Main and auxiliary control strategies of DFIG under asymmetrical grid voltage dips

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Abstract. When the Doubly Fed Induction Generator (DFIG) asymmetrical dips in the grid, the stator current will not only generate transient DC components, but also generate negative sequence components, especially when the motor impedance is small. The negative sequence component is larger, which will further deteriorate the grid voltage. In this paper, the DFIG is taken as the research object. When the grid is unbalanced, the main and auxiliary control strategies are adopted for the rotor-side converter, which can control the rotor current quickly and effectively, and improve the uninterrupted operation of the entire wind turbine. The MATLAB simulation software was used to simulate the 1.5MW wind turbine model, and the test was carried out on the 1.5MW wind turbine test bench. The simulation results and test results verify the feasibility and effectiveness of the control strategy.

1. Introduction
With the expansion of wind power installed capacity, the impact of grid-connected wind power on the grid is becoming more and more serious. Therefore, it is necessary to improve the ability of wind turbines to respond to grid faults. When the grid voltage is asymmetrically dropped, its transient process will also form a strong current and voltage shock to the stator and rotor of DFIG, which will affect the normal operation of the generator, such as increased loss, increased heat, torque ripple, and the gearbox and mechanical drive shaft fatigue loss, reactive power pulsation which is caused by the torque ripple, etc. [1-4], if the corresponding measures are not taken, the power grid will be further deteriorated, according to the technical regulations for wind farms connected to the grid [5], the wind turbines are required to ride through a symmetrical grid fault and the waveform quality is good.

At present, there are many researches on the control strategy of DFIG under asymmetric grid voltage. Literature[6] proposes the goal of realizing grid voltage imbalance control by positive and negative sequence and double dq axis current control schemes in the forward and reverse synchronous coordinate system. The dynamic response delay controlled by the scheme system and the calculation process is complicated. Literature [7] optimizes the positive and negative sequence calculation process, accelerate the respondence. In [8], the rotor transient current and negative sequence current are injected into the rotor end when the grid is in an asymmetric drop fault, but in the fault recovery process the rotor surge current is also increased. Literature [9] proposed a tracking control scheme of transient flux linkage, which effectively reduces the impact of rotor current, but causes the wind turbine to absorb reactive power from the grid side. The rotor voltage compensation control strategy of the rotor-side converter proposed by the literature [10] can reduce the rotor current impulse in the
asymmetric fault of the power grid and enhance the low voltage ride-through capability of the DFIG. This strategy has not been effectively applied in practice.

In this paper, the dynamic modeling and control strategy of the DFIG under the grid voltage asymmetry drop is described. The rotor-side converter adopts the main and auxiliary control strategy, which can control the rotor current quickly and effectively, and improve the ability of wind turbine to run without interruption. Finally, the feasibility of the improved strategy is verified by simulation and experiment.

2. The mathematical model of DFIG under unbalanced condition

A three-phase symmetric DFIG system with isolated midpoint, can be considered to have no zero sequence component [11]. Therefore, under unbalanced grid conditions [12-13], only the positive and negative sequence components of the system electromagnetic quantity can be considered. Therefore, the vector form of DFIG, rotor voltage and flux linkage equations in the \( \alpha \beta \) stationary coordinate system are expressed as follows:

\[
U_{s\alpha\beta} = R_s I_{s\alpha\beta} + \frac{d\psi_{s\alpha\beta}}{dt} \quad (1)
\]

\[
U_{r\alpha\beta} = R_r I_{r\alpha\beta} + \frac{d\psi_{r\alpha\beta}}{dt} - j\omega_r \psi 
\quad (2)
\]

\[
\psi_{s\alpha\beta} = L_s I_{s\alpha\beta} + L_m I_{r\alpha\beta} 
\quad (3)
\]

\[
\psi_{r\alpha\beta} = L_m I_{s\alpha\beta} + L_r I_{r\alpha\beta} 
\quad (4)
\]

Where, \( R_s \) is the stator resistance; \( R_r \) is rotor resistance; \( L_s \) is the stator self-induction; \( L_r \) is rotor self-induction; \( L_m \) is the mutual inductance between stator and rotor; \( \psi_{s\alpha\beta} \) is stator flux; \( \psi_{r\alpha\beta} \) is rotor flux; \( U_{s\alpha\beta} \) is stator voltage, \( U_{r\alpha\beta} \) is rotor voltage; \( I_{s\alpha\beta} \) is the stator current; \( I_{r\alpha\beta} \) is the rotor current.

According to the paper [2], in the positive and negative synchronous rotating coordinate systems, the stator voltage, rotor voltage, current and flux equations in the stationary \( \alpha \beta \) coordinate system is expressed by the respective positive and negative sequence components are:

\[
U_{s\alpha\beta} = U_{s\alpha\beta}^{+} e^{j\Omega t} + U_{s\alpha\beta}^{-} e^{-j\Omega t} \quad (5)
\]

\[
U_{r\alpha\beta} = U_{s\alpha\beta}^{+} e^{j\Omega t} + U_{s\alpha\beta}^{-} e^{-j\Omega t} \quad (6)
\]

\[
\psi_{s\alpha\beta} = \psi_{s\alpha\beta}^{+} e^{j\Omega t} + \psi_{s\alpha\beta}^{-} e^{-j\Omega t} \quad (7)
\]

\[
\psi_{r\alpha\beta} = \psi_{s\alpha\beta}^{+} e^{j\Omega t} + \psi_{s\alpha\beta}^{-} e^{-j\Omega t} \quad (8)
\]

\[
I_{s\alpha\beta} = I_{s\alpha\beta}^{+} e^{j\Omega t} + I_{s\alpha\beta}^{-} e^{-j\Omega t} \quad (9)
\]

\[
I_{r\alpha\beta} = I_{s\alpha\beta}^{+} e^{j\Omega t} + I_{s\alpha\beta}^{-} e^{-j\Omega t} \quad (10)
\]

Substitute equation (5) ~ (10) into equation (1) ~ (4), After finishing, in forward and reverse synchronous coordinates \( dq^+, dq^- \), which is represented by the respective positive and negative sequence components, The stator, rotor voltage, and flux equations of DFIG are:

\[
U_{s\alpha\beta}^{+} = R_s I_{s\alpha\beta}^{+} + \frac{d\psi_{s\alpha\beta}^{+}}{dt} + j\Omega \psi_{s\alpha\beta}^{+} \quad (11)
\]
\[ U_{sdp}^+ = R_l I_{sdp}^+ + \frac{d\psi_{sdp}^+}{dt} + j\omega_{\text{slip}} \psi_{sdp}^+ \]  
\[ \psi_{sdp}^+ = L_s I_{sdp}^+ + L_m I_{sdp}^+ \]  
\[ \psi_{sdp}^- = L_m I_{sdp}^- + L_r I_{sdp}^- \]  
\[ U_{nlp}^- = R_l I_{nlp}^- + \frac{d\psi_{nlp}^-}{dt} + j\omega_{\text{slip}} \psi_{nlp}^- \]  
\[ U_{nlp}^- = R_l I_{nlp}^- + \frac{d\psi_{nlp}^-}{dt} + j\omega_{\text{slip}} \psi_{nlp}^- \]

Where,
\[ \omega_{\text{slip}^+} = \omega_l - \omega_r \]  
\[ \omega_{\text{slip}^-} = -\omega_l - \omega_r \]

Here, \( \omega_{\text{slip}^+} \) is the forward slip angular frequency; \( \omega_{\text{slip}^-} \) is the reverse slip angular frequency.

Therefore, according to equations (11)–(14), The equivalent T-type circuit of the positive-sequence component can be obtained in the synchronous rotating coordinate system \( dq^+ \), as shown in Figure 1; based on (15)–(18) The equivalent T-type circuit of negative-sequence component can be obtained in the reverse synchronous rotating coordinate system \( dq^- \), it is shown in Figure 2.

**Figure 1.** The equivalent T-type circuit of the positive-sequence component in the synchronous rotating coordinate system.  
**Figure 2.** The equivalent T-type circuit of negative-sequence in the reverse synchronous rotating coordinate system.

### 3. Master and auxiliary control strategy

It can be seen from the above analysis that when the grid is unbalanced, the double-frequency fluctuation occurs on the rotor side of the DFIG, but the conventional PI-regulator-based DFIG cannot realize isochronous control to the AC disturbance caused by the negative sequence voltage. so this paper proposes a new control strategy, adding negative sequence adjustment in the traditional PI regulator. The main and auxiliary control is to add an auxiliary compensator for rejecting the negative sequence current based on the traditional vector control designed under normal operating conditions, that is, the main controller in the forward synchronous coordinate system does not need to decompose
and extract the positive and negative current. and the auxiliary controller in the reverse synchronous rotating coordinate system is used to compensate. The auxiliary controller needs to extract the negative sequence current component to compensate the insufficient control for the negative sequence current of the system and control separately to the negative sequence component of the current.

In the positive synchronous rotating coordinate system and the negative rotating coordinate system, respectively, the motor stator voltage orientation is used, and the stator voltage integrated vector is oriented on the axis  

\[
\begin{align*}
U_{rd} &= U_s \\
U_{sq} &= 0 \\
U_{rd}^- &= U_s^- \\
U_{sq}^- &= 0
\end{align*}
\]

When the rotor current  

\[
\begin{align*}
\dot{i}_{rd}^* & \text{ and } \dot{i}_{rq}^* \text{ are respectively controlled as the average value of the active power and the average value of the reactive power on the stator side, the control of the negative sequence } (\dot{i}_{rd}^- \text{ and } \dot{i}_{rq}^-) \text{ of the rotor current can be performed to achieve the auxiliary control of the negative sequence component of the stator current. According to the control of DFIG in the positive sequence coordinate system} \ [3], \text{ the output of PI regulator is taken as the dynamic term of rotor current in the control rotor voltage equation, and the control equation can be written as:}
\end{align*}
\]

\[
\begin{align*}
U_{rd} &= (K_p + K_i) (\dot{i}_{rd}^* - i_{rd}) + u_{rdc} \quad (23) \\
U_{rq} &= (K_p + K_i) (\dot{i}_{rq}^* - i_{rq}) + u_{rqc} \quad (24)
\end{align*}
\]

Where,

\[
\begin{align*}
U_{rdc} &= \frac{L_m}{L_s} U_s - \frac{L_m}{L_s} \left( \frac{R_s}{L_s} \psi_{rd} + \omega r \psi_{sq} \right) + (\omega t - \omega r) \left( L_r - \frac{L_m^2}{L_s} \right) i_{rd} \quad (25) \\
U_{rqc} &= \frac{L_m}{L_s} \left( \frac{R_s}{L_s} \psi_{sq} + \omega r \psi_{sd} \right) + (\omega t - \omega r) \left( L_r - \frac{L_m^2}{L_s} \right) i_{rd} \quad (26)
\end{align*}
\]

Similarly, the negative sequence auxiliary control also adopts PI control. According to the expression of negative sequence rotor voltage, the control in the  \(dq^+\) coordinate system can be designed, and the control equation of rotor voltage in the coordinate system  \(dq^-\) can be obtained as follows:

\[
\begin{align*}
U_{rd}^- &= (K_p + K_i) (\dot{i}_{rd}^- - i_{rd}^-) + u_{rdc} \quad (27) \\
U_{rq}^- &= (K_p + K_i) (\dot{i}_{rq}^- - i_{rq}^-) + u_{rqc} \quad (28)
\end{align*}
\]

Where,

\[
\begin{align*}
U_{rdc}^- &= \frac{L_m}{L_s} U_s^- - \frac{L_m}{L_s} \left( \frac{R_s}{L_s} \psi_{rd}^- + \omega r \psi_{sq}^- \right) + (\omega t + \omega r) \left( L_r - \frac{L_m^2}{L_s} \right) i_{rd}^- \quad (29)
\end{align*}
\]
4. System experiment

According to the control strategy mentioned above, a simulation model is built for the unbalanced drop control of the system. The system simulation control model is shown in Figure 3. According to the system setting parameters, in Figure 4, the simulation shows that the grid has an asymmetrical 20% drop at 0.5s. This is the rotor current output waveform under the control condition of the conventional control strategy. From the waveform, there is a large amount of negative sequence current due to the rotor current. It will cause overcurrent on the rotor side current. As the grid voltage imbalance increases, the negative sequence current increases faster. Figure 5 shows the rotor current output waveform of the main and auxiliary control strategies described in this paper. The negative sequence current is eliminated by the auxiliary control of the negative sequence.

\[
U^- = \frac{L_m}{L_s} \left( \frac{R}{L_s} \psi^- + \omega_s \psi^0 - (\omega_1 + \omega_t) \left( \frac{L_r}{L_s} \right)i_r^- \right)
\]

(30)

**Figure 3.** The system simulation control model.

**Figure 4.** Rotor current output waveform of DFIG under conventional control strategy.

**Figure 5.** Rotor current output waveform of DFIG under main and auxiliary control strategies.
In order to further verify the effectiveness of the control strategy, a test was carried out on a 1.5 MW converter test-bed. At a motor speed of 1700 rpm, the grid bc phase was subjected to a 20% unbalanced drop, as shown in Figure 6. Under the conventional control strategy, the peak-to-peak value of the rotor current reaches 2200A; as shown in Figure 7, the peak-to-peak value of the rotor current is 1340A. Compared with the conventional control strategy, the rotor current is reduced by 860A, which improves the system performance.

![Figure 6. Rotor current output waveform using conventional control strategy for 20% grid voltage drop at 1700 rpm.](image1)

![Figure 7. Rotor current output waveform with main and auxiliary control strategies at 20% grid voltage drop at 1700 rpm.](image2)

5. Conclusions
In this paper, the main and auxiliary control is to add an auxiliary compensator for rejecting the negative sequence current based on the traditional vector control designed under normal operating conditions, which is to compensate for the lack of the negative sequence current control, and realize the independent control of sequence components; double closed-loop PI current control of the model can control active and reactive currents respectively, realize decoupling of active and reactive currents, and obtain better dynamic and steady-state characteristics.

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