ESPRIT-based fast broadband measurement method

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Abstract. As the penetration rate of power electronic devices in the power system is getting higher and higher, the broadband characteristics of electrical quantities are becoming more and more significant, and it has caused new network-related stability problems. The monitoring frequency band range and response speed of power system signals are proposed New requirements. This paper uses the super-resolution characteristics of spatial spectrum estimation to propose a short-time window wide frequency measurement method, and estimates the number of signal frequency components through the kurtosis of the signal singular value, and proposes a method based on ESPRIT. The fast broadband data measurement method has shorter response time and higher resolution for fast-changing broadband signals, and at the same time improves the performance of this method in the case of lower signal-to-noise ratio.

1. Introduction

With the development and utilization of large-scale renewable energy and the development of smart grids, China has now built a super-large-scale complex interconnected power system. High penetration power electronic devices make the dynamic characteristics of power system signals increasingly complex, and the frequency band range presents the characteristics of broadband.

Power electronic devices can also cause frequency components up to 300Hz in the system, which also causes new network-related stability problems. The analysis of a large number of on-site recording data shows that the frequency points of the above 0~300 Hz component are dense, and the frequency and amplitude can change rapidly with time (the amplitude can change by 50% within 1s). In addition, more and more power electronic equipment has been put into operation. The operation of these devices has improved the flexibility and reliability of grid operation, but it has also produced a large amount of harmonic pollution, which affects the power quality of the grid [1]. Power electronic devices also generate a large number of high-order harmonics (up to the 50th harmonic), which makes the harmonic pollution of the power system more serious. Therefore, it is urgent to carry out real-time synchronous measurement of broadband signals from 0 to 2500 Hz to provide data for research on broadband signal sources, propagation paths, and safety control.

In terms of measurement methods for broadband signals, FFT (fast Fourier transform) and its improved algorithms have been widely used in power system electrical power spectrum analysis due to the advantages of small calculation and easy hardware implementation [2-3]. However, the frequency resolution of FFT is proportional to the time window length, that is, a longer time window is needed to achieve a higher frequency resolution. This makes it impossible to take into account the measurement accuracy and tracking speed at the same time when measuring the rapidly changing
frequency components of 0–300 Hz. It has better measurement results for integer harmonics with a large frequency interval and relatively stable. In addition, wavelet transform \[4,5\] and Prony algorithm \[6\] are also commonly used spectrum analysis methods, but these two methods have poor stability and cannot maintain good performance in the case of lower signal-to-noise ratio. The rotation invariant subspace ESPRIT (estimation of signal parameters via rotation invariance technique) algorithm is a spatial spectrum estimation method that uses the orthogonal characteristics of the signal subspace and the noise subspace of the sampled signal.

Aiming at the problem that it is difficult for existing methods to have both accurate measurement and fast tracking capabilities for fast-changing broadband signals, this paper uses the "super-resolution characteristics" of spatial spectrum estimation to propose a short-time window broadband measurement method, and through the singular value of the signal Kurtosis estimates the number of signal frequency components, and proposes a fast broadband data measurement method based on ESPRIT (kurtosis-ESPRIT), which has a shorter response time and higher resolution for fast-changing broadband signals. The performance of the method under lower signal-to-noise ratio.

2. Theoretical basis

2.1. ESPRIT algorithm

The most basic assumption of the ESPRIT algorithm is that there are two identical sub-arrays, and the distance between the two sub-arrays $\Delta$ is known. Because the structure of the two sub-arrays is exactly the same, and the number of elements of the sub-array is $m$. For the same signal, the output of the two sub-arrays has only one phase difference $\phi, i \notin [1, N]$. The following assumes that the received data of the first sub-array is $X_1$; the received data of the second sub-array is $X_2$, $N_1$ is Gaussian white noise with zero mean and $\sigma_1^2$; $N_2$ is white Gaussian noise with zero mean and $\sigma_2^2$.

Available according to the knowledge of the array model:

$$X_1 = AS + N_1$$

$$X_2 = A \phi S + N_2$$

In the above formula, the array flow pattern of sub-array 1 is $A_1 = A$; the array flow pattern of sub-array 2 is $A_2 = A \phi$. And there are $\phi = \text{diag}(e^{j\phi_1}, \ldots, e^{j\phi_m})$, $\phi_k = (2\pi |\Delta| \sin \theta_k) / \lambda$, where $\theta_k$ is the incident azimuth of the $k$-th signal, and $\lambda$ is the signal wavelength.

The direction information of the signal is contained in the matrices $A$ and $\phi$. Therefore, as long as the rotation invariant relationship $\phi$ between the two sub-arrays is obtained, the information about the signal arrival angle can be obtained. Combine the models of the two sub-arrays, namely:

$$X = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} A \\ A \phi \end{bmatrix} S + N = \bar{A} S + N$$

The eigenvalue decomposition of the above covariance matrix $R$ can be obtained:

$$R = E \left[ X X^H \right] = \sum_{i=1}^{2m} \lambda_i e_i e_i^H = U_s \sum_s S_s^H + U_N \sum_N N_N^H$$

In the above formula, $U_s$ is the signal subspace formed by the feature vector corresponding to the large eigenvalue, and $U_N$ is the noise subspace formed by the feature vector corresponding to the small eigenvalue. For the actual snapshot data, the above formula should be revised as:

$$R' = U_s' \sum_s S_s'^H + U_N' \sum_N N_N'^H$$

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According to the knowledge of the array model, the signal subspace formed by the large eigenvector expansion in the above eigen decomposition is equal to the signal subspace formed by the array flow pattern. At this time, there is a unique non-singular matrix $T$. Then there are:

$$\text{span}\{U_s\} = \text{span}\{\tilde{A}(\theta)\} \quad (6)$$

$$U_s = \tilde{A}(\theta)T \quad (7)$$

Where $\theta$ is the signal incident azimuth.

Due to the subspace $U_{S1}$ formed by the large feature vector of subarray 1, the subspace $U_{S2}$ formed by the large feature vector of subarray 2 is equal to the subspace formed by array flow pattern $A$. The relationship between the two sub-arrays is:

$$A_2 = A_1\phi \quad (8)$$

The relationship between the signal subspaces of the two subarrays is derived as:

$$U_{S2} = U_{S1}T^{-1}\phi T = U_{S1}\psi \quad (9)$$

The above equation (8) reflects the rotation invariance between the array flow patterns of the two sub-arrays; and equation (9) reflects the rotation invariance of the signal subspace of the data received by the two sub-array arrays. If the array flow pattern $A$ is a full-rank matrix, we can also get from equation (9):

$$\phi = T\psi T^{-1} \quad (10)$$

Therefore, once the above-mentioned rotation invariant relationship matrix $\psi$ is obtained, the incident angle of the signal can be obtained.

2.2. ESPRIT algorithm flow

The basic principle of the ESPRIT algorithm is the rotation invariance of equation (9). The conventional rotation invariant subspace algorithm uses the above basic principle to solve the incident angle information of the signal. The ESPRIT algorithm belongs to the signal subspace algorithm. It is solved by using the rotation invariance of the signal subspace between subarrays, which is different from other algorithms. The standard ESPRIT algorithm is a weighted signal subspace fitting algorithm.

3. Algorithm noise test and field data test

3.1. Noise test

The above test signal with 60dB Gaussian white noise is used in this paper to estimate the number of signal frequency components. The division parameters at the 2 sub-space boundary of 50 measurements are shown in Figure 1.
It can be seen from Figure 1(a) that in a noisy environment, it is difficult to accurately determine the number of signal frequency components using only the difference of the singular values obtained by SVD. Although the GDE algorithm can also amplify the singular value to a certain extent the effect of the difference, but the performance is not stable in the case of noise. The method in this paper is basically the same as the parameter fluctuation trend of the GDE algorithm, but the method in this paper can use high-order parameters to amplify the sudden change of the signal. The division parameter at the boundary of the seed space is always maintained above 10, presenting more obvious characteristics, and thus has stronger anti-noise ability. When L and M are set to 120~300, the number of signal frequency components can be accurately estimated, as shown in Figure 1(b).

3.2. Field data test
The algorithm in this paper is used to analyze the 25s current recording data of a power plant, and it is compared with the windowed zero-filling FFT algorithm with a 10s time window and the windowed zero-filling FFT algorithm with a 0.2s time window, as shown in Figure 2.

In Figure 3(a), taking the frequency components around 76.6 Hz as an example, the windowed zero-padding FFT algorithm with time windows of 10s and 0.2s and the algorithm of this paper (K-ESPRIT) with time windows of 0.2s are used as an example. Compare the measurement results. It can be seen that the method in this paper is consistent with the trend of interharmonic changes reflected by the windowed zero-filled FFT algorithm with a 10s time window, while the windowed zero-filled FFT algorithm with a 0.2s time window is affected by the sidelobes of the fundamental frequency component, which is similar to other 2. The measurement results of this method have large deviations.

In particular, for the dynamic process of interharmonics in the range of 0~6s from scratch, as shown in Figure 3(b), it can be seen that the method in this paper is compared with the windowed zero padding with a longer time window (10s). The FFT algorithm can produce a faster response to the dynamic process of the signal, which can better reflect the dynamic process of the signal.
4. Conclusion
Aiming at the measurement problem of power system broadband dynamic signal under high penetration of power electronic devices, this paper proposes a fast broadband measurement method based on ESPRIT. This method can break through the limitation of time window length on frequency resolution in FFT algorithm. When the window is shorter, it has higher frequency resolution, and estimates the number of signal frequency components through the kurtosis of the signal singular value, which improves the performance of the broadband measurement method in a lower signal-to-noise ratio environment; and implements the above algorithm on hardware. Tests and field data verification show that the method proposed in this paper has high accuracy, has better tracking ability for fast-changing broadband signals, and can accurately measure and quickly track broadband dynamic signals in power systems. However, the data processing process of the method in this paper is more complicated than the FFT algorithm and requires higher hardware performance. For large-scale applications, the algorithm data processing process needs to be optimized to reduce device costs.

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