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Review Article

INVESTIGATION OF EFFECT OF CONTROL PARAMETERS ON DYNAMIC BEHAVIOR OF DOUBLY FED INDUCTION GENERATOR

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ABSTRACT
This paper deals with the modeling and simulation of a doubly fed induction generator and its control components. A 3th order model is used for DFIG modelling. The aim of this paper is investigating the effect of control parameters variations such as proportional and integral coefficients on dynamic behavior of DFIG. The result has been validated by DigSILENT Power Factory.

Keywords: *DFIG, Dynamic Behavior, Wind Turbine, Control Parameters Component, Form*

INTRODUCTION
Nowadays governments are searching other new energy resources. Rapid growth of energy consumption has obliged to use other renewable energy resources especially these resources produce no greenhouse gas and air pollution. Under this condition, the idea of using other renewable energy resources such as wind, solar, geothermal, biomass energy has been proposed.

The use of wind energy has numerous benefits such as compatible with environment, undependability, cleanness; therefore, most of industrial countries generate a considerable part of their energy by wind energy and pay more attention to this type of energy in their future developing plan.

In recent decades doubly fed induction generators (DFIG) have been used in wind farms. DFIG is a wound rotor induction generators fed through rotor as well. The advantages of DFIG are low mechanical stress on turbine shaft, independent and stable control of active and reactive power, low nominal current and torque ripple reduction. Due to the mentioned benefits, the number of wind power plant equipped with DFIG has increased continuously in power system. Therefore, their effect on power network must be investigated especially in dynamic behavior point of view. When an uncommon generator is used in power system it indicates a different behavior under normal conditions and contingencies.

Nunes *et al.*, (2004) compared the margin of transient stability of variable speed DFIG and fixed speed squirrel cage induction generator in a wind power plant. DFIG is controlled by a voltage source inverter and current source inverter and it has been proved that transient stability of induction generator is lower than DFIG because of lower reactive power consumption. In Meegahapola *et al.*, (2008) transient and voltage stability of wind power plant equipped with induction generator and DFIG are compared for two cases of connection to low voltage grid (distribution network) and high voltage grid (transmission network).

Since the number of wind farms connected to 220 KV transmission network increase in china, Chi *et al.*, (2006) has studied the effect of wind power plant on static voltage stability by plotting P-V and Q-V curves and dynamic voltage stability by time-domain simulation for two cases of fixed speed and variable speed.

The paper is organized as follows:

In the second section, the topology of DFIC is illustrated. In the third section, various order model of DFIG are introduced especially third order model and the method of control will be presented in forth section. In the next part the dynamic behavior of wind power plant is analyzed when a disturbance occurs. The disturbance can be wind speed change, transmitted power variation and change of network structure. In the end, the conclusion of this study is presented.

DFIG Topology
DFIG is a wound rotor induction generation which can be fed via rotor winding as well. The stator is connected to network directly whereas rotor is connected to network via a bidirectional electronic power

converter. This converter feeding rotor circuit through slip rings and brushes can transmit power in two directions by changing voltage and frequency of rotor.
Consequently, the machine can act as either generator or motor. Figure (1) shows the topology of DFIG.

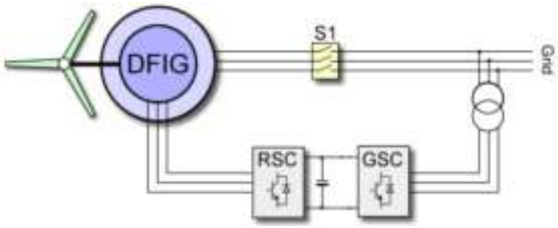

Figure 1: Scheme and Structure of DFIG Based on Wind Turbine Da Silva *et al.*, (2008)

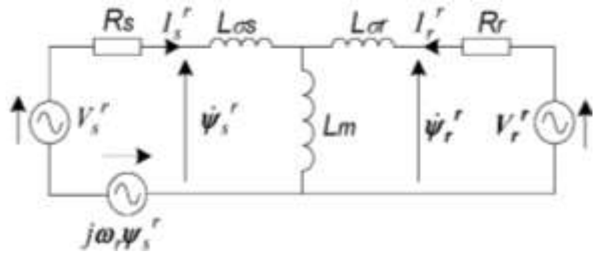

Figure 2: The Equivalent Circuit of DFIG (Pokharel, 2011)

DFIG Modeling

Fifth Order Model

In order to investigate the dynamic behavior of DFIG the electrical and mechanical equations must be described.
Figure (2) shows the equivalent circuit of the doubly fed induction generator in rotor reference frame.
These equations comprise a model of DFIG with five state variables. This model known as a fifth order model overlooks the effect of magnetic saturation, eddy currents and hysteresis but it captures the important dynamics in dynamic studies.
We can write the fifth order model in arbitrary reference frame as:

$$\bar{v}_s = -R_s \bar{i}_s + \frac{1}{\omega}\frac{d\bar{\psi}_s}{dt} + j\frac{\omega_b}{\omega}\bar{\psi}_s \quad (1)$$

$$\bar{v}_r = -R_r \bar{i}_r + \frac{1}{\omega}\frac{d\bar{\psi}_r}{dt} + j\left(\frac{\omega_b - \omega_{er}}{\omega}\right)\bar{\psi}_r \quad (2)$$

$$\bar{\psi}_s = -X_s \bar{i}_s - X_m \bar{i}_r$$

$$\bar{\psi}_r = -X_r \bar{i}_r - X_m \bar{i}_s \quad (3)$$

$$X_s = \omega L_s, X_r = \omega L_r, X_m = \omega L_m$$

$$\frac{d\omega_{re}}{dt} = \frac{T_m - T_e}{T_{ag}} \quad (4)$$

The fifth order model includes high frequency dynamics, which are not always of interest in classical electro-mechanical dynamic studies of large power systems for this reason, the third order model is introduced in the next section.

Third Order Model

The fifth order model represents the behavior of the generator in detail and comprises dynamic behaviour of stator current. Since the term of $\frac{1}{\omega}\frac{d\bar{\psi}_s}{dt}$ has little influence on system dynamic it can be neglected and equation (1) can be written as follows:

$$\bar{v}_s = -R_s \bar{i}_s + j\frac{\omega_b}{\omega}\bar{\psi}_s \quad (5)$$

And mechanical equation is described by (4).
In stability domain studies, since power system includes a large number of generators, transformers, transmission lines and loads, the third order model is used in order to reduce the order of system and consequently decrease the volume of calculations.
Under this condition some high transmit frequencies are eliminated in stator flux while the steady state response is unchanged.

DFIG Controller Implementation

When a four regions ac-ac converter connects to rotor winding of DFIG the vd and vq can be controlled independently.

It is useful that the equation of stator side of DFIG is represented as a voltage source $\frac{\omega_b}{\omega}E'$ behind a transient impedance as $\frac{\omega_b}{\omega}(R_s + jX')$. In this case, the relationship between stator voltage and stator become

$$v_s = \frac{\omega_b}{\omega}\left(E' - \left(R_s + jX'\right)i_s\right) \qquad (6)$$

Where $E' = j\frac{X_m}{X_r}\bar{\psi}_r$, $X' = X_s - \frac{X_m^2}{X_r}$

Also (2) can be written as

$$\bar{V}_r = -\frac{X_m}{X_r}R_r\bar{i}_r + \left(\frac{\omega_b - \omega_{er}}{\omega}\right)\bar{E}' - \frac{1}{\omega}\frac{X_m}{X_r}\left(X'\frac{X_r}{X_s}\frac{d\bar{i}_r}{dt}\right) \qquad (7)$$

Where E' can be rewritten as follows

$$\bar{E}' = \frac{1}{X_s}\left(\bar{V}\frac{\omega}{\omega_b}(X_s - X') - jX'X_m\bar{i}_r\right) \qquad (8)$$

Substituting (8) in (7) we have

$$V'_{dr} = V_{dr} - \left(\frac{\omega_b - \omega_{er}}{\omega}\right)E'_{dr}$$
$$V'_{qr} = V_{qr} - \left(\frac{\omega_b - \omega_{er}}{\omega}\right)E'_{qr} \qquad (9)$$

Therefore, v'_{qr} and v'_{dr} can be regulated separately. If the speed of reference frame is selected as the term of $\left(\frac{\omega_b - \omega_{er}}{\omega}\right)$ becomes small, i_{dr} and i_{qr} can be controlled by v'_{dr} and v'_{qr} respectively.

Active and reactive power can be calculated in terms of stator voltage and rotor current by stator voltage and rotor current.

If the speed of reference frame is equal to stator frequency and voltage vector coincides with direct axis the equation will be as follow:

$$P_s = \frac{3}{2}\frac{X_m}{X_s}v_{ds}i_{dr} \qquad (10)$$

$$Q_s = \frac{3}{2}\left[\frac{X_m}{X_s}v_{ds}i_{qr} - \frac{\omega}{\omega_b}\frac{V_{dr}^{2}}{X_s}\right] \qquad (11)$$

Therefore, the active power can be controlled by i_{dr} and reactive power can be controlled by i_{qr} respectively.

Power Control Converter

Power converter of DFIG is connected to rotor winding in one side through brush and slip ring and to power system through a step-up transformer in other side.

Its nominal power approximately is s_{max} p_n where s_{max} is the maximum amount of slip and p_n is nominal stator power.

In general, the maximum amount of slip ranges between 0.2 and 0.3. This converter comprises a PWM six legs inverter and a rectifier placed back to back and connected together through a capacitor as shown in figure (3).

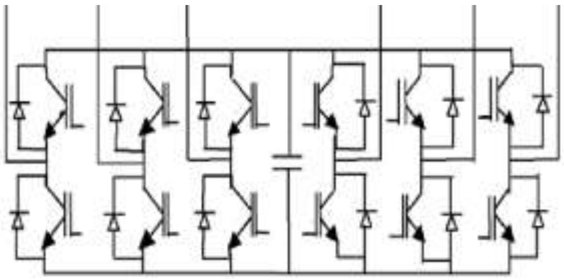

Figure 3: Back – Back Converter (Poller, 2003)

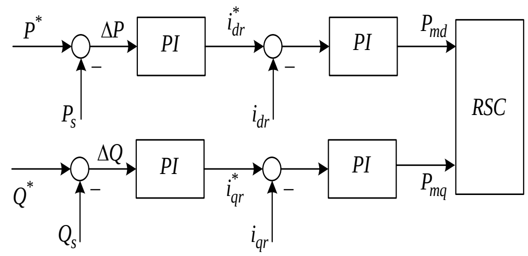

Figure 4: Control scheme of RSC (Pokharel, 2011)

Since active and reactive power are controlled by rotor side inverter its strategy control will be demonstrated only.

In the section IV, it was proved that the transmitted stator active and reactive power have linear relationship with i_{dr} and i_{qr} respectively. Also, v_{dr} and v_{qr} can be related to i_{dr} and i_{qr} by a linear relation respectively. According to the control scheme of rotor side converter can be shown as follows.

The first PI controller produces reference rotor current from the error of active power and reactive power. The second controller is used to produce modulation index of rotor side converter.

Dynamic Behavior of Wind Power Equipped with DFIG

In previous section the control strategy of wind turbine equipped with DFIG was illustrated and in this section the DFIG is connected to a real 8 buses network and the behaviour of DFIG is evaluated under various disturbances.

These disturbances consist of wind speed changes, active power variations and change of network structure result from a three phase short circuit and loss of a line. The variation of transmitted active power and speed generator are investigated as two important electrical and mechanical parameters, when the control parameters vary.

Case Study Power System

This section introduces the case study power system. The all of simulations has been done by DigSILENT Power Factory software in this paper. The sample network is an actual grid comprising a wind power plant, diesel generator and PV and connects to transmission grid through a 220 KV bus.

This grid has also been used in Petersson (2005). Figure (5) indicates the single line diagram of grid.

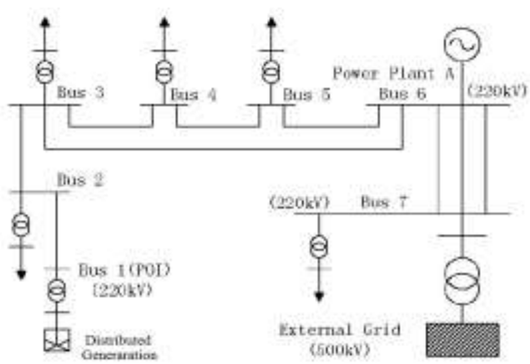

Figure 5: Single Line Diagram of the Studied System

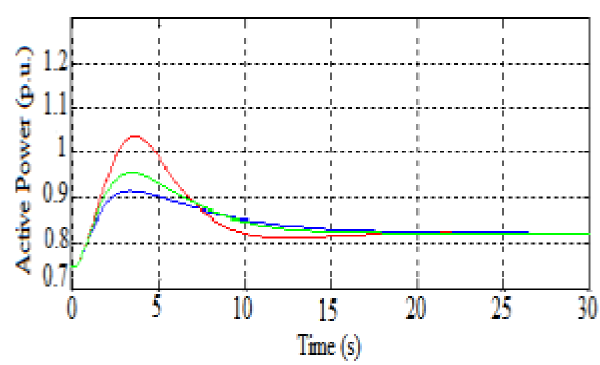

Figure 6: Variation of Active Power for Wind Speed Change for K_p=40 (Red) – 80 (Green) – 120 (Blue) and K_{ii}=0.1, K_{pp}=4, K_i=25

The Effect of Wind Speed Variations

In fact wind speed is one of the inputs of variable speed wind turbine system having a oscillating nature. The speed of wind oscillates frequently during all day.

Therefore, this parameter can directly affect power of turbine, wind turbine operation and even the entire of system. Figures (6) to (9) and tables (1) and (2) show the variation of transmitted power and speed for various control parameters when wind speed changes from 10 m/s to 15 m/s. The parameters are mechanical and electrical proportional (K_p, K_{pp}) and integral (K_i, K_{ii}) controllers in control circuit of mechanical and electrical parts of DFIG.

Table I: Overshoot and Settling Time of Active Power for Wind Speed Change for Kp=40 (Red) – 80 (Green) – 120 (Blue) and K_{ii}=0.1, K_{pp}=4, K_i=25

K_p	**Overshoot**	**Settling Time**
20	34.17%	20.74
40	26.04%	15.78
60	20.54%	11.52
80	16.63%	14.08
100	13.62%	16.45
120	11.3%	18.82

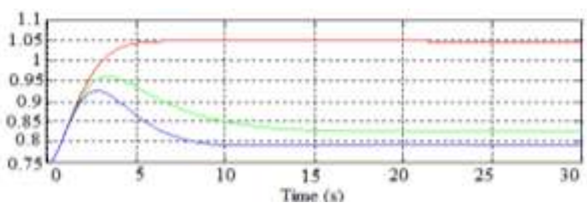

Figure 7: Variation of Active Power for Wind Speed Change for K_i=5 (Red) – 25 (Green) – 45 (Blue) and K_{ii}=0.1, K_{pp}=4, K_p=80

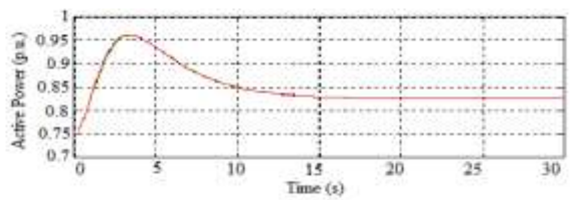

Figure 8: Variation of Active Power for Wind Speed Change for K_{ii}=0.1 (Red) –0.4 (Green) – 1 (Blue) and K_i=25, K_{pp}=4, K_p=80

Table II: Overshoot and Settling Time of Active Power for Wind Speed Change for Ki=5 (Red) – 25 (Green) – 45 (Blue) and K_{ii}=0.1, K_{pp}=4, K_p=80

K_i	**Overshoot**	**Settling Time (s)**
5	-	Infinite
15	%14.04	22.16
25	%15.66	14.08
35	%17.03	10.44
45	%18.86	8.384

As seen in above figures and tables when the mechanical proportional controller increases the overshoot of transmitted active power decrease but there is no specific trend in setting time variation. In other words, at first these parameters decrease and then increase. When mechanical integral value rises the active power overshoot increases gradually while settling time decrease. Also, steady state error is very high for low integral coefficients.

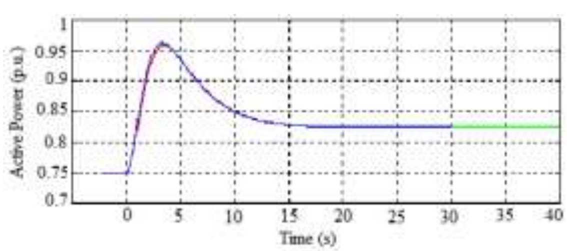

Figure 9: Variation of Active Power for Wind Speed Change for K_{pp}=0.4 (Red) – 4 (Green) – 8 (Blue) and K_{ii}=0.1, K_{pp}=4, K_p=80

The variation of transmitted active power are shown in figures (8) and (9) for various electrical proportional and integral values. As seen, overshoot and settling time have no change when they vary.

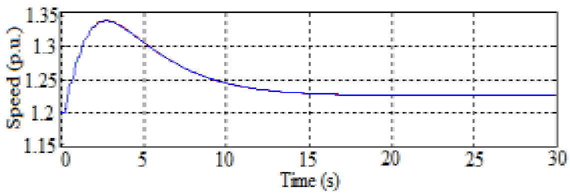

Figure 10: Variation of Speed for Wind Speed Change for K_{ii}=0.1 (Red) – 0.4 (Green) – 4 (Blue) and K_i=25, K_{pp}=4, K_p=80

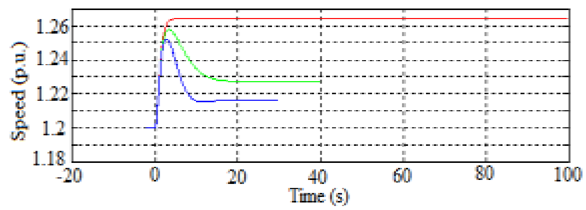

Figure 11: Variation of Speed for Wind Speed Change for K_i=5 (Red) – 25 (Green) – 45 (Blue) and K_{ii}=0.1, K_{pp}=4, K_p=80

Table 3: Overshoot and Settling Time of Speed for Wind Speed Change for K_i=5 (Red) – 25 (Green) – 45 (Blue) and K_{ii}=0.1, K_{pp}=4, K_p=80

K_i	**Overshoot**	**Settling Time (s)**
15	%8.95	20.54
25	%8.8	12.94
35	%8.84	9.233
45	%2.96	7.425

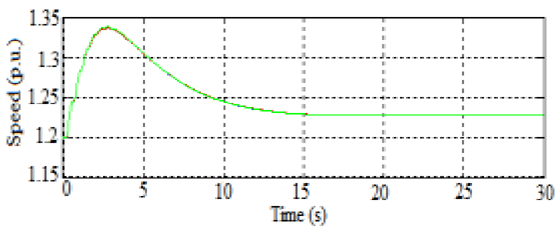

Figure 12: Variation of Speed for Wind Speed Change for K_{pp}=0.4 (Red) – 4 (Green) – 8 (Blue) and K_{ii}=0.1, K_i=25, K_p=80

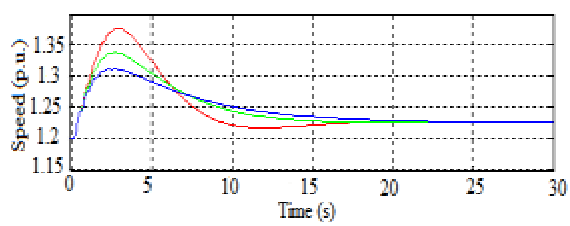

Figure 13: Variation of Speed for Wind Speed Change for K_p=40 (Red) – 80 (Green) – 120 (Blue) and K_{ii}=0.1, K_i=25, K_{pp}=4

Table 4: Overshoot and Settling Time of Speed for Wind Speed Change for K_p=40 (Red) – 80 (Green) – 120 (Blue) and K_{ii}=0.1, K_i=25, K_{pp}=4

K_p	**Overshoot**	**Settling Time (s)**
20	%15.02	12.32
40	%12.31	14.32
60	%10.16	10.254
80	%9.13	12.94
100	%8.25	14.16
120	%7	17.03

Figures (10) to (15) and tables (3) and (4) indicate the variation of DFIG's Speed and overshoot and settling time for various proportional and integral coefficients. As seen in these figures, the proportional and integral value change has no effect on speed of DFIG but when mechanical proportional coefficients increases the overshoot decreases.

Effect of Structure Changes

Change of structure grid is a disturbance which can cause fluctuation of network and generator parameters. The most severe disturbance is three phase short circuit that if it occurs on transmission line it

can trip the circuit breaker of line. Therefore, this disturbance causes fluctuation in generator parameters and changes operating point of grid because the equivalent impedance seen from generator changes.
In this section a short circuit is applied to one of transmission line near the DFIG (the line between bus 3 and 6) and then the line is disconnected by a circuit breaker. The effect of control parameters variations on the fluctuation of generator and grid is investigated.
The duration of the short circuit is 150 ms and is removed when the line is disconnected. Figures (14) and (15) indicate the variation of active power and speed for various control parameters.
When a fault occurs near a generator, the speed of generator increases as long as it is not eliminated. If the generator remains stable the variation of speed is attenuated and return to its regulated value. Unlike synchronous generators, the active power rises during fault because when the voltage of generator bus plunges the amount of active power decreases drastically. Also, as shown in these figures the change of control parameters has no effect on active power and speed of generator and their response is independent from these parameters.

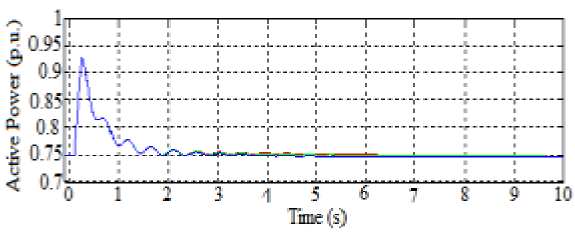

Figure 14: Variation of Active Power for Structure Grid Changes Wind Speed Change for Ki=5 (Red) – 25 (Green) – 45 (Blue) and Kii=0.1, Kp=80, Kpp=4

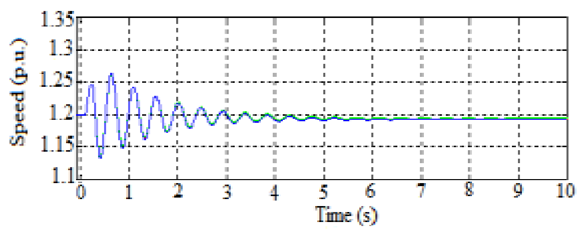

Figure 15: Variation of Speed for Wind Speed Change for K_p=40 (Red) – 80 (Green) – 120 (Blue) and K_{ii}=0.1, K_i=25, K_{pp}=4

Conclusion

Considering the shown figures and given tables in this paper, it can be conclude that as (K_p) and (K_i) (mechanical parameters) increase the setting time and overshoot of active power and speed increase and this can continue till stability margin of generator. However, change of (K_{pp}) and (K_{ii}) (Electrical parameters) has no impact on system response.
When a short circuit associating with changing the structure of network occurs, none of mechanical and electrical control parameters has no impact on transmitted active power and speed of generator. This indicates that when a three phase short circuit occurs at one of transmission lines, change of control parameters is not able to improve fluctuation of active power and speed. Generally, speaking, it can be concluded that mechanical control parameters (K_{pp}) and (K_{ii}) have no influence on active power and speed oscillation. However, electrical control parameters can increase the speed of response and overshoot of speed and active power for all disturbances except short circuit.

REFERENCES

Chi Y, Liu Y and Wang W (2006). Member IEEE, Huizhu Dai "Voltage Stability Analysis of Wind Farm Integration into Transmission Network. *2006 International Conference on Power System Technology.*
Da Silva JL, de Oliveira RG, Silva SR, Rabelo B and Hofmann W (2008). A Discussion about a Start-up Procedure of a Doubly-Fed Induction Generator System" *NORPIE/2008, Nordic Workshop on Power and Industrial Electronics, Helsinki, Finland.*
Kundur P (1994). *Power Systems Stability and Control*, (USA, New York: McGraw-Hill).
Meegahapola L, Flynn D and Littler T (2008). Transient Stability Analysis of a Power System with High Wind Penetration. *Proceedings of the 43rd International Universities Power Engineering Conference, (UPEC 2008).*

Muñoz JC and Cañizares CA (2011). Comparative Stability Analysis of DFIG-based Wind Farms and Conventional Synchronous Generators. *Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES.*
Nunes MVA, Lopes JAP and Zürn HH (2004). Influence of the Variable-Speed Wind Generators in Transient Stability Margin of the Conventional Generators Integrated in Electrical Grids. *IEEE Transactions on Energy Conversion* **19**(4).
Nunes MVA, Lopes JAP and Zürn HH (2004). Influence of the Variable-Speed Wind Generators in Transient Stability Margin of the Conventional Generators Integrated in Electrical Grids. *IEEE Transactions on Energy Conversion* **19**(4).
Petersson A (2005). Analysis, Modeling and Control of Doubly-Fed Induction Generators for Wind Turbines", Ph.D. dissertation, Chalmers Univ. of Technology, Sweden.
Pokharel B (2011). Modeling, Control and Analysis of a Doubly Fed Induction Generator Based Wind Turbine System with Voltage Regulation. Master of Science in Electrical Engineering, Tennessee Technological University.
Poller MA (2003). Doubly-Fed Induction Machine Models for Stability Assessment of Wind Farms. In *the IEEE Conference of the Power Tech,* Bologna.
Technical Documentation (2007). *Doubly-Fed Induction Machine,* published by (DIgSILENT GmbH, Germany).
Yang SY, Zhang X, Zhang CW and Chang L (2007). Development of a Variable Speed Wind Energy Conversion System Based on Doubly Fed Induction Generator. In: *Applied Power Electronics Conference, IEEE* 1334-1338.