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Performance Analysis Of Operation And Control Of PMSG Based Grid Connected Variable Speed Wind Energy Conversion System Using SVPWM

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Abstract

Wind is one of the most prominent renewable sources of energy. Wind energy conversion system (WECS) is based on a variable speed wind turbine with direct driven permanent magnet synchronous generator (PMSG) and transmits its electrical power to an AC grid using advanced power electronic converter system. This paper describes operation and control of variable speed WECS based on gearless PMSG to developing a maximum power point tracking (MPPT) method in order to capture maximum wind energy and implementation of grid side converter control strategy to control active and reactive powers injected into the grid. A popular technique for control of the PMSG is field oriented control in which the torque is indirectly controlled by controlling the q axis stator current. Active and reactive power is controlled by direct and quadrature current components respectively. In this system the PMSG is connected to Grid by means of a fully controlled back-to-back converter with voltage source inverter (VSI) which consists of a space vector pulse width modulation (SVPWM) and an intermediate dc link circuit. The proposed model is implemented in MATLAB/SIMULINK environment.

Key words—*PMSG, WECS, SVPWM, Controlled Rectifier, Voltage source inverter DC-link voltage, MPPT.*

1. INTRODUCTION

Day by day the energy consumption is increasing very rapidly. The world´s fossil-fuel supply (coal, petroleum and natural gas) will be depleted in few hundred years. Alternative or non-conventional or renewable energy resources are very much required to develop for future energy requirements. Power generation from the fossil fuel has many adverse effects on the environment. The climate change due to the emissions of carbon has harmful effects that created a higher demand for clean and sustainable energy sources. Being non-polluting in nature and with the advancement in the arena of power electronics, the non-conventional energy resources (Solar, Wind, Biomass, Geothermal etc) has become most promising alternative for fossil fuel in power generation[2]. Wind is one of the most abundant renewable sources of energy which can be extracted by a WECS. The development of a WECS involves technologies in various aspects. Up-to-date technologies have been consistently applied to WECS and results in miscellaneous designs available on the market. However, the modern Grid connected high power WECS utilizes power converters without exception and shares a common configuration, as shown in Fig. 1. A variable-speed WECS typically consists of a wind turbine, an optional drive train (gear or gearless), a generator (synchronous or induction), a power converter and a step-up transformer.

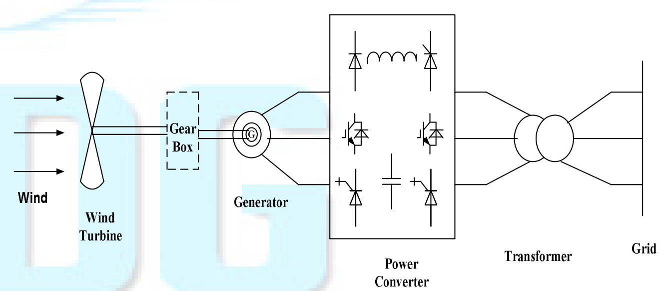


Fig.1. Basic configuration of the contemporary WECS

The generator rotor is mechanically coupled with the wind turbine through the drive train, which can be either directly connected or through a gearbox. The gearbox works as a speed multiplier to step up the rotational speed of wind turbine to match that of the generator. The power converter for WECS can be: voltage source converter (VSC) and current source converter (CSC). Microgrids are combinations of Distributed Generations and loads. The steady state, dynamic operation, reliability, power quality and stability have to be investigated in order to sustain power system operation. Based on the types of components used; different WECS structures can be realized to convert the wind energy at varying wind speeds to electric power at the grid frequency [1]. As a result, variable speed wind turbine (VSWT) systems with the power electronics interfaces have gained interest.

The most widely used of generators in wind power system are induction generator, doubly fed induction generator (DFIG) and PMSG [3]. Wind turbines based on squirrel cage induction generator (SCIG) are typically equipped with a soft-starter mechanism and an installation for reactive power compensation, as SCIGs consume reactive power. The term 'doubly fed' refers to the fact that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter. This system allows a variable-speed operation over a large, but limited range [3]. PMSG is an attractive choice for variable-speed generation system. It is connected directly to the turbine without gearbox and do not require any external excitation current. So it is able to operate at low speeds and reduce weight, costs, losses and maintenance problem. It has full controllability of the system for maximum wind power extraction and grid interface. Benefit is that power can be generated at any speed so as to fit the current conditions. Thus the efficiency reliability and controllability of a VSC-based PMSG wind turbine is higher than that of a DFIG wind turbine [4]. The use of full scale VSC-based (IGBT) converters makes it more favorable.

This paper describes operation and control of variable speed WECS based on gearless PMSG to developing a maximum power point tracking (MPPT) method in order to capture maximum wind energy and implementation of grid side converter control strategy to control active and reactive powers injected into the grid [5]. For PMSG, a popular field oriented control technique is used to control the torque indirectly by controlling the q axis stator current. The vector oriented control scheme is used for independent active and reactive power control by controlling d-q current component respectively while maintaining the maximum converter efficiency, constant dc link voltage and extracting the maximum power In this system the PMSG is connected to Grid by means of a fully controlled back-to-back converter with Voltage Source Inverter (VSI) which consist of a Space vector pulse width modulation (SVPWM) and an intermediate dc link circuit. The proposed model is implemented in MATLAB/SIMULINK environment and the experimental results are presented to verify the performance of the system.

2. PROPOSED SYSTEM CONFIGURATION

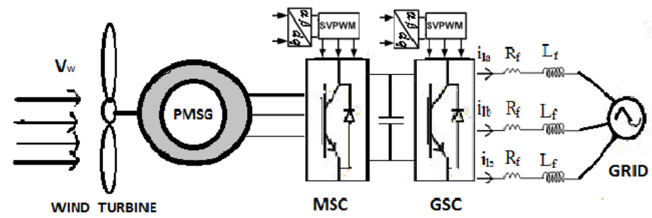


Fig.2.1 Configuration of PMSG based WECS

In this system the PMSG is connected to Grid through fully controlled back-to-back converter with Voltage Source Inverter (VSI) which consists of a Space vector pulse width modulation (SVPWM) and intermediate dc link circuit as shown in fig.2.1. Generator torque is controlled indirectly by controlling the q axis stator current [7]. Active and reactive power is controlled by d-q current components respectively

2.1 Wind Turbine Model

In order to provide an overview of the generic model, it is sufficient to express the mechanical power output of a wind turbine with specific constructional data as a function of rotational speed, wind speed and blade angle, as in Eq. 2.1. Depending on the modeling environment the link between the aerodynamic system and the mechanical system will be either mechanical power P_T or mechanical torque T_T [6]. They are related to each other by the rotational speed ω_T as shown in Eq. 2.2.

$$P_T = \frac{1}{2}\rho A C_p(\lambda,\beta)V_W^3 \quad (2.1)$$

$$T_T = \frac{1}{2\omega_T}\rho A C_p(\lambda,\beta)V_W^3 \quad (2.2)$$

Where P_T = mechanical power extracted from turbine

T_T = mechanical torque extracted from turbine rotor

A = area covered by the rotor= πR^2 where R is turbine rotor radius [m]

V_W = velocity of the wind [m/s]

C_p = performance coefficient (or power coefficient)

ρ = air density [kg/m3]

λ = tip-speed-ratio (TSR)

β = rotor blade pitch angle [rad.]

ω_T = angular speed of the turbine shaft (rad/s).

The blade tip speed ratio is given as-

$$\lambda = \frac{\omega_T R}{V_w} \quad (2.3).$$

In modern variable speed based PMSG Wind turbine system, the generator and turbine are coupled on the same shaft without gearbox. Therefore, the generator speed ω_g and wind turbine rotor speed ω_T are actually equal. The rotor efficiency of wind turbine C_p is a non-linear function of the pitch angle β and tip speed ratio (TSR) λ and approximately modeled as follows [6]

$$C_p(\lambda,\beta)=0{\cdot}22\left(\frac{116}{\phi}-0.4\beta-5\right)e^{\frac{-12.5}{\phi}} \qquad (2.4)$$

$$\phi=\frac{1}{\left(\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1}\right)} \qquad (2.5)$$

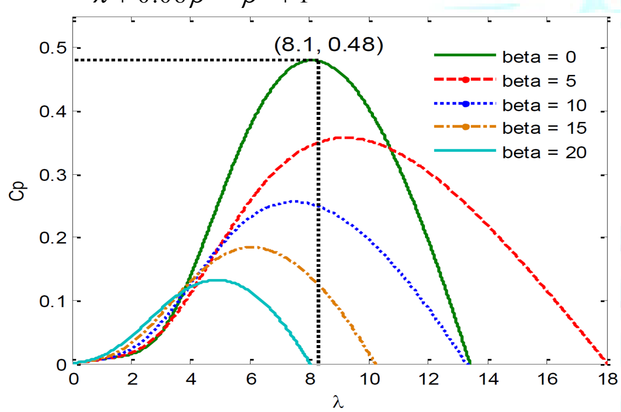


Fig. 2.2 *Cp*- λ characteristics curve for different values of β

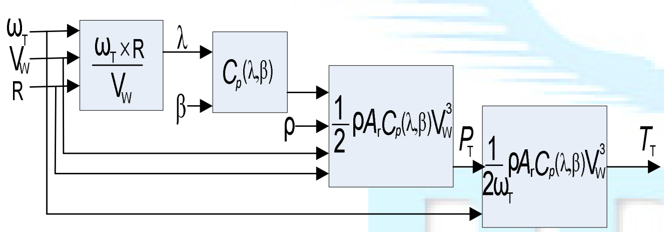


Fig. 2.3 Block diagram of the aerodynamic wind turbine model.

From Eq. 2.4 and Eq. 2.5, the *Cp*- λ characteristics curve for different values of β is shown in Fig. 2.2. Eq. 2.1- Eq. 2.5 give a model for the transfer of wind kinetic energy to mechanical energy on the shaft of wind turbine [6]. The block diagram of wind turbine model is shown in Fig. 2.3

2.2. PMSG MODEL

The dynamic model of PMSG is derived from the two-phase synchronous reference frame in which the *q*-axis is 90° ahead of the *d*-axis with respect to the direction of rotation [9]. The synchronization between the *d-q* rotating reference frame and the *abc*-three phase frame is maintained by a phase locked loop (PLL) [7].

The electrical model of PMSG in the synchronous reference frame is given in Eq. 2.9 and Eq. 2.10.

$$\frac{di_{sd}}{dt}=-\frac{R_a}{L_d}i_{sd}+\omega\frac{L_q}{L_d}i_{sq}+\frac{1}{L_d}u_d \qquad (2.9)$$

$$\frac{di_{sq}}{dt}=-\frac{R_a}{L_q}i_{sq}-\omega\left(\frac{L_d}{L_q}i_{sd}+\frac{1}{L_q}\psi_m\right)+\frac{1}{L_q}u_q \qquad (2.10)$$

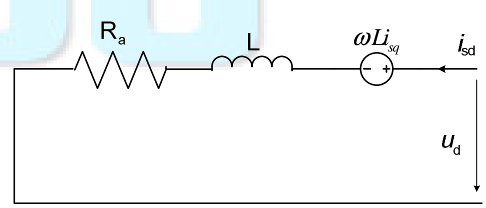
where subscripts '*d*' and '*q*' refer to the physical quantities that have been transformed into the *dq*-synchronous rotating reference frame; R_a is the armature resistance; ω is the electrical rotating speed which is related to the mechanical rotating speed of the generator as $\omega=p\omega_T$ where p is the number of pole pairs; ψ_m is the permanent magnetic flux. The electric frequency is determined by $f_e=\omega/2\pi$. The inductances, L_d and L_q are the summation of the inductances of the generator on the *d*- and *q*-axis respectively. u_d and u_q are the *d*- and *q*-axis components of output voltage of PMSG generator, respectively.

The *q*-axis counter electric potential $e_q=\omega\psi_m$ and the *d*-axis counter electric potential e_d =0. We assume $L_d=L_q=L$ and (2.9) and (2.10) can be rewritten as

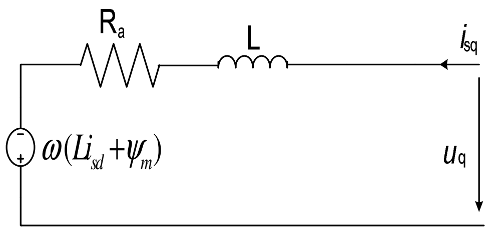
$$\frac{di_{sd}}{dt}=-\frac{R_a}{L}i_{sd}+\omega i_{sq}+\frac{1}{L}u_d \qquad (2.11)$$

$$\frac{di_{sq}}{dt}=-\frac{R_a}{L}i_{sq}-\omega\left(i_{sd}+\frac{1}{L}\psi_m\right)+\frac{1}{L}u_q \qquad (2.12)$$

Fig. 2.4 shows the equivalent circuit of the PMSG on the *dq*-rotating reference frame [13].



(a) *d*-axis equivalent circuit



(b) q-axis equivalent circuit

Fig. 2.4 Equivalent circuit of PMSG in the synchronous frame

The electromagnetic torque can be derived from

$$T_e = \frac{3}{2} p((L_d - L_q) i_{sq} i_{sd} + i_{sq}\psi_m) \quad (2.13)$$

As the inductances on the d- and q-axis are equal, the electromagnetic torque can be regulated by i_q as

$$T_e = \frac{3}{2} p\, i_{sq}\psi_m \quad (2.14)$$

3. MAXIMUM POWER POINT TRACKING METHODS

At a given wind velocity, the mechanical power available from a wind turbine is a function of its shaft speed. To maximize the power captured from the wind, the shaft speed has to be controlled by a variable-speed method The wind turbine is not operating under optimal conditions (where C_P is low) most of the time. Optimal operating conditions can be achieved by employing a MPPT method. Implementing a MPPT method depends on wind turbine structure[11]. The wind turbine mechanical output power P_T is affected by the ratio of the turbine shaft speed and the wind velocity, i.e., tip-speed-ratio ($\lambda = R\omega_T / V_W$). As a result wind turbine power P_T will change as in change wind velocity and the turbine shaft speed ω_T (or generator shaft speed ω_g). Fig 3.1 shows a family of typical P_T versus ω_r curves for different wind velocities for a typical system

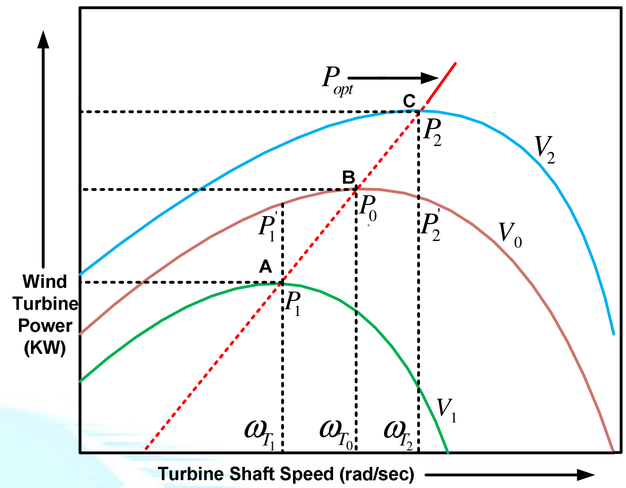


Fig. 3.1 Wind turbine mechanical output power versus shaft speed

3.1 Wind Speed Measurement Method

The aim of the turbine speed control is to maintain turbine shaft speed at optimal value, i.e., $\omega_{P\max}$ so that maximum mechanical power can be captured at any given wind velocity (V_W). In the wind speed measurement (WSM) method, both wind velocity and shaft speed (ω_T) should be measured. Also, optimal tip-speed-ratio (λ_{opt}) must be determined for the controller [1]. The concept and schematic diagram of the tip ratio speed control method is shown in Fig. 3.2

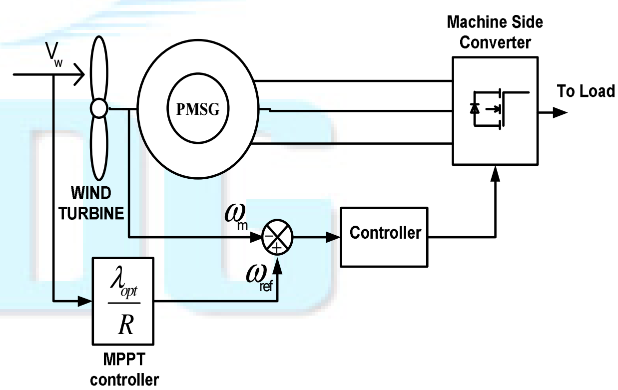


Fig. 3.2 Tip speed ratio control of WECS

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4. CONTROL STRATEGY OF PMSG BASED WECS

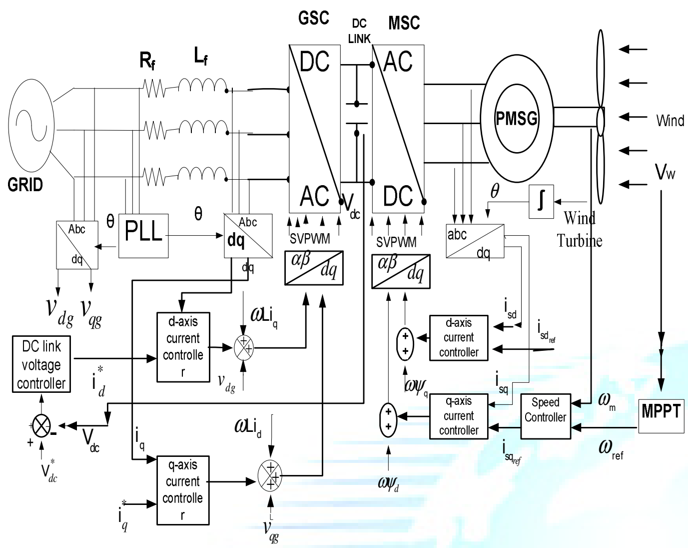

Fig. 4.1 Schematic of control strategy for generator side and Grid side converter.

4.1 Control of Generator Side Converter

The generator side converter is a controlled rectifier can be used as a driver controlling the generator to extract maximum energy from wind operating at rotor optimum speed. For PMSG side control a popular technique, field oriented control, is used in which torque is controlled indirectly by controlling the stator current. The control strategy is represented in the d-q reference frame. The torque expression in the d-q system for the PMSG is given as:

$$T_e = 1.5 p \psi_m i_{sq} \quad (4.1)$$

As the Eq. 4.1 clearly shows that the torque can be controlled by controlling the quadrature- axis stator current while Ψm is constant. The torque can be controlled by keeping the torque angle as desired. In this control strategy the d axis current is kept zero, while the vector current is align with the q axis in order to maintain the torque angle equal with 90°. This control strategy is simply used for SPMSM.

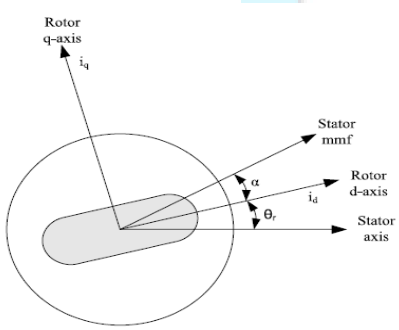

Fig. 4.2 a space vector diagram

At any time t, the rotating rotor d-axis makes and angle θr with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. In Fig. 4.2 a space vector diagram of the control is presented. The torque is kept as desired by controlling the current vector. In the figure α is the torque angle, θ_r is the load angle .The structure of the control algorithm is presented in Fig. 4.1

The i_{sd} reference current is set to be 0 and i_{sq} reference current is given by the PI (Proportional Integral) speed controller. The required d-q voltages are obtained from two PI current controllers. Integrating the speed (rad/s), angle will be obtained which is desired to d-q transformation. In order to control the currents independent one of each other and to improve the dynamic response, the compensation terms, $\omega\psi_d$ is added, and $\omega\psi_q$ is subtracted, at the output of the PI current controllers. Space vector modulation technique is used to create the duty cycles for the reference voltages and PWM provides the switching pulses to the power converter circuit.

4.2 Control structure for grid side converter

The control strategies used to perform the control of the DC-link voltage, active and reactive power delivered to the grid, grid synchronization and to ensure high quality of the injected power and focus on the synchronous reference frame control scheme. The synchronous reference frame control strategy contains two control loops. The inner loop is used to control the grid current while the outer loop controls the DC-link voltage and the reactive power. The outer loops regulate the power flow of the system by controlling the active and reactive power delivered to the grid [8]. The synchronous reference frame control scheme is based on the coordinate transformation (ie *abc to d-q*). The controlling and filtering is easier due to this transformation [9].A schematic of the *d-q* control is represented in Fig. 4.1

In this structure, the dc-link voltage is controlled in accordance to the necessary output power. The output of dc-link voltage controller is used as the reference current for the d-axis current controller whereas the reference for the q-axis current controller is set to zero. In the case that the reactive power has to be controlled, a reactive power reference must be imposed to the system. The *d-q* control structure is normally associated with proportional-integral (PI) controllers since they have satisfactory behavior when regulating dc variables.

Since the controlled current has to be in phase with the grid voltage, the phase angle used by the $abc \rightarrow dq$ transformation module has to be extracted from the grid voltages. In this strategy, a conventional PLL is used to detect the phase grid angle and the grid frequency, f. The frequency is needed in order to monitor the grid condition and to comply with the requirements while the grid angle is required for Clark and Park transformations.PWM is used to produce the control signal to control the grid-side converter [10].The voltages and currents of the inverter at low frequency can be written as [11]:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_f \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} + \begin{bmatrix} v_{ga} \\ v_{gb} \\ v_{gc} \end{bmatrix} \quad (4.3)$$

Where, v_{ga}, v_{gb} and v_{gc} are the grid voltages, and v_a, v_b and v_c are the inverter output voltages. Currents i_{ga}, i_{gb} and i_{gc} are the grid current of A, B and C phase, R_f and L_f are the values of the resistance and the reactance ($L_f = L_g + L_i$) in the filter.

After *abc-dq* transformation, (5.2) becomes as

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_f \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} + L_f \omega \begin{bmatrix} i_{gq} \\ i_{gd} \end{bmatrix} + \begin{bmatrix} v_{gd} \\ v_{gq} \end{bmatrix} \quad (4.4)$$

Where, ω is the angular speed of the synchronous reference frame. The *d*-axis is synchronized with the grid-voltage space vector, thus v_{gq} is zero [12]. There are coupling terms in Eq. 4.4, and thus a feed-forward term to decouple the control system is used. Then, in a linear and symmetric three phase system active and reactive power is reduced to control the d-axis and q-axis currents (v_{gq} =*0*).

$$P = \frac{3}{2}\left(v_{gd} i_d + v_{gq} i_q\right) = \frac{3}{2} v_{gd} i_d \quad (4.5)$$

$$Q = \frac{3}{2}\left(v_{gd} i_q + v_{gq} i_d\right) = \frac{3}{2} v_{gd} i_q \quad (4.6)$$

Equations (4.5) and (4.6) show how to control the active and reactive power [7]. It can be seen that by changing the d and q-components of the current, the active and reactive power are controlled respectively. The main purpose of whole control system is to transfer the active power produced by proposed WECS to the grid and also to produce no reactive power so that unity power factor is obtained while maintaining the constant dc link voltage with maximum converter efficiency.

5. SIMULATION RESULTS

Table 5.1 PMSG Wind Turbine Parameters

Electrical PSM generator rating	10KW
Stator resistance	0.975 ohm
Flux linkage	0.91 Weber
Ld (PMSG inductance)	0.01H
Lq (PMSG inductance)	0.01H
Pole pairs	3
Wind Turbine rating	10 KW
Blade swept area	40 m^2
Air density	1.218 kg/m^2
Pitch angle beta	2 degree
Base wind speed	12m/s
DC-link capacitor *C*	15,000 μF

Using the proposed model, the dynamic behavior of the system was observed under the varying wind speed conditions. The study of the results proves that the control strategy developed in this paper is well performed. In this simulation a step variation from 8 (m/s) to 11 (m/s) in the input wind speed is employed. This step is changed at 1 second. It can be analyzed that how the control parameters vary with the input wind speed variation.

The dynamic behavior of the proposed system under variable wind speed is shown in fig5.1 (a) (b) and 5.2.The real power drown the maximum power output from the wind turbine and reactive power is nearly zero with approximately constant dc link voltage which can be realized in fig.5.3 The variation in three phase stator output voltage and current and d-q voltage component is shown in Fig.5.4 and fig.5.5 respectively. There is no variation in Grid voltage while Grid current varies according to change in wind speed, shown in fig. 5.6. It can be noticed that the grid current and voltage are in phase for the value of the reactive power fixed to zero (ie unity power factor).It can also be noticed that if the variation step input (wind speed m/s) is changed as 5-6-8-10-11(m/s) with the time variation of 0-0.5-1-1.5-2 respectively then the behavior of whole system is shown in figures 6.(a), 6(b) and 6(c).

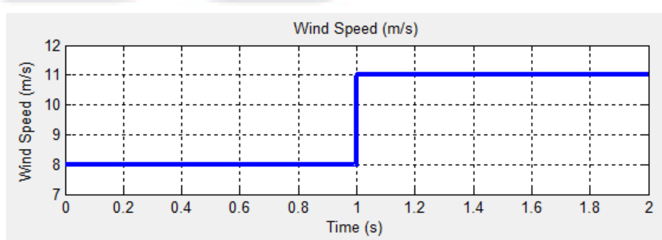

Fig.5.1 (a) Step variations in input wind speed

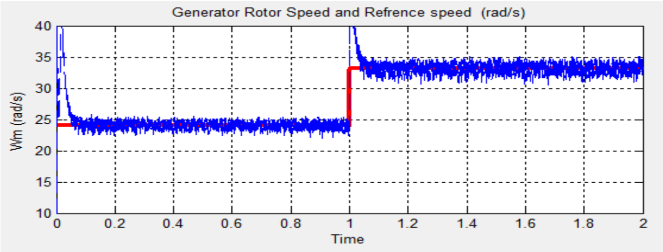

Fig.5.1 (b) actual rotor speed and reference rotor speed

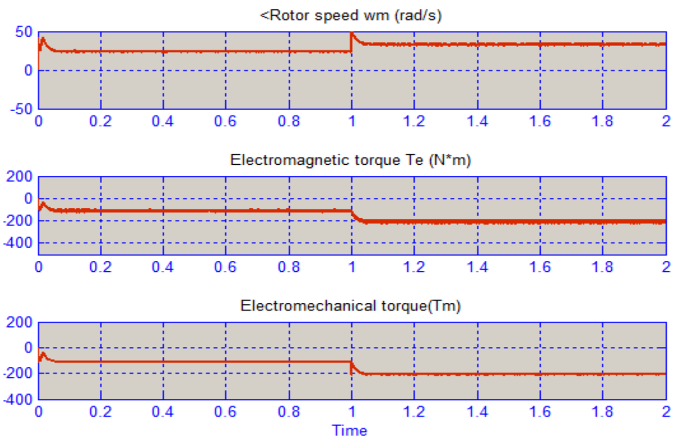

Fig.5.2 Variations in rotor speed, electromagnetic and electromechanical torque.

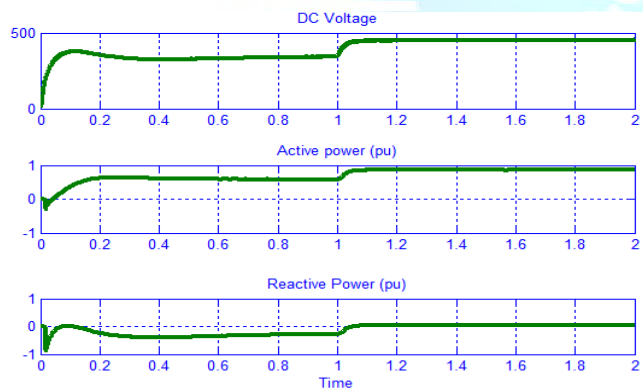

Fig.5.3 DC Voltage ,Active Power and Reactive Power

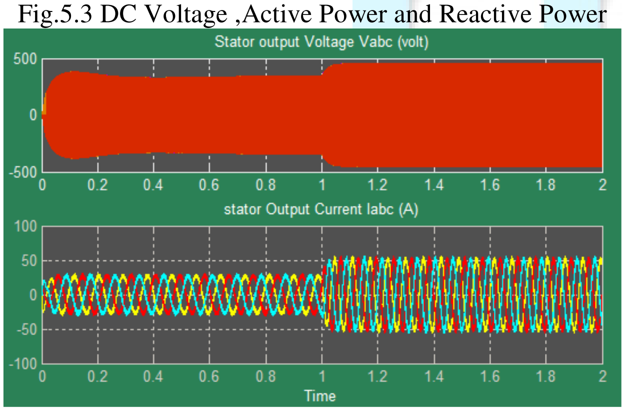

Fig.5.4 Three phase stator output voltage and current

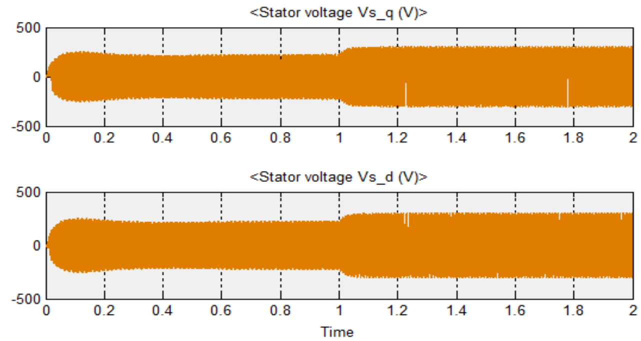

Fig.5.5 Variation in stator direct and quadrature voltage components

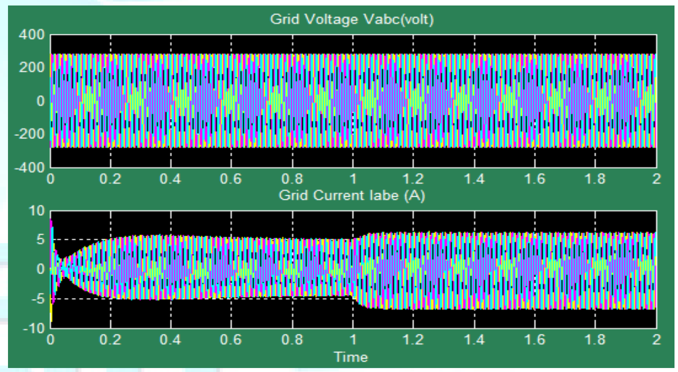

Fig.5.6 Grid Voltage and Grid Current

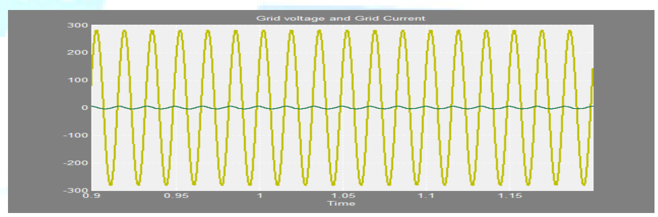

Fig.5.7 Grid current and voltage are in phase for unity p.f..

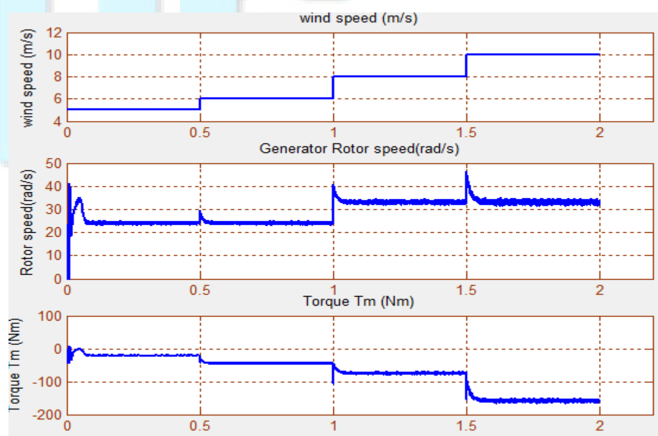

Fig.6(a) Rotor Speed and Torque variation with wind speed

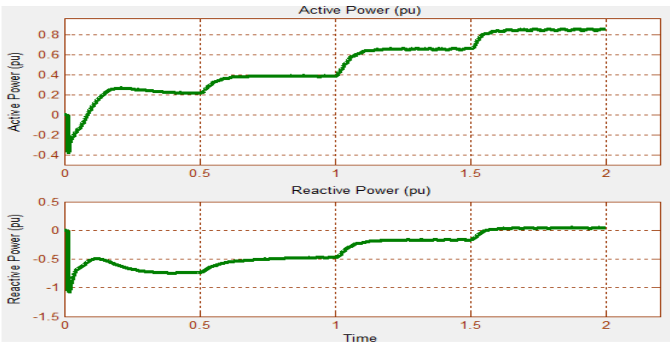

Fig.6(b) Active and Reactive Power

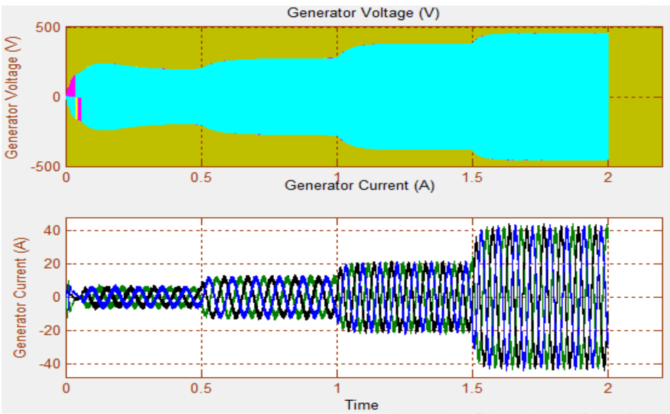

Fig.6(c) Generator voltage and Current

6. CONCLUSION

In this paper the above proposed system based on direct-driven permanent magnet synchronous generator with variable wind speed shows that how the overall energy conversion process takes place in order to transmit the wind power to the Grid using advanced power electronic techniques. A PMSG is selected for low-cost, robustness, high efficiency, high reliability and variable wind turbines. Back to back converter consists of a pulse width modulation (PWM) rectifier, an intermediate dc circuit, and a PWM inverter, is used to connect the PMSG with the grid by maintaining the dc link voltage constant. The control method used at the generator side converter to control the torque by controlling the q axis stator current in order to extract maximum power from the variable wind turbine using MPPT. The vector oriented control scheme is used at the grid side converter for independent active and reactive power control by controlling d-q current component respectively while maintaining the maximum converter efficiency, constant dc link voltage and extracting the maximum power .The simulation results verify the performance of the proposed system used.

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