Multi-criterion integrated method for low-frequency oscillation-type identification

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Abstract: Low-frequency oscillation is one of the major threats to power system security. Online analysis and control decision system for low-frequency oscillation is in urgent need. Natural oscillation and forced oscillation are two types of low-frequency oscillation. Different oscillation types need different treatment measures. Thus oscillation-type identification is an important part of the defense system. A new multi-criteria integrated method for identifying low-frequency oscillation type is proposed. It has multiple criteria and overcomes the shortcomings of the previous single-criterion method which has low accuracy. It chooses harmonic content, characteristic index of starting oscillation waveform, and the startup-stage intrinsic damping ratio together with noise response damping ratio as criteria. The flowchart of the method is provided. The effectiveness of the multi-criteria integrated method is verified by real-power grid simulation cases. The results show that the method can reliably distinguish the low-frequency oscillation type and is practical in the real-power system.

1 Introduction

Low-frequency oscillation has been one of the major threats to the stability and security of power system. Low-frequency oscillation can be classified into natural oscillation and forced oscillation. The oscillation-type classification is relative of great importance since the emergency control and assistant decision system highly relies on it. The mechanisms of natural oscillation and forced oscillation diverse from each other. The natural oscillation occurs when the system exhibits oscillation modes with close to zero damping or even negative damping and under that condition any small turbulence may lead to large-scale power oscillation. The forced oscillation occurs when the system is disturbed by external disturbance source with almost the same frequency as the frequency of one of the systems intrinsic oscillation mode, even if all the system oscillation modes have positive damping ratio. A phenomenon is also a form of resonance. Due to the discrepancy between the mechanism of natural oscillation and forced oscillation, the emergency control measures to cope with these two kinds of oscillations are diversiform. When the natural oscillation occurs, it is required to increase the damping ratio of the system by adjusting system operation mode. Once the damping ratio is increased to a proper level, the oscillation will disappear. However, such emergency control measures are not applicable to forced oscillation. Forced oscillation can only be eliminated by clearing up external disturbance sources. The difference between emergency control measures for the two types of oscillation is so large that accurate identification of oscillation types is of great significance for online analysis and control decision system for low-frequency oscillation.

Identifying low-frequency oscillation type is hard on account of the similarity between the stable waveforms of natural oscillation and forced oscillation. Under normal conditions, the waveform of forced oscillation will be similar to that of the external disturbance source in the steady state, which is usually sine wave with constant amplitude. When it comes to the natural oscillation, with the existence of some non-linear factors, the oscillation amplitude will not increase forever and will converge to a certain value in the steady state. Thus natural oscillation and forced oscillation show very similar waveform with constant amplitude in the steady state, leading to the difficulty in identifying oscillation type.

Up to now, there are plenty of research findings on oscillation-type identification. Ju et al. [1] analyse oscillation characteristic index by support vector machines (SVMs). Ju et al. [2] and Yanfeng et al. [3] worked on the envelope of oscillation waveform. Ruichao and Daniel [4] compared power spectral density of deterministic clean sinusoid component and the noise component at the frequency of the oscillation. Lixin et al. [5] applied coherent spectrum analysis to the data of the startup stage. Hua et al [6] and Dong et al. [7] focused on the oscillation mode difference by working on the component of oscillation response. However, most of the above methods adopt only one criterion that may probably have low accuracy due to the complexity of practical power system oscillation waveform. According to extensive application experience, it is difficult to ensure the reliability of identification result if only one criterion is applied.

This paper proposed a new multi-criteria integrated method for identifying low-frequency oscillation type according to the actual situation of the power grid. Information in the power grid, including waveform harmonic content, startup-stage waveform characteristic index, system intrinsic damping ratio obtained in the startup stage and noise response damping ratio, is chosen as criteria. The method overcomes the drawbacks of single-criterion methods and distinguishes oscillation-type reliably.

The paper is organised as following: Section 2 gives a brief introduction of principles of the criteria utilised in the method. Section 3 gives the flow of the method. Section 4 verifies the effectiveness of the method by real power system oscillation accident records simulations. Section 5 gives the conclusion and the prospect of the method.

2 Principles of criteria for low-frequency oscillation-type identification

The dominant difference between natural oscillation and forced oscillation is the system damping ratio. In natural oscillation cases, system damping ratio is zero or even negative and any small turbulence would lead to huge power fluctuation. By the way, in forced oscillation cases, system damping ratio is positive, but there exists eternal disturbance. Such difference leads to discrepancy in the damping ratio both in the startup stage and the steady state. During the startup stage, the envelope shapes of the waveform are also different between natural and forced oscillation. Furthermore
The steady-state waveform of natural oscillation is mainly sinusoidal model. Even if it deviates from the sine form due to the influence of nonlinear factors, the deviation would be small. However, the steady-state waveform of forced oscillation is significantly influenced by the waveform shape of external oscillation source. If the external oscillation source presents a non-sinusoidal form, the forced oscillation waveform would present similar form, which deviates a lot from sine wave. Such waveform would be shown in the reliability of oscillation-type identification, the criteria are combined together to form the multi-criteria integrated method for oscillation-type identification. The principles of criteria chosen in the method are shown as follows.

2.1 Steady-State waveform harmonic content

The steady-state waveform of natural oscillation is mainly sinusoidal model. Even if it deviates from the sine form due to the influence of nonlinear factors, the deviation would be small. However, the steady-state waveform of forced oscillation is significantly influenced by the waveform shape of external oscillation source. If the external oscillation source presents a non-sinusoidal form, the forced oscillation waveform would present similar form, which deviates a lot from sine wave. Such waveform would be shown in the reliability of oscillation-type identification, the criteria are combined together to form the multi-criteria integrated method for oscillation-type identification. The principles of criteria chosen in the method are shown as follows.

2.2 Start-up stage waveform characteristic Index

The following differential equation can be used to describe power system low-frequency oscillation as the system usually has only one dominant oscillation mode

$$\frac{T_f}{\omega_0} \frac{d^2 \Delta \delta}{dt^2} + \frac{K_D}{\omega_0} \frac{d \Delta \delta}{dt} + K_s \Delta \delta = \Delta P_m$$

$\Delta \delta$ is the deviation angle of the generator rotor, $T_f$ is the generator inertia time constant, $K_D$ is the generator damping ratio, $K_s$ is the generator synchronous power coefficient, $\Delta P_m$ is the mechanical power variation. $\Delta P_m$ is generally recognised as zero when natural oscillation occurs. So the general solution of the above equation is

$$\Delta \delta(t) = B_0 e^{\text{sign}(\omega_0t)} \sin(\omega_0t + \phi_0) + B_1 \sin(\omega_0t + \phi_1)$$

$$2\omega_0\zeta = \frac{K_D}{T_f} \quad \phi_1 = \omega_0 K_s - \frac{T_f}{T_s} \quad \phi_0 = \omega_0 \sqrt{1 - \zeta^2}$$

Where $\zeta$ is the damping ratio. The envelope of startup-stage waveform of the natural oscillation can be written as, where $B_1 > 0$ and $\zeta > 0$. Since $|\zeta| < 1$ it can be approximately considered that the envelope is upper convex.

When there exists external disturbance source with almost the same frequency as the frequency of one of the system intrinsic oscillation mode, the solution of rotor motion equation is composed of free component (general solution) and forced component (special solution). Due to the damping effect, the free component will decay until it disappears, and only the forced component will be left in the system response. The output power variation of the generator can be written as $\Delta P_m = \Delta P \sin(\omega t)$, where $\Delta P_1$ is the disturbance amplitude and $\omega$ is the disturbance angular frequency. The solution of the equation can be written in the following form:

$$\Delta \delta(t) = B_0 e^{\text{sign}(\omega_0t)} \sin(\omega_0t + \phi_0) + B_1 \sin(\omega_0t + \phi_1)$$

$$B_1 = \frac{\Delta P_1}{\sqrt{(K_s - (T_f/\omega_0)^2)}^2 + (K_s/\omega_0)^2} > 0$$

where, and $B_0 e^{\text{sign}(\omega_0t)} \sin(\omega_0t + \phi_0)$ is the free component while $B_1 \sin(\omega_0t + \phi_1)$ is the forced component.

The initial conditions of the forced oscillation variables are generally zero. After careful deduction, the envelope of startup-stage waveform of the forced oscillation can be written as, where $B_1 > 0$ and $\zeta > 0$. Since $|\zeta| < 1$ it can be approximately considered that the envelope is upper convex.

The waveform envelope of free oscillation and forced oscillation can be unified into the form of $Ae^{\phi} + B$, where $A = \zeta \omega_0$. It is apparent that $\sigma$ is positive in natural oscillation case and is negative in forced oscillation case. Therefore, we can identify oscillation type by analysing waveform data and get the sign-off $\sigma$. Details of steps are shown in the following.

Step 1: If, the oscillation type is determined as forced oscillation. If, the oscillation type is determined as forced oscillation.

Step 2: If the oscillation type is determined as forced oscillation. If the oscillation type is determined as forced oscillation.

Step 3: If the oscillation type is determined as forced oscillation. If the oscillation type is determined as forced oscillation.

2.3 Identification of system intrinsic damping ratio at startup stage

According to Section 2.2, forced oscillation waveform consists of two components in the startup phase. One is the free decaying component caused by the positive damping of the system. The other is the steady-state forcing component. Nevertheless, natural oscillation consists of only one component in the startup phase, which is the free component. If we implement Prony analysis in the waveform and find one component with similar frequency as the dominant oscillation frequency and with positive damping ratio, the oscillation type can be determined as forced oscillation. Details of steps are shown in the following.

Step 1: Implement modal parameter identification of startup-stage waveform using the Prony method (Table 1).

Step 2: Choose the damping ratio of the component with frequency closest to the dominant oscillation frequency as the estimation of the intrinsic damping ratio of the system, $d_{\text{max,START}}$. According to application experience, such frequency should be in the range of 70–130% of the dominant oscillation frequency. If no such component is obtained, skip this step.

Step 3: If, the oscillation type is determined as forced oscillation. $d_{\text{max,START}}$ is a preset threshold.

2.4 Identification of system intrinsic damping ratio by noise response analysis

System intrinsic damping ratio is zero or negative in natural oscillation cases and positive in forced oscillation cases. Therefore,

| Table 1 Main part of prony analysis result in startup stage |
|----------------------------------------------------------|
| Component | Frequency, Hz Damping ratio |
| dominant oscillation component | 0.59 | 0.04 |
| component for damping ratio calculation | 0.62 | 0.39 |

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damping ratio can be used to identify oscillation type. When the power system is operating, it is always disturbed by random excitation such as load change. The fluctuation with small amplitude triggered by such random excitation is called noise response or ambient signal. It can be used to identify system modal parameter. The identification of modal parameters based on noise response in steady-state operation of power systems has been extensively studied [8, 9]. When forced oscillation happens, in addition to periodic disturbances that cause sustained oscillations, random excitations, such as load variations, still exist. This leads to a result that system response embodies both forced oscillation response and noise response. Thus system damping ratio can be identified from noise response which contains the damping information.

The theoretical basis of identifying system mode information from noise response is that the autocorrelation function of the system impulse response function, which contains the modal information, is given by [10]:

\[ R_s(\tau) = R_s(\tau) + h(\tau) + h(-\tau) \]  

(2)

where \( R_s(\tau) \) is autocorrelation function of output \( y(t) \) and \( R_s(\tau) \) is autocorrelation function of input \( x(t) \). \( h(\tau) \) is the impulse response function of the system which contains the modal information. \( \ast \) represents convolution calculation.

Then implement autocorrelation calculation in steady-state waveform containing noise response. Steady-state waveform can be approximately divided into sinusoidal signal \( s(t) \) and noise response \( u(t) \), \( y(t) = s(t) + u(t) \). Then we have

\[ R_s(\tau) = \int_{-\infty}^{\infty} y(t)(t + \tau)\, dt \]

\[ = \int_{-\infty}^{\infty} [s(t) + u(t)][s(t + \tau) + u(t + \tau)]\, dt \]

\[ = \int_{-\infty}^{\infty} s(t)(s(t + \tau) + \int_{-\infty}^{\infty} s(t)u(t + \tau)\, dt) \]

\[ + \int_{-\infty}^{\infty} u(t)(s(t + \tau) + \int_{-\infty}^{\infty} u(t + \tau)\, dt) \]

\[ = R_s(\tau) + R_u(s) + R_u(\tau) + R_u(\tau) \]

(3)

In (3) \( R_s(\tau) \) is autocorrelation function of \( s(t) \). \( R_u(\tau) \) is also periodic function and has the same period as \( s(t) \). Next, we prove that \( R_u(\tau) \) and \( R_s(\tau) \) are also periodic functions and have the same period as \( s(t) \) denoted as \( T \)

\[ R_u(\tau + T) = \int_{-\infty}^{\infty} u(t)(t + \tau + T)\, dt \]

\[ = \int_{-\infty}^{\infty} u(t)-(t-T)\, dt \]

\[ = \int_{-\infty}^{\infty} -u(t)\, dt \]

\[ = R_u(\tau) \]

\[ R_u(\tau + T) = \int_{-\infty}^{\infty} u(t)(t + \tau + T)\, dt \]

\[ = \int_{-\infty}^{\infty} u(t)\, dt \]

\[ = R_u(\tau) \]

Thus \( R_u(\tau) \) and \( R_u(\tau) \) are also periodic functions and have the same period as \( s(t) \). Then we get

\[ R_s(\tau) = R_s(\tau) + R_u(s) + R_u(\tau) + R_u(\tau) \]

\[ = g(\tau) + h(\tau) = g(\tau) + h(\tau) \]

\[ where \ g(\tau) = g(\tau + T) \]. Now it is easy to see that the autocorrelation function of the output signal retains the characteristic information of the system impulse response function, and the system modal parameters can also be identified from the output signal. Details of steps are shown in the following.

Step 1: Obtain autocorrelation function of steady-state oscillation waveform.

Step 2: Implement modal parameter identification of autocorrelation function using the Prony method (Table 2).

Step 3: Choose the damping ratio of the component with frequency closest to the dominant oscillation frequency as the estimation of the intrinsic damping ratio of the system, \( \xi_{STABLE} \). According to application experience, such frequency should be in the range of 70–130% of the dominant oscillation frequency. If no such component is obtained, skip this step.

Step 4: If, the oscillation type is determined as forced oscillation. \( d_{max,STABLE} \) is a preset threshold.

3 Multi-criteria integrated method for Low-frequency oscillation-type identification

As mentioned before, the oscillation waveform in the actual system is very complex. Thus using only one oscillation criterion is difficult to obtain reliable discrimination results. Therefore, this paper uses a variety of criteria. For each criterion, a larger threshold is chosen to ensure that the discrimination result is reliable. The next step will be implemented when the threshold condition of the criterion in the previous step is not satisfied.

The oscillation type can be reliably determined as forced oscillation if the harmonic content in the steady-state waveform is high. When considering harmonic content threshold, we choose the harmonic index of triangle wave that is 0.11. If the harmonic index is higher than \( h_{\text{TH}} \), the waveform must deviate more from sinusoidal waveform than triangle wave.

The sign of startup-stage waveform characteristic index can be utilised to classify natural and forced oscillation. A relatively greater threshold is chosen to ensure reliable identification. The startup-stage oscillation waveform characteristic index \( S = ST \approx -2\xi_c \), where \( \xi_c \) is system damping ratio. If we choose \( \pm 0.01 \) as the value for \( S \), then the threshold of \( \xi_c \) will be equal to \( \pm 0.06 \). It means that if \( S < -0.06 \), the oscillation type is forced oscillation, and if \( S > 0.06 \), the oscillation type is natural oscillation.

If the damping ratio in the startup state is high, the oscillation type can be reliably recognised as forced oscillation. In consideration of the situation in the practical power system, choose 0.08 as the value for \( d_{max,START} \). Meanwhile, if the noise response damping ratio is high, the oscillation type can also be reliably recognised as forced oscillation. In consideration of the situation in the practical power system, choose 0.08 as the value for \( d_{max,START} \).

Furthermore, if we cannot identify the oscillation type through the above steps, the oscillation type is classified as hard to identify and the situation should be handled according to grid corporation operating procedure.

After careful consideration of each criterion, the flowchart of a multi-criteria integrated method for low-frequency oscillation is shown in Fig. 1.

| Component | Frequency, Hz | Damping ratio |
|-----------|--------------|--------------|
| dominant oscillation component | 0.59 | 0.0001 |
| component for damping ratio calculation | 0.72 | 0.11 |

Table 2 Main part of proxy analysis result in steady state
4 Analysis of examples of actual power system and simulations

4.1 Forced oscillation accident in Fa'er power plant

On 26 Feb 2011, No. 4 generator in Fa'er power plant in Guizhou province, China, went wrong because of the failure in No. 2 high-pressure control servo system (Fig. 2). This led to the fluctuation in the output power of the generator and forced oscillation in power system. It can be seen from the active power data of No. 4 generator that the waveform is almost triangle waveform with a high proportion of harmonic content. After Fourier analysis, the harmonic content is calculated as \( h = 0.34 \), which means that the oscillation type is forced oscillation.

4.2 Natural oscillation accident in pingban power plant

On 2 Dec 2010, a power oscillation occurred in Pingban Power Plant in Guangxi Province, China. Before the accident, No. 1 and 2 generators transmit power to the nearby Baise Region through Pingbai and Pingsha transmission line. A fault happened in Pingbai line, and the transmission structure was severely weakened. The damping ratio of generators decreased and persistent natural oscillation occurred.

The data of active power of Pingsha transmission line is chosen for analysis (Fig. 3). The harmonic content is \( h = 0.09 \). The startup-stage oscillation waveform characteristic index is calculated as \( S = 0.14 > 0.06 = \varepsilon \). So the oscillation type is determined as a natural oscillation in accordance with the actual situation.

4.3 Forced oscillation case simulation

Applying external perturbation containing sinusoidal component and the noise component in Generator 3 in the four-machine-two-area system (Figs. 4 and 5). Analyse the active power of Bus 9. The harmonic content is \( h = 0.06 \). The startup-stage oscillation waveform characteristic index is calculated as \( S = -0.16 \), which means that the oscillation type is determined to be forced oscillation. The intrinsic damping ratio of the system in the startup stage is \( d_{\text{START}} = 0.39 \), and the noise response damping ratio is \( d_{\text{STABLE}} = 0.11 \). Both of them verify the conclusion in oscillation-type identification.

The above simulation cases show that multi-criteria integrated method for low-frequency oscillation-type identification can precisely and reliably identify low-frequency oscillation and simultaneously provide necessary information for emergency control and assistant decision system (Tables 1 and 2).

5 Conclusion and prospect

Low-frequency oscillation-type identification is of great significance for power grid emergency control and assistant decision system because different types of oscillation need different control measures. A new multi-criteria integrated method for low-frequency oscillation-type identification can precisely and reliably identify low-frequency oscillation and simultaneously provide necessary information for emergency control and assistant decision system.
for low-frequency oscillation-type identification is proposed based on the analysis on the divergence of multiple indexes of natural oscillation and forced oscillation including waveform harmonic content, start up the stage waveform characteristic index, system intrinsic damping ratio obtained in the startup stage and noise response damping ratio. The method operates by combining the judgment results of each criterion. The simulation results show that the new method can overcome the drawbacks of single-criterion identification methods and reliably distinguish oscillation type.

Next, it is necessary to further analyse differences between the two oscillation types on other indexes and combine more reliable criteria to this method to further improve the reliability of the method. In addition, the Prony method is currently adopted in the identification module of system intrinsic damping ratio, and the Hilbert-Huang transformation (HHT), auto-regressive and moving average (ARMA) and other methods can also be tested to optimise the damping ratio calculation module of the oscillation-type identification method.

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7 References

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