Research on Control Strategies for Doubly Fed Induction Generator

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Keywords: Doubly fed induction generator, Variable speed constant frequency, Trace of maximum wind-energy, Decouple, Double close-loop control.

Abstract. The control methods of the source-side (stator-side) and rotor-side converters of Doubly Fed Induction Generator (DFIG) are researched in the paper. The rotor-side converter of the DFIG introduces the stator flux linkage oriented vector control strategy, realizes track of maximum wind-energy, independently controls the active power, reactive power. The source-side converter of the DFIG maintains the voltage of DC bus, regulates the power factor of source-side by adopting grid voltage oriented vector control strategy. Based on PSCAD/EMTDC software for the power system simulation, this paper constructs simulation models including wind speed, wind turbine, DFIG, the rotor-side and source-side converters. The result of simulation proves rationality and efficiency of the proposed method.

Introduction

The operational control in the variable speed constant frequency wind power generation system with Doubly Fed Induction Generator (DFIG) are researched in the article. The rotor-side converter of the DFIG introduces the stator flux linkage oriented vector control strategy. An algorithm is derived to control independently stator active and reactive power of wind power generator by two components of exciting current in the rotor[1-2]. Double closed-loop control system which contains reactive power outer loop and current inner loop is introduced in d-axis. While double closed-loop control system which contains speed outer loop and current inner loop is introduced in q-axis, this control system can realize track of maximum wind-energy, independently control the active power, reactive power and regulate the reactive power of stator output. The source-side converter of the DFIG maintains the voltage of DC bus, regulates the power factor of source side by adopting grid voltage oriented vector control strategy. The grid-side converter diverts the rotor power to or from the grid using a DC-link between the two converters. The grid-side converter adopts grid voltage oriented vector control strategy. It takes advantage of a double closed-loop control method which contains voltage outer loop and current inner loop to maintain the voltage of DC bus and regulate the power factor of source side.

Basic Theory of DFIG

The relationship among \( w_1, w_2, w_r \) of doubly fed wind-driven generator is:

\[
f_1 = f_2 + f_r. \tag{1}
\]

\( f_1 \) is frequency of stator magnetic field, \( f_2 \) is frequency of rotor magnetic field. \( f_r \) is mechanical frequency.

When mechanical frequency of doubly fed induction generator \( f_r \) varies, we can maintain frequency of the stator magnetic field \( f_1 \) constant by regulating the frequency of rotor magnetic field \( f_2 \), thus the generator can realize variable speed constant frequency operation. When \( f_2 > 0 \), generator works in subsynchronous operating state, power flows from grid to stator, the stator-side converter works as a rectifier, the rotor-side converter works as an inverter. When \( f_2 < 0 \), generator works in supersynchronous operating state, power flows from rotor to grid, the stator-side converter works as an inverter, the rotor-side converter works as a rectifier. When \( f_2 = 0 \), generator keeps synchronous operation. The excitation current is direct current.
Control System for the Stator-side Converter

The following equations hold \[2\].

\[
\begin{align*}
    u_d &= -u_q + \Delta u_d + e_d \\
    u_q &= -u_q - \Delta u_q + e_q \\
    u_d' &= L\frac{di_d}{dt} + Ri_d \\
    u_q' &= L\frac{di_q}{dt} + Ri_q \\
    \Delta u_d &= w_1 L i_q \\
    \Delta u_q &= w_1 L i_d
\end{align*}
\]

(2)

(3)

(4)

\(e_a, e_b, e_c\) are three-phase voltages of AC sides of stator -side converter, \(i_d, i_q\) are obtained by three-phase currents \(-i_a, i_b, i_c\) of AC sides of stator -side converters through the Park transformation. In the above formula, \(u_d', u_q'\) and \(i_d, i_q\) respectively have a first order differential relationship; these two voltage components are referred to as decoupling items. \(\Delta u_d, \Delta u_q\) are voltage coupling compensation items. At the same time, we introduce grid voltages \(e_d, e_q\) for feedforward compensation to realize the decoupling control of \(d, q\)-axis current, so the active and reactive power can be independently and effectively controlled. Based on the above analysis, we can get control strategy chart for the grid-side converter. As shown in the Figure 1.

Figure 1. Illustration of control strategy for the source-side converter.

In the Figure 1, \(\theta\) is the angle between \(a_1\)-axis and \(d\)-axis. \((a_1-b_1\) is two-phase static coordinate system for stator winding, \(d-q\) is synchronous rotating coordinate system). The control system adopts a double closed-loop control method which contains voltage outer loop and current inner loop. \(i_q^*\) is determined by the power factor. We set \(i_q^* = 0\) to achieve adjusting method for realizing unity power factor. We compare \(i_d^*\) and \(i_q^*\) respectively with the value of current feedback \(i_d, i_q\), then the result after compared is sent to the PI controller, the outputs are \(u_d^*, u_q^*\). Finally, we get command voltage \(u_d^*, u_q^*\) by making sample addition and subtraction with \(u_d^*, u_q^*\) and their own voltage coupling compensation items \(\Delta u_d, \Delta u_q\) and voltage feed forward compensation items \(e_d, e_q\). Voltage components \(u_{d\alpha}^*, u_{d\beta}^*, u_{q\alpha}^*, u_{q\beta}^*\) in \(\alpha-\beta\) coordinate system are get by command voltage \(u_d^*, u_q^*\) through coordinate transform. By using pulse width modulation (PWM), drive signal generated can achieve the control for stator -side converter.
Control System for the Rotor-side Converter

In the variable speed constant frequency wind power generation system, the stator flux linkage oriented vector control strategy is often used for the rotor-side converter of the DFIG.

Make the following assumptions: $\Psi_1$ is directed to d-axis in synchronous coordinate system. The flux components in the d-q axis respectively are:

\[ \Psi_{ds} = \Psi_1, \Psi_{qs} = 0 \]  \hspace{1cm} (5)

$\Psi_1$ is amplitude of stator flux $\dot{\Psi}_1$. According to the motor practice, \[ \begin{align*}
\Psi_{ds} &= 0 \\
\Psi_{qs} &= \Psi
\end{align*} \]  \hspace{1cm} (6)

where $\Psi$ is the amplitude of the stator voltage vector. According to instantaneous power theory, active power and reactive power of the DFIG output are [4-5]:

\[ \begin{align*}
P_s &= \frac{3}{2}(u \, i_{ds} + u \, i_{qs}) \\
Q_s &= \frac{3}{2}(u \, i_{qs} - u \, i_{ds})
\end{align*} \]  \hspace{1cm} (7)

The formulas (5) and (6) are taken to the formula (7), and then we get

\[ \begin{align*}
P_s &= \frac{-3uL_mi_{qr}}{2L_s}, \\
Q_s &= \frac{3u}{2L_s} (\Psi_1 - L_m i_{dr})
\end{align*} \]  \hspace{1cm} (8)

From the foregoing, the active power and reactive power of the DFIG output are respectively proportional to rotor current $i_{qr}$ and $i_{dr}$. Therefore regulating $i_{qr}$ and $i_{dr}$ respectively can achieve the goal of adjusting the active power and reactive power independently. Thus we can get control strategy chart for the rotor-side converter. As shown in Figure 2.

In the Figure 2, $\theta$ is the angle between $a_1$-axis and $a_2$-axis. ($a_2$-$\beta_2$ is two-phase static coordinate system for rotor winding, d-q is synchronous rotating coordinate system). The angle between $a_2$-axis and d-axis is get by subtracting $\theta_r$ from $\theta$. According to the current wind speed, calculate speed value corresponding to the state that wind turbine works at optimal tip speed ratio. using it as reference value of speed, compare reference value with actual speed feedback value of wind turbine, then sent the result to the PI controller, in the end output current setting value $i_{qr}$ of rotor. Reactive current setting value $i_{dr}$ can be calculated according to the reactive power requirements of wind power system. Meanwhile, the reactive power of wind power system is adjusted by stator-side converter.
Operating Characteristic Analysis of Variable Speed Constant Frequency Doubly Fed Generator

Simulation Model of Doubly Fed Wind Power Generation System

DFIG’s main simulation parameters are as follows: rated active power is 850kW; rated voltage U is 0.69KV; rated frequency f is 50HZ; stator resistance Rs is 13Ω; stator leakage inductance Ls is 76mH; magnetizing inductance LM is 76mH; rotor resistance Rr is 20Ω; rotor leakage inductance Lr is 76mH; radius of fan R is 30.6m; optimal tip speed ratio \( \lambda_{opt} \) is 6 as wind speed is 9.5 m/s; the ratio of gearbox N is 150; the simulation time is 8s.

The Simulation Results and Corresponding Analysis

Reference value of stator reactive power is zero in the process of simulation. In 0-3 seconds of simulation, basic wind V is 9.5m/s. In 3-8 seconds, basic wind V is 9.2m/s. As we see in Figure 3, after a short transit time, in the first 3 seconds, the Per-unit value of generator speed (Wpu) firstly stabilizes at 0.889p.u (Reference value is 314rad/s). Our verification is as follows.

Optimal tip speed ratio:

\[
\lambda_{opt} = \frac{W_\text{r} * R}{V}
\]  

(9)

Wt is rotational speed of wind turbines. From the formula (9), we can get the formula:

\[
W_\text{r} = \frac{\lambda_{opt} * V}{R} = 6 * \frac{9.5}{30.6} = 1.863 \text{rad/s}
\]  

(10)

The ratio of gearbox:

\[
N = \frac{314 * W_{pu}}{W_\text{r}}
\]  

(11)

\[
W_{pu} = \frac{N * W_\text{r}}{314} = \frac{150 * 1.863}{314} = 0.889
\]  

(12)

The calculated results coincide with the Figure 3.

Figure 3. Actual speed.

Figure 4 and Figure 5 respectively show the dynamic adjusting process of stator active power, reactive power and DC bus voltage. From the Figure 3, the Per-unit value of generator speed (Wpu) is firstly stable at 0.889p.u after a short transit time. When the wind speed changes, control loop for rotor speed rapidly and steadily modulates generator rotational speed so that the speed eventually stabilizes at 0.86p.u, thus realizing track of maximum wind-energy. From Figure 4, stator active power varies with the change of the rotational speed and its dynamic response is quickly, while reactive power is not impacted. This suggests that the stator flux linkage oriented vector control strategy of DFIG realizes active power and reactive power decoupling control. From Figure 5, sudden change in the wind speed leads to the slight fluctuation of DC-bus voltage, nevertheless, control system for stator side has a significant effect on maintaining voltage, the DC-bus voltage soon returns to the initial operating point again. So, control system for DC-bus voltage is very efficient.
Conclusion

In the doubly fed wind power generation system, the rotor-side converter of the DFIG introduces the stator flux linkage oriented vector control strategy which could realize track of maximum wind-energy, independently control the active power, reactive power. The source-side converter of the DFIG effectively maintains the voltage of DC bus. It satisfies the controlling requirement of doubly fed wind power generation system. The simulation validates the feasibility and effectiveness of the control algorithm. This paper only simulates running state of system under basic wind, the next phase, whether the controller can meet the requirement of the doubly fed wind power generation system under the most unfavorable random wind.

References