Review on Sub-synchronous Oscillations in Wind Farms: Analysis Method, Study System, and Damping Control

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Abstract

More and more attentions on wind farm sub-synchronous oscillation (SSO) have been paid since many SSO incidents in wind farms have occurred. This paper presents an overview of recent SSO issues in wind farm from the perspective of control, including, the analysis methods, the study system, and the SSO mitigation by damping control. Three major analysis methods, as well as different study systems for wind farm SSO study are comprehensively reviewed. The adaptability and complexity of the methods and study systems are analyzed, and an overall survey of recent SSO analysis are given. Among the wind farm SSO mitigation methods, sub-synchronous damping controller (SSDC) is one of the most common used method in practice. Its configuration and signal selection are introduced in this paper.

Key Words

Wind power, Sub-synchronous oscillation, Sub-synchronous resonance, Wind turbine generator,

1. Introduction

Wind power, one of the most important renewable energies, has been rapidly exploited from 7.6 GW to 539.58 GW from 1997 to 2017, and is expected to reach 2000 GW by 2030. Large scale wind farms are

*Manuscript received **08 December 2018, accepted 15 June 2019***

usually located far from load centers, which make their utilization highly rely on the high-rating and long-distance power transmission, such as series capacitor compensated transmission system, or high-voltage direct-current (HVDC) transmission [1, 2]. However, sub-synchronous oscillation (SSO) is introduced to the generation system by the inappropriate operation of compensated capacitor or electronic devices, and lead to damages in generators, turbine shafts, and transformers within few seconds [3].

SSO is a significant energy exchange between wind turbine generator (WTG) and oscillation sources below the power frequency. The classification of recent wind farm SSO is shown in Fig.1 [4-7]. When the SSOs occur in the shaft system of the WTG, and caused by the resonance near the driven train natural frequencies, the SSOs are torsional interaction (TI) and sub-synchronous torsional interaction (SSTI) [6]. When the energy exchanges are between the generators and the SSO sources, these SSOs are classified to IGE (when the SSO source is series capacitor) or emerging SSO (when the SSO source is electronic devices) [7]. Typically, the IGE in type-3 WTG, i.e., the doubly-fed induction generator (DFIG), also named as sub-synchronous control interaction (SSCI), for the converter control system take participate in. The SSCI is now the most serious and the most studied SSO problems, for type-3 WTG is installed worldwide [4]. The E-SSO and SSTI are the relatively new phenomena and becoming the hotspots [8].

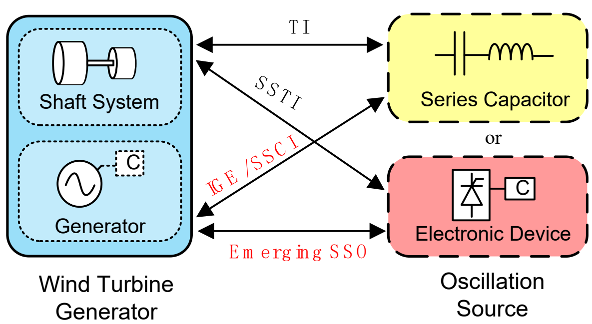

Figure 1. The classification of wind farm SSO.

SSO, one of the traditional power system stability problem, is becoming a big challenge for modern power system due to the expansion of the scale of wind power, and increase application of electronic devices. The modelling, analysis, and mitigation of the SSO incidents attract more and more attentions in recent years. The objective of this paper is to give a better understanding of different study systems, analysis methods, and mitigation methods of wind farm SSO. The remaining of this paper is organised as follows. In section 2, SSO analysis methods, as well as their corresponding models are presented. In Section 3, three types of study system for wind farm SSO are introduced. Section 4 introduces the mitigation by damping controller. The conclusion and future prospects draws in section 5.

2. Analysis Methods of Wind Farm SSO

Analysis methods, such as eigenvalue, frequency scanning, Nyquist criterion, as well as time-domain simulation, can be employed for large-scale wind farm SSO analysis.

2.1 Small-Signal Model with Eigenvalue Analysis

The dynamic model of WTG and the SSO source should be used for establishing the small-signal model for wind farm SSO analysis. After the driven-train system, the induction machine, the electronics and the controllers of WTG, and the series compensated capacitor are taken into consideration [9-11], the behavior of a dynamic system can be expressed by a set of differential equations. After linearized around the operating point, the system dynamics can be express as [12, 13]:

$$\Delta\dot{x} = \mathbf{A}\Delta x + \mathbf{B}\Delta u \tag{1}$$

where x, and u are the state vectors and input vectors, respectively; **A** is the state matrix, and **B** is the input matrix, respectively. The time-domain response of the system to small disturbances, is revealed as the eigenvalues of the state matrix **A** to the n-th oscillation mode as:

$$\lambda_n = \sigma_n + i2\pi f_n \tag{2}$$

where σ_n is the real part of the eigenvalues, and f_n is the oscillation frequency. If the real part is non-negative, the system will be unstable [14, 15].

The small-signal model can be easily established, for all mathematical models of WTGs and transmission systems can be easily found. The relationship between the stability and different parameters can be determine the through participation factors calculation. Meanwhile, the conducted eigenvalues can be used for further SSO damping controller design. The aforementioned advantages make the small-signal model become one of the most widely used method for wind farm SSO mechanism and impact factors analysis. However, the small-signal model cannot deal with the E-SSO caused by HVDC, because of the non-linear characteristic of electronic devices cannot be presented in the model. Meanwhile, due to the high order of WTGs, the dimensionality problem may appears when establishing a small signal model of a large scale power system. The dynamic behaviour of continuous frequency variation also cannot be present in the small signal model.

2.2 Impedance Model based Analysis

Impedance model simplification is another common way for wind farm SSO analysis. In an impedance model, the system is represented by a resistance-inductance-capacitor (RLC) circuit [16]. A typical impedance model of a type-3 WTG to series capacitor compensated power system is shown in Fig.2 [17].

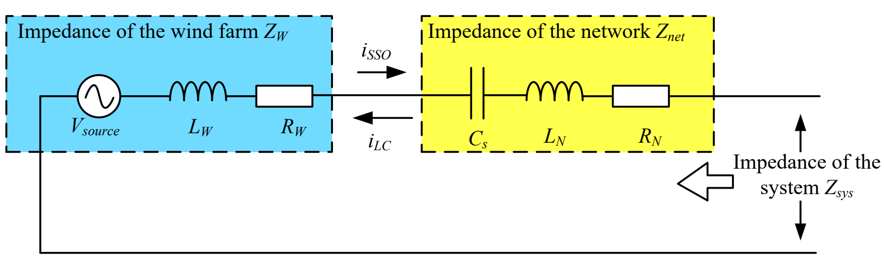

Figure 2. Impedance model of DFIG to series capacitor compensated power system

The overall impedance of the system in S-domain, $Z_{sys}(S)$, consists two impedances, respectively, the impedance of the wind farm $Z_W(S)$, and the impedance of the network $Z_N(S)$, which are calculated by:

$$Z_{sys}(S) = R_W + SL_W + R_N + SL_N + 1/(SC_S) \tag{3}$$

where R_W, L_W are the resistance and inductance of the wind farm, respectively; R_N, L_N are the resistance and inductance of the network, respectively; and C_S is the series compensated capacitor. Based on the impedance model, frequency domain approaches such as Frequency scanning and Nyquist criterion can be used to investigate wind farm SSO.

In frequency scanning analysis, the stability of the overall system is revealed by calculating the equivalent resistances under SSO frequency, i.e. the real part of $Z_{sys}(S)$. The equivalent resistances reflects the SSO damping. If the equivalent resistances of a component is negative under SSO frequency, the component will decrease the SSO stability of the system [18, 19].

In the Nyquist criterion analysis, when the wind farm is considered as a voltage source as $V_{source}(S)$, the SSO current flows form wind farm to the system, $i_{SSO}(S)$, is:

$$i_{SSO}(s)=\frac{V_{source}(s)}{Z_{sys}(s)}=\frac{V_{source}(s)}{Z_W(s)+Z_N(s)}=\frac{V_{source}(s)}{Z_N(s)}\bullet\frac{1}{1+Z_W(s)/Z_N(s)} \tag{4}$$

The stability of the system is judged by the loop gain division between $Z_W(S)$ and $Z_N(S)$. If and only if the number of counter-clockwise encirclement around (−1, 0) of $Z_W(S)/Z_N(S)$ is equal to the number of the right-half-plane poles of $Z_W(S)/Z_N(S)$, the system will be stable [20].

By using the impedance model simplification, the energy exchanges, namely, the SSO interactions is revealed by the current flow. It can easily point out how the SSO occurs, and how the different components influences the SSO current. Meanwhile, the impedance of the wind farm and the impedance of the network changes along with the adjustment of parameters. The impact parameters can be conducted by the equivalent resistances calculation or the Nyquist criterion. The accuracy of the impedance model may decrease for it use assumptions and equivalences to simplify the model. For instance, the electronic devices are often simplified to RLC, and flux linkage in WTG are often ignored.

2.3 Time-domain Simulation

The time-domain simulations are usually carried out in different simulation softwares, such as

SIMULINK, PESCAD, DigSilent, to analysis the dynamic characteristics of the wind farm SSO. Benefits from the easy application, the time-domain simulation is a best way for beginners to understand how the SSO performs in WTGs, and to test how different parameter changes will influence the time-domain response of SSO. On the other hand, it is especially suitable to verify the theoretical analysis and the mitigation validities, for the non-linear characters of electronics and the dynamic process of control and fault can be performed. The time-domain simulation usually used as the verification method, for the mode information and the SSO mechanisms cannot be analyzed or explained. Time-domain simulation is also the only way to analysis the complex torque amplification SSO effect.

3. The Study Systems for Wind Farm SSO Analysis

Study system and analysis method are the major components of the Wind farm SSO analysis. wind farm SSO Study systems for can be classified to (1) Single-WTG model based study system (SMS), (2) Multi-WTG models based study system (MMS), and (3) case based study system (CS).

3.1 The Configuration of Different Study Systems

The configuration of SMS and MMS is shown in Fig.3. The wind farm connects to the main grid through a transmission system with different SSO sources. The SSO sources are selected according to the research subject. In a SMS, the wind farm is replaced by a single-WTG aggregation model, with assumptions that all individual WTGs have same parameters and working conditions [21]. In a MMS, the WTGs in the wind farm are divided into different groups, and each group is aggregated to one WTG aggregated model. The division condition of WTGs can be types of WTGs, operation conditions, and electrical distances and transmission connections etc. [21-23].

On the other hand, in a large-scale wind farm, the in-service WTGs constantly changes, and the configuration of the WTG connection is complex [7, 20]. These factors are hardly to be presented in a SMS or a MMS. Therefore, CS is carried out to analysis complex interactions and coupling effects of an actual wind farm included power system. A typical CS of the Hami power system, China, provided by [24] is shown in Fig.4. Other CSs for practice power systems, such as the ECORT system, the Argentinian power system are respectively shown in [25-27].

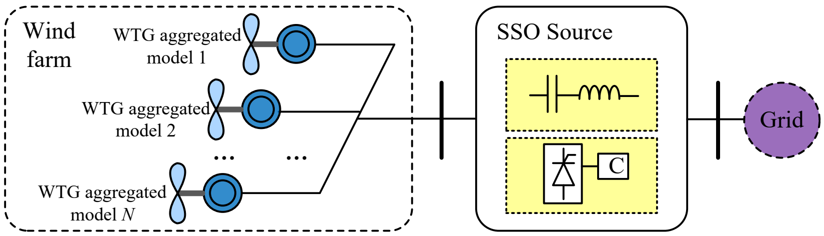

Figure 3. The configuration of the SMS and MMS for wind farm SSO analysis

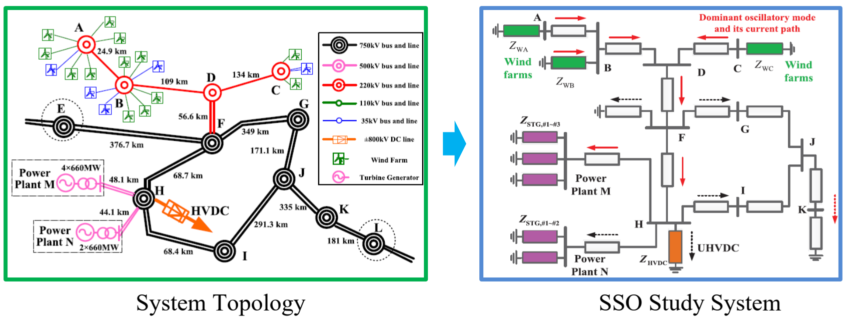

Figure 4. The topology and the corresponding CS of the Hami power system.

3.2 The Computational Complexity Comparison

The SMS is the most simplified study system, which make it become a good choice for wind farm SSO mechanism studies. The MMS is an extension of SMS and its computational complexity is higher [21]. The complexity of a CS is much higher than that of a SMS or a MMS, for many other components in power system should be considered in addition to wind farm and SSO source. Take the small-signal models of these three different study systems as an example. In a common used state-space model of a type-3 WTG, its state variables is 17. And the state variables of the series compensated network is 2. Therefore, the composition of these two parts make the order of the SMS state matrix become 19. But for a MMS, if the WTG group number is chosen to be 3, the order of the MMS state matrix is 17×3+2, i.e. 53. For a CS, the order of its state matrix can easily exceed 200. High computational complexity also means long simulation time in the time-domain simulation. In SIMULINK, when using type-3 WTG detailed model to analyze its SSO incident, the simulation time for 2 seconds period in SMS is about 19.4 seconds, while that in a two-WTG MMS is about 35.9 seconds.

In conclusion, if the parameter differences do not have large impact on WTG aggregation process, the SMS is the best choice to analyze the mechanism of SSO. When dealing with factors that cannot be performed in SMS, or the factors may have large impact on WTG aggregation process, for instance, the dynamic behaviours between different WTGs, the impact of wind spatial distribution and WTG distribution on SSO, the MMS should be used instead of the SMS. For example, the performances of a SMS and a MMS when dealing with the impact of wind speed distribution on SSO is shown in Fig.5 [28]. The accuracy of SMS decreases along with the increase of wind speed difference between WTGs. The CS is used to solve actual problems in practice power systems rather than mechanism analysis. A SSO mitigation strategy for an actual power system usually being test in a CS in advance, to verify the validly and to prevent potential problems that the strategy may introduce. All analysis methods can be carried out in SMS and MMS, although the small-signal models does not often used in high order MMS and CS. But in CS, only impedance model and time-domain simulation are used due to its high order. The CS is complex and its time-domain simulations cost a lot of time. Therefore, in order to reduce the simulation time, the operation conditions and potential faults should be selected in advance [29].

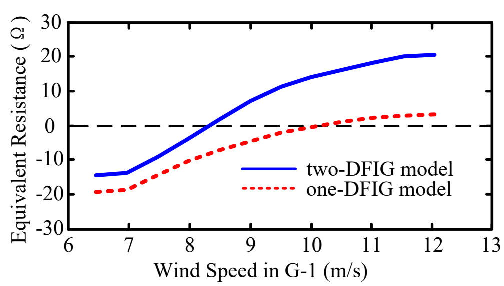

Figure 5. The performances of SMS and MMS when dealing with wind speed distribution

3.3 The Survey on Study Systems

A general survey of wind farm SSO analysis references is shown in Table 1, where the readers and researchers, based on the interests, can found the corresponding references that carried out in different analysis methods and study systems.

Table 1
Survey on the Study System and Analysis Methods for Wind Farm SSO

Study Systems	Small Signal Model	Impedance Model	Time-domain Simulation
SMS	In [8], [9], [19], [37], [40], [43];	In [17], [18], [20], [25], [30];	In [8], [9], [10], [17], [30], [40];
MMS	In [31], [33], [35], [41], [42];	In [28], [31] , [32], [41], [42], [44];	In [28], [31] , [32], [33], [34], [41], [42], [44];
CS	In [26], [39];	In [16], [18], [24], [25], [27];	In [3], [16], [18], [24], [25], [26], [27], [36], [39];

4. Sub-synchronous Damping Controller for SSO Mitigation

Recently, there are two major categories to mitigated wind farm SSO. One is cutting off the interaction between the SSO source and the wind farm, the other is improving SSO damping. Among recent SSO mitigation methods, using band-pass filter, retrofitting WTG configuration, and regulating the transmission configuration can be classified to the first category [4, 45, 46]. Using FACTS devices, such as SVC, TCSC, and STATCOM, can be used to suppress SSO energy [47, 48]. Using sub-synchronous damping controller (SSDC) is also the valid way in SSO damping improvement.

For WTGs in a wind farm or FACTS devices, their original control strategies may already been used for specific purposes. For instance, a STATCOM is usually used to support the reactive power of the power plant. However, using SSDC as an auxiliary controller that append in original controllers is of great value. It can efficiently increase the damping provided by the original controller with very small cost in control performance. Meanwhile, the SSDC has strong adaptability and can be applied in both WTG controllers and FACTS devices. Therefore, SSDC is often used to mitigate practical wind farm SSO problems [49]. Generally, auxiliary SSDC for WTG convertor controller is used more often, for FACTS devices are usually governed by the transmissions dispatching, other than governed by the wind farms.

A typical configuration of the auxiliary SSDC for the grid side converter (GSC) of type-3 WTG in [50] is shown in Fig. 6. The optimal position and input signal of SSDC also discussed. Local measurable SSO signal of the WTG is a better choice rather than wide-area measured signals, for communication time-delays can be avoid. In addition, robust controller design method, small-signal stability region, and other controller design method can be used for SSDC design [51-54], and optimization methods can be applied to obtain the optimal controller parameters [55]. The actual effect of SSDC in a particle wind farm in [49] shows that, the SSDC can effectively mitigating while reduce the costs significantly.

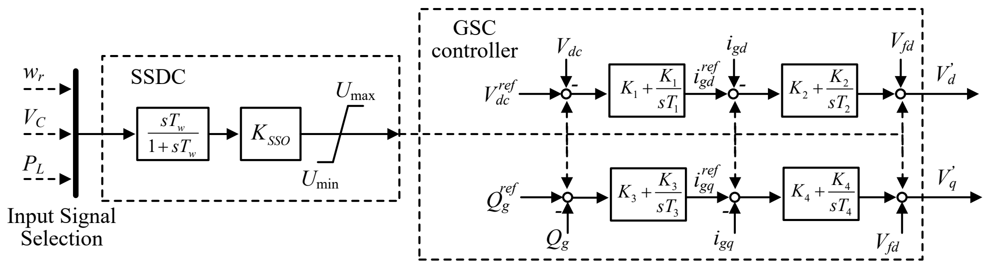

Figure 6. The configuration of the auxiliary SSDC

5. Conclusion and Future Prospects

In this article, a comprehensive review on wind farm SSO is carried out from the perspective of control. The small-signal model can be easily established and can be used for SSDC design, but how to solve the non-linear characteristics of power electronics should be considered. Time-domain simulation is the most easy-application for beginner to understand the dynamic behaviour and the performances for SSO, but it cannot reveal the mechanisms of SSO. Study systems should be chosen by the purpose of study. SMS is the best choice to analyze the mechanism, while CS is usually used to analysis SSO in practice. SSDC, installed as auxiliary controller for WTG or FACTS devices, can improve the SSO damping and suppress SSO energy with significant effectiveness and economic benefit. Apart from the typical research, other works can be focused on in the future are, the new analysis methods for E-SSO in type-4 WTG or for HVDC based SSOs; the SSDC design with consideration of the dynamic of MMS; and the SSO early-warning system for wind farm.

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