Dynamic Virtual Resistance Control of Doubly Fed Induction Generator during Grid Faults

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Abstract. With the vigorous development of renewable energy, wind power accounts for a higher proportion of power systems, so wind power generation must have a certain low voltage ride through capability. This paper first establishes a transient mathematical model of doubly-fed wind turbines under grid voltage symmetrical drops, and analyze the transient characteristics of DFIG. A dynamic virtual resistance control strategy is proposed for the case of over-voltage and over-current on the rotor side of the DFIG under grid faults. The control method can suppress the oscillation of the current component on the rotor side and improve the transient stability of the DFIG. The resistance of the virtual resistor will change with the voltage drop and it can better meet the synergistic suppression of the rotor side electrical stress under different conditions. The simulation of a 2-MW DFIG in DIgSILENT well demonstrates the enhanced capability of DFIG to ride-through symmetrical faults.

1. Introduction
As a clean and pollution-free new energy power generation technology, wind power technology has developed rapidly and has become the most promising new energy power generation technology. In the variable-speed constant-frequency wind power generation system, the wind power generation system based on the DFIG is widely used due to its advantages of small converter capacity, independent control of active power and reactive power. Compared with the permanent magnet direct-drive wind power generation system of the same capacity, the doubly-fed wind power generation system has the advantages of small size, light weight, low loss and low cost [1].

In the doubly-fed wind power generation system, the generator stator is directly connected to the grid, and the converter capacity is relatively small, which can only provide control of the DFIG’s slip power, which leads to the dependence of the doubly-fed wind power generation system on the grid [2]. During the grid faults, the overcurrent and the overvoltage of the DC bus must be avoided to ensure the operational control of the DFIG’s converter.

There are two types of protection measures that can be taken to address grid faults in different situations. When the grid voltage drops is small, the wind turbine can be operated without the off-grid by improving the control strategy of the DFIG. Based on the transient flux linkage characteristics caused by grid faults, the LVRT scheme based on the principle of demagnetization is proposed [3]. The dynamic process of stator flux current between grid voltage dips is considered in the literature [4], and the DFIG accurate mathematical model to suppress the rotor current fluctuation is established when the voltage grid is symmetrically dropped. The literature [5] proposes to use the current
hysteresis PWM modulation technology in the moment of grid voltage change to achieve the suppression of rotor overcurrent. The literature [6] uses phase angle compensation technology to make the phase angle orientation of the control system more accurate during the grid voltage recovery, thus achieving the suppression of rotor current fluctuation.

When the grid voltage drop is more serious, the above control strategy can not remain DFIG in the safe operation state. At this time, the cascaded crowbar device can be used to bypass and block the machine-side converter [7], and the DC link of the converter increases the chopper resistance to prevent DC overvoltage [8], machine-side converter string resistance or DFIG’s stator series resistance to avoid the converter’s short-time out of control [9], the voltage dynamic recovery device is used to ensure that the terminal voltage is constant [10], grid-side converter is seriesed resistor to remain in the safe operation state [11].

Therefore, it is necessary to enhance the adaptability of the wind power system when the grid voltage drops by improving the control strategy. In order to solve this problems, some authors proposed a "demagnetization" control strategy [12]. However, the control effect is limited by the converter capacity. “Demagnetization” control requires a larger capacity rotor converter, so a comprehensive scheme using active rotor fast short-circuit protection combined with “demagnetization” control is proposed [13]. When the calculated rotor current transient DC and negative sequence component command reference value is too large, the rotor fast-short (crowbar) protection device is applied to assist the rapid decay of the transient stator flux component. The flux DC component is needed to extract in this method. And the crowbar inputting and the cutting time need to have strict control, which is not conducive to engineering implementation.

To enhance the operation capability of DFIG under grid faults, the ability of DFIG system to resist grid voltage disturbance can be enhanced by combining virtual resistors with traditional DFIG alternating current excitation control strategies. Some authors [14] proposed to improve the rotor current transient characteristics of power command step changes through virtual resistors. All of the above measures are controlled by a fixed resistance of a virtual resistor. The problem of rotor overvoltage and overcurrent is not well solved for different voltage drops.

In view of this, this paper first analyzes the electromagnetic transient process of the doubly-fed induction motor in the case of grid voltage dips. Based on this, a control strategy combining dynamic virtual resistance and AC excitation is proposed, which can effectively restrain the over-currents, and expand DFIG’s uninterrupted operating range. Then the design principle of dynamic virtual resistance is given. Finally, the experimental results is verified the rationality of the dynamic virtual resistance and the effectiveness of improving the fault operation capability of the DFIG’s system.

2. DFIG transient process analysis

2.1. mathematical model of the DFIG

The mathematical model of the doubly-fed wind turbine is first established to analyze the DFIG transient process during grid voltage dips. In the stationary coordinate system, the DFIG mathematical model expressed in vector form is:

\[ u_{saf} = R_s i_{saf} + \frac{d}{dt} \psi_{saf} \]  

\[ u_{raf} = R_r i_{raf} + \frac{d}{dt} \psi_{raf} - j\omega \psi_{raf} \]  

\[ \psi_{saf} = L_s i_{saf} + L_m i_{raf} \]  

\[ \psi_{raf} = L_r i_{raf} + L_m i_{saf} \]
Where \( u_s \) and \( u_r \) represent rotor and stator voltages respectively; \( R_s \) and \( R_r \) represent rotor and stator resistances respectively; \( i_s \) and \( i_r \) represent rotor and stator currents respectively; \( \psi_s \) and \( \psi_r \) represent rotor and stator flux linkage; \( \omega_r \) represent the rotor angular velocity; \( L_s, L_r, L_m \) represent stator inductance, rotor inductance and mutual inductance between them.

Analyzed by the above formula, the DFIG equivalent circuit as shown in figure 1.

\[
\begin{align*}
\psi_{rafl} &= \frac{L_m}{L_s} \psi_{sfl} - \sigma L_r i_{rafl} \\
\sigma &= 1 - L_s^2 / L_s L_r
\end{align*}
\]

According to (3) and (4), the rotor flux equation as followed

\[
\begin{align*}
\psi_{rafl} &= \frac{L_m}{L_s} \psi_{sfl} - \sigma L_r i_{rafl} \\
\sigma &= 1 - L_s^2 / L_s L_r
\end{align*}
\]

According to (5) and (1), the rotor voltage as followed

\[
\begin{align*}
u_{rafl} &= \frac{L_m}{L_s} \left( \frac{d}{dt} - j \omega_r \right) \psi_{sfl} + \left[ R_s + \sigma L_r \left( \frac{d}{dt} - j \omega_r \right) \right] i_r \\
& \quad \frac{L_m}{L_s} \left( \frac{d}{dt} - j \omega_r \right) \psi_{sfl} \quad (6)
\end{align*}
\]

Where the rotor electromotive force is

\[
E = \frac{L_m}{L_s} \left( \frac{d}{dt} - j \omega_r \right) \psi_{sfl} \quad (7)
\]

According to equation (6), the equivalent circuit diagram of the rotor side can be obtained as shown in figure 2.

Figure 1. DFIG equivalent circuit

Figure 2. Equivalent circuit diagram
2.2. Transient analysis of the DFIG during grid faults

When the grid voltage drops symmetrically at time $t_0$, the magnitude of under grid voltages sages is $U_{sm2+}$, the stator voltage is expressed as

$$u_{safβ} = \begin{cases} u_{sm+} e^{j(αs+φ_s)}, & t < t_0 \\ u_{sm2+} e^{j(αs+φ_s)}, & t \geq t_0 \end{cases}$$

From equations (1) to (3), the stator flux change rate in static two-phase coordinate when the rotor is open can be expressed as

$$\frac{dΨ_{safβ}}{dt} = u_{safβ} - \frac{R_s}{L_s}Ψ_{safβ}$$

According to (8) and (9), the stator flux linkage equation during grid voltage drops can be expressed as

$$Ψ_{safβ}(t) = \begin{cases} \frac{u_{sm+}}{jω_1} e^{j(αs+φ_s)}, & t < t_0 \\ \frac{u_{sm2+}}{jω_1} e^{j(αs+φ_s)} + \frac{u_{sm+} - u_{sm2+}}{jω_1} e^{j(αs+φ_s)} e^{-iτ_1}, & t \geq t_0 \end{cases}$$

The flux linkage equation can be obtained that when the breakdown suddenly occurs, the stator flux linkage is composed of a forced flux linkage and a natural flux linkage. Among them, the forced flux linkage is determined by the voltage sag degree and rotates at the synchronous speed $ω_1$; the flux linkage is related to the degree of grid voltage drops, which is the constant flow rate and decays to zero with time.

Ignore the stator current, bring the equation (10) into (7) at $t \geq t_0$ to obtain the rotor electromotive force equation after the voltage dips:

$$E_{raβ} = \frac{L_m}{L_s} \left[ su_{sm2+} e^{j(αs+φ_s)} - (1-s)(u_{sm+} - u_{sm2+}) e^{j(αs+φ_s)} e^{-iτ_1} \right]$$

Converted to the rotor coordinate system, the rotor electromotive force equation is:

$$E'^{raβ} = \frac{L_m}{L_s} \left[ su_{sm2+} e^{j(αs+φ_s)} - (1-s)(u_{sm+} - u_{sm2+}) e^{j(αs+φ_s)} e^{-iτ_1} \right]$$

According to formula (12) that the electromotive force can be consisted of two parts, the steady-state component makes up the first part, which is AC component that rotates counterclockwise at the slip angular frequency $ω_1$. Its amplitude is proportional to the voltage and slip of the falling voltage. Since the slip s is small, ranging from -0.3 to 0.3, the steady-state component is small and only has this component during normal operation. The second part is the transient component caused by the voltage drops. The magnitude of this component is proportional to the degree of voltage drop and (1-s). Compared to a stable running state, the electromotive force is much higher, according to formula (12). The electromotive force is much higher than that in steady-state operation. When the EMF exceeds the maximum voltage that the rotor-side converter can withstand, it will cause overcurrent on the rotor side and damage the rotor-side converter.
3. Dynamic virtual resistance control

3.1. Stability analysis of DFIG

Using the rotor flux dq component as a state component, using the stator current dq component as an input variable, and using the grid voltage dq component as an output variable, the rotor flux transient equation is:

\[
\begin{align*}
\frac{d\psi_{rd}}{dt} &= -\frac{R_r}{L_r}\psi_{rd} + \omega_s\psi_{rq} + \frac{R_r L_m}{L_r} i_{rd} + u_{rd} \\
\frac{d\psi_{rq}}{dt} &= -\frac{R_r}{L_r}\psi_{rq} - \omega_s\psi_{rd} + \frac{R_r L_m}{L_r} i_{eq} + u_{rq}
\end{align*}
\]  

(13)

According to formula (13), the characteristic equation can be expressed as:

\[s^2 + 2\frac{R_r}{L_r}s + \frac{R_r^2}{L_r^2} + \omega_s^2 = 0\]  

(14)

Characteristic root can be derived as

\[
\lambda_{1,2} = \frac{R_r}{L_r} \pm j\omega_s
\]  

(15)

Where

\[
\omega = \sqrt{\frac{R_r^2}{L_r^2} + \omega_s^2} \\
\zeta = \frac{R_r}{\omega L_r}
\]  

(16)

The generator rotor flux is prone to oscillation. According to formula (16) that as the rotor resistance increases, the rotor side damping coefficient also increases, so the control of increasing the DFIG rotor resistance can be used.

3.2. Dynamic virtual resistance control

Analysed formula (6) and the equivalent DFIG model shown in Figure 2, the inner current loop of the DFIG is shown in Figure 3.

\[
G(s) = \frac{1}{R_r + \sigma L_r s} = \frac{K_1}{K_2 s + 1}
\]  

(17)

Where \( K_1 = 1 / R_r \), \( K_2 = \sigma L_r / R_r \)

\[\text{Figure 3. Control block diagram of DFIG inner current loop}\]
To accelerate the attenuation of the rotor current, a virtual resistance control scheme is introduced, and the control block diagram is shown in Figure 4.

![Virtual resistance control block diagram of DFIG inner current loop](image)

**Figure 4.** Virtual resistance control block diagram of DFIG inner current loop

After the virtual resistor is introduced, the DFIG current inner loop is controlled by the object transfer function:

\[
G(s) = \frac{K_r K_1}{1 + R_s K_r K_1} \frac{1}{s + 1}
\]  

(18)

Where \( T(s) = K_r \)

Comparing (17) and (18), it can be seen that after the introduction of the virtual resistor, the time constant is reduced by \( 1 + R_s K_r K_1 \). Therefore, the inertia of the controlled object of the current inner loop after the addition of the virtual resistor is reduced.

Rotor side equivalent circuit diagram after introducing virtual resistor is shown in figure 5.

![Equivalent DFIG model viewed from rotor side after introducing virtual resistor](image)

**Figure 5.** Equivalent DFIG model viewed from rotor side after introducing virtual resistor

The rotor voltage equation in the rotor coordinate system is

\[
\dot{u}_r = R_s \dot{i}_r + R_r i_r - j \omega_\sigma L_r \dot{i}_r + E
\]  

(19)

According to (19), the virtual resistance can be expressed as

\[
R_v = |\Delta u| - \sqrt{R_r^2 + X_r^2}
\]  

(20)

Where \( |\Delta u| = \frac{u_r - E}{i_r} \)

It can be seen from (19) that although the control method can inhibit the oscillation of the rotor current when power grid voltage drops, the DFIG rotor side damping is improved, but as the rotor
electromotive force increases, the rotor side voltage also increases. Since the DFIG rotor voltage is related to the motor speed and the grid voltage drops degree, it is necessary to select a suitable virtual resistor to ensure that the rotor current oscillation is suppressed and the rotor voltage is not too high, and the transient time is not lengthened under a certain speed and grid voltage dips.

According to the formula (12), the rotor side induction electromotive force is related to the slip rate and the degree of voltage drop when the voltage dips. When the DFIG runs in the super-synchronous state ($s<0$), the degree of voltage drops increases and the induction electromotive force of the rotor side increases accordingly. In order to ensure the normal operation of the rotor-side converter, the required rotor excitation voltage also increases. In this case, the rotor virtual resistance is too large to cause the rotor side overvoltage, so the virtual resistance value should change with the voltage drop depth, to meet the stable operation of the doubly-fed fan during the fault, when the voltage drop is small At this time, there is a margin in the rotor side voltage, and a larger virtual resistor is selected; when the grid voltage drop is large, a smaller virtual resistor is selected. According to the design goal, the maximum voltage drop of the normal operation can be controlled by the voltage dip of 30%, and the range of the virtual resistance of the voltage drop in the range of 0–30% is as follows:

$$\frac{u'_{r_{\text{max}}} - E_{p=30\%}}{i'_{r_{\text{max}}}} \leq R_a \leq \frac{u'_{r_{\text{max}}} - E_{p=0}}{i'_{r_{\text{max}}}} - \sqrt{R_a^2 + X_r^2}$$

(21)

Where $p$ represents the degree of voltage drops, when the voltage drops are 30%, the minimum value of the virtual resistance is obtained. When the voltage drops to 0, that is, in the stable operation state, the maximum value of the virtual resistance is obtained, at this time, the current is the rated current. The relationship between the virtual resistance and the voltage drop is as followed.

![Figure 6. Dynamic virtual resistance value](image)

According to the figure 6, the dynamic virtual can be expressed as $R_a = kp + R_{\text{max}}$, according to the formula, the value of the dynamic virtual resistance can be obtained under different voltage drop degrees. As the grid voltage dips increase, the virtual resistance decreases monotonically to achieve the rotor voltage is limited. Within the maximum allowable voltage range, the current oscillation caused by the fault is rapidly attenuated.

Figure 7 shows the DFIG control block diagram after adding a virtual resistor.
4. Simulation and experimental results
To verify the correctness of the dynamic virtual resistance control, this paper takes the 5MW DFIG as the research object and carries out the simulation research. Doubly-fed generator parameters: stator rated voltage is 3.3KV, stator rated current is 0.902KA, rotor open circuit voltage is 2kV, pole logarithm is 2, stator inductance $L_s$ is 0.125pu, rotor inductance $L_r$ is 0.05pu, mutual inductance $L_m$ is 2.5pu, rotor resistance $R_r$ is 0.004 pu and the stator resistance $R_s$ is 0.003 pu. A simulation model based on dynamic virtual resistance control was built in DIgSILENT.

The following figures show that the voltage drop is 30%, 25%, and the fault start time is 0.5s. Under the conventional control scheme, the dynamic virtual resistance control scheme and the fixed virtual resistance control, the rotor current dq-axis component, and the rotor voltage can be shown in figure 8 and figure 9. After the addition of the virtual resistor, the rotor current shock caused by the sudden voltage drop of the grid is well suppressed. Taking the voltage drop of 30% as an example, the rotor current impact caused by the dynamic virtual resistance is 79.7% of the rotor inrush current under conventional control; after adding the virtual resistor, the rotor voltage will increase. Because the value of the virtual resistor is different under different voltage drops, the rotor voltage does not exceed the maximum capacity of the rotor-side converter.

Compared with the fixed resistance value, the control method of the dynamic virtual resistance weakens the suppression of the rotor current, but the generated rotor voltage impact value is smaller, which satisfies the purpose of the rotor side not being over-pressured. The control method using a fixed resistor, although the resistance value is a fixed value, the rotor current oscillation can be suppressed, when the grid voltage sudden decrease is increased, the rotor side overvoltage is caused, and the rotor converter is damaged.
5. Conclusion
In this paper, the transient process of DFIG under the symmetrical faults of grid voltage is analyzed. The dynamic virtual resistance control scheme is proposed, and the calculation method of dynamic virtual resistor is given. The control method can effectively suppress the rotor current oscillation under different degrees of voltage drops, and avoid the rotor side overvoltage. Finally, the simulation analysis prove the correctness and effectiveness of the proposed control strategy.

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