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Dynamic Analysis of PMSG Wind Turbine under Variable Wind Speeds and Load Conditions in the Grid Connected Mode

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Abstract

Dynamic performance investigation of Wind Turbine (WT) implementing Permanent Magnet Synchronous Generator (PMSG) under variable wind speeds and load circumstances are investigated in this paper. The injected active and reactive power respectively regulate by d-axis current and q-axis current using active and reactive power (P-Q) control method. The P-Q controller can adjust DC link voltage, active and reactive power. The generated reactive power via the WT is adjusted at zero so that the Power Factor (PF) is retained unity. The proposed system is containing of WT, PMSG, rectifier, a DC bus by capacitor and voltage source inverter. The simulation results depict the accuracy and credibility of the WT and the strategy of inverter controller. The thorough Wind Power Generation System (WPGS) and power electronic converters interfaces are proposed by using Matlab/Simulink.

Keywords: Dynamic Analysis, Load Circumstances, PMSG, P-Q Controller, Wind Turbine (WT)

1. Introduction

In last decade, miscellaneous technologies of renewable energy such as Wind Power Generation System (WPGS), Photovoltaic Systems (PV) and biomass have made many impressive developments in efficiency improvement and costs continue to come down. As regards to less power and efficiency in PV system and enormous costs in comparison with wind system, WPGS is proposed as one of the outstanding renewable energy sources[1,2]. Amongst the synchronous and asynchronous generators, Permanent Magnet Synchronous Generator (PMSG) is more favorable because of self-excitation, lower weight, smaller size, less maintenance cost and the elimination of gearbox have high efficiency and high PF comparing to WRSG, SCIG, DFIG etc. Permanent magnet generators do not require a supplementary supply for magnetic field excitation or slip rings and brushes[3,4]. The major disadvantage of the PMSG is the risk of demagnetization caused by too high temperatures or high currents. There are two modes for inverter operating: 1. Active and reactive control mode (P-Q Control) and 2. Voltage and frequency control mode (V-F control)[5–8].

The analysis responses of WT based PMSG under variable wind speeds and load circumstances and have been studied. The P-Q control strategy is taken from park transformation and is simulated by Simulink/Matlab. This paper consists of part (2) system where topology is illustrated. In part (3) the major equipment of system are described that include: wind turbine, PMSG generator, P-Q control strategy. Simulation results and analysis are shown in part (4). Finally the conclusions based on present studies are presented in part (5).

2. System Configuration

In Figure 1, the diagram of a wind energy system based on PMSG connected to network is demonstrated. The DC link

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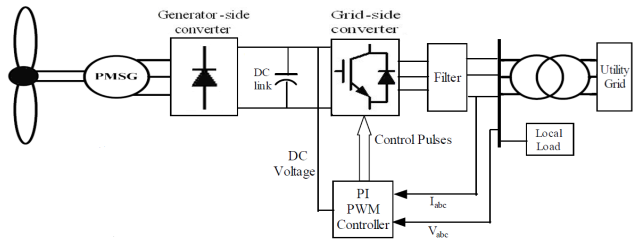

Figure 1. The block diagram of system.

voltage is regulated by PI controller till it reaches a rated value and then this fixed voltage is converted to AC voltage applying inverter. The inverter adjusts the DC link voltage and moreover, reactive and active power is injected via q-axis and d-axis respectively, using P-Q control method.

3. System Modeling

3.1 Power of Wind Turbine

The wind power is computed as following equation[9,10]:

$$P = 0.5\rho A C_p(\lambda,\beta) V_w^3 \tag{1}$$

Where, P = power, ρ = density of air, A = wind turbine rotor swept area, V_w = speed of wind in m/sec, C_p is the aerodynamic efficiency of rotor. The ratio of tip speed (λ), determined as the the linear speed ratio and is given by following equation[7–12]:

$$\lambda = \frac{W_m R}{V_w} \tag{2}$$

W_m = Speed of rotor in rad/s and R: turbine radius

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-21}{\lambda_i}} \tag{3}$$

$$\lambda_i = \left[\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right]^{-1} \tag{4}$$

Furthermore, the C_p is depending on the blade pitch angle and TSR. The generic change of C_p based on TSR for different values of (β) is illustrated in Figure 2.

3.2 PMSG Modeling

The equations of PMSG voltage are defined by[9]:

$$\frac{di_{ds}}{dt} = \frac{1}{L_d}\left[-V_{ds} - R_s i_{ds} + \omega L_q i_{qs}\right] \tag{5}$$

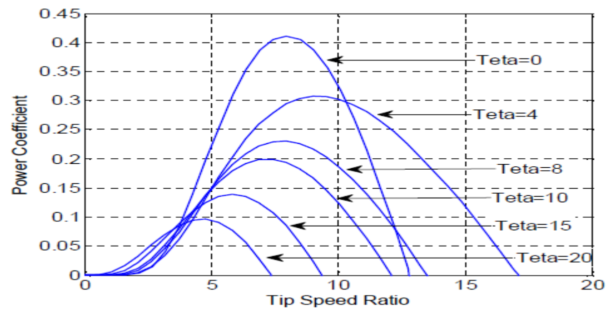

Figure 2. C_p vs λ for various pitch angles (β).

$$\frac{di_{qs}}{dt} = \frac{1}{L_q}\left[-V_{qs} - R_s i_{qs} - \omega L_d i_{ds} + \omega\phi_m\right] \tag{6}$$

Where V_{ds} and V_{qs} are q and d axis machine voltages and I_{ds} and I_{qs} are q and d axis machine currents, respectively. R_s: Resistance of Stator, W: frequency of electrical angular, L_d: inductance of d-axis, L_q: q axis inductance, ϕ_m: flux linkage amplitude. If rotor is cylindrical ($L_d \approx L_q = L_s$), the equations of electromagnetic torque are presented as following:

$$T_e = \frac{3}{2} p \phi_m i_{qs} \tag{7}$$

Which p is the PMSG pole pair's number.

3.3 P-Q Control Strategy

The rectifier determined AC to DC and then, DC link voltage applying PI controller to get fixed value, then DC Voltage is converted to obtain favorable AC voltage[11].

$$P = \frac{3}{2}(V_{gd} I_d + V_{gq} I_q) \tag{8}$$

$$Q = \frac{3}{2}(V_{gq} I_d - V_{gd} I_q) \tag{9}$$

In Figure 3, the synchronous reference will compute amount of d axis, q axis and zero sequels in two axis rotational reference vector for three phases is depicted.

For this, we use equations (12) and (13).

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = C \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}, \quad \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = C \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{10}$$

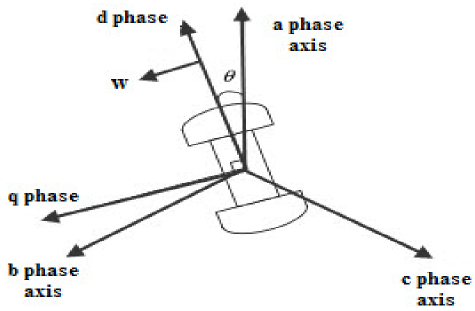

Figure 3. Synchronous Reference Machine.

$$C_{dq0} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (11)$$

In Figure 4, model of converter controller is demonstrated. One of the most significant specifications of P-Q control is the ability of autonomous performance of network. The loop capacitor voltage control is applied to locate reference current for d-axis for controlling active power . The q-axis reference current is assigned to output reactive power[11,12]. If PF is unit, hence this current is zero[13–16].

4. Simulation Results

Simulation results under various circumstances are presented by implementing Matlab. The block diagram is demonstrated in Figure 5. The grid voltage and frequency

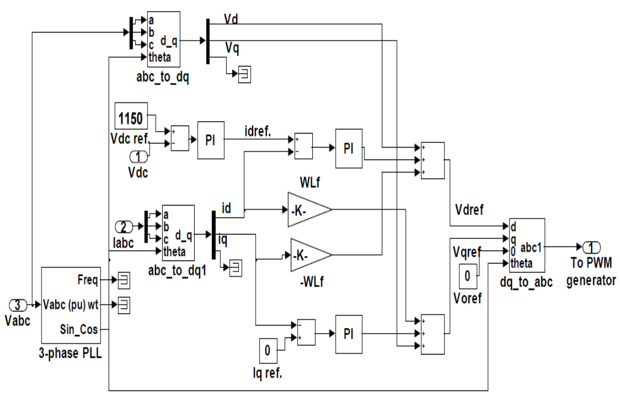

Figure 4. Modeling of inverter controller.

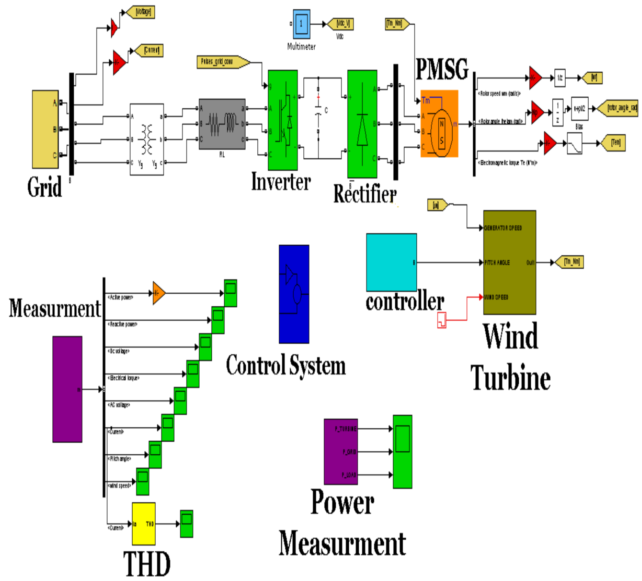

Figure 5. The block diagram of system in MATLAB/SIMULINK.

were 480 V and 60 Hz, respectively. The PMSG parameters as follows: resistance of stator: 2.9 Ω, inertia: $0.9e^{-3}$ kg-m^2, torque constant: 12N-M/A, Pole pairs: 8, power: 95kW, Nominal speed: 12 m/s, $L_d = L_q$ = 9 mH. Alternative parameters, DC link Capacitor: 5500µF, DC link voltage: 1150 V.

4.1 Case Study 1

The aim of this case is dynamic analysis of grid connected PMSG wind turbine in state of fixed load and variable wind speed. In this case, speed of wind, during $0 < t < 4$ sec is 11 m/sec and in t = 4 s is declined to 9 m/s and load is the constant 110 kW. Active powers are shown in Figure 6.

According to reduction of wind speed, the turbine torque decrease and based on this active power output from wind system the inverter current declines. Power shortage is fed by network. The DC link voltage remained at a fixed value (1150V) and in Figure 7, the effectiveness of the appointed controller as demonstrated.

Turbine output power is depicted in Figure 8, which is decreased to 79 kW in t = 4.

In Figure 9, inverter output current is shown. One of the most significant aspects of applying DGs and connecting them to network is maintenance the THD at the least value. The THD should be around 5%, due to IEEE Std.1547.2003.

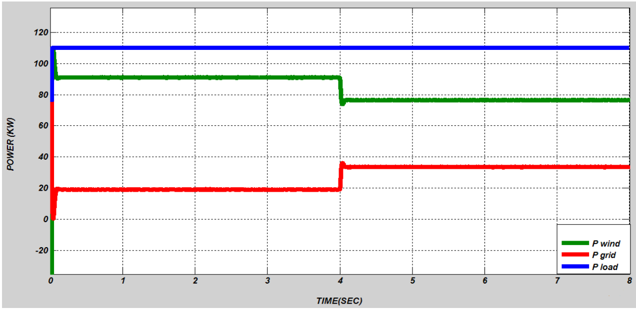

Figure 6. Active powers.

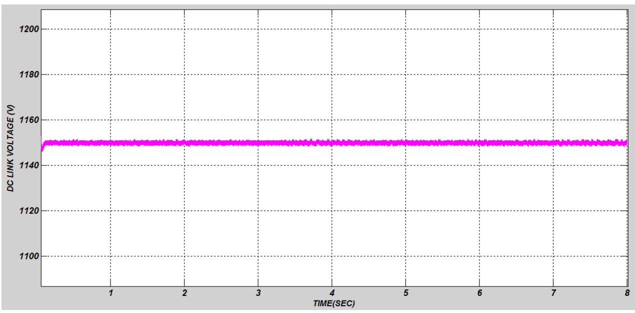

Figure 7. The DC link voltage.

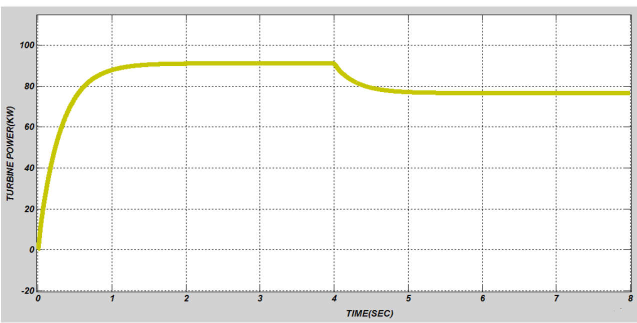

Figure 8. Turbine output power.

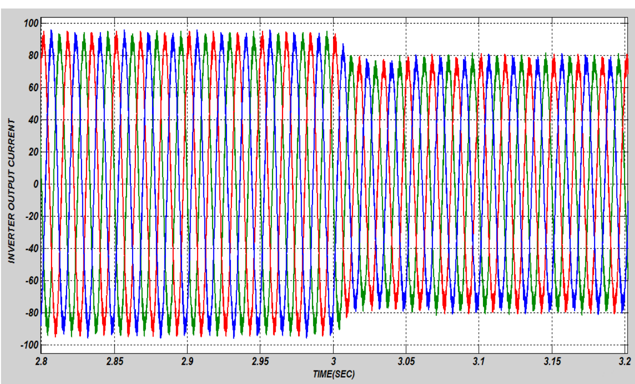

Figure 9. Inverter output current.

In Figure 10, the THD curve was demonstrated around 5% to 6.5%.

According to reduction of wind speed, the turbine torque decrease and based on this active power output from wind system and inverter current declined.

4.2 Case Study 2

The aim of this case is dynamic analysis of grid connected PMSG wind turbine in state of variable load and fixed wind speed. In this case, during $0 < t < 4$ sec load is 110 kW and in $t = 4$, it has 40% step increase in load and also, wind speed is 11 m/s. The active powers shown in Figure 11, which is depicted the imported power by grid to supply the load.

Grid current is illustrated in Figure 12.

It's been obvious that turbine output power is invariant, because of fixed wind speed which is shown in Figure 13.

Figure 14 is depicted the inverter output current.

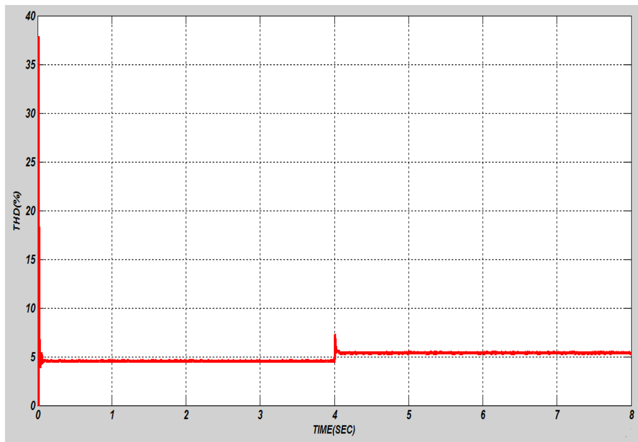

Figure 10. THD %.

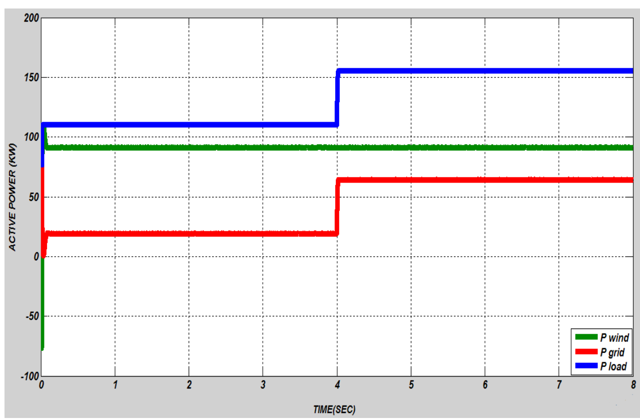

Figure 11. Active powers.

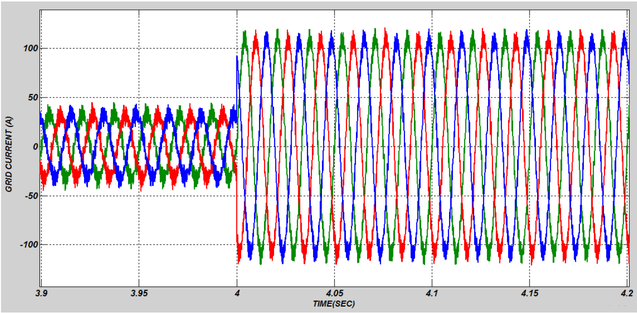

Figure 12. Grid current.

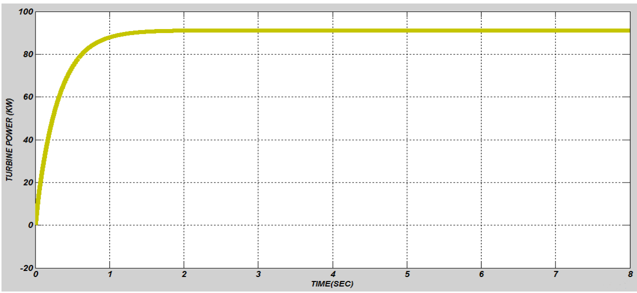

Figure 13. Turbine output power.

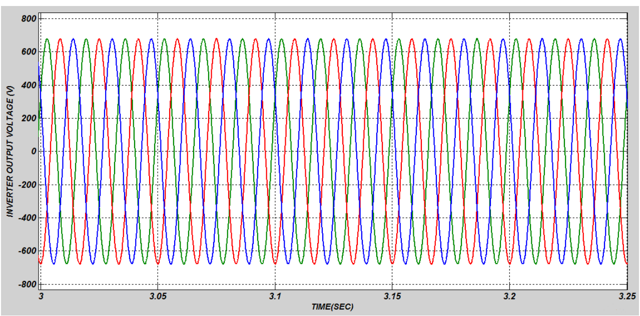

Figure 14. Inverter output current.

The generated reactive power by the wind turbine was adjusted at zero which the PF kept up unity as demonstrated in Figure 15. Wind turbine by applying appropriate controller could meet the load demand assuredly.

4.3 Case Study 3

The aim of this case is dynamic analysis of grid connected PMSG wind turbine in state of variable load and variable wind speed. In this case, during $0 < t < 5$ sec the load power is 110 kW and in $t = 5$, it has %55 step increase in load. Also wind speed is 11 m/s which in $t = 3$ reduced to 9 m/s. Figures (16–20) show the simulation results for active powers, inverter output current, grid current, turbine output torque and inverter output voltage. It's

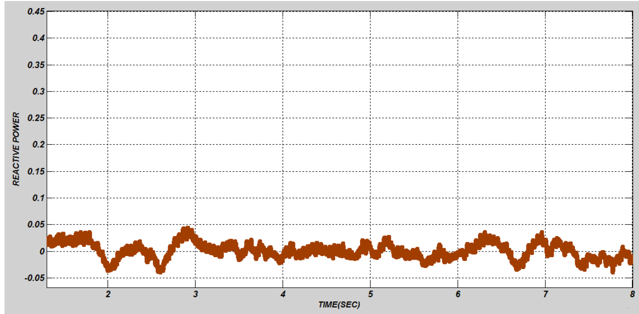

Figure 15. Reactive power.

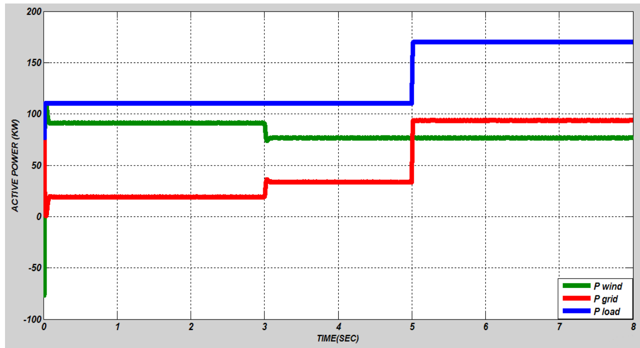

Figure 16. Active powers.

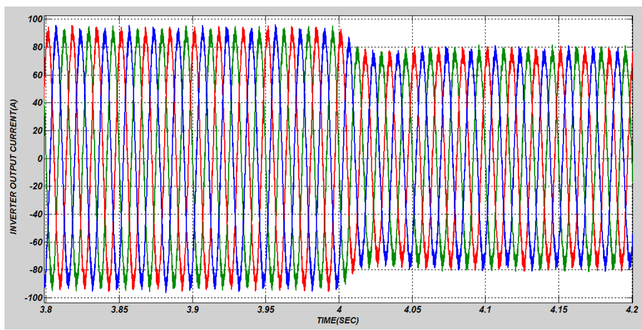

Figure 17. Inverter output current.

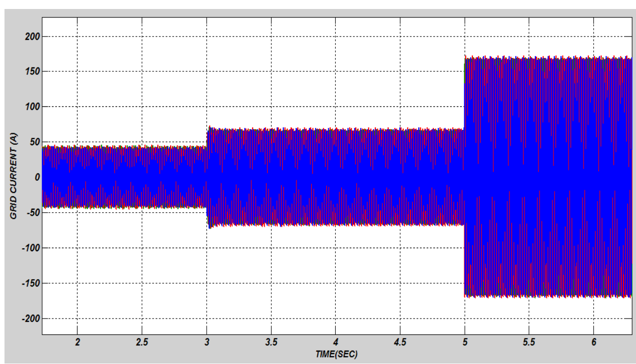

Figure 18. Grid current.

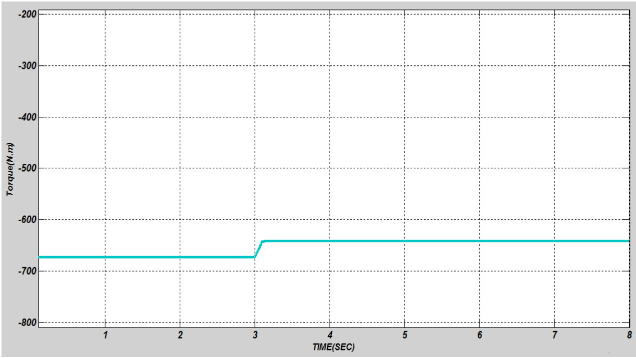

Figure 19. Turbine output torque

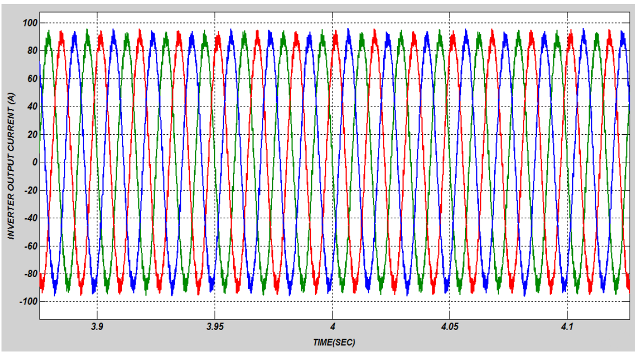

Figure 20. Inverter output voltage.

been clear that grid with cooperation of wind system by applying PQ controller can easily meet the load demand.

5. Conclusion

The presented study is a modeling and dynamic analysis of grid connected permanent magnet synchronous generator using Matlab/Simulink software under load circumstances and variable wind speed. Modeling of DC/AC grid connected inverter is proposed. The converter adjusts the DC link voltage and also, active power and reactive power are injected by d-axis and q-axis respectively, using P-Q control method. The reactive generative power turbine is located at zero value and PF is kept at unity. The simulation result in presented model is satisfactory.

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