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High voltage ride-through of doubly-fed induction generator based on grid side and rotor side converters cooperative control

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Abstract: *In order to further improve the doubly-fed wind turbine high voltage ride-through ability, this article is different from the traditional control research only considering the rotor side converter in the power grid failure in stator flux dynamic changes of active and reactive power decoupling, the influence of the coupling current and the additional quantity of the stator flux changes as the feedforward compensation component in the current reference value. On this basis, an improved control strategy is also proposed for the grid-side converter, which takes into account the power imbalance between the two ends of the DC bus and the voltage mutation of the grid. Simulation in power grid voltage surge, coordinated control based on the grid-side converter and rotor-side converter control strategy of doubly-fed wind power generator of high voltage ride-through the active power and reactive power of wind power unit, the rotor over current, DC bus voltage fluctuations, etc all have better inhibition, effectively improve the doubly-fed wind turbine high voltage crossing ability.*

Keywords: *Doubly-fed induction wind turbine; High voltage traversal; Grid-side converter; Rotor side converter; Cooperative control strategy*

1. Introduction

In today's world, the wind power market is developing rapidly in the context of striving to achieve the goal of "double carbon", and the proportion of power grid stroke system continues to penetrate in a large scale. According to the statistics of the Global Wind Energy Council (GWEC), the installed capacity of Wind turbines in China is in the leading position in the world, and the Doubly Fed Induction Generator (DFIG) for the Wind power market, DFIG is the mainstream model in the wind power market due to its low cost and the ability to operate at variable frequency and constant speed. However, its stator is directly connected to the power grid and its converter capacity is small, which makes DFIG susceptible to grid disturbance and the fault crossing problem becomes increasingly significant. Therefore, the research on fault crossing of DFIG wind power system should be improved. In recent years, many scholars at home and abroad have done a lot of researches on the Low Voltage Ride Through (LVRT) problem, in order to improve the ability of DFIG to operate without taking off the grid when the Voltage sag on the grid side occurs. However, due to excessive reactive power, large load removal, short circuit fault, the instant after low Voltage crossing, and the failure of DC system commutation, the High Voltage Ride Through (HVRT) crossing technology should also receive extensive attention.

The main factors affecting the high voltage off-grid of wind power generation system are wind farm factors, unit factors and power grid factors. According to these factors, it can be seen that the cause of high voltage off-grid problem is complex. Effective solutions should be adopted according to the actual situation, and a complete governance scheme should be formed finally. At present, the measures to deal with HVRT can be divided into two categories: improving the control strategy and adding hardware devices. For wind farm factors, the input and removal of reactive power compensation device can be realized by improving the control strategy by checking the capacity of reactive power compensation device. For unit factors, fault ride-through control strategy can be improved, hardware devices can be added, and reactive power control ability can be improved to participate in reactive power regulation. For power grid factors, the tolerance to high voltage during unit operation can be increased by improving the control strategy.

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In reference [1], a series improved Crowbar hardware circuit is used to stabilize the rotor current during the fault. Although this method can inhibit the occurrence of rotor side overcurrent phenomenon, and realize reactive power compensation by inductors and capacitors to reduce the reactive power absorbed by DFIG from the power grid during the fault, Crowbar's action response has a certain time delay. This will cause the DC bus voltage to fluctuate greatly due to the influence of time delay. References [2][3] proposes an energy storage system to reduce the impact of rotor fault current on DC bus during grid faults, but the discharge process of energy storage system after fault removal is not considered, and the influence of wind turbine frequency conversion is ignored. In reference [4], rotor output voltage and current are controlled by the method of rotor side series resistance and capacitance. In reference [5], the rotor transient process after the power grid voltage surge is treated as the superposition of the steady-state component and the stator-side voltage transient component by using the superposition principle in circuit foundation, and the transient current of the rotor-side converter is solved, which is used as the regulating parameter for the fault crossing of the DFIG unit. In reference [6], proposed to improve the fault traversal ability of DFIG units by controlling pitch Angle, introducing pitch compensation value and establishing the relationship between frequency and pitch Angle, but the derivation process was relatively complex.

In view of the above problem, in this paper, the power grid failure after excision of a voltage surge and fault caused by the electromagnetic transient process is analyzed, based on a grid side and rotor side converter combined control method of HVRT of rotor overvoltage, rotor overcurrent, DC bus voltage fluctuation all have better inhibition, effectively improve the doubly-fed wind turbine high voltage across the ability. According to the simulation results, it is shown that the scheme can not only complete the on-grid operation of DFIG when the voltage surges, but also meet the requirements of reactive power output current of the unit, and realize the operation requirements of HVRT.

2. DFIG fault transient analysis and traditional converter control strategy

2.1 DFIG mathematical model

The stator side and the rotor side are in accordance with the convention of the motor, and the magnetic saturation phenomenon is ignored. The mathematical model of DFIG in the synchronous dq rotating coordinate system is [7]

$$\begin{cases} u_{sd} = i_{sd}R_s + \psi_{sd}p - w\psi_{sq} \\ u_{sq} = i_{sq}R_s + \psi_{sq}p - w\psi_{sd} \end{cases} \tag{1}$$

$$\begin{cases} u_{rd} = i_{rd}R_r + \psi_{rd}p - (w - w_r)\psi_{sq} \\ u_{rq} = i_{rq}R_r + \psi_{rq}p - (w - w_r)\psi_{rd} \end{cases} \tag{2}$$

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = L_s i_{sq} + L_m i_{rq} \end{cases} \tag{3}$$

$$\begin{cases} \psi_{rd} = L_m i_{sd} + L_r i_{rd} \\ \psi_{rq} = L_m i_{sq} + L_r i_{rq} \end{cases} \tag{4}$$

Where, the subscripts ‘s’ and ‘r’ are fixed rotor components respectively; Subscripts ‘d’ and ‘q’ are dq axis components respectively; u, R, i, ψ are voltage, resistance, current and flux, respectively; ‘w’is the synchronous angular velocity; ‘w_r’is rotor angular velocity; ‘p’ is the differential operator; ‘Lm’ is equivalent winding mutual inductance of fixed rotor in dq coordinate system; ‘L_s, L_r’is the self-inductance of the equivalent winding of stator and rotor in dq coordinate system.

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2.2 Conventional strategy for rotor-side converter

The conventional DFIG rotor-side converter is used to control the rotor current. Firstly, the DFIG speed or active power of maximum wind tracking is controlled, and then the DFIG reactive power is controlled. In grid-connected operation, the DFIG stator is directly connected to the grid, and the stator voltage is the grid voltage. When the grid voltage is constant, the dynamic process of the grid stator excitation current can be ignored, so the current control system of the rotor-side converter can be expressed as [8]

$$\begin{cases} u_s = R_s I_s + jw\psi_s \\ u_r = R_r I_r + \sigma L_r \dfrac{\mathrm{dI}_r}{\mathrm{dt}} + j(w - w_r)\psi_r \end{cases} \tag{5}$$

When the stator flux is oriented, the active and reactive power of the stator can be expressed as

$$\begin{cases} P_s = -\dfrac{3}{2} u_{sq} i_{rq} \\ Q_s = \dfrac{3}{2} u_{sq} (\dfrac{\psi_{sd}}{L_s} - i_{rd}) \end{cases} \tag{6}$$

2.3 Traditional control strategy for grid-side converter

Mathematical model of grid-side converter

$$\begin{cases} v_{gd} = u_{gd} - R_g i_{gd} - L_g p i_{gd} + wL_g i_{gq} \\ v_{gq} = u_{gq} - R_g i_{gq} - L_g p i_{gq} + wL_g i_{gd} \\ Cpu_{dc} = \dfrac{P_g - P_r}{u_{dc}} \end{cases} \tag{7}$$

Where: $v_{gd}, v_{gq}, i_{gd}, i_{gq}$ are the dq axis components of the voltage and current of the grid-side converter, respectively; L_g, R_g are resistance, inductance, respectively; C is DC bus capacitor; U_{dc} is DC bus voltage; P_g, P_r are the grid side and rotor side active power.

The active and reactive power output of the grid-side converter is

$$\begin{cases} P_g = \dfrac{3}{2} u_{gd} i_{gd} \\ Q_{\mathrm{g}} = -\dfrac{3}{2} u_{gd} i_{gq} \end{cases} \tag{8}$$

Combined with equations (6), (7) and (8), it can be seen that the grid side current i_{gd}, i_{gq} can be controlled by controlling the rotor voltage at steady state, so as to achieve the requirements of controlling the DC bus voltage u_{dc} and reactive power.

2.4 DFIG transient process analysis [9]

The structure of the doubly-fed induction generation system is shown in Figure 1. The stator windings are directly connected to the power grid, and the double PWM converters provide excitation to the rotor windings to realize the bidirectional flow of energy.

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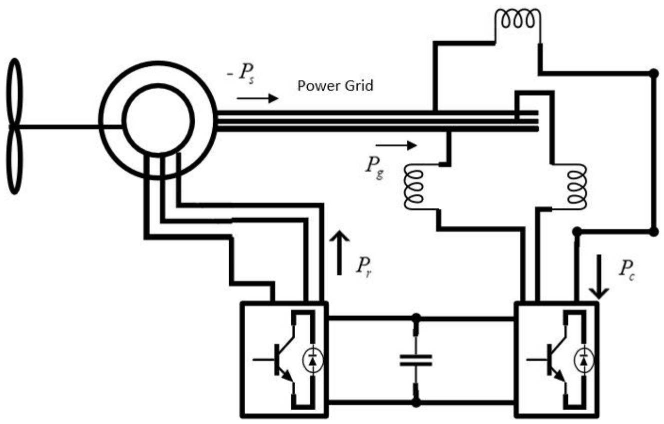

Figure 1: Structure diagram of doubly-fed induction wind power generation system

If t=0, the voltage surges; t=t1, when the fault is removed, then the grid voltage Us before and after the change can be represented as

$$U_s = \begin{cases} e^{jw't}, t < 0 \text{ or } t > t_1 \\ (1+d)e^{jw't}, 0 < t < t_1 \end{cases} \tag{9}$$

Where: 'w'' is the synchronous rotation angular velocity; 'd' is the voltage increase amplitude. Ignoring the DFIG stator resistance, the stator flux can be expressed as

$$U_s = \frac{\mathrm{d}\psi_s}{\mathrm{dt}} \tag{10}$$

The sudden rise of grid voltage and fault removal will cause electromagnetic dynamic changes. However, since the stator flux cannot be edgy, it can be considered that the whole process ψ_s is composed of two parts, the attenuated component ψ_{s1} and the transient component ψ_{s2}, and can be expressed as

$$\psi_{s2} = \begin{cases} \frac{U_S}{jw'} e^{jw't}, t < 0 \text{ or } t > t_1 \\ (1+d)\frac{U_s}{jw'} e^{jw't}, 0 < t < t_1 \end{cases} \tag{11}$$

According to the circuit change theorem in circuit theory $\psi(t_-) = \psi(t_+)$, the decayed component of stator flux is

$$\psi_{s1} = \begin{cases} -\frac{\mathrm{dU}_s}{jw'} e^{-t/\tau_s}, 0 < t < t_1 \\ \frac{\mathrm{dU}_s}{jw'} (e^{jw't_1} - e^{-t_1/\tau_s}) e^{-(t-t_1)/\tau_s}, t > t_1 \end{cases} \tag{12}$$

Where decay time constant $\tau_s = L_s / R_s$ .In summary, according to Equations (9), (10), (11) and (12), it can be seen that the flux size after fault removal is related to the power grid rise amplitude and fault duration. Therefore, shortening the fault duration and improving the dynamic response speed of the converter play an important role in realizing DFIG high-voltage crossing.

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3. Modified strategy for DFIG high voltage crossing

3.1 Modified strategy for rotor-side converter

When the stator resistance is ignored, it can be obtained from Equation (1)

$$\begin{cases} u_{sd} = \psi_{sd} p - \psi_{sq} w \\ u_{sq} = \psi_{sq} p - \psi_{sd} w \end{cases} \tag{13}$$

In the synchronous rotating coordinate system where the stator axis d is oriented to the grid voltage vector, before the fault occurs $\psi_{sd} = 0$, $u_{sq} = 0$ and the stator active power Ps, and the reactive power Qs respectively

$$\begin{cases} P_s = \dfrac{3}{2} u_{sd} i_{rd} \\ Q_s = \dfrac{3}{2} u_{sd} (\dfrac{\psi_{sq}}{L_s} - i_{rq}) \end{cases} \tag{14}$$

During the fault, the stator flux changes, at this time $\psi_{sd} \neq 0$ $u_{sq} \neq 0$, the stator active power, reactive power can be expressed as

$$\begin{cases} P_s = \dfrac{3}{2} [u_{sd} i_{rd} - u_{sq} (\dfrac{\psi_{sq}}{L_s} - i_{rq})] \\ Q_s = \dfrac{3}{2} [u_{sd} (\dfrac{\psi_{sq}}{L_s} - i_{rq}) + u_{sq} i_{rd}] \end{cases} \tag{15}$$

By comparing equations (14) and (15), it can be seen that during the sudden rise of grid voltage, stator flux will migrate, stator active power changes $-u_{sq}(\dfrac{\psi_{sq}}{L_s} - i_{rq})$, reactive power changes $u_{sq} i_{rd}$, The values of these two terms are 0 in the steady state, but they cannot be ignored when the grid voltage surges and faults occur. Therefore, in this paper, $-u_{sq}(\dfrac{\psi_{sq}}{L_s} - i_{rq})$ and $u_{sq} i_{rd}$ are added as power feedforward compensation components to the 'd' and 'q' axis components of the rotor side current instruction values, and the traditional control strategy is improved to stabilize the DC bus voltage. The control block diagram of the improved rotor side converter is shown in Fig. 2.

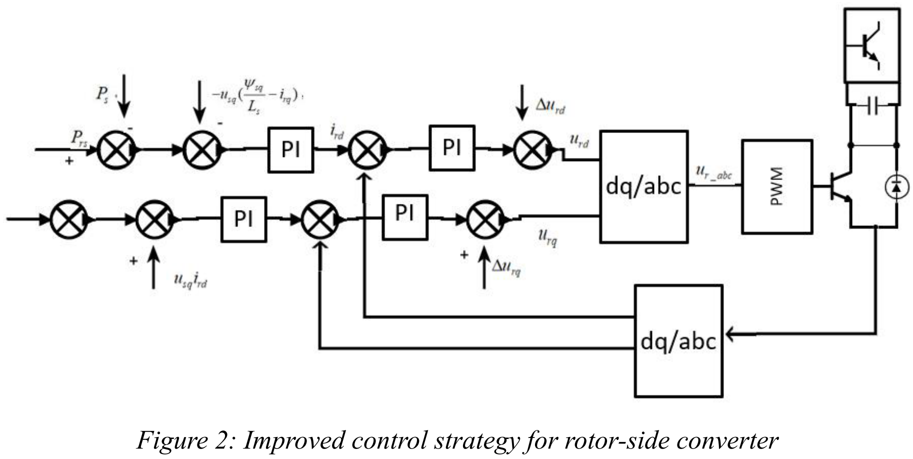

Figure 2: Improved control strategy for rotor-side converter

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3.2 Modified strategy for grid-side converter

The main functions of the grid-side converter are to keep DC bus voltage stable, output current sinusoidal and control power factor. During faults, when the voltage surge amplitude of the grid is small, the rotor-side converter can be controlled to limit the rotor-side current and voltage. However, if the voltage surge amplitude is large, the active power of the rotor-side input DC link increases, and the grid side converter is required to release the energy quickly. Therefore, speeding up the response speed of the grid-side converter, restraining the high voltage of the DC bus, and balancing the active power of AC side and DC side are the keys to ensure that the wind power system does not run off the grid. In this paper, based on literature [10], the feedforward component P_r/U_s representing the power change of the rotor-side converter is introduced into the grid side d axis current reference component, and its control principle is shown in Fig. 3.

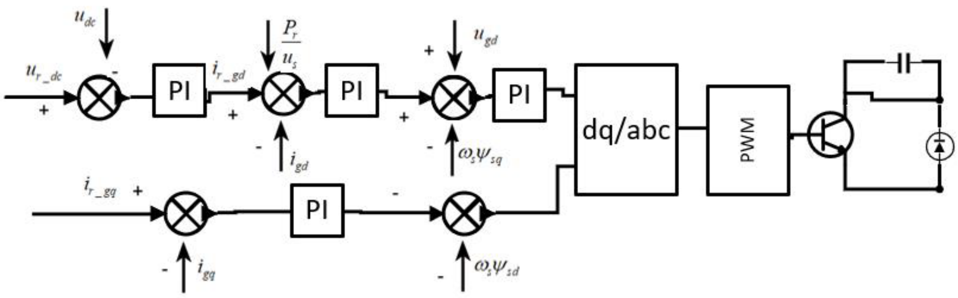

Figure 3: Improved control strategy for the grid-side converter

4. Simulation Analysis

Based on MATLAB/Simulink simulation platform, a DFIG simulation model under modified control is built. The parameters of the DFIG induction generator are as follows: Rated power 1.5mw, stator rated line voltage 575V, DC bus rated voltage 1200V, rated frequency 60HZ, polar logarithm 3, stator electrical group 0.023p.u. rotor electrical group 0.016p.u., stator leakage inductance 0.18p.u., rotor leakage inductance 0.16p.u., mutual inductance between fixed rotors 2.9p.u.

In order to verify the effectiveness of the improved control strategy when the power grid is faulty, the combined control strategy of the grid side and the rotor side is adopted. Compared with the traditional control strategy, the superiority of the improved control strategy is studied by comparative simulation analysis. The grid fault was set artificially and lasted for 0.1s, and the fault was removed at t= 0.1s. The comparison of simulation waveforms of each electrical volume is shown in Figure 4-7.

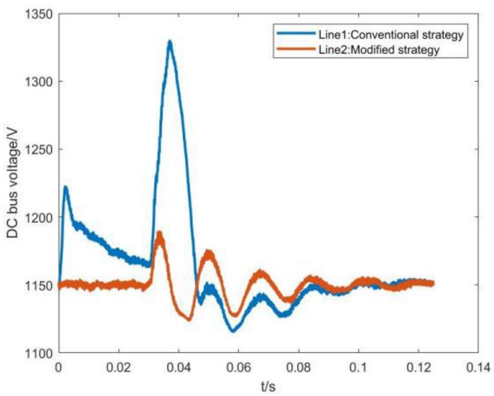

Figure 4: DC bus voltage comparison

As shown in figure 4 shows that within the duration of the fault, the conventional strategy and modified strategy can achieve high voltage crossing, but at the beginning of the failure moment t = 0 seconds, improvement strategy under the rotor side converter and grid side converter cooperative control

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can inhibit DC bus voltage rise and basic stable, at t = 0.03 seconds when the power grid voltage surge, contrast can be found, The modified control strategy can make dynamic response quickly in a short time, effectively suppress the large fluctuation of DC bus voltage, speed up the transient transition process, and balance the power of the wind turbine.

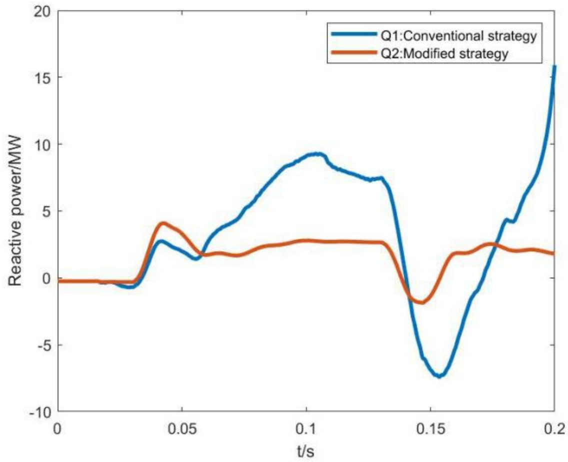

Figure 5: Comparison of reactive power

At the fault onset moment of t=0-0.03 seconds, the reactive power of the modified strategy is consistent with that of the conventional strategy. However, when the fault persists for a long period of time, it can be seen from Fig. 5 that compared with the conventional control strategy, the inductive reactive power output of the modified control strategy does not fluctuate significantly, which effectively avoids the excess reactive power and is conducive to the rapid recovery of grid faults.

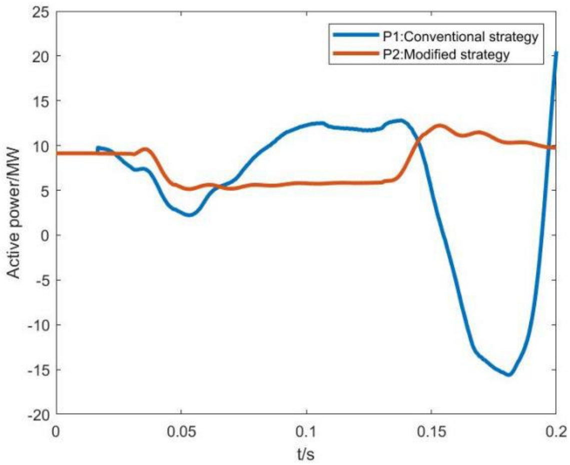

Figure 6: Comparison of active power

The active power of the modified strategy is consistent with that of the conventional strategy at the fault onset moment within t=0-0.03 seconds. The figure 6 shows that when the failure after a period of time, at t = 0.03 seconds when the power grid voltage surge, improve the control strategy of active power is more stable, thus the rotor side converter feedback of active power will not significantly increase, that is, from another Angle to prove that the modified strategy by controlling the rotor side converter to control the size of the rotor current, To suppress the large fluctuation of DC bus voltage and balance the power at both ends of DC bus.

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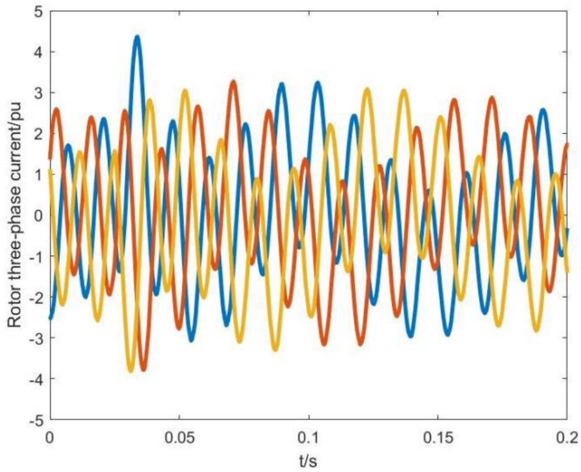
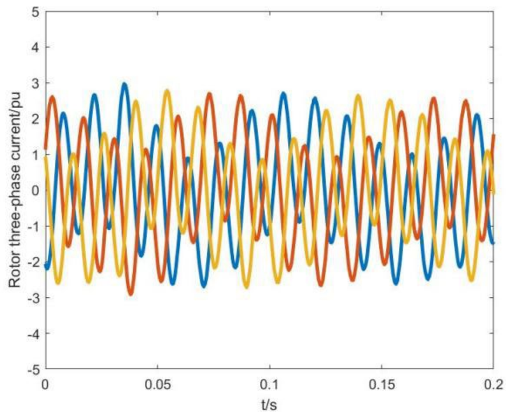


(a) Conventional control strategy rotor three-phase current



(b) Modified control strategy rotor three-phase current

Figure 7: Comparison of rotor three-phase current

In figure 7 (a) and (b) the two charts respectively give the conventional control strategy and modified control strategy of rotor three phase current waveform, compare the found in the grid voltage surge, modified the control strategy under the rotor three phase current wave fluctuation is smaller than conventional strategy, shows that modified control strategy is effective and stable rotor current, and suppress the rotor side converter overcurrent.

5. Conclusion

In this paper, a modified HVRT control strategy based on the cooperative control of grid-side and rotor-side converters is proposed to improve the transient over-performance of wind turbines during faults. The proposed control strategy realizes fault traversal through software without adding hardware equipment or reactive power compensation device, which has good economic efficient and application feasibility. When the grid voltage surges, the instantaneous responses of each electrical volume under the conventional strategy and the modified strategy are compared and analyzed by simulation. The modified strategy can further reduce the voltage fluctuation amplitude of the DC bus and suppress the occurrence of over-current and over-voltage phenomenon of the rotor-side converter. The simulation results show that compared with the conventional control strategy, the modified control strategy can improve the high-voltage crossing ability of DFIG to a certain extent, and further realize the normal operation of DFIG in the transient fault state. This paper focuses on the control optimization of a single wind turbine, and the next step will be to study the joint control of fault traversal for wind farm groups.

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