Active and Reactive Power Control of Doubly Fed-Induction Generator Based on Variable Speed Wind Power Generation

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Abstract. This paper deals with the control of Doubly Fed Induction Generator (DFIG) in wind energy conversion system (WECS), to regulate the real and reactive power exchanged with the grid. The control architecture consists of two pulse width modulation converters allowing the generator to work in both sub-synchronous and super-synchronous mode. The real power is controlled by the energy maximization strategy, while the reactive power is controlled to operate the system under the unity power factor. The dynamic behavior of DFIG and its control are modelled based on the stator flux orientation (SFO) strategy. The control algorithm design based on anti-windup integration is developed in Matlab-Simulink.

Introduction

In the latest years, environmental pollution has turn out to be a primary challenge in humans’ daily lives, and a possible energy crisis has led researchers to develop new technology for generating clean and renewable energy. Today, there has been a strong penetration of wind energy into the power supply network. Consequently, Wind energy Conversion systems (WECS) using DFIGs have attracted increasing research interest as renewable generating units with a dominating market percentage of approximately 50% [1]. The DFIGs are widely used in WECS since they combine advantages of variable speed and the use of a fractional converter that leads to an enhanced efficiency and reduced costs [1][2]. Therefore, it powers converters rated is 30% of the overall generator output power under steady-state. Several control strategy have been reported in the literature for the control of wind turbine system based on DFIG [2]. In [3], vector control based on stator flux-oriented control of the DFIG has been developed where the maximum power point tracking (MPPT) algorithm was detailed. The author in [8], also used RQ control due to lack of performance of classical PI during transient response. The overall modeling of the DFIG system in a power systems is given in [4][5]. The MPPT control algorithm for power regulation is discussed in [4][8] where the aim is to regulate the power factor of the overall wind turbine. The MPPT with the use of the phase locked loop (PLL) was investigated in [6][7], where the authors investigated the control of the grid-connected DFIG system using voltage oriented control (VOC) technic [5]. However, there is still room for research on the power factor regulation direct speed control (MPPT). In this paper a control method for the machine inverter to regulate the active and reactive power exchanged between the machine and the grid is developed. The active power is controlled to be adapted to the wind speed of the wind turbine system and the reactive power control allows unitary power factor operation. The compromise between dynamic performances of generator and robustness of PI controller is not an easy task to handle due to integral anti windup problem, therefore anti-windup action is incorporated to the PI controller.

Wind Energy Conversion System

The common composition of the DFIG system is displayed figure 1, where the back-to-back converter is connected to the rotor side of the DFIG on one side and on the other side it is connected to the grid through a transformer. The stator of the DFIG is also connected to the grid through a
transformer so that the DFIG voltage matches the grid voltage level. The total active power generated
by a lossless DFIG system is given as

\[ P_g = P_s + P_r = (1 \pm s)P_s \]  \hspace{1cm} (1)

Where \( P_g \) is the total power generated by the DFIG; \( s \) is the slip; \( P_s \) is the stator active power and
\( P_r = \pm sP_s \) is the rotor active power.

Wind Turbine Model

The mechanical power captured by a wind turbine in the presence of wind speed is given by

\[ P_m = 0.5 \rho \pi R^2 V_{wind}^2 C_p(\lambda, \beta) \]  \hspace{1cm} (2)

\[ \lambda = \frac{\Omega_m R}{V_{wind}} \]  \hspace{1cm} (3)

Where \( C_p(\lambda, \beta) \) is the Power coefficient; \( \lambda \) is the tip speed ratio; \( \beta \) is the Pitch angle (deg); \( R \) is the
radius of turbine (m) \( \Omega_m \) is the mechanical shaft speed of the generator (rad /s); \( V_{wind} \) is the wind
speed (m/s); and \( \rho \) is the air density (1:225kg/m3). The expression of the power coefficient is given
by:

\[ C_p = f(\lambda, \beta) = C_1(\frac{C_2}{\lambda} - C_3\beta - C_4)e^{\frac{C_5}{\lambda} - C_6\lambda} \]  \hspace{1cm} (4)

With

\[ \frac{1}{\lambda_l} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \]  \hspace{1cm} (5)

DFIG Mathematical Model

The classical equations of the DFIG model in the d-q reference frame rotating at \( \omega_s \) speed are
written as follows:

Stator and rotor voltage components:

\[ \begin{align*}
    v_{ds} &= R_s i_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \\
    v_{qs} &= R_s i_{qs} + \frac{d\phi_{qs}}{dt} + \omega_s \phi_{ds}
\end{align*} \]  \hspace{1cm} (6)

\[ \begin{align*}
    v_{dr} &= R_r i_{dr} + \frac{d\phi_{dr}}{dt} - \omega_r \phi_{qr} \\
    v_{qr} &= R_i i_{qr} + \frac{d\phi_{qr}}{dt} + \omega_r \phi_{dr}
\end{align*} \]  \hspace{1cm} (7)

The electromagnetic torque generated by the DFIG is given by

\[ T_{em} = -\frac{3p L_m}{2} \frac{L_r}{L_r} (\phi_{ds} i_{qr} + \phi_{qs} i_{dr}) \]  \hspace{1cm} (8)

The mechanical relationship between the electromagnetic torque \( T_{em} \) and the mechanical torque
\( T_m \) is given by

\[ \frac{d\Omega_m}{dt} = T_{em} - T_m - f \Omega_m \]  \hspace{1cm} (9)
The stator active and reactive powers produced by the DFIG are given:
\[
\begin{align*}
P_s &= \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \\
Q_s &= \frac{3}{2}(v_{qs}i_{ds} - v_{ds}i_{qs})
\end{align*}
\] (10)

Control Strategy of Rotor Side and Grid Side Converter

In the variable speed wind turbine, the generated power of the DFIG is regulated to extract the maximum mechanical power from a given wind. In order to fulfil this aim, a power control strategy is developed based on field oriented control (FOC) Fig 4. At the end, we can achieve decoupled control of active-reactive powers. The RsC variables are expressed in the synchronous reference frame, with the d-axis oriented along the stator flux vector position Figure 4. using the stator flux in figure 4, the following equations are obtained:

\[
\begin{align*}
\phi_s &= L_s i_{ds} + L_m i_{dr} \\
0 &= L_s i_{qs} + L_m i_{qr}
\end{align*}
\] (11)

\[
\begin{align*}
i_{ds} &= \frac{\phi_s}{L_s} - \frac{L_m}{L_s} i_{dr} \\
i_{qs} &= -\frac{L_m}{L_s} i_{qr}
\end{align*}
\] (12)

Replacing the stator currents by their expressions given in the system (15), the equations below are expressed:

\[
\begin{align*}
P_s &= -\frac{3}{2} v_{qs} \frac{L_m}{L_s} i_{qr} \\
Q_s &= \frac{3}{2} v_{qs} \left( \frac{\phi_s}{L_s} - \frac{L_m}{L_s} i_{dr} \right) = -\frac{3}{2} \omega_s \phi_s \frac{L_m}{L_s} (i_{dr} - \frac{\phi_s}{L_m})
\end{align*}
\] (13)

The electromagnetic torque is as follows

\[T_{em} = -\frac{3p}{2} \frac{v_{qr}}{L_s} \phi_s i_{qr} = K_T i_{qr}\] (14)

We could express the rotor voltages according to the rotor currents, thus we obtain

\[
\begin{align*}
v_{dr} &= (R_r + s\omega L_r) i_{dr} - \omega_r \sigma L_r i_{qr} + \frac{L_m}{L_s} \frac{d}{dt} |\phi_s| \\
v_{qr} &= (R_r + s\omega L_r) i_{qr} + \omega_r \sigma L_r i_{dr} + \omega_r \frac{L_m}{L_s} |\phi_s|
\end{align*}
\] (15)

Rotor Side Controller

Control of this converter shall monitor the operating point for maximum wind energy capture, taking into account wind conditions, and turbine speed. In addition, it must provide control of the extracted and transmitted active power (which is can be torque control, or speed control) as well as control of the magnetic state of the generator, (which can be done to controlling the reactive power). The generic control scheme of the rotor side converter is illustrated in Figure 5.

Grid Side Controller

Since the network imposes the voltage, the grid side converter will be controlled in current and must

\[
\begin{align*}
\psi_s &= L_s i_{ds} + L_m i_{dr} \\
0 &= L_s i_{qs} + L_m i_{qr}
\end{align*}
\] (11)

\[
\begin{align*}
i_{ds} &= \frac{\psi_s}{L_s} - \frac{L_m}{L_s} i_{dr} \\
i_{qs} &= -\frac{L_m}{L_s} i_{qr}
\end{align*}
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Replacing the stator currents by their expressions given in the system (15), the equations below are expressed:

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\begin{align*}
P_s &= -\frac{3}{2} v_{qs} \frac{L_m}{L_s} i_{qr} \\
Q_s &= \frac{3}{2} v_{qs} \left( \frac{\psi_s}{L_s} - \frac{L_m}{L_s} i_{dr} \right) = -\frac{3}{2} \omega_s \psi_s \frac{L_m}{L_s} (i_{dr} - \frac{\psi_s}{L_m})
\end{align*}
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We could express the rotor voltages according to the rotor currents, thus we obtain

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\begin{align*}
v_{dr} &= (R_r + s\omega L_r) i_{dr} - \omega_r \sigma L_r i_{qr} + \frac{L_m}{L_s} \frac{d}{dt} |\psi_s| \\
v_{qr} &= (R_r + s\omega L_r) i_{qr} + \omega_r \sigma L_r i_{dr} + \omega_r \frac{L_m}{L_s} |\psi_s|
\end{align*}
\] (15)

Rotor Side Controller

Control of this converter shall monitor the operating point for maximum wind energy capture, taking into account wind conditions, and turbine speed. In addition, it must provide control of the extracted and transmitted active power (which is can be torque control, or speed control) as well as control of the magnetic state of the generator, (which can be done to controlling the reactive power). The generic control scheme of the rotor side converter is illustrated in Figure 5.

Grid Side Controller

Since the network imposes the voltage, the grid side converter will be controlled in current and must
ensure the connection and disconnection to the grid. It must have the ability to "monitor the network" and disconnect when necessary or reconnect when all conditions are met. The condition of connection are those of the synchronization, which is an equality in amplitude, phase and frequency of the voltages coming from the converter with the grid. As shown in Figure 6, the DC-link voltage is regulated by the grid converter control system, which is often a dual-loop control structure. The outer DC-link voltage control loop and the inner d-axis current tracking control loop, are used to realize the stable control of the dc-link voltage [5]. While the q-axis current loop, controls the reactive power of grid side converter.

![Figure 5. Control scheme of the rotor side converter.](image)

![Figure 6. Control scheme of the grid side converter.](image)

**Simulation Results**

A 2MW Doubly Fed Induction Generator (DFIG) wind turbine is developed using simulink. The rotor side and grid side controller have been implemented based SFO technic. As the wind speed varies from time to time due to uncertain wind condition we are considering a ramp change from 5 to 8 and then 8 to 12 m/s which can be seen in Figure 7. The system performance is tested for both sub-synchronous and hyper-synchronous mode. Due to the integral anti-windup added the transient response of the DFIG is improved in term of duration also it has strong rejection of perturbation. The DFIG starts operating under sub-synchronous at generator speed of $\Omega_m=147$ rad/s, there is a short transient period before the stator power settle to the steady-state values corresponding to the MPPT, as shown in figure 11. These transient patterns of the generated stator active and reactive powers (11) lead to a surge of the stator power. Since a unity power factor is expected in this system the reactive power should stay to zero and from the figure 11 it is shown that the reactive power is well regulated to zero, no matter what the wind speed fluctuation is. Figure 12 shows the grid-side converter performance which keep the DC-link voltage constant and the voltage ripple was found to be less than 5%.

![Figure 7. Control scheme of the rotor side converter.](image)

![Figure 8. Generator rotor speed in rad/s.](image)

![Figure 9. Three-phase rotor current.](image)

![Figure 10. Three-phase stator current.](image)
Conclusion

In this paper, a control algorithm based on the classical stator orientation was developed where the q-axis of the synchronous reference frame is aligned along the stator voltage angle. It was shown that the proposed control algorithm with wind up integration on the PI controller gives satisfactory performance. More importantly, the control algorithm not only allows the users to regulate the stator power factor, but also it guarantees a good energy maximization.

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