2009 3rd International Conference on Power Electronics Systems and Applications

Steady State Analysis and Control of Wind Turbine Driven Double-Output Induction Generator

Chitti Babu B[1]   K.B. MOHANTY[2]   C. POONGOTHAI[3]

[1] Department of Electrical Engineering, National Institute of Technology, Rourekla-769008, INDIA
E-mail: bcbabunitrkl@ieee.org
[2] Department of Electrical Engineering, National Institute of Technology, Rourekla-769008, INDIA
E-mail: kbmohanty@nitrkl.ac.in
[3] Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai-600036, INDIA
E-mail: cpkothai.pediit@gmail.com

Abstract–In this paper the steady state analysis and control of double-output induction generator (DOIG) for variable speed wind energy conversion system is studied. The objective is to analyze the performance of DOIG under steady state conditions. In addition, IGBT based current regulated voltage source converter with carrier-based Sinusoidal Pulse Width Modulation (PWM) method for rotor side converter has been proposed. Stator oriented flux vector control is employed to achieve the independent control of active and reactive power of the machine. The machine is modeled in vectorized form in a synchronous reference frame. The complete simulation model is developed for such machine under variable speed operation using MATLAB Simulink environment for effectiveness of the study.

Keywords–Vector control, Double-output induction generator (DOIG), dynamic d-q model, PWM inverter, steady state equivalent circuit.

I. INTRODUCTION

The conventional energy sources are limited and have pollution to the environment. So more attention and interest have been paid to the utilization of renewable energy sources such as wind energy, fuel cell and solar energy. Wind energy is the fastest growing and most promising renewable energy source among them due to economically viable [1-3]. In India, the total installed capacity of wind power generation is 8754 MW in the year 2008.By the end of 2012, the total installed capacity is going to be reached to 12000 MW according to ministry of new and renewable energy, India and total installed capacity of wind energy is estimated to be more than 160 GW [WWEA] all around the world. There were several attempts to build large scale wind powered system to generate electrical energy. The first production of electrical energy with wind power was done in 1887 by Charles brush in Cleveland, Ohio.DC generator was used for power production and was designed to charge the batteries. The induction machine was used at the first time in 1951. Many applications of wind power can be found in a wide power range from a few kilowatts to several megawatts in small scale off-grid standalone systems or large scale grid-connected wind farms. Recently Enercon constructed a wind turbine of 4.5 MW with rotor diameter of 112.8 meters. Due to lack of control on active and reactive power, this is type of dispersed power generation causes problems in the electrical connected system. So this requires accurate modeling, control and selection of appropriate wind energy conversion system.

There are two basic options of wind power conversion systems such as fixed speed and variable speed operation. In fixed operation, the wind turbine can be operated at a constant speed by pitch control even under varying wind speeds. This option was very common because of the cost involved with the power converter needed in the variable speed generation to convert the variable frequency to match the constant grid frequency. In variable speed operation, the wind turbine rotational speed can be allowed to vary with wind to maintain a constant and optimum tip speed ratio. The variable speed operation by active pitch control allows optimum efficiency operation of the turbine over a wide range of wind speeds, resulting in increasing power outputs and reduced mechanical stresses on the rotor [4].

For variable speed generation, an induction generator is the ultimate choice due to its flexible rotor speed characteristics in contrast to the constant speed characteristics of synchronous generator. DOIG configuration is best suited for variable speed generation since it can be controlled from rotor side as well as stator side. This is possible since rotor circuit is capable of bidirectional power flow. The rotor will observe slip power from the in sub-synchronous operation and can feed slip power back to grid in super-synchronous operation. The rotor converter needs thus only to be rated for a fraction 25% (Slip Power) of the total output power [5]. All these advantages make the DOIG a favorable candidate for variable speed operation.

In this paper, the steady state analysis and control of double-output induction generator (DOIG) for variable speed wind energy conversion system is studied. The machine is modeled in vectorized form in the synchronous frame. An attempt to develop a vectorized dynamic model of induction machine which can be simulated as both motoring and generating mode when testing control strategies. The choice of synchronous rotating reference frame makes it particularly favorable for the simulation of doubly-fed configuration in transient as well as steady state conditions. The d-axis is aligned with the stator space voltage vector. Stator oriented flux vector control is employed to achieve the independent control of active and reactive power of the machine. The injected rotor voltages (at slip frequency) are derived from PI controllers that regulate the active and reactive powers delivered by the generator. In addition, IGBT based current regulated voltage source converter with carrier-based sinusoidal PWM method for rotor side converter has been proposed. The complete simulation model is developed for such machine under variable speed operation using MATLAB simulink environment for effectiveness of the study.

Digital Reference: K210509066

II. DYNAMIC MODELING AND STEADY STATE EQUIVALENT CIRCUIT OF DOIG

A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Fig. 1.The stator of the wound rotor induction machine is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back IGBT voltage-source inverters with a common DC bus. The grid side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The proper rotor excitation is provided by the rotor side power converter. The general model for wound rotor induction machine is similar to any fixed-speed induction generator as follows.

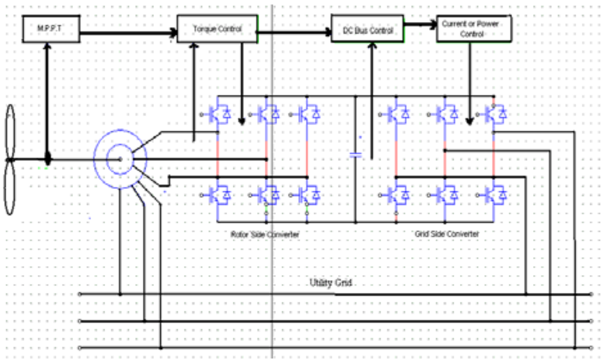

Fig.1: System configuration of DOIG

Stator Voltage Equations:

$$V_{qs} = p\lambda_{qs} + \omega\lambda_{ds} + r_s i_{qs}$$
$$V_{ds} = p\lambda_{ds} - \omega\lambda_{qs} + r_s i_{ds} \qquad (1)$$

Rotor Voltage Equations:

$$V_{qr} = p\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} + r_r i_{qr}$$
$$V_{dr} = p\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} + r_r i_{dr} \qquad (2)$$

Power Equations:

$$P_s = \frac{3}{2}\left(V_{ds} i_{ds} + V_{qs} i_{qs}\right)$$
$$Q_s = \frac{3}{2}\left(V_{qs} i_{ds} - V_{ds} i_{qs}\right) \qquad (3)$$

Torque Equation:

$$T_e = -\frac{3}{2}\frac{P}{2}\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \qquad (4)$$

Flux Linkage Equations:

Stator Flux Equations:

$$\lambda_{qs} = \left(L_{ls} + L_m\right) i_{qs} + L_m i_{qr}$$
$$\lambda_{ds} = \left(L_{ls} + L_m\right) i_{ds} + L_m i_{dr} \qquad (5)$$

Rotor Flux Equations:

$$\lambda_{qr} = \left(L_{lr} + L_m\right) i_{qr} + L_m i_{qs}$$
$$\lambda_{dr} = \left(L_{ls} + L_m\right) i_{dr} + L_m i_{ds} \qquad (6)$$

Therefore, for the doubly fed induction machine in steady state, then the desired amount of reactive power flow into the stator can be controlled by controlling i_{ds} as indicated by the equation (3) If the reactive power consumed by the stator leakage inductance is very small and neglected. Since the control of stator active power P_s via i_{qs} and the control of stator reactive power Q_s via i_{ds} are essentially decoupled, The stator flux oriented control is generally necessary since it maintains a constant level, while the control of reactive power becomes possible. From the above expressions, the steady state equivalent circuit of DOIG drawn as follows.

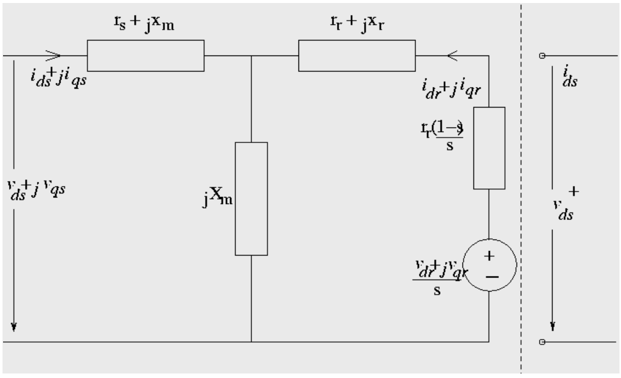

Fig.2: Steady state equivalent circuit of DOIG

2.1 Steady State Analysis

How the rotor speed of induction generator involves on the power flow of the studied system is discussed below. Fig. 3 shows the reactive power of the rotor, stator, grid and output of grid side converter respectively with respect to rotor speed. It is observed that the induction machine operated as motor mode when the rotor is driven below the synchronous speed. The negative sign of active power means that the power absorbed by the induction machine, while the rotor runs at a speed more than synchronous speed of the revolving magnetic field and the active power is supplied from induction generator to the grid. The reactive power always absorbed by the induction machine, despite its operating mode. Fig. 4 shows the reactive power of the rotor Vs active power of the rotor. It is observed that the grid side absorbed the reactive power when the induction machine operated in motor mode, since the rotor side converter provided the amount of reactive power which the induction motor cannot absorb completely. Fig. (5) depicts the locus of reactive power of stator and rotor during steady state conditions. It is evident that the both are almost equal, except the losses of the transmission lines. From the above observations, the motor mode has higher efficiency than the machine operated in generator mode, since the stator of the machine sinks more reactive power in the generator mode. The correlation with the steady-state analysis results are seems to be fair. In fact at the higher speeds the DOIG produces slightly more power.

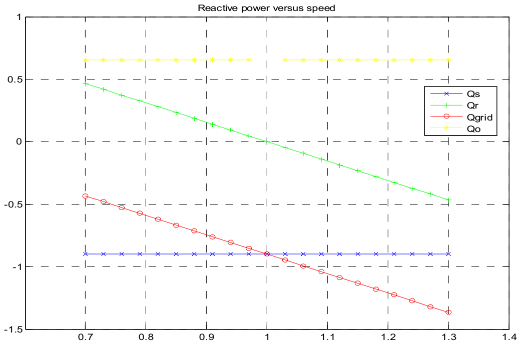

Fig. 3: Response of reactive power of the stator, rotor, grid and output

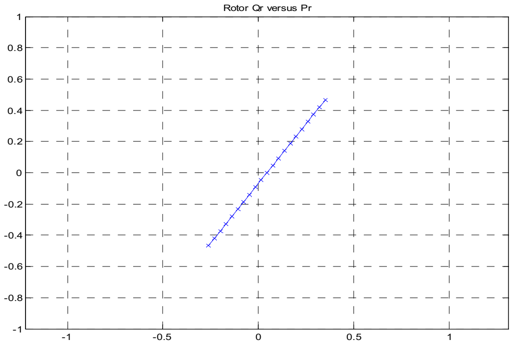

Fig. 4: Response of rotor active power with respect to reactive power

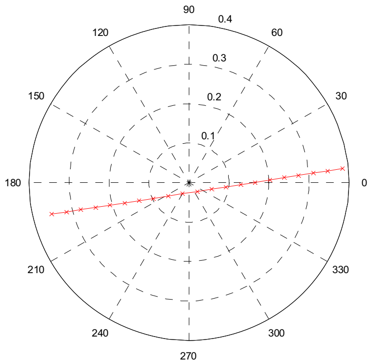

Fig. 5: Locus of the reactive power of the rotor with respect to stator

2.2 Rotor Side Converter Control:

Aligning the d-axis of reference frame to be along the stator flux linkage (stator flux oriented control) will result in

$\lambda_{qs}^e = 0$

And hence from (8):

$$i_{qs}^e = -\frac{L_m}{L_{ls}+L_m} i_{qr}^e \tag{7}$$

Substituting for i^e_{qs} into (7) will result in:

$$T_e = -\frac{3}{2}\frac{P}{2}\frac{L_m}{L_{ls}+L_m}\lambda_{ds}^e i_{qr}^e \tag{8}$$

For λ_{ds}^e to remain unchanged at zero, $p\lambda_{ds}^e$ must be zero. Substituting for $p\lambda_{ds}^e$ using (1) and (2) will result in $V_{ds}^e = r_s i_{ds}^e$ Neglecting stator resistance will lead to $V_{ds}^e = 0$ .Substituting for $V_{ds}^e = 0$ eqn. (3) will be simplified as follows:

$$\begin{aligned} P_s^e &= \frac{3}{2}\left(V_{qs} i_{qs}^e\right) \\ Q_s^e &= \frac{3}{2}\left(V_{qs} i_{ds}^e\right) \end{aligned} \tag{9}$$

Therefore, the above equations show that active and reactive powers of the stator can be controlled independently. PWM schemes are used to synthesize the output voltage of a voltage source inverter. In PWM methods switching instants are chosen so that the desired fundamental component is obtained while acceptable harmonic performance is achieved.

III. RESULTS AND DISCUSSION

Based on the control strategy discussed above, Fig.6 shows the rotor side converter control strategy with current regulated PWM. A current-regulated PWM voltage source inverter provides field oriented currents i_{qr} and i_{dr} to the rotor circuit, controlling active power and stator reactive power, respectively. Active power command is given by the turbine optimal torque speed profile and reactive power command is calculated to minimize the machine copper losses. Overall active power generated is directly related to the torque, as indicated by (7) and (8). In the d-q reference frame as determined by the machine stator flux, its currents i_{qr} and i_{dr} are also field oriented, controlling Active and Reactive power of grid (Ps and Qs) respectively. Therefore, as discussed earlier, Ps is controlled through I_{qr} to stabilize the dc bus voltage and Qs is controlled through i_{dr} to meet the overall reactive power command. Fig. 7 & Fig. 8 illustrate the stator voltage for the doubly-fed connection over a speed range increasing from the normal generator synchronous speed of 1500rpm and d-q rotor voltages respectively. It is clear from this figure that constraining the stator reactive power results in a small increase in the turbine speed but a more significant increase in the rotor current i_{dr}. This additional current has to be provided by the rotor converter and is needed to inject reactive power into the rotor to ensure stator active power as shown in Fig. 12. The rotor current in this case however remains relatively constant as the speed increases. The rotor voltage on the other hand is determined mainly by the rotor speed and increases linearly as the rotor slip increases, or speed reduces.

A detailed set of simulated results using dynamic vector control models were undertaken over a speed range from approximately 10% below synchronous speed (1500 rpm) to 40% below. Fig. 11 illustrates the electromagnetic torque of the DOIG during generating. Again there is a close correlation between the steady-state model and the

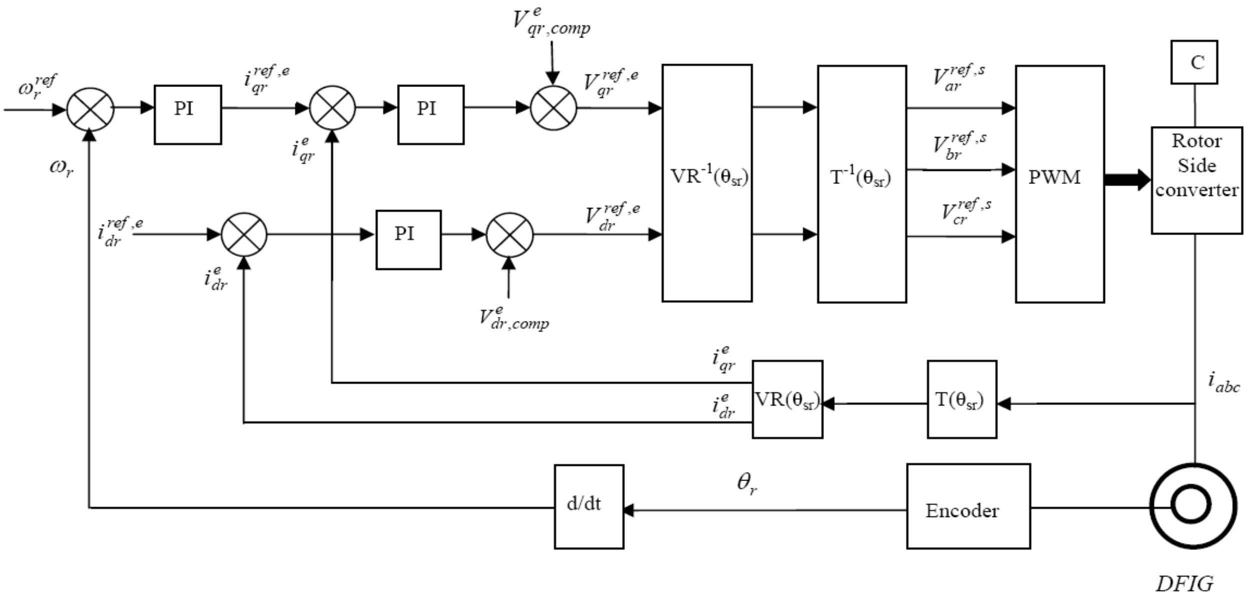

Fig.6. Rotor side Converter control strategy

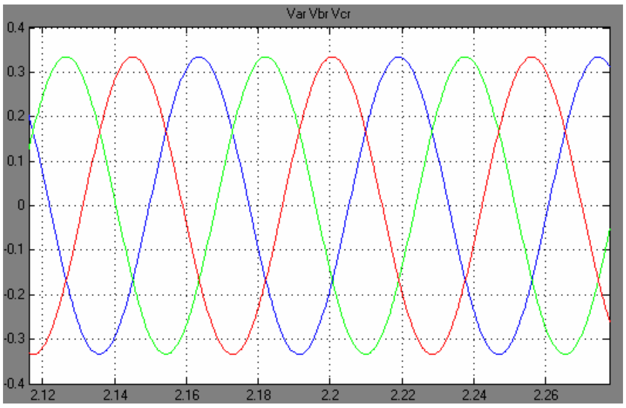

Fig. 7: Response of three-phase Stator voltages

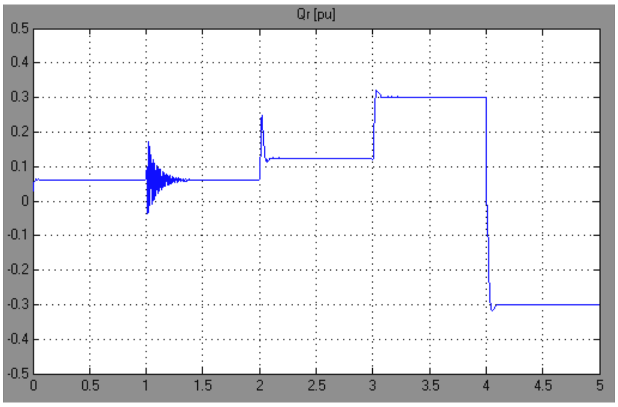

Fig. 9: Response of reactive power of the stator

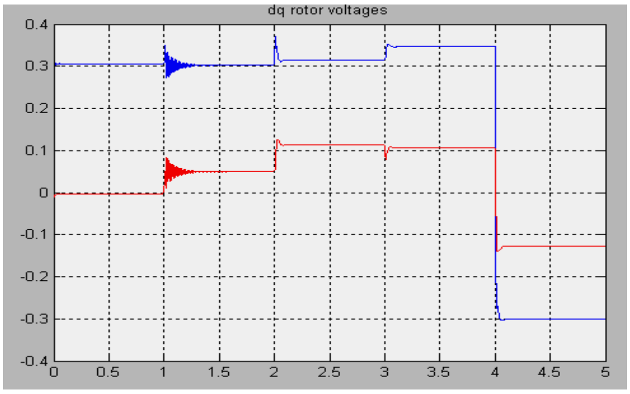

Fig. 8: Response of d-q rotor voltages

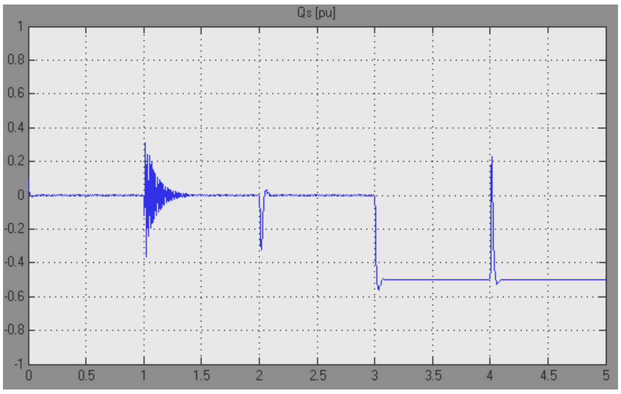

Fig. 10: Response of reactive power of the rotor

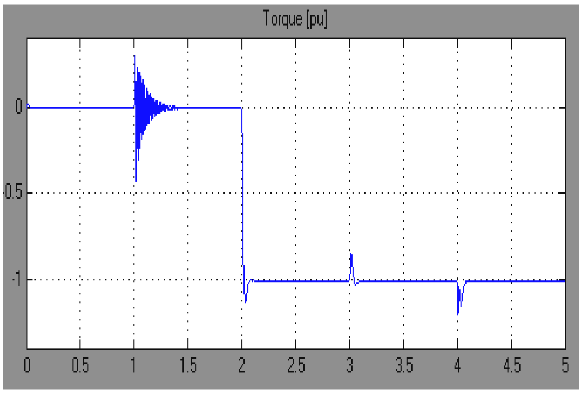

Fig. 11: Response of Electro magnetic torque of DOIG

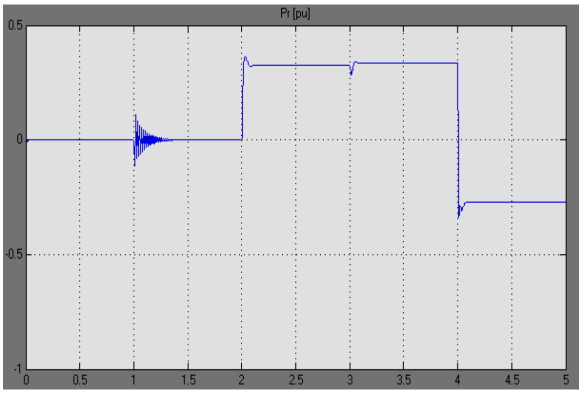

Fig. 12: Response of active power of the stator

simulated results using the dynamic control model. It is evident that the search for maximum grid power results in a reducing rotor voltage as the speed reduces. This particular operational feature is important and is due to the constraint that the air gap fluxes is maintained below the rated value to avoid over-fluxing the machine. In this case as the speed reduces, the rotor supply frequency reduces to keep the slip low and as a result the terminal voltage also reduces to avoid saturating the magnetizing paths in the generator.

Fig. 4 illustrates the simulated results of rotor active power vs. reactive power using dynamic vector model described in the previous section. The correlation with the steady-state model results is on the whole very good. In fact at the higher speeds the DOIG produces slightly more power. The benefits would therefore appear to lie in the rotor converter ratings. The overall rating of the converter is related to the required speed range, typically 30% of the generator rating as mentioned previously. However the VA converter rating would be translated into maximum current and voltage ratings of the switching devices in the converter. Fig. 9 and 10 illustrates the response of reactive power of both stator and rotor sides. This has been done by the control of d-q components of rotor.

IV. Conclusion

In this paper, steady state analysis and control of DOIG has been studied. The induction machine is modeled in vectorized form in the synchronous frame. By using this model steady state equivalent circuit of such machine has also been drawn. Furthermore, stator flux oriented vector control strategy has been examined for controlling active and reactive power of grid, stator and rotor sides. The behavior of the system was investigated during step change in wind variations. It was shown that it is possible to develop a set of equations describing the behavior of the wind turbine. In the further paper, SVPWM technique will be proposed for power quality study of grid connected DOIG system.

REFERENCES

[1] S. Muller, M. Deicke and R. W. De Doncker, “Doubly fed induction generator systems for wind turbine”, IEEE Industry Applications Magazine, Vol.8, No. 3, 2002, pp. 26-33.

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

[3] Luianc Mihet-Popa, Frede Blaabrierg, “Wind Turbine Generator Modeling and Simulation Where Rotational Speed is the Controlled Variable”, IEEE Transactions on Industry Applications, Vol.21, No.1, January/February 2004, pp. 257-264.

[4] J.G. Slootweg, H. Polinder and W.L. Kling, “Dynamic Modeling of a Wind Turbine with Doubly Fed Induction Generator”, Proceedings of IEEE, 2001.

[5] S. Chondrogiannis M. Barnes “Stability of doubly-fed induction generator under stator voltage orientated vector control”, Transaction on IET Renewable Power Generation, Vol. 2, No. 3, 2008, pp. 170–180.

[6] Yazhou Lei, Alan Mullane, Gordon Lightbody, and Robert Yacamini “Modeling of the Wind Turbine with a Doubly Fed Induction Generator for Grid Integration Studies”, IEEE Transactions on Energy Conversion, Vol.21, No.1, March 2006, pp.257-264.

[7] B.H.Chowdhary, Srinivas Chellapilla, “Doubly-fed induction generator for variable speed wind power generation”, Transactions on Electric Power System Research, Vol.76, Jan 2006, pp. 786-800.

[8] B.Chitti Babu, k.B.Mohanty and C.Poongothai, “Performance of double-output induction generator for wind energy conversion systems”, Proceedings of IEEE, 2008, pp. 933-938.

[9] B.Chitti Babu, K.B.Mohanty and C.Poongothai, “Control of double-output induction machine for variable speed wind energy conversion systems using dynamic vector approach”, IEEE Proceedings of TENCON 2008, International conference, 2008.

[10] Jamel Belhadj and Xavier Roboam “Investigation of different methods to control a small variable-speed wind turbine with PMSM drives”, Journal of Energy Resources Technology, Vol. 129 / 201, September 2007.