A Study on Dual-Rotor Doubly Fed Induction Wind Power Generator

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Abstract — **A mathematical model of the dual-rotor doubly fed induction generator (DRDFIG) is derived, and the control study for DRDFIG under the conditions of steady state operation are analyzed. The stator current can be decreased lower than that of DFIG under the same conditions. The transient process of DRDFIG was analyzed. Finally, in order to validate the crowbar control effect for DRDFIG in serious grid fault, the crowbar resistance and stator current peak were discussed. The simulation results show that DRDFIG is capable of improvement of grid steady under grid voltage severe dip conditions.**

Keywords - Wind power generation; Dual-rotor doubly fed induction generator (DRDFIG); grid-connection; Voltage vector oriented control; Grid voltage dip; Crowbar circuit

I. INTRODUCTION

Nowadays, wind energy is one of the most important and promising sources of renewable energy in many countries, mainly because it is considered to be nonpolluting and economically viable. At the same time, there has been a rapid development of related wind turbine technology [1,2]. In recent years, with the wind power market continues to expand, large wind power plants have been built around the world, the wind generator capacity is also increasing rapidly. The traditional wind turbine with constant speed constant frequency is highly dependent on the mechanical system, which will lead to the fluctuations in voltage and output power. Permanent magnet direct drive wind turbine without external excitation power supply, improve the efficiency, the low voltage ride and capability, direct coupling of wind turbine can eliminate gear box and greatly reduce system noise in order to improve reliability. Ordinary DFIG widely used in wind power generation system, which provides several merits including sinusoidal input ac current with controllable power factor, high-quality dc output voltage with a small filter capacitor and capability of independent regulation of active and reactive powers with bidirectional power. Back to back converter make it possible to maintain the terminal voltage constant when the doubly fed induction generator (DFIG) is operating under variable speed. The main disadvantage of traditional DFIG system are large the rotor excitation capacity and low ability to resist the disturbance. However, if the DFIG structure are well designed, it is possible to avoid the rotor voltage reaching excessive values, and also to increased the damped oscillations in the rotor current, reducing the over-current in the grid-side converter (GSC) and the over-voltage in the dc-link during the fault.

Dual-rotor induction generator can overcome the main problems of ordinary doubly-fed wind power generator. Literature [3,4] studied and developed a prototype, the results show that the DRDFIG can decrease the exciting current. The equivalent circuit of DRDFIG was studied in literature [5, 6]. The steady-state performance of generator was verified, the research shows that operation performance than that of ordinary DFIG. Literature [7, 8] has carried on the theoretical analysis and experimental verification, research shows that DRDFIG can still run efficiently when the grid voltage asymmetry and internal permanent magnet rotor was affected by negative sequence magnetic field is very small. These researches were mainly aimed at in motor control research, The above literature research mainly focus on the experimental study of the motor, the analysis and control theory of DRPMIM is a little literature [9, 10].

To reduce the over current and DC link over voltage to the rotor side converter, and to determine the DRDFIG stator fault contribution and the power rating required for fault ride through capability and protection requirements, it is essential to propose a suitable control models and associated control strategy for DRDFIG system[11].

The main objective of this paper is to propose an integrated and particular DRDFIG model. The model takes into account the flux transient and magnetic saturation effects during the process of the fault analysis and LVRT operation.

Firstly, a dynamic DRDFIG model by considering the transients of stator magnetizing current but neglecting the effect of magnetic circuit saturation is developed. Simulation was carried out on a 1. 5 MW wind-turbine driven DRDFIG system in the synchronously rotating reference frame. System performances from the developed models with steady and dynamic were considered during grid voltage dips. The results are compared and the comparative results show that the proposed DRDFIG approaches to the actual better characteristics than that of DFIG in the practical wind power generation system.

II. MATHEMATICAL MODEL

Fig. 1 shows the basic structure of the DRDFIG. The stator is the same as that of the usual induction machines equipped with a three-phase winding. However, there are two rotors, an outer wound rotor and an inner permanent magnet rotor (PM rotor) . The outer wound rotor is linked to the shaft, while the inner PM rotor is free to rotate against the shaft.

The PM rotor are separated from the wound-type rotor by bearings, so the PM rotor and wound rotor are rotated at different speeds. The wound-type rotor speed is slightly slower than the synchronized speed. The PM rotor speed is the same as the synchronized speed because it is no load.

Generally, the rotation of the PM rotor is similar to that of the rotating field synchronous motor with no load. In this kind of machine, the air-gap flux is provided by both

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rotating PM rotor and the stator coil current.

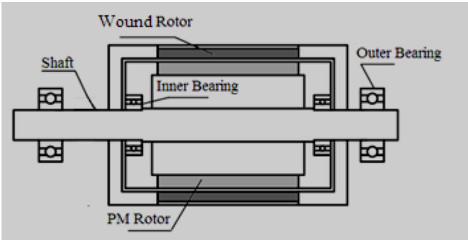


Fig. 1 Schematic rotor diagram of the DRDFIG.

Fig. 2 is DRDFIG composition of power generation system schematic diagram, which is the same back-to-back converter rotor ac excitation control as that of DFIG. For the analysis of convenient, make the following assumptions: each phase winding structure is symmetry, magnetic circuit is linear, regardless of the saturation effect, ignored the cogging effect, regardless of the core loss. Rotating coordinate system was adopted to establish the equation, and d axis is in the direction of a permanent magnet flux linkage.

Air-gap magnetic field is composed of three parts, wound rotor magnetic field, stator magnetic field and permanent magnet magnetic field. Because PM rotor speed is invariable when DRDFIG is normal operation. So permanent magnet magnetic field can be equivalent to a constant flux. Flux linkage vector relation in DRDFIG is shown in Fig. 3. Where, ψ_r is wound rotor flux , ψ_s is the stator flux linkage and ψ_{pm} is the PM rotor flux linkage, respectively, α is the angle of the stator flux and wound rotor winding magnetic chain, β is the PM rotor flux and wound winding flux linkage .

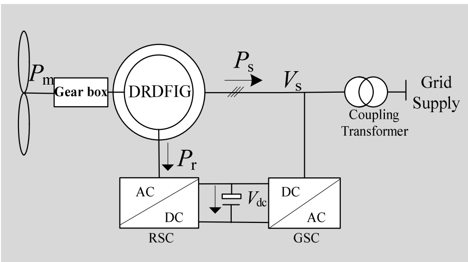


Fig. 2 Diagram of the DRDFIG wind energy generation system.

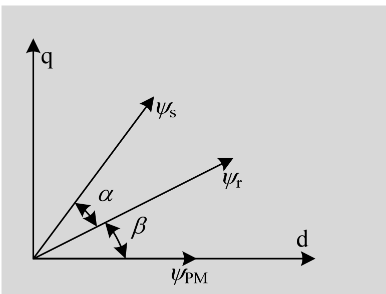


Fig. 3. Diagram of stator and rotor flux vectors

Flux equation is as follows

$$\begin{cases} \psi_{ds} = -L_s I_{ds} + L_m I_{dr} + \psi_{PM} \\ \psi_{qs} = -L_s I_{qs} + L_m I_{qr} \\ \psi_{dr} = -L_m I_{ds} + L_r I_{dr} + \psi_{PM} \\ \psi_{qr} = -L_m I_{qs} + L_r I_{qr} \end{cases} \quad (1)$$

where, ψ, I, Ls, Lr, Lm, Ψ_{PM} is magnetic chain, the current, self inductance of stator winding, self-induction for wound rotor winding, mutual inductance of stator winding, and the permanent magnet rotor chain, respectively. Subscript s and r is on behalf of the stator and rotor, respectively. Subscript d and q is on behalf of the synchronous coordinate system fixed rotor shaft and d , q axis component, respectively.

Voltage equation:

$$\begin{cases} V_{ds} = p\psi_{ds} - \omega_1 \psi_{qs} - R_s i_{ds} \\ V_{qs} = p\psi_{qs} + \omega_1 \psi_{ds} - R_s i_{qs} \\ V_{dr} = p\psi_{dr} - \omega_s \psi_{qr} + R_r i_{dr} \\ V_{qr} = p\psi_{qr} + \omega_s \psi_{dr} + R_r i_{qr} \end{cases} \quad (2)$$

where, V, R, ωs, ω1, ωr is the voltage, the resistance, slip angular velocity, synchronous angular velocity and wound rotor angular velocity, respectively, p=d/dt is the differential operator.

DRDFIG torque is divided into wound rotor torque and PM rotor torque. The sum of them should be electromagnetic stator torque. Stator torque TS, outer rotor torque TWR and PM rotor torque TPM is expressed as follows:

$$\begin{cases} T_S = \frac{3}{2} p(i_{ds}\psi_{qs} - i_{qs}\psi_{ds}) \quad (3) \\ T_{WR} = \frac{3}{2} p(i_{dr}\psi_{qr} - i_{qr}\psi_{dr}) \\ T_{PM} = T_S - T_{WR} \end{cases}$$

III. STEADY SIMULATION ANALYSIS

There is a double rotor structure, which improves the performance of the DRDFIG. Stator voltage oriented vector control method was adopted for the rotor side converter, the d axis oriented in the direction of stator voltage, which makes the q axis voltage is zero in order to realize the decoupling control for rotor side converter by this way.

The active and reactive output power from DRDFIG are represented as

$$\begin{cases} P = v_{ds} i_{ds} + v_{qs} i_{qs} = v_{ds} (\frac{L_m}{L_s} i_{dr} + \frac{1}{L_s} \psi_f) \\ Q = v_{qs} i_{ds} + v_{ds} i_{qs} = v_{ds} (\frac{L_m}{L_s} i_{qr} + \frac{v_{ds}}{\omega_1 L_s}) \end{cases} \quad (4)$$

$$\begin{cases} \boldsymbol{v}_s = -R_s \boldsymbol{i}_s + p\boldsymbol{\psi}_s + j\omega_s \boldsymbol{\psi}_s \\ \boldsymbol{v}_r = R_r \boldsymbol{i}_r + p\boldsymbol{\psi}_r + j\omega_{s1} \boldsymbol{\psi}_r \end{cases} \tag{5}$$

$$\begin{cases} \boldsymbol{\psi}_s = -L_s \boldsymbol{i}_s + L_m \boldsymbol{i}_r + \boldsymbol{\psi}_f \\ \boldsymbol{\psi}_r = -L_m \boldsymbol{i}_s + L_r \boldsymbol{i}_r + \boldsymbol{\psi}_f \end{cases} \tag{6}$$

The equivalent stator magnetizing current i_{mo} is defined as

$$i_{mo} = \frac{\psi_s}{L_m} = \frac{L_s}{L_m} i_s + i_r \tag{7}$$

$L_m/L_s \approx 1$,

Based on (2) and (3), the equation for rotor flux linkage given next is derived

$$\begin{aligned} \psi_r &= -\psi_s + (\frac{L_m^2}{L_s} - L_r) i_r + \psi_f \\ &= -\frac{L_m^2}{L_s} i_{mo} + (L_r + \frac{L_m^2}{L_s}) i_r + 2\psi_f \end{aligned} \tag{8}$$

Voltage equation can been given below

$$\begin{cases} \boldsymbol{v}_s = -R_s \boldsymbol{i}_s + L_m \frac{di_{mo}}{dt} + j\omega_s \boldsymbol{\psi}_s \\ \boldsymbol{v}_r = R_r \boldsymbol{i}_r + j\omega_{s1} \boldsymbol{\psi}_r - \frac{L_m^2}{L_s} \frac{di_{mo}}{dt} + (L_r + \frac{L_m^2}{L_s}) \frac{di_r}{dt} \end{cases} \tag{9}$$

The vector control diagram oriented stator voltage considering stator excitation current change was shown in Fig. 4. Where, PI expresses the proportion integral module, Superscript * denotes the reference value. V_α 、V_β is alpha shaft and rotor voltage beta axis component, V_{dc}, i_{sabc}, i_{rabc} , is DC bus voltage, three-phase stator current of network side and three-phase rotor current of network side, respectively. SVPWM and S_{abc} represents space vector pulse width modulation and inverter circuit on-off function, respectively.

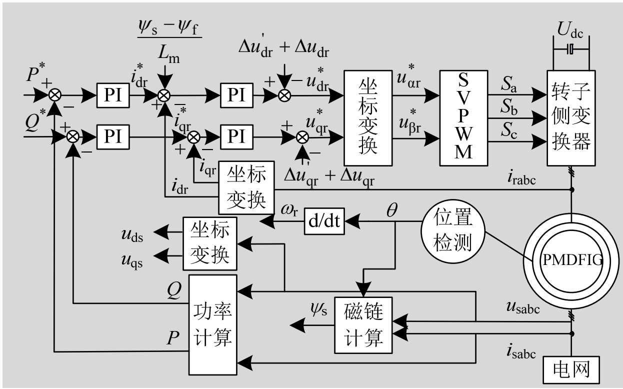


Fig. 4 Schematic diagram of the stator voltage vector oriented control.

In order to compare performance of DRDFIG and the ordinary DFIG, the contrast simulation research was conducted under the same condition for two kinds of generators. Rated voltage is 690V, Rated power is 1. 5 MW, permanent magnet is made of Nd-Fe-B, driving power is direct current power supply, and the surface mounted magnets shape and radial magnetization. Residual flux density is 1. 04T, coercive force *H*c is 890kA/m. The other main technical parameters of motors are shown in Table 1.

TABLE I. PARAMETERS OF THE SIMULATION

Parameters	Values (pu)
Stator resistance	0. 01
Stator leakage	0. 171
Rotor leakage inductance	0. 156
Mutual inductance	2. 9
Rotor resistance	0. 009
PM magnetic chain	0. 5
Crowbar bypass resistor	0. 8
Turns ratio of stator and the rotor	0. 38

Rotor current simulation waveforms of two kinds of generators was shown in Fig. 5. It shows the stator current of DRDFIG was smaller than that of DFIG in the same conditions, , which is reduced by 18%. Due to the presence of the PM rotor , stator excitation current is reduced, so that the magnetic field under the same conditions, the stator current is less than that of DFIG, This will reduce the excitation capacity of DRDFIG.

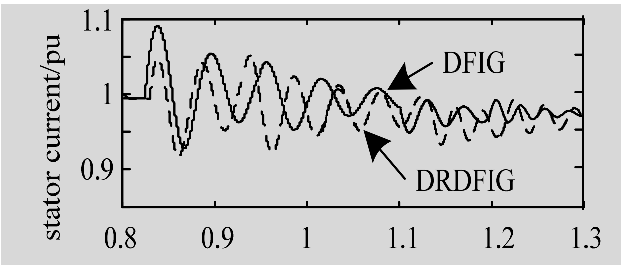


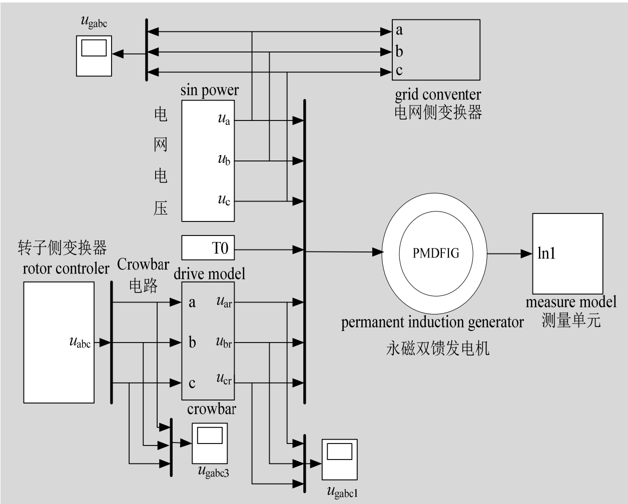
Fig. 5 Comparison of the stator current between DFIG and DRDFIG based on stator voltage vector oriented control.

IV. CROWBAR SIMULATION ANALYSIS

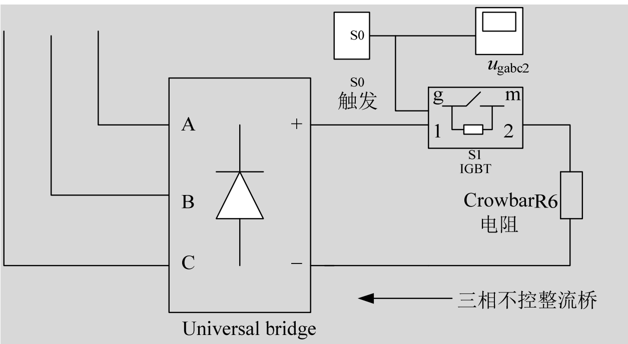
A. Simulation Control Model

According to the analysis above, there are three main parameters affecting Crowbar control effect, they are resistance, voltage sag and the phase before voltage drop. At the same time, the starting time of Crowbar resistance will also affect the control effect.

According to the basic principle of Crowbar circuit, a Crowbar circuit simulation control model was established when voltage drop. Before the voltage drops, the rotor side converter adopts the vector control oriented stator voltage considering stator excitation current change. When the voltage seriously drops, the rotor side converter is removed from the Crowbar circuit. The simulation model diagram was shown in Fig. 6. Among them, the Crowbar main circuit uses three-phase uncontrolled rectifier load model with resistance, with IGBT as the switch control circuit, Crowbar input and removal.



(a) Crowbar Control Simulation Model

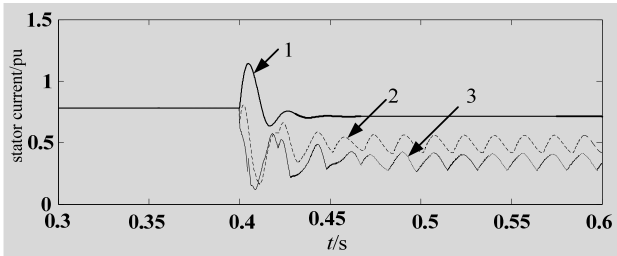


(b) Crowbar Main Circuit

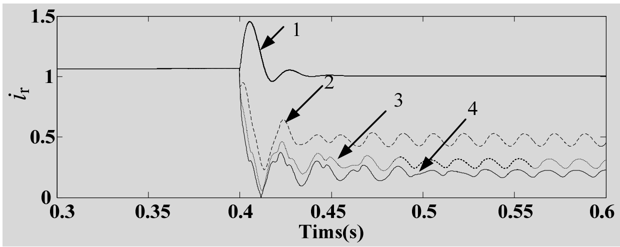
Fig. 6 Crowbar Simulation Model Diagram.

B. Simulation under Different Crowbar Resistance

In the simulation study on the effect of Crowbar resistance drops fault. If the voltage drops to 85% of the rated value, when crowbar resistance is 0, 0. 4pu, and 0. 8pu, respectively. The simulation results were shown in Fig. 8. Through the analysis above, the current peak will gradually decrease with the increase of Crowbar resistance.



(a) Stator Current



(b) Rotor Current
1- No Crowbar resistance, 2-0. 4pu, 3-0. 8pu

Fig. 7 The simulation curves of different crowbar resistance.

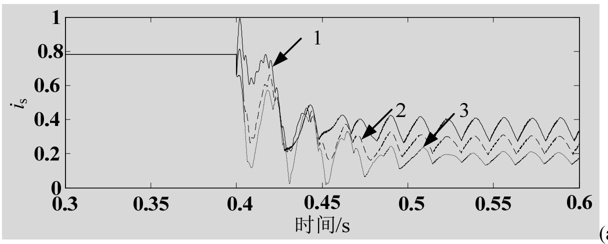
As shown in Fig. 7 (a), when the voltage drops, stator current increases rapidly without crowbar resistance, however, when crowbar resistance was adopted, stator current was restricted. As shown in Fig. 7 (b), when the voltage drops, rotor current increases rapidly without crowbar resistance, however, when crowbar resistance was adopted, rotor current was restricted.

The current was obviously limited with the increase of crowbar resistance. From the rotor current, active power and reactive power can get the same conclusion. Among them, the active power, the system can effectively restrain the fluctuation of active power, but the output power is reduced, the power will be in the form of heat consumption in Crowbar resistance.

C. Simulation under Different Voltage Drop

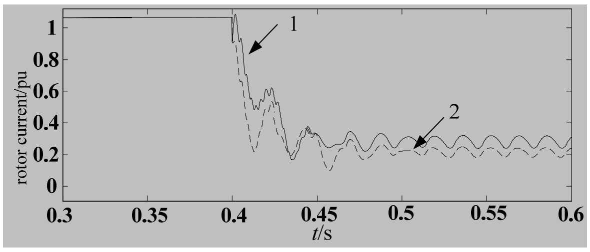
According to the above derivation, also affect the control effect of voltage drop on Crowbar, we simulate the voltage sag effect analysis on Crowbar control. If the value of Crowbar resistor is 0. 8pu, voltage drops to the original 45%, 65% and 85%. Study on these three kinds of voltage drops, Crowbar circuit effects on the motor of each physical quantity.

As shown in Fig. 8, From Fig. 8(a) and (b), shows, with the voltage drop depth is different, the stator current peak value and the stable value are different.



(a)

stator current



(b) rotor current

1-0. 65pu, 2-0. 85pu

Fig. 8 The simulation curves of different voltage dip.

From the analysis above, we can see:

When the voltage drops, crowbar circuit still can well inhibit the fault current fluctuations, reducing the fluctuation of output power and the impact of mechanical system. With the depth of voltage drop, fault current increases.

Ⅴ. CONCLUSIONS

DRDFIG combines the advantages of the traditional permanent magnet direct drive wind generator and usual DFIG: high efficiency, high power density, variable speed and constant frequency. This research can draw the following conclusions:

DRDFIG uses stator voltage oriented control mode in power grid voltage under constant conditions, compared with ordinary DFIG, In the same power control effect, the excitation current is smaller than that of DFIG. When grid voltage serve sags, the appropriate crowbar resistance can effectively suppress the fault current, active power, as well as the the DC voltage.

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