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Direct Power Control of Grid Connected Double-fed Induction Generator in Wind Energy Conversion System

Danduboyina Dimple[1] | Dr Yerra Sreenivasa Rao[2]

[1]EEE Department, Lingaya's Institute of Management and Technology, Vijayawada, Andhra Pradesh, India.
[2]EEE Department, Lingaya's Institute of Management and Technology, Vijayawada, Andhra Pradesh, India.

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ABSTRACT

Direct Power Control is a rotor side control of a doubly fed induction generator by which decoupled control of stator active and reactive power can be obtained is presented. It is based on the measurement of active and reactive power on the grid side where voltages and currents are alternating at fixed frequency. The active and reactive powers are made to track references using hysteresis controllers. The measurements are taken on stator side and the control is made on rotor side. This control system eliminates the need for rotor position sensing and gives an excellent dynamic performance with simulation results for a variable speed constant frequency induction generator system. The system can be operated below, at and above synchronous speed. The modeling of the Doubly Fed Induction Generator (DFIG) system is discussed in this paper. The power is controlled by rotor current injection. The controlling scheme is explained and the modeling of the complete system is done in MATLAB-SIMULINK. The performance of this control technique is observed in wind power applications. Optimum power control and pitch angle control for wind turbine is proposed and the response of generator speed, pitch angle, optimum power, turbine torque, stator current, stator and rotor powers for different wind speeds are shown by simulation results. The direction of stator and rotor power flow is explained with simulation results.

KEYWORDS: *WECS, DFIG, DPC, CSCF*

I. Introduction

With exhausting of traditional energy resources and increasing concern of environment, renewable and clean energy is attracting more attention all over the world to overcome the increasing power demand. Out of all the renewable energy sources, Wind energy and solar energy are reliable energy sources. Now a day, Wind power is gaining a lot of importance because it is cost- effective, environmentally clean and safe renewable power source compared to fossil fuel and nuclear power generation.

A Wind Energy Conversion System (WECS) can vary in size from a few hundred kilowatts to several megawatts. The size of the WECS mostly determines the choice of the generator and converter system. Asynchronous generators are more commonly used in systems upto 2MW, beyond which direct-driven permanent magnet synchronous machines are preferred. A grid connected WECS should generate power at constant electrical frequency which is determined by the grid. Generally Squirrel cage rotor induction generators are used in medium power level grid-connected systems. The induction generator runs at near synchronous speed and draws the magnetizing current from the mains when it is connected to the constant frequency network, which results in Constant Speed Constant Frequency (CSCF) operation of generator. However the power capture due to fluctuating wind speed can be substantially improved if there is flexibility in varying the shaft speed.

In such variable Speed Constant Frequency (VSCF) application rotor side control of grid-connected wound rotor induction machine is an attractive solution. In double fed induction generator, the stator is directly connected to the three phase grid and the rotor is supplied by two back-to-back PWM converters as shown in Figure1. Such an arrangement provides flexibility of operation at both sub synchronous and super synchronous speeds.

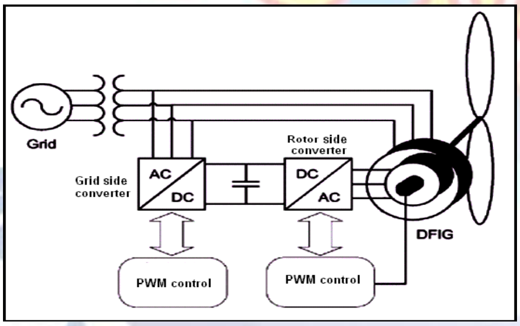

Fig.1. Wind Energy Conversion System

II. MATHEMATICAL MODELING OF THE DFIG

The wind generation system studied in this paper consists of two components: the Doubly-Fed Induction Generator (DFIG) and the variable speed wind turbine. A detailed description of these two components is given below. The DFIG may be regarded as a slip-ring induction machine, whose stator winding is directly connected to the grid, and whose rotor winding is connected to the grid through a bidirectional frequency converter using back-to-back PWM voltage-source converters.

The electrical part of the DFIG is represented by a fourth-order state space model, which is constructed using the synchronously rotating reference frame (dq-frame), where the d-axis is oriented along the stator-flux vector position. The relation between the three phase quantities and the dq components is defined by Park's transformation. The voltage equations of the DFIG are

$$V_{ds} = R_s i_{ds} - \omega_s \Psi_{qs} + (d\Psi_{ds}/dt) \quad (1)$$
$$V_{qs} = R_s i_{qs} + \omega_s \Psi_{ds} + (d\Psi_{qs}/dt) \quad (2)$$
$$V_{dr} = R_r i_{dr} - (\omega_s - \omega_r) \Psi_{qr} + (d\Psi_{dr}/dt) \quad (3)$$
$$V_{qr} = R_r i_{qr} - (\omega_s - \omega_r) \Psi_{qr} + (d\Psi_{qr}/dt) \quad (4)$$

where V_{ds}, V_{qs}, V_{dr}, V_{qr} are the d- and q-axis of the stator and rotor voltages; Ids, Iqs,Idr,Iqr are the d- and q-axis of the stator and rotor currents; Ψ_{ds}, Ψ_{qs}, Ψ_{dr}, Ψ_{qr} are the d- and q-axis of the stator and rotor fluxes; ω_s is the angular velocity of the synchronously rotating reference frame; ω_r is the rotor angular velocity; and R_s,R_r are the stator and rotor resistances[9].

The flux equations of the DFIG are

$$\Psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad (5)$$
$$\Psi_{qs} = L_s I_{qs} + L_m I_{qr}, \quad (6)$$
$$\Psi_{dr} = L_m I_{ds} + L_r I_{dr}, \quad (7)$$
$$\Psi_{qr} = L_m I_{qs} + L_r I_{qr} \quad (8)$$

Where L_s, L_r, and L_m are the stator, rotor, and mutual inductances, respectively.
From the flux equations (5)–(8), the current equations can be written as

$$I_{ds} = (1/\sigma L_s) \Psi_{ds} - (L_m / \sigma L_s L_r) \Psi_{dr} \quad (9)$$
$$I_{qs} = (1/\sigma L_s)\Psi_{qs} - (L_m/ \sigma L_s L_r)\Psi_{qr} \quad (10)$$
$$I_{dr} = (-L_m/ \sigma L_s L_r)\Psi_{ds} + (1/\sigma L_r)\Psi_{dr} \quad (11)$$
$$I_{qr} = (-L_m/ \sigma L_s L_r) \Psi_{qs} + (1/ \sigma L_r)\Psi_{q} \quad (12)$$

where $\sigma = (1 -(L^2_m /L_s L_r))$ is the leak coefficient.
Neglecting the power losses associated with the stator and rotor resistances, the active and reactive stator and rotor powers are given by

$$Ps = -V_{ds} I_{ds} - V_{qs} I_{qs} \quad (13)$$
$$Qs = -V_{qs} I_{ds} + V_{ds} I_{qs} \quad (14)$$
$$Pr = -V_{dr} I_{dr} - V_{qr} I_{qr} \quad (15)$$
$$Qr = -v_{qr} I_{dr} + V_{dr} I_{qr} \quad (16)$$

and the total active and reactive powers of the DFIG are

$$P = Ps + Pr, \quad (17)$$
$$Q = Qs + Qr, \quad (18)$$

where positive (negative) values of *P* and *Q* mean that the DFIG injects power into (draws power from) the grid[9].

The mechanical part of the DFIG is represented by a first-order model

$$J(d(\omega_r)/ dt) = Tm - Te - C_f \omega_r, \quad (19)$$

where C_f is the friction coefficient, T_m is the mechanical torque generated by the wind turbine, and T_e is the electromagnetic torque given by

$$Te = \Psi_{ds} \; I_{ds} - \Psi_{qs} \, I_{qs}, \qquad (20)$$

Where positive (negative) values mean the DFIG acts as a generator (motor).

III. DIRECT POWER CONTROL OF DFIG

The conventional approach for independent control of active and reactive powers handled by the machine is stator flux oriented vector control with rotor position sensors. The performance of the system in this case depends on the accuracy of computation of the stator flux and the accuracy of the rotor position information derived from the position encoder. Alignment of the position sensor is moreover, difficult in a doubly-fed wound rotor machine.

An algorithm is developed for independent control of active and reactive powers with high dynamic response. The schematic diagram of direct power control of DFIG is shown in Figure 2.The instantaneous switching state of the rotor side converter is determined based on the active and reactive powers measured in the stator circuit. Measurements are carried out at one terminal of the machine whereas the switching action is carried out at another terminal. Here the directly-controlled quantities are the stator active and reactive powers; hence the algorithm is referred as direct power control. It can be applied to VSCF applications like wind power generation.

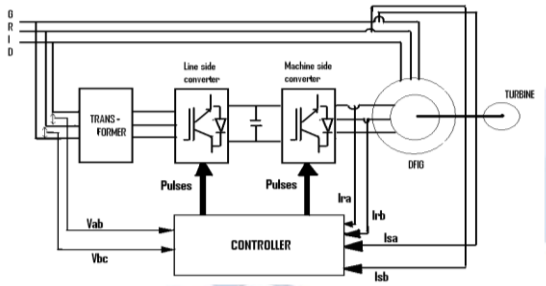

Fig.2. Direct power control of DFIG

A. Concept of Direct Power Control

The two basic notions used to determine the instantaneous switching state of the rotor side converter to control the active and reactive power are

i) The stator active power can be controlled by controlling the angular position of the rotor flux vector.

ii) The stator reactive power can be controlled by controlling the magnitude of the rotor flux vector.

B. Voltage vectors and their effects

Assuming that the orientation of the three phase rotor winding in space at any instant of time is as given in Figure 3(a), the six active switching states $S_1, S_2 \ldots S_6$ would result in the voltage space vectors $U_1, U_2 \ldots U_6$ at that instant as shown in Figure 3(b). In order to make an appropriate selection of the voltage vector the space phasor plane is first subdivided into six 60^0 sectors 1, 2…6. The instantaneous magnitude and angular velocity of the rotor flux can now be controlled by selecting a particular voltage vector depending on its present location. The effect of the different vectors as reflected on the stator side active and reactive powers, when the rotor flux is positioned in Sector 1 is illustrated in the following subsections. Considering anti clockwise direction of rotation of the flux vectors in the rotor reference frame to be positive, it may be noted that Ψ_s is behind Ψ_r in generating mode. In the rotor reference frame the flux vectors rotate in the positive direction at sub-synchronous speeds, remain stationary at synchronous speed and start rotating in the negative direction at super-synchronous speeds[13].

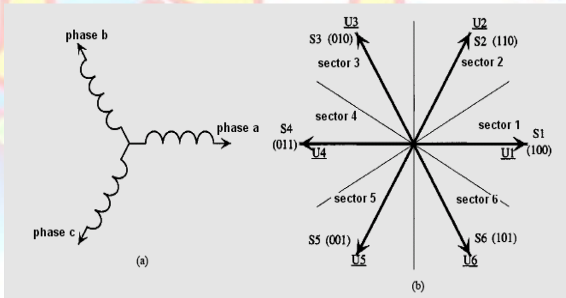

Fig.3(a). Orientation of the rotor winding in space with respect to which the voltage space phasors are drawn and (b) voltage space phasors.

C. Implementation of Direct Power Control (DPC) algorithm in Simulink

The reference for the stator active power can be calculated as $Ps^* = T_{ref} * \omega_s$ and Q_s^* is selected depends on the requirement of power factor. The active and reactive powers on the stator side can be directly computed from the stator currents and voltages.

D. DPC algorithm

The simulink model of direct power control scheme is shown in Figure 4.

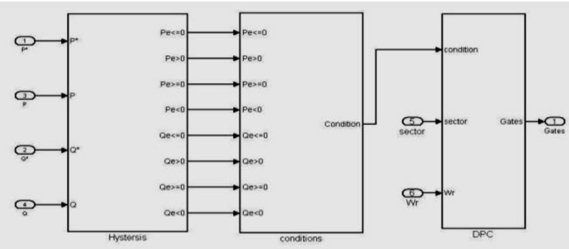

Fig.4. Simulink model of DPC scheme

E. Hystersis controllers:

P_s^* is the reference for stator active power. The actual active power P_s is to be controlled is to be within a band of width P_{band} which is about P_s^*. Similarly Q_s^* is the reference for stator reactive power. The actual reactive power Q_s is to be controlled to stay within a band of width Q_{band} about Q_s^*.

F. Conditions According To Power Requirements:

In order to determine the appropriate switching vector at any instant of time, the errors in P_s and Q_s, and the sector in which the rotor flux vector is presently residing are taken into consideration. The two switching tables for active vector selection are shown in Table 1 and Table 2 correspond to negative and positive, active power errors respectively. If the rotor side converter is switched in accordance to these tables it is possible to control the active and reactive powers in the stator side within the desired error bands.

Table 1: Selection of Active switching states when (P_{err} <= 0)

	Secto r 1	Secto r 2	Secto r 3	Secto r 4	Secto r 5	Secto r 6
Qerr>0	S3	S4	S5	S6	S1	S2
Qerr<= 0	S2	S3	S4	S5	S6	S1

Table 2: Selection of Active switching states when (P_{err} > 0)

	Secto r 1	Secto r 2	Secto r 3	Secto r 4	Secto r 5	Secto r 6
Qerr>0	S5	S6	S1	S2	S3	S4
Qerr<= 0	S6	S1	S2	S3	S4	S5

By considering the effect of the zero vector on active and reactive powers, the logic for selecting the zero vector can be summarized as in Table3. Whenever a zero vector has to be applied, the one nearest to the present active vector is selected to minimize the number of switchings.

Table 3: Condition for selection of zero vectors

Speed	
Sub-Synchronous speed	Qerr<0 And Perr>=0
Super-Synchronous speed	Perr<0 And Qerr<=0

G. Pulse Generation

With the inferences drawn in the previous section it is possible to switch an appropriate voltage vector in the rotor side at any given instant of time to increase or decrease the active or reactive power in the stator side. Therefore, any given references for stator active and reactive powers can be tracked within a narrow band by selecting proper switching vectors for the rotor side converter.

H. Sector Identification

Sector Identification method uses integration of the PWM rotor voltage to compute the rotor flux. Then the flux angle is calculated hence the sector in which the rotor flux resides can be identified.

$$\Psi_{dr} = \int (V_{dr} - R_r I_{dr})\, dt \quad (23)$$

$$\Psi_{qr} = \int (V_{qr} - R_r I_{qr})\, dt \quad (24)$$

$$\Phi_r = \tan^{-1} (\Psi_{dr} / \Psi_{qr}) \quad (25)$$

IV. DIRECT POWER CONTROL OF DFIG IN WIND POWER APPLICATIONS

When the direct power control scheme is applied in wind power applications the optimum power control can be achieved. The maximum generator speed can be limited by pitch angle control. The simulink block diagram of direct power control of DFIG in wind power applications is shown in Figure 5.

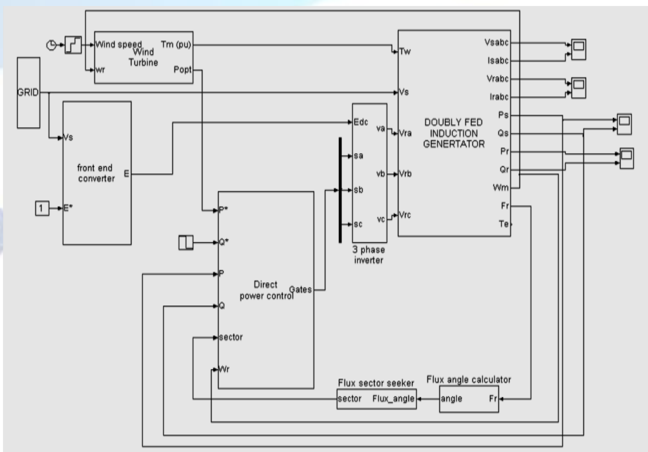

Fig.5. Wind power generation by DFIG incorporated with DPC

For the below system input is wind speed. The response of Turbine torque, generator speed, stator current, pitch angle, stator and rotor active powers are observed for change in the wind speed and are shown by simulation results.

V. SIMULATION RESULTS

A. Response of generator speed, mechanical torque and optimum power with change in wind velocity

The wind speed is varied in steps and with the variations in wind speed the variation in generator speed, turbine torque and optimum power are shown in Figure 6.

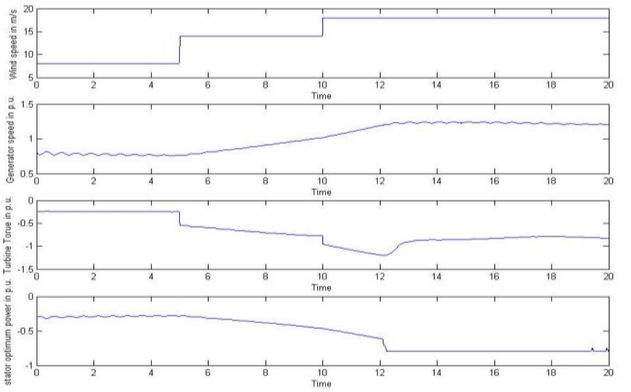

Fig.6. *Response of generator speed, mechanical torque and optimum power with change in wind velocity*

The maximum optimum power is 0.8 pu and the maximum generator speed is 1.2 pu. The system can be operated below and above and at synchronous speeds as shown by the simulation results.

B. Pitch angle control

Whenever the generator speed reaches the maximum value pitch angle control comes into action and the generator speed is limited to the maximum value. Here in this case maximum speed is 1.2 pu. The pitch angle control works as shown in Figure 7.

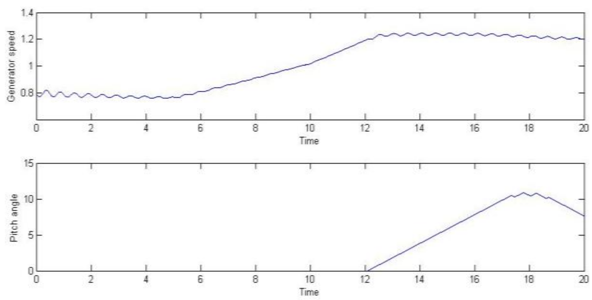

Fig.7. *Response of speed and pitch angle with change in wind speed*

C. Response of Stator active power with change in optimum power

The stator active power follows the optimum power within a band of width P_{band} as shown by the simulation results. The dynamic response of the system is very good. Hence the optimum power control can be achieved by this control system.

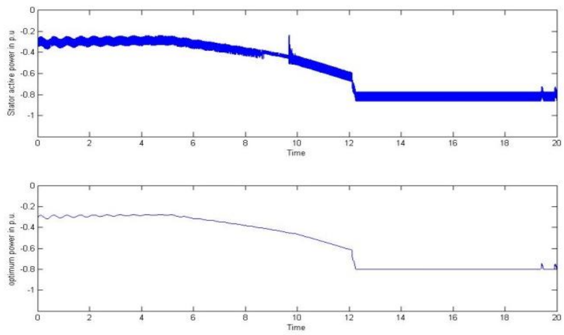

Fig.8. Stator active power and Optimum power

D. Response of Stator current with change in Stator active & reactive powers

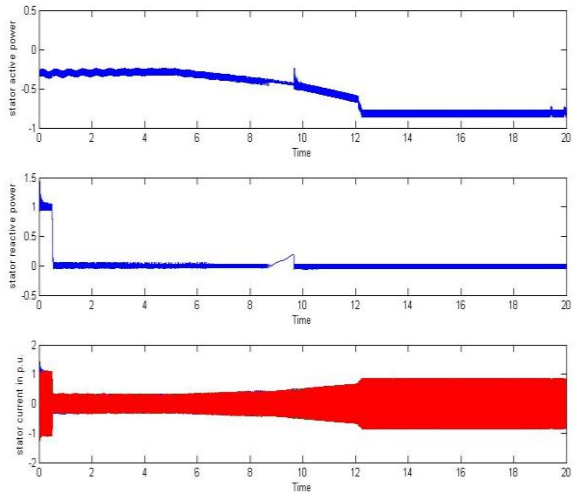

Fig.9. Stator active power, reactive power and current

E. Rotor active power

Stator active power of DFIG is always negative that means it always feeds power to the grid. Direction of rotor active power depends upon the speed of the turbine. In the sub-synchronous operation, the rotor power is positive i.e power flows from grid to the rotor circuit and in case of super-synchronous operation power flows from rotor to grid i.e rotor power is negative. At synchronous speed rotor power is zero. The rotor power is always equal to slip times the stator power.

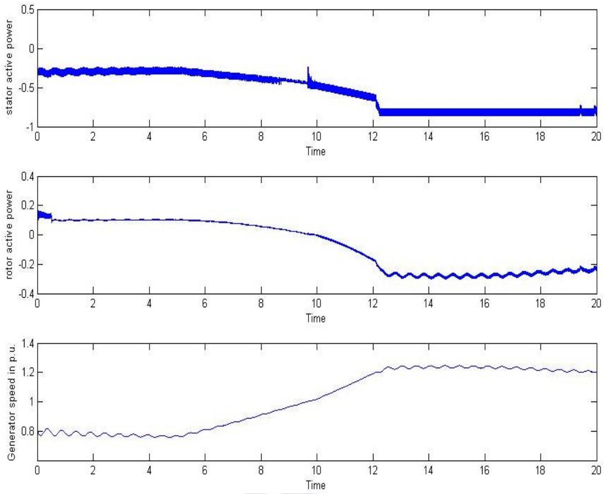

Fig.10. Change in Rotor active power with speed

5.6 Response of Pitch angle and generator speed for different wind speeds

There is step change wind speed from 8m/s to certain value. Then the change in pitch angle and the generator speed are observed. Here for some values of wind speeds the response of the system is shown and from those results we can conclude that up to what speed of wind the system can work satisfactorily.

VI. CONCLUSIONS

The direct power control of the doubly fed induction generator is capable of controlling the active and reactive powers of a wound rotor induction generator without rotor position sensors. Decoupled control of stator active and reactive power can be obtained and system has good dynamic response as shown by the simulation results. Since it depends only on voltage and current measurements on the stator side, it is insensitive to the parameters of the machine. Direct power control is more advantageous than vector control since the settling time and peak overshoot in case of vector control scheme is higher than that of direct power control scheme. The direct power control of the generator has been embedded in an optimal power controller for maximum energy capture in a wind energy application. Pitch angle control for wind turbine also implemented to limit the generator speed to maximum speed at higher wind speeds so that the system can work satisfactorily for higher wind speeds also.

REFERENCES

[1] Joris Soens, Vu Van Thong, Johan Driesen, Ronnie Belmans, "Modeling w ind turbine generators for power system simulations" , European Wind Energy Conference EWEC, Madrid, 16 – 19 June 2003.

[2] Branislav Dosijanoski, "Simulation of Doubly-Fed Induction generator in a Wind Turbine", XI International PhD Workshop OWD 2009, 17–20 October 2009.

[3] I. Takahashi and Y. Ohmori, " High performance direct torque control of an induction motor", IEEE Trans. Ind. Applicat.,vol.25, pp.257–264, Mar./Apr. 1989.

[4] Carlos J. Ramos António P. Martins Armando S. Araújo Adriano S. Carvalho "Current Control in the Grid Connection of the Double-Output Induction Generator Linked to a Variable Speed Wind Turbine", pp 7803-7474, 2002 IEEE Explore.

[5] E.Bogalecka, "Power control of a double fed induction generator without sensor," "in Proc. Conf. Rec. EPE Brighton vol. 8, ch. 50, 1993, pp. 224–228

[6] L. Xu and W. Cheng, " Torque and reactive power control of a doubly fed Induction Machine by position sensorless scheme", IEEE Trans.Ind.Applicat.,vol.31, May/June 1995, pp.636–642.

[7] 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," Proc. Inst. Elect. Eng., pt. B, vol.143, May 1996, pp. 231–241.

[8] B.Shanker, S.P.Gupta and P.Agarwal, "Investigation on static slip energy recovery system operated in generating mode", Journal of Institution of Engineers, july 1996, pp. 98-102.

[9] Yi Guo, John N. Jiang, and Choon Yik Tang, "Nonlinear Control of Wind Power Generation Systems", 2009 IEEE explore.

[10] R. Datta and V.T.Ranganathan, 1999 "Decoupled control of active and reactive power for a grid - connected doubly - fed wound rotor induction machine without position sensors," in Proc. Conf. Rec. 1999 IEEE/IAS Anu.Meeting, pp. 2623–2630.

[11] R. Datta and V. T. Ranganathan, "Method for direct control of active and reactive power from the rotor side for a grid connected doubly-fed slip-ring induction machine without position encoder," Indian Patent 797/MAS/99, June 8, 1999.

[12] S. Muller ,M. Deicke and R.W. De Doncker, "Adjustable Speed Generators for Wind Turbines based on Doubly-fed Induction Machines and four Quadrant IGBT Converters Linked to the Rotor", 35th Annual Meeting - IEEE Ind. App. Soc. (IAS), Rome, Italy, Oct. 8-12,2000.

[13] Rajib Datta and V. T. Ranganathan, "Direct Power Control of Grid- Connected Wound Rotor Induction Machine Without Rotor Position Sensors" IEEE Transactions on Power Electronics, Vol. 16, No. 3, MAY 2001,p.p.390-399.

[14] Zbigniew Krzeminski ," in proc. 2002 Power Conversion Conference on Sensorless Multiscalar Control of Double Fed Machine For Wind Power Generators ", Volume1, 2-5 April 2002, pp.334 – 339.

[15] Rajib Datta and V.T. Ranganathan, "Variable-Speed Wind Power Generation Using Doubly Fed Wound Rotor Induction Machine - A Comparison With Alternative Schemes", IEEE Transactions on Energy Conversion vol.17,NO. 3, SEPTEMBER 2002, pp. 414-421.

[16] S.Muller , M.Deicke And Rik W.De Doncker , "Doubly Fed Induction Generator System For Wind Turbines" , IEEE Industrial Applications Magazine. May/June 2002, pp. 26-33.

[17] Arantxa Tapia,G erardoTapia et.al, "Modeling and Control of a Wind Turbine Driven Doubly Fed Induction Generator", IEEE Transactions on Energy Conversion vol.18,NO. 2, June 2003 , pp.194-204.

[18] Christian Dufour and Jean Belanger, "in 35th Annul lEEE Power Elecronics Specinlisrs Conference, 2004 ,A Real-Time Simulator for Doubly Fed Induction Generator based Wind Turbine Applications" , pp.3597-3603.

[19] Gautam Poddar and V. T. Ranganathan, "Direct Torque and Frequency Control of Double – Inverter - Fed Slip – Ring Induction Motor Drive" IEEE Trans. Ind. Applicat., vol.51, NO. 6, DECEMBER 2004, pp. 1329–1337.

[20] J. A. Baroudi, V.Dinavahi and A. M. Knight , "in proc.2005 IEEE Conference, A Review Of Power Converter Topologies For Wind Generators ", Electrical Machines And Drives, pp 458 – 465.

[21] Gautam Poddar and V. T. Ranganathan, "Sensorless Double-Inverter-Fed Wound-Rotor Induction - Machine Drive" , IEEE Transactions on Industrial Electronics, Vol. 53, NO. 1, February 2006, pp. 86-95.