Analysis of Forced Power Oscillation Based on FFT

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Abstract. Low-frequency oscillations occur frequently in many interconnected power grids around the world. In severe cases, even system-wide chain reactions are triggered, resulting in system unwinding and large-scale blackouts. In this paper, a FFT-based forced power oscillation disturbance source localization method is introduced. Using the active power and frequency of the steady-state oscillation phase of the low-frequency oscillation, the dominant component of the oscillation is obtained by the fast Fourier transform (FFT), and then the disturbance source is automatically positioned according to the energy function. Taking the low-frequency oscillation accident occurring in Hunan power grid as an example, the energy function based on FFT and the traditional energy function method are compared, which shows that the proposed method can locate the disturbance source more accurately.

1. Introduction

Power system low frequency oscillation problem belongs to dynamic stability category. After about half a century’s development, scholars have made extensive research on the occurrence mechanism, analysis methods and control measures. However, due to the complexity of the low-frequency oscillation mechanism, the low-frequency oscillation is still an important problem that threatens the safety and stability of the interconnected power system.

The mechanism of low frequency oscillation mainly includes negative damping theory and forced power oscillation theory [1-3]. In the dispatching operation, the oscillations caused by the negative damping mechanism mainly adopt various measures to enhance the system damping, including reducing the active output of the relevant generators, reducing the transmission power of the inter-system tie line, and putting into the power system stabilizer. For forced power oscillation, the most direct and effective way to suppress oscillations is to find and remove the disturbance source quickly. Currently, there are mainly three types of forced power disturbance source localization methods: oscillation discrimination method based on phase relationship [4], oscillation discrimination method based on envelope fitting [5] and disturbance source location method using energy functions [6-10]. By analysing the phasor relationship among mechanical input, electric output, and rotor speed (frequency), an online method for forced power oscillation detection is proposed [4]. If the fluctuation phase of the mechanical power is ahead of the fluctuation phase of the electrical power, the generator prime mover can be considered as a forced oscillation source. On the basis of comparing the
characteristics of negative damped oscillation and forced oscillation [5], it is pointed out that the power oscillations of different mechanisms have different envelope expressions. Based on the extracted power oscillation dominant mode signal, the oscillation type is determined by fitting the envelope. Energy function analysis method is one of the basic methods for power system transient stability assessment. The literature [6, 7] analyzes the change relations and characteristics of internal and external energy during the oscillating process of forced power oscillation from the perspective of energy, and points out that the disturbance source can be located by using the energy conversion characteristics in the steady-state phase of forced oscillations. Then, the energy function model of the branch is established to identify the rough orientation of the disturbance source according to its energy change characteristics and network dynamic information. By constructing energy function based on tie-line, Dong C et al. decompose the traditional branch potential energy into periodic and non-periodic components, and use the direction of dissipation of non-periodic component in the network to realize the rapid localization of periodic forced disturbance sources [8]. In [9], Hu W et al. improve the energy function and obtain the corresponding energy flow direction by discriminating the positive/negative power dissipation of the generator and the line, and determine the location of the disturbance source according to the energy flow direction. On the basis of literature [9], Yang D et al. conduct Prony analysis on the active power and frequency variation in the steady-state stage of low-frequency oscillations, and determine the location of the disturbance source by extracting the dominant component to obtain the energy flow direction factor [10].

As a multi-scale separation algorithm, EMD is introduced into the low-frequency oscillation analysis to extract the electrical dominant oscillation component [11]. In order to overcome the shortcomings of the traditional energy function method including non-disturbing source components, Chu X et al. propose the concept of empirical mode energy flow, and extract characteristic of disturbance source by calculating the empirical mode energy flow [12].

Aiming at the complexity of extracting dominant oscillatory components by Prony and EMD, a simple FFT-based forced oscillation disturbance source localization method is proposed in this paper. Using the active power and frequency of the steady-state oscillation phase of the low-frequency oscillation, the dominant component of the oscillation is obtained by the FFT, and then the disturbance source is automatically positioned according to the energy function. Taking the low-frequency oscillation accident occurring in Hunan power grid as an example, the energy function based on FFT and the traditional energy function method are compared, which shows that the proposed method can locate the disturbance source more accurately.

2. Energy function method for forced oscillation disturbance source location

2.1. Energy Function Construction

Based on the energy function construction method in [7], the oscillation energy transmitted from the bus \( i \) through the branch \( L_{ij} \) is defined as:

\[
W_{ij} = \int \text{Im}(I_{ij}^*dU_i)
\]

\[
= \int (P_{ij}d\theta_i + Q_{ij}/U_i dU_i)
\]

\[
= \int (P_{ij}2\pi\Delta f dt + Q_{ij}d(lnU_i))
\]

(1)

Where \( P_{ij} \) and \( Q_{ij} \) are the active and reactive power of the branch \( L_{ij} \), \( U_i \) and \( \theta_i \) are the voltage amplitude and phase angle of the bus \( i \), and \( f \) is the bus frequency.

When the change of the node bus voltage and reactive power is ignored, the energy function becomes:

\[
W_{ij} = \int P_{ij}2\pi\Delta f dt
\]

(2)
2.2. Energy Function Construction Using Deviations

In the analysis of low-frequency oscillations, the focus is on the consumption or generation of energy. The transient energy term of the branch needs to be removed from the energy flow, and the net energy flow in the network can be calculated by the amount of change. Replace the variables in (2) by their deviations, the traditional energy function becomes:

\[ W_{ij} = \int \Delta P_{ij} 2\pi f \Delta f \, dt \]  
\[ \Delta P_{ij} = P_{ij} - P_{ij,s} \]

Where \( P_{ij,s} \) is steady state value of active power.

In the steady state phase of forced power oscillation, each state quantity changes periodically with the dominant disturbance frequency:

\[ \Delta P_{ij} = A_1 \cos(2\pi \omega t + \phi_1) \]  
\[ \Delta f_{ij} = A_2 \cos(2\pi \omega t + \phi_2) \]

Where \( A_1 \) and \( A_2 \) are the magnitudes of power variation and frequency variation, respectively. \( \phi_1 \) and \( \phi_2 \) are the initial phase angles of power variation and frequency variation.

Bringing (5) and (6) into (4), the energy function considering the dominant oscillation mode becomes:

\[ W_{ij} = a \sin(2\omega t + \phi_1 + \phi_2) + bt + c \]

\[ a = \frac{\pi}{2\omega} A_1 A_2 \]  
\[ b = \pi A_1 A_2 \sin(\phi_1 - \phi_2) \]  
\[ c = \frac{\pi}{2\omega} - A_1 A_2 \sin(\phi_1 + \phi_2) \]

According to (7), the energy function is composed of a sine curve, a line with a slope of \( b \) and a constant term. This line represents the non-periodic component of the energy function and determines the direction of the dissipated energy in the network.

3. FFT-based energy function calculation

3.1. Fast Fourier Transformation

When a signal is discrete and periodic, we don’t need the continuous Fourier transform. Instead we use the discrete Fourier transform, or DFT. Suppose our signal is \( a_n \) for \( n = 0 \ldots N-1 \), and \( a_n = a_{n+N} \) for all \( n \) and \( j \). The discrete Fourier transform of \( a \), also known as the spectrum of \( a \), is:

\[ A_n = \sum_{n=0}^{N-1} e^{-\frac{2\pi in}{N}} a_n \]

FFT is a fast algorithm of Discrete Fourier Transform (DFT). It is based on the odd, even, imaginary and real properties of the DFT and is improved by DFT. Periodic components extraction of discrete signals can be realized by FFT [13].

3.2. Case study

The Hunan power grid WAMS recorded a forced power oscillation accident during the power up of the generator, the active power oscillation waveform is shown in figure 1.
Figure 1. Active power oscillation waveform.

The WAMS data for a period of 12.5s in the steady-state oscillation phase of figure 1 is extracted for analysis. Perform FFT on the active power and frequency of the generator terminal bus, respectively. Related harmonic and DC components for active power and frequency are shown in figure 2 and figure 3. We can see that $P_1$ and $f_1$ are the dominant electrical oscillation components with an oscillation frequency of 0.8 Hz.

Figure 2. FFT decomposition of active power in steady-state oscillation.

According to (7), the FFT-based energy function calculation result is shown in figure 4. It can be seen that the energy function waveform is ideal, and consists of a sine function, a straight line with a positive slope and a constant term. A positive slope of the line indicates that the branch potential energy flows from the generator to the system, and the generator set is the disturbance source, which is consistent with the actual survey results of the low frequency oscillation accident.
Figure 3. FFT decomposition of frequency in steady-state oscillation.

Figure 4. Energy function based on FFT.
3.3. Comparative analysis

The traditional energy function method only considers the amount of change in active power and frequency, which may include non-dominant oscillatory components. The energy function based on FFT is compared with traditional energy function in figure 5. It can be seen that the traditional energy function is negative at some moments, which is not conducive to the precise location of the forced power oscillation disturbance source.

![Figure 5. Energy function comparison analysis result.](image)

4. Conclusions

In this paper, a FFT-based forced power oscillation disturbance source localization method is investigated. By performing FFT on the active power and frequency of the generator terminal bus respectively, the energy function considering the dominant oscillation mode is computed to locate the forced power oscillation disturbance source. Taking a low-frequency oscillation accident as example, the proposed method and the traditional energy function method are compared, which shows that the FFT-based method can locate the disturbance source more accurately.

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