Subsynchronous Oscillation Analysis of Large-scale Wind Power Transmission System

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Abstract

With the rapid development of wind power generation in China, large-scale wind power transmission has gradually become the main way to absorb wind power and improve the utilization rate of wind power. However, ultra-high voltage AC transmission and high voltage DC transmission with series compensation capacitors, as important ways of large-scale wind power transmission, may induce subsynchronous oscillation. Therefore, it is of great significance to study the mechanism of subsynchronous oscillation of large-scale wind power transmission. This paper analyzes the structural characteristics of squirrel cage asynchronous, doubly-fed induction and permanent magnet synchronous wind turbines, discusses subsynchronous resonance, subsynchronous oscillation caused by devices and subsynchronous oscillation caused by wind turbine controllers, and analyzes and summarizes the types of subsynchronous oscillation that may occur in different types of wind turbines. Finally, it points out the problems that need to be solved urgently.

Keywords

Subsynchronous oscillation, Subsynchronous resonance, Wind power generation system.

1. Introduction

Nowadays, the large-scale development and utilization of wind power has become an important part of China's energy strategy. Many large-scale wind power generation bases have started construction in northwest provinces of China and have been connected to the grid one after another. However, the southeast coastal area is the main load center of our country. This "reverse distribution" of load centers and wind power generation bases makes large-scale long-distance transmission of wind energy an urgent problem to be solved [1]. Series capacitance compensation technology can economically and effectively increase the transmission capacity of long-distance transmission lines and improve the stability of power systems. Installing series capacitor compensation device on long-distance AC transmission line can not only reduce reactance of transmission line and electrical length of transmission line, but also reduce line loss, increase transmission capacity of power grid and improve static stability limit of system. The problem of subsynchronous oscillation of conventional thermal power units began in the US MOHAVE power plant in the 1970s. At that time, the interaction between two large turbine-generator units and series compensation capacitor transmission lines caused subsynchronous oscillation accidents, and the generator shaft was seriously damaged. This makes large-scale wind farms face severe subsynchronous oscillation problems [2]. Therefore, in-depth study of subsynchronous oscillation in large-scale wind power transmission is conducive to the safe and stable operation of China's power network.

2. Wind Turbine Structure

2.1 Squirrel cage asynchronous wind turbine generator set

Cage asynchronous wind turbine has simple structure, convenient maintenance and low cost. This type of wind turbine consists of fixed pitch wind turbine, gear box, cage asynchronous generator, soft starter and a group of parallel capacitors for reactive power compensation. As the generator is directly connected with the power grid, the expensive high-power converter is saved; Its shafting mainly includes three parts: high-speed shaft, gear box and low-speed shaft, which is shorter than that of thermal power units, and the existence of gear box makes the shafting stiffness of wind power units very small, about 0.15 ~ 0.40. When the active power is reduced by controlling the generator, when the wind speed changes little, the output power of the wind turbine will exceed the electromagnetic power of the generator, and the excess mechanical power on the shaft will cause the rotation speed of the generator set to rise. However, because it can only operate at "constant speed", the wind energy conversion efficiency of cage-type asynchronous wind turbine is relatively low.

2.2 Doubly-fed asynchronous wind turbine

Doubly-fed asynchronous wind turbine adopts wound rotor asynchronous generator. Its stator is directly connected to the power grid, and its rotor side is connected to the power grid through converter. It is currently the mainstream wind turbine. Doubly-fed induction generators are used to convert energy, and the generator stator is directly connected with the power grid. The rotor is connected with the power grid through an AC/DC/AC frequency converter. The wind turbine generator does not need to operate at a fixed speed, and the rotating speed can be dynamically controlled and adjusted through the frequency converter [3]. Therefore, there is a strong coupling relationship between the rotating speed and the power of the doubly-fed fan. When considering the influence of power on subsynchronous oscillation, the change of rotational speed should also be considered. And grid companies now require doubly-fed wind farms to participate in the voltage regulation of the power system. Through the dynamic regulation of the converter, variable speed operation of the wind turbine can be realized, and active and reactive power decoupling control [4]. Its main advantages include continuous variable speed operation and high wind energy conversion rate. The converter capacity is 25% ~ 30% of the rated capacity of the wind turbine, and the converter cost is relatively low. The induction generator effect is a self-excited phenomenon that only considers the dynamic behavior of the electrical system and has nothing to do with the turbogenerator shafting. Therefore, the simple induction generator effect will not lead to the occurrence of shafting torsional vibration.

2.3 Permanent magnet direct drive synchronous wind turbine

Permanent Magnet Synchronous Wind Turbine (PMSG) is another mainstream type of wind turbine in the current market due to its high efficiency and permanent magnet excitation. Permanent Magnet Synchronous Wind Turbine (PMSG) uses permanent magnet synchronous generator to realize energy conversion. Full-power converter transfers all power from wind turbine to effectively isolate generator from power grid. Therefore, the electrical frequency of the generator can change with the change of wind speed, while the grid frequency is constant, thus realizing variable speed operation of the wind turbine. Based on the derivation of mathematical models of doubly-fed induction motor, converter control system, aerodynamic system, transmission line with series compensation capacitor and mechanical transmission system of doubly-fed wind turbine, a small signal model suitable for doubly-fed wind power transmission system is established to analyze subsynchronous oscillation characteristics. Therefore, it is difficult for the shafting to directly couple with the electrical quantity of the power grid to generate torsional vibration. Since there is no gearbox in the shafting of the permanent magnet synchronous motor set, and the wind wheel is directly connected with the generator, the shafting stiffness is greater than that of the above two wind turbine sets.

3. Analysis of Subsynchronous Oscillation in Large-scale Wind Power Transmission

3.1 Subsynchronous resonance(SSR)

Subsynchronous resonance is one of the subsynchronous oscillation phenomena frequently encountered in thermal power generation. As early as 1970 and 1971, the torsional vibration damage of generator shaft in MOHAVE power station in the United States was caused by this type of subsynchronous oscillation [5]. It caused a large number of tripping of wind turbine generator units and damage of internal crowbar circuits. The accident was caused by a ground fault and disconnection of a line near the wind farm, resulting in a change in the connection mode of the system, forming a radial power supply mode in which the wind farm is connected to the system via a single-circuit line with fixed series compensation. That is, the system electrical resonance frequency is complementary to the natural torsional vibration frequency of the generator shafting, then the generator and the series compensation system will exchange energy through continuous weak damping oscillation or transient action, which will lead to fatigue or critical failure of the generator shafting. The rotor windings of doubly-fed induction motor are connected to the power grid through the rotor-side converter, the grid-side converter and the isolation transformer, while the stator windings are directly connected to the power grid. The dynamic process in which electrical systems and turbo-generators exchange energy significantly at one or more oscillation frequencies lower than the synchronization frequency of the system, thus endangering the safety of the turbo-generators [6].

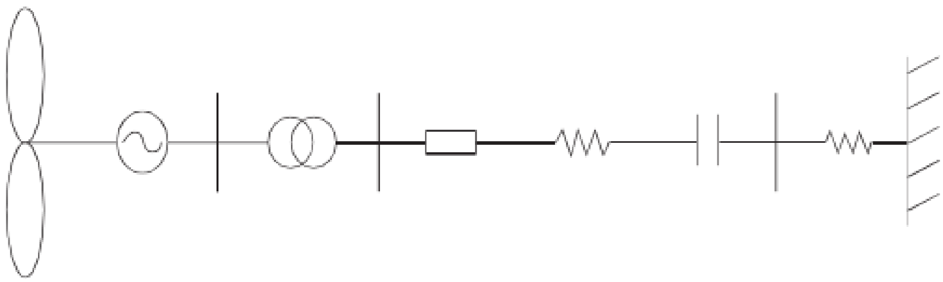

Figure 1 Schematic diagram of wind power transmission system adopting series compensation transmission

In the process of large-scale wind power transmission through series compensation, due to the low natural torsional vibration frequency (1 ~ 2hz) of the shaft system of the wind turbine, a high series compensation degree is required to excite the torsional vibration mode of the shaft system, the series compensation degree in engineering practice is difficult to meet the excitation condition, and the probability of occurrence of SSR of wind turbine is small [7]. Moreover, the control system of the rotor-side converter of the doubly-fed wind turbine generally decouples its active and reactive power through stator flux linkage directional control or stator voltage directional control. Due to the complicated structure of the stator flux observer, the stator flux observer is usually omitted in practical engineering and vector control is directly carried out on the converter on the rotor side of the fan through stator voltage orientation. Considering the wind power external equivalent system shown in fig. 1, the natural resonant frequency of the electrical system is:

$$f_{er} = f_0\sqrt{X_C / X_L} \tag{1}$$

Where f_0 is the synchronous frequency. At the subsynchronous frequency, the equivalent resistance of the generator is negative. If the negative value exceeds the equivalent resistance of the transformer and transmission line, the system will generate negative damping, and the system will generate subsynchronous resonance due to the induction generator effect [8].

Electromechanical torsional vibration interaction and induction motor effect can both cause subsynchronous oscillation of power systems with series compensation. However, the physical essence, occurrence conditions and phenomena of the two are different and should be paid attention to. Suppose the generator rotation frequency f_m, when the current I_{s1} with electrical resonance frequency fer flows through the stator winding, a current component I_{r1} of frequency $f_{er} = f_m$ is induced on the rotor, and the power frequency current component I_{s2} in the stator is induced on the rotor Current I_{r2} with frequency $f_0 - f_m$. As shown in Table 1. The sum of the four electromagnetic torque components is the electromagnetic torque of the generator, and its frequency $f_T = f_0 - f_{er}$.

Table 1 Each torque component

Torque	Correlation	Frequency
T_1	I_{s1}, I_{r1}	0
T_2	I_{s1}, I_{r2}	$f_0 - f_{er}$
T_3	I_{s2}, I_{r1}	$f_0 - f_{er}$
T_4	$I_{s2}, I_{r2},$	0

Relevant literature research shows that SSCI is caused by the negative damping of the system caused by the fast direct current control of wind turbines. The resonant current generated by the disturbance of the system will induce corresponding subsynchronous current on the generator rotor, thus causing the change of rotor current [9]. In order to coordinate with power balance, wind farms sometimes need to abandon wind and carry out active power regulation. When the active power is regulated by controlling the change of pitch angle, the rotational speed is kept unchanged, and the active power will change accordingly. The research finds that the lower the wind speed and the higher the series compensation degree, the more serious the subsynchronous resonance of doubly-fed induction wind turbine generator. Document [10] designs SSR damping controller for doubly-fed induction wind turbine generator, and the effectiveness is verified by numerical simulation.

3.2 Device-induced subsynchronous oscillation(SSTI)

Unreasonable controller parameters of power electronic devices such as high voltage direct current transmission (HVDC) and facts may also cause generator subsynchronous oscillation, collectively referred to as device-induced subsynchronous oscillation. converter controllers will adjust inverter output voltage after sensing this change, causing changes in actual current in the rotor. If the output voltage increases, the rotor current increases. If the damping of the system at this frequency is very small, the shafting may generate large amplitude oscillation under the action of corresponding electromagnetic torque. At this time, even if the outlet switch of the motor set is tripped, the shaft system will still slowly attenuate torsional vibration under weak damping, causing fatigue damage and affecting the service life of the shaft pump. The controller of power electronic device controls or responds to power and current rapidly in the subsynchronous frequency range, which will affect the phase difference between the electromagnetic torque and the rotating speed of the generator. In order to form reactive power support for the power grid, doubly-fed wind turbines need to adjust their reactive power output under certain circumstances. At this time, the reactive power output of the wind turbine will change accordingly. The oscillation of resonant current will intensify, which will lead to the destruction of system stability.

The changes of active and reactive power reference values have great influence on SSO, and the influence of wind speed on subsynchronous oscillation is mainly due to the wind speed changing the rotation speed of the fan. Therefore, we select the fan speed, active reference value and reactive reference value as the key parameters. When the degree of series compensation is 8%, the traditional stability region boundary and the practical small disturbance stability region boundary are calculated respectively, as shown in the following figures 2 and 3:

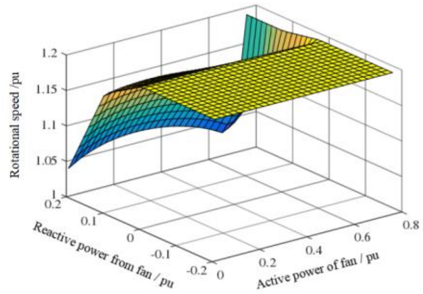

Figure 2 Three-dimensional SSSR stable boundary

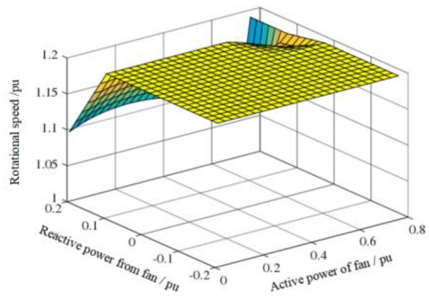

Figure 3 Three-dimensional P-SSSR stable boundary

The stable region is above the curved surface shown in fig. 3. it can be seen that p-SSSR is smaller than sssr, which is mainly due to the fact that P-SSSR takes into account the damping level requirement of doubly fed wind power transmission system to suppress subsynchronous oscillation and is more conservative. Therefore, when designing the damping controller, the maximum P-SSSR can be directly designed.

Squirrel-cage asynchronous and doubly-fed induction wind turbines are closely coupled with the power grid. Negative damping may be introduced to the generator when there are power electronic devices nearby, resulting in subsynchronous oscillation. As the proportional gain of the inner loop of the rotor-side current control loop increases, the system tends to be unstable. From the early vertical-axis wind turbine to the current horizontal-axis wind turbine, from constant-speed pitch control to variable-speed pitch control, from squirrel cage asynchronous generator to doubly-fed induction generator to permanent magnet synchronous generator, the conversion efficiency and control effect of wind turbine have been continuously improved. In addition, doubly-fed induction and permanent magnet synchronous wind turbines have converter controllers inside themselves. If the parameters of the converter controllers are unreasonable, they will show negative damping characteristics in the subsynchronous section, which may also be the excitation source of subsynchronous oscillation of wind turbine generators. As the control object of generator control is electromagnetic torque, it is relatively easy to control the electrical system, with small time constant and fast dynamic response of the system.

3.3 The subsynchronous oscillation caused by the coupling of the wind turbine controller and the external controller(SSCI)

The problem of subsynchronous oscillation caused by wind turbine controller is a new subsynchronous oscillation phenomenon with the rapid development of wind power generation. Unlike subsynchronous resonance and subsynchronous oscillation caused by devices, subsynchronous oscillation caused by wind turbine controller has no connection with mechanical system. The speed of generator changes only in a small range during normal operation. The generator stator circuit is directly connected with the power grid by AC, and the rotor is connected with the wind wheel of the wind turbine through the shafting. The drive system state variables are not involved. Literature [11] Through eigenvalue analysis, the results show that the inner loop current control of the rotor-side converter has little influence on the oscillation mode. Therefore, when the wind farm needs to limit its output or abandon the wind, it is better to control the generator to adjust the active power output, which is conducive to avoiding the risk of subsynchronous oscillation. When the wind speed is higher than the rated wind speed, the pitch angle increases, the wind energy utilization coefficient decreases, and the mechanical power obtained by the wind turbine decreases, finally running at the rated power point.

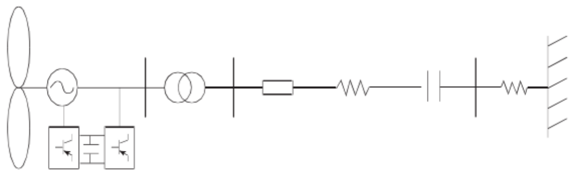

Figure 4 Doubly-fed induction wind turbine with series compensation

The subsynchronous oscillation caused by the wind turbine generator controller is caused by the resonant current of the electrical resonant circuit. An abnormal state of the power system in which the power system and the turbine generator significantly exchange energy at one or more oscillation frequencies lower than the synchronization frequency of the system, thus endangering the dynamic process of the turbine generator shafting. Therefore, when planning the operation mode of the system, the possibility of SSCI occurring in the system under each operation mode can be analyzed based on electromagnetic transient program, so as to avoid the operation mode that may cause SSCI. For the wind power transmission system with series compensation as shown in fig. 4, the resonant current induces the corresponding subsynchronous frequency current on the generator rotor, which will cause the waveform distortion and phase shift of the rotor current. the converter controller will adjust the inverter output voltage after sensing the change, causing the change of the actual current in the rotor, thus forming a closed-loop system. however, from the perspective of inhibiting subsynchronous oscillation, it is not the most advantageous to alleviate subsynchronous oscillation by adjusting the active power, because the increase of rotational speed is a mechanical process and the adjustment speed is relatively slow.

The subsynchronous oscillation problems that may be generated by different types of wind turbines are shown in Table 2. In fact, since large-scale wind farms or farms are generally composed of multiple types of wind turbines, the subsynchronous oscillation and suppression problems generated by them will be more complicated.

Table 2 Comparison of subsynchronous oscillations of different types of wind turbines

Unit	SSR	STI	SSCI
Squirrel cage asynchronous wind turbine generator set	√	√	—
Doubly-fed Induction Wind Turbine	√	√	√
Permanent Magnet Synchronous Wind Turbine	—	√	—

There is no power electronic device in squirrel cage asynchronous wind turbine. Therefore, there is no SSCI problem when using series compensation capacitor to send wind power. The stator of doubly-fed induction wind turbine is directly connected to the power grid, and AC/DC/AC frequency converter is used on the rotor. Resonance current is easy to enter into the controller of the generator, which may cause unstable oscillation of the system. In order to excite the low frequency torsional vibration mode of the wind turbine shaft system, high resonance frequency current, i.e. high line series compensation degree, is required. Therefore, compared with conventional thermal power units, squirrel cage asynchronous wind power units and doubly fed induction wind power units have less probability of subsynchronous resonance under the same series compensation degree. Permanent magnet synchronous wind turbine not only does not cause SSCI problem, but also can provide positive damping and inhibit SSCI to some extent. In the planning and design stage of wind farms, the proportion of DFIG and permanent magnet synchronous wind turbines is reasonably arranged. Therefore, SSCI is easy to occur when doubly-fed induction wind turbines use series compensation capacitors to deliver wind power. Although there are power electronic devices in permanent magnet synchronous wind turbines, resonance current cannot enter the generators due to the decoupling of generators and power grids. In addition, the grid-side converter is limited by its capacity and has little ability to regulate reactive power. Therefore, during the operation of the wind power transmission system, the reactive power of the stator side of the doubly-fed wind turbine is usually changed to provide voltage support for the power grid.

4. Summary

The structure and grid connection mode of wind power generation system are essentially different from those of traditional thermal power generation units, and the wind farm/farm group is composed of various types of wind power generation units, which makes the subsynchronous oscillation problem sent from large-scale wind power bases very complicated. The subsynchronous oscillation of doubly-fed induction wind power generation units is caused by the rotor-side controller of the unit, and has nothing to do with the shafting part. The generation mechanism is essentially different from that of conventional thermal power generation units. The oscillation frequency of wind turbine generator output active power is mainly determined by the series compensation degree. The higher the series compensation degree, the lower the oscillation frequency. The effect of active power regulation characteristics of doubly-fed wind turbine on subsynchronous oscillation depends on the selected regulation mode. By changing the pitch angle of wind turbine, the output active power of doubly-fed wind turbine will aggravate subsynchronous oscillation phenomenon. In a certain range, increasing the proportional coefficient of the phase-locked loop and decreasing the integral coefficient of the phase-locked loop will increase the frequency of the main oscillation modes. Wind farm clusters are made up of many types of wind turbines. How the subsynchronous oscillations between different types of wind turbines, even with conventional thermal power units, affect each other is also a problem that needs in-depth study.

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