An Oscillation Energy Calculation Method Suitable for the Disturbance Source Location of Generator Control Systems

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Abstract. Low frequency power oscillation threatens the secure and stable operation of power systems. Since the appearance of low frequency oscillation there are lots of approaches to analyze this problem. The oscillation source location method based on oscillation energy is adopted to find the cause of the oscillation, and to locate the oscillation source. Forced power oscillation is a kind of low frequency oscillation based on resonance mechanism, and the key is to quickly locate and remove the disturbance source. Aiming at the shortcomings of the existing disturbance source location methods, an oscillation energy calculation method suitable for the generator control systems level location is proposed. With the rich acquisition of generator data by means of phasor measurement unit (PMU), this method has the advantage of not relying on generator parameters. Taking the forced power oscillation caused by the abnormality of the governor system as an example, the superiority of the method is verified.

1. Introduction

The forced power oscillation is generated since there is a periodically varying disturbance source in the system, causing the power oscillation of the system in the same period. When the frequency of the disturbance source is close to the frequency of a certain natural oscillation mode in the system, it causes resonance and further exacerbates the oscillation. In practice, there have been many cases of forced power oscillations caused by pressure pulsation, poor valve flow characteristics, excessive frequency regulation, and abnormal excitation system [1]. In general, if the location of the disturbance source can be quickly found when an oscillation occurs, effective measures can be taken to quickly eliminate the oscillation. So far, scholars have proposed a variety of disturbance source localization techniques, including traveling wave-based methods, damping torque-based methods, mode shape estimation-based methods, energy-based methods and so on [2]. Among these methods, the energy-based method is the most promising one and has been successfully applied in many dispatch systems.

In literature [3], Chen et al. proposed an energy-based disturbance source location method, which relies only on wide-area measurement system (WAMS) data and is suitable for natural oscillations with weak damping and forced oscillations with external disturbances. Although the location result of this method is greatly affected by the load model [4], it is still extended to the quantitative evaluation of the generator damping level [5-6]. After verification by simulation examples [7], the energy-based method in [3] can achieve accurate location in the case where multiple disturbance sources coexist.
Despite the establishment of rigorous theoretical derivation, the examples in [3] are based on simulated data rather than real PMU recordings. In order to enhance the robustness and adaptability, the modification of the energy-based method is proposed, considering the oscillation mode of interest by filtering [8-9]. In order to improve the location accuracy of the energy-based method, it is necessary to extract the dominant component reflecting the oscillation source characteristic from the electrical quantities recorded by PMU. Three algorithms of Prony [10], empirical mode decomposition (EMD) [11] and fast Fourier transform (FFT) [12] are applied to extract the dominant component of oscillations separately and serve as the basis for the calculation of oscillation energy.

The use of oscillation energy to locate the disturbance source is a two-level problem, the generator level [3-12] and control system level [13-18]. By constructing the oscillation energy function flowing into the generator's field winding, Chen et al. proposed an approximate calculation formula for the dissipated energy flowing into the prime mover system [13]. Compared with [13], Li et al. derived the expression of the oscillation energy flowing into the control systems, and considered the influence of the damper windings [14-15]. According to Li's method, Guo et al. applied it to a case of forced power oscillation caused by an excitation system abnormality [16], which shows that the method has good applicability to real PMU data. However, the oscillation energy solved by Li's method is the sum of the entire power oscillations, and does not distinguish different oscillation modes and corresponding oscillation energy. In order to reduce the influence of non-dominant components on the calculation of oscillation energy, FFT [17] and total least square estimation of signal parameters via rotational invariance techniques (TLS-ESPRIT) [18] are used to extract the dominant components respectively and calculate the oscillation energy of the control device level. The energy function structure of the former [17] has errors, while the energy function structure of the latter [18] is not intuitive for PMU data.

By means of the digital realization of the synchronous generator phasor diagram in PMU, an oscillation energy calculation method for control systems independent of the generator parameters is proposed in this paper, and the influence of the dominant mode in the oscillation process is considered. Using a field case, the superiority of the method is proved.

2. Oscillation energy for control systems

Li et al. analyzed the internal energy structure of the generator [14-15], and split the transient energy injected into two components, corresponding to the governor system and the excitation system. These two components are used as indicators for determining the control systems where the disturbance source is located:

\[ W_{i}^{gov} = \int P_{i} \delta_{i} dt \]  \hspace{1cm} (1)

\[ W_{i}^{exc} = \int (I_{di} \dot{U}_{qi} - I_{qi} \dot{U}_{di}) dt \]  \hspace{1cm} (2)

With

\[ \delta_{i} = \frac{d\delta_{i}}{dt} \]  \hspace{1cm} (3)

\[ \dot{U}_{di} = \frac{dU_{di}}{dt} \]  \hspace{1cm} (4)

\[ \dot{U}_{qi} = \frac{dU_{qi}}{dt} \]  \hspace{1cm} (5)

Where \( P_{i} \) and \( \delta_{i} \) are the active power and power angle of the \( i \)th generator, \( U_{di} \) and \( U_{qi} \) are the \( d \)-axis and \( q \)-axis components of the terminal voltage \( U_{i} \), \( I_{di} \) and \( I_{qi} \) are the \( d \)-axis and \( q \)-axis components of the terminal current \( I_{i} \).
Since the variables in (1) and (2) cannot be used for direct calculation, Li et al. conducted a complicated derivation and proposed a calculation formula that depends on the generator reactance parameters. The details can be found in [14].

3. The new oscillation energy calculation method

3.1. The mathematical relationship in phasor diagram of generator

According to the principle of synchronous generator, the electrical quantity in the form of phasor is shown in Figure 1. \( \delta \) is the power angle, \( \varphi \) is power factor angle. \( E_q \) is generator internal potential, \( U \) is the terminal voltage, \( I \) is the terminal current, \( r \) is stator resistance. \( x_d \) and \( x_q \) are \( d \)-axis and \( q \)-axis synchronous reactance.

![Figure 1. The phasor diagram of synchronous generator.](image)

\[
\varphi = \text{angle}(U) - \text{angle}(I)
\]  

(6)

Since PMU has achieved simultaneous recording of power angles by direct measurement method, the internal power factor angle in the generator is:

\[
\psi = \delta + \varphi
\]  

(7)

And the \( d \)-axis and \( q \)-axis components of \( U \) and \( I \),

\[
\begin{align*}
U_d &= U \sin \delta \\
U_q &= U \cos \delta \\
I_d &= I \sin \psi \\
I_q &= I \cos \psi
\end{align*}
\]  

(8)
It is the pre-processing of the measurement data that makes it possible to calculate the oscillation energy of (1) and (2) directly.

3.2. FFT-based oscillation energy for control systems

In the steady-state phase of forced power oscillation, the deviation of active power is not ideal cosine functions that periodically alternate with the oscillation frequency, including the clutter signal determined by the undisturbed source:

\[ \Delta X = \Delta X^1 + \Delta X^{else} \]  

(10)

The dominant component of \( \Delta X \) is in the following form:

\[ \Delta X^1 = A \cos(\omega t + \phi) \]  

(11)

where \( A \) is the magnitude of the dominant component \( \Delta X^1 \), and \( \phi \) is the initial phase angle.

Therefore, it is necessary to extract a dominant oscillation component capable of reflecting the characteristics of the disturbance source. As a fast algorithm of discrete Fourier transform (DFT), the FFT can extract harmonic signals of different frequencies from stationary signals. Perform FFT on \( X \) in the steady-state phase of oscillations; the \( \Delta X^1 \) can be obtained.

Replace \( \Delta X \) in (1) and (2) by the dominant oscillation component \( \Delta X^1 \), the FFT-based oscillation energy for control systems becomes:

\[
W_{i}^{gov(Di)} = \int \Delta P_{d1} \cdot \Delta \delta_{d1} dt
\]  

(12)

\[
W_{i}^{exc(Di)} = \int (\Delta I_{d1} \Delta \hat{U}_{q1} - \Delta I_{q1} \Delta \hat{U}_{d1}) dt
\]  

(13)

4. Example and verification

A low frequency oscillation case occurred in a power plant unit of Hunan grid during the power-up process. The oscillation recording is shown in figure 2, which is a forced power oscillation caused by abnormal governor system.

![Figure 2. Active power oscillation waveform.](image)

4.1. Basic variables

In order to calculate the oscillation energy, it is necessary to extract the PMU recording in the steady-state oscillation phase to calculate the variables. Figure 3 shows the power factor angle according to (6), power angle based on direct measurement and internal power factor angle by (7) within 12.5s. Furthermore, the \( d \)-axis and \( q \)-axis components of \( U \) and \( I \) are easy to draw from the trigonometric relationship. In figure 4, the FFT decomposition is performed on variables above to extract dominant
component in steady-state oscillation, which has the largest amplitude in the harmonics and is shown in red.

Figure 3. Variables in steady state oscillation phase.
inject energy into the system, which is not conducive to system stability, so the disturbance source

Using (14.2), it can be seen that oscillations of both periodic components of both oscillation energy are shown in figure 5 and figure 6. It can be seen that oscillation energy of both is increasing or decreasing smoothly, and the non-periodic components of both oscillation energy are shown in figure 7 and 8 respectively. The non-periodic component in figure 7 has a positive slope, meaning that the governor system continues to inject energy into the system, which is not conducive to system stability, so the disturbance source

Figure 4. FFT decomposition of variables in steady-state oscillation.

4.2. FFT-based oscillation energy for control systems
exists on the governor system. Meanwhile, a negative slope of the non-periodic component in figure 8 indicates that the excitation system extracts energy from the system continuously, which is conducive to the stability of the power grid. The indication result is consistent with the site survey, proving the proposed method has superiority for the control systems level location of disturbance source.

![Figure 5. Oscillation energy for governor system.](image1)

![Figure 6. Oscillation energy for excitation system.](image2)

![Figure 7. The non-periodic component for governor system.](image3)

![Figure 8. The non-periodic component for excitation system.](image4)

5. Conclusions
In this paper, an oscillation energy calculation method suitable for the generator control systems level location is proposed. The following conclusions could be made:

1) The variables for calculating the oscillation energy in this method are all based on the PMU data and do not depend on the generator reactance parameters.

2) The FFT-based oscillation energy for control systems has good effect on the disturbance source location due to filtering out the non-dominant components, which is convenient for quantification in engineering practice.

Acknowledgments
This work was supported by State Grid Hunan Electric Power Company Limited Scientific Research Project (5216A5170017), and High-Level Talent Research Start-up Fund of Central South University of Forestry and Technology (2015YJ007).

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