Low frequency oscillation online identification based on synchronous phasor of distribution network

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Abstract. With the advancement of the interconnection process of power grid, the low-frequency oscillation (LFO) problems in the interconnected power grid greatly affect the economic and stable operation of the system. In recent years, the research of synchronous measurement system of distribution network has made great progress, which makes it possible to construct a new generation of low-cost, flexible and reliable online monitoring system of low-frequency oscillation based on the synchronous phasor of distribution network (LFO-DPMU). Based on this, the physical structure and processing flow of LFO-DPMU are constructed in this paper. The LFO-DPMU can extracts dominant mode of oscillation from the distribution network information in real time. For the identification algorithm, this paper selects Prony and HHT algorithm, which two kinds of commonly used oscillation identification algorithms in high-voltage power grid, and compare the characteristics of algorithm in anti-noise, stability and analysis efficiency. Then, combined with the characteristics of distribution network signal, this paper analyses the applicability of the two algorithms. Finally, two algorithms are used to extract the oscillation mode of the measured synchronous phasor signal of distribution network. The analysis result shows the feasibility and accuracy of the whole identification system.

1. Introduction

With the development of large power grid interconnection, UHV transmission lines with heavy load and long distance become the power exchange channels of regional power grid. But at the same time, the low-frequency oscillation (LFO) in the interconnected power grid has a great impact on the economic and stable operation of the system [1]. Among them, the continuous oscillation caused by the weak damping mode seriously restricts the transmission power of the interconnection line. The amplification oscillation caused by the negative damping mode is very easy to affect the stability of the power grid, and even lead to large-scale blackouts. Therefore, it is of great practical significance to identify the dominant mode of system oscillation and take effective measures to suppress it.

At present, two main methods for low-frequency oscillation analysis are model analysis and signal processing. The method based on the grid model analyzes the stability of the system according to Lyapunov’s first theorem after establishing the algebraic and differential equations [2]. This method is easy to form dimension disaster with the increase of power grid scale, and it is difficult to meet the needs of real-time analysis. The other method based on signal processing can identify the oscillation characteristics directly according to the measured data in real-time, but it also requires the high precision of the measured data and the identification algorithm [3].
Wide area monitoring system (WAMS) can provide high-precision data support for signal analysis of low-frequency oscillation [4]. However, due to the high cost of PMU under WAMS and the strict requirements of installation location and transmission line, the coverage of PMU is limited. In recent years, great progress has been made in the research of synchronous measurement system for distribution network. The system places the measurement device DPMU in the low-voltage network, which has the characteristics of low cost and flexible installation, making the dynamic monitoring of distribution network possible. Depending on the high-precision and high-density synchronous phasor signal provided by DPMU, a new generation of on-line monitoring system for low-frequency oscillation (LFO-DPMU) can be established in the distribution network.

In the identification of low-frequency oscillation, common algorithms include Fourier transform, wavelet analysis, Prony algorithm, HHT algorithm. [5]. When the distribution network is connected with a large number of distributed generation and flexible load equipment, its dynamic characteristics are characterized by high disturbance and nonlinearity. When the above identification algorithm is applied to the distribution network, there are problems in the identification effect due to the mechanism of the algorithm. Therefore, it is necessary to study the applicability of the existing identification algorithm according to the characteristics of the measured signal.

On the basis of the above, this paper presents the physical structure and algorithm flow of LFO-DPMU, and compares the identification performance of Prony and HHT algorithm in oscillation mode analysis under synchronous phasor of distribution network. Finally, according to the measured synchronous phasor signals of distribution network in central and north China, the applicability of the two algorithms is compared, and the on-line identification system is further verified accuracy.

2. System architecture of LFO-DPMU

2.1. System physical architecture

The physical structure and processing flow of LFO-DPMU are shown in figure 1. The whole system consists of four layers: synchronous monitoring layer, data transmission layer, data reception layer and LFO online identification layer. The first two layers are distributed at the key nodes of wide area power grid, and the second two are set at the master station of the system.

![Figure 1. The architecture of LFO-DPMU](image)

DPMU is installed on the key node or bus on the 220V or 10kV side of the low-voltage power grid to record the dynamic behavior of the power grid, and the synchronous time scale is sealed under GPS satellite timing. Because there is no optical fiber laying in the power line of the distribution network,
the data transmission network of the device adopts Internet wired network and 3G/4G wireless network. The firewall set in the master station can manage the access rights of the internal and external network of the dispatching center, so as to prevent the illegal network intrusion from threatening the data security. After decoding and extracting the real-time data, the receiving server stores data in the distributed database. Based on this, the identification application server extracts the oscillation modes in real time and presents the analysis results in the front end.

2.2. Identification processing flow
The on-line identification algorithm of LFO is built in the application server. After extracting the phase difference signal according to the voltage phasor in the two regional power grids, the phase difference waveform is detected if there is oscillation feature. Then the oscillation signal is sent to the modal identification module for real-time analysis after preprocessing. The data preprocessing module mainly includes the following three aspects:

(1) Phase mutation detection. When calculating the phase difference according to the measured phase data, as the phase change period is 360 °, the continuous decline from 0 ° will step to 360 °. And the continuous growth from 360 ° will suddenly change to 0 °. This results in the existence of pulse signal in the phase difference waveform. It is necessary to ± 360 ° in the signal step to remove the pulse caused by the angle mutation.

(2) DC and low-pass filtering. The frequency of typical low frequency oscillation signal is generally 0.1~2.5 Hz. Among them, oscillation of 0.1~0.7 Hz usually occurs in the long-distance transmission line with heavy load. Considering the influence of multiple signal interference sources, the high frequency and DC signals should be filtered.

(3) Sliding mean filtering. In the process of measurement and transmission, it is easy to introduce random noise disturbance. With the help of sliding mean filtering, the random noise pollution in the measurement data can be eliminated, and the calculation amount is small, which is suitable for the application in the real-time data analysis process.

3. Adaptability analysis of low frequency oscillation algorithm
Prony and HHT algorithm are two common methods of low-frequency oscillation analysis in WAMS system of high-voltage power grid at present. Therefore, these two algorithms are selected to analyse the adaptability of oscillation mode extraction from synchronous phasor of distribution network.

3.1. The Prony algorithm
Prony algorithm will instead the discrete sampling data \(x(n) (i=0…N-1)\) as \(p\) exponential functions \(\hat{x}(n)\) with any amplitude, phase, frequency and attenuation factor. According to the expression of the exponential function, the characteristic parameters of the measured data can be approximately obtained. In low frequency oscillation analysis, each approximate exponential function represents an oscillation mode, then the original signal is composed of \(p\) modes, which can be expressed as:

\[
\hat{x}(n) = \sum_{i=1}^{p} b_i z_i^n
\]

\(b_i = A_i \exp(j\theta_i)\)

\(z_i = \exp((\alpha_i + j2\pi f_i)\Delta t)\) (1)

Among them, \(A_i, \theta_i, a_i, f_i (i=1…p)\) are the amplitude, phase, attenuation factor and oscillation frequency of the signal, \(\Delta t\) is the sampling interval. In order to make the approximate function close to the actual sampling data, the error \(\epsilon\) between them should be minimized

\[
\epsilon = \sum_{n=1}^{N} (x(n) - \hat{x}(n))^2
\] (2)

The above equation is solved by the least square method, and eventually can be reduced to the following formula
\[ Zb = x \]  

where \( Z = \begin{bmatrix} 1 & 1 & \ldots & 1 \\ z_1 & z_2 & \ldots & z_p \\ \vdots & \vdots & \ddots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \ldots & z_p^{N-1} \end{bmatrix} \) and \( b = [b_1, b_2, \ldots, b_p]^T \). Then the amplitude \( A_i \), phase \( \theta_i \), attenuation factor \( \alpha_i \), and oscillation frequency \( f_i \) (for \( i = 1, \ldots, p \)) of each oscillation mode are calculated directly:

\[
\begin{align*}
A_i &= |b_i| \\
\theta_i &= \arctan(\text{Im}(b_i) / \text{Re}(b_i)) / 2\pi \Delta t \\
\alpha_i &= \ln|z_i| / \Delta t \\
f_i &= \arctan(\text{Im}(z_i) / \text{Re}(z_i)) / 2\pi \Delta t
\end{align*}
\]  

3.2. The HHT algorithm

The HHT algorithm consists of empirical mode decomposition (EMD) and Hilbert transform. EMD can decompose the sampled data into multiple intrinsic mode function (IMF) components and residual components. Each IMF component must meet the following two conditions:

1. The envelope of the maximum point and the minimum point is symmetric with respect to the time axis;
2. The number of maximum and minimum points is equal to or at most different from the number of zero crossing points by 1.

Furthermore, Hilbert transform is used to calculate the instantaneous amplitude, frequency, and phase of each IMF component. Considering the large margin error of HHT algorithm, the middle analysis result is selected as the initial value, and the amplitude, damping coefficient, frequency, and phase parameters of each mode are fitted according to the least square method.

3.3. Applicability analysis of two algorithms

According to the above algorithm mechanism, the performance of Prony and HHT algorithm in noise interference, signal stability and solution speed are compared as follows:

1. Noise interference. Prony algorithm is sensitive to the influence of noise. The algorithm can get better identification results only when the signal-to-noise ratio is not less than 50–60 dB[6]. Therefore, it is necessary to build a prefilter before using Prony algorithm. HHT algorithm has the ability to filter out the high-frequency disturbance, so it has strong anti-noise interference ability.

2. Stationary signal identification. The two algorithms can achieve good identification results for stationary signals. Prony algorithm has better identification results for small amplitude components and stronger signal resolution.

3. Nonstationary signal identification. Prony algorithm is a global oriented method, which can only match a set of oscillation modes. Therefore, the identification results cannot show the transient characteristics of non-stationary signals. HHT algorithm introduces the concept of instantaneous frequency and amplitude, which can extract the oscillation mode of non-stationary signal.

4. Identification speed. With the increase of the scale of the measurement data set, the order of the equation needed to be solved by Prony algorithm is increasing. And the solution of the high dimension equation limits the speed of identification. HHT algorithm mostly involves elementary operation, and the analysis speed is linear with the data scale.

According to the above four points, the applicability of the two identification algorithms is considered in combination with the characteristics of distribution network. Because the distribution network has many harmonic sources, the noise content of the measured signal is high. And the measurement
signals of power system are non-stationary and non-linear. Therefore, HHT algorithm is more suitable to extract the oscillation mode from the synchronous phasor of distribution network. When the measurement data is stationary, the oscillation information can be extracted by Prony algorithm after the measurement signal is filtered, so as to obtain higher accuracy identification results.

4. Case study
In this paper, the measured synchronous phasor signal of distribution network in China’s central and north interconnection power grid is taken by LFO-DPMU as the research object. The signal data is got from WAMS Light, a wide area measurement system of distribution network exploited by Shandong University [7]. PMU light, a measurement device under the WAMS Light, has been widely used in six major power grids of China. The device is arranged at the low-voltage user side and collects high-precision synchronous phasor of distribution network to the main station all day long, which has become a representative application of distribution network dynamic monitoring in China.

Figure 2 shows the measured phase waveforms of Jinan and Wuhan distribution networks under WAMS light. It shows that the phase difference between the two places is about 40°.

![Figure 2. Measured phase waveform](image)

The phase difference is calculated according to the measured phase data. After the mutation, low-pass filtering and DC elimination, the phase difference waveform is shown in figure 3 (a).

![Figure 3. Analysis results of Prony algorithm](image)

When Prony algorithm is used to analyse the signal, three dominant oscillation modes listed in Table 1 can be obtained. The waveform restored from analysis results are shown in figure 3 (b). It shows that the phase difference waveform measured in figure 3 (a) is quite different from the waveform in figure 3 (b), which proves that Prony is difficult to process non-stationary synchronous phasor information of distribution network.
Table 1. Prony analysis results of measured phasor in distribution network

| Oscillation mode $i$ | $f_i$  | $\alpha_i$ | $A_i$  | $\theta_i$ |
|----------------------|--------|------------|--------|------------|
| 1                    | 0.178  | -0.154     | 1.426  | 116.405    |
| 2                    | 0.184  | -0.566     | 1.278  | -113.228   |
| 3                    | 1.280  | -5.993     | 0.114  | 112.316    |

The HHT algorithm is used to analyse the measured phase difference data in figure 3 (a). The amplitude $A_i$, phase $\theta_i$, attenuation factor $\alpha_i$ and oscillation frequency $f_i$ of the dominant oscillation mode are 1.197, 2.339, 0.116 and 0.157 respectively. The waveform restored from HHT analysis results are shown in figure 4 (a), which is very close to the original data waveform. The error between the original waveform and restored waveform is shown in figure 4 (b), which shows that the error is large at the boundary. This is because the boundary effect of the Hilbert transform, and in the middle of the waveform, HHT algorithm has accurate identification results for the oscillation mode.

Figure 4. Analysis results of HHT algorithm

5. Conclusion

Based on the synchronous phasor of distribution network, this paper constructs an online monitoring system of low-frequency oscillation (LFO-DPMU), which makes full use of the low-cost, flexible and reliable characteristics of measuring equipment, and realizes the real-time extraction of low-frequency oscillation in low-voltage distribution network. The whole process of measurement data acquisition from distribution network to modal extraction is completed with four-layer physical architecture. The mechanism and performance of Prony and HHT are compared, and the applicability of the two algorithms is analysed based on the characteristics of distribution network signals. Finally, the feasibility and accuracy of the LFO-DPMU are proved by the measured synchronous phasor of distribution network, which makes it possible to monitor the low frequency oscillation of the interconnected power grid at the distribution network side.

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