

A review of recent studies on the mechanisms and analysis methods of sub-synchronous oscillation in wind farms

Chenggen Wang¹, Qian Zhou¹, Shuning Gao², Jia Luo², Junchao Diao², Haoran Zhao²
and Jing Bu³

¹ State Grid Jiangsu Electric Power Company Research Institute, Nanjing, China

² Shandong University, Jinan, China

³ Nanjing University of Science and Technology, Nanjing, China

Abstract. This paper reviews the recent studies of Sub-Synchronous Oscillation(SSO) in wind farms. Mechanisms and analysis methods are the main concerns of this article. A classification method including new types of oscillation occurred between wind farms and HVDC systems and oscillation caused by Permanent Magnet Synchronous Generators(PMSG) is proposed. Characteristics of oscillation analysis techniques are summarized.

1. Introduction

Wind power generation has achieved a rapid development in the last decade, leading to a steady growth of wind power penetration. The existing transmission system need to be enhanced by using series compensation to accommodate the increased production by wind power. However, there is a possibility of an adverse interaction between the turbine generators and the series compensation, called the sub-synchronous resonance (SSR), which may result in damages to the generator shaft system.

So far, the SSR phenomenon and its mitigation techniques for conventional turbine-generator system have been well documented. However, the mechanism and mitigation techniques of sub-synchronous oscillation phenomenon occurred in series compensated wind farm as well as HVDC linked wind farm systems are still not fully understand. In recent years the emerging type of sub-synchronous phenomenon has been detected worldwide, for instance in the wind farm of USA (ERCOT) [1] and China (Qomul, Xinjiang; Guyuan, Hebei province) [2,3]. These events often accompanied with tripping of generator and damage of crowbar circuit which poses a severe threat to the stability of wind power transmission system. It becomes urgent to study on its mechanism and develop the effective damping algorithm.

The objective of this paper is to summarize the literatures in last few years about mechanisms and

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analysis methods of sub-synchronous oscillation in modern wind power system.

2. Classification

Sub-Synchronous Oscillation (SSO) is a general concept. It defines an electric power condition where two power systems exchanges significant energy at one or more of the natural frequencies of the combined system below the synchronous frequency. It is also called Sub-Synchronous Interaction (SSI) in number of studies [4,5]. According to the different elements involved, the phenomenon can be further distinguished and classified into Sub-Synchronous Resonance, Sub-Synchronous Torsional interaction (SSTI) and Sub-Synchronous Control Interaction (SSCI) [6,7].

2.1. Sub-Synchronous Resonance

SSR is a condition where a series capacitor compensated system exchanges significant energy with a turbine-generator at a frequency below the synchronous frequency. SSR can be further classified into three types: induction generator effect (IGE), torsional interaction (TI) and torque amplification (TA). IGE is a purely electrical phenomenon and takes place in the power system, which requires a high degree of series compensation [2,8,9]. Different from IGE, TI is not only an electrical phenomenon but also involves mechanical dynamics. It generally occurs when the natural frequency of generator shaft is close to the frequency of induced sub-synchronous electromagnetic torque. However, as the shaft stiffness of wind turbine is rather low, TI is rarely induced. Recent studies clarified that IGE instead of TI is the major cause of SSR instability in the case of variable speed-DFIG based wind generation [9]. TA is also referred to as "transient torque" or "transient SSR" occurs due to faults in the network or during switching operations. Although TA can cause severe mechanical torsional oscillations in shaft system, there is no such record of severe shaft damage due to TA occurred in wind farm.

SSR is proved to be possible in DFIG-based wind farm interconnected with series compensated networks. SSR occurred in wind farm is mainly affected by three factors 1) series compensation level; 2) wind speed; and 3) current loop gains [2,8-11]. Ref. [12] assessed SSR under uncertain wind speed conditions by using a piecewise probabilistic collocation method. The location of DFIGs is considered as a factor of SSR in ref. [11], which confirmed that DFIGs closer to PCC is more seriously affected by series compensation degree.

2.2. Sub-Synchronous (Control) Interaction

There are narrow sense and broad sense for the concept "SSCI", the narrow sense SSCI defines an interaction between series compensated transmission system and a power electronics control system (such as HVDC link, SVC or wind turbine control system) [6,13]. The concept of narrow sense of SSCI is often confused with the concept of IGE [14] since it has been widely proved that the characteristics of IGE between wind farm and series compensation is strongly affected by proportional gains in current control loops of DFIG converters [8,9,13,15,16]. It has also confirmed that the DFIG input measuring filters have significant impact on SSCI [17].

There are some new types of SSR/SSO appeared recently which is similar to SSCI but difficult to incorporate them into existing categories.

Field experience has shown that the SSO can occur between the wind farms and HVDC, since the collection bus power of transmission system is often connected to a weak system [18-21]. The

oscillation is arguably originated by the interaction between the wind energy conversion system inverter controller and the HVDC rectifier [18,21]. Full converter of wind turbine generator divides the system into two such that the oscillatory modes have participation only from the states located at one of the two sides. Hence, the generator, turbine and machine side controller models are not included for the modes between wind farms and HVDC. Possible origins of the SSO and resonances observed in the interconnection of a WF and a VSC-based HVDC system is discussed in [18,21].

Recent studies also shown that Permanent Magnet Synchronous Generators(PMSG) would be exposed to unstable SSO [22]. The frequency and stability of such SSO depends on many factors including the short circuit ratio and the control strategies & parameters of wind turbine generator converters [5]. Ref. [22] confirmed that the delay time of feed forward voltage link is the direct drive to SSO in PMSGs connected with power grid. Oscillatory modes present in an PMSGs based offshore wind farm system connected to a VSC-HVDC system using modal analysis tools is proposed in [23], the characteristics of the modes are influenced by the PMSG parameters, such as GSC controller, PLLs, LCL filter, and controller parameters of VSC-HVDC.

To incorporate these new types of SSR/SSO into existing categories, it is necessary to reconsider SSR/SSO definitions and patterns. A concept of broad sense of SS(C)I is proposed in [24]. SS(C)I defines an coupling interaction between two power electronics control systems or between the electronics control system and the grid-side elements. The inherent oscillatory mode of such interaction is hard to find from the machine or grid side.

2.3. Sub-Synchronous Torsional Interaction

SSTI defines the interaction of a turbine-generator near a power electronic controller when the mechanical system resonates with the negative damping of the controller at sub-synchronous frequencies. SSTI is different from SSR because there is no system resonance involved. Due to the low-shaft stiffness coefficient, SSTI rarely happened in wind turbine generator system [2]. Ref. [20] investigated SSTI associated with a practical multi-terminal MMC-based VSC-HVDC.

3. Oscillation analysis techniques

The most common techniques available for the study of sub-synchronous oscillation phenomenon can be classified into three types: impedance based analysis, eigenvalue analysis and time domain simulation analysis. Time domain simulation analysis implies the utilization of simulation program such as PSCAD/MATLAB/DigSILENT, which is widely used to validate results obtained by impedance based analysis and eigenvalue analysis [18,25,26]. The accuracies of various analytical tools used for SSCI problem identification is compared in ref. [17].

3.1. Impedance based analysis

According to the difference of stability criterion, impedance based analysis can be further classified into two types: impedance based frequency scanning method and impedance based Nyquist stability analysis.

The frequency scanning method is a basic technique for analysing SSR, which is widely used in industry. In this technique, the equivalent resistance and reactance of the system as viewed from driving point are computed as a function of frequency. Aspects such as the injection/measurement

point or the choice of injected signal waveform need to be considered in frequency scanning method are discussed in detail [25]. The SSR may induced once the reactance is zero (or close to zero), and resistance is negative at sub-synchronous frequency. Another potential risk assessment for SSCI issue is presented [27].

Impedance based Nyquist stability analysis is a well-established technique to analyse such interconnected systems. The essence of this method is to partition the system under study into a source subsystem and load subsystem. The ratio of the equivalent source output impedance to the equivalent load input impedance must satisfy the Nyquist stability criterion to guarantee the stability of interconnected source-load system [28]. Equivalent impedance models of a DFIG along with its rotor-side converter (RSC) and grid-side converter is derived in ref. [8]. The improved impedance model which incorporates DFIG's full-scale control system is proposed in [29]. Another refined approach that represents both the wind farm and the grid using two-by-two impedance matrices is proposed in [4].

Nyquist criterion is also widely used in recent publications for the analysis of sub-synchronous oscillations between wind farms and HVDC power transmission system [18,21,30].

A detailed model of wind farm and HVDC impedance model were derived and the potential resonance points were identified by using this criterion [18]. A reformulated positive-net-damping criterion based on Nyquist stability analysis to evaluating net damping between HVDC and wind farm is proposed in [21].

3.2. Eigenvalue analysis

Eigenvalue analysis is the most commonly used analytical method, based on mathematical model of system under study using a set of linear ordinary differential equations. The standard form of differential equations can be written as following:

$$\dot{x} = Ax + Bu \quad (1)$$

The eigenvalues are then defined as the solution to equation:

$$\det[\lambda U - A] = 0 \quad (2)$$

Where λ is eigenvalue vector of the differential equation.

The eigenvalue can clearly indicate the frequencies and damping of oscillation modes, i.e. the relationship between the system parameters (series compensation level, PI parameters of current controller, wind speed, number of wind turbine generators) and oscillation characteristics can be easily shown by the movement of eigenvalues [6,9]. D.H.R. Suriyaarachchi et al. provide a two steps procedure to study sub-synchronous interactions, a frequency scanning method is applied in step.1 and a detailed small signal eigenvalue analysis is performed in step.2 to obtain information about oscillatory modes [15]. Ref. [23] used participation factor analysis and confirmed that characteristics of the modes are influenced by the PMSG parameters, such as GSC controller, PLLs, LCL filter, and controller parameters of VSC-HVDC.

However, the eigenvalue analysis approach requires a detailed representation of both the mechanical and electrical systems. Thus, higher order models than the 2nd or 4th order models are therefore required. The model parameters for these high order models are not readily known [25].

Table 1. Overview of research publications on sub-synchronous oscillation in wind farm.

SSR	SSCI	SSCI(PSMG)	SSCI(HVDC)	SSTI
[2, 11-13, 15, 16, 31, 32]	[4, 6, 17, 27, 29, 33]	[5, 22, 34]	[18, 21, 23, 26]	[20]

4. Conclusion

This paper is a summary of recent studies about SSI/SSO observed in wind field and the wind power transmission system. The conclusions can be summarized as follow: SSR, SSCI and SSTI are three main classifications of subsynchronous phenomenon. SSTI caused by controlling unit in the components of the WF and the HVdc system is an emerging oscillation type been widely observed and studied recently. The frequency scanning analysis, eigenvalue analysis, time domain simulation analysis and impedance based Nyquist stability analysis are the most commonly used analyzing method for the studies of the SSI/SSO.

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