Research on Control Strategy of Grid-side Converter of Permanent Magnet Direct-drive Wind Turbine

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Abstract. In order to make the permanent magnet direct-drive wind turbines stable and grid-connected operation, a double closed-loop control strategy based on grid voltage-oriented vector and current decoupling is proposed. First, the topology of the grid-side converter of the wind turbine is determined, then the mathematical model of the control strategy is derived, and the parameters of the PI regulator are calculated. Finally, the control strategy is verified by the simulation results. Through the analysis of the experimental results, it is found that the control strategy can achieve the functions of stabilizing the DC bus voltage of the fan and controlling the input power factor, ensuring the stable operation of the fan.

Keywords: Permanent magnet direct drive wind turbine, grid-side converter, control strategy, PI adjustment.

1. Introduction

Permanent magnet direct drive wind turbines have become another important type of wind turbines following doubly-fed wind turbines due to their low mechanical loss, high operating efficiency and low maintenance costs. With the continuous development of renewable energy, the capacity of wind turbine assembly machines has increased significantly, and it is very necessary to ensure the safe and stable grid-connected operation of wind turbines [1]. Meng et al proposed a control strategy for generator-side and grid-side converters based on dual space vector pulse width modulation. Simulations show that this control strategy can achieve the control requirements for grid-connected wind turbines [2]. Lin et al proposed a system simulation model based on dual closed-loop PI control to build a machine-side system, which achieved maximum power tracking at 4 different wind speeds, and improved the operating characteristics of wind turbines[3]. Yang et al completed the control of generator speed and output voltage by separately controlling the wind turbine-side converter and grid-side converter. The results show that the control strategy is highly feasible [4]. Lin et al proposed a field-circuit coupling simulation of the dual closed-loop PI control of wind turbines based on Maxwell and Simplore for megawatt offshore wind turbines, and realized the function of maximum power tracking at different wind speeds [5]. Meng et al uses a fuzzy-PID compound controller to control the pitch based on the dual closed-loop control strategy, which realizes the maximum tracking control strategy of the wind turbine and has good stability and dynamic performance [6]. Wang et al solved the problem of slow response of the current closed-loop control strategy of the grid-side converter of asymmetric grids. According to the current difference and the conversion rate of the current difference,
the fuzzy PID control strategy of the online fuzzy adaptive proportional integral derivative controller parameters improved the network. The ripple component of the side DC bus voltage, and the corresponding speed of the control strategy is faster [7].

In order to make the wind turbines run on the grid stably, this paper firstly determines the basic topology of the grid-side converter, and then derives and calculates the mathematical model of the dual closed-loop control strategy, and calculates the parameters of the PI regulator of the dual-closed-loop system. The control strategy is verified through simulation results.

2. Topological structure and mathematical model of network side transformation

This research is the grid-side converter of 500kW wind turbine, and its main topology is shown in Figure 1. $e_a, e_b, e_c$ are ideal voltage sources, $i_a, i_b, i_c$ are input currents, and $v_{dc}$ is the DC bus voltage. $L$ and $R$ are equivalent resistance and inductance, $C$ is filter capacitor. The switching device uses IGBT and rectifier diode in parallel.

![Figure 1. Topological structure of grid-side converter of permanent magnet direct drive wind turbine](image)

The values of the grid-side three-phase voltage change with time, which is difficult to model in a stationary coordinate system. Therefore, the coefficient equations in the three-phase stationary coordinate system $a, b, c$ are transformed through Clarke transformation Is the equation on the two-phase rotation $d$ and $q$ axis, as shown below

$$v_d = -R_i i_d - L \frac{d i_d}{dt} + \omega_L i_q + e_d$$

$$v_q = -R_i i_q - L \frac{d i_q}{dt} - \omega_L i_d + e_q$$

In (1) and (2), $v_d, v_q$ are the components of the $d, q$ axes of the converter's rotating coordinate system, $i_d, i_q$ are the current components of the converter in the $d$ and $q$ axes of the rotating coordinate system. $e_d, e_q$ are the voltages on the $d$ and $q$ axes of the converter's AC side Component, $R_s$ is the equivalent resistance. $\omega_L$ is the angular velocity, $L_s$ is the equivalent inductance.

3. Control strategy of grid-side converter

It can be seen from Figure 2 that if the speed in the $d, q$ axis rotating coordinate system is synchronous speed, and the $q$ axis is ahead of the $d$ axis, set the grid side three-phase AC voltage $e_a, e_b, e_c$ to synthesize the space voltage vector $e_m$ and define the grid voltage comprehensive vector $e_m$. Oriented on the $d$ of the synchronous rotating coordinate system, it can be obtained that the component of $e_m$ in the $q$ is 0, that is, the $d$-axis voltage $e_d = e_m$, the $q$-axis voltage $e_q = 0$.

Based on the above analysis, the mathematical model of the active power $P$ and reactive power $Q$ of the grid-side converter under the $d, q$ axis coordinate under the grid voltage-oriented control can be obtained as shown below.
It can be seen that the decoupling of active power and reactive power is realized through grid voltage-oriented control, and the function of independent control of active power and reactive power by d-axis and q-axis current is realized. A subsection

\[ P = e_d i_d + e_q i_q = e_d i_d \]  \hspace{1cm} (3)

\[ Q = e_q i_d + e_d i_q = e_d i_q \]  \hspace{1cm} (4)

It can be seen from formulas (1) and (2) that they all contain \( i_d, i_q \), which shows that the currents of the d and q axes are coupled. And there are also cross-coupling quantities \( \omega_2 L_s i_q \) and \( \omega_1 L_s i_d \), for which decoupling control is needed to realize independent control of current components \( i_d, i_q \). The control strategy diagram of the entire control system is shown in Figure 3. It is a double closed-loop control. The voltage outer loop is the grid voltage-oriented vector control. Its main function is to control the output of the DC bus voltage. The output voltage error obtained by the DC bus voltage feedback, the value of \( i_d^* \) is calculated by the voltage regulator, which determines the active power of the converter, and the sign determines the direction of the active power.

**Figure 2.** Voltage and current components in the d, q rotating coordinate system.

**Figure 3.** Grid-side converter control strategy diagram

The current loop is the decoupling control of the current decoupling loop. PI adjustment is adopted. In order to realize the decoupling, \( i_d^*, i_q \) feedforward control and \( e_d \) feedforward compensation are introduced, and voltage command formula is as follows.
In (5) and (6), $V^*_d, V^*_q$ are the reference values of converter $d$ and $q$-axis voltage output, $i^*_d, i^*_q$ are converters $d$, $q$-axis current output reference values. $K_{dp}, K_{dq}$ is the proportional and integral regulator of the $d$-axis, $K_{iq}$ is the proportional and integral regulator of the $q$-axis.

Through (7) and (8), it can be seen that the complete decoupling of the voltage command is realized, the independent control of the $d$-axis and $q$-axis current is realized, and the effect of improving the dynamic performance of the system is achieved.

4. PI parameter calculation

4.1. Current loop parameter calculation

In order to make the current loop have better current followability, according to the I model system design, the open loop transfer function of the current loop is as follows.

$$G_{cd}(s) = \frac{K_{dp} + K_{di}}{s}$$

(7)

The closed-loop transfer function of the current loop is as follows.

$$G_{cd}(s) = \frac{Ka + Ki}{1 + Ka + Ki + \frac{1}{s}}$$

(8)

Because $\frac{K_{dp}}{K_{di}} = \frac{L}{R}$, simplified to $G_{cd}(s) = \frac{1}{1 + \frac{1}{K_{dp}}}$, the current loop is actually an inertia link. We already know that $\frac{L}{K_{dp}} = \tau$, and then according to $\frac{1}{1 + \tau s^2} = \frac{1}{\tau}$, calculate the time constant, and the PI regulator parameters of the current loop can be calculated through the above formula.

4.2. Voltage loop parameter calculation

The main function of the voltage outer loop is to keep the DC bus voltage stable. In order to improve its resistance, the voltage outer loop can be designed according to the II row system, and its open loop transfer function is shown below.

$$G_{ov}(s) = \frac{1}{1 + \tau s} \left(K_{ov} + \frac{K_{oi}}{s} \right) \frac{1}{1 + \tau s C_{ov} s}$$

(9)

After simplifying and merging two small inertia links, the open-loop transfer function of the voltage loop is obtained as shown below.

$$G_{ov}(s) = \frac{0.75K_{ov} \left(\frac{K_{dp}}{K_{di}} + 1\right)}{C_{ov} \tau s(1 + (\tau s + \tau)s)}$$

(10)

According to the design of the voltage regulator of a typical type II system, the setting relationship can be obtained as follows.
\[
\frac{0.15k_{vi}}{C_{dc}} = \frac{h_v}{2n_p^{2}(T_{\delta S}^{2} + \tau^{2})} \quad h_v = \frac{K_{vp}}{T_{\delta S}}
\]  

(11)

In (9), (10), (11), \(k_{vi}, k_{vp}\) are the integral and proportional gain parameters of the voltage loop. \(T_{\delta S}\) is the sampling time of the voltage loop, \(h_v\) generally takes 5 in engineering.

5. Analysis of results

The main parameters of the fan and its control system are shown in Table 1.

| Parameter | Value |
|-----------|-------|
| \(V_{dc}\) | 1300V |
| \(P_1\)  | 500kW |
| \(I\)    | 241.5A|
| \(C\)    | 0.017F|
| \(L\)    | 0.00476H|
| \(I_{c}\) | 384A  |

In the table, \(V_{dc}\) is the DC side bus voltage, \(P_1\) is the rated power of the wind turbine, \(I\) is the rated current of the converter, \(C\) is the equivalent capacitance, \(L\) is the equivalent inductance, and \(I_{c}\) is the controlled current source. According to the calculation in Chapter 4, the PI adjustment parameters of the current loop are \(K_{dp} = 0.149, K_{di} = 9.39\), and the PI adjustment parameters of the voltage loop are \(k_{vp} = 4.56\) and \(k_{vi} = 304\). The simulation time is 40ms, and the sampling frequency is \(1e^{-8}\)s.

5.1. Current loop parameter calculation

Figure 4(a) shows the voltage waveform of the DC side bus. It can be seen that the control strategy of the double closed loop grid-side converter starts to drop after the voltage rises to a certain high value, and the voltage stabilizes at 1300V at 15ms. It is concluded that the control strategy can realize the function of controlling the voltage stability of the DC bus.

5.2. Active power and reactive current waveform

It can be seen from Figure 4(b) that the active power is maintained at 500kw after 10ms of adjustment, which tends to be stable. Figure 4(c) is the reactive current, that is, the current on the q-axis. It can be seen that its value has been around 0A, indicating that the control strategy can realize the control and adjustable power factor.

6. Conclusions

This paper derives and validates the mathematical model and control strategy of the wind turbine network measurement converter. The results show that the dual closed-loop control strategy based on the voltage outer loop and the current inner loop can achieve the functions of stable DC bus voltage and adjustable power factor of the wind turbine. Stable operation of the fan puts forward a feasible method.
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