Study on the Subsynchronous Resonance Control Method Based on the DFIG Grid-Side Converter

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Abstract. DFIG-based series-compensated can increase the capacity of wind power transmission, but it can also cause the sub-synchronous resonance (SSR) problem. Based on the mechanism of subsynchronous resonance in DFIG, the electromagnetic torque variation under the variation of rotor speed can be divided into two parts, i.e. rotor torque variation and stator torque variation. Supplementary controller is added to the stator side converter, which is generated to provide positive damping. MATLAB simulation is carried out to compare the result of supplementary damping. Results show that supplementary damping controller makes DFIG keep stable under various rotor speeds and RSC inner-loop gain.

1. Introduction

Wind energy has been widely used and developed worldwide as a clean and environmentally friendly renewable energy source in recent years. China has now become the country with the largest installed capacity of wind power in the world. However, wind power is mainly concentrated in remote areas and is far from the load center. Therefore, the long-distance large-scale delivery of wind power is imperative. Series-compensated technology is often used to increase the transmission capacity and perform long-distance power transmission, but it also leads to SSR problems. There have been many subsynchronous resonance accidents caused by series-compensated at home and abroad [1]-[3].

At present, subsynchronous resonance suppression methods for wind power series-compensated systems are mainly divided into two types: one is controlled by adding FACTS devices, and the other one is controlled by additional damping control in the wind turbine itself. The addition of FACTS to control SSR will not only increase investment, but also will be underutilized [4]. In terms of the additional damping control of the wind turbine, [5], [6] mainly control on the GSC side which analyze the results using the eigenvalue analysis method by adding a damping control strategy to the GSC DC voltage control loop (active power control loop) or the terminal voltage control loop (reactive power control loop) and verify its accuracy and effectiveness by time domain simulation. [7] adds damping control to the RSC to achieve SSR control. [12] separately uses the rotor speed, transmission line active power, and series capacitor voltage as input control signals. After the high-pass filter and the proportional limiting section with additional damping control, SSR control is implemented in the GSC and RSC, respectively [9]. Because of the lack of research on the SSR mechanism, the physical...
significance of the control method is not clear enough, and the design of the parameters is not specific enough [10].

In this paper, starting from the GSC, the additional damping suppression increases the positive damping of the torque to the system and realizes the control of SSR. The complex torque analysis method is used to explain the mechanism of subsynchronous resonance and the design of the controller. Detailed controller design parameters and procedures are given. The system can run safely and stably with low wind speed and high inner loop proportional coefficient. And verified with time domain simulation.

2. DFIG-series-compensated system modeling

This paper takes the equivalent modeling of a certain wind farm in North China. The wind farm is boosted by the transformer and then connected to the series-compensated transmission system, taking account of the impedance of the low-voltage transmission line, from the perspective of the wind farm, the equivalent series compensation degree of the grid is 6.67% [1]-[3]. When the operating conditions of each wind turbine in the wind farm are not much different, the entire wind farm can be equivalent to a DFIG [11], [12]. The equivalent system is shown in figure 1.

![Figure 1. The equivalent model of wind farm series-compensated system](image)

In figure 1, Rs, resistance of the stator windings; Lgsc, connection inductance of the GSC side; Rg, Lg, Cg, the equivalent resistances, inductances, and capacitances of the series-compensated transmission lines, respectively; ig represents the GSC output current, is represents the stator current, idfig represents the DFIG current, ug represents the GSC output voltage, us represents the stator voltage, ucss represents the series-compensated capacitor voltage, and usg represents the grid voltage. DFIG and transmission line parameters are shown in Table 1.

| Parameters                          | Value       | Parameters                          | Value       |
|-------------------------------------|-------------|-------------------------------------|-------------|
| Capacity base value                | Sg/MVA 100  | Line equivalent resistance         | Rg/pu 1.8948|
| Stator resistance Rs/pu             | 0.023       | Line equivalent inductance          | Lg/pu 0.05314|
| Stator leakage reactance Lls/pu     | 0.18        | Series compensated capacitor Cg/pu  | 0.003290    |
| Rotor resistance Rr/pu              | 0.016       | Excitation reactance Lm/pu          | 2.9         |
| Rotor leakage reactance Llr/pu      | 0.16        |                                      |             |

3. SSR mechanism interpretation based on complex torque analysis

3.1 DFIG torque analysis

Electromagnetic torque relationship of asynchronous motor in DFIG:

\[
T_e = -n_p L_{ms} \left( i_{sd*} i_{rd*} - i_{sd} i_{rq*} \right) \tag{1}
\]

n_p is the number of pole pairs, i_{sd*}, i_{sq*}, i_{rd*}, i_{rq*} are the currents of the dq axis of the stator and the rotor, and L_{ms} is the mutual inductance between the stator and the rotor. Linearize (1) to get
\[
\Delta T_{es} = -n_p L_{m*} \left( i_{sd*} \Delta i_{sd} - i_{sd0*} \Delta i_{ref} \right) \\
- n_p L_{m*} \left( i_{rd0*} \Delta i_{sq} - i_{sq0*} \Delta i_{sd} \right) \\
= \Delta T_{es*} + \Delta T_{es*}
\]

From the formula (2), it can be seen that the amount of change in the electromagnetic torque when the rotational speed changes is divided into two parts: the rotor variation \( \Delta T_{es*} \) and the stator variation \( \Delta T_{es*} \).

This article mainly analyzes the relationship between the variation of the stator torque and the variation of the speed. There is the following internal relationship between the variation of the stator torque and the variation of the speed:

Speed increment → Stator flux increment → Stator induced EMF increment → Stator current increment → Stator torque increment

In order to simplify the derivation process, this paper makes the following assumptions: ignore the ratio and integral coefficient of RSC control strategy, and the integral coefficient of inner loop. For details, see the next section.

3.2 The relationship of stator torque variation and speed variation

The steady-state value of the rotor speed of DFIG is \( \omega_{s0} \). At the same time, there is perturbation \( \Delta \omega_{s} \) with an amplitude \( \varepsilon \), and the angular frequency \( \Omega \), i.e. \( \Delta \omega_{s} = \varepsilon \sin(\Omega t + \varphi) \). The flux linkage equation, Lenz’s law and Laplace transformation of an induction motor can get the variation of the induced electromotive force of the stator \( dq \) axis.

\[
\begin{bmatrix}
\Delta E_{sd*}(s) \\
\Delta E_{sq*}(s)
\end{bmatrix} = \begin{bmatrix}
-L_{m*} i_{qd0*} - \frac{\omega_{Base} \omega_{s*} L_{m*} i_{rd0*}}{s} \\
-L_{m*} i_{rd0*} - \frac{\omega_{Base} \omega_{s*} L_{m*} i_{sq0*}}{s}
\end{bmatrix} \Delta \omega_{s*}(s)
\]

\( \omega_{Base} \) is the reference angular frequency, and \( \omega_{s*} \) is the standard value of the stator angular frequency.

From the circuit of the stator part and the stator-side converter part in figure 1, we can get the equations in \( abc \) coordinates and then \( dq \) transformation, divided by the reference value, and after the Laplace transformation, the circuit equations of these two parts are:

\[
\begin{bmatrix}
\Delta U_{sd*}(s) \\
\Delta U_{sq*}(s)
\end{bmatrix} = \begin{bmatrix}
\Delta E_{sd*}(s) \\
\Delta E_{sq*}(s)
\end{bmatrix} + \begin{bmatrix}
R_{s} & 0 \\
0 & R_{s}
\end{bmatrix} \begin{bmatrix}
\Delta I_{sd*}(s) \\
\Delta I_{sq*}(s)
\end{bmatrix}
\]

The GSC control strategy is shown in figure 2. The \( dq \) axis adopt a double closed-loop control strategy. The \( d \)-axis control target is to maintain the converter DC bus voltage constant and the \( q \)-axis control target is to maintain the input current sine. Assuming that the output voltage of the converter is equal to the reference voltage, the variation of the output voltage at the GSC side can be

**Figure 2.** GSC side control figure
\[
\begin{align*}
\Delta U_{cqds}(s) &= (K_{puc} + \frac{K_{lda}}{s})(K_{pi} + \frac{K_{ii}}{s})\Delta U_{dc}(s) \\
&\quad - (K_{pi} + \frac{K_{ii}}{s})\Delta I_{d-gc*}(s) \\
\Delta U_{cqs}(s) &= -(K_{pi} + \frac{K_{ii}}{s})\Delta I_{q-gc*}(s) \\
\end{align*}
\]
(5)

The current relationship is available in figure 1.

\[
\begin{align*}
\Delta I_{d-gqs}(s) &= \Delta I_{d-ws}(s) + \Delta I_{gqs}(s) \\
\Delta I_{d-fgs}(s) &= \Delta I_{d-ws}(s) + \Delta I_{q-ws}(s) \\
\end{align*}
\]
(7)

According to the line-side voltage relationship, the dq transform is performed, divided by the reference value, and is obtained after Laplace transformation:

\[
\begin{align*}
\left[ s + \frac{\omega_{base} R_{qs}^*}{L_{qs}^*} \right] \Delta I_{d-gqs}(s) &= \frac{\omega_{base}}{L_{qs}^*} \Delta U_{d-ws}(s) - \frac{\omega_{base}}{L_{qs}^*} \Delta U_{q-ws}(s) \\
\left[ s \right] \Delta U_{q-ws}(s) &= \frac{\omega_{base}}{C_{gs}^*} \Delta I_{d-fgs}(s) \\
\end{align*}
\]
(8-9)

Eliminating the intermediate variables, (3)-(5) can obtain the stator current variation as

\[
\begin{align*}
\Delta I_{d-ws}(s) &= G_{tds}(s)\Delta \omega_{rs}(s) \\
\Delta I_{q-ws}(s) &= G_{tqs}(s)\Delta \omega_{rs}(s) \\
\end{align*}
\]
(10)

Substituting (10) into (2) gives the relationship between \( \Delta T_{es} \) and \( \Delta \omega_{rs} \), which can be expressed as

\[
\frac{\Delta T_{es}(j\Omega)}{\Delta \omega_{rs}(j\Omega)} = G_{T_{es}}(j\Omega) = \left| G_{T_{es}}(j\Omega) \right| \angle \varphi_{T_{es}} = G_{T_{ex}} + jG_{T_{ey}}
\]
(11)

### 3.3 Mechanism Explanation

Without loss of generality, it can be assumed that the initial phase of the rotational speed \( \Delta \omega_{rs} \) is 0, and the position of \( \Delta \omega_{rs} \) on the vector diagram coincides with the positive direction of the x-axis, as shown in Figure 3. For a rotational speed variation with an angular frequency of \( \Omega \), if the projection of \( \Delta T_{es} \) on the x-axis is in the same direction as \( \Delta \omega_{rs} \), that is, when \( G_{T_{ex}} \) is in the first or fourth quadrant, \( \varphi_{T_{es}} \in [90^\circ, -90^\circ] \), when the real part of \( G_{T_{ex}} \) is \( G_{T_{ex}} > 0 \), then the effect of \( \Delta T_{es} \) will cause the amplitude of \( \Delta \omega_{rs} \) to increase, and thus it will act as a negative damping, and the larger the \( G_{T_{ex}} \), the greater the negative damping.

On the other hand, if the projection of \( \Delta T_{es} \) on the x-axis is opposite to that of \( \Delta \omega_{rs} \), when the vector \( G_{T_{es}} \) is located in the second or third quadrant, \( \varphi_{T_{es}} \in [90^\circ, 270^\circ] \), when \( G_{T_{ex}} < 0 \), the effect
of $\Delta T_{es}$ is to reduce the amplitude of $\Delta \omega_{rs}$, and therefore it acts as a positive damping, and the larger the projection, the greater the positive damping.

**Figure 3.** The relationship between stator torque variation vector and angular velocity variation vector

4. **Design of GSC damping controller**

According to the analysis in the previous section, the purpose of the rotor-side additional damping control strategy is to generate an electromagnetic torque that is in anti-phase with the rotational speed variation, thereby acting as a positive damping. Therefore, the rotational speed of the rotor is selected as feedback, and the $d$-axis of the GSC introduces feedback. The block diagram of the additional damping control strategy is shown in Figure 4, where $G_{SED} (s)$ is the additional damping control. At this point, the GSC reference voltage can be expressed as:

$$u_{cgdref} = u_{cgdref} + u_{cgdsc} = u_{cgdref} + G_{SED} (s) \omega_{rs}$$  \hspace{1cm} (12)

$u_{cgdref}$, output reference voltage without GSC additionally controlled; $u_{cgdsc}$, output voltage generated by additional torque control.

Therefore, when the rotor speed includes the variation of $\Delta \omega_{rs}$, the variation of GSC reference voltage can be expressed as:

$$\Delta u_{cgdref} = \Delta u_{cgdref} + \Delta u_{cgdsc} = \Delta u_{cgdref} + G_{SED} (s) \Delta \omega_{rs}$$  \hspace{1cm} (13)

According to the superposition theorem, the GSC output voltage change $\Delta u_{cgdsc}$ generated by the additional torque control will generate additional currents $\Delta i_{sdc}$ and $\Delta i_{sqdc}$ in the rotor. These two currents will generate additional torque $\Delta T_{esdc}$, which affects the damping of subsynchronous oscillations. Note

$$\Delta T_{esdc} = G_{esdc} (s) \Delta \omega_{rs}$$  \hspace{1cm} (14)

Among them, $G_{esdc} (s)$ is the relationship between torque and speed. According to the analysis in the previous section, as long as the phase of $G_{esdc} (s)$ at the system’s subsynchronous oscillation
frequency is placed in the second or third quadrant, the maximum positive damping of the additional torque can be achieved.

4.1 The design of high-pass filter

The high-pass filter is used to block straight and avoid the influence of additional damping control on the system in the steady state. The high-pass filter \( G_{HP}(s) \) can be expressed as:

\[
G_{HP}(s) = \frac{T_s}{T_s + 1}
\]

(15)

\( T \) generally takes 5~10.

\[G_{HP}(s) = \frac{T_s}{T_s + 1}\]

\[T \text{ generally takes } 5~10.\]

4.2 The design of proportional phase-shifting

In order to make the phase of the additional torque at the sub-synchronous frequency in the second or third quadrant, the \( G_{SEDC}(s) \) must be added with a proportional phase shift \( G_{BP}(s) \) with a time constant of \( T_{ps}(s) \) and a gain of \( K \):

\[
G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}
\]

(16)

5. Simulation verification

5.1 Under different wind speed

The simulation results under various wind speed conditions are shown in the Figure 7. From the Figure 7, we can see that when there is no additional damping control when the wind speed is 5m/s or 6m/s, the system will oscillate. After adding additional damping control, the oscillation is controlled.

\[G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}\]

\[5. \text{ Simulation verification}\]

\[G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}\]

\[5.1 \text{ Under different wind speed}\]

\[G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}\]

\[5. \text{ Simulation verification}\]

\[G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}\]

\[5.1 \text{ Under different wind speed}\]

\[G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}\]

\[5. \text{ Simulation verification}\]

\[G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}\]

\[5.1 \text{ Under different wind speed}\]

\[G_{ps}(s) = K \frac{1 - T_{ps} s}{1 + T_{ps} s}\]

\[5. \text{ Simulation verification}\]
5.2 Different RSC inner-loop gain
In the case of different RSC inner-loop gains, compare whether there is an additional damping control strategy to control the SSR, as shown in the Figure 8. When $K_{pir}$ is 0.5 and 0.6, the system oscillates when there is no damping controller, and the system converges quickly when there is a damping controller.

![Figure 8](image)

Without additional damping control: With additional damping control

6. Conclusion
1) Based on the study of the subsynchronous resonance mechanism of the DFIG series-compensated system, a control strategy for damping control on the stator side is proposed, which mainly contains the high-pass filter and the proportion of phase shift two parts. The high-pass filter is used to block straight and avoid the influence of additional damping control on the system in the steady state. The phase-shifting link makes the phase of the additional torque at the subsynchronous frequency lie in the second or third quadrant, and acts as a positive damping role.
2) Supplementary damping controller on GSC makes DFIG keep stable under various rotor speeds and inner-loop gain.

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