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Maximum Power Control of Variable Speed Wind Turbine Connected to Permanent Magnet Synchronous Generator Using Chopper Equipped with Superconductive Inductor

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Abstract: In this study, maximum power control of wind turbine and induction generator connected with two back to back voltage source converters to grid are studied. 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: Wind systems, permanent magnet synchronous generator, maximum power point tracking, superconductive inductor

INTRODUCTION

Nowadays, among the all renewable energy sources, wind systems are more economic in compare with others. Variable wind speed systems deliver 20 to 30% more energy in compare with the constant speed systems. They also decrease power oscillation and improve reactive power injection (Weisser and Garcia, 2005). Various technologies are developed for wind systems as their application has developed. During the earlier years, PMSGs are greatly used in wind turbine applications because of their advantages such as low weight and velocity, high efficiency and gearless structure (Spooner and Williamson, 1996; Chinchilla *et al*., 2006). Extracting maximum power of turbine and delivering an appropriate energy to grid are two important purposes in wind turbines. According to these purposes, AC-DC-AC structure is the best structure to convert the power in wind turbines (Bana Sharifian *et al*., 2008; Spooner and Williamson, 1996; Chinchilla *et al*., 2006; Arifujjaman *et al*., 2006; Hana *et al*., 2007). Figure 1 shows one of the most common structures applied for PMSGs. This structure contains a full wave diode rectifier, a DC-DC boost converter and a 3-phase inverter. In this structure, inverter satisfies the requirements related to grid connection and boost converter provides the ability of extracting maximum power using DC bus control in output of rectifier (Spooner and Williamson, 1996; Chinchilla *et al*., 2006).

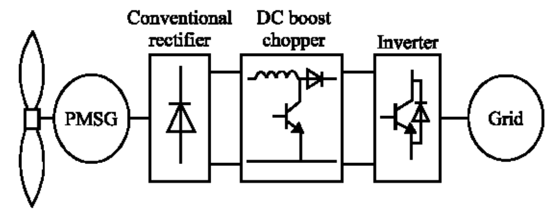

Fig. 1: Wind turbine system with PMSG and boost converter

The power extracted by the wind is related to the third order of wind speed. Applying power electronics converters to transfer the power to grid with the possibility of speed variation in a great range of values is preferred because of their great advantages. Various methods are presented to control the maximum power where almost all of the efficient methods apply rotor speed feedback (Spooner and Williamson, 1996; Chinchilla *et al*., 2006; Senjyu *et al*., 2006). In this study, maximum power point tracking is executed by sampling the rotor and wind speeds.

MATERIALS AND METHODS

The proposed system is consisted of five main parts: wind model, wind turbine, boost converter and superconductive inductor, power injection to grid and

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maximum wind power extraction. These parts have 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 (Surgevil and Akpınar, 2005):

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

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 (Karrari *et al.*, 2005):

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

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

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

where, V_{WIND} is wind speed, R is the blades radius, P 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 follow:

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

where, B is blade's pitch angle. For a turbine with constant pitch, β is considered as a constant value, Fig. 2 is C_P variations in terms of λ for different β-values. In this study, β is considered zero where the C_P value would be 0.48 then.

Table 1 shows the wind turbine parameters values applied in simulation.

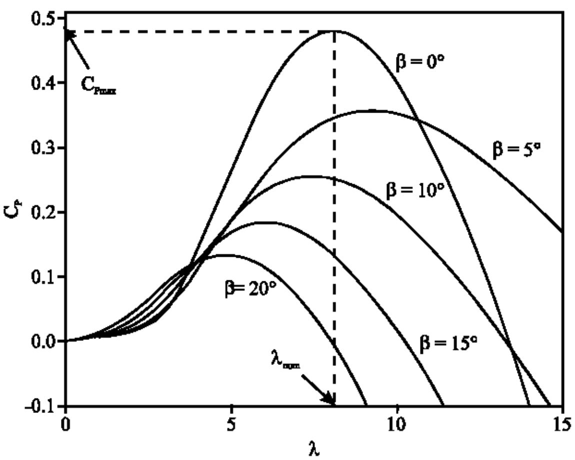

Fig. 2: C_P in terms λ of for different β-values

Table 1: Wind turbine parameters

Parameters	Values
Rated power	15 kW
Blade radius	5.5 m
Nominal wind speed	12 m sec^{-1}
Minimum wind speed	4 m sec^{-1}
Maximum wind speed	18 m sec^{-1}
Blade pitch angle	0

Boost converter and superconductive inductor: Boost converter stabilizes the voltage of DC link unrepentantly from the output voltage of rectifier which is caused by speed variation of synchronous generator. DC link voltage is stabilized through regulating the boost converter switch conduction ratio (D). D is the result of dividing the conduction time of switch in each period by the switching period. Stabilized DC link voltage in the inverter terminals leads to efficiency increase and appropriate exploitation of Power semiconductor devices. Boost converter behaves like a second order system which has an additional zero at the right side of imaginary axis. Right side zero makes system to operate like a non minimum phase system which is not desirable in voltage regulators. Because of any variation in output voltage might increase before being corrected by the controller. As it is shown in Fig. 3, the energy storage device plays the main roll in the operation of boost converter. During each switching period of DC converter and also during the conduction time of switch, energy is stored in magnetic field of inductor and then during the 2nd part of period where the switch does not conduct, energy is injected to the capacitor bank of DC link. If a superconductive inductor is used to exchange the electromagnetic energy, the ability of energy storing and the efficiency increases greatly. These energy storage devices are commonly applied to improve the dynamic behavior of power systems and to correct the oscillations

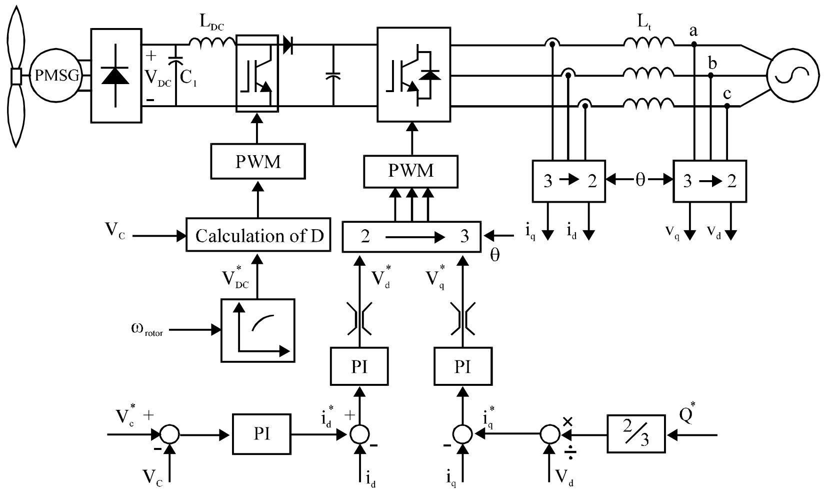

Fig. 3: Configuration and control system of proposed wind energy system

of industrial loads. Especially when the system rating is not high, cost of using high temperature superconductors has been reduced obviously and the system has been economized nearly. In order to compare, it should be noted that what is presented by Nomura *et al*. (2005) is the application of systems with tens of MJ rating, but as what is proposed here, the storing devices limit the rating of the systems applied in boost converter to tens of kJ.

Natural frequency and damping ratio of boost converter are computed as follow (Ang and Oliva, 2005):

$$\xi = \sqrt{\frac{L}{C}}\frac{1}{2R(1-D)}$$
$$\omega_m = \frac{(1-D)}{\sqrt{LC}} \tag{6}$$

Equation 6 shows that a considerable increase in L-value reduces the frequency of system and decreases the ripple components of state variables. At the other hand, as L-value increases, ΔI_L (current ripple of superconductive inductor) will decrease to the value in which the operation of controlling system will face with distortion. Thus, correct selection of superconductive inductor will lead to an economic system in addition to all advantages presented in Nomura *et al.* (2005).

Power injection to grid: In Fig. 3, inverter control system to control the injected active and reactive powers is shown. The relations of these powers in synchronous reference frame are as follow (Nomura *et al.*, 2005; Knight and Peters, 2005):

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \tag{7}$$

$$Q = \frac{3}{2}(v_q i_d - v_d i_q) \tag{8}$$

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

$$P = \frac{3}{2}v_d i_d \tag{9}$$

$$Q = -\frac{3}{2}v_d i_q \tag{10}$$

According to the Eq. 9 and 10, by controlling the currents of d-axis and q-axis, active and reactive powers can be controlled respectively. Two controlling loops are used to control these currents. The outer loop of capacitor voltage control is used to generate the d-axis reference current. This control will end in transferring the total generated power to grid. Q-axis reference current is specified by desirable selecting the grid injected reactive power. If unit power factor is considered, this current would be regulated at zero value.

Maximum wind power extraction: Figure 4 shows the relation between the output power of turbine and its speed for different wind speeds. It is seen that the optimum rotor speed is different in various wind speeds to obtain the maximum power of turbine.

In PMSG, the relation between torque and inducted voltage is as follow Eq. 5 and 12:

$$T = K_t I_a \tag{11}$$

$$E = K_e \omega \tag{12}$$

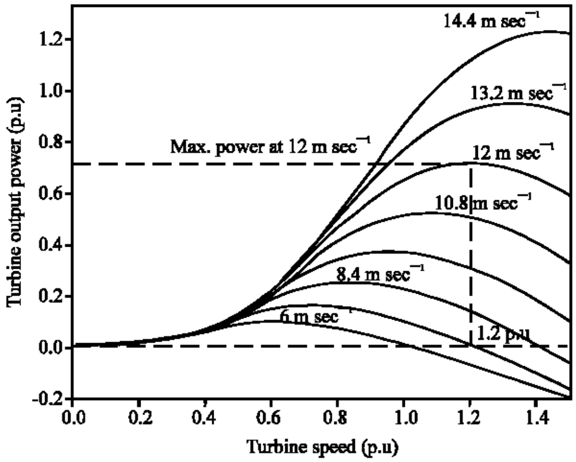

Fig. 4: Maximum power of turbine in term of wind and rotor speed

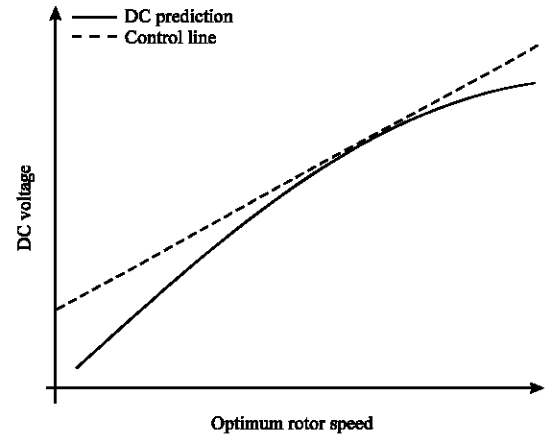

Fig. 5: DC link voltage curve in term of optimum rotor speed

where, ω is the angular rotor speed and I_a is stator current. In the other hand, it is obvious that:

$$E^2 = V^2 + (I_a\ \omega_s)^2 \tag{13}$$

where, V is the terminal phase voltage and L_s is the inductance of generator. DC voltage at the output of rectifier (V_{DC}) is as follow:

$$V_{DC} = \frac{3\sqrt{6}}{\pi} V \tag{14}$$

where, V_{DC} according to the Eq. 11-14 is as follow:

$$V_{DC} = \frac{3\sqrt{6}}{\pi} \omega \sqrt{K_e^2 - \left(\frac{TL_s}{K_t}\right)^2} \tag{15}$$

In respect to the fact that the torque is determined by the rotor and wind speeds, a specific voltage value is estimated for a specific rotor and wind speed as Eq. 15.

If DC voltage relation is obtained in terms of optimum speed, resulted diagram would be as Fig. 6. Now, a feedback from rotor speed, DC bus voltage can be obtained through Fig. 6 and can be applied to the system. By applying this control, speed and voltage vary continuously until they reach to their balance mode in a point on the curve shown in Fig. 5. In this case, maximum power of wind energy is obtained from the wind turbine.

As it is obvious, Fig. 6 is a nonlinear curve. But it can easily be applied using a linear approximation around the nominal operation point. In this study, a second order approximation is used. Determining optimum DC voltage, switching ratio of boost converter (D) is calculated to reach this voltage.

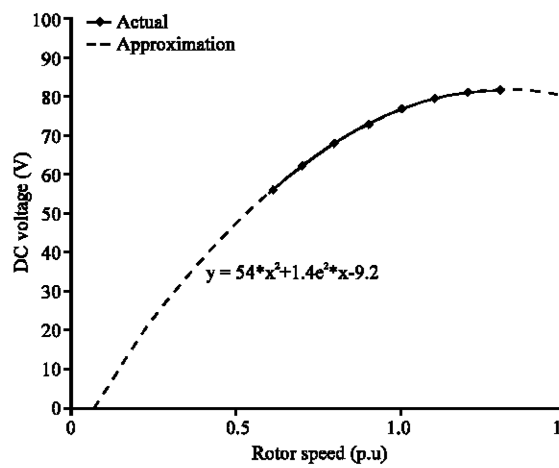

Fig. 6: DC voltage bus curve in term of optimum rotor speed obtained simulation and approximation

$$D = \frac{V_C - V_{DC\text{-}Ref}}{V_C} \tag{16}$$

RESULTS AND DISCUSSION

In order to study the operation of proposed wind turbine, the mentioned system is simulated using MATLAB/SIMULINK software with the parameters of Table 2, 3. Table 4 shows the parameters of controllers.

Figure 6 shows the DC voltage curve in terms of optimum rotor speed. Mentioned curve is derived through simulating system in various wind and rotor speeds. The dotted line is a second order approximation of the above curve which is used to control the maximum power in coming simulations. Maximum and minimum rotor speeds are considered 1.3 and 0.6 p.u, respectively.

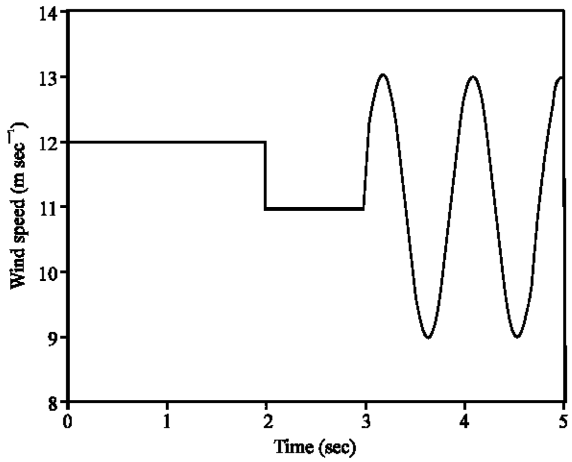

Fig. 7: Simulated wind speed

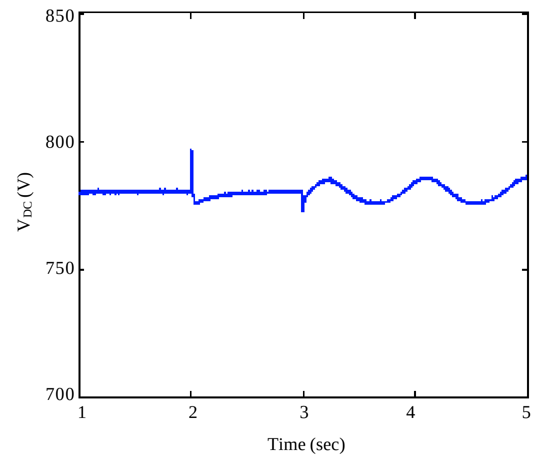

Fig. 8: Capacitor voltage

Table 2: PMSG parameters

Parameters	Values
R_s	2.875 Ω
L_q	8.5 mH
L_d	8.5 mH
P	4.0
J	0.0008 kg m^2

Table 3: Simulation parameters

Parameters	Values
Vi	63.33 V
L_i	5 mH
L_{DC}	2 mH
C_1	2200 µF
C_2	2200 µF
F_s	10 kHz

Table 4: Controllers parameters

Parameters	Values
K_{id}	10
K_{pd}	1
K_{iq}	10
K_{pq}	1
K_{ic}	100
K_{pc}	1

The proposed system is simulated for two seconds with variable wind speed as shown in Fig. 7.

In Fig. 8 and 9 capacitor voltage and grid injected reactive power are shown, respectively. These two figures show that the system has satisfied the requirements of grid connection appropriately. Because the voltage level of capacitor is kept constant and reactive power transition is almost zero.

Figure 10 shows the electrical and mechanical power curves. It is obvious that after a short period of time, generated mechanical power of turbine tracks the maximum mechanical power of turbine (considering the wind speed). Also in Fig. 10, grid injected active electrical power is shown which differs from the generated mechanical power according to the electrical and mechanical losses. As it is obvious, grid injected power curve tracks the maximum power curve of the turbine with about 0.1 sec delay time which is the result of using PI controllers in controlling circuit of inverter.

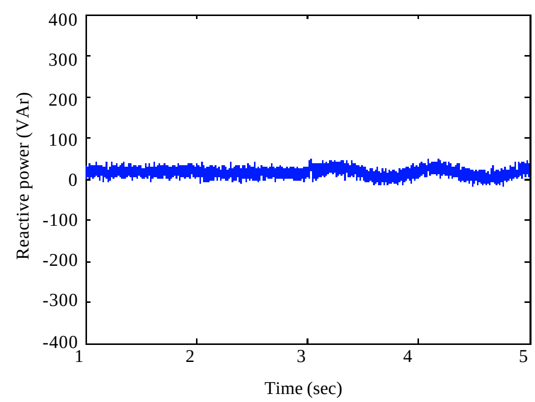

Fig. 9: Injected reactive power to grid

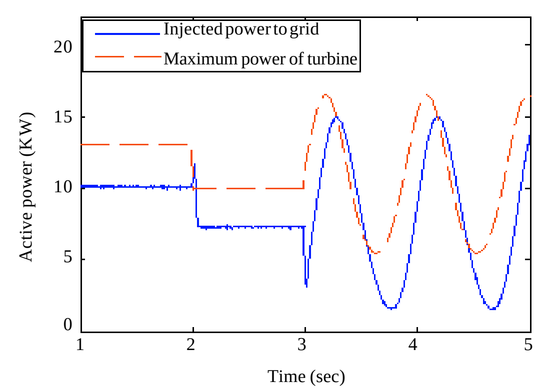

Fig. 10: Injected active power to grid, maximum mechanical power of turbine

Comparison of the simulation results (Karrari *et al*., 2005; Bana Sharifian *et al*., 2008; Kim and Kim, 2007) show that the results of this study have correlation with related studies. The maximum power of variable speed wind energy by a new MPPT algorithm has been extracted successfully.

CONCLUSION

As wind turbines develop, various technologies are presented to improve their application. PMSG is under attention of these technologies because of its special abilities. In most PMSG wind systems, generated voltage of the generator is converted into DC voltage through a full-bridge diode rectifier and this voltage is controlled to control the maximum power of turbine. The grid side inverter is controlled by grid injected active and reactive power control method. Simulation results show that the maximum power is obtained from the turbines correctly for different wind speeds and active and reactive powers are injected to grid appropriately.

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