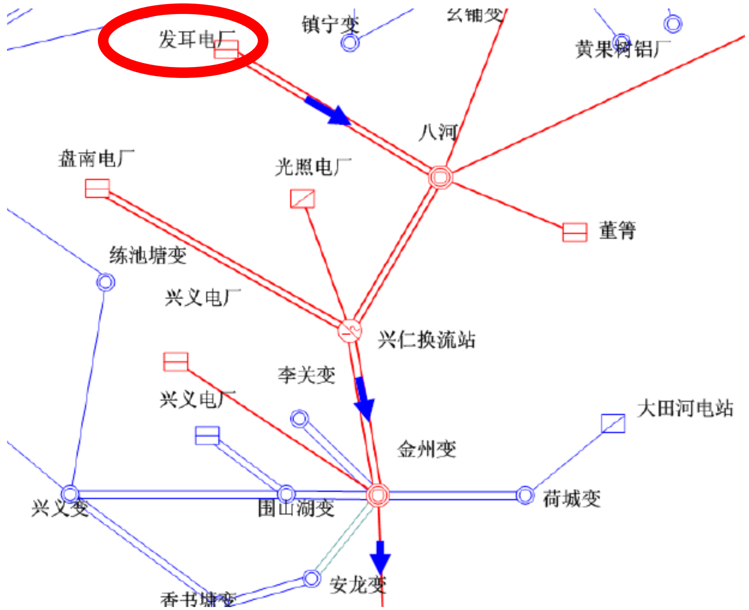


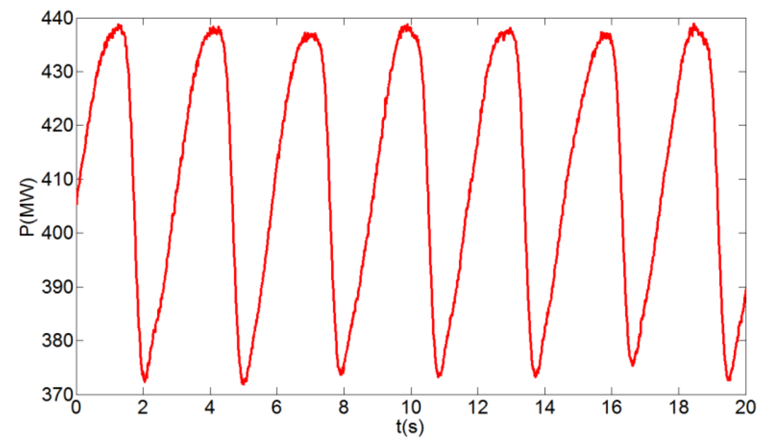
Energy flow from different plants to the system

Three gorges station oscillation - 0.82Hz

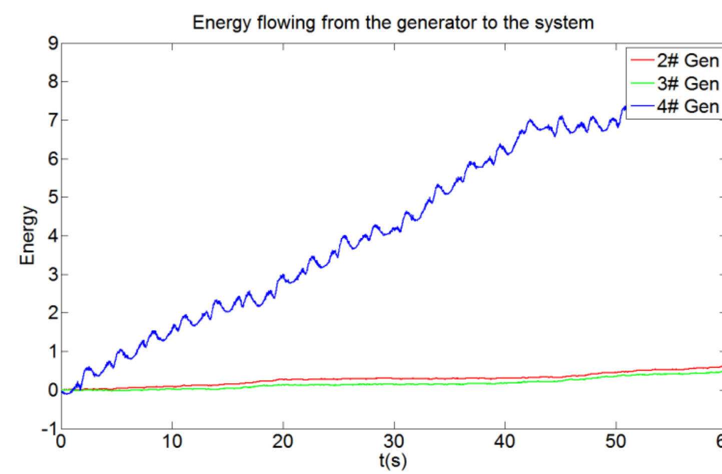
- Caused by wrong PSS parameters in Youer plant
- Nearly zero damped free oscillation
- The Youer plant is producing energy

Actual Oscillation Incidents Analysis





P of line gen #4



Energy flow from generators 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

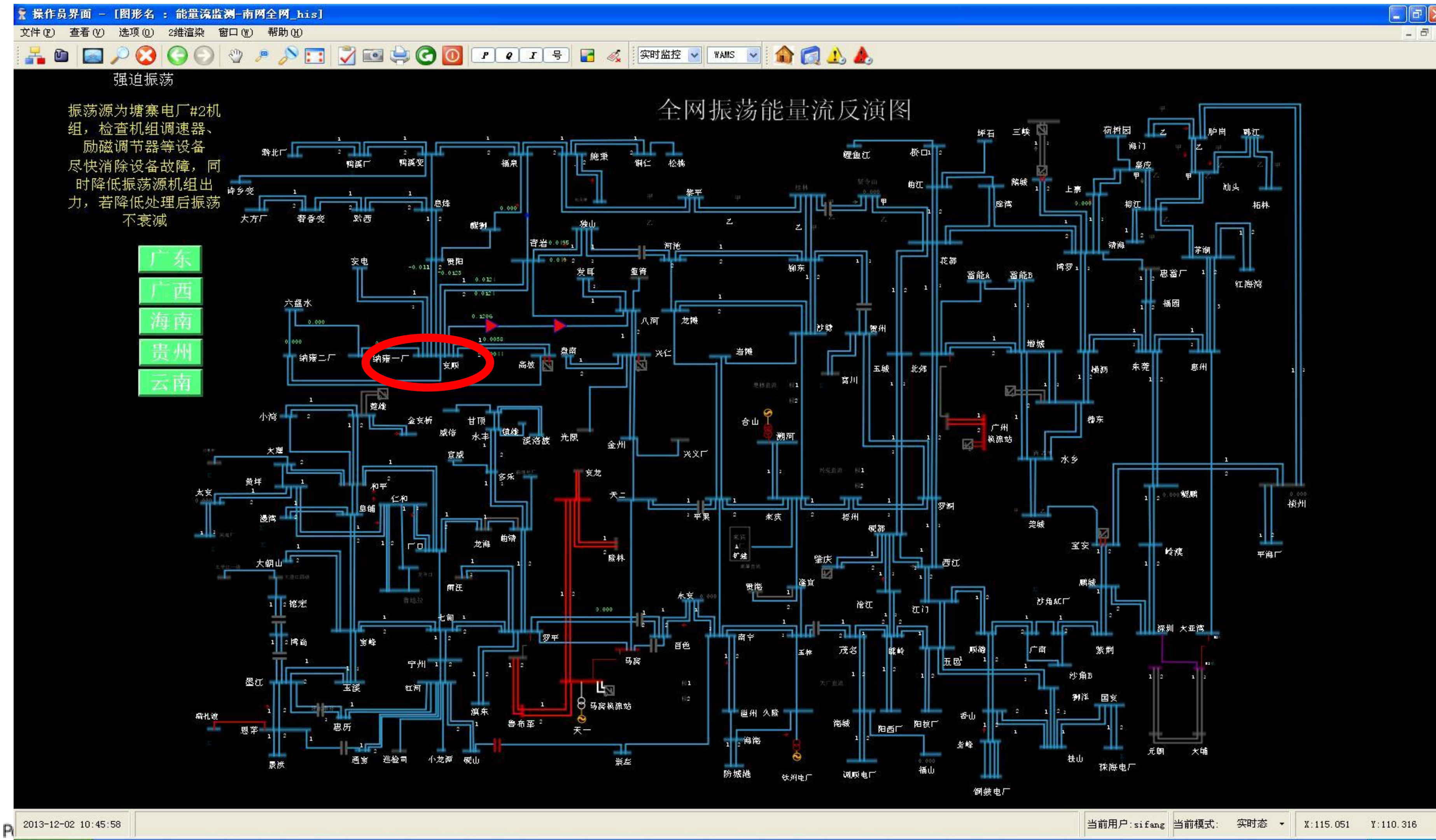
Online System Implementation

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

Main interface

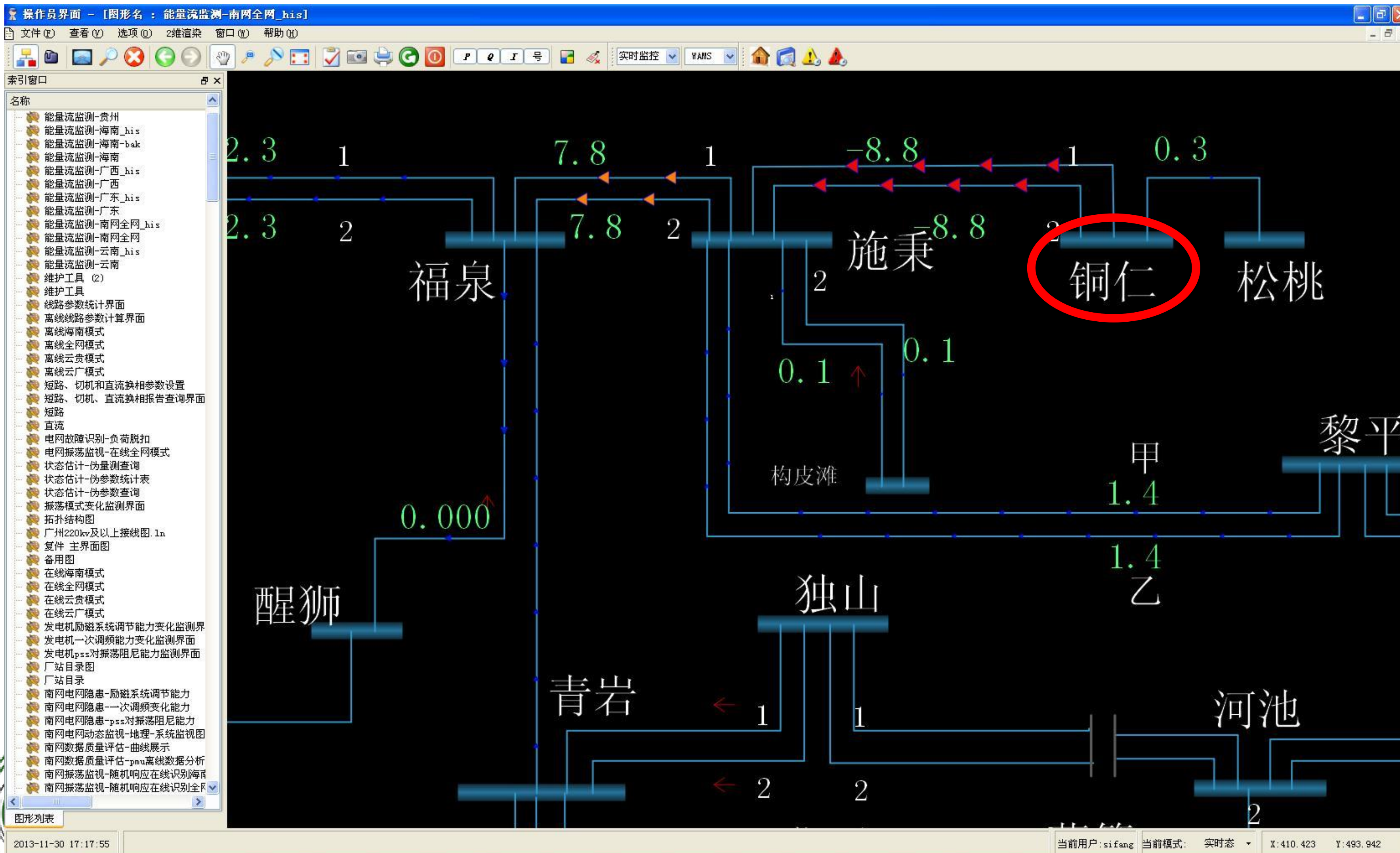
Online System Implementation

When oscillation detected



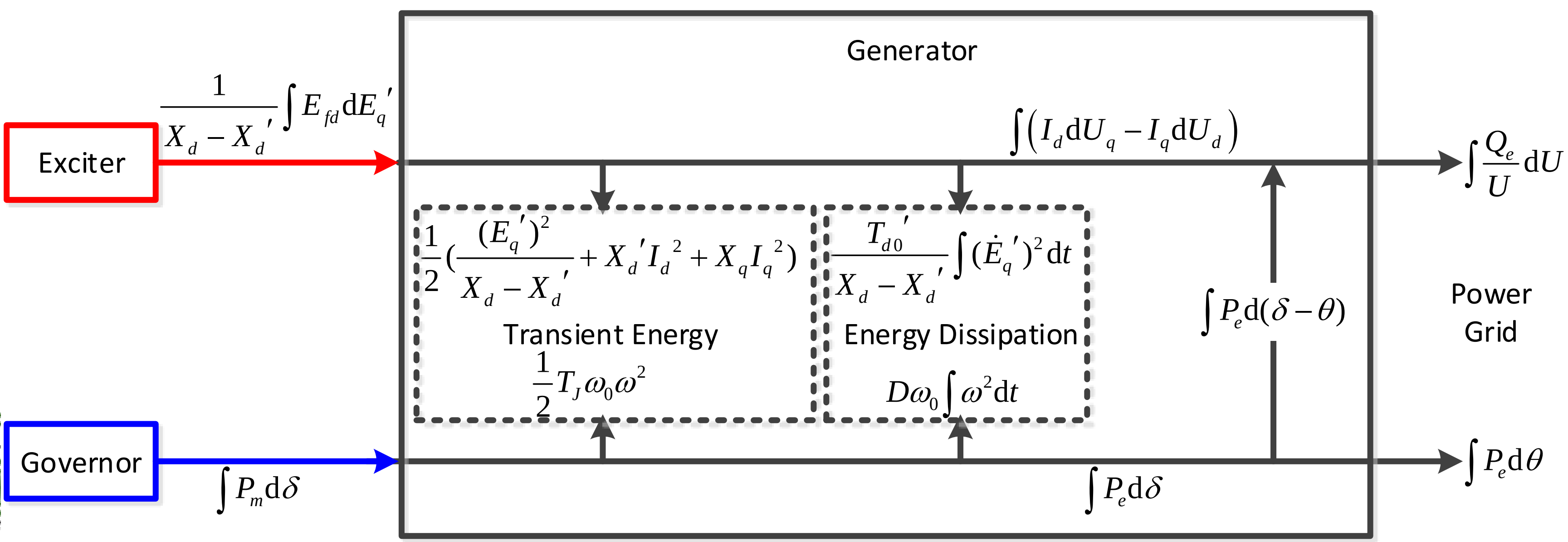
Online System Implementation

When oscillation detected



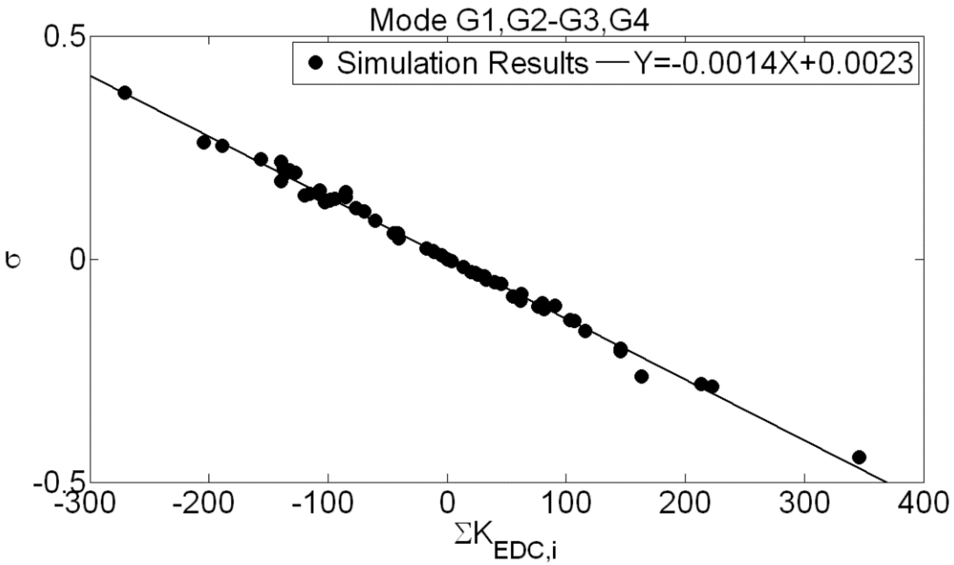
Other Applications

- 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]



$$\sigma = -\gamma \sum_{i} K_{EDC,i}$$

σ : 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

[3] Lei Chen, Yong Min, Yiping Chen, et al. Evaluation of generator damping using oscillation energy dissipation and the connection with modal analysis. IEEE Trans Power Syst, 2014, 29(3): 1393-1402.

Discussions on New Developments

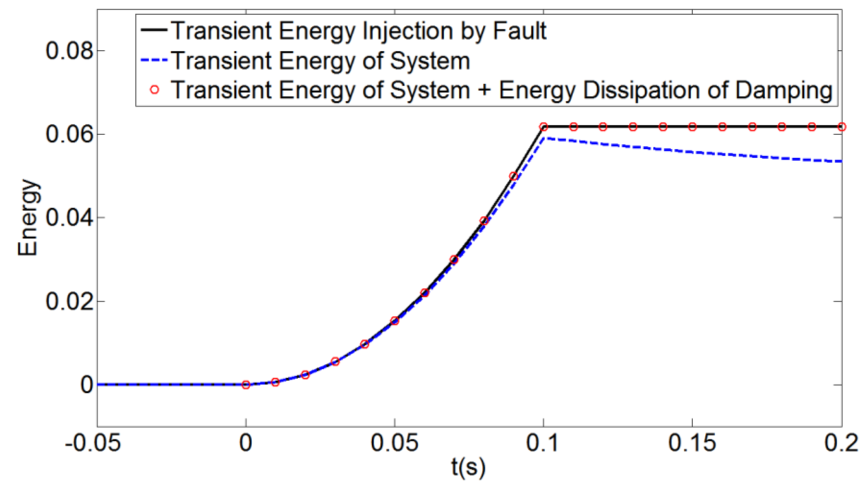
- Physical meaning of oscillation energy flow
  - Connection with the actual electrical power

$$W_{1d} = \int I_{1d}^2 R_{1d}\, dt$$

$$W_{1q} = \int I_{1q}^2 R_{1q}\, dt$$

$$W_{2q} = \int I_{2q}^2 R_{2q}\, dt$$

- 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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