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Research on Sub-Synchronous Oscillation Mode and Parameter Identification of Wind-Fire Bundling System
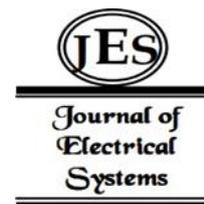
Abstract: - The structure of grid-connected wind power system is complex and constantly changing operating conditions.It is challenging to establish a physical model of grid-connected wind power and analyze its modal parameters to ensure the stable operation of the system. A hybrid algorithm for modal parameter identification based on blind source separation is proposed in this work. In this paper, based on the detailed model of the wind-fire bundling of the double-fed fan, combined with the impedance analysis method, the principle of the system's sub-synchronous oscillation is analyzed, the detailed structural model and mathematical formula are established, and the strongly correlated variables are selected as the basis for the following research. Then, the algorithm of removing noise and harmonic interference is combined with the identification algorithm to analyze the sub-synchronous oscillation modes and related parameters in the grid-connected wind power system. Finally, this paper constructs the ideal model and the IEEE first model containing doubly-fed fan system simulation t, and the accuracy and effectiveness of the BSS-DMD method are proved. The frequency error can reach less than 1%, and the damping ratio error does not exceed 3%. This identification method with high accuracy can provide a new solution and basis for the power system stability problem caused by the sub-synchronous oscillation phenomenon of wind power connected to the grid.

Keywords: Sub-Synchronous Oscillation;Parameter Identification; Doubly-fed Wind Turbine; Impedance Analysis;

I. INTRODUCTION

With the complexity of power grid scale and the rapid development of new energy generation, the power system gradually presents a "double height" feature[1-2].The construction of a new grid-connected power system with new energy has become the main measure to achieve the dual-carbon goal and solve the shortage of fossil energy. In China, the "bundle" of wind power and thermal power is adopted to solve the problem of uneven distribution of resources, but it also brings new challenges to the stable operation of the power system[3-5].

Subsyn-Shronous Oscillation (SSO) causes system oscillation instability, which affects the safety and stability of power system and large-scale power grid operation[6-8].With the continuous improvement of the scientific and technological level of monitoring technology, Wide Area Measurement System (WAMS) has received a lot of attention in the field of power industry and has been promoted and applied in power systems [9-13], providing a reliable data source for the research of system parameter identification. Therefore, the signal analysis method derived from the measured data of WAMS is favored by researchers in terms of modal parameter identification .

Modal parameter identification methods mainly include Prony[14], Hibert-Huang Transform (HHT)[15]and empirical wavelet transform. In literatures [16], the Prony algorithm is used to analyze the sub-synchronous oscillation signal, and the parameter information such as amplitude and frequency of the signal can be accurately obtained. However, this algorithm is particularly sensitive to noise and has poor robustness, resulting in a significant decline in identification accuracy. HHT algorithm has good time-frequency localization characteristics and can capture instantaneous characteristics of signals. However, the analysis shows that frequency aliasing occurs during the application of HHT, and the identified SSO signal results have large errors. At the same time, HHT also has the end effect, and the identification error of frequency and amplitude at the boundary is large. The key to identify the sub-synchronous oscillation signal is to obtain the complete SSO mode[17-19].

In this paper, a method combining BSS-DMD is proposed to identify sub-synchronous oscillation parameters of power system.Firstly, the sub-synchronous oscillation mechanism is analyzed, then the required source signal is obtained from the measured signal with noise and harmonics based on BSS technology, and then DMD is used to identify the frequency and damping ratio of the processed signal. The results of two examples of ideal signal and IEEE First standard model with doubly-fed wind turbine show that the proposed method can accurately identify the frequency and damping ratio of the subsynchronous oscillation. Compared with the identification results obtained by Prony algorithm, the feasibility and effectiveness of the proposed method are verified.

II. MECHANISM ANALYSIS OF SUB-SYNCHRONOUS OSCILLATION

The grid-connected doubly-fed wind power system is shown in Figure 1, which mainly includes DFIG fan and its control system (rotor-side converter RSC and grid-side converter GSC), thermal power unit and series

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compensation line. Where, X_{T1} and X_{T2} are transformer reactance; R_L is line resistance; X_L is line reactance; X_C is the series complement capacitor; XS is the equivalent reactance of the infinity system.
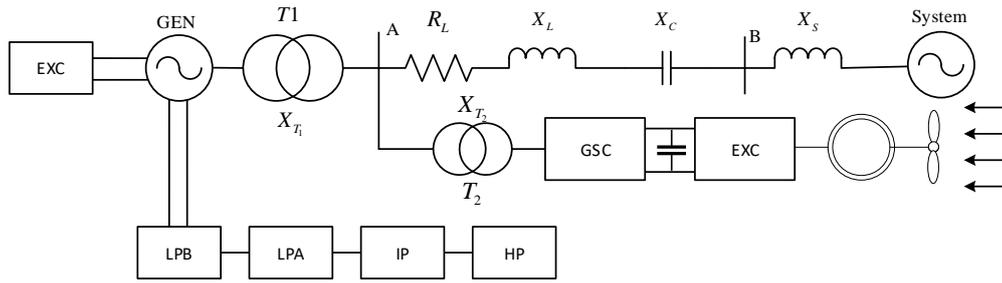
Figure 1. model of wind-fire bundling and series compensation grid-connected system

In the system, transmission lines, transformers and thermal power units are directly represented in impedance form, while the stator side of the induction generator of wind power is transformed into the dq coordinate system by Park transformation. The rotor side converter adopts double closed-loop control of power outer loop control and current inner loop control, so as to realize the decoupling control of active power and reactive power. The control block diagram of RSC is shown in Figure 2.
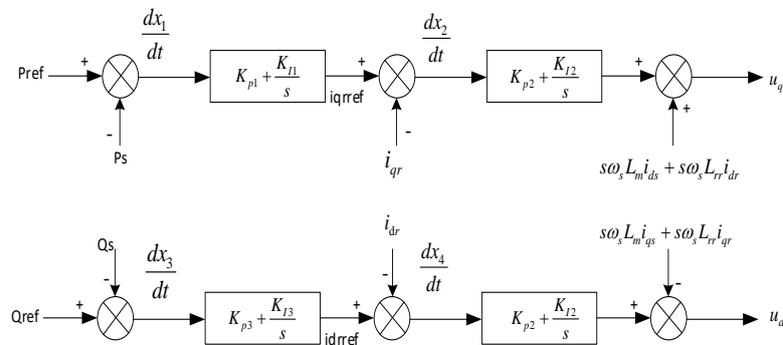
Figure 2. block diagram of rotor side converter control system

In Fig. 2, *Pref* and *Qref* represent the preset reference values of the stator output active power and reactive power respectively, which are used for comparison and control with the actual output value. *Ps* and *Qs* are the actual measured values of stator output active power and reactive power respectively, reflecting the current operating state of the generator. *irdref* and *irqref* represent the reference values of d axis and q axis respectively in the current control link of the rotor side converter, which are important bases for the current inner loop control. *KP1* and *KI1* are proportional coefficients and integral coefficients of the active power control link of the rotor side converter, which are used to adjust the control effect of the active power. Similarly, *KP3* and *KI3* are used for reactive power control to ensure stable reactive power output. In addition, *KP2* and *KI2* are the proportional and integral coefficients of the rotor-side converter current control link, which are responsible for fine-tuning the rotor current for more efficient energy conversion.

The grid-side converter adopts D-axis directional stator voltage vector control, which is mainly used to maintain constant DC bus voltage and reactive power control.

However, the equivalent impedance of the grid-side converter is large and the influence of the grid-side converter on the secondary synchronous oscillation is small. At the same time, the mutual inductance between the stator windings and the rotor windings in the doubly-fed fan is much greater than the leakage inductance of the stator windings and the rotor windings. Therefore, the influence of the mutual inductance between the fan and the rotor windings and the grid-side converter is ignored. At this time, the equivalent circuit for sub-synchronous oscillation analysis of the doubly-fed wind power grid-connected system is shown in Figure 4.
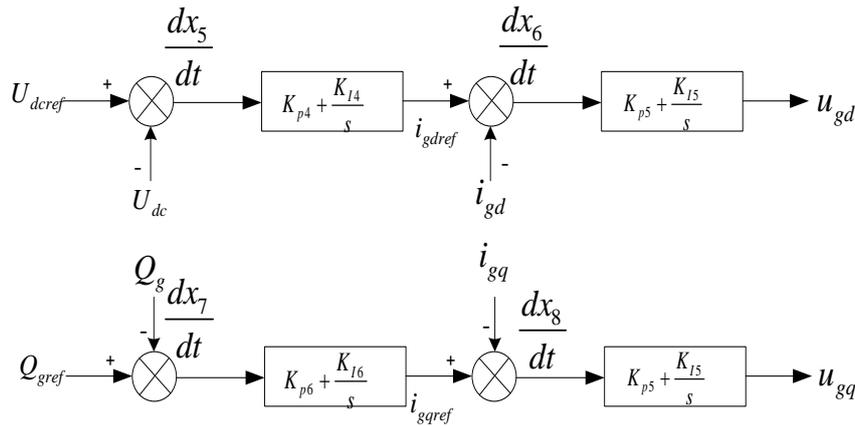
Figure 3. Grid side converter control system structure block diagram
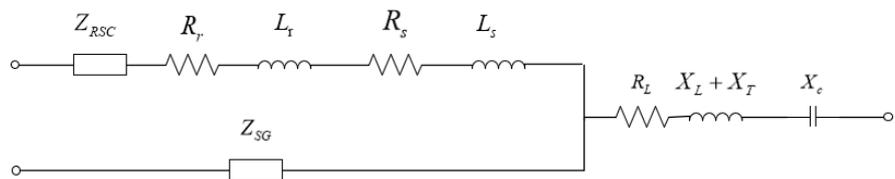
Figure 4. equivalent circuit diagram of doubly fed wind power grid-connected system

In Figure 4, *Rr* and *Lr* are the rotor impedance of DFIG, *Rs* and *Ls* are the stator impedance of DFIG, Z_{RSC} is the impedance of the rotor side converter, and Z_{SG} is the impedance of the thermal power unit.

The fan rotor side component and slip rate are reduced to the stator side, and under the sub-synchronous oscillation frequency fer, the fan rotor slip rate is shown in formula (1) :

$$s = \frac{f_{er} - f_r}{f_{er}} \tag{1}$$

In the formula, *fr* is the rotor frequency of the doubly-fed fan.

At this time, the equivalent impedance of the whole system is shown in formula (2) :

$$
\begin{aligned}
Z_{eq} = R_{eq} + jX_{eq} \\
= \left(\left(\frac{R_{RSC}}{s} + \frac{R_r}{s} + R_s \right) \square R_{SG} \right) + R_L \\
+ j \left(\left(\left(X_r + X_s - X_{RSC} \right) \square X_{SG} \right) + X_L + X_T - X_C \right)
\end{aligned}
\tag{2}
$$

fr is usually higher than the sub-synchronous resonant frequency *fer*, so the slip rate *s* is less than 0. If the slip rate s is less than 0 at the oscillation frequency, the equivalent resistance of the doubly-fed fan rotor is negative, providing negative damping for the system. When the absolute value of the negative resistance of the rotor is greater than the sum of the total positive resistance of the system, the equivalent resistance of the system is negative, and the system will have sub-synchronous oscillation and oscillation divergence. The greater the absolute value of the system equivalent negative resistance, the faster the divergence rate.

According to the above analysis, the occurrence of sub-synchronous oscillation is mainly caused by the rotor side converter of the fan in the wind-fire bundling system. Due to the small rigidity of wind turbine shafting, it is difficult to cause sub-synchronous oscillation, and there is no large-scale fan shafting oscillation problem at present. However, after the output of sub-synchronous oscillation component of the fan system, it will affect the thermal power system and cause SSO phenomenon of the turbine unit, affecting the stable operation of the system. Therefore, we will select the turbine speed variable analysis later, to provide a strong theoretical support for the system dynamic stability analysis and control.

III. ALGORITHM SUBSYNCHRONOUS OSCILLATION MODAL IDENTIFICATION BASED ON BSS-DMD

3.1 Signal preprocessing in blind source separation

Most of the signals collected in the power system contain noise and harmonic interference, which will be more and more serious when the sub-synchronous oscillation occurs. Through blind source separation technology, we can accurately separate the interference signal from the original signal containing the subsynchronous oscillation component, and extract the pure signal containing the subsynchronous oscillation component that we need.

When sub-synchronous oscillation occurs in the system, the linear model is shown in formula (3) :

$$Y = A \cdot S \qquad (3)$$

In the formula, Y is the acquisition signal; A is a mixed matrix; S is the source signal.

In many cases, both the mixed matrix and the source signal are unknown. Therefore, it is necessary to construct the unmixing matrix B to separate the source signal from the collected signal, and the expression is shown in formula (4) :

$$S = B \cdot Y \qquad (4)$$

To accurately isolate the source signal, we need the unmixing matrix B to be best approximated to A^{-1}. Maximizing negative entropy is selected as the objective function to extract the source signal, and negative entropy $J(s)$ is usually shown in formula (5) :

$$J(s) \approx \left[E|G(s)| - E|G(s_{gauss})| \right]^2 \qquad (5)$$

In the formula: E represents statistical expectation; $G(s)$ is a non-quadratic function; s is an independent source signal; sgauss is the Gaussian distribution vector of s.

The maximum negative entropy is taken as the objective function, that is, the value of $w_i(n)$ is constantly iteratively adjusted to maximize the negative entropy of the result. The iterative formula is shown in formula (6) :

$$w_i(n+1) = E\left\{ xG'\left(w_i^T(n) \cdot x \right) \right\} - $$
$$E\left\{ xG^n\left(w_i^T(n) \cdot x \right) \right\} \cdot w_i(n) \qquad (6)$$

In the formula, $w_i(n)$ represents the i th row vector corresponding to the independent component in the unmixing matrix; i is the number of independent components; n is the number of iterations; x is obtained by data centralization and other preprocessing of observation signal X.

Normalization is performed as shown in formula (7) :

$$w_i(n) = w_i(n) / \| w_i(n) \| \qquad (7)$$

Let $w_i(0)$ be the unit norm vector. When formula (8) is established, the iteration converges and a source signal is successfully separated from the measured signal. If it does not, repeat the process until it does.

$$\left\| w_i(n+1) \times w_i^T(n) \right\| = 1 \qquad (8)$$

Assuming that the source signal contains several independent components, the separation of multiple components can also be realized through the above process. When an independent component is separated, it is subtracted from the measured signal, and this process can be repeated to achieve complete separation of the signal.

Through this process, we can separate the collected sub-synchronous oscillation signal from the interference signal, and can also separate the signal containing a variety of different sub-synchronous oscillation information.

3.2 BSS-DMD algorithm implementation process

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Power system is usually a nonlinear system, DMD constructs the nonlinear system as an approximate linear system between each cell, and the model can be expressed as formula (9) :

$$\Delta \dot{x}(t) = A_d \Delta x(t) \qquad (9)$$

In the formula, $\Delta x(t)$ is the system state variable; A_d is a state matrix.

The data matrix X obtained by sampling X_m times at an interval of Δt is shown in formula (10) :

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{10}$$

The measurement data are shown in formula (11) :

$$\begin{cases} X_m = \begin{bmatrix} \vdots & \vdots & & \vdots \\ \Delta x_1 & \Delta x_2 & \cdots \Delta x_m \\ \vdots & \vdots & & \vdots \end{bmatrix} \\ X_{m+1} = \begin{bmatrix} \vdots & \vdots & & \vdots \\ \Delta x_2 & \Delta x_3 & \cdots \Delta x_{m+1} \\ \vdots & \vdots & & \vdots \end{bmatrix} \end{cases} \tag{11}$$

The discrete form of the system state equation is shown in equation (12) :

$$X_{m+1} = A_d X_m \tag{12}$$

In the formula: Ad is the discrete form of the system state matrix A.

Ad is usually a high-dimensional matrix, so it is difficult to directly solve the generalized inverse in the current power system containing new energy. By considering the eigenvalue analysis of the low order approximate matrix of Ad.

The lower order approximate matrix of A_d can be obtained by singular value decomposition (SVD). First, SVD is performed on the original data matrix Xm, and formula (13) is obtained:

$$X_m = U \sum V^* \tag{13}$$

In the formula: U and V are unitary matrices, * represents transpose, $V^* V = I$, I is the identity matrix; $\sum$ is a diagonal matrix with singular values.

The system state matrix A_d and its approximate matrix are orthogonal decomposed by this proof, as shown in equation (14) :

$$A_d \approx U \overline{A} U^* \tag{14}$$

In the formula: U is the mode.

The calculation process of the low-dimensional approximate matrix can be regarded as solving an optimization problem, as shown in formula (15) :

$$\min_F = \left\| X_{m+1} - U \overline{A} \sum V^* \right\|_F^2 \tag{15}$$

In the formula: $\left\| \cdot \right\|_F^2$ is Frobenius norm.

Combining formula (13)-formula (15) , the formula (16) is obtained:

$$A_d \approx \overline{A} = U^* X_{m+1} V \sum{}^{-1} \tag{16}$$

On this basis, the eigenvalue decomposition of the low-dimensional approximate state matrix is performed, as shown in formula (17) :

$$\overline{A} = \phi \Lambda \varphi \tag{17}$$

It is converted to continuous eigenvalues, and the transformation relationship between discrete eigenvalues λi and continuous eigenvalues ηi is shown in formula (18).

$$\eta_i = \log(\lambda_i) / \Delta t = \alpha_i + j\beta_i \tag{18}$$

Therefore, the oscillation frequency fi and damping ratio σi corresponding to the i th mode can be obtained, as shown in formula (19).

$$\begin{cases} f_i = \beta_i / 2\pi \\ \sigma_i = -\alpha_i / \sqrt{\alpha_i^2 + \beta_i^2} \end{cases} \tag{19}$$

Through the above process, we can obtain one or more frequencies of the desired sub-synchronous oscillation and the parameter information of the damping ratio.

To sum up, the mode identification process of double-fed wind turbine SSO signal based on BSS-DMD algorithm proposed in this paper is shown in Figure 5. The specific process is as follows:

(1) The signal data of the system when the sub-synchronous oscillation occurs is col lected. The measurement signal in this paper is the generator rotor speed signal

(2) Pre-process the collected signal data, such as de-trending and eliminating the correlation of each component.

(3) The blind source separation technology is used to process the signal, which can separate the original signal and the interference signal, and extract the pure SSO signal.

(4) DMD algorithm was used to identify the extracted signal modes, and related parameters such as frequency and damping ratio were calculated.

(5) Stability analysis is carried out using the obtained relevant parameters to provide theoretical and data support for the safe and stable operation of the system.

(6)
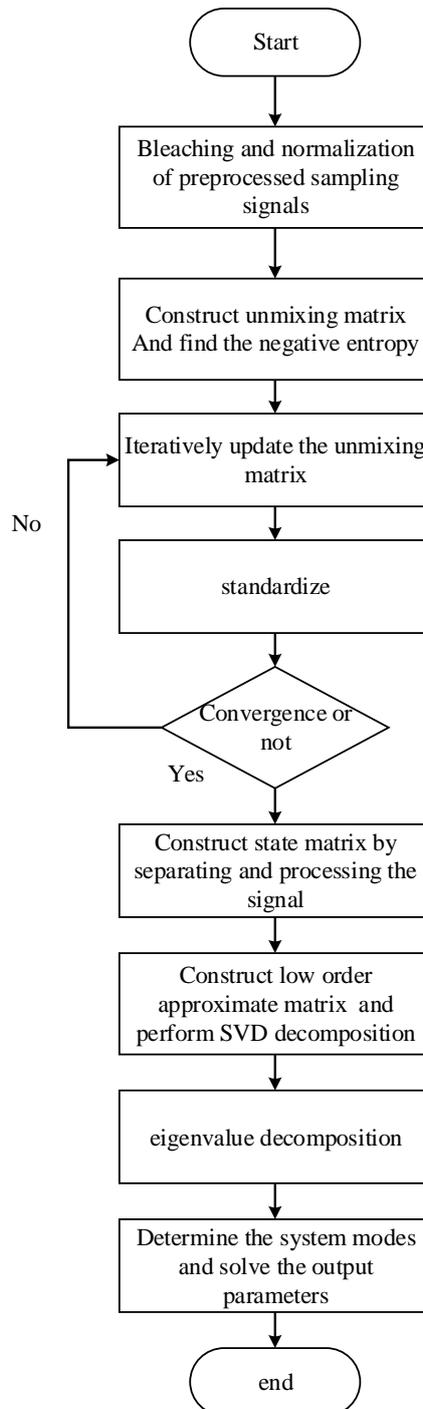
Figure 5. The model implementation flowchart

<center>IV. EXAMPLE ANALYSIS</center>

4.1 Ideal example

Construct a set of sub-synchronous oscillating signals $X(t)$ as shown in formula (20) :

$$x(t) = x_1(t) + x_2(t) + x_3(t) + \eta \tag{20}$$

in the formula：

$$\begin{cases} x_1(t) = 1.6e^{-0.13t} \cos\left(2\pi \times 15.7t + \dfrac{\pi}{4}\right) \\[2mm] x_2(t) = 2.2e^{-0.25t} \cos\left(2\pi \times 20.2t + \dfrac{\pi}{6}\right) \\[2mm] x_3(t) = 3.0e^{-0.6t} \cos\left(2\pi \times 32.2t + \dfrac{\pi}{3}\right) \end{cases} \tag{21}$$

Its parameters are shown in Table 1, and the resulting signal graph is shown in Figure 6.
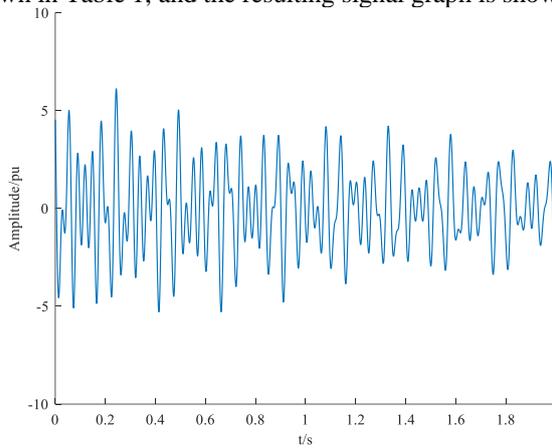
Figure 6. Ideal signal

Table 1. Ideal signal parameters

mode	Frequency/Hz	Amplitude/pu	Damping ratio
1	15.7	1.6	0.132
2	20.2	2.2	0.197
3	32.2	3.0	0.297

Since the measured signal mostly contains noise signal and harmonic signal, this paper simulates the ideal signal by adding Gaussian white noise. Gaussian white noise with a signal-to-noise ratio of 5dB is constructed and added into the ideal signal, and the waveform is shown in Figure 7.
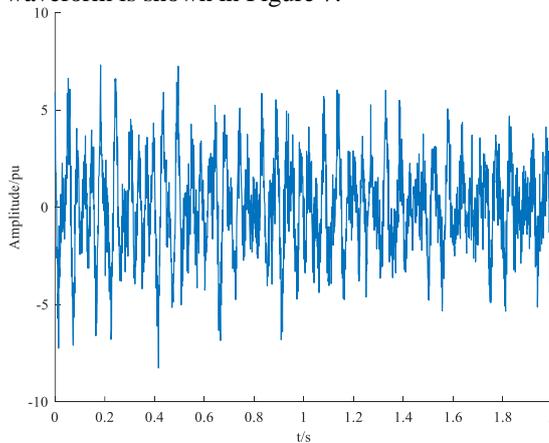
Figure 7. Mixed signals

Compared with the original signal, there are many burrs in the mixed signal waveform, which will affect the identification accuracy in the process of parameter identification.

The blind source separation technology is used to separate and process the signal, as shown in Fig. 8, it is obvious that the original signal can be better separated.
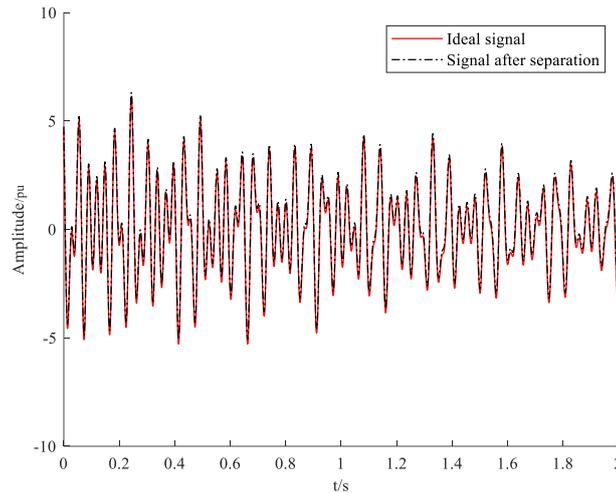
Figure 8. Separation of the original signal and the ideal original signal

Signal quality after noise reduction is evaluated by signal-to-noise ratio. The better the noise reduction effect of the algorithm, the larger the signal-to-noise ratio value. Signal noise is shown in formula (22) :

$$SNR=10\lg \frac{\sum_{i=1}^{N} x_1^2(i)}{\sum_{i=1}^{N}\left(x_1(i)-x_2(i)\right)^2}$$

(22)

In the formula, SNR is the signal-to-noise ratio; X_1 and X_2 are the ideal signal and the signal after noise reduction. Through the calculation of the above formula, the signal-to-noise ratio of the separated signal is 10.274db, which is improved to some extent compared with the original, indicating the effectiveness of the blind source separation technology used in this paper in the face of signals containing interference.

Prony algorithm and the method proposed in this paper are used respectively to identify the frequency and damping ratio of the ideal signal containing 5db Gaussian white noise. The results are shown in Table 2 and Table 3.

Table 2. Prony algorithm identifies the results

mode	Frequency/Hz	Frequency error /%	Damping ratio	Damping ratio error/%
1	16.85	7.325	0.115	12.879
2	19.75	2.228	0.215	9.137
3	31.68	1.615	0.385	26.630

Table 3. BSS-DMD algorithm identification results

mode	Frequency/Hz	Frequency error /%	Damping ratio	Damping ratio error/%
1	15.642	0.369	0.134	1.515
2	20.275	0.371	0.203	3.046
3	32.259	0.183	0.304	2.357

As can be seen from Table 2, the error of Prony algorithm is relatively large, especially in the identification of damping ratio. This is due to the unsatisfactory anti-noise ability of Prony, which leads to a large identification error of the algorithm, even up to 30%. In terms of fitting accuracy, the proposed method can reach 13.0458, while prony is only 4.7625.Therefore, in the process of parameter identification, it is necessary to pre-denoise the signal.

The method proposed in this paper has high accuracy and good robustness in the identification of frequency and damping ratio. The results show that the method can accurately identify the sub-synchronous oscillation modes.

4.2. IEEE first standard model with doubly fed fans

Because of the reverse distribution of wind energy resources and electric energy demand in China, the external power supply based on wind and fire bundling has been widely used. Therefore, in this section, the wind-fire bundling system with double-fed fan series supplementing connected to the grid is selected as the research object to verify the effectiveness of the proposed method for SSO modal parameter identification. The simulation software adopts PSCAD, and the system simplified wiring diagram is shown in Figure 1. By applying some controllable disturbance to stimulate the speed oscillation, the speed curve after the disturbance is removed is observed, and the sub-synchronous oscillation phenomenon is analyzed. Some parameters and information of the simulation model are given in [20]

At 1.5s, a three-phase short circuit occurs at B of the fault logic module. The fault lasts for 0.075s and then is cleared. The simulation duration is 3.5s. In this paper, the turbine unit shafting speed deviation signal is selected as the identification signal, and the response signal of the turbine unit is shown in Figure 10. As can be seen from Figure 10, the speed signal of the turbine unit has obvious oscillation phenomenon and divergence trend. In order to facilitate the analysis and observation in this paper, signals from 1.5s to 3.5s are selected for data analysis and converted into speed deviation signals, as shown in Figure 9.
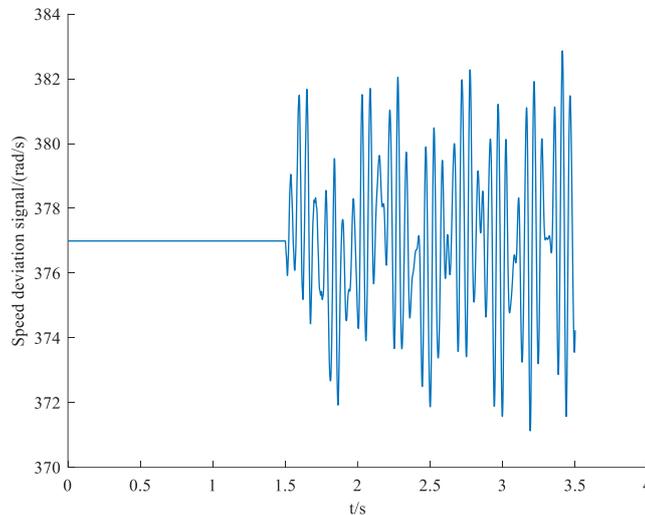
Figure 9. Turbine speed response signal

As can be seen from Figure 9, the speed signal of the turbine unit has obvious oscillation phenomenon and divergence trend. In order to facilitate the analysis and observation in this paper, signals from 1.5s to 3.5s are selected for data analysis and converted into speed deviation signals, as shown in Figure 10.
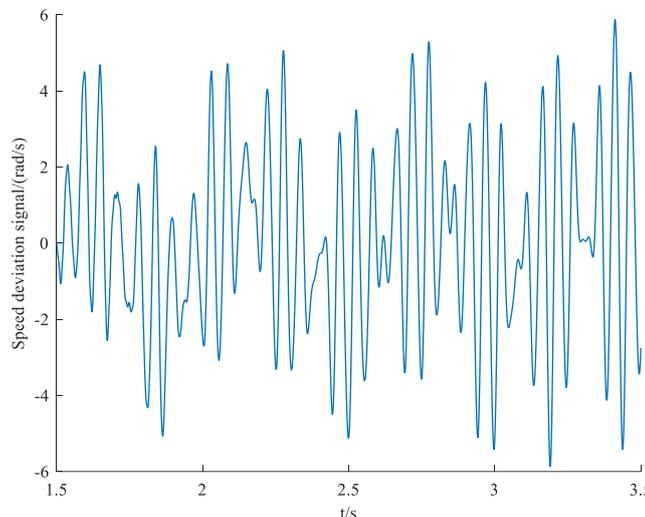
Figure 10. Speed deviation signal

In order to simulate the interference under real operating conditions, 5dB Gaussian white noise was added to the speed deviation signal, and then Prony and the algorithm in this paper were used for parameter identification, and the results were shown in Table 4 and Table 5.

Table 4. Prony algorithm identifies the simulation signal results

mode	Frequency/Hz	Frequency error /%	Damping ratio
1	14.785	6.002	0.332
2	21.215	4.833	-4.521
3	24.325	4.862	0.574
4	30.714	4.798	-4.458

Table 5.this artticle algorithm identifies the simulation signal results

mode	Frequency/Hz	Frequency error /%	Damping ratio
1	15.745	0.102	0.375
2	20.210	0.133	-3.706
3	25.678	0.430	0.484
4	32.212	0.155	-4.011

It can be seen from Table 4 and Table 5 that both identification methods can identify the modal parameters of the wind-fire bundling system with DFIG series complement connected to the grid. The damping ratio of mode 1 and mode 3 is positive damping, but in weak damping state, sub-synchronous oscillation is easy to occur; Mode 2 and mode 4 have negative damping ratios, and the system is unstable, oscillating and diverging. The anti-noise capability of Prony is not ideal, resulting in large errors in the parameter process. In terms of fitting accuracy, the proposed method can reach 15.2547, while prony is only 5.4475.The proposed algorithm has good robustness and identification accuracy than Prony, and the obtained identification results are not much different from the actual values, which further verifies the feasibility of the combined method of BSS and DMD in parameter identification.

V. CONCLUSIONS

The large-scale grid-connection of wind turbines changes the structure of the power system. In this paper, a method based on blind source separation and dynamic mode decomposition is proposed to identify SSO parameters using the data of the system under disturbed operation. The simulation results of ideal signal with interference signal and IEEE first standard model with doubly-fed wind farm show that BSS-DMD algorithm can accurately identify system parameters including oscillation frequency and damping ratio under noisy environment, which has high practical engineering significance. Research on applications in different environments and multi-energy systems will be the focus of subsequent research.

Data Availability Statement:

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest:

The authors declare that the research was conducted in the absence of any commerical or financial relationships that could beconstrued potential conflict of interest.

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