Research on additional damping control of sub-synchronous oscillation in series-compensated DFIG system

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Abstract—Since series-compensated grid-connected system of doubly fed induction generator (DFIG) may cause sub-synchronous oscillation, with the purpose of improving the system stability, in this paper, the mechanism of sub-synchronous oscillation (SSO) is analyzed from the perspective of system damping, according to the mechanism, an additional damping controller is designed to suppress SSO. The controller uses rotor speed as the input signal and adds it into the d-axis current inner loop of the grid-side converter through filtering and proportional amplification, with the purpose of providing positive damping to the system. Finally, the model of DFIG series-compensated grid-connected system is established on PSCAD/EMTDC simulation platform to verify the suppression effect of the additional damping controller through time-domain simulation. The simulation results show that the device has good respond speed and suppression effect.

1. Introduction
As a new energy source with established technology, conditions for large-scale development and prospects for commercialization, wind power has been developing rapidly all over the world. China’s wind energy resources are distributed in northwest and north regions, while the load centers are deployed along the southeast coastal areas, so that they are distributed in opposite directions[1]. Therefore, the large-scale long-distance transmission of wind energy is critical to the safe and stable operation of power system. Series-compensated capacitor technology can effectively improve the line transmission capacity, increase the stability margin of the system, and reduce the transmission line losses, and has mature technology and high cost performance, so it has been widely used in long-distance transmission[2].

However, the series-compensated grid connection of DFIG system is prone to the risk of sub-synchronous oscillation. In 2009, a wind farm in Texas, U.S. experienced sub-synchronous oscillation caused by fixed series compensation, resulting in massive off-grid wind turbines and damage to the crowbar circuits. At the end of 2012, oscillation of 6 ~ 8 Hz occurred in a wind farm in North China[3]. Therefore, sub-synchronous oscillation in DFIG series-compensated system aroused great attention from domestic and foreign scholars. Studies show that the phenomenon of sub-synchronous oscillation in DFIG series-compensated system is caused by the interaction between the controller of wind turbines and the series compensation, which is called sub-synchronous control interaction (SSCI) [4-5].

At present, studies of suppression methods for sub-synchronous oscillations in DFIG series-compensated system have yielded some achievements, which can be divided into two categories:
one is to suppress by adding a flexible AC transmission (FACTS) device\cite{6,7}, and the other is adding a damping controller in the wind turbine control system\cite{8}. Compared with the FACTS device, suppression via wind turbines can greatly reduce costs and has good response speed and suppression performance, giving it a strong engineering value, but there are a few studies related to it. In the literature\cite{9} a unified admittance model of rotor-side converter (RSC) and grid-side converter (GSC) in DFIG wind turbines is established to analyze the operation stability of DFIG under series compensation, and to examine the effect of additional damping controller to both RSC and GSC on the stability of system. Literature\cite{10} directly built a resonant closed loop on RSC and introduced a current loop to increase damping of the system and suppress sub-synchronous oscillation. Literature\cite{11} developed a method based on stator simulation resistance for the suppression of sub-synchronous oscillation without any additional devices. The simulation results verified its suppression effect. Literature\cite{12} used control signal to track the sub-synchronous current variation, and adjusted sub-synchronous voltage from converter by additional damping to force the converter present positive resistance at sub-synchronous frequency, realizing the suppression of sub-synchronous oscillation. As mentioned above, such studies suppressed SSO, but they did not analyze the mechanism of SSO, so the damping controller design lacks theoretical support.

Based on the analysis of mechanism of SSO in DFIG series-compensated grid-connected system, this paper proposes a suppression method by introducing additional damping control. First, it analyzes the mechanism of SSO from the perspective of system damping, and then introduces an additional damping controller into the d-axis control loop of grid-side converter, and uses rotor speed as the input signal of the additional damping controller, so that the stator electromagnetic torque opposite to the rotor speed variation is generated in the stator and sub-synchronous oscillation are suppressed. Finally, time-domain simulation is used to verify this method. The simulations results show that the method can stabilize the system quickly and suppress sub-synchronous oscillation at different wind speeds and line series compensation degrees.

2.DFIG series-compensated grid-connected system model

The DFIG series-compensated grid-connected system model is shown in Fig. 1, including wind turbine, doubly fed induction generator, grid-side converter, rotor-side converter, transformer, and transmission line with series compensation. In figure 1, DFIG is the doubly fed induction generator, XT is the reactance of line transformer, RL and XL are the line equivalent resistance and reactance, XC is the capacitive reactance of the series-compensated capacitor, RSC and GSC are the rotor-side converter and grid-side converter, and L is the grid-side smoothing reactor. As mentioned above, the control system of DFIG consists of the control system of grid-side converter and the control system of rotor-side converter, and has a great influence on the sub-synchronous oscillation of DFIG series-compensated grid-connected system.

![Fig.1 Model of DFIG series-compensated grid-connected system](image)

The control objective of the grid-side converter is to maintain the direct current (DC) capacitor voltage constant and control the grid-side power factor, which uses double closed-loop control, and
consists of voltage outer loop and current inner loop. The grid-side converter control uses grid-side voltage vector orientation, and the control sketch is shown in Fig. 2. In the figure, \( K_{p1} \) and \( K_{p2} \) are the proportional parameters, and \( K_{i1} \) and \( K_{i2} \) are the integral parameters of the voltage and current control loops of the grid-side converter, respectively.

![Fig.2 Control schematic of grid voltage based grid-side converter](image)

The rotor-side converter control strategy consists of the power outer loop and the current inner loop. The rotor-side converter control uses vector control with stator voltage orientation, and orients the stator voltage \( U_s \) of DFIG to the d-axis in the synchronous rotation coordinate system, which enables the decoupling control of active and reactive components of the rotor current of DFIG. The control block diagram is shown in Fig. 3, where \( K_{p3} \) and \( K_{p4} \) are the proportional parameters, \( K_{i3} \) and \( K_{i4} \) are the integral parameters of the power control loop and current control loop, respectively.

![Fig.3 Control schematic of stator voltage based rotor-side converter](image)

3. Stator-side additional damping controller

3.1 Sub-synchronous oscillation mechanism

For the system shown in Fig. 1, by adding series compensation capacitors in the transmission line, the system has a natural resonant frequency \( f_0 \):

\[
f_0 = f_1 \sqrt{\frac{X_c}{\sum X}}
\]  

(1)

Where, \( f_1 \) is system synchronous frequency, \( \sum X \) is the sum of DFIG equivalent reactance, step-up transformer XT and line reactance XL, and \( X_c \) is the capacitive reactance of series compensation capacitor at synchronous frequency, \( X_c = k \cdot X_L \), where \( k \) is the series compensation
degree (k<1), so the resonant frequency $f_0$ is called sub-synchronous frequency, which increases with the increase of the series compensation degree at sub-synchronous frequency $k$.

For the DFIG to be studied, when there are resonant oscillation in series compensated transmission line, the increment of the stator electromagnetic torque caused by the sub-synchronous current component is:

$$ \Delta T_e = K_e \Delta \delta + D_e \Delta \omega $$ \hspace{1cm} (2)

Where, $\Delta T_e$, $\Delta \delta$, and $\Delta \omega$ are the increments of electromagnetic torque, power angle, and rotational speed, respectively. $K_e$ and $D_e$ are the synchronous torque coefficient and damping torque coefficient\[13\]. Making Laplace’s transformation to equation 2, the damping torque coefficient can be expressed as:

$$ D_e = R_e (\Delta T_e / \Delta \omega) $$ \hspace{1cm} (3)

Assuming that the initial phase of the increment of rotational speed $\Delta \omega$ is 0, and the frequency of the rotational speed variation is $\Omega$. As shown in Fig. 4, if the projection of $\Delta T_e$ on the x-axis moves along with $\Delta \omega$, which means that $\Delta T_e$ is in the first or fourth quadrant, the action of $\Delta T_e$ increases the amplitude of $\Delta \omega$, causing a negative damping effect. If the projection of $\Delta T_e$ on the x-axis moves in the reverse direction of $\Delta \omega$, which means that $\Delta T_e$ is in the second or third quadrant, the action of $\Delta T_e$ decreases the amplitude of $\Delta \omega$, rising the positive damping effect.

According to the analysis of the mechanism of SSO, the DFIG series-compensated grid-connected system is prone to resonance under the influence of small external disturbances, which causes the occurrence of SSO, while the sub-synchronous current component produces an electromagnetic torque $\Delta T_e$ on the motor stator. The torque produced by the current component is actually a driving torque in phase with the increment of disturbance speed $\Delta \omega$, which has a negative damping effect on the system oscillation, exacerbating the sub-synchronous oscillations, and forming a mutual excitation between the mechanical system and electrical system.

Therefore, this paper proposes a sub-synchronous oscillation suppression method to improve the control system by using a grid-side converter, that is, it uses rotor speed as the input signal of the additional damping controller to generate an electromagnetic torque opposite to the speed variation to provide positive damping for the system, thus suppressing sub-synchronous oscillation.

### 3.2 Design of stator-side damping controller

The objective of the stator-side additional damping controller is to generate an electromagnetic torque opposite to the rotational speed variation, which acts a positive damping effect on the rotational speed variation. Therefore, the rotor speed is selected as the feedback quantity, and an additional damping controller is introduced into the d-axis control loop of GSC, as shown in Fig. 5. In the figure, $\omega_r$ is the rotor angular velocity, $G_{SSD}(s)$ is the transfer function of the additional damping control, $u_{SSD}$ is
the output voltage of the additional damping controller, $u_{ds}$ is the output voltage reference value of GSC in d-axis, $u_{ds,ref}$ is the output voltage reference value of GSC in d-axis with additional damping control.

Accordingly, as there is a variation of $\Delta\omega_r$ in the rotor speed, the variation of reference voltage of GSC in d-axis can be expressed as:

$$\Delta u_{ds,ref} = \Delta u_{ds} + \Delta u_{SSD} = \Delta u_{ds} + G_{SSD}(s)\Delta\omega_r \quad (4)$$

Where, $\Delta u_{ds,ref}$ is the reference voltage variation of CSC in d-axis with additional damping control, $\Delta u_{ds}$ is the reference voltage variation of GSC in d-axis without additional damping control, and $\Delta u_{SSD}$ is the reference voltage variation generated by additional damping control.

According to the superposition theorem, $\Delta u_{SSD}$, the output voltage variation of GSC generated by the additional torque control, will produce an additional current in the stator and eventually generate the additional torque $\Delta T_e$, we can have:

$$\Delta T_e = G_{TSSD}(s)\Delta\omega_r \quad (5)$$

Where, $G_{TSSD}(s)$ is the transfer function of torque and rotational speed. Taking the analysis in section 3.1 into account, when the phase of $\Delta T_e$ at the sub-synchronous oscillation frequency in the system is equal to 180° and the amplitude reaches its maximum value, the positive damping generated by the additional torque is maximal.

Given all that, to make the amplitude of the electromagnetic torque $\Delta T_e$ reach its maximum value at the sub-synchronous frequency, a band-pass filter must be added to the additional damping controller to generate the maximum positive damping effect. The band-pass filter is:

$$G(s) = \frac{s/\omega_c}{(s/\omega_c)^2 + 2\xi s/\omega_c + 1} \quad (6)$$

Where, $\omega_c$ is the characteristic frequency of the band-pass filter, $\omega_c = 2\pi f_{SSR}$. $f_{SSR}$ is the sub-synchronous oscillation in the dq coordinate system, and $\xi$ is the damping ratio, which is taken as 0.05.

In Fig. 6, $G(s)$ is the transfer function of the filter, which is used to extract the sub-synchronous frequency band components, $K$ is the proportional link, which amplifies the damping appropriately at the sub-synchronous frequency and increases the positive damping of the system. It is necessary to extract the sub-synchronous frequency band component of rotor angular velocity in the stator-side additional damping control, as the sub-synchronous frequency range is relatively wide, filter phase shift degree changes with the resonant frequency, so it is difficult to obtain the sub-synchronous frequency component by using band-pass filter. Because DC component has no phase problem, and the high-pass filter has a small phase deviation and little effect on the suppression measures, in the design of the filter, a low-pass filter is used to filter out the DC component from $\omega_r$, and a high-pass filter is used to filter out the high-frequency component above 50 Hz from $\omega_r$, further a sub-synchronous resonant frequency component is obtained with the band-pass filter.
4. Simulation results and analysis

In this section, a simulation model of DFIG series-compensated system is established in PSCAD/EMTDC to verify the performance of the additional damping controller. The parameters of DFIG and controller are listed in Table 1.

| Parameter/Unit          | Value   | Controller   | Proportional coefficient | Integral coefficient |
|-------------------------|---------|--------------|--------------------------|----------------------|
| Frequency/ Hz           | 50      | RSC current loop | Kp4=1                   | Ki4=0.05             |
| Mechanical damping/ pu  | 0.0001  | RSC power loop  | Kp3=2                   | Ki3=0.02             |
| Rated capacity/ MVA     | 5.5     | GSC current loop | Kp2=1                   | Ki2=0.01             |
| Rated line voltage/ kV  | 0.69    | GSC DC voltage | Kp1=0.4                 | Ki1=0.1              |
| Stator winding resistance/ pu | 0.0054 |              |                          |                      |
| Rotor winding resistance/ pu | 0.00607|              |                          |                      |
| Stator winding inductance/ pu | 0.10  |              |                          |                      |
| Rotor winding inductance/ pu | 0.11   |              |                          |                      |
| Motor magnetizing inductance/ pu | 4.5   |              |                          |                      |

When the simulation starts, series-compensated capacitor is bypassed and is put in when the simulation time is 2s. The simulation results of the wind turbine output power with and without additional damping control are studied at different wind speeds and series compensation degrees. Under the condition that series compensation degree is 15%, setting wind speed of 9 m/s as the base parameter, with univariate research method, three operating conditions at series compensation degree of 50% and wind speed of 5.5 m/s are selected to verify the suppression performance. The output active power of DFIG before and after suppression and the line current spectrum analysis under the three operating conditions are obtained as shown in Fig. 7 to Fig. 9.
Fig. 7 Active power and current spectrum analysis at series compensation degree of 15% and wind speed of 9 m/s.

Fig. 8 Active power and current spectrum analysis at series compensation degree of 50% and wind speed of 9 m/s.

Fig. 9 Active power and current spectrum analysis at series compensation degree of 15% and wind speed of 5.5 m/s.
As shown in Fig 7(a), when the series capacitor with series compensation degree of 15% is accessed at 2s, the output active power of wind turbine starts to oscillate without additional damping controller, and the spectrum analysis of line current is performed. As shown in Fig. 7(b), in addition to the fundamental frequency component of 50 Hz, there is a frequency component of 10 Hz in the line current, indicating that sub-synchronous oscillation occurred in the system. After accessing the stator-side additional damping controller, the output active power of wind turbine starts to oscillate, and soon attenuation and convergence are observed. Fig. 8 and Fig. 9 show the output active power and DFIG and line current spectrum analysis by increasing the series compensation degree and decreasing the wind speed under fundamental conditions that series compensation degree is 15% and wind speed is 9 m/s, respectively. Since the wind turbine outputs active power before and after accessing the stator-side additional damping controller, sub-synchronous oscillations can be effectively suppressed by the additional damping controller at high series compensation degree and low wind speed.

5. Conclusion
This paper addresses the sub-synchronous oscillation in the DFIG series-compensated grid-connected system, and adds a damping controller to suppress SSO through grid-side converter based on the mechanism of sub-synchronous oscillation in DFIG series compensation system. The additional damping controller is constituted of two parts, band-pass filter and proportional link. The characteristic frequency of band-pass filter is the sub-synchronous oscillation frequency of the system, while the proportional link can amplify the system damping. The results of time-domain simulation of DFIG under different operation conditions show that stator-side additional damping controller can make the DFIG operate safely and stably under different working conditions and suppress sub-synchronous oscillation, with good respond speed and certain engineering practical significance.

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