The Role of Doubly-fed Motor with Low Voltage Ride Through by Controlling Converter in Wind Power Generation

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Abstract: To improve the performance of the doubly-fed wind power converter system, according to the doubly-fed wind turbine system and its mathematical model, a vector control based on doubly-fed wind power converter control strategy and the rotor side stator flux linkage attenuation in the grid voltage drop of the doubly-fed wind power system are proposed. MATLAB/Simulink software is used to simulate different voltage sags and to compare and analyze the changes of stator flux and zero-sequence current between original control and stator flux attenuation control based on rotor side. It is found that when the grid voltage drops by 20%, the impact on the system is small, and when it falls to 80%, it would cause huge damage to the converter. And compared with the original control, the low voltage crossing control based on stator flux attenuation on the rotor side can restore the stable running state of the system more quickly. The results show that the stator flux decay control based on rotor side can make the doubly-fed wind machine transit the process quickly and reach a stable state, which lays a foundation for better control of power grid and reactive power support. The results of this study are intended to provide a basis for the control strategy of the converter in the doubly-fed wind power generation system and the stable operation of the system.

Keywords: Double-fed wind turbine; Converter; Voltage drop; Low voltage ride through.

1. Introduction
The development of human society and economic and social life are inseparable from energy. The degree of development of modern society is closely related to the state of social energy supply and consumption. The issue of energy has now become one of the top 10 issues in the world. Electricity supply is the main form of energy supply. With the continuous increase of industrial electricity and civil electricity, the supply of energy through fossil dyes has caused great damage to the environment [1]. And there are data showing that renewable energy such as nuclear energy, solar energy and wind energy is the most important energy supply method since the 21st century [2]. Wind energy can be used as a power or directly used to generate electricity, mainly through the flow of air, driving special mechanical devices to achieve energy supply [3]. At present, the research hotspots and key points of wind power generation are mainly concentrated on large-scale grid-connected power generation, offshore wind
power generation and the impact of wind power environment. The total installed capacity of wind energy installed on land and at sea in China has reached more than 1.2 billion KW. Close to the US wind resources [4].

As the development speed of wind power generation shows a rapid growth trend, the proportion of wind power capacity in the power grid is now increasing. At this time, the operation of the power system has encountered new problems. When the voltage in the power grid drops, the wind turbine will start the self-protection measures of the off-grid operation, but it will cause the frequency reduction in the power system after the voltage recovery, which has a huge impact on the stable operation of the power grid and the quality of the output power. Therefore, wind turbines are required to have effective protection measures for low voltage ride through [5-6]. In the doubly-fed wind turbine system, the converter is part of the important control system performance in the whole system. At present, the control strategies mainly used for the doubly-fed wind power converter are PID control, vector control and robust control [7].

In this study, the doubly-fed wind turbine system is taken as the research object. The mathematical model of the system is constructed and analyzed. The vector control strategy of the doubly-fed wind turbine converter is constructed. The rotor-side stator flux linkage in the grid voltage drop is analyzed and proposed. Attenuated low voltage ride through control, using simulation technology to simulate the influence of zero sequence components of different voltage drop degrees, comparative analysis of the original control and the stator flux linkage of the low voltage ride through control based on rotor side stator flux linkage attenuation in the grid voltage drop zero sequence current change. The results of this study are intended to provide a basis for the solution of voltage drop faults in doubly-fed wind power generation systems.

2. Methodology

2.1. Wind power generation system with doubly-fed electric machine

The doubly-fed motor consists of two sets of three-phase windings. One set of three-phase windings is located on the stator of the motor, and the other is located on the rotor of the motor. These two sets of three-phase windings need to be powered separately, but the energy between different windings and the power supply. It can be bidirectionally circulated, and thus forms a special structure with a star or a triangle with the three-phase winding of the rotor. The doubly-fed motor is provided with the excitation current by the rotor, and controls the excitation current to control the reactive power of the electronic absorption power system. If a three-wire symmetrical alternating current flows in the three-phase winding of the doubly-fed electric machine, a rotatable magnetic field is generated in the air gap of the motor. The relationship between the electric frequency of the alternating current and the pole number of the motor and the magnetic field is:

\[ n_r = 60 \cdot \frac{f_r}{p} \]  

(1)

In the above equation, \( n_r \) is the rotational speed of the three-phase current flowing through the rotor compared to the magnetic field of the rotor itself; \( f_r \) is the electrical frequency of the three-wire symmetrical alternating current flowing through the rotor; and \( p \) is the number of pole pairs of the rotor.

The wind power generation system based on the doubly-fed electric machine is composed of pitch, generator and main control three-part system. The specific structure is shown in figure 1. The doubly-fed wind turbine itself is a wound rotor induction motor, which is similar to the control strategy and the asynchronous winding induction motor principle, and is also known as an AC excitation synchronous motor. The stator of the doubly-fed wind power generator can be directly connected to the power grid, and the side of the electronic rotor is connected to the power grid through the back-to-back converter. This special driving topology can effectively drive the stator and rotor circuits of the doubly-fed wind electrode to participate in the feeding.
2.2. Mathematical model construction of doubly-fed wind turbine

The doubly-fed wind motor is a high-order, strongly coupled nonlinear multivariable system. The energy exchange of the system is mainly due to the interaction between the fundamental magnetic fields. It is similar to the ordinary AC motor and has complexities inside the doubly-fed wind turbine. The electromagnetic relationship, and there are many different operating modes, so the operating theory of the doubly-fed wind turbine can be analyzed using the relevant theory of ordinary induction motors. In this study, the coordinate transformation is performed by the principle of equal weight. Taking the current vector as an example, when the α-axis of the two-phase stationary coordinate system coincides with the A-axis of the three-phase stationary coordinate system, and the β-axis and the A-axis are at a phase angle of 90°, then The conversion equation of the two-phase stationary αβ coordinate system and the three-phase stationary ABC coordinate system can be written as:

\[
\begin{bmatrix}
    i_a \\
    i_\beta \\
    i_\gamma
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    1 & -\frac{1}{2} & -\frac{1}{2} \\
    0 & -\sqrt{3} & -\frac{\sqrt{3}}{2} \\
    -\frac{1}{2} & 1 & 1
\end{bmatrix} \begin{bmatrix}
    i_\alpha \\
    i_\beta \\
    i_\gamma
\end{bmatrix} = M_{3s/2r} \begin{bmatrix}
    i_\alpha \\
    i_\beta \\
    i_\gamma
\end{bmatrix}
\]  

(2)

Where \( M_{3s/2r} \) is a matrix in which a three-phase stationary coordinate system is converted into the two-phase stationary coordinate system.

When the sum of the three-phase currents is 0, that is, \( i_\gamma \) is equal to 0, the C-axis can be ignored. The two-phase stationary \( \alpha\beta \) coordinate system is converted into a two-phase synchronous rotation \( dq \) coordinate system \( 2s/2r \). According to the principle of equal conversion, the inverse matrix can be expressed as follows.

\[
M_{2s/2r} = \begin{bmatrix}
    \cos \varphi & -\sin \varphi \\
    \sin \varphi & \cos \varphi
\end{bmatrix}
\]  

(3)

Among them, \( \varphi \) is the phase angle formed by the \( \alpha \) axis and the \( q \) axis.

The equivalent physical model of transforming the doubly-fed wind turbine in the two-phase stationary \( \alpha\beta \) coordinate system into the \( dq \) coordinate system of two-phase synchronous rotation is shown in figure 2.
Since the dq coordinate system of the two-phase synchronous rotation is perpendicular to each other, there is no magnetic coupling between the two-phase windings, so the three-phase sinusoidal quantity needs to be expressed in the form of direct current in the rotating coordinate system, and it can be considered that the doubly-fed wind motor is symmetric in three phases. In this case, the dq coordinate axis is 90° out of phase and there is no coupling relationship between the two coordinate axes.

2.3. Control strategy of doubly-fed wind turbine converter

The doubly-fed wind turbine is very similar to the wound-type asynchronous motor, so it is possible to control the doubly-fed wind turbine using a general control strategy. Vector control can realize the decoupling of active power and reactive power, and achieve the purpose of accurately controlling the active power and reactive power of the stator side of the motor by controlling the motor-side converter. In this study, the d-axis of the two-phase synchronous rotating coordinate system is set in the stator flux linkage, and the q-axis is the rotor current for controlling the stator output active power.

The active power of the stator side of the motor is controlled by $i_{dq}$, and the reactive power is controlled by $i_{d}$. Decoupling $i_{dq}$ and $i_{d}$ in the two-phase synchronous rotating dq coordinate system can realize Decoupling control of active power and reactive power on the stator side of the motor. PI regulator is a classic control method. In the doubly-fed wind turbine, the PI regulator is used to control the closed-loop control of the rotor current, which can improve the transient response speed of the application system and eliminate the DC steady-state error in the application system. The grid-side converter generally adopts a topology of a voltage-type PWM converter, which can adjust the power factor of the grid side arbitrarily, and the output current is a sine wave, which can realize bidirectional transmission of energy. In the doubly-fed wind power generation system, both electric and power generation operations need to be completed, so that the grid-side converter is required to complete the two-way exchange of energy. The basic circuit structure of the AC side of the grid is shown in figure 3.

![Diagram](image-url)
The converter on the grid side uses a three-phase voltage type PWM converter to simultaneously output the required power factor power while maintaining the DC voltage constant. And when the grid is in a normal state, due to the characteristics of the three-wire symmetrical circuit, the current in the grid does not contain low-order harmonics, so the converter on the grid side exhibits direct current in the dq coordinate system.

2.4. Stator flux linkage attenuation control based on rotor side
Low voltage faults can cause overvoltage or overcurrent and cause the power torque in the system to oscillate because of the gradual decay of the DC component in the originally stable AC flux linkage, if the DC flux linkage is accelerated. The attenuation speed can correspondingly reduce the transition time of the process, which is very beneficial for the protection of the mechanical components in the doubly-fed wind turbine and the reactive support for the grid. The DC component attenuation process in the flux linkage is expressed as follows.

\[
\frac{d\psi_{s,dc}}{dt} = R_s \cdot i_{s,dc}
\]  

(4)

It can be observed from the above equation that the attenuation of the DC flux linkage is mainly related to the leakage resistance of the stator in the classics and the DC component in the stator current. When these two variables are properly adjusted, the speed of the DC flux linkage can be accelerated in the voltage drop, and the transition time of the process can be correspondingly reduced. Since the voltage required to change the inductance changes before the current, after the DC component of the attenuated rotor current is over-dried, a flux component that is the same as the direction of the DC component of the rotor current is generated, and a stator current component that is opposite in direction is generated. In order to achieve the purpose of speeding up the decay of the DC flux linkage and reducing the transition time of the process. Therefore, it is necessary to add an additional control system to the rotor side. The DC flux linkage can be used to calculate the magnitude and direction of the DC flux linkage; the trigger of the rotor current setpoint is added to obtain the rotor side control command current generated by the DC component of the stator flux linkage; or the current controller is added to control the rotor. Side current.

3. Results and discussion

3.1. Simulation of grid voltage drop failure
Using the Matlab/Simulink software to build a 1.5MW doubly-fed wind power generation system, the motor-side rotor converter of the system uses the stator flux vector control to maintain the motor in a stable output state; the grid-side converter will The DC voltage is controlled to 1100V and the power factor of the current in the grid is reasonably adjusted. The simulation results of a 20% voltage drop in a three-phase symmetrical drop fault are shown in Fig. 5. It can be seen from figure 4A and 4B that when a fault occurs at 0.5 s, the current on the rotor side and the voltage on the DC side fluctuate, but the fluctuation occurs is not serious, and the traverse of the voltage drop fault can be realized without triggering the protection circuit.
The simulation results of 80% voltage drop in a three-phase symmetrical drop fault are shown in figure 5. It can be observed from figure 5A and figure 5B that when a fault occurs at 0.5 s, the current on the rotor side and the voltage on the DC side fluctuate very severely. When the fault occurs, the converter on the rotor side is still in operation, overvoltage and overshoot. The flow is all added to the converter, which increases the overload pressure on the converter and cause serious damage to the structure of the converter.

3.2. Simulation of stator flux linkage attenuation control of rotor-side converter

Figure 6A shows that the zero-sequence component of stator flux flux fluctuates in the dq axis when the voltage of the grid drops by 50%. At 0.5 s, the voltage fluctuates from the fault, and the fluctuation of the flux linkage is almost completed at 0.7 s. The entire fluctuation process takes about 0.2 s. As shown in figure 6B, after the stator flux attenuation control, when 50% drop fault occurs in 0.5s power grid voltage, the fluctuation of zero-sequence component in stator flux in dq axis basically ends at about 0.6s.
Figure 6. The component of the stator flux linkage in the dq axis (A is the original control; B is the attenuation control of the stator flux linkage)

It can be observed from figure 7A that when the 0.5s grid voltage has a 50% drop fault, the zero sequence component in the stator current also has corresponding fluctuations, and the zero sequence current decays to 0 at 0.7s, indicating that the grid voltage appears. After a drop failure of 0.2 s, the effect on the zero sequence component is almost eliminated. After the attenuation control of the stator flux linkage, it can be seen from Fig. 7B that when the 0.5 s grid voltage has a 50% drop fault, the zero sequence current decays to 0 at 0.6 s, indicating that the grid voltage has a drop fault of 0.1 s. The effect on the zero sequence component is almost eliminated.

Figure 7. Zero-sequence component in stator current (a is the original control; b is the attenuation control of the stator flux linkage)

Figure 7 shows that the flux linkage attenuation control using the stator can effectively influence the voltage drop on the system, which enables the doubly-fed wind turbine to quickly transition the process and reach a stable state, laying a foundation for better control of the grid and providing reactive power support.

4. Conclusion
The doubly-fed wind power generation system is an important object in wind power research. In this study, the doubly-fed wind power generation system is taken as the research object, the mathematical model of the doubly-fed wind power generation system is analyzed and constructed, and the doubly-fed wind power generation based on vector control is proposed. The control strategy of the flow controller is studied. The role of the stator flux attenuation technique for accelerating zero-sequence flux attenuation in the low-voltage ride-through control of converter control is studied. The simulation model
of the doubly-fed wind turbine is built by MATLAB/Simulink software. And it is found that compared with the original control, the stator flux attenuation control of the converter can restore the stable running state of the system more quickly when the voltage is dropped. However, there are still some shortcomings in this study. For example, the test of the doubly-fed wind power system has not been carried out, and only the simulation is carried out. All in all, the results of this study provide a theoretical basis for the establishment of subsequent doubly-fed wind power systems.

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