Modeling and control of a doubly fed induction generator for grid integrated wind turbine

Siraj, Kiran; Nasir, Mashood; siraj, haris

Published in:
Power Electronics and Motion Control Conference and Exposition (PEMC), 2014 16th International

DOI (link to publication from Publisher):
10.1109/EPEPEMC.2014.6980613

Publication date:
2014

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Siraj, K., Nasir, M., & siraj, H. (2014). Modeling and control of a doubly fed induction generator for grid integrated wind turbine. In *Power Electronics and Motion Control Conference and Exposition (PEMC), 2014 16th International* https://doi.org/10.1109/EPEPEMC.2014.6980613

Modeling and Control of a Doubly Fed Induction Generator for Grid Integrated Wind Turbine

Kiran Siraj
12003079012@umt.edu.pk
Haris Siraj
13005079001@umt.edu.pk
Mashood Nasir
mashood.nasir@umt.edu.pk
Department of Informatics and Systems
University of Management and Technology
Lahore- Pakistan

Abstract— **This paper presents the modeling, simulation and control of a grid connected doubly fed induction generator (DFIG) coupled with the wind turbine. Among all the renewable energy resources, wind energy is rapidly gaining interest of developed as well as underdeveloped countries. Due to the increase in demand of electrical energy and increase in environmental pollution the use of wind energy to meet the domestic and industrial power demands is essential and inevitable. The main benefit is the production of economically justified and ecofriendly energy in bulk quantity. Because of the irregularity of wind speed, the output of wind turbine varies and that is why, variable speed wind turbines are more practical these days. In order to integrate the variable output of the wind turbine with the power grid, doubly fed induction generators are used due to their inherent advantages like active and reactive power control, absence of large capacitive banks and improved power quality. A DFIG is modeled using the electric equivalent circuit and dq_0 transformation along with the stator flux oriented vector control approach is used to decouple active and reactive power. Back to back power converters serve the purpose of controlling active and reactive powers at sub/super synchronous speeds. So the implementation of the proposed scheme ensures the constant output frequency and voltages with the control of active and reactive power and is highly suitable for grid integration in Distributed Generation (DG) Applications. The proposed scheme is implemented in SIMULINK / MATLAB environment and the simulation results validate the efficacy of the proposed scheme.**

Key Words – Doubly Fed Induction Generator (DFIG), Active and Reactive Power Control, Grid Integrated Wind Turbine, Vector Control Method

I. INTRODUCTION

Among all the renewable energy resources, wind energy has proven itself the most economical and efficient type of energy. Wind energy has been used since the dawn of the time. At that time, it was mostly used for grinding grains or drawing well. Wind energy is abundant and it produces no harmful effects on nature. The inherent environment friendly characteristics associated with the wind energy conversion systems (WECS) along with high conversion efficiencies and absence of hazardous emissions like NO_x and CO_x make them the best possible choice for the production of electricity.

Scottish scientist James Blyth built the first wind turbine in 1887 as a battery charger [1]. Until world war one, these were primarily used for mechanical purposes only. Further, subsequent developments were made to make it more suitable for electricity production. The first grid was installed in California but the world was still completing its electricity demands by oil, probably because it was an easy mean by which the superpowers maintain balance of authority. Nevertheless, the world has to come to its senses and indeed it has. Currently, wind power is being developed at a fast rate [2]. Wind energy conversion system mainly consists of wind turbine, shaft and alternator. Wind turbine rotor harvests the mechanical energy of the wind. The harvested mechanical energy is transferred to alternator via shaft and gearbox. Permanent magnet synchronous generator (PMSG) based WECS are used for constant speed wind turbines while induction generator (IG) based WECS are used for variable speed wind turbines [3]. Because of the intermittent nature of the wind, the power extracted from the wind is of variable nature. Thus, in order to integrate the wind power with the national grid, its variable nature must be countered such that the output of the WECS remains within the specified standards of voltages and frequency, even at the variable wind speeds. Now-a-days, doubly fed induction generator (DFIG) is the popular choice for this purpose [4]. Many control schemes are being recently developed to control the output of DFIG [3].

In [5] a sinusoidal approach to control the grid side converter is presented. However, this scheme involves a complex control system. In [3] a Scherbius scheme to control the converter output is drafted. However, such a methodology is functional only in sub synchronous mode and power flow is possible just outside from the rotor. The DFIG model presented in the paper uses a simplified vector control approach by which the output power quality of the turbine and the frequency associated with the output of the DFIG is adjusted and controlled in both cases i.e.

i. Super synchronous mode

When the turbine speed exceeds its synchronous speed and the slip of the machine is negative.

ii. Sub synchronous mode

When the turbine speeds lags behind synchronous speed and the slip of the machine is positive.

The simplified back-to-back converter control scheme developed in this paper using the vector control makes the DFIG very attractive choice for grid integration. The scheme adjusts the frequency in both sub and super synchronous speed. Reactive power is absorbed or supplied to the power source to match the standard frequency in real time. The methodology of using back-to-back converter consisting of a rotor and grid side converter is efficient, because rather than handling all the system power, the inverter handles only a fraction of rotor power i.e. (20%_30%) [10].

This paper explicitly models the DFIG and examines the current and voltage relationships associated with the stator and rotor. The dq0 transformation is given in the paper for aided analysis. Finally, a scheme is presented to find the desired active and reactive power. The two powers are decoupled to find their individual effects using stator side flux orientated technique. Simulations and results from Simulink/MATLAB validate the efficacy of the presented methodology.

II. OVERVIEW OF DOUBLY FED INDUCTION GENERATOR

Doubly fed induction generator are attaining tremendous progress since the installation of first modern wind turbine that was connected to the grid in 1980 [9]. The term doubly fed reflects that in this machine both the stator and rotor are connected to electrical sources. DFIG is attractive because it provides the constant power to the grid and handles the variable wind speed. The back-to-back PWM converter approach has made doubly fed cost effective and less complex [11]. A DFIG connected to the grid via two side by side converters as shown in figure 1. The stator is connected to the grid while rotor is connected to a voltage source inverter (VSI) scheme through slip rings. The VSI is a back-to-back converter consisting of a rotor side converter (RSC) and grid side converter (GSC). A dc link is provided via a capacitor between the GSC and RSC where it acts as a storage filter to smooth the voltage ripples.

A. WORKING PRINCIPAL OF DFIG

In a grid connected DFIG based WECS, the basic requirement is to maintain the output frequency to a standard value, so that it may match the grid frequency.

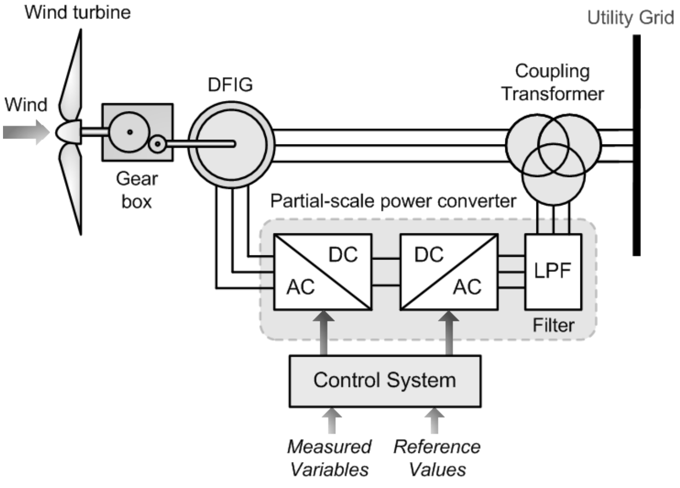

Figure 1: Schematic Representation of a Grid Connected DFIG

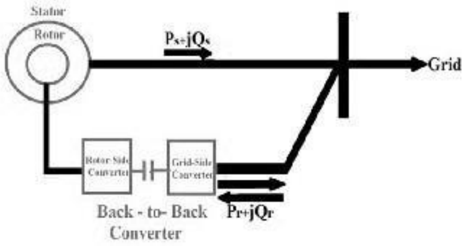

Figure 2: Flow of active and reactive power in DFIG

GSC controls the power of the DFIG at normal or synchronous speed while at super/sub synchronous speed the control is provided by the rotor side. The slip power is the power between the rotor and the converters and it can flow bi-directionally from the grid side to the rotor side and vice versa. So, by using DFIG, constant power may be supplied under both sub and super synchronous speeds. When the mechanical speed of the rotor is less than the stator revolving magnetic field speed, the machine is in sub synchronous mode and the slip power is absorbed by the rotor. The control scheme is constantly monitoring the active and reactive power of the DFIG and comparing it with the reference power thus the required power is fed into the grid. While in super-synchronous mode, the rotor power is supplied to the grid. This bi-directional flow of the power is shown in figure 2 [11].

B. MODELING OF DFIG

To avoid the complexity related to dynamic simulation of a DFIG, park transformation is used. Figure 3 shows the representation of DFIG in two phase axis using park transformation. Stator winding variables like voltages, currents and flux are represented as the imaginary winding variables that are in synchronization with the rotor axis. Using dq0 transformation, the angular displacement of the rotor and stator windings can be transformed into a two phase fictitious winding. These two windings have zero displacement with respect to the rotating three phase windings and are termed as dq0 windings [7, 8, 12, 20].

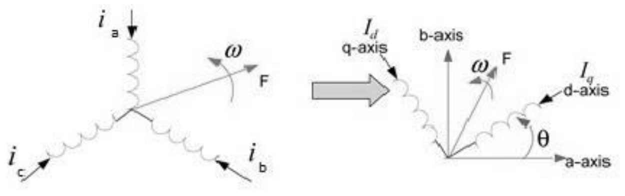

Figure 2:dq0 reference frame

Using the electrical model shown in figure 4, the three phase voltages and currents equations can be represented as dq0 axis equation [15, 16].

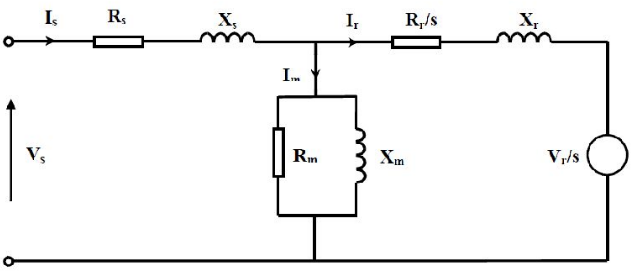

Figure 3: Electrical equivalent circuit of DFIG

Direct axis is aligned with the rotor's pole. Quadrature axis refers to the axis whose electrical angle is orthogonal to the electric angle of direct axis. The mechanical angle θ_m and electrical angle θ_{me} is related by (1) [6, 17, 18]

$$\theta_{me} = \frac{P}{2}\theta_m \tag{1}$$

And the relation between rotor angle θ_r and electrical angle θ_{me} is given be (2)

$$\theta_r = \theta_{me} + \frac{\pi}{2} \tag{2}$$

Stator quantities i.e. current, voltage or flux S_{abc}, for the phase a, b and c can be transformed to quantities S_{dq0}, referred to the rotor. This conversion comes through the Transformation matrix K [22].

$$S_{dq\,0} = KS_{abc} \tag{3}$$

$$S_{abc} = K^{-1}S_{dq\,0} \tag{4}$$

$$K = \frac{2}{3}\begin{bmatrix} \cos(\theta_{me}) & \cos(\theta_{me} - 2\pi/3) & \cos(\theta_{me} + 2\pi/3) \\ -\sin(\theta_{me}) & -\sin(\theta_{me} - 2\pi/3) & -\sin(\theta_{me} + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \tag{5}$$

$$K^{-1} = \begin{bmatrix} \cos(\theta_{me}) & -\sin(\theta_{me}) & 1 \\ \cos(\theta_{me} - 2\pi/3) & -\sin(\theta_{me} - 2\pi/3) & 1 \\ \cos(\theta_{me} + 2\pi/3) & -\sin(\theta_{me} + 2\pi/3) & 1 \end{bmatrix} \tag{6}$$

For stator winding, the voltages of phase a,b and c V_{abc} are related to stator resistance R_s, stator three phase current i_{abc} and three phase flux linkages λ_{abc} and are given by (7)

$$V_{abc} = R_s i_{abc} + \frac{d}{dt}\lambda_{abc} \tag{7}$$

Using (4), (7) may be transformed as

$$\left(K^{-1}V_{dq0}\right) = R_S\left(K^{-1}i_{\,dq0}\right) + \frac{d}{dt}\left(K^{-1}\lambda_{dq\,0}\right) \tag{8}$$

Multiplying by K on both sides yields

$$K.\left(K^{-1}\,V_{dq0}\right) = KR_s.\left(K^{-1}i_{dq0}\right) + K\frac{d}{dt}\left(K^{-1}\lambda_{dq\,0}\right) \tag{9}$$

$$V_{dq0} = (KR_sK^{-1})i_{dq0} + \left[KK^{-1}\frac{d}{dt}\lambda_{abc} + K\left(\frac{d}{dt}K^{-1}\right)\lambda_{abc}\right] \tag{10}$$

(10) can be written as

$$V_{dqo} = R_S i_{dqo} + \frac{d}{dt}\lambda_{abc} + K\left(\frac{d}{dt}K^{-1}\right)\lambda_{dq0} \tag{11}$$

Similarly for field windings,

$$v_f = R_f i_f + \frac{d}{dt}\lambda_f \tag{12}$$

Where,

V_f =Field winding voltage

I_f = Field winding current

λ_f = field winding flux

$\frac{d}{dt}K^{-1}$ in (11) is a complex quantity and may be calculated through following sequence of steps.

$$\frac{d}{dt}K^{-1} = -\omega_{me}\begin{bmatrix} \sin(\theta_{me}) & -\cos(\theta_{me}) & 0 \\ \sin(\theta_{me} - 2\pi/3) & \cos(\theta_{me} - 2\pi/3) & 0 \\ \sin(\theta_{me} + 2\pi/3) & \cos(\theta_{me} + 2\pi/3) & 0 \end{bmatrix} \tag{12}$$

Where,

$$\omega_{me} = angular\ electrical\ frequency = \frac{\theta_{me}}{dt}$$

(13) is obtained as,

$$K\left(\frac{d}{dt}K^{-1}\right) = \begin{pmatrix} 0 & -\omega_r & 0 \\ \omega_r & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{13}$$

Where $\omega_{me} = \omega_r$

Putting (13) in (11),

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ v_0 \end{bmatrix} = \begin{bmatrix} R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \lambda_{sq}\omega_s \\ R_s i_{sq} + \frac{d}{dt}\lambda_{sq} - \lambda_{sd}\omega_s \\ R_s i_\circ + \frac{d}{dt}\lambda_\circ \end{bmatrix} \tag{14}$$

Where, $\frac{d}{dt}\lambda_s = transient\ term$

$\lambda_s\omega_s = speed\ voltage\ term$

$R_s i_s = stator\ windings\ voltage\ drop\ term$

Similarly, the equations for rotor are formulated and are given in (15)

$$\begin{bmatrix} v_{rd} \\ v_{rq} \\ v_0 \end{bmatrix} = \begin{bmatrix} R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \lambda_{rq}s\omega_s \\ R_r i_{rq} + \frac{d}{dt}\lambda_{rq} + \lambda_{rd}s\omega_s \\ R_r i_\circ + \frac{d}{dt}\lambda_\circ \end{bmatrix} \tag{15}$$

$\lambda_r s\omega_s =$ Rotor speed voltages created in the rotor windings moving at slip speed w.r.t the synchronously rotating flux wave and d q subscripts shows direct and quadrature transformations respectively.

Similarly flux linkages for stator direct and quadrature axis λsd, and λsq can be written in terms of self-inductance of the stator L_s , mutual inductance L_m and the direct and quadrature axis rotor and stator currents.

$$\lambda_{sd} = L_s i_{sd} + L_m i_{rd} \tag{16}$$

$$\lambda_{sq} = L_s i_{sd} + L_m i_{rq} \tag{17}$$

Inductances at the stator side are given by (18) and (19)

$$L_{sd} = L_s + L_{md} \tag{18}$$

$$L_{sq} = L_s + L_{mq} \tag{19}$$

Inductances rotor side

$$L_{rd} = L_r + L_{md} \tag{20}$$

$$L_{rq} = L_r + L_{mq} \tag{21}$$

The active power input to the stator P_s and reactive power input to the stator Q_s is calculated as:

$$P_s = \frac{3}{2}\left(v_{sd}i_{sd} + v_{sq}i_{sq}\right) \tag{22}$$

$$Q_s = \frac{3}{2}\left(v_{sq}i_{ds} - v_{sd}i_{qs}\right) \tag{23}$$

Similarly active and reactive power input to the rotor P_r and Q_r are given by (24) and (25)

$$P_r = v_{rd}i_{rd} + v_{rq}i_{rq} \tag{24}$$

$$Q_r = v_{rq}i_{rq} - v_{rd}i_{rd} \tag{25}$$

Electromagnetic torque T_e in terms of no. of poles P is given by (26)

$$T_e = \frac{3}{2}PL_m\left(i_{sq}i_{rd} - i_{sd}i_{rq}\right) = \lambda_{rq}i_{rq} - \lambda_{rd}i_{rq} \tag{26}$$

III. CONTROL SCHEME OF DFIG USING STATOR FLUX ORIENTED VECTOR CONTROL

Stator flux oriented vector control scheme is used to decouple the effect of stator and rotor current in the reactive power. The following assumptions are made as explained in [13, 6].

- In comparison to the grid voltage, the stator voltage is very less. So it is neglected.
- The DFIG is connected to a grid having constant load.
- The dq axis, orthogonal to each other is rotating at synchronous speed and d axis is lagging the q axis by 90 degree.
- Grid will determine the current of magnetizing branch in stator.
- Stator flux vector is aligned with d axis of the stator. All these equations result in the following set of equations

$$V_{sd} = 0,\ V_{sq} = V_s,\ \lambda_{sd} = \lambda_s,\ \lambda_{sq} = 0$$

Using these assumptions along with R_s=0 in (14) and (15) yields,

$$\begin{aligned} V_{sd} &= 0 = \frac{d}{dt}\lambda_{sd} - \lambda_{sq}\omega_s \\ V_{sq} &= \omega_s\lambda_{sd} = V_s = \frac{d}{dt}\lambda_{sq} + \lambda_d\omega_s \\ V_{rd} &= R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - s\omega_s\lambda_{rq} \\ V_{rq} &= R_r i_{qr} + \frac{d}{dt}\lambda_{rq} - s\omega_s\lambda_{rd} \end{aligned} \qquad (27)$$

The flux linkages for these assumptions are transformed into

$$\begin{aligned} \lambda_s &= L_s i_{sd} + L_m i_{dr} \\ 0 &= L_s i_{sq} + L_m i_{rq} \\ \lambda_{rd} &= L_r i_{rd} + L_m i_{ds} \\ \lambda_{qr} &= L_r i_{rq} + L_m i_{qs} \end{aligned} \qquad (28)$$

Rotor voltages are than obtained by (29) and (30)

$$V_{rd} = R_r i_{rd} + \left(L_r - \frac{L_m^2}{L_s}\right)\frac{di_{rd}}{dt} - \left[(\omega_s - \omega_r)\left(L_r - \frac{L_m^2}{L_s}\right)\right] i_{rq} \qquad (30)$$

$$V_{qr} = R_r i_{rq} + \left(L_r - \frac{L_m^2}{L_s}\right)\frac{di_{rq}}{dt} + (\omega_s - \omega_r)\left[\left(L_r - \frac{L_m^2}{L_s}\right) i_{rd} + \frac{L_m V_s}{\omega_s L_s}\right] \qquad (31)$$

Active reactive power produced in the stator can now be represented in terms of rotor fluxes and voltages and are given by (32) and (33)

$$P_s = -\frac{L_m}{L_s} V_s\left(i_{rq}\right) \qquad (32)$$

$$Q_s = \frac{V_s^2}{\omega_s L_s} - \frac{V_s L_m}{L_s}\left(i_{rd}\right) \qquad (33)$$

Using i_{rq} the active power generated by the stator of DFIG can be controlled. While i_{dr} is used to control the reactive power of stator.

IV. SIMULATIONS AND RESULTS

A. MODEL IMPLEMENTATION OF DFIG

From (32) and (33) torque is calculated as

$$T_e = \frac{3}{2} P L_m \lambda_{sd} i_{rq} \qquad (34)$$

(34) Explains that torque of a DFIG can be regulated by controlling the q component of rotor currenti_{rq}.

Similarly the reactive power is controlled by i_{rd} and is given by (35)

$$Q_s = \frac{V_s^2}{\omega_s L_s} - \frac{V_s L_m}{L_s}\left(i_{rd}\right) \qquad (35)$$

Using the above equations and controlling variables, a Simulink based model for DFIG is developed as shown in figure4.

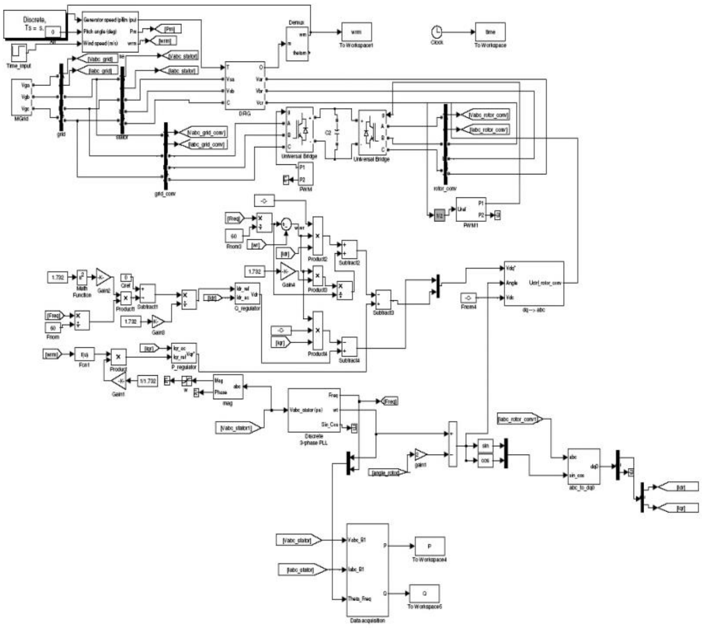

Figure 4: Simulation diagram of a DFIG

B. Rotor side converter

RSC controls the active and reactive power of the rotor as determined by the equations (32) and (33). The control scheme ensures the maximum power extraction from wind [13, 18,19].

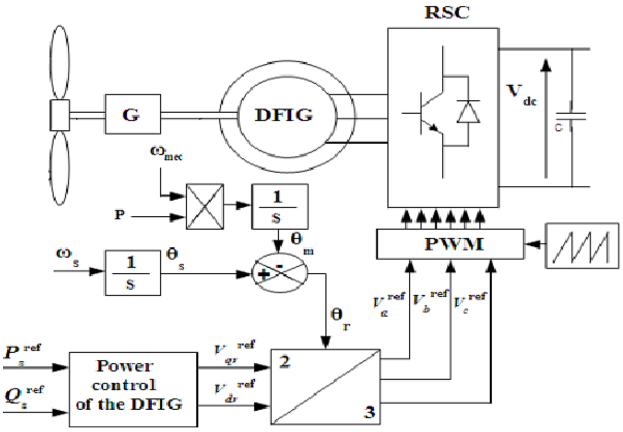

Figure 5: Rotor side control scheme

C. Grid side converter

GSC maintains the power factor of the utility side. Thus, it allows regulating the dc link voltages. GSC acts as a rectifier in sub synchronous mode the slip is positive and the direction of slip power is from grid to the dc link. While, in super synchronous mode, GSC acts as an inverter, the slip is negative. The direction of slip power is from dc link to the grid [13, 18, 19]. The block diagram of GSC is shown below in figure 6.

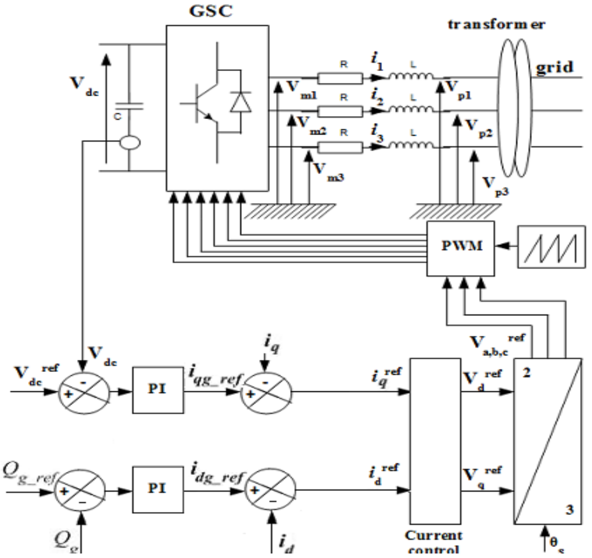

Figure 6: Grid side converter control scheme

Simulations are performed in MATLAB Simulink. The results are given in graphical form. In Fig.7 active and reactive powers are decoupled using field oriented vector control approach. As the wind speed increases, the active power produced by the wind turbine also increases. During this time the reactive power of the DFIG is kept constant thus minimizing the impact of variable wind speed on the output power. Fig. 8 shows that both the windmill and the rotor's speed changed quite smoothly. For this purpose the stator power is decreased and the rotor power is increased to account for the changing shaft speed. During this process, the operating state of the wind turbine goes from sub-synchronous to super-synchronous and the process takes place almost in a step less manner. The above simulation also confirmed similar changes in the power flow through the stator and rotor, caused by changing the wind speed.

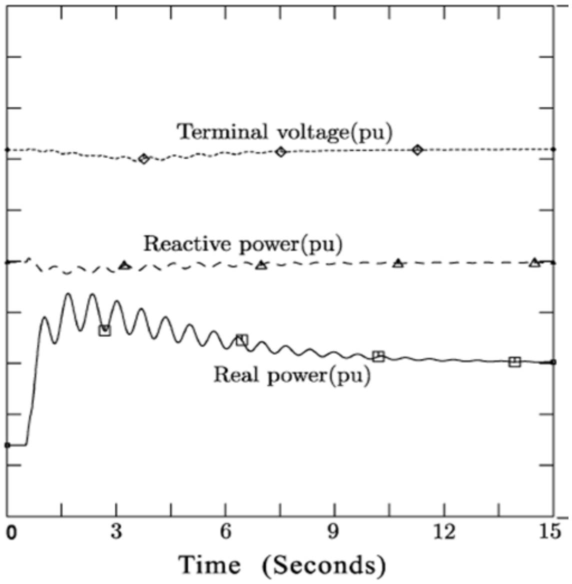

Figure.7 Wind turbine terminal voltage and power output

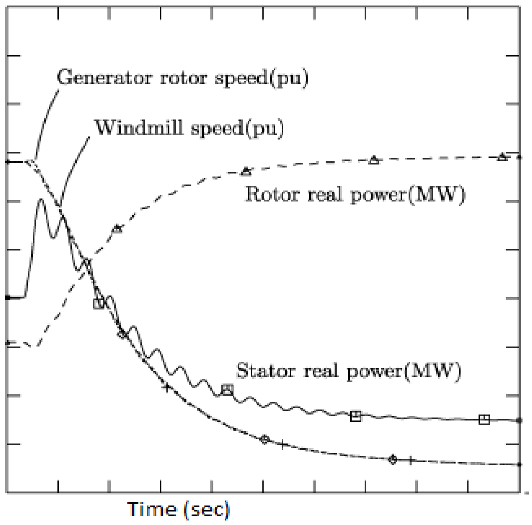

Figure 8: Mechanical power of wind turbine

V. CONCLUSION

In this paper, using electrical equivalent model parametric equations for the DFIG are developed. Using park transformation these equations are converted to dq0 reference frame. Active and reactive powers were found and are decoupled for efficient control of reactive power using stator flux oriented vector control. This method adequately controls the slip power by regulating the reactive power. The model is simulated in MATLAB and the resulting graphs are analyzed. This control scheme proposed in this paper assures the constant power output for the grid connected DFIG under varying speed by optimally controlling the active and reactive power flow.

REFERENCES

[1] James Blyth, 'On the application of wind power to the production of electric currents', Transactions of the Royal Scottish Society of Arts, vol. 13, (1894), pp. 170-181, 25 January 1892.

[2] Bradley, Robert L. Jr. 1999. The Increasing Sustainability of Conventional Energy. Policy Analysis Paper No. 341.

April 22. Washington, DC: Cato Institute.

[3] Baroudi, Jamal A., Venkata Dinavahi, and Andrew M. Knight. "A review of power converter topologies for wind generators." Renewable Energy 32.14 (2007): 2369-2385.

[4] Tazil, M., et al. "Three-phase doubly fed induction generators: an overview." Electric Power Applications, IET 4.2 (2010): 75-89.

[5] Byeon, Gil-Sung, In-Kwon Park, and Gil-Soo Jang. "Modeling and control of a doubly-fed induction generator (DFIG) wind power generation system for real-time simulations." Journal of Electrical Engineering and Technology 5.1 (2010): 61-69.

[6] Pena, R. S., et al. "Vector controlled induction machines for stand-alone wind energy applications." Industry Applications Conference, 2000. Conference Record of the 2000 IEEE. Vol. 3. IEEE, 2000.

[7]] A.Tapia, G.Ostolaza and J.X. Saenz, “Modeling and control of a wind turbine driven doubly fed induction generator,” IEEE Energy Conversion, vol. 18, pp. 194-204, 2003.

[8] 194–204, June. 2003. Lei, Yazhou, et al. "Modeling of the wind turbine with a doubly fed induction generator for grid integration studies." Energy Conversion, IEEE Transactions on 21.1 (2006): 257-264.

[9] Gross, Robert, Matthew Leach, and Ausilio Bauen. "Progress in renewable energy." Environment International 29.1 (2003): 105-122.

[10] Tang, Yifan, and Longya Xu. "A flexible active and reactive power control strategy for a variable speed constant frequency generating system." Power Electronics, IEEE Transactions on 10.4 (1995): 472-478.

[11] “Electric power systems Pena, R., J. C. Clare, and G. M. Asher. "A doubly fed induction generator using back-to-back PWM converters supplying an isolated load from a variable speed wind turbine." Electric Power Applications, IEE Proceedings-. Vol. 143. No. 5. IET, 1996.esearch 8.1 (1984): 15-26.

[12] Singh, S. N., Ankit Gupta, and Dheeraj K. Khatod. "Modeling and Simulation of Doubly Fed Induction Generator Coupled With Wind Turbine-An Overview." Journal of Engineering Computers & Applied Sciences 2.8 (2013): 45-54

[13] Li, Shuhui, and Timothy A. Haskew. "Analysis of decoupled dq vector control in DFIG back-to-back PWM converter." Power Engineering Society General Meeting, 2007.

[14] Machmoum, Mohamed, and Frederic Poitiers. "Sliding mode control of a variable speed wind energy conversion system with

[15] Lei, Yazhou, et al. "Modeling of the wind turbine with a doubly fed induction generator for grid integration studies." Energy Conversion, IEEE Transactions on 21.1 (2006): 257-264.

[16] Salman, S. K., and Babak Badrzadeh. "New Approach for modelling Doubly-Fed Induction Generator (DFIG) for grid-connection studies." European wind energy conference an exhibition, London. 2004.

[17] Lee, Hansang, et al. "Compensation for the power fluctuation of the large scale wind farm using hybrid energy storage applications." Applied Superconductivity, IEEE Transactions on 22.3 (2012): 5701904-5701904.

[18] M. Verij Kazemi, A. Sadeghi Yazdankhah, H. Madadi Kojabadi, Direct power control of DFIG based on discrete space vector modulation, Renewable Energy, Vol. 35, pp. 1033-1042, 2010.

[19] R Pena,., J. C. Clare, and G. M. Asher. "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation." IEE Proceedings-Electric Power Applications 143, (1996): 231-241.

[20] Lee, R. J., P. Pillay, and R. G. Harley. "D, Q reference frames for the simulation of induction motors." Electric power systems research, (1984): 15-26