Maximum Power Point Tracking for Grid Integrated Variable Speed Wind based Distributed Generation System with Dynamic Load

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Abstract- The production of electricity from renewable energy sources like wind energy increases in recent years due to environmental problems and the shortage of traditional energy sources in the near future. This paper presents modeling, simulation and performance study of wind energy based distribution generation (DG) systems for grid connected mode with MPPT controller. The wind power generation system uses wind turbine (WT), a permanent magnet synchronous generator (PMSG), a three-phase uncontrolled diode rectifier bridge, dc/dc boost converter with MPPT controller, a dc bus with a capacitor and a current regulated PWM voltage source inverter. Perturb and Observe (P&O) technique is used for maximum power tracking. The performance of the developed model is studied for different wind speeds and load conditions. The wind power output is compared for the cases of with and without maximum power point tracking system. In this work the PQ control strategy is adopted for the inverter of the grid connected wind generation system. Simulation results show that the controllers can regulate the DC link voltage, active and reactive power produced by the wind based DG system.

1. Introduction

The worldwide concern about the environment has led to increasing interest in technologies for generation of renewable electrical energy. Most of these renewable sources are abundant and pollution free. Inter connection of these generators to distribution network will offer a number of benefits such as improved power quality, efficiency, reliability, alleviation of system constraints along with the environmental benefits [1]. The wind energy has been considered as one of the significant renewable energy sources in recent years. Wind energy can be transformed to electric energy using a wind turbine and an electric generator. In wind-energy production application of PMSG has received much attention compared to other electric generators, because of its property of self-excitation, which allows an operation at a high power factor and efficiency.

With the developments in permanent magnetic materials in recent years, the performance of PMSG based wind turbine systems has been improved and they are widely used. They can also operate in a relatively wide range of wind speeds [2]. It is essential to include a maximum power point tracking (MPPT) algorithm in the system in order to determine the optimal operating point of the wind turbine [3]. A maximum power point tracking (MPPT) controller increases the power conversion efficiency of the system by regulating the turbine rotor speed according to actual wind speeds [4].

Basically, there are three types of MPPT algorithms, namely, perturb and observe (P&O) technique, Tip Speed Ratio (TSR) control and Optimum Relationship Based (ORB) control [5, 6]. P&O control adjusts the turbine speed toward the MPP, according to the result of comparison

between successive wind turbine generator output power measurements. TSR control directly regulates the turbine speed to keep the TSR at an optimal value by measuring wind speed and turbine speed [7, 8]. ORB control ensures MPPT with the aid of knowledge of optimum relationships between system parameters. In [9, 10] the relationship between electrical torque and rotor speed is employed to track maximum power point. In this paper, perturb and observe (P&O) technique is used for maximum power tracking. The proposed maximum power point algorithm suitable for large inertia systems and it is operated at without measurement values of wind speed [4].

The control schemes adopted to operate an inverter device are: (i) the active and reactive power control scheme (PQ control), when the inverter is operated to meet a given real and reactive power set point and (ii) the control of active power and voltage (PV control), when the inverter is controlled to supply the load with fixed values of voltage and frequency [11]. In this work the PQ control strategy is adopted for the inverter by means of Park transformation and has been implemented in Matlab/Simulink environment.

A detailed mathematical modeling and control for three-phase grid-connected wind based DG systems with MPPT algorithm, using Matlab/Simulink simulation package is presented in this paper. A control strategy is developed for the inverter of the grid connected wind generation system to control DC link voltage, active and the reactive power produced by the system. The dynamic load such as a 3 phase induction motor is considered for the performance analysis of the system.

2. Configuration of the Wind Based DG System

The block diagram of the grid integrated wind based DG system driven by PMSG is shown in Fig. 1.
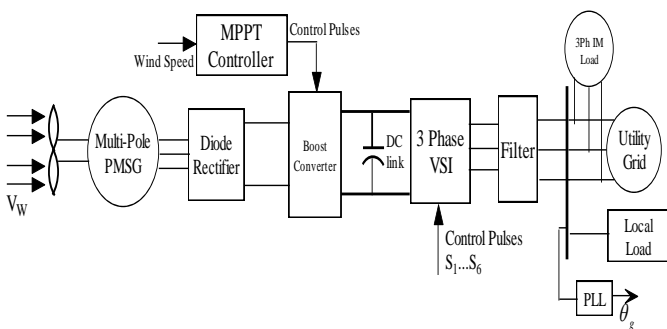

Fig. 1. The block diagram of wind based DG system

Aerodynamic power available in the wind can be calculated using equation [12].

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

Where P = Power in watts, ρ = air density, A = rotor swept area, V_w = wind speed in m/sec, C_p is coefficient of performance. The relationship between rotor speed and wind speed can be given by [4]

$$\lambda = \frac{\omega_m R}{V_w} \qquad (2)$$

Where R = rotor radius, ω_m = rotor speed in rad/sec, λ = tip speed ratio (TSR) = ratio between the linear speed of the tip of the blade with respect to the wind speed. The wind turbine torque on the shaft can be calculated from the power [13]

$$T_m = \frac{P_m}{\omega_m} = \frac{1}{2}\rho\pi R^5 \frac{\omega_m^3}{\lambda^3}C_p(\lambda, \beta) \qquad (3)$$

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} \qquad (4)$$

$$Where \quad \lambda_i = \left[\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right]^{-1} \qquad (5)$$

The MPPT algorithm keeps the power coefficient C_p at its maximum, $C_p = C_{pmax}$, corresponds to λ_{opt} [14, 15].

$$Where \qquad \omega_{ref} = \frac{V_w \lambda_{opt}}{R} \qquad (6)$$

We deduce

$$P = 0.5\rho A C_{p\max}\left(\frac{R\omega_{ref}}{\lambda_{opt}}\right)^3 \qquad (7)$$

The reference turbine speed ω_{ref} is generated by the MPPT code using P&O method. The wind turbine model is shown in Fig. 2 and Fig. 3 illustrates the mechanical power versus the rotating-speed at various wind speeds, assuming the blade pitch angle $\beta = 0°$.
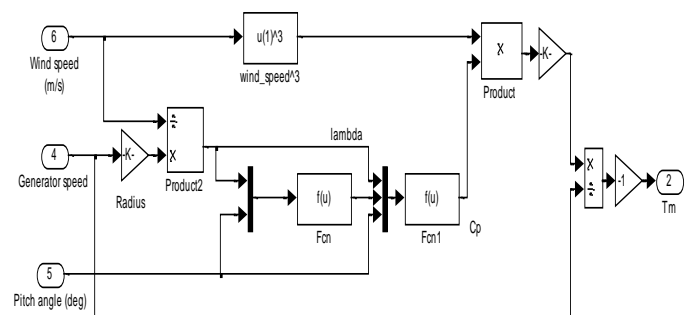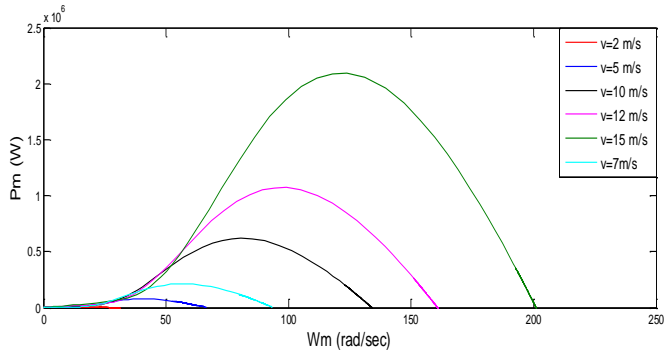

Fig. 2. Wind Turbine Model

Fig. 3. Power versus rotor speed for different wind speeds

The synchronous generator model is expressed in the (d, q) synchronous Park's model, where the d-axis is rotating along the magnetic field direction. The voltage equations of the PMSG are given by [16, 17]

$$V_{ds} = -R_s i_{ds} - L_d \frac{di_{ds}}{dt} + \omega L_q i_{qs} \tag{8}$$

$$V_{qs} = -R_s i_{qs} - L_q \frac{di_{qs}}{dt} - \omega L_d i_{ds} + \omega \phi_m \tag{9}$$

Where V_{ds} and V_{qs} are d and q-axis machine voltages; i_{ds} and i_{qs} are d and q-axis currents; R_s is the stator resistance, ω is the electrical angular frequency; L_d and L_q are d-axis q-axis inductances; ϕ_m is the amplitude of the flux linkages established by the permanent magnet. The expression for the electromagnetic torque in the rotor is given as

$$T_e = \frac{3}{2} p \left[(L_d - L_q) i_{ds} i_{qs} - \phi_m i_{qs} \right] \tag{10}$$

Where 'p' is the number of pole pairs of the PMSG and if the rotor is cylindrical, $L_d \approx L_q = L_s$ so that

$$T_e = \frac{3}{2} p \phi_m i_{qs} \tag{11}$$

3. MPPT Algorithm and Control Strategy for Inverter

The reference turbine speed ω_{ref} is generated by using perturb and observe (P&O) technique. The different steps for maximum power point tracking (MPPT) algorithm are

i. ωref is the initial reference speed for rotor and corresponding output power of the generator (P_{ref}) is calculated.
ii. The reference rotor speed ($\omega refnew$) increased or decreased by one step and corresponding output power (P_{refnew}) is calculated again.
iii. Calculate $\Delta\omega = \omega refnew - \omega ref$ and $\Delta P = P_{refnew} - P_{ref}$;
iv. Calculate sign($\Delta\omega$); If $\Delta\omega > 0$ then sign($\Delta\omega$) = 1, else sign($\Delta\omega$) = -1;
v. Calculate sign(ΔP); If $\Delta P > 0$ then sign(ΔP) = 1, else sign(ΔP) = -1;

vi. Determine $\omega_{ref}(n) = \omega_{ref}(n-1) + sign(\Delta P)*sign(\Delta\omega)*\omega_{step}$;
vii. Step (ii) is repeated to reach to optimum operating point of the system.

Let us assume the initial wind speed is V_{w1} and operating point of the turbine represented as (ω_1, P_1) in P vs. ω characteristic curve. Also, let us now assume that the turbine speed is increased by ω_{step}, which results in a new speed ω_2. The new operating point will be (ω_2, P_2) which gives:

$\Delta\omega = \omega_2 - \omega_1 > 0$; then sign ($\Delta\omega$) = 1

$\Delta P = P_2 - P_1 > 0$; then sign (ΔP) = 1; Therefore, $\omega_2 = \omega_1 + \omega_{step}$

The flowchart for maximum power point tracking (MPPT) algorithm is given in Fig. 4.
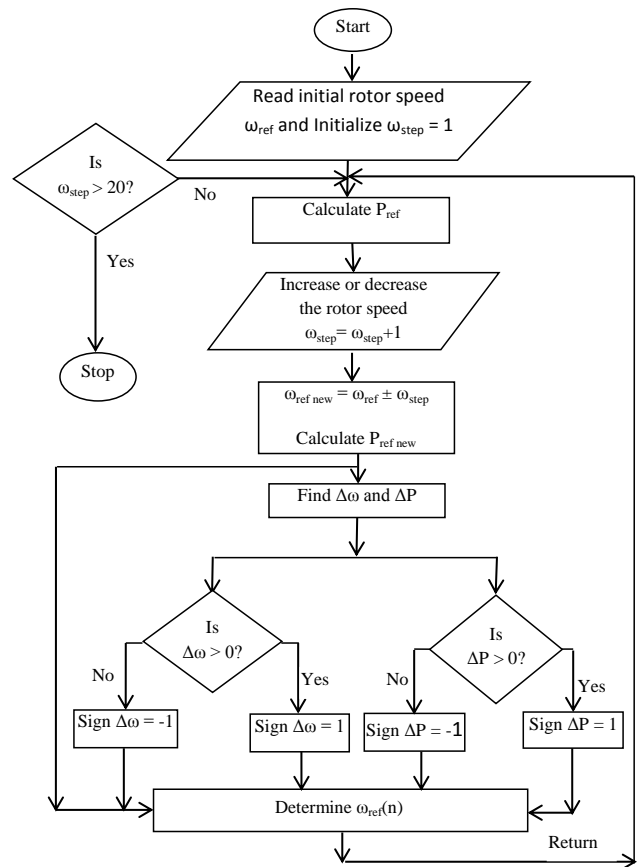

Fig. 4. Flowchart for maximum power point tracking (MPPT) algorithm

For connecting renewable energy sources to the distribution utility grid the power conditioning system (PCS) is used. In this work the PQ control strategy is adopted for the inverter by means of Park transformation and has been implemented in Matlab/Simulink environment. In a three-phase system the instantaneous power is given by

$$P(t) = v_A i_A + v_B i_B + v_C i_C \tag{12}$$

In synchronous reference frame the relations of these powers are as follows

$$P = \frac{3}{2}(V_{gd}I_d + V_{gq}I_q) \qquad (13)$$

$$Q = \frac{3}{2}(V_{gq}I_d - V_{gd}I_q) \qquad (14)$$

The grid voltage vector is $V = V_{gd} + j0$, if the reference frame is synchronized with the grid voltage, then active and reactive power may be expressed as

$$P = \frac{3}{2}(V_{gd}I_d) \; and \; Q = \frac{3}{2}(V_{gd}I_q) \qquad (15)$$

Active and reactive-power control can be implemented by controlling the direct and quadrature currents respectively with PI controllers. The control scheme of the grid-side converter is shown in Fig. 6. The outer loop of voltage control is used to set the *d*-axis current reference for active-power control. The q-axis reference current is specified by desired inverter reactive power output injected to the grid [18]. If unity power factor is considered, this current would be regulated at zero value. And the decoupling voltage components are added to the output of current PI controllers to have independent control of the current components I_d and I_q. The phase locked loop (PLL) block [19] which measures the grid voltage phase angle θ_g is used to implement Park transformation and to synchronize the inverter with grid. In synchronous reference frame the *d-q* component with decoupling terms can be represented as [20]:

$$u_d = v_d^1 - R_f I_d - L_f \frac{dI_d}{dt} + \omega L_f I_q \qquad (16)$$

$$u_q = v_q^1 - R_f I_q - L_f \frac{dI_q}{dt} - \omega L_f I_d \qquad (17)$$

Where, the d-q currents are controlled by means of the right choice of the d-q converter side voltages. Two PI regulators are command a PWM modulator to generate the voltage that should control the current. A lower bound on the dc bus voltage can be determined from the following equation at a unity power factor [21].

$$0.6124 m_a V_{DC} \geq \sqrt{(V_{ACLL})^2 + 3(\omega L_f I_{AC})^2} \qquad (18)$$

Where V_{ACLL}=line-line RMS voltage on the inverter side, L_f=filter inductance, I_{AC}=maximum possible RMS Value of the AC load current m_a=modulation index of the inverter.

4. Results and Discussions

In this section, time domain simulated responses of the proposed system using Matlab/Simulink under different operating conditions are presented. The block diagrams of the grid connected wind based DG systems in Matlab/Simulink are shown in Fig. 5(a). The variations in wind velocity and load conditions are considered for the simulation study. A simulation interval of 3 sec has been chosen. The simulation parameters of the system are given in Table 1.

Table 1: Simulation parameters of the system

PMSG Parameters	Stator Phase Resistance = 2.875Ω, Inertia = 0.8e-3Kg-m², $L_d=L_q$=8.5mH, Torque constant 12N-m/A peak, Pole pairs = 8, P_{out} = 100kW, V_{wrated} = 12m/sec;
DC link capacitor	5000μF; DC link voltage=780V;
Load	3 phase 20HP IM load and resistive load
RL Filter	R=0.5Ω; L=5mH
Grid Parameters	415V, 50Hz, X/R ratio=7;

The reference turbine speed ω_{ref} is generated by the MPPT code using P&O method written in Embedded MATLAB Function block with Boost Converter in Matlab/Simulink is shown in Fig. 5(b). This reference rotor speed is compared with the actual value and the difference is fed to a PI Controller. This is then compared with the input current of the Boost Converter and the difference is fed to a comparator. The pulse is generated by comparing it with a repeating sequence and this pulse is then fed to the gate of the DC/DC Converter to control its duty cycle and maximum power output is obtained. The purpose of this circuit is to control the shaft speed of the PMSG so that the maximum power can be captured from wind by the turbine.
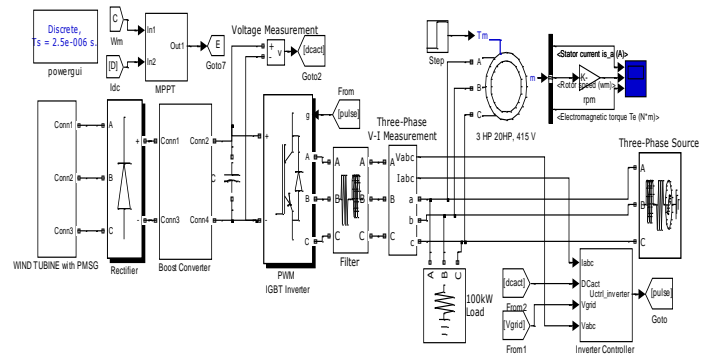

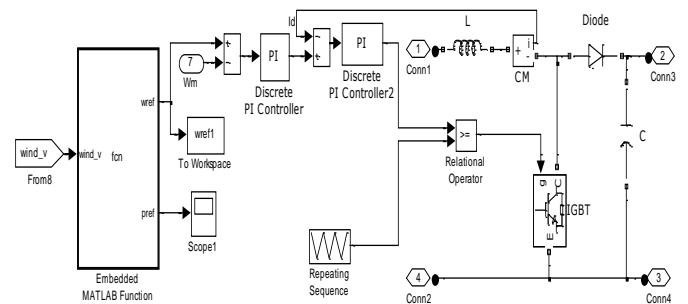**Fig. 5(a).** Block diagram of the grid tied wind based DG system in Matlab/Simulink

Fig. 5(b). Boost Converter Pulse Generation using MPPT algorithm for wind system with Boost Converter
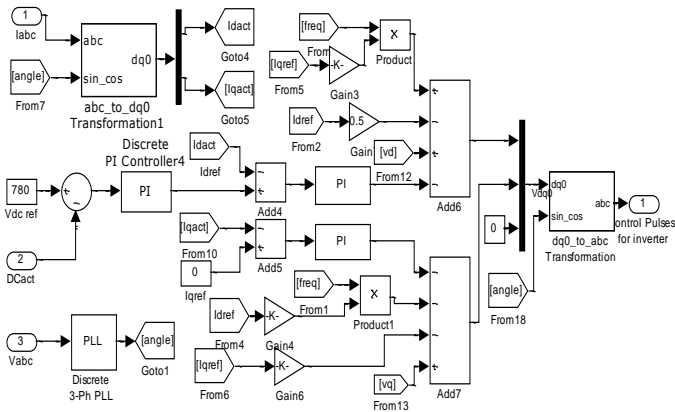
Fig. 6. Schematic of PQ control strategy for inverter

A heating load of 100kW and 20HP, 415V, 50Hz, 1430RPM three phase squirrel-cage induction motor load is considered to study the dynamic behavior of the system. The wind speed is varied from 8m/sec to 12m/sec. Fig. 7 illustrates the time domain simulated results for wind speed and reference turbine speed ω_{ref}. The simulated results for DC link voltage and inverter output voltage are shown in Fig. 8 and Fig 9 respectively. It can be clearly observed that the proposed model has constant DC link voltage and a purely sinusoidal controlled ideal voltage source at the inverter terminals. From the above simulated results it is seen that due to sudden variations in wind speed, the turbine reference speed ω_{ref} changes. Accordingly the active power output of the wind generation system changes. The generator output tracks the corresponding maximum power very successfully with just small delays in the dynamic response. In order to meet the load demand, the deficit power will be supplied from the utility grid.
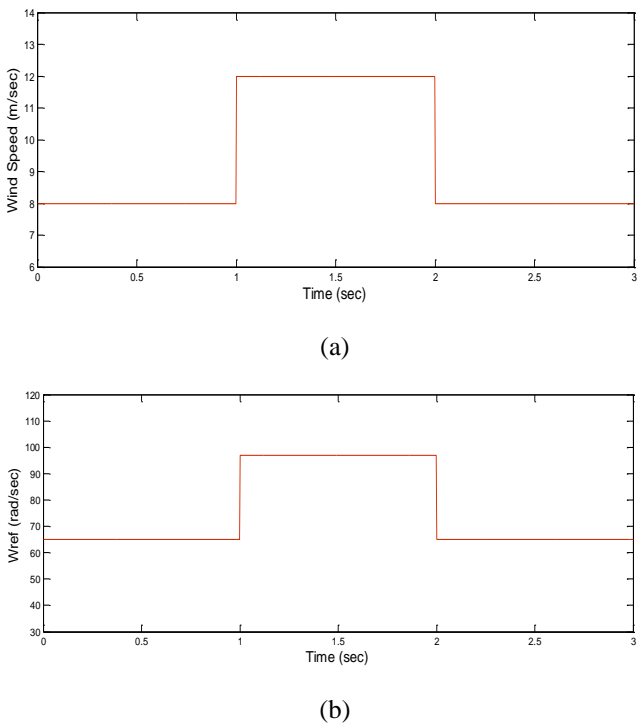

(a)

(b)

Fig. 7. Simulated results– wind speed and reference turbine speed ω_{ref}
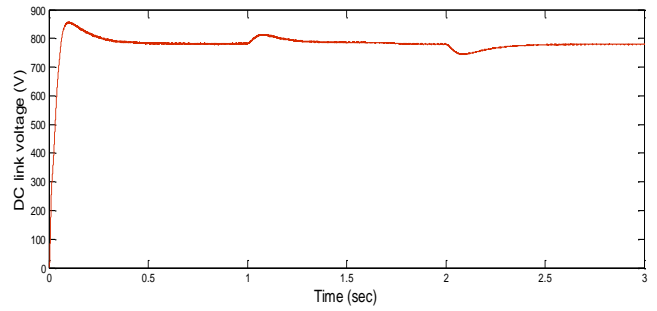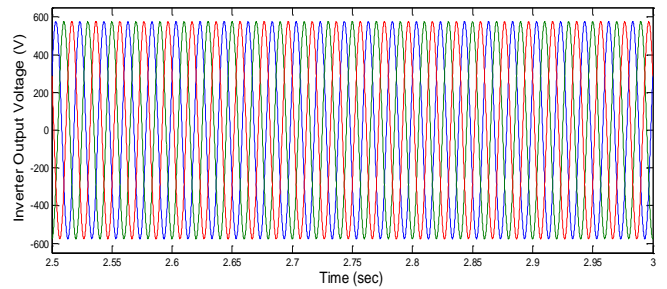

Fig. 8. DC link voltage
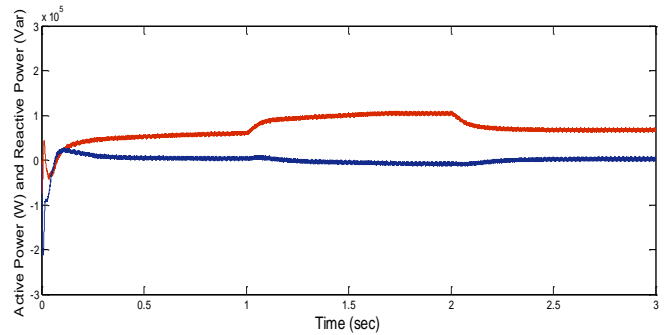

Fig. 9. Inverter output voltage

Fig. 10(a). Simulated results for injected active and reactive power outputs for the case with Maximum Power Point Tracking system
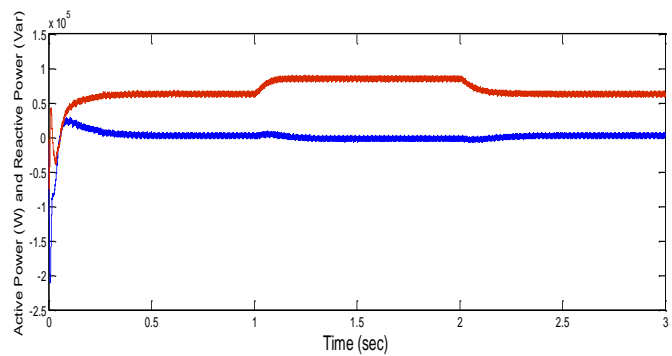

Fig. 10(b). Simulated results for injected active and reactive power outputs for the case without Maximum Power Point Tracking system

Fig. 10(a) and 10(b) shows wind power output for the cases of with and without Maximum Power Point Tracking system respectively. In the case of operating the WECS with no MPPT control, the output power drawn from the WTG is almost 14% lesser. From the power response it is evident that

no reactive power is injected by wind power system. Since the reactive power injected by wind power system is zero and the utility grid will supply the reactive power demand of the induction motor load.

Initially the load torque applied to the shaft of the 3 phase induction motor is 50 N-m and is suddenly increased to 90 N-m at t=1.5sec. As the load on the induction motor increases the electromagnetic torque also increases and rotor speed reduces. The results for induction motor torques, rotor speed and stator current for step change in torque T_m are shown in fig. 11 below
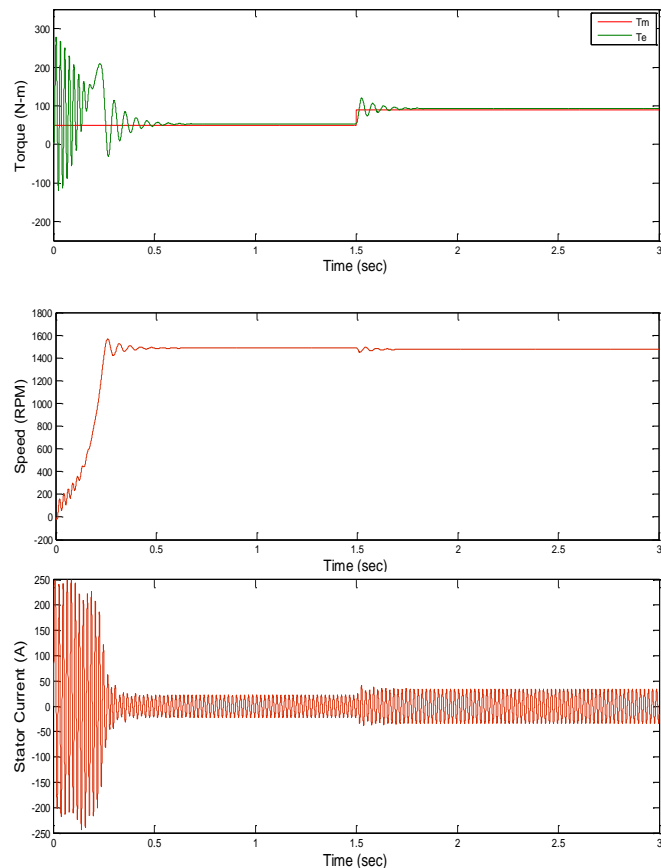

Fig. 11. Simulated results for induction motor torques, rotor speed and stator current for step change in torque T_m

5. Conclusion

In this paper, modeling and simulation results of a grid connected PMSG based DG system with MPPT Algorithm are analyzed and presented using Matlab/Simulink tool. Variations in wind velocities and load conditions are considered for the study. Detailed modeling and control strategy of a DC-AC converter connected to utility grid have been proposed. The inverter controller regulates the DC link voltage and regulates injected active power by d-axis current and the injected reactive power by q-axis current. The reactive power produced by the wind turbine is regulated at zero so that unity power factor is maintained. The wind power output is compared for the cases of with and without Maximum Power Point Tracking system. Simulation results show that the proposed method operates satisfactorily.

Acknowledgements

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