Control strategy of doubly-fed induction wind turbine

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Abstract. Based on the principles of DFIG, this paper establishes a DFIG model in a synchronously rotating dq coordinate system. For the grid-side control system, the vector control technology facing the grid voltage is used to realize the decoupling of DFIG active power and reactive power. The methods of feedforward compensation and PI control are used to control the rotor side of the DFIG. When the voltage drops above the low voltage ride-through operating standard curve, DFIG should not leave the grid. When the grid voltage drops below 0.9 times the standard unit value, DFIG should also provide reactive power to the grid to support the grid voltage. Since the reactive power that can be provided by the stator side is much greater than the reactive power on the rotor side, when the grid voltage drop is small, the stator side first provides reactive power to the grid. When the grid voltage drops more, the stator side and the rotor side share power to the grid to provide reactive power. Finally, using MATLAB/Simulink software to simulate DFIG, verify the effectiveness of the control strategy proposed in this paper, and lay a foundation for fault characteristic analysis.

1. Introduction
In modern times, wind turbines are mostly variable-speed constant-frequency wind turbines, of which DFIG is the most common. As one of the promising clean energy power generation technologies, DFIG has the advantages of high energy conversion efficiency, low mechanical stress on wind turbine blades, and no emission of pollutant gases such as SO₂. DFIG has developed rapidly in my country and has become the most widely used commercial wind turbine.

With the continuous increase in the number and capacity of DFIG in the distribution network, DFIG off-grid accidents have occurred many times at home and abroad. DFIG has brought great challenges to the relay protection devices of the distribution network. To study the important fault characteristics of DFIG in the distribution network, it is very important to establish an accurate and complete DFIG simulation model and analyze it.

2. Network side system control
The grid-side PWM converter plays a very important role in the operation of DFIG. Its control objectives are: to ensure power quality and reduce the harmonic content of DFIG current; to adjust the power factor of DFIG, theoretically requiring its power factor to be adjustable; Ensure that the DFIG DC bus voltage is stable within a certain range. Only the DC bus voltage is stable can the decoupling control of the rotor PWM side converter and the grid side PWM converter be realized. The grid-side PWM converter has
two control methods: grid voltage-oriented vector control (SVO) and stator flux vector control (SFO). This paper uses SVO to analyze the grid-side system.

2.1. Equivalent circuit in dq coordinate system

The equivalent circuit of the stator and rotor of DFIG in the synchronous speed rotation dq coordinate system is shown in Figure 1 [1].

![Figure 1. Equivalent circuit of DFIG stator and rotor in synchronous speed coordinate system](image)

Among them, \( \psi_s \) and \( \psi_r \) are the stator and rotor flux linkages; \( U_s, U_r \) are the stator and rotor voltage vectors respectively; \( I_s, I_r \) are the stator and rotor current vectors; \( \omega_s \) is the grid voltage angular velocity, \( \omega_m \) is the rotor rotation angular velocity, \( \omega_s = \omega_m \) is defined as the slip angular velocity. The voltage equation and flux linkage equation of DFIG are equations (1) and (2):

\[
\begin{align*}
U_{sd} &= I_s R_s + \frac{d\psi_{sd}}{dt} + j \omega_s \psi_{sd} \\
U_{sq} &= I_s R_q + \frac{d\psi_{sq}}{dt} + j \omega_s \psi_{sq} \\
U_{rd} &= I_r R_s + \frac{d\psi_{rd}}{dt} + j \omega_m \psi_{rd} \\
U_{rq} &= I_r R_q + \frac{d\psi_{rq}}{dt} + j \omega_m \psi_{rq}
\end{align*}
\]  

(1)

\[
\begin{align*}
\psi_{sd} &= I_s L_s + I_r L_{sr} \\
\psi_{sq} &= I_s L_q + I_r L_{sq} \\
\psi_{rd} &= I_s L_r + I_r L_{rd} \\
\psi_{rq} &= I_s L_q + I_r L_{rq}
\end{align*}
\]  

(2)
2.2. Power grid voltage oriented vector control

The structure of the grid-side PWM converter of DFIG is shown in Figure 2. Set the three-phase voltages $U_{gA}, U_{gB}, U_{gC}$ as A, B, and C of the power grid; $i_{gA}, i_{gB}, i_{gC}$ each is the three-phase current of the grid; $C$ is the DC bus capacitance; $R_g$ is the filter resistance; $L_g$ is the filter Inductance; $U_{dc}$ is the DC bus voltage; the load is the rotor-side PWM converter.

$$
\begin{align*}
U_{gd} &= i_{gd} R_g + L_g \frac{di_{gd}}{dt} + U_{gd} - \omega_s L_i i_{gd} \\
U_{gq} &= i_{gq} R_g + L_j \frac{di_{gq}}{dt} + U_{gq} - \omega_s L_j i_{gq}
\end{align*}
$$

(3)

When the d-axis is oriented to the grid, the active power and reactive power exchanged between the grid-side converter and the grid are:

$$
\begin{align*}
P_j &= \frac{3}{2} \text{Re}(U_g \times i_g) = \frac{3}{2} (U_{gd}^2 + U_{gq}^2 - 2 U_{gd} U_{gq} i_{gdq}) = \frac{3}{2} U_g i_{gq} \\
Q_j &= \frac{3}{2} \text{Im}(U_g \times i_g) = \frac{3}{2} (U_{gd}^2 - U_{gq}^2 + 2 U_{gd} U_{gq} i_{gdq}) = -\frac{3}{2} U_g i_{gd}
\end{align*}
$$

(4)

In stable operation, the grid voltage is constant, and equation (4) realizes the decoupling control of active power and reactive power. $i_{gd}$ controls active power, $i_{gq}$ controls reactive power.

3. Rotor side control

The rotor-side PWM converter also has specific control objectives in DFIG: provide excitation current for the DFIG stator side; adjust the amplitude, phase angle and frequency of the stator side current; adjust the active power on the stator side and the reactive power on the stator side; The maximum power tracking technology (MPPT) of DFIG is realized by controlling the reference value of the q-axis component of the current.
3.1. Rotor side current control loop

The flow chart of current control is [2]:

![DFIG rotor side current control diagram](image)

Figure 3. DFIG rotor side current control diagram

Since the stator flux linkage depends on the grid voltage, it can be compensated by control. The control block diagram obtained after the cross term is also compensated is:

![Simplified diagram of DFIG rotor side current](image)

Figure 4. Simplified diagram of DFIG rotor side current

3.2. Torque control

In the dq coordinate system, the torque expression can be simplified as:

\[
T = \frac{3}{2} p \left| \Psi_s \right| \frac{L_m}{L_s} i_{iq} = K_T i_{iq}
\]  

(5)

Side reactive power is controlled by the rotor d-axis current component.

\[
Q_s = \frac{3}{2} (U_{sq} i_{sd} - U_{sd} i_{sq}) = K_Q (i_{sd} - \frac{\left| \Psi_s \right|}{L_m})
\]  

(6)

Among them, the expression of \( K_Q \) is:

\[
K_Q = -\frac{3}{2} \frac{L_m}{L_s} \alpha_\omega \left| \Psi_s \right|
\]  

(7)
4. Low voltage ride through characteristics of DFIG

In the previous grid connection guidelines, when the DFIG terminal voltage drops to a certain level, DFIG will automatically disconnect from the grid. For power systems with low penetration rates, this method has little effect on the system. However, in a power system with a high penetration rate, the frequent disconnection of DFIG may affect the grid voltage and frequent disturbances in active power. This phenomenon will seriously affect the stability of the power system and affect residential electricity consumption and industrial production. In response to this problem, strategies for low voltage ride through operation have been proposed at home and abroad. According to the standard Q/GDW392-2009 technical regulations for connecting wind farms to the power grid, the standard curve for low voltage ride through operation is as follows [3].

![Figure 5. Standard curve of low voltage ride through operation](image)

When the grid voltage per unit value is \((0.4-0.9)\) p.u., the low voltage ride-through starts, and the stator side provides reactive power to the grid [4].

\[
\begin{align*}
    i_{rd}^* &= 2(1 - U_{pu}) \frac{P}{1.5U_i \sqrt{\frac{3}{2}}} \quad 0.4 \leq U_{pu} < 0.9 \\
    i_{rq}^* &= \sqrt{1.2^2 - (i_{rd}^*)^2} \frac{P}{1.5U_i \sqrt{\frac{3}{2}}} \\
\end{align*}
\]

(8)

When the grid voltage is below 0.4p.u., the stator side and the grid side jointly provide reactive power to the grid:

\[
\begin{align*}
    i_{rd} &= 1.2 \times \frac{P}{1.5U_i \sqrt{\frac{3}{2}}} \\
    i_{rq} &= 0 \\
    i_{gs} &= 1.2 \times \frac{P_{s_{max}}}{1.5U_i \sqrt{\frac{3}{2}}} \quad U_{pu} < 0.4 \\
    i_{gu} &= 0 \\
\end{align*}
\]

(9)
Based on the above discussion, the rotor side control block diagram of DFIG is shown in Figure 6.

![The control block diagram of the rotor side of DFIG](image)

**Figure 6.** The control block diagram of the rotor side of DFIG

5. Conclusion
When the voltage drops above the low voltage ride-through operating standard curve, DFIG should not leave the grid. When the grid voltage drops below 0.9 times the standard unit value, DFIG should also provide reactive power to the grid to support the grid voltage. Since the reactive power that the stator side can provide is much larger than that of the rotor side, when the grid voltage drops less, the stator side first provides reactive power to the grid; when the grid voltage drops more, the stator side and the rotor side share the power to the grid provide reactive power.

Acknowledgments
This work was supported by School of Electrical Engineering, North China Electric Power University, Baoding, China.

References
[1] Singh, A; Bhatia, R.S; Chanana, S. An Anti-Islanding Technique for Grid-Connected DG and Multi DG System. 2018: 1-6.
[2] Gjonaj, E; Weiland, T. A projection penalization approach for the high-order DG-FEM in the time domain [J]. Radio Science, 2011, 46(05; 05): 1-10.
[3] Kaur, P; Kaur, S; Khanna, R. Optimal placement and sizing of DG comparison of different techniques of DG placement. 2016: 1-4.
[4] Moon, W-S; Hur, J; Kim, J. A Protection of interconnection transformer for DG in Korea distribution power system. 2012: 1-5.