Analysis and Suppression Strategy of Sub-synchronous Oscillation for Wind-Thermal-Bundled Power Transmitted by Series-Compensated System

Asaah Philip, Yushuo Zhang, Lili Hao, Yantong Zhou and Wei Li

Abstract Large-capacity wind farms may increase the risk of torsional vibration of turbine generator shafts in the wind-thermal-bundled power transmitted by series-compensated system, therefore the analysis and suppression strategy of sub-synchronous oscillation (SSO) in such system needs to be thoroughly studied. In this paper, the mechanism of electromechanical torsional interaction and the influence of wind farm integration on system oscillation are analyzed. In order to suppress the SSO, the mechanism of electromagnetic torque increment produced by additional damping control of static synchronous compensator (STATCOM) is studies, based on which, a SSO damping controller is designed. Based on the complex torque coefficient approach and time domain simulation approach simulation cases are built in DIgSILENT/PowerFactory. The results show the impact of wind farm integration and series compensation degree on system damping and verify the suppression effect of STATCOM on system SSO.

Keywords Wind-thermal-bundled system · Sub-synchronous oscillation (SSO) · Series compensation degree · Electromechanical torsional interaction · Additional damping control · Static synchronous compensator (STATCOM) · Complex torque coefficient approach

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1 Introduction

In order to improve the consumptive ability of wind power and make full use of the existing transmission channels, combining thermal generators and wind turbine generators is an effective transportation way [1–3]. In order to further improve the transmission capacity of the line and enhance the stability of the power grid, capacitor series compensation is often adopted for transmission lines. However, the excessive capacity of the series compensator may cause the SSO of the shaft system, which will cause rupture of the shaft in serious case, and then threaten the safety of the system [4]. Since the wind farm integration and series compensation degree of transmission lines will affect SSO, it is necessary to study the torsional vibration law of the shaft system, so as to effectively suppress the SSO and ensure the safe and stable operation of the power system.

The researches of wind-thermal-bundled system at home and abroad are mainly focused on transient stability, the operation characteristics and control strategies [5]. Some literatures have studied the influence of wind farm integration on SSO of the turbine generator. Literature [6] took the first IEEE SSO benchmark model with a doubly-fed induction generator (DFIG) as an example and established the mathematical model for small signal stability analysis, found that the damping ratio of the SSO mode decreases and the system damping decreases along with the increase of active output of wind farm. Literature [7, 8] built the transfer function between the output power of the wind farm and the rotational speed of the thermal power unit, and deduced the influence of active and reactive power of DFIG on system damping respectively, then proposed the conditions which can provide positive damping to the system. Because the additional damping control signal used is superimposed on the outer loop of the double-closed-loop control of the wind turbine, it is easy to create the oscillation of wind turbines. Based on the first IEEE SSO benchmark model connected with DFIG, literature [9] adopted eigenvalue method and time domain simulation method to analyze the wind farm influence on the thermal power units. Literature [10] established a typical model of wind-thermal-bundled system via DC system and analyzed the SSO mechanism, results showed that DFIG can alleviate the SSO caused by DC transmission. Current researches mostly focus on the impact of wind power access capacity on system oscillations and rarely consider the effect of line complement compensation. Most of the researches qualitatively discuss the suppression effect on sub-synchronous oscillations using time domain simulation, while few studies carry out the quantitative comparison of the system damping before and after the implement of suppression strategy, which may impede the display of suppression effect on the SSO of specific frequencies.

This paper analyzes the SSO mechanism of wind-thermal-bundled system via series compensation lines, introduces the basic principle of the complex torque coefficient approach, and studies the rules of electromagnetic torque increment produced by additional damping control of STATCOM and designs a SSO damping controller. The complex torque coefficient approach is used to analyze the influence of the series compensation on the electrical damping coefficient of the system using the first IEEE SSO benchmark model combined with DFIG. Based on the DIgSILENT simulation platform, a typical system model of wind-thermal-bundled power transmitted by series-compensated lines is built, and the complex torque coefficient approach is used to analyze the influence of the series compensation on the electrical damping coefficient of the system, and the system short circuit test is used to verify it executed. Then the system electrical damping characteristic curve is compared before and after the STATCOM added, and the SSO suppression effect of the SSO is verified by the electromagnetic torque responses of thermal generator and wind turbine generators.

2 Mechanism Analysis of SSO for Wind-Thermal-Bundled Power Transmitted by Series-Compensated System

The serial access of a fixed capacitor in a line may lead to the interaction of electrical and mechanical systems, which may cause the instability of the generator shafting, and this phenomenon is called electromechanical torsional interaction [11, 12]. For electrical systems, the electrical system is stable if the total system damping is positive at the resonance frequency. For the shaft system of generators, the mechanical system is stable when the generator is not connected to power grid because of the existence of positive mechanical damping of the shafting, but when the generator is connected to the grid, if a tiny oscillation $\Delta\omega$ whose frequency is f_m appears on the rotor, the voltage and current components whose frequency are $f_0 - f_m$ and $f_0 + f_m$ respectively will be generated on the stator winding (f_0 is the power frequency). If f_m happens to be a shafting torsional vibration frequency, and it is complementary to the electrical resonance frequency f_e (that is, $f_0 = f_m + f_e$), the electrical and mechanical systems will interact with each other. The electromagnetic torque generated by the sub-synchronous current may be in phase with the rotor oscillation $\Delta\omega$, which may drive the amplitude of the oscillation $\Delta\omega$ increase. If the system damping is too small to prevent such torsional vibration interaction, the generator shaft system may be destroyed.

Researches show that neither the SSO modes nor their frequencies will be changed after the wind farm integration, but the system damping will be reduced. Because of the electromechanical torsional interaction in thermal power unit and the current disturbance in series compensation line, the SSO current component in the DFIG rotor winding is caused by magnetomotive equilibrium, and the current component will also induce the current component of the same resonance frequency in the stator winding because of the rotor magnetic field, which will further enhance the original disturbance and reduce the system damping.

3 Sub-synchronous Oscillation Suppression Using STATCOM

When the electrical distance between STATCOM and generator is small, the output voltage and current of the generator can be adjusted slightly by adjusting the reactive power output of STATCOM, so an electromagnetic torque increment can be produced in the steady-state electromagnetic torque of the generator shaft system. When the frequency and phase of the electromagnetic torque increment are suitable, the SSO can be suppressed. That is to say, the SSO can be suppressed by the fast continuous adjustment ability of STATCOM reactive power.

An important characteristic of shafting torsional vibration is the oscillation of generator shafting on the basis of synchronous speed. Intuitively, when the generator is accelerated, STATCOM increases its output of inductive reactive power, raises the output voltage and power of generator, also increases the electromagnetic torque, and for a constant mechanical torque input, the increment of electromagnetic torque makes the rotor decelerate; when the generator speed is slows down, STATCOM reduces its output of inductive reactive power, decreases the output voltage and power of the generator, then also reducing the electromagnetic torque, and for a constant mechanical torque input, the reduction of electromagnetic torque makes the rotor accelerate. If SSO occurs, STATCOM can response quickly to the torsional vibration of the turbine shaft system and suppress SSO.

The frequency complementary relationship between electrical quantity and electromagnetic torque increment in the damping control process is further analyzed. Assuming that the unit has a torsional vibration of ω_m in the shaft system, so the rotor speed of the unit is the sum of synchronous speed ω_0 and a torsional vibration ω_m. Only considering the reactive current component of the sub-synchronous frequency, the frequency components of the current between STATCOM and system are mainly sub-synchronous and hyper-synchronous components whose frequencies are $\omega_0 \pm \omega_m$

$$\begin{cases} \Delta i_a = A_m \sin(\omega_0 - \omega_m)t + A_m \sin(\omega_0 + \omega_m)t \\ \Delta i_b = A_m \sin\left[(\omega_0 - \omega_m)t - \frac{2}{3}\pi\right] + A_m \sin\left[(\omega_0 + \omega_m)t - \frac{2}{3}\pi\right] \\ \Delta i_c = A_m \sin\left[(\omega_0 - \omega_m)t + \frac{2}{3}\pi\right] + A_m \sin\left[(\omega_0 + \omega_m)t + \frac{2}{3}\pi\right] \end{cases} \tag{1}$$

After Park transformation

$$\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin \omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} \Delta i_a \\ \Delta i_b \\ \Delta i_c \end{bmatrix} = \begin{bmatrix} 0 \\ -2A_m \cos \omega_m t \\ 0 \end{bmatrix} \quad (2)$$

When the torsional vibration occurs, the electromagnetic torque increment in the shaft system is mainly composed of two parts: one is caused by the interaction between the main flux of the generator and the current component of sub-synchronous frequency, and the other one is caused by the interaction of the magnetic field produced by the sub-synchronous frequency current component and the stator circuit current. Since the amplitude of the shafting torsional vibration speed is very small relatively to the synchronous speed, the magnetic field produced by the sub-synchronous current component is very weak relative to the main flux of the generator, the magnetic flux produced by the sub-synchronous current component can be ignored, and the main magnetic flux is still a stable magnetic field. The increment of electromagnetic torque generated by STATCOM additional damping control on the generator shafting is as follows

$$\Delta T_e = \psi_d \Delta i_q - \psi_q \Delta i_d = -2\psi_d A_m \cos \omega_m t \quad (3)$$

It can be seen that the additional damping control of STATCOM will produce an electromagnetic torque increment whose frequency is ω_m, which is the same as the frequency of the torsional vibration. When the phase of the torque increment is suitable, the shafting torsional vibration can be suppressed.

The reason for the generator torsional vibration is that the phase difference between the generator angular frequency deviation $\Delta\dot{\omega}$ and the electromagnetic torque variation $\Delta\dot{T}_e$ is more than 90°. In this paper, the generator angular frequency deviation $\Delta\omega$ is used as the input signal, after appropriate proportional amplification and phase shift, the output signal provides an additional electromagnetic torque $\Delta\dot{T}_e$ through the double-loop control loop, which makes the phase difference between the total electromagnetic torque variation $\Delta\dot{T}_e$ and the generator angular frequency deviation $\Delta\omega$ within 90°, and the system will eventually have a positive damping torque. Their phase relation is shown in Fig. 1.

Figure 2 is the structure diagram of the STATCOM damping controller. The generator angular frequency deviation $\Delta\omega$ is used as the input signal of additional damping control. Using the modal separation filter, each modal speed signal can be separated from the generator rotor speed deviation. The STATCOM reactive instruction ΔV_{aci} for restraining the torsional vibration of each mode can be obtained through the appropriate proportional amplification and phase compensation for each modal speed signal. The whole reactive instruction ΔV_{ac} for SSO

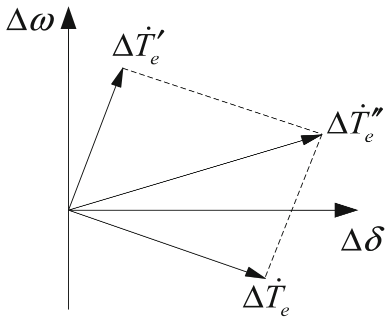

Fig. 1 The phase diagram of the additional electromagnetic torque and angular variation

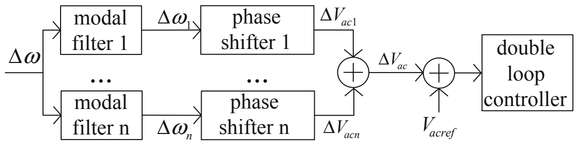

Fig. 2 The block diagram of STATCOM sub-synchronous damping controller

suppressing can be obtained by adding all the reactive instructions above. The final reactive power instruction is the sum of ΔV_{ac} and the reactive power instruction in steady state control mode, and the series switch signals of the STATCOM converter are generated by trigger control.

The phase compensation is the most critical step in STATCOM design, which directly affects the ability of STATCOM to suppress SSO. If the parameter selection is not appropriate, it may make STATCOM not only impossible to inhibit but also stimulate the SSO. The STATCOM uses the lead-lag stages for phase compensation such as $((1+sT_1)/(1+sT_2))^N$. N is the number of the lead-lag stages. The calculation method of its time constant T_1 and T_2 is as follows

$$\begin{cases} \alpha = \dfrac{T_2}{T_1} = \dfrac{1-\sin\varphi}{1+\sin\varphi} \\ \omega = 2\pi f \\ T_1 = \dfrac{1}{\omega\sqrt{\alpha}} \\ T_2 = \alpha T_1 \end{cases} \tag{4}$$

where f: the central frequency of the lead-lag stages, and φ: the compensation angle provided by the lead-lag stage at the center frequency. The central frequency can usually be selected according to the frequency of the oscillating mode to be compensated. If there are multiple oscillation modes in the system need to be compensated, the dominant mode with the weakest damping is generally chosen. According to the STATCOM controller structure, the phase to be compensated is the sum of the phase shift of modal filter and the link from STATCOM constant AC voltage controller to generator electromagnetic torque. Among them, the transfer function of the link from STATCOM constant AC voltage controller to generator electromagnetic torque is difficult to be obtained by analytic method. In this paper, the lagging phase of this link will be obtained by the test signal method. The steps are as follows: a series of small AC voltage oscillation ΔV_{aci} (whose frequency range is from 5 to 55 Hz and frequency interval is 0.5 Hz) is applied to the external loop reference link of the constant AC voltage controller. When the system is simulated to steady state, the output response, the generator electromagnetic torque T_e is measured. And ΔT_e is obtained from the difference of the T_e before and after the small oscillating signals are applied to the generator. Then, ΔT_e and ΔV_{aci} are decomposed by Fourier transform and the phase difference between ΔT_e and ΔV_{aci} at different frequencies are calculated, that is the lagging phase required.

4 Case Studies

4.1 The System Model

The structure of the simplified wind-thermal-bundled power system is shown in Fig. 3. The G represents the thermal power unit and through the transformer T_1 access bus A; The C represents the doubly-fed wind farm and through the transformer T_2 access bus A. G and C will transmit power to the infinite power grid E by wind-thermal bundling via series compensation line. GSC and RSC represents the grid side converter and rotor side converter of doubly-fed generator respectively. $R_L + jX_L$ represents the impedance of transmission lines. X_c and X_{sys} represent capacitance reactance of series capacitor and connection reactance of infinite system respectively.

In Fig. 3, the thermal power unit, with the rated capacity of 892.4 MVA, the rated frequency of 60 Hz and the rated voltage of 500 kV, is modified from the first IEEE SSO benchmark model [13]. The unit shafting system is composed of six concentrated mass blocks: high pressure cylinder (HP), intermediate pressure cylinder (IP), low pressure cylinder A (LPA), low pressure cylinder B (LPB), generator (GEN) and exciter (EXC). The natural torsional frequencies of the

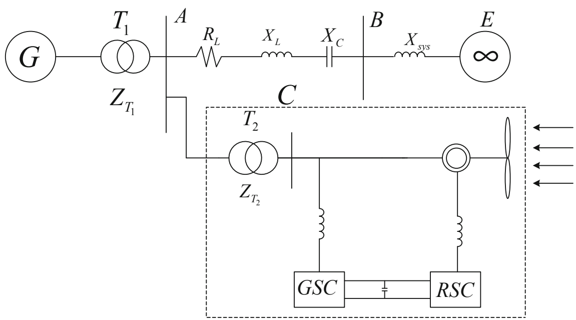

Fig. 3 The block diagram of STATCOM sub-synchronous damping controller

shafting are 15.71, 20.21, 25.55, 32.28 and 47.45 Hz. The ratio of mechanical torque applied to rotors of HP, IP, LPA and LPB are 0.3, 0.26, 0.22, and 0.22 respectively. The wind farm is equivalent to a DFIG model with the stator winding connected to the power grid directly and the rotor winding connected to the power grid through an AC-DC-AC converter. The DFIG model is mainly composed of wind turbine, generator, rotor-side converter, grid-side converter, DC bus, capacitor and the corresponding control module of each part. The converter adopts a double-loop control structure. The rotor-side converter realizes active and reactive decoupling control, and the grid-side converter realizes voltage control of DC bus between the two converters [14–16].

4.2 The Suppression of STATCOM on SSO

In the wind-thermal-bundled system as shown in Fig. 3, the wind farm integration capacity is supposed to be 100 MW, the corresponding thermal power unit is 703 MW, and the series compensation degree is 0.6. The SSO is suppressed by adding a STATCOM at bus A. The STATCOM DC capacitor voltage is set to be 1 kV, the converter output AC voltage is set to be 0.4 kV, and the converter capacity is 300 MVA. The frequency of minimum electrical damping coefficient is 20.5 Hz, which is the dominant oscillation mode, so 20.5 Hz is selected as the central frequency f need to be compensated. The lagging phase between the STATCOM constant AC voltage controller and generator electromagnetic torque is calculated to be about 55° at 20.5 Hz by test signal method, and the lagging phase of the modal filter is supposed to be about 5°. Therefore, four lead-lag stages are used to compensate for 60° of phase lag at 20.5 Hz, and each of which compensates for 15°. Calculated by formula (4), $T_1 = 0.101$ and $T_2 = 0.006$. The electrical damping characteristics curves, the electromagnetic torque response of the turbine generator and wind turbine before and after STATCOM is added are shown as below.

From Fig. 4, it can be seen that after the addition of STATCOM, at the original SSO frequency of 20.5 Hz, the electrical damping coefficient changes from negative to positive, which indicates that the addition of STATCOM increases the damping of the system and is beneficial to the suppression of SSO. From the time-domain simulation in Fig. 5, it can be seen that STATCOM has a significant suppression effect on the electromagnetic torque oscillation of thermal power units and wind turbines.

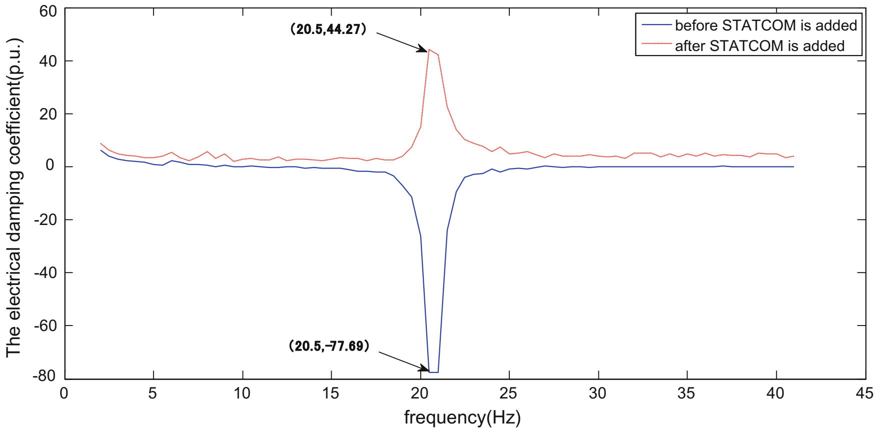

Fig. 4 The electrical damping characteristic curve with and without STATCOM

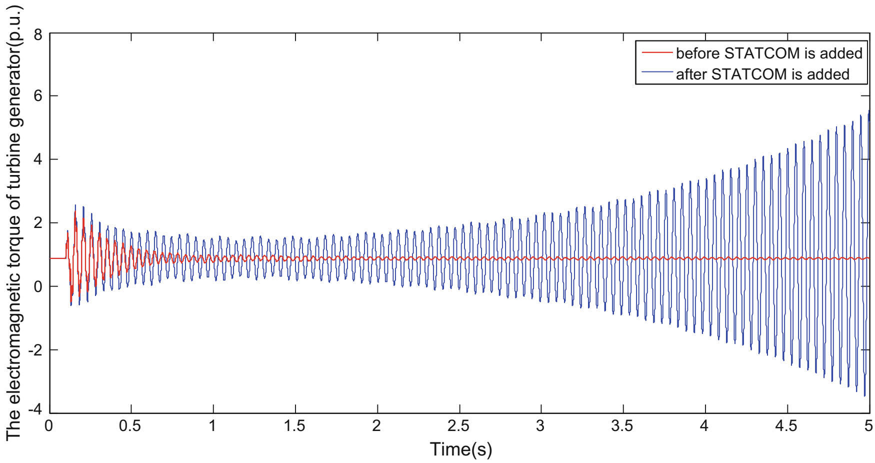

Fig. 5 The electromagnetic torque response of wind turbine with and without STATCOM

5 Conclusions

Through the mechanism analysis of STATCOM for SSO suppression, the STATCOM additional damping control will produce an electromagnetic torque increment with the same frequency as the torsional vibration of the shaft system. Reasonably controlling the frequency and phase of the electromagnetic torque increment can suppress the sub-synchronous oscillation. Through the time-domain analysis of wind-thermal-bundled power transmitted by series-compensation system, the STATCOM really has a significant suppression effect on electromagnetic torque oscillation of thermal power units and wind turbines.

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