Power Characteristics Analysis and Modeling Method of DFIG Wind Systems

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Abstract. Wind power generation technology is developing rapidly on a global scale. In many wind power generation systems, which we use most commonly is the double-fed wind power generation system. This paper mainly focuses on the power relationship, modeling and simulation of the double-fed wind power generation system. First, based on the equivalent circuit diagram, this paper analyses double-fed induction generation (DFIG) operation theory and DFIG power relationship. Then, builds the model of double-fed wind power generation system. Finally, use PSCAD to simulate the double-fed wind power generation system, which proves the validity of DFIG output active and reactive power decoupled control and the maximum wind power tracking control.

1. Introduction
In the process of human life and social development, energy undoubtedly plays an important role. Wind energy has the advantages of wide distribution, environmental protection, easy access and inexhaustible [1]. Double-fed induction generator (DFIG) have emerged since 1940s. DFIG has the characteristics of synchronous motor and asynchronous motor. From the relationship between the generator speed and the synchronous speed, it belongs to induction motor. DFIG has its own independent excitation winding to adjustable power factor, which are the characteristics of synchronous motor.

In this paper, the operation theory of DFIG is analyzed and the model of double-fed wind power generation system is established. PSCAD is used to simulation and verification of maximum wind power tracking and the decoupling control of active power and reactive power [2].

2. Operation Theory of DFIG

2.1. The Basic Principle of DFIG
Figure 1 represents the structure diagram of DFIG wind turbine. The stator winding connects with the grid directly, and the rotor winding connects with the grid through an AC-DC-AC back-to-back PWM converter. The power enables a bidirectional flow between two PWM converters while the DFIG wind turbine is running [3]. When the wind speed is low, the rotor absorbs the power from the grid and then returns to the grid through the stator to maintain the torque balance, when the wind speed is high, the rotor and stator deliver energy to the grid simultaneously.
A low speed-rotating magnetic field will generate in the rotor of DFIG, when the three-phase low frequency current flows into it. The speed relationship are given by

\[ n_s = n_r \pm n_0 \]  

(1)

\( n_s \) is synchronous speed; \( n_r \) is rotor speed; \( n_0 \) is rotating speed of rotor magnetic field. The wind speed changes, \( n_r \) will change. At this point, keep \( n_s \) unchanged by adjusting \( n_r \), and then the output frequency remains unchanged, which is the principle of variable speed constant frequency.

2.2. Power Characteristics of DFIG

In the double-fed wind power generation system, the wind turbine converts wind energy into mechanical energy, drives the rotor to rotate through the transmission device, and makes the generator obtain the mechanical power. The rotor generates a magnetic field under the excitation current, and continuously rotates and cuts the magnetic induction line to generate the induced current in the stator, the power is transmitted to the stator side. The stator connects with the grid, finally the power is transmitted to the power grid. After ignoring the stator and rotor losses and stray losses, the power transfer equation of DFIG can be expressed as:

\[ P_m = P_1 - P_2 = P_1 - sP_1 = (1-s)P_1 \]  

(2)

\( P_m \) is mechanical power output from a wind turbine to a rotor; \( P_1 \) is output power of stator; \( P_2 \) is slip power; \( s \) is slip.

The power of DFIG can flow in two directions, which makes it have three modes of operation.

(1) Synchronous operation

Excitation power supply DC excitation, the rotor speed is less than the synchronous speed:

\( s = 0; P_m = P_1 \).

(2) Subsynchronous operation

The output power of the wind turbine is less than the output power of the stator, so the rotor needs to absorb the power from the grid to provide the slip power:

\( 0 < s < 1; P_m = P_1 - sP_1 = (1-s)P_1 \).

(3) Ultra synchronous operation

The output power of the wind turbine is greater than the output power of the stator, and then the extra power is supplied to the rotor as slip power:

\( s > 1; P_m = P_1 + sP_1 = (1+s)P_1 \).

3. Mathematical Modeling of Double-Fed Wind Power Generation System

The basic modules of double-fed wind power generation system are shown in Figure 2, including wind speed model, wind turbine model, DFIG model and so on.
3.1. Wind Model
In order to describe the characteristics of wind speed accurately, there are many researches both at home and abroad. In this paper, the four-component model is adopted, which is internationally accepted and can be simulated simply. The four-component model divides the wind speed into four variables [4]: base wind, gust wind, ramp wind, noise wind.

3.2. Wind Turbine Model
According to Bates theory, the output power of wind turbine is [5]:

$$ P_m = \frac{\rho \pi R^2 v C_p}{2} \tag{3} $$

$\rho$ is air density; $R$ is blade radius of wind wheel; $v$ is wind speed; $C_p$ is power coefficient.

Power coefficient is the utilization ratio of wind power converted into mechanical power by wind turbines, which is related to wind speed $v$, blade speed $\omega_T$, blade radius $R$ and pitch angle $\beta$, and is determined by tip speed ratio $\lambda$ and pitch angle $\beta$.

$$ C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda} - 0.4\beta - 5\right)e^{-2\lambda} + 0.0068\lambda. \tag{4} $$

Where $\frac{1}{\lambda} = \frac{1}{\lambda(0.08\beta) - 0.035(\beta^3 + 1)}. \tag{5}$

Figure 3 is the relationship between the power coefficient and the tip speed ratio when the wind speed remains constant and the pitch angle is fixed.

![Figure 3. $\lambda$-Cp Diagrammatic Curve when $\beta$ is Fixed.](image)

As shown in figure 4, when the wind turbine operates at fixed pitch, there is only one tip speed ratio, which makes the power coefficient maximum. The tip speed ratio corresponding to the
maximum power coefficient is called the optimal tip speed ratio. The definition of the tip speed ratio [6]:

\[ \lambda = \frac{\omega R}{v} \]  \hspace{1cm} (5)

Therefore, for a given wind speed, the maximum power coefficient can be obtained only when the wind turbine operates at a specific speed.

When the pitch angle changes, the relationship between the power coefficient and the tip speed ratio can be obtained, as shown in Figure 4, for any pitch angle, only the optimal tip speed ratio is found to obtain the maximum power coefficient. Therefore, when the pitch angle is known, the optimal tip speed ratio can be obtained, and then the corresponding blade speed of wind turbine can be calculated by (5), thus the power coefficient reaches the maximum.

3.3. DFIG Model

Some assumptions should be made when the DFIG model is established [7]. Then the mathematical model of DFIG under d-q coordinate system can be obtained.

(1) Voltage equation

\[
\begin{align*}
\dot{u}_{ds} &= R_s i_{ds} + p \Psi_{ds} - \omega_{dqp} \Psi_{qf} \\
\dot{u}_{qs} &= R_s i_{qs} + p \Psi_{qs} + \omega_{dqp} \Psi_{df} \\
\dot{u}_{dr} &= R_r i_{dr} + p \Psi_{dr} - \omega_{dqr} \Psi_{qf} \\
\dot{u}_{qr} &= R_r i_{qr} + p \Psi_{qr} + \omega_{dqr} \Psi_{df}
\end{align*}
\]  \hspace{1cm} (6)

\( u_{ds}, u_{qs}, u_{dr}, u_{qr} \) are the voltage of stator and rotor on d, q-axis; \( i_{ds}, i_{qs}, i_{dr}, i_{qr} \) are the current of stator and rotor on d, q-axis; \( R_s, R_r \) are the stator and rotor side resistances; \( \Psi_{ds}, \Psi_{qs}, \Psi_{dr}, \Psi_{qr} \) are the flux linkage of stator and rotor on d, q-axis; \( \omega_{dqp}, \omega_{dqr} \) are rotating angular velocity of dq coordinate system relative to stator and rotor; \( p \) corresponds to the derivative operation, \( p=d/dt \).

(2) Flux linkage equation

\[
\begin{align*}
\Psi_{ds} &= L_s i_{ds} + L_m i_{dr} \\
\Psi_{qs} &= L_s i_{qs} + L_m i_{qr} \\
\Psi_{dr} &= L_r i_{dr} + L_m i_{ds} \\
\Psi_{qr} &= L_r i_{qr} + L_m i_{qs}
\end{align*}
\]  \hspace{1cm} (7)
L_s, L_r are the stator and rotor side inductances; L_m is the magnetizing inductance.

(3) Torque equation

\[
T_e = 3p_n L_m \left( \psi_q i_d - \psi_d i_q \right) / 2 = 3p_n \left( \psi_q i_d - \psi_d i_q \right) / 2
\]

(8)

\(T_e\) is the electromagnetic torque; \(p_n\) is the pole numbers.

(4) Mechanical equation

\[T_m - T_e = \frac{J}{n_p} \frac{d\omega_m}{dt}\]

(9)

\(T_m\) is the mechanical torque; \(J\) is the moment of inertia of rotor; \(\omega_m\) is the rotor mechanical angular velocity.

3.4. Stator-Flux-Oriented Vector Control

When the doubly fed wind generator is connected with the grid, the stator resistance is far less than the reactance, so the stator resistance can be ignored, \(R_s = 0\). Make the stator flux orientation coincide with the d axis, stator voltage advances stator flux linkage 90°.

\[
\begin{align*}
\psi_d & = \psi_s \\
\psi_q & = 0 \\
u_d & = 0 \\
u_q & = u_s \\
i_d & = (\psi_s - L_m i_b) / L_s \\
i_q & = -L_m i_q / L_s
\end{align*}
\]

(10)

(11)

Put (10) and (11) into (6), put (10) into (7):

\[
\begin{align*}
u_d & = 0 \\
u_q & = \omega_{sy} \psi_{sy} \\
i_d & = (\psi_s - L_m i_b) / L_s \\
i_q & = -L_m i_q / L_s
\end{align*}
\]

(12)

(13)

The output power of stator can be obtained:

\[
\begin{align*}
P_1 & = 3 \left( u_d i_d + u_q i_q \right) / 2 = -3 u_s L_m i_q / 2 L_s \\
Q_1 & = 3 \left( u_q i_d - u_d i_q \right) / 2 = 3 u_s \left( \psi_q - L_m i_q \right) / 2 L_s
\end{align*}
\]

(14)

\(P_1, Q_1\) are the output active and reactive power of the stator; \(i_{qf}, i_{df}\) are the torque component and excitation component of rotor current. In (14), \(P_1\) is linearly related to \(i_{qf}\) and \(Q_1\) is linearly related to \(i_{df}\). \(P_1\) and \(Q_1\) can be controlled by controlling \(i_{qf}\) and \(i_{df}\) respectively, therefore decoupling of active and reactive power can be realized.
4. Simulation of Double-Fed Wind Power Generation System

4.1. Simulation of the Maximum Wind Power Tracking Control

![Graphs](image)

(a) Under base wind
(b) Under gust wind
(c) Under ramp wind
(d) Under noise wind

**Figure 5.** The Maximum Wind Power Tracking Control.

The generator speed can track the reference speed of the generator according to the wind speed as shown in figure 5, so the simulation model can better track the maximum wind power.

4.2. Simulation of the Active and Reactive Power Decoupled Control

![Graphs](image)

(a) Output reactive power and its reference value
(b) Excitation component of rotor current
(c) Output active power
(d) Torque component of rotor current

**Figure 6.** The Active and Reactive Power Decoupled Control under Gust Wind.
As shown in Figure 6 and Figure 7, the variation trend of the output active power and the torque component of rotor current is the same, and the output reactive power is almost the same as the excitation component of rotor current. The reactive power is only related to the reactive power setting value, and the active power is only related to the rotor current. Thus, the decoupling of output active power and reactive power is realized.

5. Conclusion
The paper presents the variable speed constant frequency principle of DFIG and its three operating states, established the model of double-fed wind power generation system, including wind model, wind turbine model and DFIG model, verifies the maximum wind power tracking principle and the decoupling control of active power and reactive power through simulation.

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