1 INTRODUCTION

With the continuous expansion of power grid interconnection scale, the low frequency oscillation has become an important problem threatening the security and stability of power grid. The essence of the low frequency oscillation is the relative motion between different generator rotors, and the oscillation frequency and the oscillation phase difference between the rotors are relatively fixed. Influenced by the relative oscillation of the rotors, the line power and the bus voltage, frequency will appear to be different degrees of the same frequency oscillation [1-3]. In the case of no removal of disturbance source, the oscillation will continue to exist and may result in the instability of the power system [4-5].

After the low frequency oscillation, the main problem is to locate the disturbance source quickly and accurately. The on-line identification of disturbance source based on the wide area measurement system (WAMS) is a research hotspot in the field of low frequency oscillation monitoring and control. Literature [6-8] proved the consistency of generator energy consumption and its damping torque, and put forward a practical method for calculating the energy flow to judge the disturbance source based on energy consumption and production. Literature [9-10] constructed the network cut sets in different levels based on the WAMS dynamic information of key lines, and judged the cut set whose oscillation energy flows out as an oscillation source. Literature [11] extracted the dominant component of the electrical quantity by the method of empirical mode space filtering and automatically identified the disturbance source by the empirical mode energy trend function. At present, the configuration of the phasor measurement unit (PMU) is not complete, and the electrical quantity information of the whole network can’t be obtained completely. So, the research on the method of disturbance source locating based on the local information is of great significance.

Oscillation is a physical phenomenon, which exists widely in nature, and its essence is a form of energy...
transmission. In physical oscillations, there are certain phase differences among the material elements along the propagation direction of oscillation wave, and the phase of material elements near the source is ahead of the phase of material elements away from the source. The low frequency oscillation of power system is also a kind of physical oscillation, and the oscillation generator unit is equivalent to the wave source which is an active oscillation. The non-oscillation generator units are equivalent to the material elements which are affected by the source. This paper analyzes the oscillation phase distribution of different points in the tie-line based on the simplified model of two machine oscillation. Then, a disturbance source location method is proposed based on the phase difference and the applicability of this method in multi-machine oscillation system is verified. This paper can accurately calculate the instantaneous oscillation phase of each point by the method of Hilbert-Huang transform (HHT) and realizes the location of the disturbance source only by one kind of electric quantity, which is more simple and intuitive than other disturbance source location methods.

2 DISTURBANCE SOURCE LOCATION METHOD

2.1 Overview of disturbance mechanism

In a power network, any power generated by the generator is the phasor difference function of the generator electromotive force relative to the other generators electromotive force, which can be shown in the formula (1).

\[ P_e = E_i^2 G_{ii} + E_i \sum_{j \neq i} E_j |Y_{ij}| \sin(\delta_{ij} + \beta_{ij}) \]  

\[ \beta_{ij} = \arctan\left(\frac{G_{ij}}{B_{ij}}\right) \]  

In the formula (1), \( P_{ei} \) is electromagnetic power of generator \( i \); \( E_i \) and \( E_j \) are the electromotive force of \( i \) and \( j \), respectively; \( Y_{ij} \) is the mutual admittance between the node of \( i \) and \( j \); \( G_{ii} \) is Self-conductance for the generator \( i \); \( |Y_{ij}| \) is modulus value for \( Y_{ij} \); \( n \) is the total number of generators; \( \delta_{ij} \) is the angle between \( E_i \) and \( E_j \).

According to formula (1), the active oscillation of the rotor of the disturbance source unit will affect the electromagnetic power of the disturbed units, which leads to the unbalanced torque and forced oscillation of the rotor of the disturbed unit. When the electromagnetic force of the disturbance source unit increases, the electromagnetic power of the disturbed unit will be reduced. Whose mechanical torque will be greater than the electromagnetic torque, thus the power angle of the perturbed unit also began to increase and tends to bring into correspondence with the angular deviation of the rotor of the two machine that is consistent with the initial value. In the process of oscillation, the rotor angle of the disturbed unit is always chasing after the angle of the rotor of the disturbance source unit and because of the existence of the inertia of the rotor, the oscillation phase lags behind disturbance source unit.

Because the formula (1) contains the mutual admittance between the nodes, therefore, the electromagnetic power of generator is mainly affected by the electromotive force phase near the unit. In the process of oscillation, the main influence of the disturbance source is on the nearby units, when the nearby units are disturbed, the remote units are further affected, and along the propagation direction of the oscillating energy, the oscillation phase of the generator rotors lags in turn. In the case of the same conditions, the smaller the electrical distance between the units is, the greater the mutual synchronization force is and the smaller the oscillation phase difference is.

For the low frequency oscillation caused by local disturbance source, the oscillation phase difference between the disturbance source and the near zone unit is less than \( \pi \), which may be more than \( \pi \) compared with the remote unit. But the distance unit is not directly relative to the source of the disturbance, which is mainly influenced by the phase leading units in the vicinity. Therefore, in the multi machine oscillation system, the oscillation phase distribution relationship between the disturbance source unit and each disturbed unit can be analyzed based on the two machine oscillation model whose oscillation phase difference is between \( 0-\pi \).

2.2 Analysis of Oscillation phase

Figure 1 is the simplified model of two machines oscillation, \( E_M \) and \( E_N \) are the equivalent electromotive force of generators on two sides. In this model, the reactance of the tie-line MN is evenly distributed and each part of the impedance angle is equal.

Assuming that the M side unit is a disturbance source, and the oscillation phase difference of generators on two sides is \( \phi (0<\phi<\pi) \). In order to simplify the theoretical analysis, the assumptions are \( E_M=E_N=1 \), equal amplitude oscillation, and both of the amplitudes are \( A \).
In the formula (3), $E_M$ and $E_N$ are the equivalent electromotive force of the M side and the N side, respectively; $\delta_M$ and $\delta_N$ are the initial angle of equivalent electromotive force on the M side and the N side; $\omega_0$ is the rated angular velocity of the system; $A$ is the fluctuation amplitude of the equivalent electromotive force on the M side and the N side; respectively; $E_{M0}$ and $E_{N0}$ are the electromotive force of the M side and the N side, respectively.

Where: $\delta_b = \delta_M - \delta_N$.

In the formula (3), $E_M$ and $E_N$ are the equivalent electromotive force of the M side and the N side, respectively; $\delta_M$ and $\delta_N$ are the initial angle of equivalent electromotive force on the M side and the N side; $\omega_0$ is the rated angular velocity of the system; $A$ is the fluctuation amplitude of the equivalent electromotive force angle.

Assuming that the initial angle of the electromotive force on the N side is 0, and the influence of the rated angular velocity is ignored. The instantaneous angle of force on the N side is 0, and the influence of the rated force angle.

$$\begin{align*}
\delta_M &= \delta_0^M + A \sin (bt + \varphi) \\
\delta_N &= A \sin (bt)
\end{align*}$$

In the Figure 2, $0 \leq \delta \leq \pi$, the point S is on the tie-line corresponding to the $k\delta$, the instantaneous angle of point S can be got in the formula (5).

$$\delta = k [\delta_0 + A \sin (bt + \varphi)] + A \sin (bt) = k \delta_0 + A [k \cos \varphi + 1 - k] \sin (bt) + Ak \sin \varphi \cos (bt)$$

In the formula (5):

$$\begin{align*}
\sin \varphi' &= \frac{Ak \sin \varphi}{A'} \\
\cos \varphi' &= \frac{A'[k \cos \varphi - 1] + 1}{A'} \\
\varphi' &= \arctan \left( \frac{k \sin \varphi}{k \cos \varphi + 1 - k} \right) \\
A' &= A \sqrt{k^2 + 2k(1-k) \cos \varphi + (1-k)^2}
\end{align*}$$

In the formula (5) and formula (6), $\varphi'$ is the initial oscillation phase of the voltage angle corresponding to $k\delta$. The range of the arc-tangent function is $(-\pi/2, \pi/2)$, and the arc-tangent function is meaningless when $k=1/(1-\cos \varphi)$. So, the actual change of $\varphi'$ is analyzed with the sine and cosine values. The differential function of $\varphi'$ can be shown as the formula (7).

$$\frac{d\varphi'}{dk} = \frac{\sin \varphi}{k^2 + 2k(1-k) \cos \varphi + (1-k)^2}$$

$$f(k) = k^2 + 2k(1-k) \cos \varphi + (1-k)^2 = (2 - 2 \cos \varphi)k^2 + (2 \cos \varphi - 2)k + 1$$

In the formula (8), when $k=0.5$, $f(k)_{\text{min}}=0.5(1+\cos \varphi)\geq 0$. Then, the changes of $\varphi'$ are discussed as follows:

1) When $0 \leq \varphi < \pi/2$, the sine and cosine values of $\varphi'$ are greater than 0. So, $\varphi'$ is in the first quadrant and $d\varphi'/dk > 0$, and the value of $k$ will increase with $\varphi'$.

2) When $\pi/2 \leq \varphi \leq \pi$, $g(k) = k(\cos \varphi - 1) + 1$, the value of $g(k)$ will decreases when $k$ increases, and value of $g(k)$ will value from positive to negative when $k=1/(1-\cos \varphi)$; Because $k \sin \varphi > 0$, $\varphi'$ is in the first or the second. Because $d\varphi'/dk > 0$, the value of $\varphi'$ will increases when $k$ increases.

To summarize, the oscillation phase of the $k\delta$ corresponding node will be advanced gradually. Therefore, in any moment of oscillation, the oscillation phase of the node voltage angle will change with the change of K value monotonically. The instantaneous oscillation phase difference of the voltage angle of any two nodes on the tie-line must have a single lead or lag relationship at any time after the start of the oscillation. The instantaneous frequency of point S can be obtained by the formula (5) and the oscillation phase is coincident with the voltage angle.

2.3 The disturbance source location criteria

In summary, the following criteria can be used to locate the disturbance source:

1) Local information criterion of power plant: the oscillation phase of the rotor angle (frequency) of the disturbance source unit should be ahead of the oscillation phase of the voltage angle (frequency) of the booster transformer; the oscillation phase of the rotor angle (frequency) of non-disturbance source units should lag behind the oscillation phase of the voltage angle (frequency) of the booster transformers.

2) Network information criterion: for a transmission line connecting the disturbance source and the external network, the oscillation phase of the voltage angle (frequency) of the bus near the disturbance source should be ahead of the oscillation phase of the voltage angle (frequency) of the bus away from the disturbance source.

Oscillation phase difference is a variable with directivity and the disturbance source can be identified only by the local electrical quantity information of power plant. So, according to the first criterion, in the absence of the network information and the information of the rest power plant, the disturbance source units can still be able to locate accurately. In the case
that part of network information can be obtained, the source of the oscillation energy can be judged according to the second criterion, and the suspicious area of the disturbance source can be judged.

In the process of the low frequency oscillation, the factors such as the network structure mutation may cause short-term chaos of the oscillation phase. So, the PMU data often contains much interference signals. These factors may affect the calculation results of the oscillation phase in a relatively short time, so it is difficult to ensure the accuracy of the results by comparing with the oscillation phase of individual moment. In order to accurately describe the overall phase relation of two points in a period of time, the oscillation phase difference is defined in the formula (9).

\[
\Delta \theta = \int_{t_1}^{t_2} (\theta_1 - \theta_2) \, dt
\]  

(9)

In the formula (9), for the local information criterion of power plant, \(\theta_1\) and \(\theta_2\) are the rotor angle (frequency) and the voltage angle (frequency) oscillation phase, respectively; For the network information criterion, \(\theta_1\) and \(\theta_2\) are the voltage angle (frequency) oscillation phase of the buses on the two sides, and \(t_1\) and \(t_2\) are the start time and the end time of calculation, respectively.

3 THE CALCULATION OF OSCILLATION PHASE DIFFERENCE

3.1 Hilbert-Huang Transform (HHT)

Power system is a nonlinear dynamic system, and the oscillation data may contain multiple oscillation modes, however, the phase of the composite signal has no physical meaning. What’s more in the process of oscillation, the steady state frequency of the whole network often deviates from the rated frequency. The oscillation curve of the voltage angle and frequency will be shifted by the relative horizontal axis, which is difficult to calculate the phase. Therefore, it is necessary to identify and decompose the oscillation data, and then calculate the phase of the main oscillation mode.

HHT includes two parts, the first part is the empirical mode decomposition (EMD), and the second part is the Hilbert transform (HT). EMD is an adaptive signal processing in time-frequency method, which can decompose the complex signal into a finite number of intrinsic mode function (IMF) components and residual components. That is shown in formula (10).

\[
x(t) = \sum_{i=1}^{s} \text{IMF}(i) + r(t)
\]

(10)

In the formula (10), \(x(t)\) is the original signal, \(r(t)\) is the residual component, \(\text{IMF}(i)\) is the intrinsic mode function.

Each IMF component must meet the following 2 conditions: (1) In the whole data segment, the number of extreme points and the number of zeros must be equal or at most differs 1. (2) At any point of time, the envelope formed by local maximum value point and the envelope formed by local minimum value point, and the average value is 0. The instantaneous phase of component IMF has clear physical meaning and takes the dominant component to take the Hilbert transform.

A real continuous signal \(u(t)\) is transformed to an orthogonal conjugate signal \(v(t)\) by Hilbert transform and its orthogonal conjugate signal \(v(t)\) is obtained in the formula (11).

\[
v(t) = \frac{1}{\pi} \int_{-\pi}^{\pi} \frac{u(t)}{t-\tau} \, d\tau
\]

(11)

The signal from the original signal and the transformed signal can form a complex signal in the formula (12).

\[
q(t) = u(t) + iv(t)
\]

(12)

\[
\theta(t) = \arctan \frac{v(t)}{u(t)}
\]

(13)

In the formula (13), \(\theta(t)\) is the instantaneous phase of the original signal \(u(t)\).

3.2 Calculate the start time

In the initial stage, the power grid has just been disturbed, and the oscillation is not stable and the phase may be more chaotic, so the calculation of the Hilbert-Huang transform should be taken after the disturbance occurred 1~2 cycles. Because the signal is periodic oscillation, the oscillation phase is changed in phase \(-\pi\sim\pi\), which is obtained by Hilbert transform. And if the phase is to \(\pi\), \(\pi\) will be reset to the \(-\pi\). In a short period of time after the phase reset, the original signal is less than the backward signal in the phase value. Therefore, if the calculation of the initial time of the oscillation phase difference is not proper, it may get the opposite result.

The phase difference between the nodes, which are close to each other, can be calculated by this method, so the position differences of the phase curve are not too large. The reset point for one of the signals is an observation point. If the reset at the left in the vicinity of the other signal, and the point of observation as starting point calculation; if in the right another nearby signal reset, and another signal reset points as calculation starting point. In order to calculate the overall phase difference of the oscillation period, the instantaneous phase of the system is taken as a no cycle numerical value. That is, after the first \(n\) back to \(-\pi\), and then a period of data are added \(2\pi\).

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4 EXAMPLE ANALYSIS

This chapter takes an actual power grid as an example to verify the applicability of the method to the low frequency oscillation. Weaken the damping of JY power plant by changing the control system parameters and the outlet reactance and set up the non-fault tripping in one outgoing line of JY power plant to cause the low frequency oscillation. The 500kV network structure of this actual power grid is shown in Figure 3.

Using the local information of the power plant to search for the disturbance source unit, the per unit voltage angle of the rotor of 1# unit and the high-voltage side of the booster transformer in the JY power plant is shown in the Figure 4.

Careful observation of Figure 4 and Figure 5 shows that, the rotor angle of 1# unit in JY power plant reaches the maximum or minimum value earlier than the voltage angle of the high-voltage side of the booster transformer. But, the rotor angle of 1# unit in GD power plant reaches the maximum or minimum value later than the voltage angle of the high-voltage side of the booster transformer. The oscillation phase of the dominant oscillation mode is calculated by HHT, and the 2th second after the oscillation is regard as the start time. The results of the calculation are shown in Figure 6 and Figure 7.

The per unit voltage angle of the rotor of 1# unit and the high-voltage side of the booster transformers in the GD power plant is shown in the Figure 5.

The oscillation phase difference between the rotor and the booster transformer of 1# unit in JY power plant is small, but this difference can be observed obviously and the oscillation phase of the rotor angle is ahead of the high-voltage side of booster transformer when the diagram is magnified. While, the oscillation phase of the rotor angle of 1# unit in GD power plant lags behind the oscillation phase of the high-voltage side of booster transformer. Calculating the oscillation phase difference of two units in the simulation time, the start time of 1# unit in JY power plant is 1.23s and the start time of 1# unit in GD power plant is 1.56s. The calculation results are shown in Figure 8. According to the disturbance source location
criterion, the disturbance source unit is the 1# unit in JY power plant.

![Figure 8. Oscillation phase difference.](image)

In the case of partial network information, the orientation of the disturbance source can be determined. Calculating the oscillation phase difference of 4 transmission lines, such as the SC-CQ lines, CE-MC line and the JE-NT line, the results are shown in the Table 1.

<table>
<thead>
<tr>
<th>Lines</th>
<th>Oscillations phase difference</th>
<th>Orientation judgment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HY-WX</td>
<td>201.5</td>
<td>HY</td>
</tr>
<tr>
<td>HG-BQ</td>
<td>338.2</td>
<td>HG</td>
</tr>
<tr>
<td>CE-MC</td>
<td>1048.1</td>
<td>CE</td>
</tr>
<tr>
<td>JE-NT</td>
<td>1108.8</td>
<td>JE</td>
</tr>
</tbody>
</table>

Comparing the oscillation phase difference of voltage angle of the buses at both ends of the transmission line, the oscillation phase of the end near the disturbance source is ahead of the end away from the disturbance source. So, the orientation of the disturbance source can be determined according to the network information.

5 CONCLUSIONS

This paper puts forward a method for locating the low frequency oscillation disturbance source based on the oscillation phase difference. The mechanism that how the disturbance source unit affects the other units is analyzed. Based on the simplified model of two machine oscillation, the phase distribution characteristic that the oscillation phase of voltage angle and frequency of units near the disturbance source is ahead of the units away from the disturbance source is verified. By means of the HHT, the instantaneous phase of the dominant oscillation mode can be calculated accurately and the disturbance source unit can be located according to the phase relation of the local electric quantity of the power plant. In order to avoid the short-time disturbance affected by the network structure mutation or the data quality, the overall oscillation phase relation can be quantified by calculating the oscillation phase difference. The simulation results of the actual power grid show that this method is of good accuracy and has potential value of engineering application.

REFERENCES