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Simulation of Stator Oriented Vector Controlled Doubly-Fed Induction Generator for Harnessing Wind Energy Effectively

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Abstract—- **Wind energy plays an increasingly important role in the world because it is friendly to the environment and limitless. During the last decades, the concept of a variable-speed wind turbine (WT) has been receiving increasing attention due to the fact that it is more controllable, efficient, and has good power quality. In order to most effectively utilize the wind energy and improve the efficiency of wind generation system an optimum control strategy of doubly-fed induction generators (DFIG) is proposed. This paper presents a stator flux oriented vector control strategy for a 2MW/690V doubly fed induction generator (DFIG)-based wind energy generation system to control the rotor side converter to control the active and reactive power and grid side converter control to maintain dc link voltage constant.**

Keywords— Doubly fed induction generator (DFIG), Vector control, active and reactive power control, Wind power.

I. Introduction

Due to the increasing concern about CO2 emissions, renewable energy systems and especially wind energy generation have attracted great interests in recent years. Large wind farms have been installed or planned across the world and the power ratings of the wind turbines and wind farm are increasing. Many studies [1-3] are oriented toward this type of energy production in the aim to make it more efficient. Wind turbine must be adjusted accordingly to wind speed, hence the variable speed generator based wind turbines are mostly used in wind power industry to capture more energy from wind [4].

There are many type of variable speed wind generator like permanent magnet synchronous generator (PMSG), squirrel cage induction generator (SCIG) and doubly fed induction generator (DFIG). Out of these control and performance of DFIG based wind energy conversion system is analyzed in this paper.

The DFIG based wind turbine offers several advantages over to other wind turbines including variable speed operation

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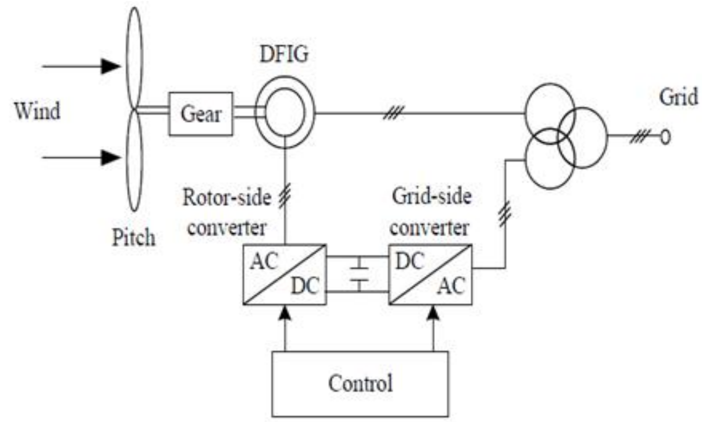


Fig.1 DFIG based wind energy conversion system

(± 30% around the synchronous speed) and four quadrants active and reactive power capabilities. Such a system also results in lower converter costs (typically 30% of total system power) and lower power losses compared to a system based on a fully fed synchronous generator with full rated converter. It is also capable of generating active power at constant frequency and the generated active and reactive power is controlled independently for better grid integration.

Figure 1 shows the DFIG system. The stator of the DFIG is directly connected to the grid and rotor is connected to grid through four quadrant power converters comprises of two back to back PWM-VSC (rotor side converter and grid side converter). The rotor side converter (RSC) controlling active and reactive power and the grid side converter (GSC) maintain DC-link constant and controlling reactive power to control power factor. The converters are controlled using vector control technique. The stator voltage oriented vector control strategy is used to de-coupled control of active and reactive power. This paper explains the model of DFIG in the “d-q reference frame” and stator flux oriented vector control strategy of DFIG.

II. Modelling of DFIG

The induction machine d-q or dynamic equivalent circuit is shown in Figure 2. Based on the equivalent circuit, the main equations of doubly fed induction generator stator and rotor voltage can be written as follows in matrix form:

$$V_{sabc} = r_s i_{abcs} + p\lambda_{abcs} \quad (1)$$

$$V_{rabc} = r_r i_{abcr} + p\lambda_{abcr} \quad (2)$$

Applying synchronously rotating reference frame transformation [9] to equation (1) and (2), the voltage equations become

$$V_{ds} = r_s i_{ds} - \omega_s \lambda_{qs} + p\lambda_{ds} \quad (3)$$

$$V_{qs} = r_s i_{qs} + \omega_s \lambda_{ds} + p\lambda_{qs} \quad (4)$$

$$V_{dr} = r_r i_{dr} - (\omega_s - \omega_r)\lambda_{qr} + p\lambda_{dr} \quad (5)$$

$$V_{qr} = r_r i_{qr} + (\omega_s - \omega_r)\lambda_{dr} + p\lambda_{qr} \quad (6)$$

Where $\omega_s$is the rotational speed of the synchronous reference frame, $\omega_r$is the rotor speed, and the flux linkages are given by

$$\lambda_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m I_{dr} \quad (7)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m I_{qr} \quad (8)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m (i_{dr} + i_{ds}) = L_r i_{dr} + L_m I_{ds} \quad (9)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m (i_{qr} + i_{qs}) = L_r i_{qr} + L_m I_{qs} \quad (10)$$

Where $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$; L_{ls}, L_{lr} and L_m are stator and rotor leakage inductance and mutual inductances, respectively.

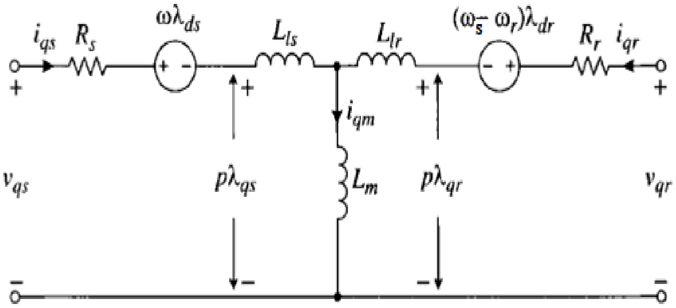
Neglecting the power losses associated with the stator resistance, the active and reactive stator powers are:

$$P_s = \frac{3}{2}(v_{qs} i_{qs} + v_{ds} i_{ds}) \quad (11)$$

$$Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (12)$$

III. Design of Control system

The objective of the RSC is to govern both the stator-side active and reactive powers independently, while the objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The GSC control scheme can also be designed to regulate the reactive power.



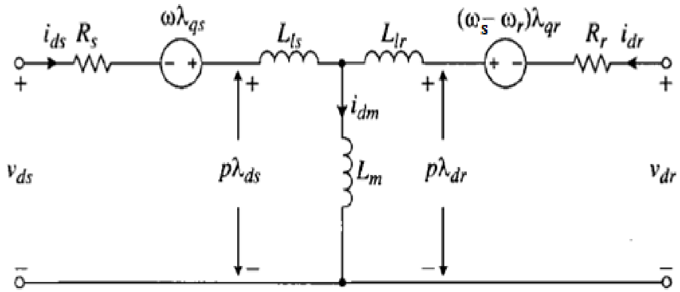


Fig.2 Equivalent circuit of DFIG in q-d axis

A. *Design of RSC controller*

The RSC control scheme consists of two cascaded control loops. The inner current control loops regulate independently the *d*-axis and *q*-axis rotor current components i_{dr} and i_{qr}, according to synchronously rotating reference frame. The stator-flux oriented reference frame [10] is the most commonly used one. The outer control loops regulate both the stator active power (or the generator rotor speed) and reactive power independently.

Aligning the q-axis of the reference frame along the stator-voltage position v_{qs}=v_s and v_{ds} is zero, since the amplitude of the supply voltage v_{qs} is constant. The active and reactive power will be proportional to i_{qs} and i_{ds} respectively.

Hence, the active and reactive power from equation (11) and (12) are

$$P_s = \frac{3}{2} v_{qs} i_{qs} \quad (13)$$

$$Q_s = \frac{3}{2} v_{qs} i_{ds} \quad (14)$$

The active and reactive power will be proportional to i_{qs} and i_{ds} respectively.

Since the stator is connected to the grid, and the influence of the stator resistance is small, the stator magnetizing current i_{ms} can be considered constant. In the stator-flux oriented reference frame, the *d*-axis is aligned with the stator flux linkage vector λ_s, namely, $\lambda_{ds} = \lambda_s$ and λ_{qs}= 0. This gives the following relationships

$$i_{qs} = -\frac{L_m}{L_s} i_{qr} \quad (15)$$

$$i_{ds} = -\frac{L_m}{L_s}(i_{ms} - i_{dr}) \quad (16)$$

Where, $$i_{ms} = \frac{v_{qs} - r_s i_{qs}}{\omega_s L_m} \quad (17)$$

$$v_{dr} = r_r i_{dr} + \sigma L_r p i_{dr} - s\omega_s \sigma L_r i_{qr} \quad (18)$$

$$v_{qr} = r_r i_{qr} + \sigma L_r p i_{qr} + s\omega_s(\sigma L_r i_{dr} + L_m{}^2 \frac{i_{ms}}{L_s}) \quad (19)$$

$$\sigma = 1 - \frac{L_m{}^2}{L_s L_r} \quad (20)$$

So, The active and reactive power are

$$P_s = -\frac{3}{2}\omega_s L_m{}^2 i_{ms} i_{qr} / L_s \quad (21)$$

$$Q_s = \frac{3}{2}\omega_s L_m{}^2 i_{ms}(i_{ms} - i_{qr}) / L_s \quad (22)$$

Equations (21) and (22) indicate that active power is proportional to the i_{qr} and can be regulated using v_{qr} (equation 19), and reactive power is proportional to the i_{dr} and can be controlled using v_{dr} (equation 20). Consequently, the reference values of i_{qr} and i_{dr} can be determined from the outer power control loops.

The stator flux angle is calculated from

$$\lambda_{\alpha s} = \int (v_{\alpha s} - r_s i_{\alpha s})$$

$$\lambda_{\beta s} = \int (v_{\beta s} - r_s i_{\beta s})$$

$$\theta_s = \tan^{-1} \frac{\lambda_{\beta s}}{\lambda_{\alpha s}}$$

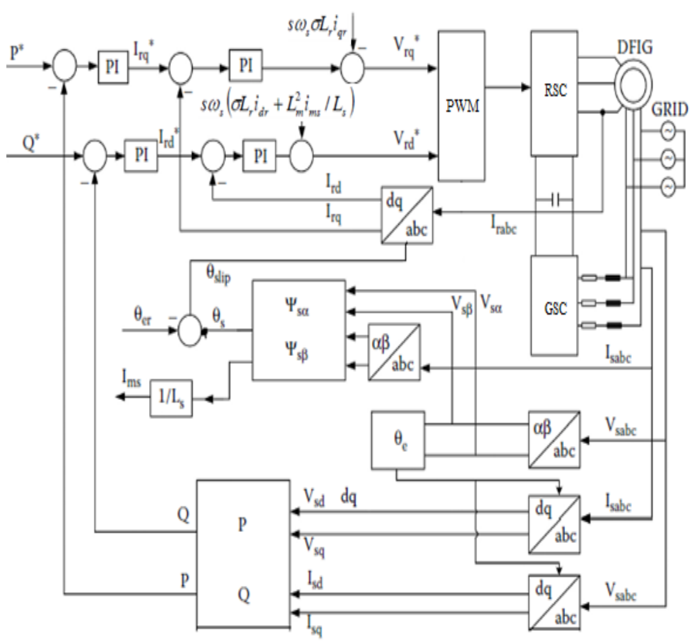


Fig. 3 schematic block diagram of RSC control.

Figure 3 shows the schematic block diagram of rotor side converter control. There are two loops, outer loop is for controlling the active and reactive power and other is inner current control loop for controlling the rotor excitation current i_{dr} and i_{qr}. The value of reference reactive power is set to be zero. The reference active and reactive power are compared with actual active and reactive power and the error is processed through PI controller, it will generate reference rotor currents. The i_{qr} and i_{dr} error are processed through PI controller to give v_{qr} and v_{dr}, respectively. To ensure good tracking of these currents, compensation terms are added to v_{qr} and v_{dr} to obtain the reference voltages $v_{qr}{}^{*}$ and $v_{dr}{}^{*}$ according to

$$v_{qr}{}^{*} = v_{qr} + s\omega_s(\sigma L_r i_{dr} + L_m{}^2 i_{ms}/L_s) \quad (23)$$

$$v_{dr}{}^{*} = v_{dr} - s\omega_s \sigma L_r i_{qr} \quad (24)$$

B. ***Design of GSC control.***

The objective of the grid-side converter is to keep the DC-link voltage constant regardless of the magnitude and direction of the rotor power. A vector-control approach is used, with a reference frame oriented along the stator (or supply) voltage vector position. The PWM converter is current regulated, with the direct axis current used to regulate the DC-link voltage and the quadrature axis current component used to regulate the reactive power. A standard regular asymmetric sampling PWM scheme [12] is used. Figure 4 shows the schematic of the supply-side converter. The voltage balance across the inductors is

The voltage balance across the inductors is

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = R \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + L \frac{d}{dt} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \end{pmatrix} \quad (25)$$

where L and R are the line inductance and resistance, respectively. Using park's transformation the above equation can be written into d-q reference frame (rotating at ω_e) as follows:

$$v_d = R i_d + L \frac{di_d}{dt} - \omega_e L i_q + v_{d1} \quad (26)$$

$$v_q = R i_q + L \frac{di_q}{dt} + \omega_e L i_d + v_{q1} \quad (27)$$

The angular position of the supply voltage is calculated as

$$\theta_e = \int \omega_e \, dt = \tan^{-1} \frac{v_\beta}{v_\alpha}$$

Where, v_α and v_β are α, β stator-voltage component.

Neglecting the harmonics due to switching in the converter and the machine losses and converter losses, the active power balance equation is as follows:

$$v_{dc} i_{dc} = \frac{3}{2} v_d i_d = P_r; \qquad v_q = 0 \quad (28)$$

From the equation 28, the DC link voltage may be controlled through i_d control. The reactive power flow from the source is given by

$$Q_r = \frac{3}{2} v_d i_q; \qquad v_q = 0 \quad (29)$$

Consequently, the reactive power from the power source to (from) the source-side converter may be controlled through i_q. In general, the reactive power from power source through the source-side converter is set to zero (i_q = 0).

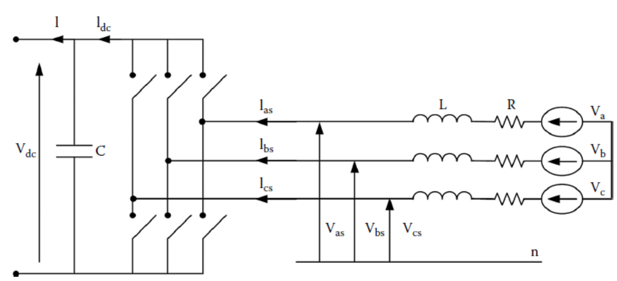


Fig. 4 schematic of supply side converter.

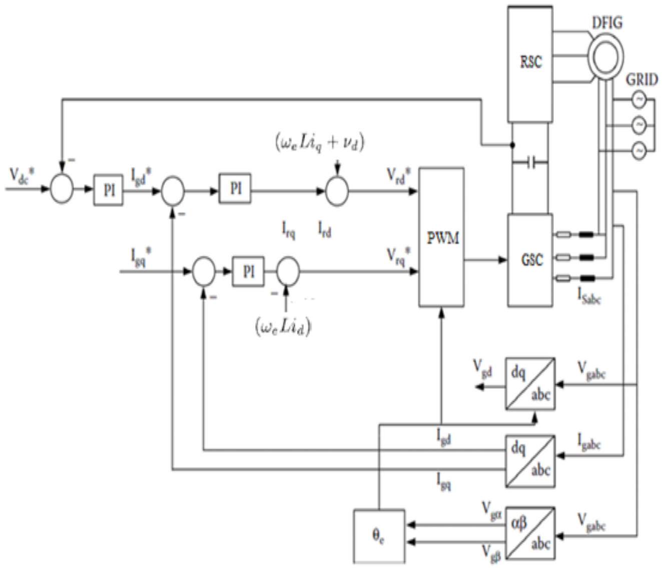


Fig 5. Schematic block diagram of GSC control.

The above vector control principles are illustrated in the generic scheme shown in Figure 5. The DC link voltage is, in general, kept constant to take advantage of full voltage for capacitor energy storage in the DC link.

Where,

$$v_{d1}^{*} = -v_d{}' + (\omega_e L i_q + v_d) \quad (30)$$

$$v_{q1}^{*} = -v_q{}' - (\omega_e L i_d) \quad (31)$$

v_{d1}^{*} and v_{q1}^{*} are the reference values for the supply-side converter, and the terms in brackets constitute voltage-compensation terms.

IV. Simulation Results

The 2MW/690V DFIG model is analyzed using PSIM under steady-state condition, the machine parameters are given in appendix below. Figure10a-10f shows the output of DFIG model in super-synchronous mode. The negative sign of active power means generated active power. It is cleared from fig. that the machine speed in super-synchronous mode is higher than the synchronous speed.

The vector control system based on the stator flux oriented reference frame is simulated in PSIM, and a reference 2MW stator active power was applied to the outer control loop, and the reactive power demand is set to zero.

The stator active power was able to track the applied reference value which confirms the validity of the control system. The Grid side converter maintain 1000 V DC-link voltage as shown in figure 6f and unity power factor as shown in figure 6e.

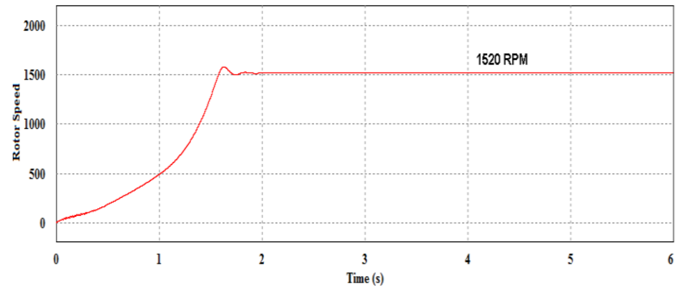


Fig.6a Machine speed (RPM)
[X-axis: 1 div = 1 sec, Y-axis: 1 div = 500 rpm]

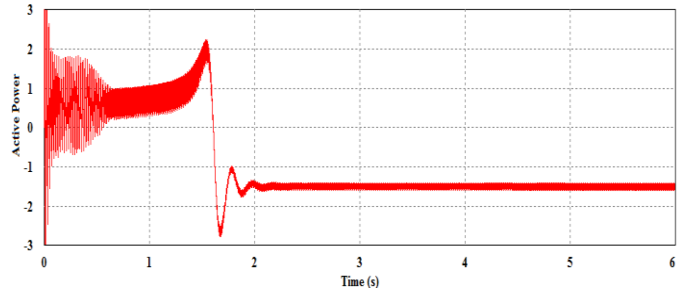


Fig.6b Stator Active power (pu)
[X-axis: 1 div = 1 sec, Y-axis: 1 div = 1 pu]

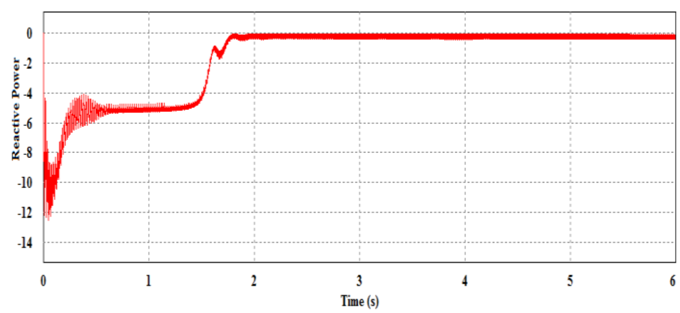


Fig.6c Stator Reactive power (pu)
[X-axis: 1 div = 1 sec, Y-axis: 1 div = 1 pu]

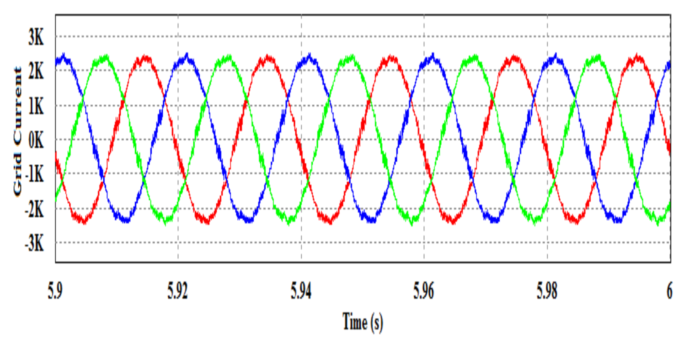


Fig.6d Grid Current (Amp)
[X-axis: 1 div = 20 msec, Y-axis: 1 div = 1k amp]

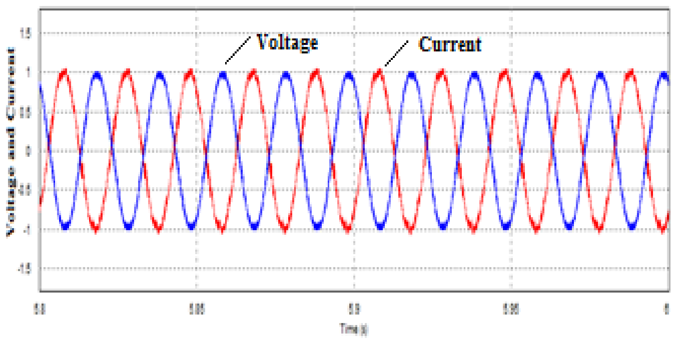


Fig.6e : Power Factor (Unity)

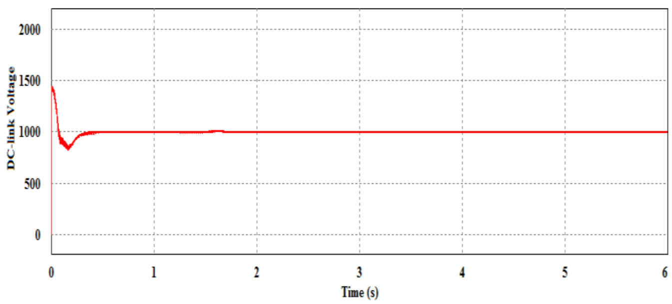


Fig.6f DC-link Voltage (Volt)
[X-axis: 1 div = 1 sec, Y-axis: 1 div = 500 volt]

V. Conclusion

The 2 MW/690 V DFIG system has been simulated in PSIM. A bi-directional IGBT based four quadrant AC-DC-AC converter with IGBT modules used in DFIG wind power generation system is presented. The converter can operate at sub-synchronous and super-synchronous modes. Based on DFIG model and field oriented control theory, the machine side converter provides good decoupling between active and reactive powers, and the grid side converter maintain DC-link voltage and power factor to be unity, which leads to high power quality and higher efficiency in harnessing wind energy effectively.

TABLEI. MACHINE PARAMETERS

Rated Power	2 MW
Rated voltage	690 V
Frequency	50 Hz
Stator resistance	2.6 mΩ
Rotor resistance	2.9 mΩ
Stator leakage inductance	87 µH
Rotor leakage inductance	87 µH
Magnetizing inductance	2.5 mH
No. of poles	4

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