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Active and Reactive Power Control of DFIG Based Grid Connected Wind Energy System

Hnin Yu Wai[1], Theingi Htun[2], Myo Win Kyaw[2]

[1]Department of Electrical Power Engineering, West Yangon Technological University, Yangon, Myanmar
[2]Department of Electrical Power Engineering, Technological University Mandalay, Mandalay, Myanmar

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ABSTRACT
Wind power is the most reliable and developed renewable energy source. This paper gives a study on power flow control of a grid-connected Doubly-Fed Induction Generator (DFIG) wind turbine. Doubly-Fed Induction Generator (DFIG) has widely used for large wind farms. A back-to-back converter is incorporated between the stator and the rotor windings of a DFIG, in order to obtain variable speed operation. The controller design methodology is presented and active and reactive power is verified. The main objective of the paper is to control the flow of the active and reactive powers produced by the DFIG based wind energy conversion system. In order to decouple of active and reactive powers generated, the vector control method is applied. A vector control strategy with stator flux orientation is applied to both the grid-side converter and the rotor-side converter for the independent control of active and reactive powers produced by the DFIG based wind energy conversion system. Simulation results on a 2MW DFIG system are provided to demonstrate the proposed control strategy and the variations of active and reactive power, rotor speed, and converter dc-link voltage.

KEYWORDS: *Doubly-Fed Induction Generator, back-to-back converter, Active and Reactive Power Control, Vector control*

I. INTRODUCTION
Wind power is one of the most important and promising sources of renewable energy all over the world. It also is a permanent source without exploring and transporting.

To solve the problem of energy's shortage and improve environmental quality, wind power is used to produce electricity by a lot of countries [3]. Wind turbines can either operate at fixed or variable speed. For a fixed speed wind turbine the generator is directly connected to the electrical grid. For a variable speed wind turbine the generator is controlled by a power electronic converter. The main advantages of using variable speed operation of the wind turbine are the possibility to reduce stresses on the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power. Unbalance in wind energy is highly impacting the energy conversion and this problem can be overcome by using a Doubly Fed Induction Generator (DFIG) [2].

Doubly fed wound rotor induction machine with vector control is very attractive to the high-performance variable speed drive and generating applications [3]. The wind is highly in nature, a variable speed DFIG based Wind Energy Conversion System (WECS) offer many advantages compared to the fixed speed squirrel cage induction generators. Due to variable speed operation, the total energy output is much more in case of DFIG based WECS. Nowadays, most large wind turbines are based on variable speed operation with pith control using a DFIG. The major advantages of the DFIG are that the power electronic equipment used that handles a fraction of (20- 30%) total system power. The back to back converter consists of two converters i.e. Grid-Side Converter (GSC) and Rotor-Side Converter (RSC) connected back to back through a dc-link capacitor for energy storage purpose [4].

In this paper, a control strategy is presented for DFIG. The vector control of DFIG based wind energy conversion system for efficient and good performance is discussed. A vector control strategy can be used for decoupled control of active and reactive power drawn from the supply. In this paper, we study the control strategy for the DFIG and the mathematical models. The complete MATLAB/SIMULINK model of a 2MW DFIG generation system is built. From the analysis of the simulation result, we can realize that the DFIG active power output will keep varying with the change of the wind speed.

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II. DFIG FOR WIND ENERGY CONVERSION

Wind Energy Conversion System (WECS) converts wind energy into useful mechanical energy in a wind-turbine that is used as the prime-mover to power an electrical (Doubly Fed Induction Generator [DFIG]) generator. The WECS basically consists of two major components; (i) turbine and associated control including the gearbox, and (ii) electrical (DFIG including the rotor converter system and associated control).

A simplified block diagram of a wind energy conversion system (WECS) using DFIG is illustrated in figure 1. It consists of a wind turbine, a gearbox, doubly-fed induction generator, and a rotor side converter and a grid-side converter. The DFIG stator winding is directly connected to the grid whereas its rotor windings are connected by a back-to-back three-level voltage source converters. By controlling the rotor and grid side converters, the DFIG characteristics can be adjusted so as to achieve the maximum of effective power conversion or capturing power. These converters are usually controlled by utilizing vector control techniques, capability for a wind turbine and to control its power flow from DFIG to grid with less fluctuation [5].

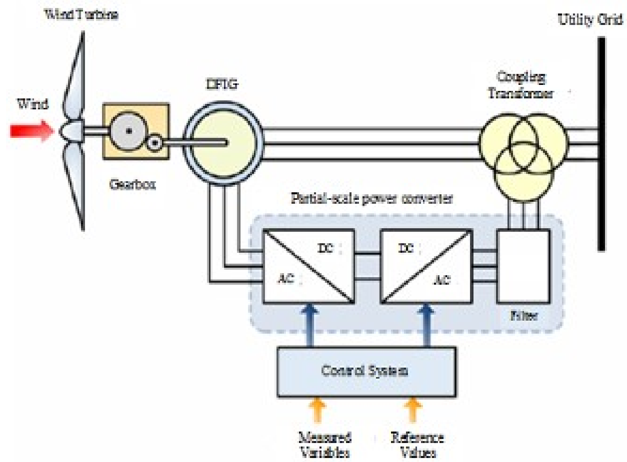

Figure1. Doubly-Fed Induction Generator Driven by a Wind Turbine

DFIG Modeling

The stator and rotor a-, b-, c- phase voltage equations and flux equations can be transformed to the d-q axis. Based on the d – q equivalent circuit model of the induction machine shown in Figure 2 [6][7],

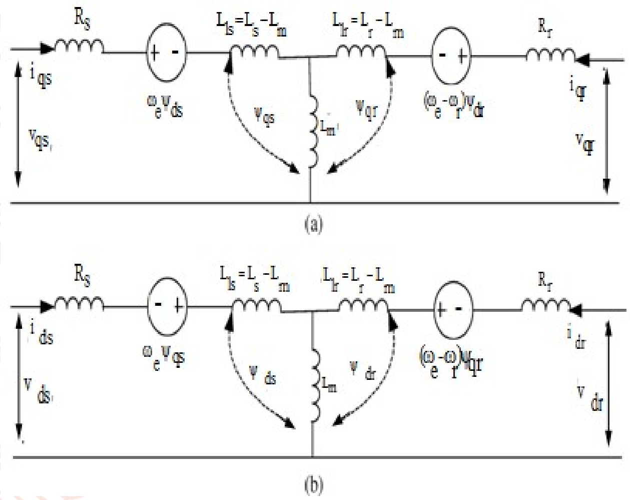

Figure 2 Dynamic Equivalent Circuit of DFIG (a) q-axis Equivalent Circuit (b) d-axis Equivalent Circuit

The classical governing equations of the DFIG in a d-q synchronously rotating reference frame can be written as following from above figure 2.

$$
\begin{aligned}
v_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds} \\
v_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \psi_{qs} \\
v_{qr} &= R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - \omega_r)\psi_{dr} \\
v_{dr} &= R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_e - \omega_r)\psi_{qr} \qquad (1)
\end{aligned}
$$

The flux equations are

$$
\begin{aligned}
\psi_{qs} &= L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr} \\
\psi_{ds} &= L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \\
\psi_{qr} &= L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) = L_r i_{qr} + L_m i_{qs}
\end{aligned}
$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) = L_r i_{dr} + L_m i_{ds} \quad (2)$$

Where,

$\omega_s = \omega_e - \omega_r$,

ω_e = the rotational speed of the synchronous reference frame,

ω_s = the slip frequency and

ω_r = the electrical speed measured in [rad/s].

R_s, R_r = equivalent resistances of stator and rotor windings

$L_{,r}$, L_s L_m = self and mutual inductance of stator and rotor windings

III. ACTIVE AND REACTIVE POWER CONTROL FOR DFIG

A. Rotor-Side Converter (RSC)

The main task of the rotor-side converter is to control the machine i.e., active and reactive powers of the DFIG. The active and reactive powers which are delivered from the DFIG to the grid are controlled by means of controlling the rotor currents of the DFIG [6]. The diagram of the vector control of the rotor-side converter can be obtained from the below analysis is shown in figure 3.

In the stator-flux oriented reference frame, the d-axis is aligned with the stator flux linkage vector the flux equation is ψ_s the flux equation is [1]

$$\psi_{ds} = \psi_s = L_m i_{ms}, \quad \psi_{qs} = 0 \quad (3)$$

To keep the stator flux ψ_s constant, the voltage equations are

$$v_{ds} \approx \frac{d}{dt}\psi_s = 0$$

$$v_{qs} \approx \omega_e \psi_s = V_s \quad (4)$$

Where,

V_s = the space vector amplitude of stator voltages

The active and reactive powers of the stator can be derived as

$$P_s = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs})$$

$$Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (5)$$

The equivalent stator magnetizing current can be considered a constant, i.e.

$$i_{ms} = \frac{\psi_s}{L_s} \approx \frac{V_s}{L_m \omega_1} \quad (6)$$

By substituting equation (5) into equation (2),

$$i_{ds} = \frac{L_m}{L_s}(i_{ms} - i_{dr})$$

$$i_{qs} = -\frac{L_m}{L_s} i_{qr} \quad (7)$$

By substituting equation (7) into equation (1), the rotor voltage can be expressed

$$v_{dr} = R_r i_{dr} + \sigma L_r \frac{i_{dr}}{dt} - \omega_s \sigma L_r i_{qr} \quad (8)$$

$$v_{qr} = R_r i_{qr} + \sigma L_r \frac{i_{qr}}{dt} - \omega_s \left(\frac{\sigma L_r i_{dr} + L_m^2 i_{ms}}{L_s}\right) \quad (9)$$

Where, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$

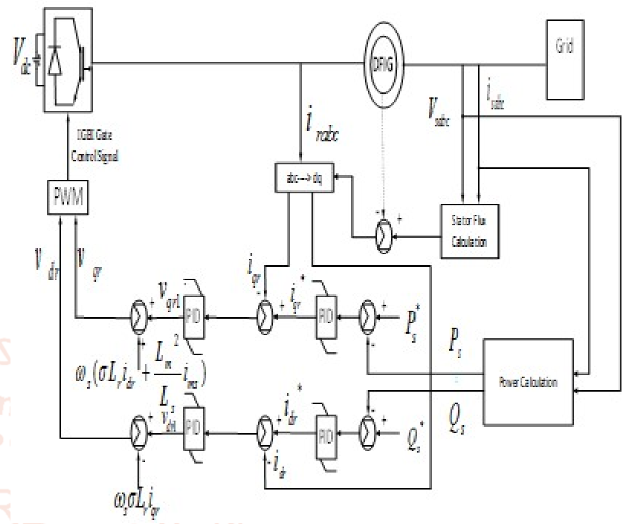

Figure3. The vector control diagram of the rotor-side converter

B. Grid-Side Converter (GSC)

The grid-side converter balance and delivers the power between the three-phase grid and the DC link capacitor. The DC-link power should be equal to the grid-side converter's output power. The grid-side converter is used to regulate the voltage of the DC bus capacitor. The diagram of the vector control of the grid-side converter can be obtained from the below analysis is shown in figure 4. Under the synchronously rotating frame, the d-axis aligns with the grid voltage [1]. The grid voltage components are

V_d = Constant

V_q = 0 (10)

The active power and reactive powers equation is

$$P_r = \frac{3}{2}(v_d i_d + v_q i_q) = \frac{3}{2} v_d i_d \quad (11)$$

$$Q_r = \frac{3}{2}(v_d i_q - v_q i_d) = \frac{3}{2} v_d i_q \quad (12)$$

According to the above equations, we assume two compensation term u_{d1} and u_{q1},

$$u_{d1} = R i_d + L\frac{di_d}{dt}$$

$$u_{q1} = R i_q + L\frac{di_q}{dt} \quad (13)$$

Applying the above compensation terms ud and uq, we can obtain the reference voltage u_{d^*} and u_{q^*}

$$u_d^* = -u_{d1} + (\omega_e L i_q + v_d)$$

$$u_q^* = -u_{q1} - (\omega_e L i_d) \tag{14}$$

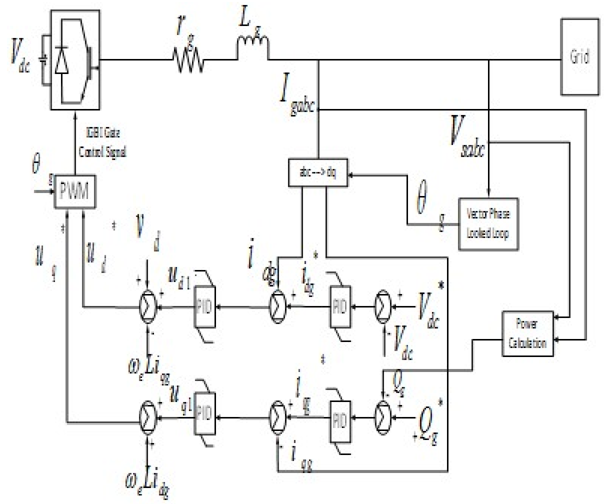

Figure4. The vector control diagram of the grid-side converter

IV. SYSTEM PARAMETERS

TABLE I. PARAMETERS OF THE SIMULATED DFIG

Parameters	Values
Rated power, P_n	2 MW
Rated voltage, V	400 V
Frequency, f	50 Hz
Number of pairs of poles, p	3
Stator resistance, R_s	0.023 pu
Stator leakage inductance, L_{ls}	0.18 pu
Rotor resistance, R_r	0.016 pu
Rotor leakage inductance, L_{lr}	0.16 pu
Rated wind speed	12 m/s
Filter capacitor	$120*10^3$ var
Magnetizing inductance, L_m	2.9 pu
Speed	1000 rpm
Wind speed variation	7-10-12m/s

V. SIMULINK MODELS OF THE SYSTEM

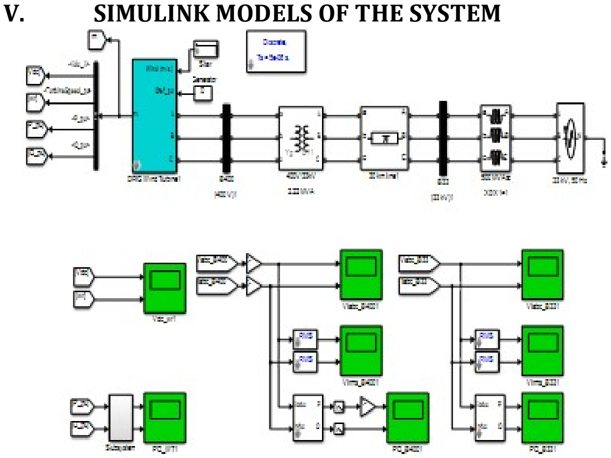

Figure5. Simulink Model of DFIG Based Grid Connected Wind Energy System

Figure 5 shown Simulink Model of DFIG Based Grid Connected Wind Energy System by using the MATLAB/SIMULINK.

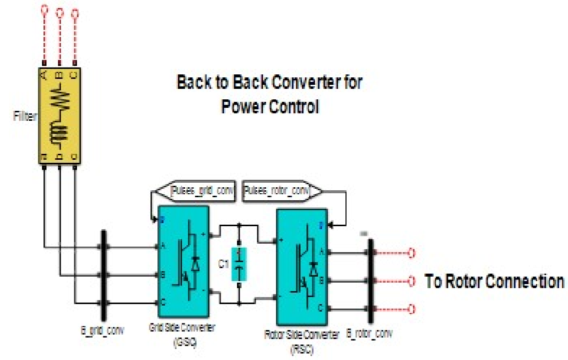

Figure6. Back-to-Back Converter

Figure 6 showing the model of a back-to-back converter of DFIG. Vector control is one of the most commonly used methods applied to control the flow of active and reactive power between the stator and the grid. The vector control technique can be applied to both RSC and GSC. Typically, the RSC controller aims to control the stator active and reactive power flow by controlling the rotor current components on d-q axis (i_{dr}, i_{qr}) while the objective of the GSC controller is to maintain the DC-link voltage constant regardless the magnitude and direction of the rotor power.

VI. SIMULATION RESULTS

Simulation of the proposed control strategy for the DFIG-based generation system using Matlab Software. The DFIG based wind energy conversion system was simulated, for the active and reactive power control on the Matlab/Simulink platform. In this section, the simulation results for the system operation are shown. Results are presented to demonstrate its behavior at variable wind speed.

The waveforms for voltage, current, active and reactive powers, rotor speed and dc-link voltage are presented for different wind speed.

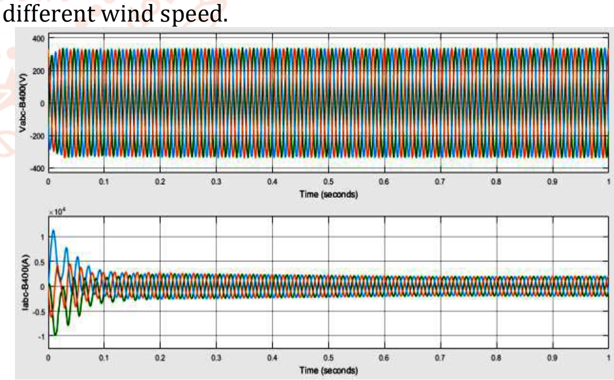

Figure7. Voltage and Current at Bus400

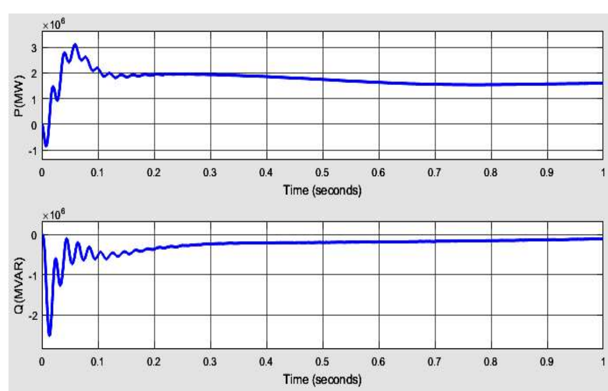

Figure8. Active and Reactive Power at Bus400

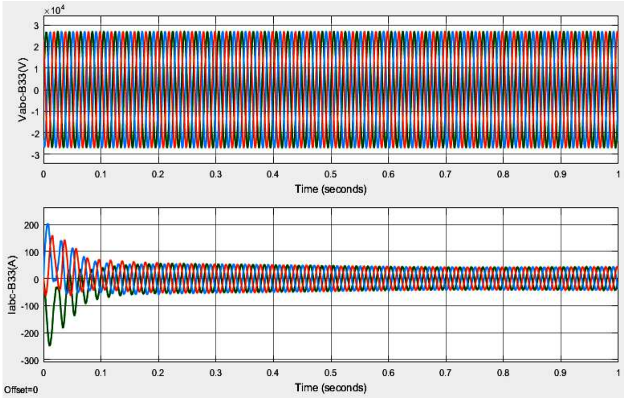

Figure9. Voltage and Current at Bus33

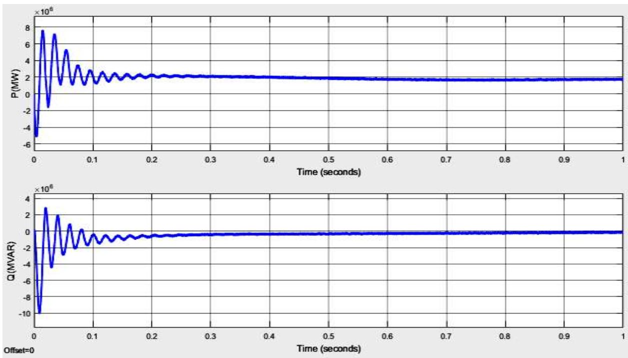

Figure10. Active and Reactive Power at Bus33

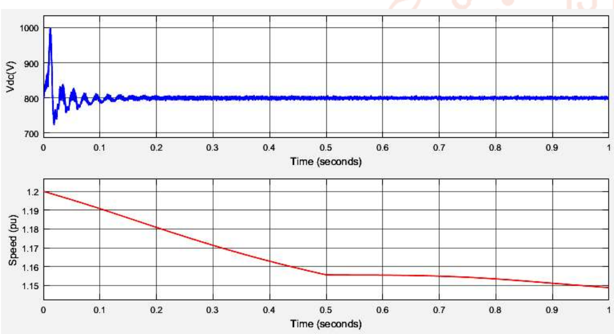

Figure11. DC Link Voltage and Rotor Speed

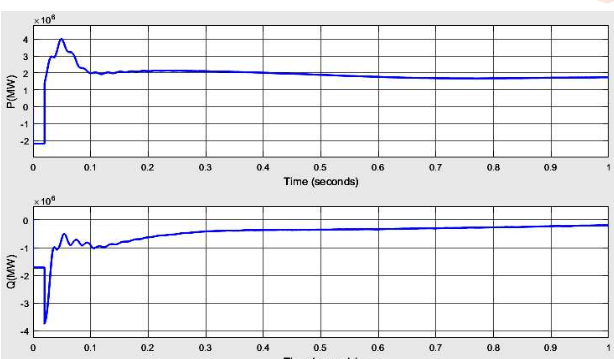

Figure12. Active and Reactive Power For Wind Turbine

The voltage and current measurement at B400 (400V bus bar) for grid-connected wind power system shown in figure 9 maintain at with wind speed variation. The active and reactive power output at B400 of the DFIG is shown in figure 10. The wind speed arrives at rated speed 12m/s at t=0.5s, at which the active power output is 1.7MW. The zero-reactive-control in the back-to-back converter keeps the reactive power output near zero regardless of the wind speed fluctuation. The voltage and current measurement at B33 (33kV bus bar) for grid-connected wind power system shown in figure 11 maintained at the rated value at t=5s. The active and reactive power output at B400 of the DFIG is shown in figure 12. The active power output is stable with a magnitude of 2MW at t=0.5s. Figure 13 shown the DC link voltage and speed at the DC link voltage varies with the wind speed fluctuation. The active and reactive power for the turbine shown in figure 14 in which the variation of the output power with the wind speed fluctuation.

VII. CONCLUSION

This research represented an active and reactive power flow control analysis of converters in wind turbines based grid-connected wind energy system. Power converters are usually controlled a utilizing vector control technique which allows the control of both active and reactive power flow to the grid. As a result the active and reactive powers are controlled by using the vector control principle which yields better results. Due to the advances in power electronics, it is advantaged to use the doubly-fed induction generator system with fixed speed connected to the electrical grid through a back-to-back converter, that improving the efficiency of the power conversion. A detail simulation model of a DFIG-based wind turbine system is developed for the 2MW wind turbine connected to the power grid. Modeling and simulation results of a DFIG based grid-connected wind energy system by using vector control concept are presented in this paper. The system was developed in MATLAB/SIMULINK software.

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