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Dynamic Modeling and Performance Analysis of Grid Connected PMSG based Variable Speed Wind Turbines With Simple Power Conditioning System

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***Abstract* - This paper presents modeling, simulation and performance analysis of grid connected wind generation system using direct-driven Permanent Magnet Synchronous Generator (PMSG). The proposed system includes a wind turbine (WT), a permanent magnet synchronous generator, a three-phase diode rectifier bridge, a dc bus with a capacitor and a current regulated PWM voltage source inverter. In this paper complete modeling of wind power generation system with PMSG and power electronic converter interface along with the control scheme is developed using a Matlab/Simulink simulation package. The performance of the developed model is studied for different wind speeds and load conditions. Simulation results show that the controllers can regulate the DC link voltage, active and reactive power produced by the wind power generation system.**

Keywords - Wind power generation systems, Permanent Magnet Synchronous Generator, PWM voltage source inverter, PQ control

I. INTRODUCTION

The worldwide concern about the environment has led to increasing interest in technologies for generation of renewable electrical energy. The ever-increasing demand for conventional energy sources has driven society towards the need for research and development of alternative energy sources. Several new forms of renewable resources such as wind power generation systems (WPGS) and photovoltaic systems (PV) to supplement fossil fuels have been developed and integrated globally. However, the photovoltaic generation has low energy conversion efficiency and very costly as compared to the wind power, in recent years, wind energy has been regarded as one of the significant renewable energy sources [1]. Wind energy can be captured and transformed to electric energy using a wind turbine and an electric generator. Among the electric generators, PMSG has received much attention in wind-energy application because of their property of self-excitation, which allows an operation at a high power factor and high efficiency. With the developments in permanent magnetic materials in recent years, the performance of PMSG based wind turbine systems have been improved and they are widely used. These systems require neither slip rings nor an additional power supply for magnetic field excitation. They can also operate in a relatively wide range of wind speeds. Therefore, their efficiency is known to be higher than that of any other system [2, 3].

In recent years, numerous topologies of power conditioning systems (PCS), varying in cost and complexity has been developed for integrating PMSG wind turbine systems into the electric grid [4]. To operate an inverter device, two kinds of control adopted are: 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 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 [5]. The performance analysis of grid connected wind generation system using direct-driven PMSG in the presence of typical network perturbed conditions the PQ control scheme. The PQ control strategy is adopted by means of Park transformation and has been implemented in Matlab-Simulink environment.

This paper focuses on the modeling and control of grid connected wind generation system using direct-driven (PMSG) with simple power conditioning system. The performance of the developed model is studied for different wind speed and load conditions by simulating wind generation system using MATLAB/Simulink simulation package. A control strategy is developed for the inverter of the grid connected wind generation system to control DC link voltage, active power generated and the reactive power produced by the wind power generation system.

This paper is divided into various sections as follows: In Section II the configuration of the system is presented. Section III is dedicated to the description of the main components of the system: the wind turbine, the PMSG machine, the power conditioning system (PCS) and the

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control scheme. The simulation model of the proposed system, results and their analysis are presented in Section IV. Finally, based on the above study the conclusion is drawn in Section V.

II. CONFIGURATION OF THE SYSTEM

The block diagram of the proposed grid integrated variable speed wind energy conversion system driven by permanent magnet synchronous generator is shown in Fig. 1. The AC output of PMSG is rectified with the help of uncontrolled rectifier. The dc link voltage is then regulated to obtain constant voltage using PI controller and the constant DC-link voltage is inverted to get the desired AC voltage employing a sinusoidal PWM inverter. The PQ control strategy is developed by means of Park transformation and has been implemented in Matlab/Simulink environment for grid connected wind energy system. The inverter regulates the DC link voltage and injected active power by d-axis current and regulates the injected reactive power by q-axis current using PQ control method.

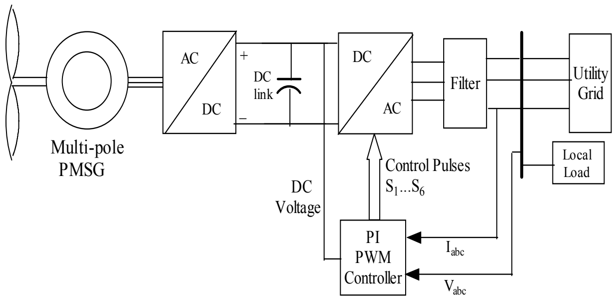

Fig. 1 The block diagram of proposed system

III. SYSTEM MODELING

A. Wind turbine power:

Wind turbine power depends on both rotor speed and wind speed [6, 8]. Aerodynamic power available in the wind can be calculated using equation (1).

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

Where P = Power in watts, ρ = air density, A = rotor swept area, V_w=wind speed in m/sec, C_p is power coefficient of the rotor. From (1), we see that the power absorption and operating conditions of a turbine are determined by the effective area of the rotor blades, wind speed, and wind flow conditions at the rotor. Thus, the output power of the turbine can be varied by effective area and by changing the flow conditions at the rotor system, which forms the basis of control of wind energy conversion system.

The tip speed ratio λ, defined as the ratio of the linear speed at the tip of the blade to the free stream wind speed and is given by the following expression [2, 7]

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

Where R = radius of the turbine, ω_m = rotor speed in rad/sec.

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

$$\text{Where}\quad \lambda_i = \left[\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}\right]^{-1} \qquad (4)$$

For a given turbine, the power coefficient depends not only on the TSR but also on the blade pitch angle. Fig. 2 shows the typical variation of the power coefficient with respect to the TSR for various values of the pitch angle β.

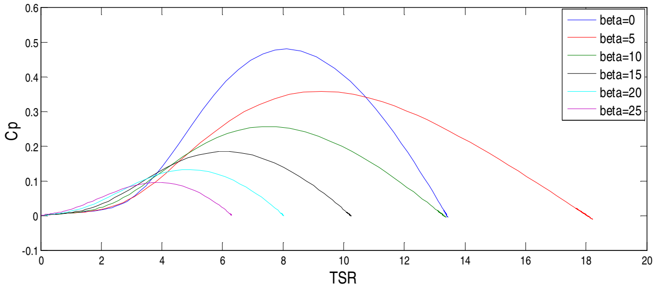

Fig. 2 C_P vs. λ (TSR) for various pitch angles β

B. Modeling of PMSG:

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 [9]

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

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

Where V_{ds} and V_{qs} are the two-axis machine voltages; i_{ds} and i_{qs} are the two-axis machine currents; R_s is the stator resistance ω is the electrical angular frequency; L_d is the direct axis inductance, L_q is the quadrature inductance; ϕ_m is the amplitude of the flux linkages established by the permanent magnet.

The expression for the electromagnetic (EM) torque in the rotor if the rotor is cylindrical, $L_d \approx L_q = L_s$ is written as

$$T_e = \frac{3}{2} p \phi_m i_{qs} \qquad (7)$$

Where 'p' is the number of pole pairs of the PMSG

C. Power Conditioning System (PCS):

The power conditioning system (PCS) used for connecting renewable energy sources to the distribution utility grid requires the generation of high quality electric power. The proposed system includes a wind turbine (WT), a permanent magnet synchronous generator, a three-phase diode rectifier bridge, a dc bus with a capacitor and a current regulated PWM voltage source inverter. A three-phase uncontrolled full-wave rectifier bridge for performing the AC-DC conversion and this device has the benefit of being simple, robust, cheap and needs no control system. A three-phase DC-AC voltage source inverter using IGBTs is employed for connecting to the grid through sinusoidal pulse width modulation (PWM) techniques. As the high-frequency harmonics produced by the inverter as result of the PWM control techniques employed are filtered by the filter, the VSI can be seen as an ideal sinusoidal voltage source, which is depicted in Fig. 5. Since the wind power fluctuates with wind velocity, the generator output voltage and frequency vary continuously. The varying AC voltage is rectified into DC in a diode bridge and the dc link voltage is then regulated to obtain constant voltage using PI controller and the DC voltage is inverted to get the desired AC voltage employing a PWM inverter.

A lower bound on the dc bus voltage can be determined from the following equation which should be satisfied between the DC side and AC side voltages of the inverter [11, 12].

$$0.6124 \mathrm{m_a} \mathrm{V_{DC}} \geq \sqrt{(V_{ACLL})^2 + 3(\omega L_f I_{AC})^2} \qquad (8)$$

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.

The active and reactive-power in synchronous reference frame are as follows [10]

$$P = \frac{3}{2}(V_{gd} I_d + V_{gq} I_q) \qquad (9)$$

$$Q = \frac{3}{2}(V_{gq} I_d - V_{gd} I_q) \qquad (10)$$

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

$$P = \frac{3}{2} V_{gd} I_d \qquad (11)$$

And

$$Q = \frac{3}{2} V_{gd} I_q \qquad (12)$$

The control scheme of the grid-side converter is shown in Fig. 3. Active and reactive-power control can be implemented by controlling the direct and quadrature currents respectively with PI controllers. The outer loop of capacitor 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 [5, 13]. If unity power factor is considered, this current would be regulated at zero value. The phase locked loop (PLL) block which measures the grid voltage phase angle θ_g is used to implement Park transformation and to synchronize the inverter with grid [14].

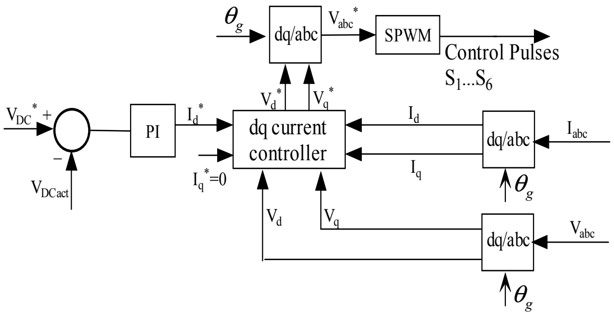

Fig. 3 Control Scheme for Inverter

IV. 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 diagram of the system in Matlab/Simulink is shown in Fig. 4. The simulation parameters of the system are given below.

PMSG Parameters: Stator Phase Resistance = 2.875Ω, Inertia = $0.8e^{-3}$Kg-m^2, L_d=L_q=8.5mH, Torque constant 12N-m/A peak, Pole pairs = 8, P_{out}=100kW, V_{wrated}=12m/sec;

Grid Parameters: 480V, 60Hz, X/R ratio=7;

DC link capacitor: 5000μF; DC link voltage=1100V;

Load: Inductive Load

The following three cases are considered for the simulation study due to variation in wind velocity and load conditions.

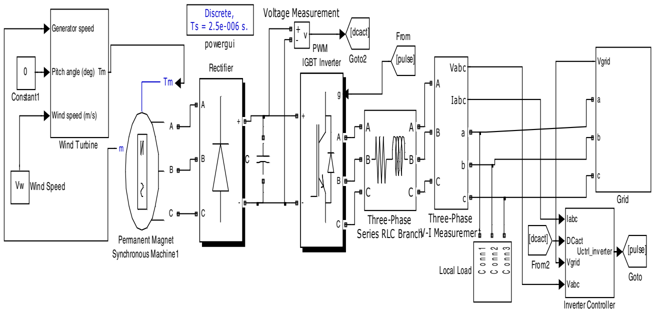

Fig. 4 Block diagram of the system in Matlab/Simulink

Case I: Constant load and variable wind speed

In this case, during 0 < t < 1 sec the wind speed is 10m/sec and is decreased to 8m/sec at t = 1 sec and the load power is 100kW. Fig. 5 illustrates the time domain simulated results for turbine torque, inverter output voltage, active powers, inverter output current and percentage THD variation in inverter output current of case I. It can be clearly observed from Fig. 5 that the proposed model has a purely sinusoidal controlled ideal voltage source at the inverter terminals. One of the important aspects of DG system interconnection to the utility network is to maintain the harmonic distortion level as minimum as possible. As per IEEE Std. 1547-2003, it should be less than 5%. It can be observed from Fig. that the harmonic distortion level is around 3 to 3.5%, which is well within the standards. Due to sudden decrease in wind speed, the turbine torque reduces. Accordingly the active power output of wind generation system and inverter output current reduces. In order to meet the load demand, the deficit power will be supplied from the utility grid.

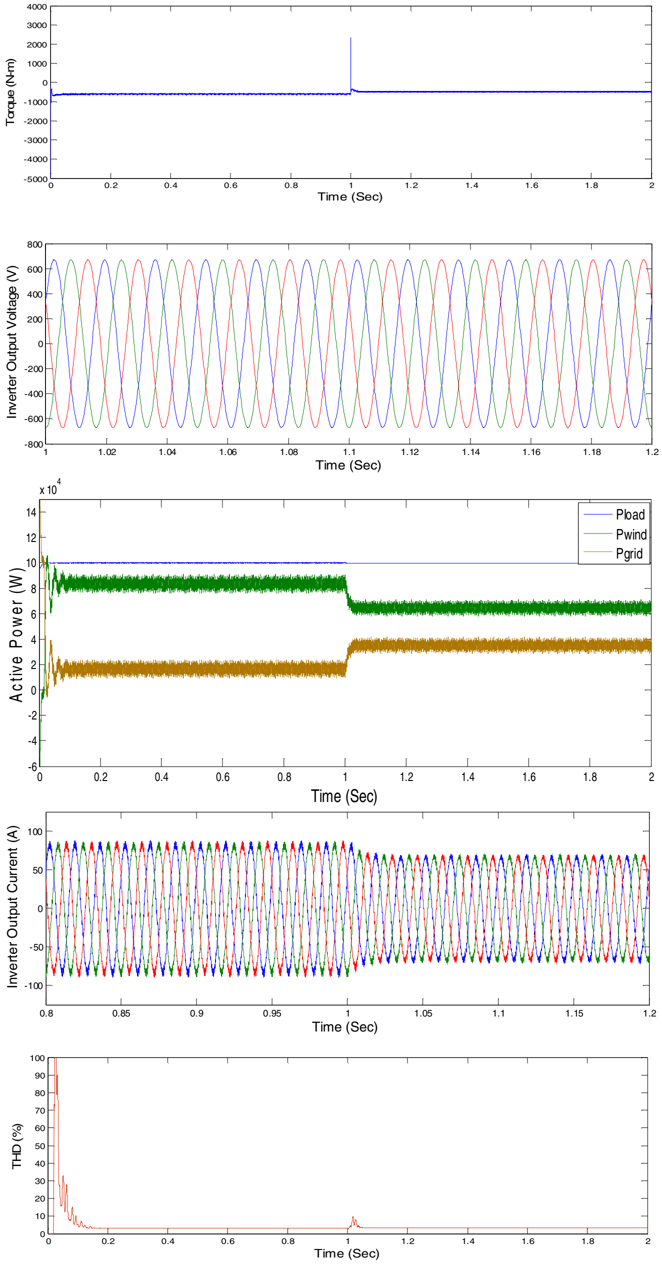

Fig. 5: Simulated results for Case I- turbine torque, inverter output voltage, active powers, inverter output current and % THD variation in inverter output current

Case II: Constant wind speed and variable load

For this case, during $0 < t < 1$ sec the load power is 100kW and a 50% step increase in load occurs at t = 1 sec and the wind speed is 10 m/sec. Fig. 6 illustrates the time domain simulated results for turbine torque, DC link voltage, active powers, inverter output current, d-axis and q-axis currents and injected reactive power for case II. It can be seen that the DC link voltage and active power output of wind generation system are constant in this case. The variation in the I_d and I_q components of the injected current are shown. From the power response it is evident that no reactive power is injected by WPGS.

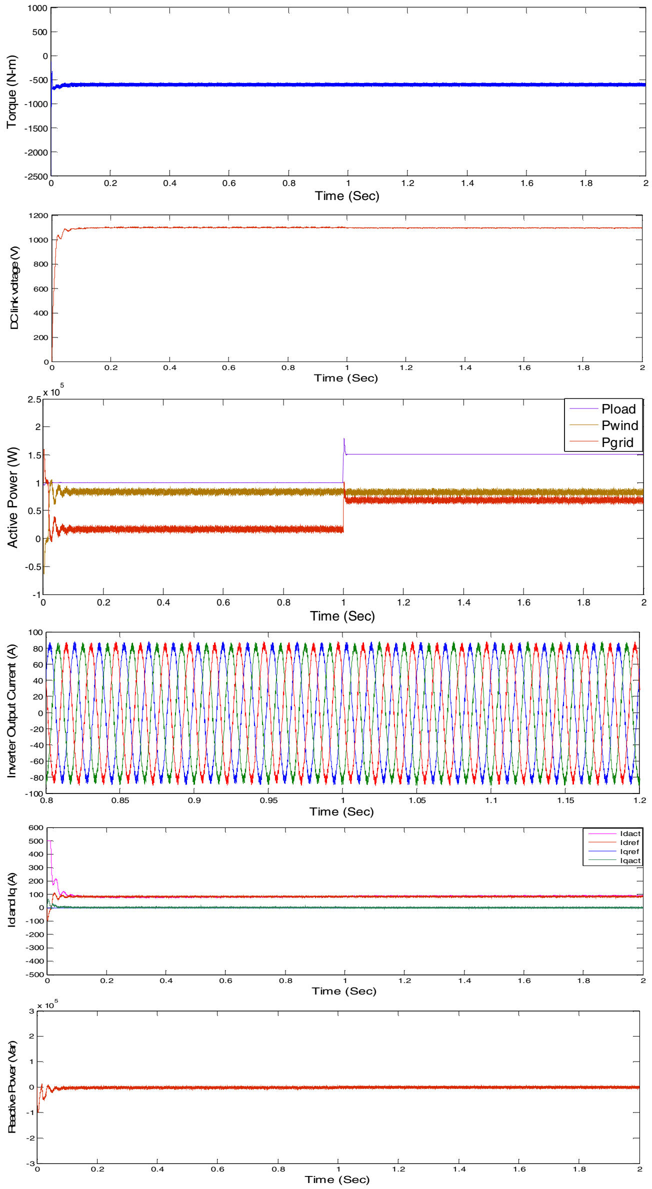

Fig. 6: Simulated results for Case II- turbine torque, DC link voltage, active powers, inverter output current, d-axis and q-axis currents and injected reactive power output of WPGS

Case III: Variable wind speed and variable load

For this case, during $0 < t < 2$ sec the load power is 100kW and a 50% step increase in load occurs at t = 2 sec.

The wind speed is 10m/sec upto 1 sec and is decreased to 8m/sec at t=1 sec. Fig. 7 illustrates the simulated results for active powers, inverter output current and current supplied by utility grid. It can be seen that the utility grid will supply the load demand in cooperated with WPGS.

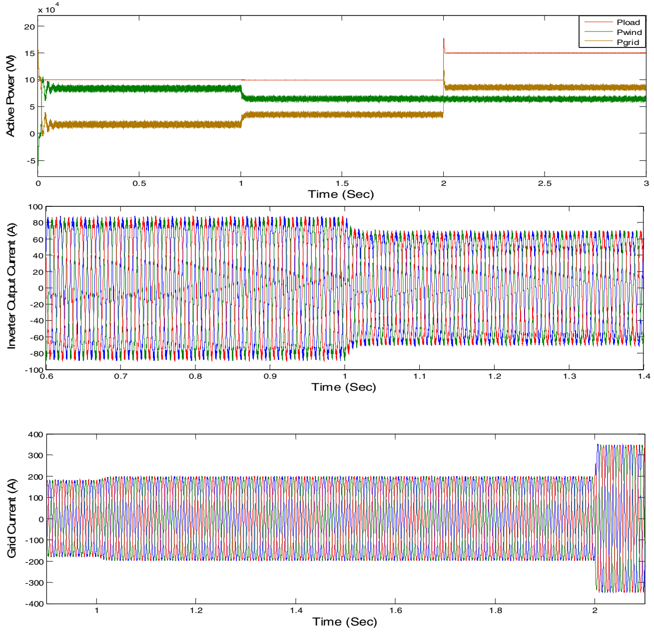

Fig. 7: Simulated results for Case III- active powers, inverter output current and grid current

V. CONCLUSION

Modeling and simulation results of a grid connected PMSG based wind turbine system is analyzed and presented in this paper 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 regulates the DC link voltage and injected active power by d-axis current and regulates the injected reactive power by q-axis current using simple PQ control method. The reactive power produced by the wind turbine is regulated at zero so that the power factor is maintained unity. Simulation results show that the proposed method operates satisfactorily.

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VII. BIOGRAPHIES

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