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Full Length Research Paper

Maximum power point tracking of variable speed wind energy conversion system

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This paper proposes a simple method to maximum power control of wind turbine and induction generator connected with two back to back voltage source converters to grid. Machine currents are controlled by indirect vector control method. In this method, generator side converter controls the maximum excitation (air gap flux) by machine's d-axis current and controls generator torque by machine's q-axis current. Induction generator speed is controlled by tip speed ratio (TSR) upon the wind speed variations in order to generate the maximum output power. Grid side converter regulates the DC link voltage and injective active power by d-axis current and regulates the injective reactive power by q-axis current using simple control method P-Q. Simulation results show that the proposed method operates correctly.

Key words: Maximum power control, variable speed wind system, squirrel cage induction generator, vector control.

INTRODUCTION

Nowadays, among the renewable energy sources, wind systems are more economic in comparison with the others (Weisser and Garcia, 2005). Variable speed wind systems deliver 20 to 30% more energy than the constant power systems. Also, they reduce the power oscillation and optimize the reactive power presentation (Kim and Kim, 2007). In order to get the maximum power in different wind seeds, turbine speed should be able to vary in a great rage. Selecting the type of generator depends on different elements, such as kind of function, machine characteristics, maintenance and price. Achieving the maximum power under direct connection of induction generator to the grid in constant frequency and voltage condition is impossible, because direct grid connection of induction generator causes its inability in wide speed variations. This results in the operation of induction generator in a speed in which the maximum power of wind turbine can not be extracted. Doubly fed induction generator (DFIG) has no ability to operate in wide range of speed variations despite the fact that it is greatly used in wind systems. Permanent magnet synchronous generators (PMSG) are too expensive to be used in high power rates.

Squirrel cage induction machines, are used greatly for industrial purposes, because of their low cost, robustness and easy maintenance. These advantages introduce this machine as an appropriate choice to be applied in variable speed wind systems (Senjyu et al., 2006).

Power created by the wind is related to the 3rd power of wind speed. Applying power electronics converters to transfer induction generator's power to grid by the possibility of speed variation in a great range is preferred, because of their great advantages. Wind turbines with power electronics circuits in the 4 to 5 MW power range will be applied, greatly in near future (Badrul and Chellapilla, 2006). The method applied to control the speed and power of synchronous and induction generators are now applied to the wind energy converting systems (WECS) to obtain the maximum power of wind

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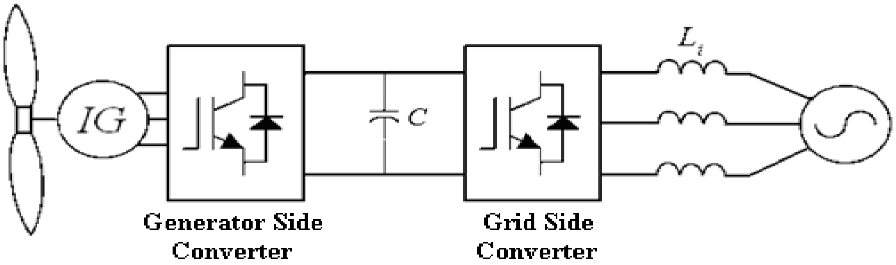

Figure 1. Connection of wind power generation system to grid through back to back inverters.

turbine (Surgevil and Akpınar, 2005). Back to back converter is an appropriate choice for squirrel cage induction generator used in wind system (Pena et al., 2001). Figure 1 shows the wind power generation system connected through two back to back converters to grid.

Vector control methods are used to separately control the torque and machine flux (Abo-Khalil et al., 2004). In this paper, indirect vector control method is used to control generator where d-axis current controls the flux and q-axis current controls the machine speed. Also, machine speed is regulated in a way that maximum energy as possible will be obtained. In order to connect the system to the grid, two back to back power electronics converters are used. In order to control the grid side converter, the grid injected active and reactive powers are calculated in d-q axis and a proportional-integral (PI) controller regulates the desired values of P and Q. In this paper, a simple method without any complicated calculations is proposed to maximum power control of wind turbine and induction generator connected with two back to back voltage source converters to grid. Simulation results are presented by MATLAB/SIMULINK software. Simulation results confirm the back to back converter's appropriate operation and also confirm the operation of power injection to grid applying induction generator.

PROPOSED SYSTEM

The proposed system consists of five main parts: wind model, wind turbine, turbine maximum power control, induction generator, generator side converter control and grid side converter control. These parts are discussed and finally the simulation results have been introduced.

Wind model

The model applied for this simulation is composed of three components and is described as follow (Kim and Kim, 2007):

$$V_{WIND} = V_{BASE} + V_{GUST} + V_{RAMP} \tag{1}$$

where V_{BASE} is the main component, V_{GUST} is the gust component and V_{RAMP} is the ramp component. The main component is a constant speed. Ramp component can be expressed by a sinusoidal function which is considered as a composition of several different sinusoidal functions and gust component is considered as storm and sudden wind.

Wind turbine

The torque generated by wind blow is described by the following relations:

$$\lambda = \frac{\omega_M R}{V_{WIND}} \tag{2}$$

$$P_M = \frac{1}{2}\rho\pi R^2 C_P V_{WIND}^3 \tag{3}$$

$$T_M = \frac{P_M}{\omega_M} = \frac{1}{2}\rho\pi R^5 C_P \frac{\omega_M^3}{\lambda^3} \tag{4}$$

where V_{WIND} is wind speed, *R* is the blades radius, ρ is the air density, ω_M is rotor angular speed and λ is the tip speed ratio (TSR), C_P is the power conversion factor which can be defined as turbine power in proportion with wind power and is related to blades aerodynamic characteristics. Resulted mechanical torque is applied as the input torque to the wind generator and makes generator to operate. Power conversion factor is expressed as the function of tip speed ratio λ as follows (Abo-Khalil et al., 2004):

$$C_P = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda-2)}{13-0.3\beta} - 0.00184(\lambda-2)\beta \tag{5}$$

where B is blade's pitch angle. For a turbine with constant pitch, β is considered as a constant value, Figure 2 is C_P variations in terms

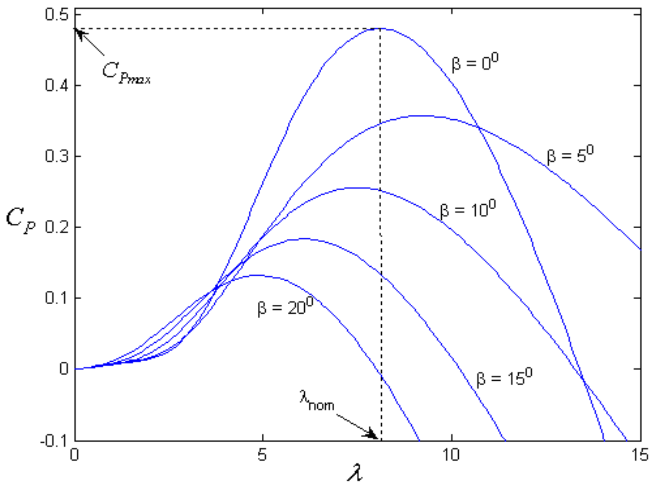

Figure 2. C_p in terms of λ for different β values.

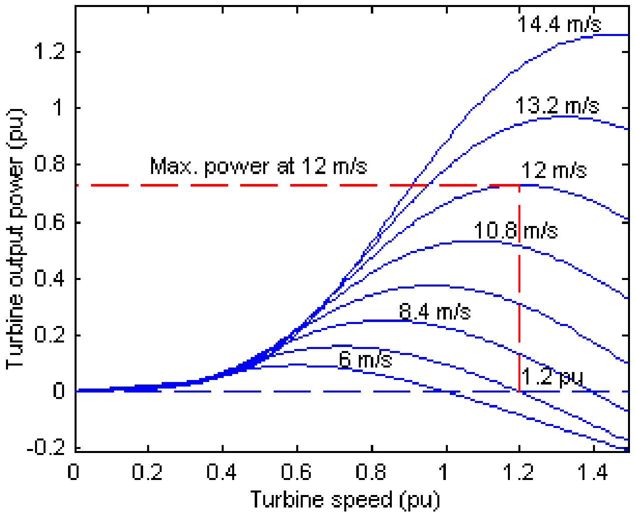

Figure 3. Maximum power of turbine in terms of wind and rotor speed.

of λ for different β values. In this paper, β is considered zero where the c_p value would then be 0.48. Table 1 shows the wind turbine parameters values applied in the simulation.

Turbine maximum power control

Figure 3 shows the relationship between turbine output power and its speed in terms of different wind speeds. It is seen that rotor's optimum speed to obtain maximum power of it is different in various wind speeds. Also, Figure 2 shows that C_p is a function of λ and its maximum value is obtained for λ_{nom}.

So, in order to obtain the maximum power of wind energy λ should always be fixed on the λ_{nom} value which is possible by blades properly designing. So, the relation of Equation 2 gives:

$$P_{M\max} = \frac{1}{2}\rho\pi R^2 C_{P\max} V_{WIND}^3 \tag{6}$$

The generator reference speed is calculated as follows:

$$\omega_M^* = \frac{\lambda_{nom}}{R} V_{WIND} \tag{7}$$

So by measuring wind speed, generator reference speed is obtained to get the maximum wind energy (Abo-Khalil et al., 2004).

Induction generator

In wind system, integrated and high degree models should be applied to simulate the induction generator in order to reach the desired answer (Karrari et al., 2005; Gandomkar et al., 2011). Several kinds of induction generators are studied in different sources (Ong, 1997). In this paper, 5th degree model is used for simulation and equations related to this model are obtained as follow by applying Park's conversion on machine voltage and current (Ong, 1997).

$$v_{qs} = R_s i_{qs} + \frac{1}{\omega_b}\frac{d\psi_{qs}}{dt} + \frac{\omega_e}{\omega_b}\psi_{ds} \tag{8}$$

$$v_0 = R_s i_{0s} + \frac{1}{\omega_b}\frac{d\psi_{0s}}{dt} \tag{9}$$

$$0 = R_r i_{dr} + \frac{1}{\omega_b}\frac{d\psi_{dr}}{dt} - \frac{(\omega_e - \omega_r)}{\omega_b}\psi_{qr} \tag{10}$$

$$0 = R_r i_{qr} + \frac{1}{\omega_b}\frac{d\psi_{qr}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b}\psi_{dr} \tag{11}$$

$$0 = R_r i_{0r} + \frac{1}{\omega_b}\frac{d\psi_{0r}}{dt} \tag{12}$$

where v_{ds}, v_{qs}, v_{0s}, i_{ds}, i_{qs} dna i_{0s} are stator voltages and currents and v_{dr}, v_{qr}, v_{0r}, i_{dr}, i_{qr}, i_{0r} are rotor voltages and currents in d-q axis and:

$$\psi_{ds} = x_s . i_{ds} + x_m . i_{dr} \tag{13}$$

$$\psi_{qs} = x_s.i_{qs} + x_m.i_{qr} \quad (14)$$

$$\psi_{0s} = x_s.i_{0s} \quad (15)$$

$$\psi_{dr} = x_r.i_{dr} + x_m.i_{ds} \quad (16)$$

$$\psi_{qr} = x_r.i_{qr} + x_m.i_{qs} \quad (17)$$

$$\psi_{0r} = x_r.i_{0r} \quad (18)$$

where for balanced load $i_{0s} = i_{0r} = 0$.

The relation of torques applied to induction generator rotor is as follow:

$$T_m - T_e = J\frac{d\omega_r}{dt} + D.\omega_r \quad (19)$$

where T_m is the mechanical torque applied to rotor and T_e is generator electrical torque and $D.\omega_r$ is the damping torque and J is the sum of turbine and generator inertia.

In reference (Ong, 1997) induction generator's, electrical torque is shown as follow

$$T_e = \frac{3}{2}\frac{P}{2\omega_b}x_m\left(i_{dr}i_{qs} - i_{qr}i_{ds}\right)$$

$$T_e = \frac{3}{2}\frac{P}{2\omega_b}\left(\psi_{qr}i_{dr} - \psi_{dr}i_{qr}\right)$$

$$T_e = \frac{3P}{4}\left(\lambda_{qr}i_{dr} - \lambda_{dr}i_{qr}\right) \quad (20)$$

where *P* is the number of induction generator's poles. The aforementioned relations express the dynamic of induction generator completely. Characteristics of generator used in simulation are presented in Table 2.

Control of grid connected system

For a specific wind speed, wind turbine's operation point (output mechanical power and rotor speed) is determined by turbine's and load's (induction generator) characteristics cross point. The generator stator voltage is determined by grid voltage which will be used in induction generator simulation.

Machine equations are converted in the rotor flux frame. Rotor flux is turning in synchronous speed but in a different angle than stator flux, if there is a sinusoidal excitation. Choosing d-axis on the rotor flux, q component will be zero. This fact simplifies the equations equations very much. Now, the torque and flux equations (Ong, 1997) expressed in previous part will be changed as follow:

$$\psi_{qr} = x_r.i_{qr} + x_m.i_{qs} = 0 \rightarrow i_{qr} = -\frac{x_m}{x_r}i_{qs} \quad (21)$$

$$T_e = -\frac{3P}{4}\lambda_{dr}i_{qr} = \frac{3P}{4}\frac{x_m}{x_r}\lambda_{dr}i_{qs} \quad (22)$$

$$\omega_r - \omega_e = \frac{x_m}{T_r}\frac{i_{qs}}{\lambda_{dr}} \quad (23)$$

$$T_r = \frac{L_r}{R_r} \quad (24)$$

$$\lambda_{dr} = \frac{x_m}{1+T_r.p}.i_{ds} \quad (25)$$

The aforementioned relations are the main relations of vector control (Ong, 1997; Chinchilla et al., 2006). This method simplifies the induction machine controlling. This method is very similar to DC machine's independent excitation, where flux is the function of field current and torque is in proportion with flux and rotor current. The main problem of vector control method is flux axis angle calculation which is done by measuring the flux in two points with 90° displacement and then angles are calculated using the resulted fluxes or estimated in regard to rotor speed (Ong, 1997).

Generator side converter control

Figure 4 shows the generator side converter controlling system and structure. In this part, generator's speed is controlled to generate the maximum power. In order to reach this aim, a PI controller is used to control the speed. Speed controlling loop generates the current component of generator to control the torque and speed of generator for different wind speed values. Proportional and integrated PI controller values used in simulation are K_P = 12 and K_I = 25. As we know, the PI controllers values in the complicated system can be found with try and error and there is no classic method to calculate them. In respect to the fact that motor power is directly related to air gap flux, this air gap flux will be maintained in its nominal value and d-axis current value can be calculated by air gap flux on the basis of the relation of Equation 25. Flux axis angle is calculated as:

$$\omega_r - \omega_e = \frac{x_m}{T_r}\frac{i_{qs}}{\lambda_{dr}} \quad (26)$$

$$\theta = \int\left(\omega_r + \omega_m\right)dt \quad (27)$$

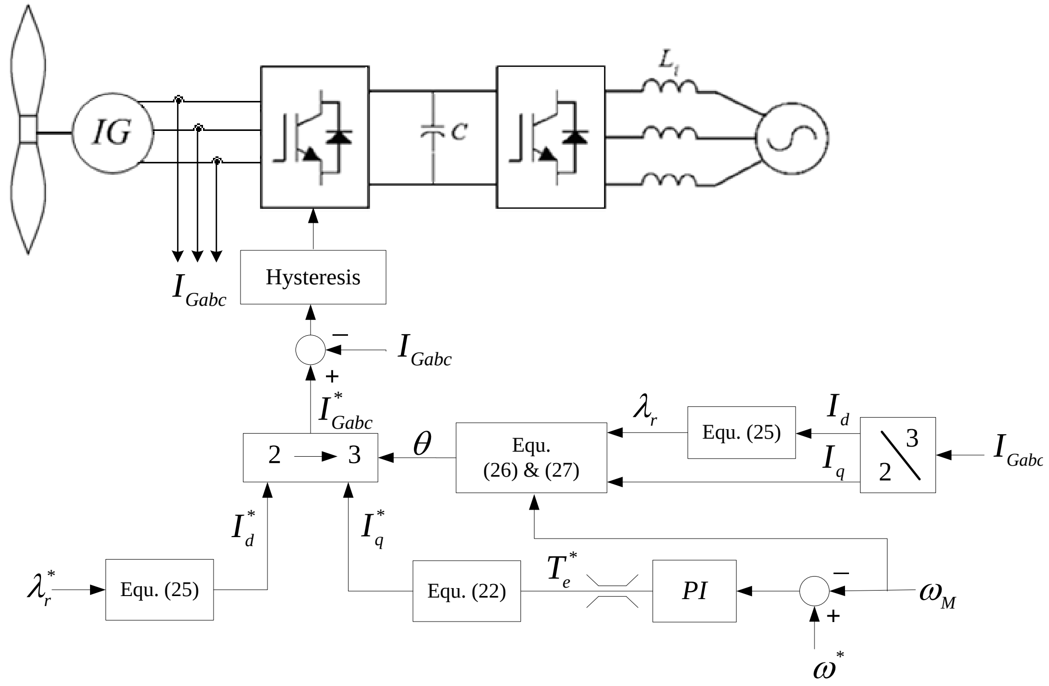

Figure 4. Configuration and control system of generator side converter.

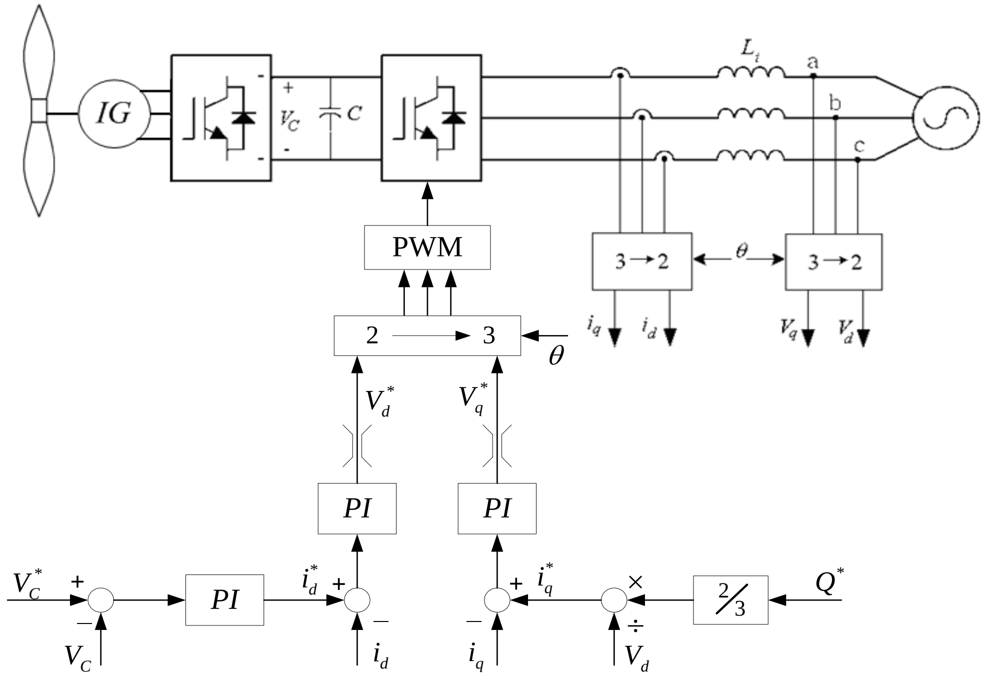

Figure 5. Configuration and control system of grid side converter.

Grid side converter control

Figure 5 shows the grid side converter controlling system used to control the injective active and reactive powers. Relations of these powers in synchronous reference are as follow (Chinchilla et al., 2006; Hana et al., 2007):

Table 1. Wind turbine parameters.

Parameter	
Rated Power	15 kW
Blade radius	5.5 m
Nominal wind speed	12 m/s
Minimum wind speed	4 m/s
Maximum wind speed	18 m/s
Blade pitch angle	0

Table 2. Induction generator parameters.

Parameter	
Rated power	*15 kW*
Nominal voltage (L-L)	*460 v*
Rated frequency	*60 Hz*
Number of poles	*4*
Stator resistance R_s	*0.2761 Ω*
Stator inductance L_{ls}	*2.2 mH*
Rotor resistance $R_r^{'}$	*0.1645 Ω*
Rotor inductance $L_{ls}^{'}$	*2.2 mH*
Magnetizing inductance L_m	*76.14 mH*
Inertia J	*0.1 kg/m^2*
Friction factor *F*	*0.018 N.m.s*

$$P=\frac{3}{2}(v_d i_d + v_q i_q) \tag{28}$$

$$Q=\frac{3}{2}(v_q i_d - v_d i_q) \tag{29}$$

If synchronous reference is synchronized with grid voltage, q-axis component of grid voltage would be zero and power relations will be as follow:

$$P=\frac{3}{2}v_d i_d \tag{30}$$

$$Q=-\frac{3}{2}v_d i_q \tag{31}$$

According to the aforementioned relations, active and reactive powers are applied to control q-axis currents, respectively. Two controlling loops are used to control these currents. Capacitor voltage controlling loop is used to control the d-axis reference power transfer. q-axis reference current is specified by injecting to grid reactive power the selected and the desired. If unit power factor is considered, q-axis reference current is regulated at zero value. In this simulation, integrated and proportional values are K_P = 2 and K_I = 10, for the PI controller which is controlling the capacitor voltage. PI controller which is controlling the currents is considered with K_P = 0.1 and K_I = 80 values.

RESULTS AND DISCUSSION

In order to study the proposed wind turbine system's operation, mentioned system is simulated by MATLAB/SIMULINK software with the parameters of Tables 1 and 2.

Mentioned system is simulated for a wind with variable speed for 4 s. Figure 6 shows the wind speed curve.

In Figures 7 and 8, capacitor voltages and injective reactive power are presented. These two figures show that the system has appropriately provided the requirements to be connected to grid. Constant and

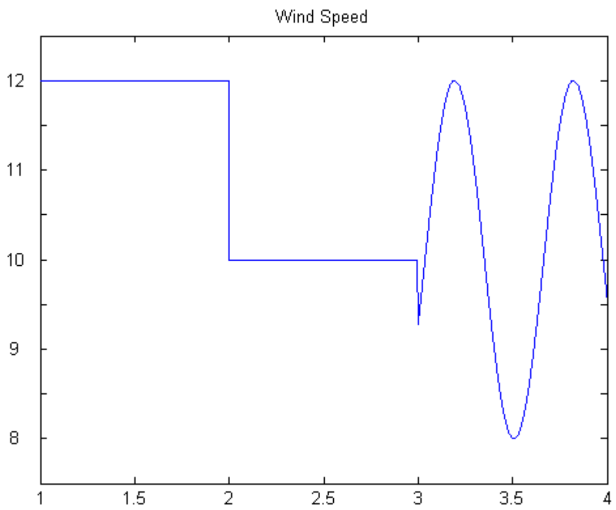

Figure 6. Simulated wind speed (m/s).

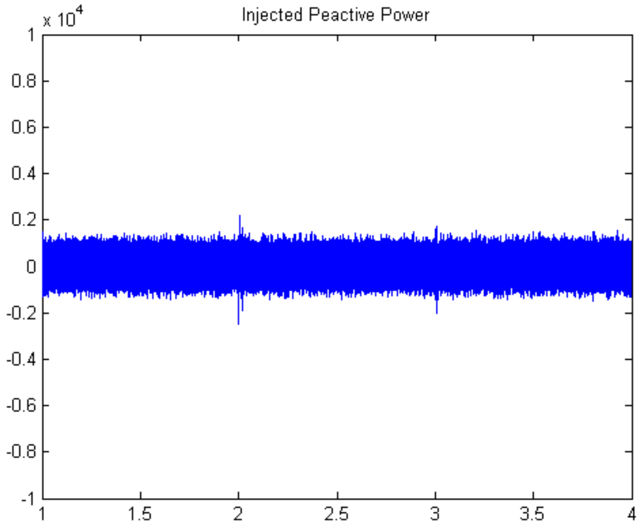

Figure 8. Injected reactive power to grid (kVAr).

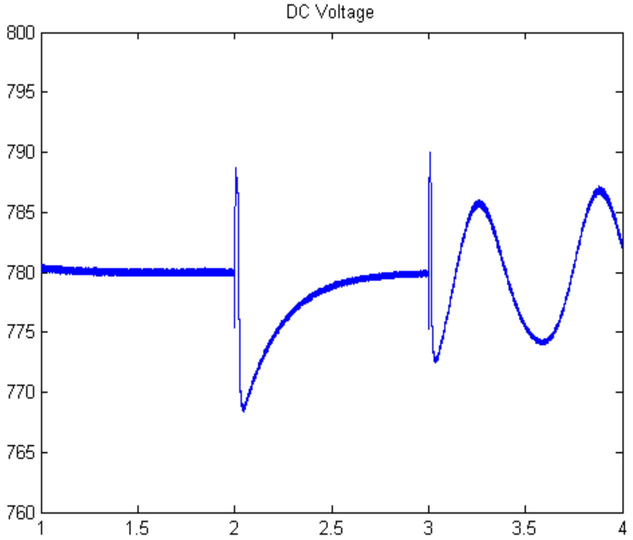

Figure 7. DC link voltage (v).

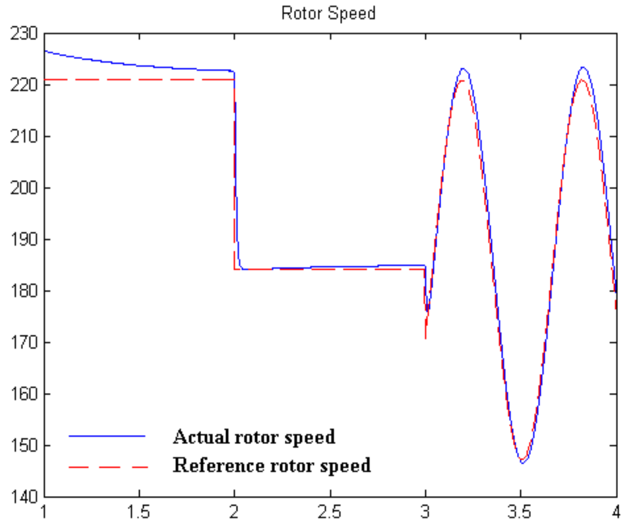

Figure 9. Actual and reference rotor speed (m/s).

reactive power transferred to grid is negligible (unity power factor is considered), because capacitor voltage value is maintained.

Figure 9 presents the true and estimated speeds of rotor. It is seen that the rotor has tracked the calculated speed correctly to obtain the maximum power of turbine.

Figure 10 shows the electrical and mechanical powers. It is seen that, injective power's curve tracks turbine's maximum mechanical power. The difference between these two curves is justified by considering mechanical and electrical losses.

Conclusion

In developing wind turbines, different technologies are presented for them. Despite of vast application of doubly fed induction generators (DFIG), speed variation possibility in direct drive squirrel cage induction generator is more than that in DFIG. In this paper, squirrel cage induction generator with two back to back voltage source converters is used to connect wind turbine to the grid. Generator side converter is controlled by indirect vector control method and the grid side converter is

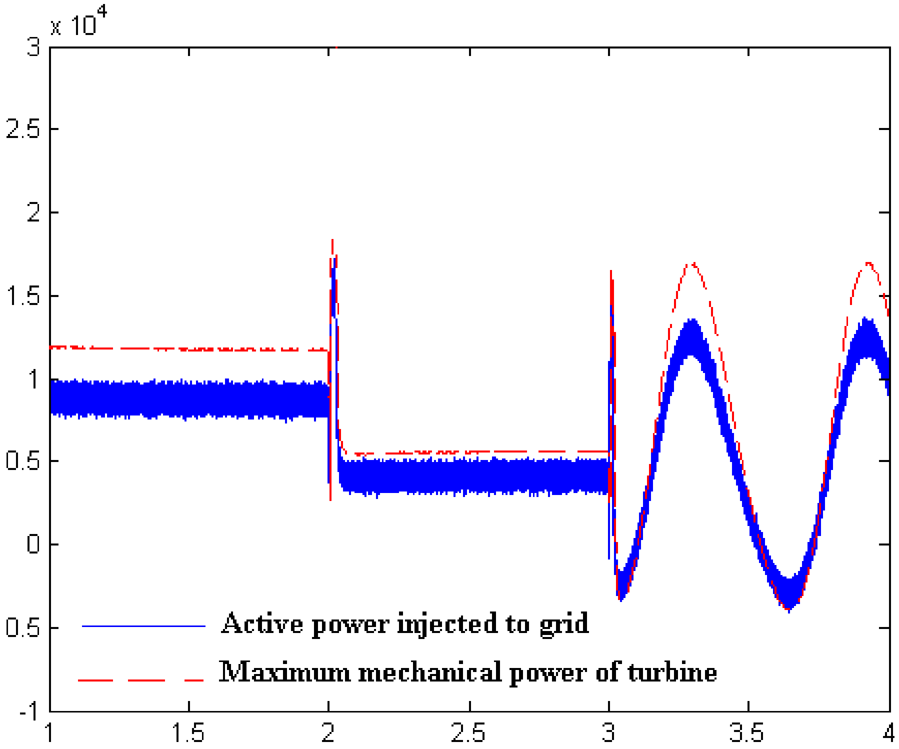

Figure 10. Actual and reference rotor speed (kW).

controlled by active and reactive powers injection to grid method. Simulation results show that the maximum power of turbine is obtained correctly for different wind speeds and also, show that expected reactive and active powers are injected properly.

Nomenclature: V_{WIND}, Wind speed (m/s); V_{BASE}, the main component of wind speed; V_{GUST}, the gust component of wind speed; V_{RAMP}, the ramp component of wind speed; ω_M, rotor angular speed (rad/s); λ, the tip speed ratio (TSR); C_P, the power conversion factor; v_{dq0s}, stator voltage in *dq0*; **axis,** rotor voltage in *dq0* axis; i_{dq0s}, stator current in *dq0* axis; i_{dq0r}, rotor current in *dq0* axis; T_m, the mechanical torque applied to rotor; T_e, the generator electrical torque; $D.\omega_r$, the damping torque; J, the sum of turbine and generator inertia; ***P,*** the number of induction generator's poles; R_s, Stator resistance; L_{ls}, stator inductance; $R_r^{'}$, rotor resistance.

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