The Strategy of Doubly-fed Induction Generator Low-voltage ride-through Based an Integrated Protection Circuit

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Abstract. Aiming at the shortcomings of single-protection circuit in the low-voltage ride-through (LVRT) process of doubly-fed induction generators (DFIG), this paper proposes an integrated protection circuit strategy for LVRT of DFIG based super-capacitor(SC). The integrated protection circuit includes a Crowbar circuit, a rotor series dynamic resistance (SDR) and SC. By adopting different protection circuits in different situations and time divisions, the LVRT capability of the DFIG is comprehensively improved, and the transient current of the rotor current during the protection circuit input is analyzed in each case. Finally, the proposed integrated protection circuit strategy is compared with the traditional single Crowbar circuit and single SDR on the simulation platform MATLAB/Simulink. The simulation results demonstrate the effectiveness of the proposed integrated protection circuit strategy.

1. Introduction

With the depletion of non-renewable resources such as global oil and coal, people around the world have gradually realized the importance of “low-carbon environmental protection”, and the development and utilization of renewable energy have become the focus of research by governments, enterprises and scientific research institutions. Clean wind energy has become a widely used renewable energy source. DFIG has become one of the mainstream models in the wind-power market by its superior performance[1].

Since DFIG is directly connected to the power grid, when the power grid breaks down and the voltage drops, the DFIG is greatly affected by the power grid, and there are phenomena such as rotor over-current, DC bus over-voltage, and electromagnetic torque fluctuation, which threaten the safe operation of the DFIG[1]. When the situation is serious, Group of DFIG large-scale break away from grid, which affects the stability of the power system. Therefore, improving the LVRT of DFIG has become a hot issue in DFIG research.

At present, improving the LVRT capability of DFIG is mainly realized by the optimization of the grid side converter control(GSC) and the machine-side converter control(RSC) and adding the externally added hardware devices[2-5]. The control optimization for the converters is mainly from adopting more advanced control algorithms, Degaussing method, Feed-forward compensation method, optimized reactive power compensation control, externally added hardware devices mainly include...
reactive power compensation equipment, series grid side converter, stator series multi-tap transformer, crowbar circuit (Crowbar) and rotor series resistance. Literature[6] proposed a new circuit structure of Crowbar protection circuit resistor series capacitor to suppress the inrush current during LVRT and compensate reactive power; the literature[7] proposed the Crowbar resistor parallel dynamic resistance (SDR) to meet the requirement of dynamic change of parameters during the LVRT process; the literature[8] proposed the Crowbar protection circuit resistance series inductance to suppress the electromagnetic torque oscillation during LVRT process. However, the above improved Crowbar circuit structure still cannot avoid the rotor-side converter being disabled during the employ of Crowbar circuit. At this time, the DFIG becomes an asynchronous squirrel-cage motor, which needs to absorb reactive power from the power grid for excitation control, which increases the voltage sag of the point of common coupling (PCC) and aggravates Grid failure. In literature[9], the protection measures of the series resistance and capacity of the rotor are proposed. The circuit topology that the rotor series resistance and capacity can avoid the limitation of the rotor-side converter being disabled during LVRT and compensate reactive power for the broken grid, but the series value of resistance of rotor is larger than that of the Crowbar. During the switching process, a larger current fluctuation and electromagnetic torque oscillation are caused. Therefore, this paper adopts an integrated protection circuit method, which combines the SDR, Crowbar and SC to protect DFIG for LVRT by a proposed control strategy and the transient analysis of rotor current in the process of putting each protection circuit into operation is also carried out.

2. Built a DFIG model

The circuit structure of the DFIG grid-connected system including the basic hardware protection circuit (SDR, Crowbar, SC) is shown in the figure 1. P and Q represent active and reactive power respectively, subscription s and g represents parameters of stator side and grid side respectively.

![Figure 1. Circuit diagram of DFIG with basic hardware protection circuit.](image)

Active Crowbar circuit: When the grid is seriously faulty and the voltage falls, the crowbar circuit comes into use and the rotor-side converter is disabled. The over-current on the rotor side is suppressed by the Crowbar resistor. When the rotor current is reduced to a certain extent, the crowbar circuit is cut off and the rotor side converter is restored to the excitation control.

Rotor Series Dynamic Resistance (SDR): When the rotor current exceeds the limit of DFIG, the rotor of DFIG series the dynamic resistor to suppress the rotor over-current. During the employ of the dynamic resistance, the rotor-side converter continues to maintain excitation control. When the rotor current is below the limit, the SDR is cut out.

Super-capacitor(SC): When the power grid fails, the DC bus voltage rises sharply. SC store energy to maintain the voltage stability of the DC bus. Double closed-loop control mode of voltage and current is adopted. After the failure, the existing energy of the SC is released to the rechargeable state.

2.1. Mathematical model of DFIG

Assuming DFIG is a conventional motor and all parameters are reduced to the stator side, under the rotor coordinate system, the motor voltage balance equation and the flux equation can be obtained:
In the above formula, \( u \), \( i \), \( \psi \) severally represents voltage, current and flux vector, and \( R, L \) represents resistance and inductance, respectively. The superscript \( r \) is expressed as the rotor reference system, and the subscripts of \( r \) and \( s \) respectively indicate the parameters corresponding to the stator and the rotor, \( L_m \) indicates the mutual inductance between the stator and the rotor.

3. **Integrated protection circuit and control strategy**

The integrated protection circuit structure adopted in this paper is shown in Figure 1. The DFIG adopts the strategy of integrated protection circuit of "Crowbar + SDR + SC". Figure 2 is the flowchart of integrated control strategy.

In order to improve the efficiency and protection reliability of the integrated circuit of DFIG, a comprehensive adaptive control strategy is developed to cope with grid fault under different conditions. The system detects the rotor current and the DC bus voltage in real time. When the rotor over-current is twice the rated current, the mode-protection one is enabled. Mode 1 protection first inputs Crowbar and SDR, SC stores energy. When the current is less than twice the rated current, Crowbar is cut off. When the current is less than 1.5 times the rated current, SDR is cut off. When the DC bus voltage is smaller than the rated voltage, SC releases energy to rechargeable state. However, when the rotor over-current is greater than 1.5 times the rated current and less than 2 times the rated over-current, the MODE 2 is enabled. Only the SDR and SC are required to implement LVRT of DFIG protection. When the rotor current and bus voltage drop within the required range, SDR is removed and SC releases energy.

![Flowchart](image)

**Figure 2.** The adaptive control strategy of integrated protection circuit

4. **The transient characteristics analysis of DFIG under integrated protection circuit**

In order to better analyze the operation of the DFIG under low voltage transient state. This paper
makes the following assumptions: (1) The time of low-voltage transient is very short, and the speed of DFIG remains unchanged during this process; (2) When the rotor current and the DC bus voltage are detected to reach the corresponding threshold, the corresponding protection circuit is immediately put into operation.

When the grid has a voltage symmetrical sag fault, it is equivalent to the stator series voltage \( \Delta u'_s = -k_s u'_s \), according to the protection mode, it is divided into the following two cases:

MODE(1): Rotor series Crowbar resistor \( R_{cb} \), \( R_{SDR} \); and reverse voltage \( \Delta u'_r = -u'_r \); MODE(2): Rotor series \( R_{sd} \). According to the superposition principle, the above process can be regarded as a linear superposition of several state quantities. Analysis of transient characteristics under MODE (1):

The speed of the DFIG before the failure of the grid is \( \omega \), and the sinusoidal quantity of the voltage, current and flux linkage in the rotor reference coordinate system is corresponding to frequency of the slip ratio \( s = 1 - \omega \). The moment of instantaneous fall of the grid voltage is the starting point of the transient time, and the obtained stator voltage is

\[
u'_s = (U_m e^{j\gamma_0})e^{jst} = U_{s0} e^{jst}
\]

(2)

Where: the peak value of the phase voltage is \( U_m \); the initial phase angle of the voltage at the moment of failure is \( \gamma_0 \). The rotor voltage before the fault can be derived as:

\[
u'_r = \left[ \frac{1}{j L_m} (R_r + j L_r) \left[ U_{s0} - (R_s + j L_s) \cdot \frac{P - j Q}{U_{s0}} \right] + j L_m \frac{P - j Q}{U_{s0}} \right] e^{jst} = U_{r0} e^{jst}
\]

(3)

In the above formula: \( P \) and \( Q \) represent the active power and reactive power on the stator side, respectively.

(1) When the \( R_{cb} \) and \( R_{SDR} \) are suddenly connected in series at the rotor side, the circuit will transit to a new transient state, in which the rotor current is:

\[
i'_{r1} = A_1 e^{jst} + B_1 e^{-jst}
\]

(4)

\[
A_1 = \frac{-s \tau_r}{1 + j s \tau_r} \frac{L_m U_{s0}}{L_s L_r} + \frac{\tau_r}{1 + j s \tau_r} \frac{U_{r0}}{L_r}
\]

(5)

\[
B_1 = j \frac{1}{1 + j s \tau_r} \frac{L_m U_{s0}}{L_s L_r} - j \frac{1}{s(1 + j s \tau_r)} \frac{U_{r0}}{L_r}
\]

(6)

In the above formula, the \( L_r \) is rotor transient inductance and the \( \tau_r \) is rotor transient time constant.

The stator side suddenly series voltage fault component \( \Delta u'_s = -k_s u'_s \) and use Laplace transform, the rotor current \( i'_{r2} \) caused by stator side voltage fault component \( \Delta u'_r \) can be obtained:

\[
i'_{r2} = A_2 e^{jst} + B_2 e^{-jst} + C_2 e^{-(j\omega + 1)s't'}
\]

(7)

\[
A_2 = \frac{s \tau_r}{1 + j s \tau_r} \frac{L_m k_s U_{s0}}{L_s L_r}
\]

(8)

\[
B_2 = -j \frac{1}{1 + s \tau_r} \frac{L_m k_s U_{s0}}{L_s L_r}
\]
\[
C_2 = j \frac{1}{1 + s \tau_s} \frac{L_e k_s U_{d0}}{L_r L_s}
\]

\[
\tau_s \text{ is stator transient time constant.}
\]

When the fault component \( \Delta u_r = -u_r^f \) on the rotor side acts alone, incremental current of rotor can be obtained by the same principle.

\[
i_r' = A_3 e^{j\omega t} + B_3 e^{\frac{t}{\tau_s}}
\]

\[
A_3 = -\frac{\tau_r}{1 + js \tau_r} \frac{k_2 U_{r0}}{L_r}
\]

\[
B_3 = \frac{U_{r0}}{1 + js \tau_r} \frac{\tau_r}{L_r}
\]

According to the superposition theorem, the expressions of rotor current:

\[
i_r = (A_1 + A_2 + A_3) e^{j\omega t} + (B_1 + B_2 + B_3) e^{\frac{t}{\tau_s}} + C_2 e^{-\left(\frac{t}{\tau_s}\right)}
\]

The current transient component of the rotor consists of three parts: The first is slip frequency component, the second is DC component attenuated by time constant \( \tau_r \), and the third is speed frequency component attenuated by time constant \( \tau_s \). After \( t_1 \) seconds, the Crowbar circuit cuts out, the expression of rotor current is as follows:

Where:

\[
i_r' = \frac{e^{\frac{-t}{\tau_s}}}{L_r} \int_1^{t_1} u_r'^{(\tau)} e^{\frac{\tau}{\tau_s}} d\tau + I_{r(1)}'(t_1) e^{j(\omega t-t_1)} + (I_{r(1)}'(t_1) + I_{r(2)}'(t_1)) e^{\frac{t}{\tau_s}(-t-t_1)} + I_{r(3)}'(t_1) e^{-\left(\frac{t}{\tau_s}\right)_{t-t_1}}
\]

\[
I_{r(1)}'(t) = (A_1 + A_2 + A_3) e^{j\omega t}
\]

\[
I_{r(2)}'(t) = (B_1 + B_2 + B_3) e^{\frac{t}{\tau_s}}
\]

\[
I_{r(3)}'(t) = C_2 e^{-\left(\frac{t}{\tau_s}\right)}
\]

\( I_r'(t_1) \) is the rotor current at the time of Crowbar removal. The new transient component is added to the rotor current when all RSC is put back into operation.

Similarly, the transient component of the rotor can be obtained in MODE (2) the protection circuit is put into operation.
In order to verify the effectiveness of the integrated protection circuit proposed in this paper, the grid-connected system of DFIG is built on MATLAB/Simulink platform for experimental analysis. The parameters of the grid-connected system: power 1.5MW, rated frequency 60HZ, pole logarithm 3, rated stator line voltage 575V, rated DC bus voltage 1200V, stator resistance 0.00706p.u, rotor resistance 0.005p.u, stator inductance 0.171p.u, rotor inductance 0.156p.u and mutual inductance 2.9p.u. Three-phase short-circuit fault occurred at the 8th second of the system operation, the voltage of grid drop to 40% and the power grid returned to normal after 300 ms. The fault point was located at 3 km of PCC point.

The resistance of Crowbar circuit is 0.04p.u[10];that of SDR is 0.5p.u[11];in integrated protection circuit, that of crowbar is 0.05p.u, and that of SDR is 0.2p.u, the capacitance value of the SC is 500F[12]. The simulation compares the parameters waveforms of non-hardware circuit protection, Crowbar-SC, SDR-SC, and integrated protection circuit respectively, in order to verify the effectiveness of the integrated protection circuit strategy proposed in this paper. There are four waveforms in each row, from left to right: without any protection, only with Crowbar and SC, only with SDR and SC, with integrated protection circuit.

\[ i_r = (A_1 + A_2)e^{\frac{\omega}{r}} + (B_1 + B_2)e^{\frac{1}{r}} + C_2e^{-\frac{j(t+1)}{r}} \]  

(19)

5. Simulation and analysis

Figure 3. Waveform of rotor current

Figure 4. Waveform of DC bus voltage
By analyzing the waveform of rotor current(Figure 3), DC voltage(Figure 4), electromagnetic torque(Figure 5) and PCC voltage(Figure 6), the advantages of the proposed integrated protection circuit can be clearly obtained. Crowbar circuit can effectively suppress the rotor over-current, but during the Crowbar circuit put into operation, the RSC converter is disabled, which leads to the aggravation of power grid fault. Although SDR can avoid the blockade of the RSC in the process of putting into operation, in order to effectively suppress the rotor side over-current, it needs more larger value of resistance than that of Crowbar. In the process of switching, the fluctuations of electromagnetic torque and rotor current will be larger. Compared with the single Crowbar protection circuit, the integrated protection circuit strategy effectively reduces the operating time of the Crowbar circuit and prevents the DFIG from absorbing reactive power further from the power grid in the process of LVRT. Compared with the voltage of PCC under the single Crowbar protection, the drop of that of the integrated protection circuit is smaller; Compared with the SDR protection circuit, and the electromagnetic torque and the rotor current oscillation during switching are smaller.

6. Conclusion
(1) Crowbar protection circuit and SDR can effectively suppress rotor side over-current and protect the safety of rotor side converter. SC can effectively suppress DC bus over-voltage and protect the safety of DC bus capacitor;
(2) When Crowbar circuit is put into operation, the DFIG becomes an asynchronous squirrel cage generator, which absorbs a lot of reactive power excitation from the grid, further increases the burden of the grid. The value of SDR resistance is larger than that of Crowbar. SO, compared with Crowbar, during the process of SDR switching, the oscillation of the rotor current and electromagnetic torque are greater;
(3) The proposed integrated protection circuit strategy can effectively suppress rotor over-current and DC bus over-voltage, and effectively avoid the shortcomings of single Crowbar protection and single SDR protection.

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