Subsynchronous oscillation mitigation strategy based on adaptive band-stop filter in DFIG-based wind farms

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Abstract. Subsynchronous Oscillation (SSO) may exist in doubly-fed induction generator (DFIG)-based wind farms connected with a series compensated transmission network, also called subsynchronous control interaction (SSCI). Different from thermal power units, the SSO frequency of wind farm varies with the change of system operating conditions, and has the characteristic of time-varying. When the operating conditions change, the existing mitigation strategies may lose the effect. To address this issue, a SSO mitigation strategy based on adaptive band-stop filter (ABSF) is proposed in this paper: When SSO occurs in the system, the ABSF parameter is adjusted according to the oscillation frequency measured by PASTd algorithm to filter out the subsynchronous component in the RSC loop effectively, so as to break the generation path of SSO and suppress SSO. Compared with the existing mitigation strategies, the proposed strategy doesn’t need the mathematical model of the system, and can ensure strong robustness under various operating conditions. Finally, the effectiveness and robustness of the proposed strategy are verified on the Matlab/Simulink.

1. Introduction

Series compensation capacitor (SSC) technology is widely applied in the wind power grid-connected system. However, it may lead to SSO caused by the interaction between the DFIG converter and SSC [1]. When SSO occurs in wind farm, the crowbar circuit will be damaged, and a noticeable number of wind turbine generators (WTGs) are tripped, affecting the stable operation of power system. Therefore, it is essential to research the mitigation strategies of SSO in DFIG-based wind farm.

Band-stop filter (BSF) inserted in the rotor-side converter (RSC) is applied to suppress SSO [2,3]. Its parameters are designed according to the SSO frequency range. And when the oscillation frequency of system is within the suppression effective range (SER) of BSF (the amplitude of the filter is less than -20dB in this range), SSO will be suppressed effectively. However, the SSO frequency has the characteristics of time-varying and wide range [4]. [5] points out that the changes in operation conditions (like compensation level, the number of DFIGs, rotor speed, etc.) will cause the change in oscillation frequency accordingly. [6] points out that the planning of wind farm in China is characterized by phased construction. When the access point of the wind farm is changed, the power system structure is adjusted, or a new distributed power generation system is connected to the grid, the oscillation frequency will change accordingly. In addition, for wind farms built in different regions, the oscillation frequency is different due to the different grid structures connected to the wind farms.
For example, the oscillation frequency in Texas is about 20Hz [7], in Minnesota is 9–13Hz [8], and in Hebei, China is 3–10Hz [9]. This makes the mitigation strategy based on BSF have several shortcomings: 1) BSF will lose effect when the oscillation frequency is not within the SER of BSF; 2) When setting the parameters of BSF, it is necessary to count the SSO frequency range that has occurred or may occur in wind farm; 3) For the wind farm that is still planning, the detailed mathematical model, environmental data of the area and the relevant information of the integrated power system are needed to estimate the range of possible oscillation frequency. This requires many data and is difficult to estimate. Meanwhile, when the parameters of the integrated power system are changed, the frequency will also be deviated, affecting the suppression effect of BSF.

To address the issue, a mitigation strategy based on adaptive band-stop filter (ABSF) is proposed in this paper: when the system has SSO, the centre frequency of ABSF is adjusted automatically according to the oscillation frequency of the system to filter out the sub-synchronous component of the RSC loop and suppress the SSO effectively. Compared with the existing research, the proposed strategy has the following advantages: 1) this method doesn’t need the mathematical model of system. 2) The physical concept is clear and the principle is simple. 3) The robustness is better, and SSO can be suppressed flexibly under various operating conditions.

This paper is organised as follows. Section 2 introduces the target system. In section 3, a mitigation strategy is proposed to suppress SSO. And the suppression principle and control scheme are described. In section 4, time-domain simulation is conducted to verify the effectiveness and robustness of the proposed strategy. Section 5 draws some conclusions.

2. Target system

The target system is a DFIG-based wind farm in North China as shown in figure 1 [10]. It is composed of 1000 DFIGs. All DFIGs are assumed to be of the same type, parameters, and operating conditions for simplification.

Figure 1. Overview of the target system.

Figure 2. Control block diagram of RSC.

The control block diagram of RSC is shown in figure 2. The stator voltage-oriented control strategy is adopted to realize the independent control of DFIG active and reactive power output.

3. Mitigation strategy based on adaptive band-stop filter

3.1. The suppression principle

The SSCI is mainly produced by the interaction between RSC and SSC. The brief process is as follows [11]: when a subsynchronous disturbance current $i_1$ with a frequency of $\omega_{er}$ appears on the line, it will cause active/reactive power fluctuations and subsynchronous current on the rotor with a frequency of $\omega_s-\omega_{er}$ ($\omega_s$ is the synchronous frequency). Power fluctuation and current distortion affect the rotor voltage (the output of RSC) through the inner and outer loops of RSC. The rotor voltage reacts to the rotor winding and generates a subsynchronous current on the rotor, resulting in a new subsynchronous current $i_2$ on the stator due to the electromagnetic induction. If the amplitude of the original and new subsynchronous current increase after superimposition, the disturbance component will be amplified, and SSO will occur in the system, like regenerative feedback loop. The schematic diagram is shown in figure 3, where the dashed line is regarded as a solid line and there is no ABSF.
If a link in the SSCI action path is break, the SSO will be suppressed effectively. As shown in the dotted line in figure 3, An ABSF is added to RSC to destroy the action path. And the parameters of ABSF is modified according to the oscillation frequency of system to ensure that the subsynchronous current on rotor is filtered out and SSO is damped effectively. The location of ABSF is shown in the green box in figure 2.

Figure 3. Block diagram of mitigating SSCI by ABSF.

3.2. The control scheme
This subsection will introduce the control scheme of the proposed strategy based on ABSF. The procedure is as follows:

Step 1: Initialize all parameters, such as reference value of attenuation coefficient $\tau_{ref}$, center frequency $f_n$ and bandwidth (BW) of ABSF ($SER\in (f_n - BW/2 . f_n + BW/2)$). In this paper, $\tau_{ref}$ is set to -0.7, and the subsynchronous component will be attenuated by 50% per second [12].

Step 2: Monitor the output active power of wind farm online at every 0.25s. The spectrum estimation algorithm based on projection approximation subspace tracking based on the deflation (PASTd) technique is utilized to extract the frequency and attenuation coefficient ($\tau$) of the SSO mode. When $\tau \leq 0$, the SSO mode is not detected, it indicates that the system has no SSO or ABSF can suppress the SSO. There is no need to modify the ABSF parameters, and repeat this step. If $\tau \leq 0$, it means that the system is experiencing SSO. And the oscillation frequency is not within the SER of ABSF which causes ABSF to be unable to filter out the sub-synchronous current in the RSC effectively. ABSF parameters need to be modified, go to step 3.

Step 3: According to the oscillation frequency ($f_{er}$) measured by PASTd algorithm, modify the center frequency ($f_n$) of ABSF, that is, $f_n = f_{er}$, to ensure that ABSF can filter out the subsynchronous current effectively, and go to step 4.

Step 4: Monitor the attenuation coefficient ($\tau$) of SSO mode. If $\tau > \tau_{ref}$, it means that parameter setting of ABSF is wrong or the error of detected oscillation frequency is large. This needs to modify the ABSF parameter again and go back to step 3. If there is an obvious attenuation trend of SSO, namely $\tau \leq \tau_{ref}$, it means that SSO is suppressed effectively, go back to step 2 and continue to monitor the system.

Accordingly, the flow chart of proposed strategy is shown in figure 4.

Figure 4. Control flow chart of control strategy based on ABSF.
The key of the strategy is the on-line identification algorithm of SSO and ABSF. These two parts will be introduced in the following subsections.

3.3. On-line identification algorithm of SSO
The on-line identification algorithm of SSO needs to meet two requirements: one is the fast calculation speed. The algorithm can real-time monitor to extract the oscillation information quickly when the system oscillates, so as to adjust the parameter of ABSF in time. The other is the detection error of the algorithm cannot be large, so as not to affect the suppression effect. The PASTd algorithm is widely used in the field of signal detection because of the low computational complexity, fast convergence speed, and small operational error. [12] utilizes the PASTd algorithm to realize the online SSO monitoring. And the simulation results show that this algorithm is fast and accurate, suitable for online signal detection. So PASTd algorithm is adopted to detect SSO of system in this paper. The detailed algorithm process and principle are detailed in [12].

3.4. The design of ABSF
The core of this strategy is to design a BSF with adjustable center frequency online and fast response speed. ABSF can automatically adjust its weight coefficients through the learning algorithm without needing to predict the prior characteristics of the signal, so as to achieve the best filtering effect [13]. Moreover, it is widely applied in practical projects due to the simple and easy implementation of its algorithm. Therefore, ABSF is utilized to filter out the sub-synchronous components in RSC loop in this paper. Next, the brief principle of ABSF will be introduced, and its structure diagram is shown in figure 5.

![Figure 5. Structure of adaptive band-stop filter](image)

x(k) is the input of ABSF, that is, signal 1 in figure 2. e(k) is the output of ABSF, corresponding to signal 2 in figure 2. According to the oscillation frequency \( f_{er} \) measured by PASTd algorithm, ABSF generates a sine and cosine signal with the same frequency, namely reference signal. The weighted value \( y(k) \) is obtained by the reference signal through the linear combination of ABSF weight coefficients \( W_1 \) and \( W_2 \). And it is still the signal with frequency \( f_{er} \). According to \( e(k) \), the adaptive algorithm modifies \( W_1 \) and \( W_2 \) to make \( y(k) \) approach the sub-synchronous component in \( x(k) \) gradually. Therefore, the output \( e(k) \) is the signal after filtering, which is equal to the difference between the input \( x(k) \) and the weighted value \( y(k) \).

The adaptive algorithm is the key of ABSF. The basic adaptive algorithms are mainly Least Mean Square (LMS) and Recursive Least Square (RLS). As RLS algorithm has fast convergence speed and strong non-stable adaptability, it is selected as the adaptive algorithm of ABSF in this paper. The flow chart of the RLS algorithm are detailed in [13].

4. Case study
In this section, the effectiveness and robustness of the proposed strategy will be verified by comparing the suppression effect of conventional BSF and ABSF on SSO under different operating conditions.
The initial center frequency and bandwidth of ABSF and BSF are set to 43Hz and 1.2Hz (i.e. SER is 42.4~43.6Hz) respectively in this section. Besides, the influence of wind speed ($v_{wind}$), the number of DFIGs ($n$) and reactive power output ($Q_{output}$) on SSO is considered. To demonstrate the robustness of proposed strategy, the operating conditions whose oscillation frequency is inside SER (as shown in table 1, point A, B, C, D) and outside (point E in table 1) are selected. Simulation experiments are conducted in the system at each operating point listed in table 1.

| Operating point | $v_{wind}$ (m/s) | $n$ | $Q_{output}$ (p.u.) | Frequency (Hz) |
|-----------------|------------------|-----|---------------------|---------------|
| A               | 8                | 1000| 0                   | 43.5          |
| B               | 8                | 1000| -0.3                | 43.5          |
| C               | 11               | 700 | 0                   | 43.1          |
| D               | 11               | 1000| 0.17                | 42.4          |
| E               | 7                | 1000| -0.3                | 44.0          |

Figure 6 shows the wind farm’s active power outputs without mitigation strategy, with BSF and with ABSF at all operating points. And the compensation level is changed to 20% at $t=10s$.

In figure 6 (a), the active power output without mitigation strategy at all operating points are unstable. In figure 6 (b), since the oscillation frequencies of operating points A, B, C and D are within SER of BSF, the SSO is effectively suppressed in these points. On the contrary, because the oscillation frequency is not within SER, BSF fails to suppress SSO at operating point E, which indicates that BSF has considerable difficulties in satisfactory robustness under all possible operating conditions.

By contrast, as can be seen in figure 6(c), the proposed strategy can suppress SSO effectively at all operating points. As the frequency of point A, B, C and D is all within the initial SER of ABSF, SSO is suppressed quickly after SSC is applied. On the contrary, because the frequency of point E is not
within the initial SER of ABSF, SSO occurs after the change of compensation level. And the attenuation coefficient of active power measured by PASTd algorithm is 2.6 at 10.25s (namely $\tau > 0$). According to the control flow described in section 3.2, the ABSF parameter is modified, so that the oscillation frequency is within SER. It can be seen that SSO is effectively suppressed after modifying the ABSF parameter, and the attenuation coefficient measured by PASTd becomes -8.4 (i.e. $\tau > \tau_{\text{ref}}$) at 10.5, which indicate that proposed strategy can maintain robust damping performance at all selected operating points.

5. Conclusion
In this paper, the SSO mitigation strategy for DFIG-based wind farms is studied. Considering that there are many uncertain factors in the operation of wind farms, such as the changes in the operation parameters of wind farm (number of DFIGs, wind speed, reactive power output, etc.), these uncertainties will lead to changes in the SSO frequency which will affect the suppression effect of existing mitigation measures. Therefore, a SSO mitigation strategy based on ABSF is proposed in this paper. Based on time-domain simulation, the performance of the proposed strategy is compared with the conventional one based BSF under various operating conditions. The results validate the effectiveness of the proposed strategy and demonstrate its higher degree of robustness over the conventional one.

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