Correlation analysis between forced oscillation modes caused by wind power

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Abstract. With the increase of the grid-connected capacity of wind power, the influence of power system forced oscillation caused by wind power is becoming bigger and bigger, so it is necessary to understand its production mechanism and general characteristics. In this paper, the nonlinear and non-stationary signal generated by the unstable wind speed is analyzed to speculate the characteristics of wind-induced oscillation. Secondly, the bispectrum analysis and the bicoherence analysis are introduced. The obtained bispectrum and bicoherence coefficients are used to analyze the oscillation caused by wind power and the quadratic phase coupling relationship between oscillation modes. Finally, the simulation is operated considering small wind farm connected to a 4-generator-2-area (4G2A) system. The simulation results verify the correctness of the proposed speculation and the effectiveness of the proposed method.

1. Introduction

When there is periodic disturbance at the generator end and the disturbance frequency is close to or consistent with the natural frequency of the system, the resonance phenomenon will be triggered, and the oscillation with an amplitude much larger than the disturbance amplitude will be generated, which is called forced power oscillation (or forced oscillation, FO)[1]. FO is a type of low-frequency oscillation (LFO). With the increase of wind turbines, the FO caused by the grid connection of wind power is becoming more and more striking. Due to the great uncertainty of wind power's input and output, there are often multi-frequency components in it, causing multi-mode FO. In the case of a strong degree of nonlinear coupling between different modes, multiple modes are very likely to evolve into dominant modes that affect system stability in the dynamic process [2]. If this nonlinear coupling phenomenon can be known and confirmed in time, it will improve the efficiency of parameter tuning of each controller in the system. Therefore, it is very important to analyse the law of this phenomenon and grasp its characteristics.

For the study of the correlation between LFO modes, there are mainly two categories of methods, respectively named as normal form method and modal series method [3]. The core idea of normal form method [4-5] is to promote the linear system theory to nonlinear systems by obtaining the second-order approximate analytical solution of power systems. However, the Taylor expansion used in the calculation will produce truncation errors. Besides, this method is not suitable for systems with higher-order resonance conditions and the data for nonlinear transformation is too large [3]. Later, the modal series method [6] was proposed. It is also based on the Taylor series expansion, but avoids the solution
of nonlinear equations, only requiring linear transformation of the state space to obtain an approximate solution. Although this method is easier in the solving part and suitable for systems with high-order resonance conditions, it still cannot avoid truncation errors and low calculation speed.

The high-order spectrum is based on high-order statistics and can provide detailed information of the signal, such as the deep relationship between the two signal components [7]. It is a new idea for detecting the correlation between modes for power system oscillation. The bispectrum and bicoherent theory which belongs to high-order spectrum, has already been widely applied in mechanical fault diagnosis [8-10]. In [11], bispectral analysis is used to determine the existence of nonlinear interactions in the fundamental oscillation modes of the system, which is manifested by the sum of electromechanical oscillation modes. In [12], the LFO is obtained by applying a short-circuit fault and the generation of the new mode is confirmed via the bispectrum and bicoherence analysis of the electrical power information. However, this study does not consider access to renewable energy sources.

In this paper, the multi-mode FO caused by variable wind speed is obtained in a four-generator-two-area (4G2A) system containing a small windfarm. Then, bispectrum and bicoherence analysis are used to identify the correlation between modes in the FO signal caused by the windfarm connecting to the system. The research results show that the quadratic phase coupling relationship between oscillating signals can be detected using the process proposed in this paper.

2. Bispectrum and bicoherence method for correlation estimation of oscillation modes

Conventional power system signal processing methods use second-order statistics (time-domain waveforms and power spectrum) as mathematical analysis tools. There are some disadvantages, such as their equivalence or multiplicity, the inability to identify non-minimum phase systems; and their excessive sensitivity to noise, which generally only deals with observational data of additive white Gaussian noise. To avoid these deficiencies, third-order or higher-order statistics are introduced, which are collectively referred to as high-order statistics. Signal analysis based on high-order statistics is called high-order statistical analysis of signals, also known as non-Gaussian signal processing. Second-order statistical analysis can only extract the main information of the signal (including peak and frequency), while high-order statistical analysis can provide detailed information of the signal. Therefore, high-order statistics become mathematical tool for signal processing.

2.1. Higher-order cumulant spectrum

When defining the power spectrum, the autocorrelation function is required to be absolutely summable. Similarly, in order to ensure the existence of the Fourier transforms of higher-order cumulant, higher-order cumulants are also required to be absolutely summable.

Assuming that the high-order cumulants \( c_{k}(\tau_1, \cdots, \tau_{k-1}) \) are absolutely summable, the relationship can be expressed as (1),

\[
\sum_{\tau_1=\infty}^{\infty} \cdots \sum_{\tau_{k-1}=\infty}^{\infty} \left| c_{k}(\tau_1, \cdots, \tau_{k-1}) \right| < \infty
\]  

(1)

Then the \( k \)th-order cumulant spectrum is defined as the \((k-1)\)th dimensional discrete Fourier transform of the \( k \)th-order cumulant, i.e.,

\[
S_{k}(\omega_1, \cdots, \omega_{k-1}) = \sum_{\tau_1=\infty}^{\infty} \cdots \sum_{\tau_{k-1}=\infty}^{\infty} c_{k}(\tau_1, \cdots, \tau_{k-1}) e^{-j(\omega_1 \tau_1 + \cdots + \omega_{k-1} \tau_{k-1})}
\]  

(2)

While there are also some other higher-order statistics, they are not usually used in practical. Therefore, the high-order cumulant spectrum is often referred to as high-order spectrum.

Higher order spectrum is also called multi-spectrum. When \( k=3 \), the third-order spectrum \( S_{3}(\omega_1, \omega_2) \) is referred to bispectrum. Conventionally, the bispectrum is represented as \( B(\omega_1, \omega_2) \), and the three spectrum is represented as \( T(\omega_1, \omega_2, \omega_3) \). In practical cases, bispectrum is more used than other higher-order spectrum. Bispectrum has the following symmetrical form:
2.2. Quadratic phase coupling and bicoherence coefficient

The quadratic phase coupling relationship was first proposed when studying random signals. The most common manifestation is that two frequency components interact and then produce a sum and/or a difference frequency. At the same time, the corresponding phase also satisfies this sum or difference relationship. This phenomenon is called quadratic phase coupling. For example, if a signal with three components, whose frequency and phase are respectively \( f_k \) and \( \phi_k \) (\( k = 1, 2, 3 \)), has the relationship of

1. \( f_3 = f_1 + f_2 \) and \( \phi_3 = \phi_1 + \phi_2 \), or
2. \( f_3 = f_1 - f_2 \) and \( \phi_3 = \phi_1 - \phi_2 \),

it is called quadratic phase coupling[13]. It can be easily seen that the two necessary conditions for quadratic phase coupling are frequency coupling and phase coupling. In the case of multi-source FO, the oscillation source can be classified according to the coupling relationship between the signal components, and then the detailed characteristics of different groups of oscillation sources can be studied.

The frequency coupling between oscillation modes can be effectively characterized using bispectrum estimation, but the phase coupling could be misidentified [12]. Besides, the actual signals are usually not simply classified as coupled or uncoupled ones, and need to be described by the degree of correlation between signal modes, that is, the degree of quadratic phase coupling. The bicoherence coefficient is an indicator used to measure the quadratic phase coupling. Its definition is based on bispectrum analysis and power spectrum analysis and can be expressed as the follow equation [14],

\[
bic(\omega_1, \omega_2) = \frac{|B_x(\omega_1, \omega_2)|^2}{P(\omega_1)P(\omega_2)P(\omega_1 + \omega_2)}
\] (4)

In (4), \( P(\omega) \) represents the power spectrum of \( \omega \). The bicoherence coefficient is normally varied from 0 to 1. The closer the value is to 1, the stronger the nonlinear interaction is between \( \omega_1 \) and \( \omega_2 \), which means the higher the degree of quadratic phase coupling.

2.3. Direct bispectral-bicoherent method for quadratic phase coupling estimation

By generalizing the (direct) periodic graph method of power spectrum estimation, a direct bispectral-bicoherent method can be obtained for quadratic phase coupling estimation.

- Divide the data into several segments.
- Calculate the discrete Fourier transform (DFT) coefficients.
- Calculate the triple correlation of the DFT coefficients.
- Estimate the total bispectrum of the given data by averaging every segment of estimate value bispectrum.
- Calculate the normalized bispectrum and obtain the bicoherence coefficient to obtain the degree of coupling between \( f_1 \) and \( f_2 \). The critical value of \( bic \) can be set to 0.5.

\[
bic(f_1, f_2) = \frac{|B_x(f_1, f_2)|^2}{P(f_1)P(f_2)P(f_1 + f_2)}
\] (5)

In (5), \( B_x(f_1, f_2) \) is the estimated bispectrum of each data segment, and \( P \) represents the power spectrum value of the corresponding frequency. The process above can be shown in the flow chart below.
3. Case study
In order to check out whether wind turbines can cause quadratic phase coupling between oscillation modes and verify the effectiveness of the bispectrum-bicoherence method proposed in this paper, this part adopts the classic 4G2A system and establishes the simulation model verification on MATLAB/Simulink. Its parameter setting is modeled after an example in Kundur's "Power System Stability and Control"[15]. The structure of the system is shown in Figure 2. The four conventional generators of this system are divided into two areas, connected by line 7-9. The system includes an inter-area oscillation mode with a natural frequency of 0.64 Hz. A small windfarm (equivalent to one DFIG) is connected to the system at bus 4. The equivalent wind turbine adopts a combined wind speed model [16]. The frequency of wind speed's gust part is set to 0.64 Hz, which is consistent with the natural frequency, expected to produce the most obvious FO. The actual wind speed is shown in figure 3.

The active output of the windfarm is shown in Figure 4. Due to the fluctuation of the wind speed, the active power windfarm output has a certain fluctuation. The power of the inter-area tie line is shown in Figure 5. It can be seen that the fluctuations are generated by the windfarm and spread to the inter-area line. What's more, it is not a regular single sinusoidal signal, which is likely to be a combination of multiple oscillation modes.

The bispectrum-bicoherence method proposed in this paper is used to detect the phase coupling between modes. Figure 6 is a bispectrum estimation plot of active power in tie-line. It can be seen that under the parameter setting mentioned above, the spectral peak of the bispectrum estimation is clear and distinct, the frequency band is not wide, and the identification effect is good. Ignoring the influence of the DC component (i.e., the peak near the vertical axis and the horizontal axis), several peaks can be obtained from Figure 6 (0.28, 0.36), (0.36, 0.28), (0.36, 0.36), (0.36, 0.64), (0.64, 0.36). Due to the symmetry of the bispectrum, it is only needed to focus on the upper half or the lower half of the line $f_1=f_2$. These peaks contain the oscillation mode of 0.36 Hz and 0.64 Hz. At the same time, the bispectrum estimation also found new modes (0.28Hz and 0.72Hz), showing that there is a possible quadratic phase coupling relationship between the modes of 0.36Hz, 0.64Hz and 0.28Hz. The mode of 0.36Hz has a self-coupling relationship. It is not difficult to find that the mode 0.28Hz ($f_3$) is obtained by the nonlinear coupling of the two modes 0.36Hz ($f_1$) and 0.64Hz ($f_2$), which satisfies the frequency relationship $f_3=f_2-f_1$. 

Figure 1. Process of direct bisp-ectral-bicoherent method.

Figure 2. Structure of 4G2A system with windfarm.
To evaluate the level of quadratic phase coupling, a bicoherence analysis method is then required. The bispectral analysis results above are further normalized to obtain bicoherence coefficient according to (5), and the bicoherence spectrum estimation diagram is obtained from the bicoherence spectrum program. Figure 7 shows the bicoherence spectrum of active power in tie-line. The calculated bicoherence coefficient is respectively bic(0.36, 0.64)=0.9068 and bic(0.36, 0.36)=0.8574, both close to 1, indicating that the three oscillation modes 0.36Hz(f1), 0.64Hz(f2), 0.28 Hz (f3) do have strong nonlinear coupling relationship, and the 0.36 Hz (f1) mode also has a strong self-coupling relationship.

In order to find the source of the oscillation, the wind speed is set to a constant value of 12m/s. In this case, the active power on the tie line is shown in Figure 8. It can be seen from Figure 8 that after 60s, there is almost no power oscillation. This shows that the FO of the system is indeed caused by wind speed fluctuations. Moreover, although the 0.64 Hz component belongs to the natural frequency of the system, it is still excited by the nonlinear wind turbine, and the 0.36 Hz mode is also generated in this complex dynamic process.

To verify if the origin of the coupling relationship is windfarm, the output power of the G1~G4 generator and the windfarm is monitored separately, and the bicoherence analysis is performed as described above, results are shown in Table 1. In Table 1, all the bicoherence coefficients indicate that the following two sets of coupling relationships are strong coupling everywhere in the system, but the degree has a certain relationship with the physical location. Since the two sets of bicoherence coefficients of the active power are both closest to 1 at the output of the windfarm, it can be inferred that quadratic phase coupling relationship is the strongest at this location. It is concluded that the source of the coupling relationship between the FO modes is also the windfarm.

| Position | Bicoherence coefficient of power signal |
|----------|----------------------------------------|
|          | (0.36, 0.64)                          |
|          | (0.36, 0.36)                          |

Figure 3. The waveform of wind speed.
Figure 4. Active power waveform of windfarm output.
Figure 5. Active power waveform of tie line.
Figure 6. Bispectrum estimate of tie line active power.
Figure 7. Bicoherence spectrum estimation diagram of tie line active power.
Figure 8. Active power in tie-line.
### 4. Conclusion

In this paper, the quadratic phase coupling estimation based on the bispectral and the bicoherence analysis is used for the FO analysis caused by wind power. According to the results of the case study in a 4G2A-windfarm system, there are new forced oscillation modes generated throughout the system, and wind turbines are the source of the new modes, which are related to the FO components caused by gusts. Strong quadratic phase coupling relationship was found between the new mode and the windfarm-driven FO component. This provides references for system preventive control, parameter setting, fault identification and location under the potential of multiple FO modes.

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