

Analysis of Low Frequency Oscillation and Source Location in Power Systems

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Abstract—The major problem in current online diagnosis and analysis for power system oscillation is mainly concerned with finding the oscillation source in a fast and correct way using the data collected by the Wide Area Measurement System (WAMS). This paper for the first time proposes a scheme of cut set energy based on WAMS. Independent of accurate parameters, the scheme can make full use of WAMS data based on cut set energy construction and fast calculation to locate the source during oscillation. Afterwards, a scheme of torque decomposition is proposed, based on which the controller's torque can be divided into damping torque and synchronous torque by calculation through WAMS data, and this paper puts forward the abnormal response and simulation models calibration of influential controllers. Analysis of an oscillation case shows how the cut set energy scheme and the torque decomposition scheme are applied in a real-world power system, and the schemes are proven to be reliable and practical in identifying and locating oscillation sources.

Index Terms—Cut set energy, low frequency oscillation, model calibration, oscillation source, power system, torque decomposition.

I. INTRODUCTION

WITH the development of large-scale power system interconnections, the problem of low frequency oscillation has attracted more and more attention. Low frequency oscillation occurs when the power system is disturbed, and a relative swing takes place between the synchronous generator rotors, which results in active power, voltage and other electrical quantities appearing with the same frequency as oscillation. If the system lacks adequate damping, power oscillation will continue for a long time and can damage the system's operational stability. Some large-scale blackouts have occurred domestically and abroad that are directly associated with low frequency oscillation; others have been accompanied by low frequency oscillation during the evolution of a blackout [1]–[9].

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A critical problem in the diagnosis and emergency control of low frequency oscillation in power systems is the need to identify the oscillation source in a timely and accurate manner. There are two methods being used currently. The first one is the use of an on-line simulation model to analyze the oscillation. The disadvantage of this method, however, is that it relies on the accuracy of the model and its parameters, and is frequently powerless when the oscillation is caused by abnormal equipment or an unreasonable model and parameters. The second method is based on the data measured by the WAMS. The drawback lies in that a large amount of real-time data needs to be processed and calculated, but often, system operators do not have adequate data of the key buses or transmission lines.

During an electromechanical oscillation in a power system, kinetic energy and potential energy of the generator rotor are mutually transformed with the potential energy in the power system. The stability of the power system is reflected in the form of transient energy in the transmission network [10]–[14]. Therefore, the concept of energy is used to analyze low frequency oscillations. A method of oscillation energy flow for low frequency oscillation analysis and oscillation source location is proposed in [15]–[18]. Some oscillation cases are analyzed in [19], [20]. The rest of the paper is organized as follows. In Section II the definition of cut set energy is put forward and in Section III the oscillation region is located by calculating the oscillation energy flow during the oscillation. In Section IV and Section V, a case using the torque decomposition scheme based on WAMS is presented. These methods are proven to be reliable and practical for locating the oscillation source through the analysis of actual oscillation events in the power system. Section VI and Section VII analyze power oscillation cases in the Three Gorges Hydropower Station and ultra-low frequency oscillation cases in Yunnan Power Grid in asynchronous interconnection mode, respectively. Finally, the paper is concluded in Section VIII.

II. CONSTRUCTION OF CUT SET ENERGY IN POWER SYSTEMS

An oscillation energy based method is proposed in [16]–[18], where low frequency oscillation analysis is executed to determine the location of the oscillation source. In this method, the damping characteristics of the elements are estimated and the oscillation source is located through the energy flow in power system. Oscillation energy is concordant with transient energy in the energy function. Elements that consume energy

have a good effect on damping; meanwhile, elements that produce energy represent the orientation of the oscillation. Thus, according to the flow of oscillation energy in the grid, the disturbance source can be identified. Units with negative damping and elements with periodic disturbance will produce oscillation energy during oscillation.

Oscillation energy from bus i to bus j (line L_{ij}) is defined as follows:

$$\begin{aligned} V_{PEij} &= \int \left(P_{ij} d\theta_i + \frac{Q_{ij}}{U_i} dU_i \right) \\ &= \int (P_{ij} d\theta_i + Q_{ij} d(\ln U_i)) \\ &= \int (P_{ij} 2\pi \Delta f_i dt + Q_{ij} d(\ln U_i)) \end{aligned} \quad (1)$$

where V_{PEij} is the oscillation energy from bus i to bus j ; P_{ij} is the active power of line L_{ij} ; Q_{ij} is the reactive power of line L_{ij} ; U_i is the voltage amplitude of bus i ; θ_i is the voltage angle of bus i ; f_i is the frequency of bus i .

If (1) is used to express the variation of oscillation energy flow, it is altered to be:

$$\begin{aligned} \Delta V_{PEi-j} &= \int (\Delta P_{ij} d\theta_i + \Delta Q_{ij} d(\Delta \ln U_i)) \\ &= \int (\Delta P_{ij} 2\pi \Delta f_i dt + \Delta Q_{ij} d(\Delta \ln U_i)). \end{aligned} \quad (2)$$

It is proven in [15] and [16] that the energy flowing into the generator is composed of the energy dissipation of the generator and the mutual transformation between the generator transient energy and external grid. Meanwhile, the energy dissipation of the generator is consistent with its damping torque. The expression of the oscillation energy produced by the disturbance applied on the generator is also proven in [17] and [18].

A cut set in the power grid is defined as a subnet; and all branches of the cut set are connected with the rest of the grid. For the convenience of analysis, oscillation energy flowing from the cut set is defined to be positive, and the energy flowing into the cut set is negative. Because disturbance means energy production and if transmission losses are ignored, the cut set energy is positive and the oscillation orientation takes place inside of the cut set. Similarly, the oscillation orientation is outside the cut set if its oscillation energy is close to zero or negative. The calculation of the cut set energy is based on (2).

As shown in Fig. 1, the cut set Ω consists of branches a, e,

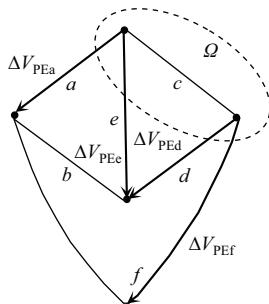


Fig. 1. Calculation of cut set energy.

d and f, i.e., the branches passed through by the dotted box, and its cut set energy ΔV_E is defined as follows:

$$\Delta V_E = \Delta V_{PEa} + \Delta V_{PEe} + \Delta V_{PEd} + \Delta V_{PEf}. \quad (3)$$

III. OSCILLATION LOCATION BASED ON CUT SET ENERGY

The flow chart for power system oscillation analysis and oscillation location based on cut set energy is presented in Fig. 2. The main steps are described as follows:

1) In consideration of the oscillation mode and governor type, the power system is divided into several large cut sets. These large cut sets are further divided into smaller cut sets based on the WAMS information. The smallest cut set contains only one unit or bus.

2) The information such as active power, reactive power, voltage, and frequency of the key branches or generators is obtained from the WAMS. This information is then decomposed into a number of oscillation modes using the Prony algorithm or Hilbert-Huang transform (HHT).

3) For the main oscillation mode, the energy flow of each large cut set is calculated based on the information obtained from step 2. We can then determine which large cut set the oscillation source belongs to.

4) By gradually narrowing the scope of the cut set until it reaches its minimum scope, we can then locate where the oscillation source is in relation to the unit or bus.

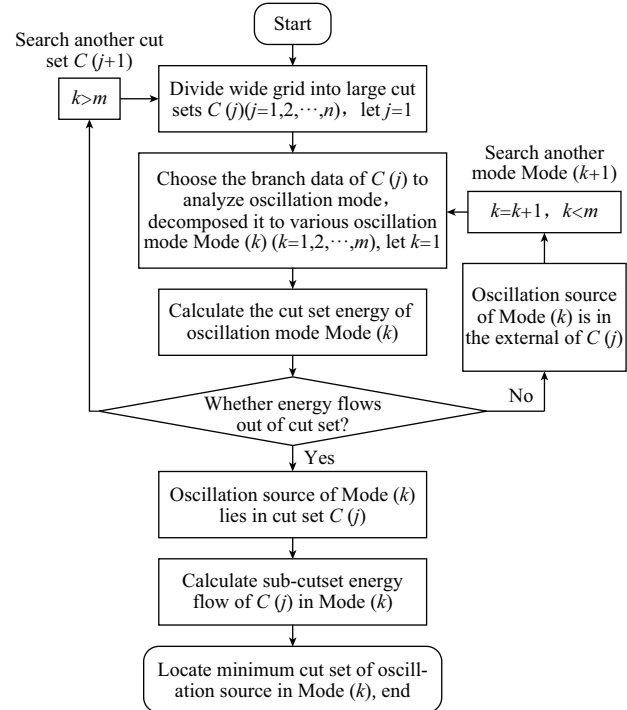


Fig. 2. Flow chart of oscillation orientation location based on cut set energy.

IV. THE TORQUE AND OSCILLATION ENERGY OF GENERALIZED CONTROLLER

The generalized controller proposed in this paper refers to an exciter or governor of the generator, a static var compensator (SVC), a static var generator (SVG), a thyristor

controlled reactor (TCR), and a thyristor controlled series compensation (TCSC) or other control equipment. The controller may be either a motor or some other dynamic load. The control feedback quantity of the generalized controller is the voltage, active power, power angle, and rotor speed of the generator or load bus.

A typical system structure using the method of torque decomposition, as shown in Fig. 3, consists of two equivalent synchronous generators.

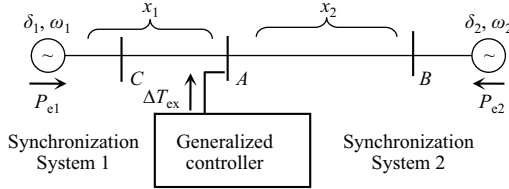


Fig. 3. A typical system structure using the method of torque decomposition.

In Fig. 3, ω_1 and ω_2 are the generator speed respectively, δ_1 and δ_2 are the power angles, P_{e1} and P_{e2} are the active power of generators, ΔT_{ex} is the control torque of the generalized controller, and x_1 and x_2 are the equivalent impedances of the transmission lines. All these variables are available in the WAMS. There is only one electromechanical oscillation mode between the two units in this system. When a small oscillation occurs, the control torque difference ΔT_{ex} of the synchronization system can be expressed by the angular velocity difference $\Delta\omega$ and power angle difference $\Delta\delta$, which are called the damping torque K_d and the synchronization torque K_s , respectively.

For synchronization system 1:

$$\Delta T_{e1} = K_{d1}\omega_0(\Delta\omega_1 - \Delta\omega_2) + K_{s1}(\Delta\delta_1 - \Delta\delta_2). \quad (4)$$

For synchronization system 2:

$$\Delta T_{e2} = K_{d2}\omega_0(\Delta\omega_2 - \Delta\omega_1) + K_{s2}(\Delta\delta_2 - \Delta\delta_1). \quad (5)$$

The control torque difference ΔT_{ex} is decomposed on the $\Delta\delta - \Delta\omega$ plane. If the projection of ΔT_{ex} is in phase with $(\Delta\omega_1 - \Delta\omega_2)$, it provides positive damping to the synchronous generator 1. On the other hand, if the projection of ΔT_{ex} is in the reverse phase with $(\Delta\omega_1 - \Delta\omega_2)$, it provides a negative damping effect. Oscillation energy of the generalized controller is defined as the integral of the product of the torque and rotational speed difference, expressed as follows:

$$\Delta E_{ex} = \int_{t=t_0}^{t=t_1} \Delta T_{ex}(\Delta\omega_1 - \Delta\omega_2)dt. \quad (6)$$

The calculation of the torque oscillation energy actually reflects whether the damping is positive or negative. This result is provided by the control system, which helps to determine if the controller function is valid. Based on this method, the oscillation source can then be located to the abnormal controller. The calculation results of the measured torque are then compared with the simulated torque, while the models and parameters of the controllers are verified through online data simulation.

The torque for a controller is computed using the Heffron-Philips model. An example can be found in [21], where the electromagnetic torque of a SVC is computed. For a generalized controller, the torque can be computed using the Heffron-Philips model following the same procedure as described in [21].

V. THE METHOD OF TORQUE DECOMPOSITION OF A TYPICAL CONTROL SYSTEM

A. Torque Oscillation Energy Calculation of the Excitation Control System

The calculation of the torque oscillation energy in the excitation system is defined as follows:

$$\Delta E_{E'_q} = \int \Delta E'_q \cdot \Delta\omega dt \quad (7)$$

where $\Delta E'_q$ is the difference of the generator transient voltage, which represents the torque of the exciter controller, and $\Delta\omega$ is the difference in the speed of the synchronizer.

Since the torque oscillation energy of the torque decomposition varies with time, the results can also show if the excitation system has good damping effect or not. For the exciter system, if the result is positive, it provides positive damping for the power system as Fig. 4 shows.

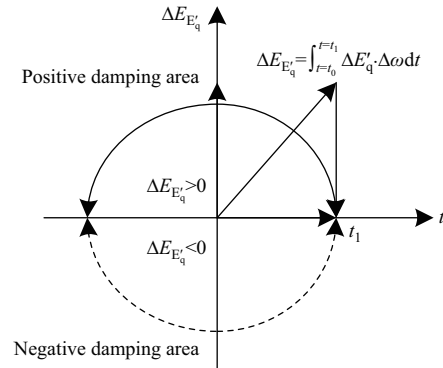


Fig. 4. The torque oscillation energy calculation of the excitation control system.

B. Torque Oscillation Energy Calculation of the Governor Control System

The torque oscillation energy calculation of the torque decomposition in the governor system is defined as follows:

$$\Delta E_{P_M} = \int \Delta P_M \cdot \Delta\omega dt \quad (8)$$

where ΔP_M is the difference between the wicket gate opening signal of the governor and the prime mover model fitting calculation. This is also calculated through the measured speed ω , electromagnetic power P_e and rotor kinematic equation:

$$P_M(k) + D\Delta\omega(k) = \frac{4\omega(k+1) - 3\omega(k) - \omega(k+2)}{T \times 2} \cdot 2H + P_e(k) \quad (9)$$

where H is the rotor time constant and T is the sample period.

For the governor system, if the result is positive, it provides

the negative damping for the power system, which is opposite to the excitation system as Fig. 5 shows.

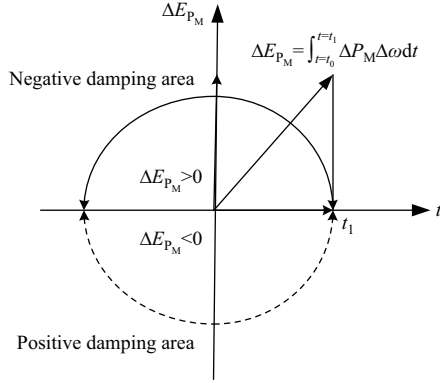


Fig. 5. The torque oscillation energy calculation of the governor control system.

The torque oscillation energy of the exciter and governor can be calculated in two ways: one is to use the data from the WAMS and the other is to base the calculations on the simulation models. In this manner, the method of torque decomposition can help us to understand the behavior of these controllers in the power system and also to check the accuracy of the models and parameters.

C. Torque Oscillation Energy Calculation of the Simulation Model

The torque oscillation energy calculation method is consistent with the previous and the simulation results can be utilized in the formula to calculate the torque decomposition energy. By comparing the oscillation energy measured by the generalized controller and what is calculated by its simulation model, we are able to check the simulation model and its parameters for accuracy.

The flow chart of oscillation source location based on torque decomposition is given in Fig. 6. Based on the method of cut set energy to locate the oscillation source to the power plant

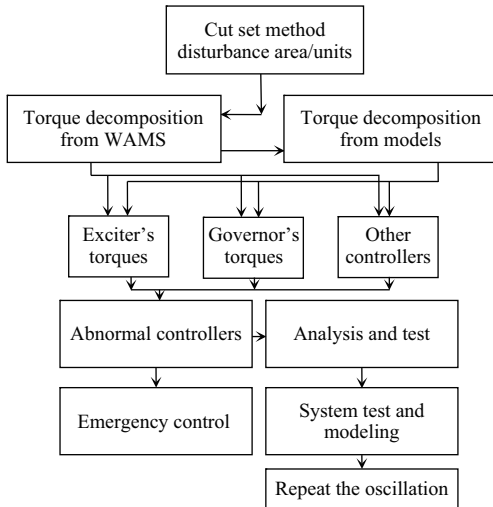


Fig. 6. Flow diagram of torque decomposition.

or generator unit level, the oscillation source can be further positioned to the controller device level using the torque decomposition method. Both the exciter's and governor's torque oscillation energies can be calculated in two ways; one is from the WAMS, the other is based on system models. Thus, this helps us to understand both system behavior and model calibration.

VI. POWER OSCILLATION CASES IN THE THREE GORGES HYDROPOWER STATION

In 2010, there were 26 units in the Three Gorges Hydropower Station, and the rated capacity reached 18.2 GW. For the first time, four sub-plants were generating power independently from their own transmission lines. On July 14, there was an abnormal periodic power fluctuation in the Three Gorges Hydropower Station and its nearby grid. The record waveform of the power fluctuation is shown in Fig. 7. It can be seen that typical characteristics of this power fluctuation was its intermittent appearance, and this was self-suppressed as time went on [22].

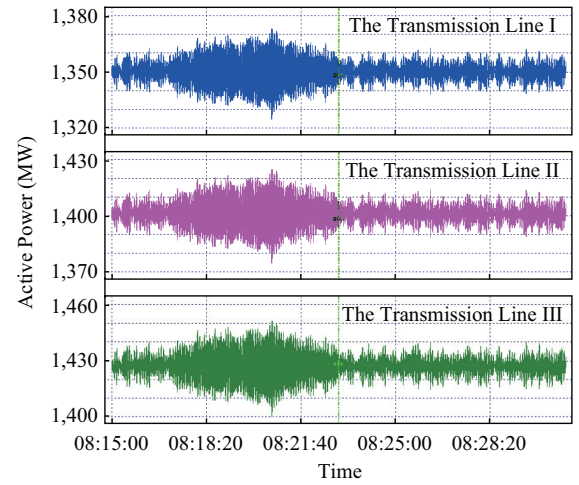


Fig. 7. Abnormal power fluctuation record curves of the Three Gorges Hydropower Station sent out on the lines.

A direct solution to power oscillation is to accurately locate the defect of the integration software of the excitation system or the governor system in the generation equipment. This can be done using the test analysis method based on the disturbed system and other comprehensive means, such as PMU monitoring, RTDS simulation, measured modeling simulation, etc. The power oscillation can be analyzed and oscillation source can be positioned accurately by the method of cut set energy.

A. Analysis of the Oscillation Mode

The power oscillation frequency is about 0.82 Hz, provided by the data obtained from the PMU and fault recorder. The record waveforms of power oscillation of the generator units of various sub-plants are shown in Fig. 8.

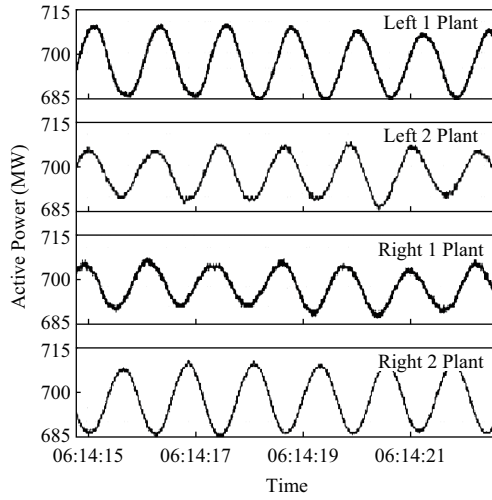


Fig. 8. Record waveforms of power fluctuation of the generator units of the sub-plants.

B. Division of Cut Set

First, as Fig. 9 shows, the interconnected system is divided into two regional cut sets, respectively, defined as cut set 1 and cut set 2. These two regions are connected with 1100 kV AC lines. Then according to the topology of regional or provincial power grid and the main oscillation mode, the two cut sets are further divided. The regional cut set 2 is divided into five smaller regions from cut set 21 to cut set 25. As shown in Fig. 10, the regional cut set 22 is further divided into three smaller regions, from cut set 221 to cut set 223. Cut set 223 includes the Three Gorges Hydropower Station and the nearby power grid. Finally, cut set 223 is divided into cut set 2231 (Left 1 Plant), cut set 2232 (Left 2 Plant), cut set 2233 (Right 1 Plant) and cut set 2234 (Right 2 Plant). Similarly, other plants within the WAMS are also divided into a separate cut set.

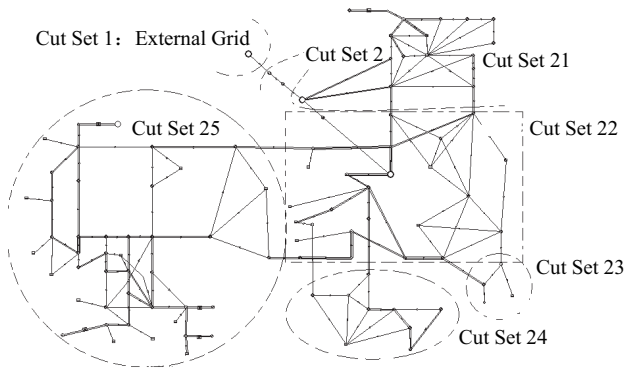


Fig. 9. Division diagram of cut set energy for a regional power grid.

C. Calculation of Cut Set Energy and Positioning the Oscillation Source to the Unit

Based on the WAMS oscillation data analyzed by the Prony method, each cut set energy is calculated respectively. The calculation results are listed in Table I. According to the analysis above, the cut set energy contains oscillation

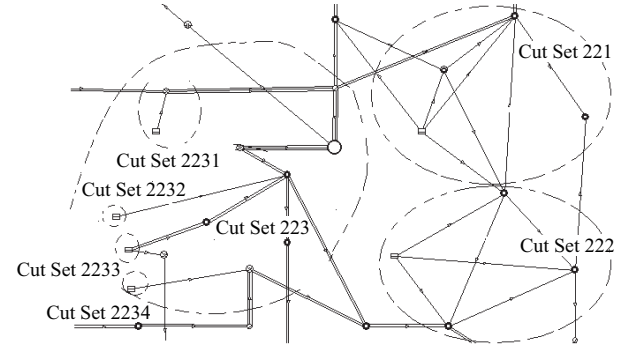


Fig. 10. Division diagram of cut set energy.

source flowing out of the cut set and the calculation result is always positive. On the basis of the cut set energy results, the oscillation source can be gradually positioned to a few smaller cut sets. The orientation is located in the order of cut set 2 → cut set 22 → cut set 223 → cut set 2234 → Right 2 Plant in the Three Gorges Hydropower Station.

TABLE I
THE CUT SET ENERGY OF EACH CUT SET

Cut Set	Energy Flow	Cut Set	Energy Flow	Cut Set	Energy Flow	Cut Set	Energy Flow
1	↓	21	↓	221	↓		
2	↑	22	↑	222	↓		
				223	↑	2,231	↓
						2,232	↓
						2,233	↓
						2,234	↑
		23	↓				
		24	↓				
		25	↓	251	↓		
				252	↓		
				253	↓		
				254	↓		
				255	↓		

↓ denotes inflow, ↑ denotes outflow

Furthermore, the smallest cut set that includes only one unit in the Right 2 Plant can be positioned. The oscillation energy primarily comes from these units included from #21 to #26 in the Right 2 Plant. The analysis results are consistent with the actual situation.

D. Calculation of the Oscillation Energy of Torque Decomposition and Position of the Exciters

The comparison between the simulated torque oscillation energy of the exciter belonging to Unit #22 in Right 2 Plant and the oscillation energy of the measured torque is shown in Fig. 11. It can be seen that the simulated exciter provides significant positive damping, while the measured exciter provides significant negative damping. During the disturbance period, the frequency change cannot cause change in the wicket gate opening of the governor, and it does not need to analyze the governor torque oscillation energy.

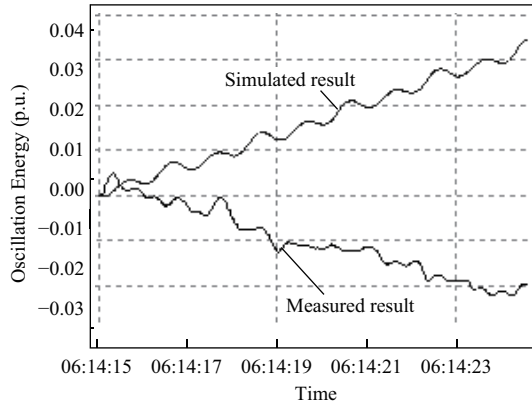


Fig. 11. The torque oscillation energy of the exciter belongs to Unit #22.

E. Analysis of the Oscillation Cause

After oscillation, the excitation test was carried out four times in the Three Gorges Hydropower Station and a similar type of backup exciter was tested in a real time digital simulator (RTDS). The field test and RTDS test were conducted simultaneously and the reason for abnormal fluctuation in these tests is that the internal reactance parameter X_q in power system stabilizer (PSS) is set in error in the Right 2 Plant. After the internal reactance parameter of PSS in the Right 2 power plant is set to the value in the simulation according to the actual field parameter, the simulated torque oscillation energy is close to the measured result, as shown in Fig. 12. The torque comparison can verify if the internal reactance parameter of PSS is set incorrectly.

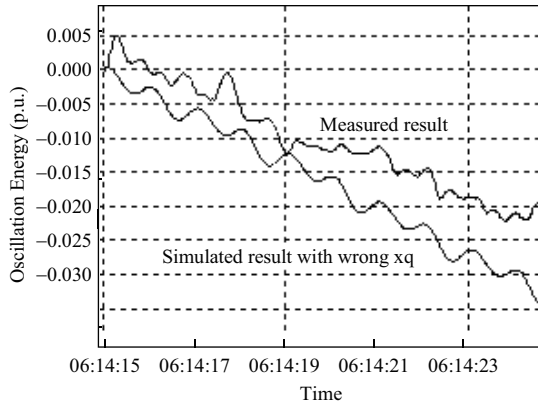


Fig. 12. The torque oscillation energy of the exciter belongs to Unit #22 after adjusting the internal reactance parameter in the PSS controller.

VII. ULTRA-LOW FREQUENCY OSCILLATION CASE OF THE YUNNAN POWER GRID IN ASYNCHRONOUS INTERCONNECTION MODE

The asynchronous interconnection mode between Yunnan Power Grid and China Southern Power Grid was put into practice in 2016 [5], [6]. However, during the practical experiment of raising DC power in asynchronous mode, an ultra-low frequency oscillation occurred in Yunnan Power Grid and lasted for a long time. Yunnan Power Grid is a typical hydropower concentrated power grid, where the

installed capacity of hydropower reaches up to 71.9% of the total installed capacity and the export DC power accounts for about 32% of the total installed capacity. Performing the small-signal stability test, the frequency of Yunnan Power Grid began to fluctuate while the DC power increased by 200 MW/min, and the main power station also suffered significant power and voltage oscillation. The record waveforms are shown in Fig. 13.

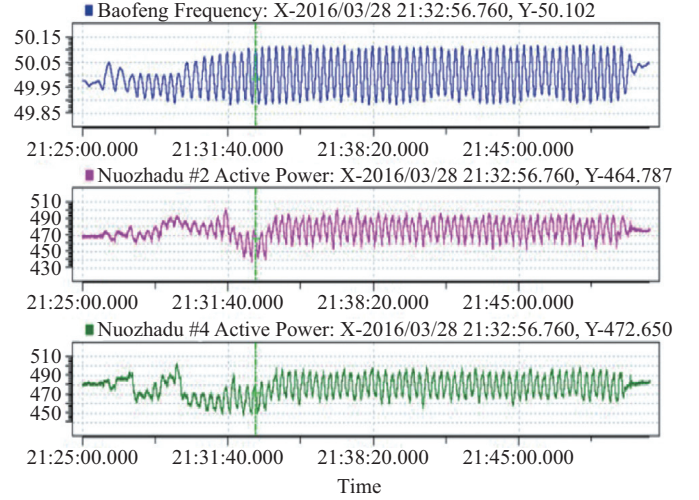


Fig. 13. Frequency oscillation recorded curves of the main power station in the Yunnan Power Grid.

A. Analysis of Frequency Oscillation

The characteristics of oscillation are summarized as follows:

- 1) Oscillation frequency is about 0.05 Hz, which belongs to the range of ultra-low frequency oscillation. Oscillation amplitude is about ± 0.1 Hz, and the maximum amplitude coincides with the dead zone of the frequency limit controller (FLC) in the DC.
- 2) The active power of the hydropower units is in phase with the frequency, but the phase of the active power of the thermal units is opposite to the frequency. Fig. 14 shows the record waveform of the frequency oscillation in Yunnan Power Grid. Fig. 15 and Fig. 16 respectively show the record waveforms of the hydropower units and thermal units.

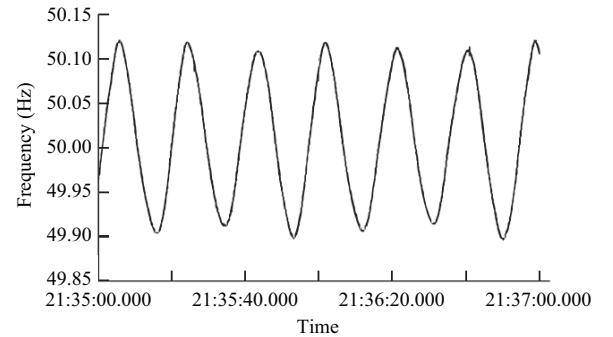


Fig. 14. The frequency recorded curve of the Yunnan Power Grid during oscillation.

- 3) With the primary frequency regulation of the main hydropower station in Yunnan Power Grid exited, the frequency

oscillation gradually disappeared and the system came back to stability.

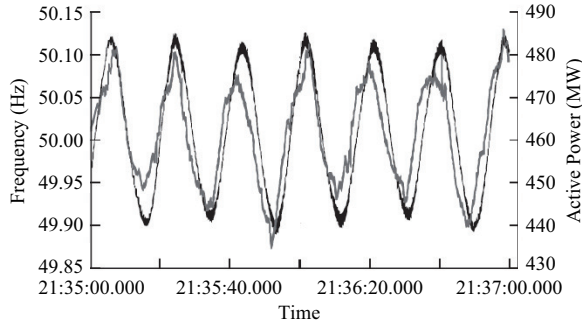


Fig. 15. The active power and frequency recorded curve of the hydropower unit during oscillation.

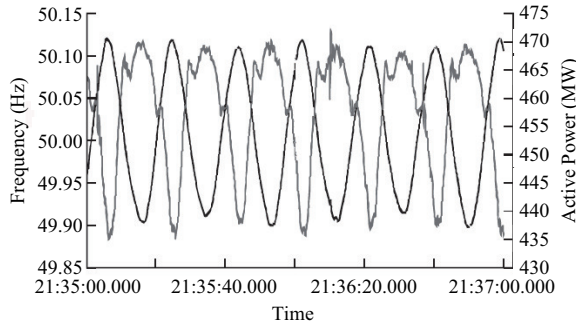


Fig. 16. The active power and frequency recorded curve of the thermal unit during oscillation.

B. Calculating the Oscillation Energy of the Torque Decomposition and Position to the Governors

In order to further analyze the reason for oscillation, the torque decomposition energy of the excitation system, the governor system, and the DC control system were calculated based on the PMU data and the damping properties provided by the relevant control system.

As shown in Fig. 17, the DC control system provided positive damping in the oscillation, and the excitation system of

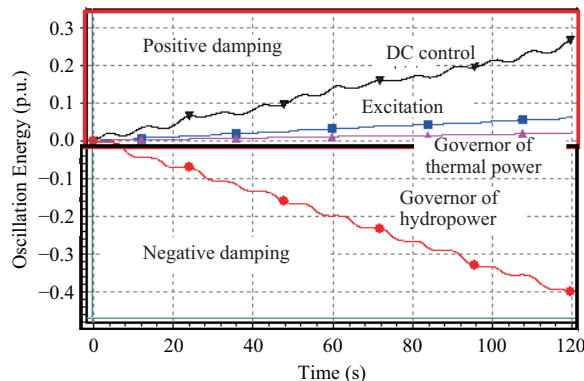


Fig. 17. The oscillation energy of the control system in the Yunnan Power Grid.

both the hydropower and thermal power also provided positive damping. The governor system of the thermal system provided positive damping, but the governor system of the hydropower obviously provided negative damping. The oscillation source was positioned to the governor system of the hydropower units in Yunnan Power Grid.

Further, the excitation system and governor system of the main units in Yunnan Power Grid were torque decomposed respectively, and the oscillation energy was then calculated with the results as shown in Fig. 18 and Fig. 19. It can be seen from Fig. 18 that all excitation systems except Xiaowan #1 provided positive damping during oscillation. All the governor systems except Diandong #4 provided negative damping during oscillation, as shown in Fig. 19. For all units analyzed as shown in the figures, only the Diandong #4 unit is the thermal unit, while other units are hydropower units. During the oscillation process, with the primary frequency regulation provided by the main hydropower station in Yunnan Power Grid, the frequency oscillation gradually disappeared. Fig. 18 and Fig. 19 also show that the governor of the hydropower units is a strong correlation factor for the oscillation.

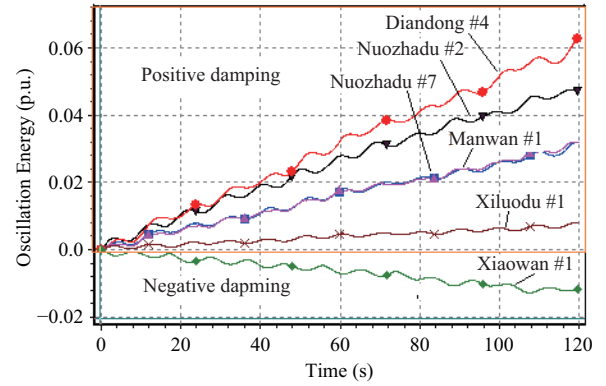


Fig. 18. The oscillation energy of the excitation system of the main units in the Yunnan Power Grid.

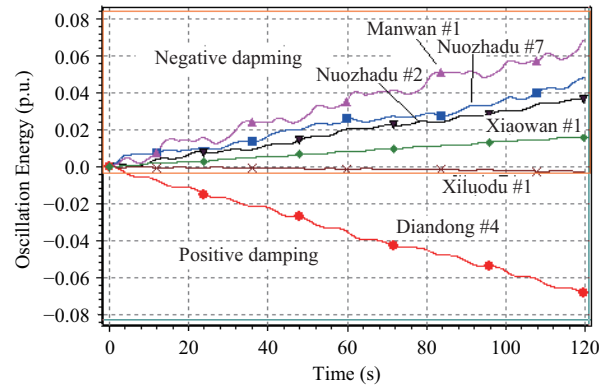


Fig. 19. The oscillation energy of the governor system of the main units in the Yunnan Power Grid.

Therefore, the source of the ultra-low frequency oscillation was located in the governor system of the hydropower units in Yunnan Power Grid.

C. Analysis of the Oscillation Cause

In general, the governor of the units provides positive damping in the low frequency zone and negative damping in the high frequency zone. There is a boundary frequency where the damping provided by the governor is zero [22]. The boundary frequency of the hydropower unit is usually relatively low, while that of the thermal power unit is usually relatively high. When Yunnan Power Grid was in asynchronous connection mode with China Southern Power Grid, the hydropower governor parameter settings were extremely sensitive, which were intended to quickly regulate the frequency deviation to normal. But these governor parameters are too sensitive and the water hammer effect of the hydropower unit may cause instability in small and independent power grids.

In order to effectively deal with ultra-low frequency oscillation, the governor parameters of the hydropower units are adjusted, including reducing response speed, decreasing the gain, increasing the action dead zone, etc. These measures provide effective guarantees for the stable operation of Yunnan Power Grid when it is in asynchronous interconnection mode with China Southern Power Grid.

VIII. CONCLUSION

This paper has proposed two methods for power system oscillation orientation location.

1) The cut set energy is the first method derived to approximately reflect the damping effect of the excitation system, the governor system, and other elements. Based on WAMS dynamic information of key branches in the power system, different levels of cut sets can be built. When the oscillation occurs in the power system, the oscillation source can be identified quickly online by observing the cut set energy variations.

2) The second method combines the cut set energy and the torque decomposition together, which more obviously show the influence of the control system on the damping. The torque energy is calculated with the data obtained from the WAMS and it directly reflects the nature of the damping provided by the control system. The torque decomposition method, on the other hand, not only determines which abnormal controllers have stronger correlations with the oscillation source, but also verifies the simulation model and parameters.

3) By using wide range information such as PMU, WAMS and the fault recorder, both the cut set energy method and torque decomposition method are able to determine accurate location of the oscillation source. As a panoramic view, it is concluded that the proposed methods are able to provide improved monitoring of the large power grid meanwhile allow us to assess the equipment's quality and performance. These methods are expected to build a strong security barrier for the safe and stable operation of the power system.

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