A Disturbance Source Location Method on the Low Frequency Oscillation With Time-varying Steady-state Points

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***Abstract*—The low frequency oscillation is a serious threat to security and stability of a power grid. How to locate the disturbance source accurately is an important issue to low frequency oscillation disposal. Existing methods have poor adaptability to the low frequency oscillation with time-varying steady-state points because of the limitations in the location criterion derivation. A disturbance source location method on a low frequency oscillation with good generality is presented in the paper. Firstly, the reasons why the steady-state points are time-varying on a low frequency oscillation are analyzed. Then, based on the energy function construction form, the branch transmission energy is decomposed into state energy, reciprocating energy and dissipation energy by mathematical derivation. The flow direction of the dissipation energy shows the source and destination of the disturbance energy, and the specific location of a disturbance source can be identified according to its flow direction. Meanwhile, to meet the needs of energy calculation, a recognition method on the electrical quantities steady-state points is also presented by using the cubic spline interpolation. Simulation results show the correctness of the derivation and analysis on energy structure in the paper, and the disturbance source can be located accurately according to the dissipation energy.**

***Index Terms*—dissipation energy, disturbance source location, energy decomposition, low frequency oscillation, steady-state point identification**

I. INTRODUCTION

THE low frequency oscillation is an important factor on affecting the safety and stability of the modern large power system operation. Some serious low frequency oscillation accidents have occurred in domestic and foreign power grids during the operation. With the development of the ultra-high voltage system and the direct current system, low frequency oscillations are also easily caused in large power grids.

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The low frequency oscillation of a large power grid includes the relative oscillation between generator clusters in the interconnected system and the weak damping or negative damping oscillation caused by a local disturbance source [1]-[6]. The low frequency oscillation caused by a local disturbance source can be divided into the forced power oscillation and the negative damping oscillation [7]-[8]. The forced power oscillation is always caused by a continuous periodic small disturbance, and when the disturbance frequency is close to the system natural frequency, the system resonance occurs [9]-[10]. The negative damping oscillation is always caused by the negative damping characteristic of the generator control system under a disturbance. Because the oscillation of the disturbed generator rotor cannot be controlled by itself, and the system behaves as a continuous increasing oscillation [11]-[12]. For a low frequency oscillation caused by the local disturbance source, the oscillation always exists until the disturbance source is removed. After the disturbance source is removed, the oscillation amplitude will decay gradually.

How to locate the disturbance source quickly and accurately is the first problem to restrain a low frequency oscillation. At present, some achievements in the disturbance source localization field have been made by scholars.

In References [13]-[15], a practical calculation method of energy flow is proposed, which can reduce the transient energy component in the network oscillation energy flow. In the method, only the consumed or generated energy by the branch is calculated, and the disturbance source can be located according to the energy flow direction. In References [16]-[17], based on the WAMS dynamic information of key lines, different levels of network cut sets are constructed, and the oscillation source is in the cut set with oscillation energy outflow. The control system abnormality can be checked up according to the oscillation energy of the excitation system torque and the governor system torque. In Reference [18], a method is presented to extract the delay time of the disturbance traveling wave in a transmission line by using the sampled data and the waveform similarity method, and the position of the low frequency oscillation source in a power grid can be calculated by using the time delay.

The low frequency oscillation in a power system is a symmetrical reciprocating motion centered on steady-state operation point. If the steady-state operation point is fixed, the middle axis of the oscillation curve is close to a horizontal line. However, due to the changes of some factors such as the network structure, the unit output (such as the fluctuation of wind power) or the load (such as load growth in morning or evening peak) in some oscillation process, the steady-state operation points of generators and transmission networks change over time. When the time-varying low frequency oscillation of a steady-state operation point occurs, the whole oscillation curve can drift. At present, the existing disturbance source location criterions are difficult to apply to this kind of oscillation, and the location accuracy can only be ensured when the steady-state operation point has a small change in amplitude.

A disturbance source location method on the low frequency oscillation with time-varying steady-state points is presented in the paper, and it is also suitable for the oscillation with a fixed steady-state point. In the method, the branch transmission energy is decomposed into state energy, reciprocating energy and dissipation energy by mathematical derivation. The flow direction of the dissipation energy shows the source and destination of the disturbance energy, and the specific location of a disturbance source can be identified according to its flow direction. An actual system of North China Power Grid is used for simulation verification. The results indicate that the disturbance source of the low frequency oscillation with time-varying steady-state points can be identified according to dissipation energy, and it can be applied to the oscillation monitoring and the offline oscillation cause analysis.

II. Time-Varying Factors Analysis Under The Steady-State Operation Point

A. Load change

During the actual operation of a power grid, the oscillation period of a low frequency oscillation is more or less than a minute generally. 1 During a oscillation period, the wind power output will change. If it is at the morning or evening peak, the system load may also change greatly. To maintain active power balance, the governors of peak-regulating units act. During the process, the steady-state operating points of electrical quantities such as the bus voltage, angle, active power and reactive power in the system will change.

A single machine infinite system is selected as an example and the small disturbance response of rotor angles when a governor acts is analyzed. The classical generator second-order model is used and the rotor motion equation is shown in Equation (1).

$$\begin{cases} M\dfrac{\mathrm{d}\omega}{\mathrm{d}t} = P_{\mathrm{m}} - P_{\mathrm{e}} - D(\omega - 1) \\ \dfrac{\mathrm{d}\delta}{\mathrm{d}t} = \omega - 1 \end{cases} \tag{1}$$

Then, the working point in Equation (1) is linearized, and the equation can be obtained as follows:

$$M\Delta\ddot{\delta} + D\Delta\dot{\delta} + K\Delta\delta = \Delta P_{\mathrm{m}} \tag{2}$$

Where K is equal to $(E'U\cos\delta_0)/X_\Sigma$.

In Equation (2), ΔP_{m} is approximately considered equal to bt, i.e. $\Delta P_{\mathrm{m}} = \mathrm{b}t$, where the symbol b is a constant. It means the generator output linearly increases with time.

Equation (2) is the second order constant coefficient nonhomogeneous linear differential equation and the general solution of its corresponding homogeneous equation is shown in Equation (3).

$$\Delta\delta_1(t) = A\mathrm{e}^{-(D/2M)t}\cos(\omega t + \varphi) \tag{3}$$

Where, $\omega = \sqrt{4MK - D^2}/2M$ and both A and φ are constants determined by the initial conditions.

The special solution of Equation (2) can be obtained in Equation (4).

$$\Delta\delta_2(t) = ct \tag{4}$$

Where, the symbol c is a constant.

Therefore, under the condition of the generator governor action, the small disturbance response of the rotor angle can be decomposed into the form of the superposition of the free component in Equation (3) and the forced component in Equation (4). The forced component is a straight line with a constant slope, which is a main cause of the steady-state operation point change and the oscillation curve drift.

B. Power grid structure change

In the process of a low frequency oscillation, the relay protection devices may cut off the power system components by mistake. To maintain the system stability, some measures such as cutting machine and load, out of step separation may also be adopted in security and stability control devices. The above devices action can make the power grid structure change. The system power flow is closely related to the grid structure. Therefore, the steady-state operation points of each component in the system change instantly with the grid structure. In addition, the low frequency oscillation of a power system may occur after a fault disturbance, and the removal of a faulted component may also bring the grid structure change. So, the steady-state operation point after an accident is different from before it.

C. Power grid operation after an accident

After a faulted component is removed, the active power of the entire system can be balanced in the case of slight deviation of system frequency. And then, the power system operates near the frequency of about 50Hz for a certain period of time. During the time, although the power grid can keep operating synchronously, the steady-state voltage angle of each component may continue to increase or decrease over time. Within a period after a fault is removed, due to the weak structure of the power grid and other reasons, the generator control system and various types of compensation devices are likely to make some adjustments. Then, the steady-state operation points of all components in the system change in the automatic adjustment process of the power grid.

III. Energy Decomposition And Disturbance Source Localization Method

A. Energy function

A method for constructing the energy function of generators, lines and loads is proposed in Literature [19-20], and the system energy conservation equation is deduced. In Equation (5), the transmitted energy from Bus i to Bus j of the Branch Lij is shown as follows:

$$\begin{aligned} E_{ij} &= \int \mathrm{Im}(\dot{I}_{ij}^{*}\,\mathrm{d}\dot{U}_i) = \int \mathrm{Im}[(\frac{P_{ij}+jQ_{ij}}{\dot{U}_i})(\mathrm{d}U_i e^{j\theta_i})] \\ &= \int \mathrm{Im}[(\frac{P_{ij}+jQ_{ij}}{U_i e^{j\theta_i}})(e^{j\theta_i}\mathrm{d}U_i + jU_i e^{j\theta_i}\,\mathrm{d}\theta_i)] \\ &= \int \left(P_{ij}\mathrm{d}\theta_i + \frac{Q_{ij}}{U_i}\mathrm{d}U_i \right) \end{aligned} \tag{5}$$

Where, the symbol $\dot{I}_{ij}^{*}$ is conjugate of current phasor of Branch L_{ij}; $\dot{U}_i$ is the voltage phasor of Bus i; P_{ij} and Q_{ij} are the active power and the reactive power transmitted from Bus i to Bus j, respectively.

B. Energy decomposition

A transformation on the relative steady-state operation point of the transmitted energy by the branch is done in Equation (6).

$$\begin{aligned} E_{ij} &= \int \left(P_{ij}\mathrm{d}\theta_i + \frac{Q_{ij}}{U_i}\mathrm{d}U_i \right) = \\ & \int (P_{ij,\mathrm{s}} + \Delta P_{ij})\mathrm{d}(\theta_{i,\mathrm{s}} + \Delta\theta_i) + \\ & \int (Q_{ij,\mathrm{s}} + \Delta Q_{ij})\,\mathrm{d}(\ln U_{i,\mathrm{s}} + \ln U_i - \ln U_{i,\mathrm{s}}) \end{aligned} \tag{6}$$

Where, $P_{ij,\mathrm{s}}$ and $Q_{ij,\mathrm{s}}$ are steady-state values of the active power and the reactive power of Branch L_{ij} at each time, respectively; ΔP_{ij} and ΔQ_{ij} are the relative change values of the active power and the reactive power at each time to the steady-state power values, respectively; $\ln U_i$ and $\ln U_{i,\mathrm{s}}$ are the natural logarithm of the fluctuating voltage and the voltage steady-state values at each time of Bus i, respectively.

The Equation (6) can be further transformed to Equation (7).

$$\begin{aligned} E_{ij} &= \int P_{ij,\mathrm{s}}\mathrm{d}\Delta\theta_i + \int Q_{ij,\mathrm{s}}\mathrm{d}(\ln U_i - \ln U_{i,\mathrm{s}}) + \\ & \int \Delta P_{ij}\mathrm{d}\theta_{i,\mathrm{s}} + \int \Delta Q_{ij}\mathrm{d}(\ln U_{i,\mathrm{s}}) + \\ & \int P_{ij,\mathrm{s}}\mathrm{d}\theta_{i,\mathrm{s}} + \int Q_{ij,\mathrm{s}}\mathrm{d}(\ln U_{i,\mathrm{s}}) + \\ & \int \Delta P_{ij}\mathrm{d}\Delta\theta_i + \int \Delta Q_{ij}\mathrm{d}(\ln U_i - \ln U_{i,\mathrm{s}}) \end{aligned} \tag{7}$$

From equation (7), the energy components contained in the transmitted energy by the branch are classified, and the discretization formula will be given.

1) State energy

The state energy of Branch Lij is defined in Equation (8).

$$\begin{aligned} E_{\mathrm{sta}} &= \int P_{ij,\mathrm{s}}\mathrm{d}\theta_{i,\mathrm{s}} + \int Q_{ij,\mathrm{s}}\mathrm{d}(\ln U_{i,\mathrm{s}}) \\ &= \sum_{k=2}^{n} [P_{\mathrm{s},k}(\theta_{\mathrm{s},k} - \theta_{\mathrm{s},k\text{-}1}) + \\ & Q_{\mathrm{s},k}(\ln U_{\mathrm{s},k} - \ln U_{\mathrm{s},k\text{-}1})] \end{aligned} \tag{8}$$

Where, n is the number of electric quantity sampling points within the calculation time period.

The state energy is the energy that corresponds to the change of the steady-state operation point of the branch. The energy can be absorbed by the branch, and then it appears a new steady-state point. If the steady-state operation point is no longer adjusted, the state energy remains unchanged.

2) Dissipation energy

The dissipation energy of Branch Lij is defined in Equation (9).

$$\begin{aligned} E_{\mathrm{dis}} &= \int \Delta P_{ij}\mathrm{d}\Delta\theta_i + \int \Delta Q_{ij}\mathrm{d}(\ln U_i - \ln U_{i,\mathrm{s}}) \\ &= \sum_{k=2}^{n} [(P_k - P_{\mathrm{s},k})(\theta_k - \theta_{\mathrm{s},k} - \theta_{k-1} + \theta_{\mathrm{s},k-1}) + \\ & (Q_{ij,k} - Q_{\mathrm{s},k})(\ln U_k - \ln U_{\mathrm{s},k} - \ln U_{k-1} + \ln U_{\mathrm{s},k-1})] \end{aligned} \tag{9}$$

The dissipation energy has a definite flow direction and it is generated by the disturbance source and consumed by the damping components. The dissipation energy can reflect the location of the oscillation source and the damping properties of components in the grid network.

3) Reciprocating oscillation energy

The adjustment of the steady-state operation point and the propagation of the dissipative energy are along with the reciprocating oscillation. The reciprocating oscillation energy of Branch Lij is defined in Equation (10).

$$\begin{aligned} E_{\mathrm{rec}} &= \int P_{ij,\mathrm{s}}\mathrm{d}\Delta\theta_i + \int Q_{ij,\mathrm{s}}\mathrm{d}(\ln U_i - \ln U_{i,\mathrm{s}}) + \\ & \int \Delta P_{ij}\mathrm{d}\theta_{i,\mathrm{s}} + \int \Delta Q_{ij}\mathrm{d}(\ln U_{i,\mathrm{s}}) \\ &= \sum_{k=2}^{n} [P_{\mathrm{s},k}(\theta_k - \theta_{\mathrm{s},k} - \theta_{k-1} + \theta_{\mathrm{s},k-1}) + \\ & Q_{\mathrm{s},k}(\ln U_k - \ln U_{\mathrm{s},k} - \ln U_{k-1} + \ln U_{\mathrm{s},k-1}) + \\ & (P_k - P_{\mathrm{s},k})(\theta_{\mathrm{s},k} - \theta_{\mathrm{s},k-1}) + \\ & (Q_{ij,k} - Q_{\mathrm{s},k})(\ln U_{\mathrm{s},k} - \ln U_{\mathrm{s},k-1})] \end{aligned} \tag{10}$$

The reciprocating oscillation energy can be understood as the carrier of energy transmission. It does not propagate in a certain direction, but periodic reciprocating flow. The curve of the reciprocating oscillation energy wave is symmetrical. Its symmetry axis is almost horizontal and the average energy is close to zero.

C. Disturbance source localization criterion

In a low frequency oscillation, the dissipation energy is generated by the negative damping component. It is consumed in the positive damping component along with the oscillation energy flowing into the grid network. If the total system energy consumption is greater than the energy generation, then the system oscillation amplitude decreases gradually. If the energy consumption is less than the energy generation, the system oscillation amplitude increases. When the energy consumption is equal to the energy generation, the system behaves as an equal amplitude oscillation [10].

The dissipation energy of generators, lines and loads can be calculated by using Equation (9). If the transmitted dissipation energy of Line L_{ij} from Bus i to Bus j is positive, the disturbance source is closer to Bus i. Referring to the cut set concept proposed in Reference [16], the entire power grid can be divided into system A and system B . If the total dissipation energy of the entire cut set flows from system A to system B, it indicates that the disturbance source is inside system A. And then, the subsystem can be further divided into more subsystems, and the suspicious area of the disturbance source can be further reduced. If the dissipation energy transmitted outward from a generator terminal is positive, it indicates that the generator is a disturbance source. If the dissipation energy is negative, it indicates that the generator is a non-disturbance source.

IV. IDENTIFICATION OF THE STEADY-STATE OPERATION POINT

To calculate each energy component, the steady-state operation points of multiple electrical quantities at each time need to be identified, including the branch active power and the branch reactive power, the bus voltage amplitude and angle. Among them, the active power, the reactive power and the bus voltage amplitude have obvious extremum points, generally. The steady-state operation point can be obtained from the residual component calculated by the empirical mode decomposition method approximately [21]. However, the steady-state operation points change more rapidly in some low frequency oscillations, and the bus voltage may have no maximum and minimum values. So, the calculation condition by using the empirical mode decomposition may not be satisfied. Therefore, it is necessary to propose a better steady-state operation point identification method.

In the oscillation process, the electrical quantities symmetrically fluctuate around the steady-state operation point. A steady-state point time-varying low frequency oscillation appears as a form of superposition of a free component and a forcing component. It can be approximated that the central axis of the oscillation curve is its steady-state operation point, and the oscillation axis can be obtained by fitting the upper envelope and the lower envelope of the oscillation curve. The process of the steady-state point identification includes three steps, i.e. the "turning point" identification, the envelopes fitting and the central axis calculation of the oscillation curve.

A. The "turning point" identification of the oscillation curve

In a low frequency oscillation with the time-varying steady state point, some oscillation curves have obvious maximum and minimum values, and some curve slopes are always positive. When the upper envelope and the lower envelope of a oscillation curve is fitted, it requires crossing the turning points of the curve, which are the points that the slope changes most rapidly during an oscillation period. In Equation (11), the tangent slope $f'(t_i)$ and the tangent slope change rate $f''(t_i)$ of the ith sampling point can be represented approximately in the form of the first order difference and the second order difference.

$$\begin{cases} f'(t_i)=\dfrac{f(t_{i+1})-f(t_i)}{t_{i+1}-t_i} \\ f''(t_i)=\dfrac{f'(t_{i+1})-f'(t_i)}{t_{i+1}-t_i} \end{cases} \quad i=1,2\cdots n \tag{11}$$

Where, t_i is the time corresponding to the ith sampling point of an electrical quantity; $f(t_i)$ is the value of the ith sampling point.

Under a low-frequency oscillation with the time-varying steady state point, the terminal voltage angle oscillation curve and the slope rate change curve of some a unit in the time span of 25s to 30s is shown in Fig. 1. In Fig.1, the terminal voltage angle is normalized. The method is that each data value is divided by the average voltage angle and the result is further obtained by subtracting 1. For observation convenience, the slope change rate is magnified by five times.

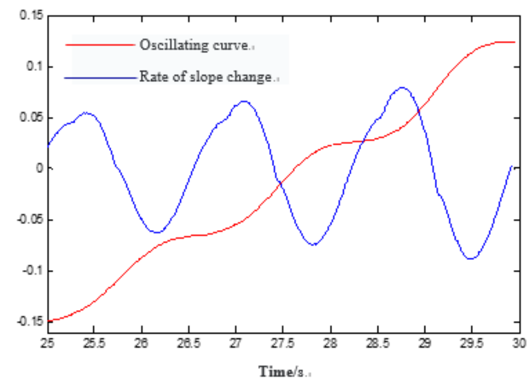

Fig. 1. The oscillation curve and the slope change rate curve.

From Fig. 1, the tangent slope change rate at the "turning point" of the upper envelope shown in first line of Equation (12) is the minimum value point. The tangent slope change rate at the "turning point" of the lower envelope shown in second line of Equation (12) is the maximum value point. According to the criterion, the "turning point" of the oscillation curve can be calculated.

$$\begin{cases} f'(t_{i-1}) > f'(t_i) < f'(t_{i+1}) \\ f'(t_{i-1}) < f'(t_i) > f'(t_{i+1}) \end{cases} \tag{12}$$

B. Envelope fitting and steady-state point calculation

It is assumed that the "turning points" number in the upper envelope of the oscillation curve is m, which can be expressed as $\left[t_k, f(t_k)\right](k=1,2\cdots m)$. In Equation (13), the cubic spline interpolation function $S_{\mathrm{up}}(t)$ is constructed to get the upper envelope of the oscillation curve.

$$\begin{gathered} S_{\mathrm{up}}(t)=a_k t^3+b_k t^2+c_k t+d_k \\ t\in\left[t_k, t_{k+1}\right] \quad k=1,2\cdots m\text{-}1 \end{gathered} \tag{13}$$

The undetermined coefficients can be calculated according to the interpolation conditions, the continuity conditions and the boundary conditions [22]. The lower envelope of the oscillation curve, i.e. $S_{\mathrm{down}}(t)$, can be obtained by using the same calculation method as that of the upper envelope.

The median value of the upper envelope and the lower envelope calculated by using the cubic spline interpolation function is taken as the steady-state operation point. For example, the active power steady-state point at time t_i, i.e. $P_{s,i}$, can be calculated according to Equation (14).

$$P_{s,i}=\frac{S_{\mathrm{up}}(t_i)+S_{\mathrm{down}}(t_i)}{2} \tag{14}$$

V. Example Verification

North China Power Grid is taken as an example, and the proposed methods, i.e. the steady-state point identification, the energy decomposition and the disturbance source localization, are verified in the paper. The unit of Tianjin Panshan plant is set to be a disturbance source, and the plant damping is weakened by modifying the parameters of the generator control system and increasing the outgoing line reactance of the power plant. To simulate a negative damping oscillation, a fault-free disconnection is set on one of three outgoing lines of the plant. At the beginning of the oscillation, the mechanical power of 5 units is increased by closing the valves quickly. The climbing speeds of generators are divided into 3 sections, i.e. 0.92% rated power per second from 0s to 7s, 0% rated power per second from 7s to 12s, 1.67% rated power per second from 12s to 18s.

A. Steady-state point identification

The forgoing method descripted in the paper is used to identify the steady-state point of the bus voltage, the phase angle and the active power and reactive power transmitted in lines. The electromagnetic power steady state point identification of Unit 1 in Panshan plant is taken as an example. According to the acceleration and deceleration principle of a generator rotor, it can be considered that the electromagnetic power of a generator fluctuates around the mechanical power, and the mechanical power can be taken as the real steady-state operation point of the electromagnetic power. The mechanical power curve and the identified electromagnetic power steady-state point curve are shown in Fig. 2.

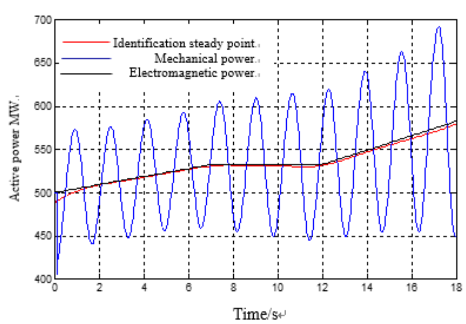

Fig. 2. Comparison chart of the actual steady point and the identified steady point.

From Fig. 2, the identified steady-state operation point by using the electromagnetic power curve is almost the same as the actual one. The deviation of the initial oscillation stage is caused by the fault disturbance, and the oscillation data from 0.5s to 1.0s at the beginning can be eliminated in the actual calculation.

B. Energy decomposition of unit 1 in Panshan plant.

According to Equation (8) to Equations (10), the state energy, the reciprocating oscillation energy and the dissipation energy of unit 1 in Panshan plant are calculated. The energy waveform is shown in Fig. 3.

From Fig. 3, the mechanical energy of Unit 1 in Panshan plant changed greatly during the oscillation, and the drift

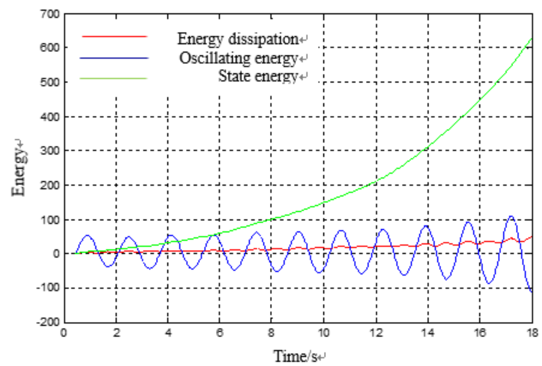

Fig. 3. Energy decomposition curve.

amplitude of the electromagnetic power, the reactive power and the voltage phase angle is relative large. The state energy value becomes larger with the time. However, the reciprocating oscillation energy fluctuates almost symmetrically around the horizontal zero axis and it does not flow toward a definite direction, which is consistent with the analysis results in the paper. The dissipation energy is the real one that can truly reflect the damping characteristics of units. The dissipation energy of unit 1 in Panshan plant is obviously greater than zero, which indicates that the unit is the disturbance source. The obtained results are consistent with the presupposition in the example.

C. Energy decomposition of unit 1 in Guohua plant

The state energy, the reciprocating oscillation energy and the dissipation energy of unit 1 in Guohua plant are illustrated in Fig.4.

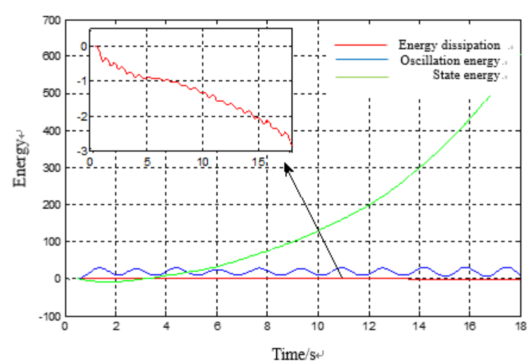

Fig. 4. Energy decomposition curve.

In the oscillation process, the electromagnetic power and the reactive power curve of unit1 in Guohua plant has a certain degree of drift, but the drift amplitude is small. The main reason why the state energy increases significantly is that the terminal voltage angle drifts by big margin with the system oscillation. The reciprocating oscillation energy oscillates symmetrically at a level slightly higher than the zero axis, and it indicates that the average reciprocating oscillation energy is zero in most of the oscillation time. The overall curve level is raised only at the beginning of the oscillation stage because of the existence of the slightly larger positive energy. The dissipation energy value of unit 1 in Guohua plant is less than 0, and it has a significant downward trend by magnifying the view. The results show that unit 1 in Guohua plant absorbs dissipation energy and it is not a disturbance source, which is consistent with the expected result.

VI. CONCLUSIONS

Existing low frequency oscillation location methods have poor adaptability to the low frequency oscillation with time-varying steady-state points, and a new disturbance source location method is presented in the paper. In this method, the branch transmission energy is decomposed into state energy, reciprocating energy and dissipation energy by mathematical derivation. The flow direction of the dissipation energy shows the source and destination of the disturbance energy, and the specific location of a disturbance source can be identified according to its flow direction. At the same time, a recognition method on the electrical quantities steady-state points is also presented by using the cubic spline interpolation. An actual system of North China Power Grid is used for simulation verification. Simulation results show the correctness of the derivation and analysis on energy structure in the paper, and the disturbance source of the low frequency oscillation with time-varying steady-state points can be located accurately according to the dissipation energy.

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