

Optimization and Control of a Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator

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Abstract: - The aim of this paper is to propose a control strategy and also analyse a fairly typical configuration of a wind turbine generating system connected with permanent magnet synchronous generator under varying speed. To reduce output power variations in wind turbine generating system, pitch angle controller of wind turbine has been used broadly. When the wind speed crosses the rated speed pitch angle controller become s active and control the power and speed to their rated values. To obtain this model multi pole PMSG chosen on the place of doubly fed induction generator because it offers better performance. PMSG does not have rotor current and also used without gearbox, which intern improves its efficiency, offers less maintenance and also indicates a reduction of the weight of nacelle, size, and reduction of costs. Simulation of VSWTGS is carried out in Matlab / Simulink / Sim Power System.

Index Terms- Permanent magnet synchronous generator (PMSG), variable speed wind turbine generating system (VSWTGS), DC bus, voltage control, MATLAB.

I. INTRODUCTION

Energy is one of the biggest important factors that continue to affect the shape of human Society in the 21st Century. The price and availability of energy easily affect our amenity of life, the health of national industry and the adherence of our environment. Nowadays there has been a large global attention to develop clean and alternative forms of energy resources and it is predicted that [1] by 2020 10% of world electricity will be generated from renewable resources, and there is a belief that this value will grow up to 50% by 2050. Among renewable energy resources, wind electricity generation technology has grown significantly, and wind is adequately distributed around the globe and therefore easily available to world communities. The last few decades have seen the growth of renewable energy system based mainly on wind and solar power. The main advantage of electricity generation from renewable sources is the absence of harmful substances and also the infinite availability of the prime mover that is

converted to electricity. Wind energy technology has developed very rapidly [2] and many commercial wind turbines is available in the market nowadays have capacity of 2 MW or more. To attain maximum aerodynamic efficiency over a broad range of wind speeds Variable Speed Wind Turbines (VSWTs) [3]-[7] are designed and their rotation speed is universally adapted (accelerated or decelerated) to wind speed. Corresponds to the maximum power coefficient the tip speed ratio λ is kept constant at a predefined value. VSWTs are typically connected with permanent magnet synchronous generators and connected to the grid through power converters. An asynchronous generator is normally used and it is directly connected to the grid. Maximum efficiency is obtained for the variable-speed operation; to maximize the power extracted from the wind, the system is controlled. Nowadays the trend is to use variable-speed wind turbines because they offer more efficiency and flexibility in control which is becoming very important to comply with the grid requirements [8].

There is an interesting solution which is based on variable-speed operation named as Permanent Magnet Synchronous Generator, (PMSG). There is no need for a DC excitation system as they use permanent magnets. Now it is possible to operate at low speeds and without gearbox with a multi pole synchronous generator. Hence the losses and maintenance of the gearbox are avoided [9]. When wind speed crosses turbine rated speed, excess aerodynamic power should be limited in order to keep the shaft torque within its permissible design limits. To keep the dc link voltage at a constant value the resulting electrical power should also be controlled. To control the excess power output from wind turbines there are following two ways. The primary braking system is mechanical which limits the aerodynamics forces (powers) on the rotor of turbine above rated wind speed by changing the pitch angle of the blades. The secondary braking system is electrical and where either the output power of generator or the powers of dc bus are limited. In this paper the under-study VSWT

system is first described. Then the strategy of the power excess control is developed and finally simulation results are presented.

II. WIND ENERGY CONVERSION

The following equation describes the kinetic energy of wind (air mass m , wind speed v) and given as:

$$E_c = \frac{1}{2}mv^2$$

Where $m = \rho vS\Delta t$

With: (With S : Covered surface of the turbine and ρ : the air density). The wind power has the following expressions:

$$P_w = \frac{d}{dt}E_c \Rightarrow P_w = \frac{1}{2}\rho Sv^3$$

Mechanical power extracted by the turbine from the wind, P_m , is inferior to P_w . It is due to the fact that the wind speed after the turbine isn't zero (the air needs to be carried off after the turbine). So, the turbine's power coefficient C_p can be defined by:

$$C_p = \frac{P_m}{P_w}; \quad C_p < 1$$

The recuperated power [10]-[13] is given by:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p$$

With R : radius of the rotor.

C_p depends of the tip speed ratio λ of the wind turbine and β , angle of the blades.

$$C_p = C_p(\lambda, \beta) \quad \text{With: } \lambda = \frac{R\omega}{v}$$

ω is the rotation speed of the rotor.

Maximum value of C_p for this function can be found and this maximum is known as the limit of Betz:

$$C_{pmax} = \frac{16}{27} = 0.593$$

The wind turbine torque on the shaft can be calculated from the power:

$$T_m = \frac{P_m}{\omega} = \frac{1}{2}\rho\pi R^2 \frac{v^3}{\omega} C_p$$

On introducing: $\lambda = \frac{R\omega}{v}$,

$$T_m = \frac{1}{2}\rho\pi R^3 v^2 \frac{C_p}{\lambda}$$

Often the torque coefficient C_T is used:

$$C_T = \frac{C_p}{\lambda}$$

This gives:

$$T_m = \frac{1}{2}\rho\pi R^3 v^2 C_T$$

III. MODELLING OF THE SYSTEM

The system examined for a variable speed wind turbine connected with a multi-pole PMSG. The rotor shaft is connected directly to the generator, due to low generator speed, which means that no gearbox is needed. Via an AC/DC/AC converter, the generator is connected to grid, which consists of a diode bridge rectifier, an internal DC-Link shown as a capacitor and a PWM IGBT inverter [21]. A transformer is connected between the inverter and the Point of Common Connection (PCC) in order to raise the voltage by avoiding losses in the transport of the current. The layout of the electrical part is depicted in Fig.1.

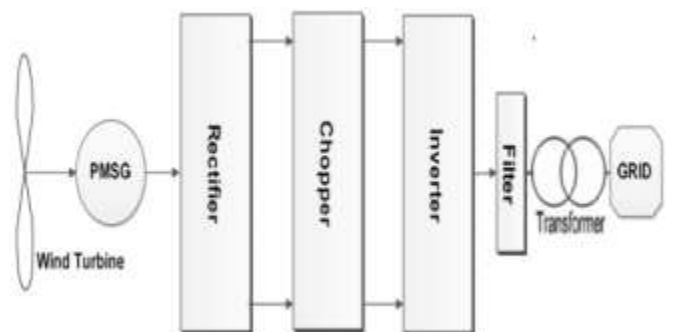


Fig.1. Electrical scheme for a variable speed wind turbine equipped with a direct-drive PMSG.

IV. SUBSYSTEM MODELS

A. Wind Turbine Model

The Wind Turbine model is shown in the following model:

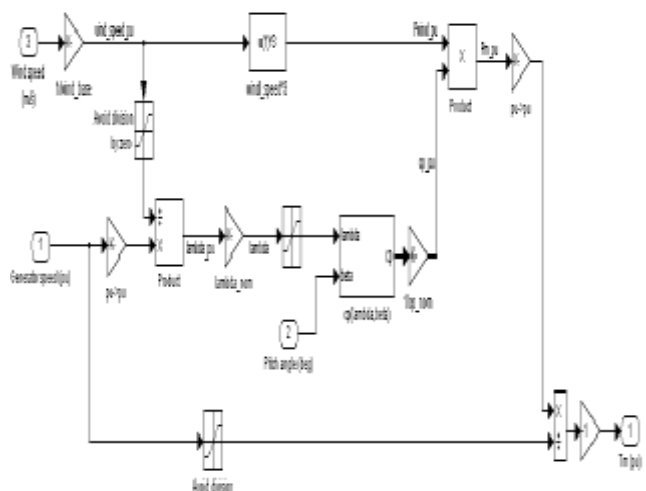


Fig.2. Wind Turbine model with Simulink.

The Tip Speed is Ratio calculated in the first subsystem using:

$$\lambda = \frac{R\omega}{v}$$

Where ω is the angular velocity of rotor [rad/s], R is the rotor radius [m] and v is the wind speed upstream of the rotor [m/s].

C_p Value is calculated in the next subsystem by using the following formula:

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{-\frac{c_5}{\lambda_i}} + c_6 \lambda$$

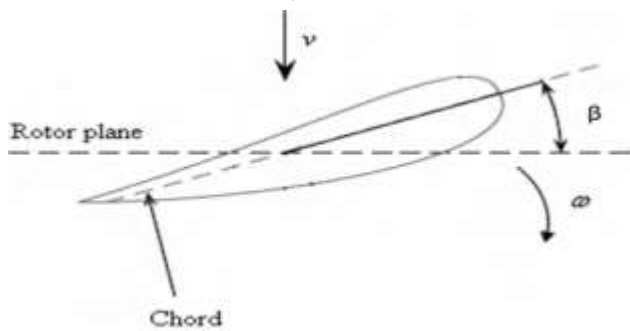


Fig.3. Blade pitch angle β .

Additionally λ_i is defined as [10]-[12]:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} + \frac{0.035}{\beta^3 + 1}$$

The proposed coefficients c_1 to c_6 are equal to: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$, and $c_6 = 0.0068$. The C_p - λ characteristics, for different values of pitch angle β , are given below. The maximum value of C_p (0.48) is achieved for $\beta = 0$ degree and $\lambda = 8.1$. This specific value of λ is defined as the nominal value (λ_{nom}).

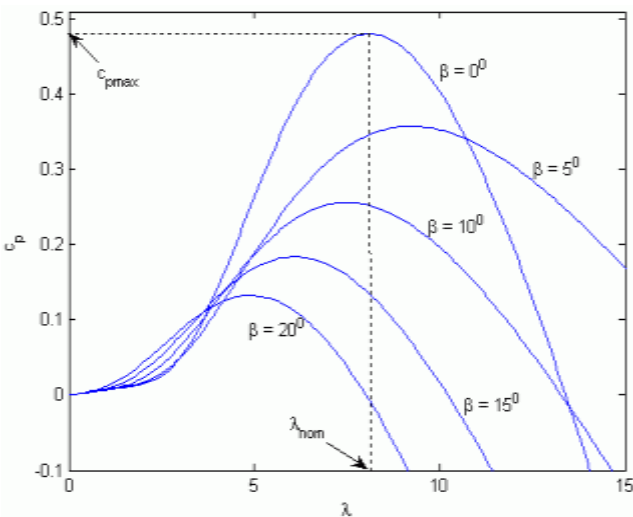


Fig.4. Analytical Approximation of $C_p(\lambda, \beta)$ characteristics.

The rotational speed is calculated in the last subsystem by considering the followings:

$$J \frac{d\omega}{dt} = T_m - T_{em} - F_w$$

Where,

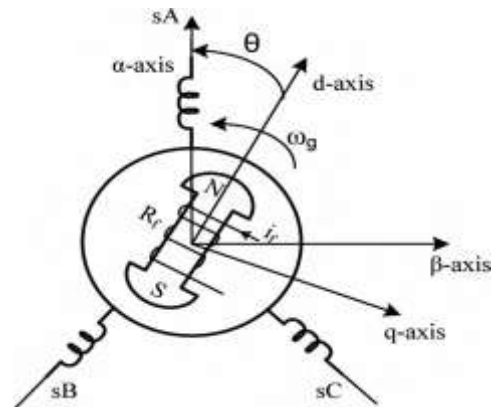
J = Inertia moment of the turbine, axle and generator

T_{em} = Electromagnetic torque

F_w = Axle friction

B. Generator Model

T0 makes possible to convert mechanical energy obtained from the wind into electricity PMSG system has been considered. The dynamic model of the PMSG is created from the two phase synchronous reference frame, which the q-axis is 90° ahead of the d-axis with respect to the direction of rotation. By utilizing a phase locked loop (PLL) the synchronization between the d - q rotating reference frame and the abc -three phase frame is maintained [14]. Fig. 5 shows the d - q reference frame for a salient-pole synchronous machine (which is the same reference as the one used in a PMSG), where θ is the mechanical angle, which is the angle



between the rotor d-axis and the stator axis.

Fig.5. d - q and α - β axis of a typical salient-pole synchronous machine.

For representing the mathematical model of the PMSG the state equations are given below [14], [15]:

$$\frac{di_d}{dt} = \frac{1}{L_{ds} + L_{ls}} (-R_s i_d + \omega_e (L_{qs} + L_{ls}) i_q + u_d)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs} + L_{ls}} (-R_s i_q + \omega_e [(L_{ds} + L_{ls}) i_d + \Psi_f] + u_q)$$

Where subscripts d and q classify the physical quantities that have been changed into the d - q synchronous rotating reference frame, R_s is the stator resistance [Ω], L_d and L_q are the inductances [H] of the generator on the d and q axis, respectively, Ψ_f is the permanent magnetic flux [Wb] and the electrical rotating speed [rad/s] of the generator is given by ω_e , also

$$\omega_e = p\omega_m$$

Where p represents the number of pole pairs of the generator, and ω_m is mechanical angular speed.

Mechanical equation is needed in order to execute the mathematical model of the PMSG, and it is given by the following electromagnetic torque equation [14]:

$$\tau_e = 1.5 p ((L_{qs} + L_{ls}) i_d i_q + i_q \Psi_f)$$

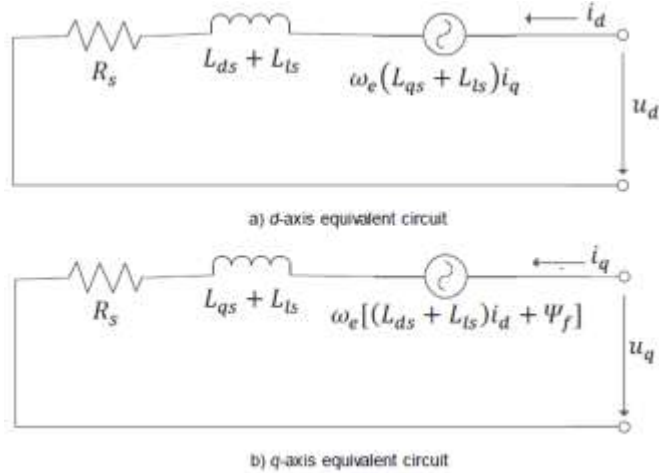


Fig.6. Equivalent circuit of PMSG in the synchronous frame.

Above Fig. 6 shows the equivalent circuit of the PMSG in the *d-q* synchronous rotating reference frame. The model of the PMSG implemented in Simulink is represented in Fig. 7.

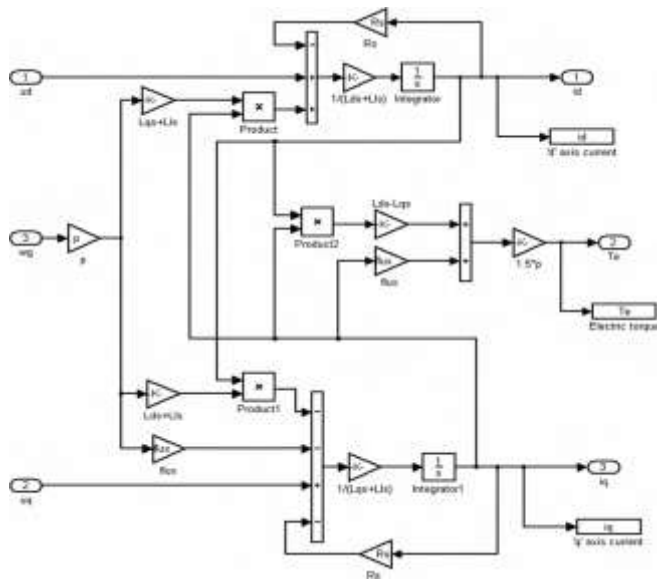


Fig.7. PMSG modelled with Simulink.

We analysed the power generated by the wind turbine at different wind and rotor speeds, as shown in Fig. 8, and found that an optimum power coefficient constant $K_{p\ out}$ exists. This coefficient exhibit the generated power related with the corresponding optimum rotor speed [10]-[12]. $K_{p\ out}$ is calculated from individual wind turbine characteristics. The corresponding optimum rotor speed can

be calculated and set as the reference speed, by measuring generated power and given by

$$\omega_{r\ out} = \sqrt[3]{\frac{P_{gen}}{K_{p\ out}}}$$

Where $\omega_{r\ out}$ is the optimum rotor speed [rad/s] and P_{gen} is the measured generated power [W] [16].

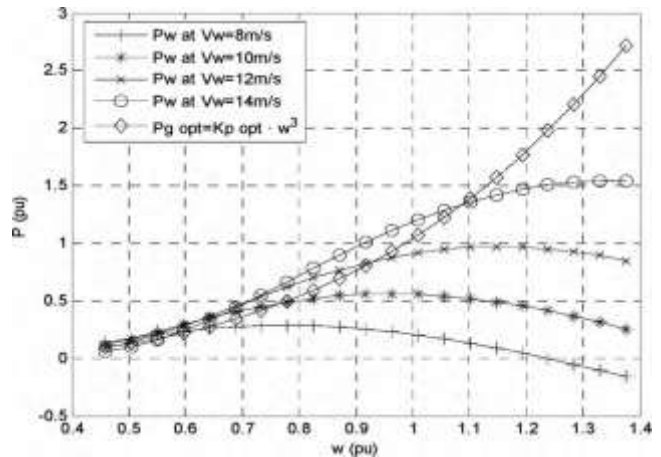


Fig.8. Power vs. speed curves for different wind speeds and optimum power generated as a function of generator speed and wind speed.

This is the base of the well-known Maximum Power Point Tracking (MPPT) [17], [18]: from the prior treatment of the wind turbine model it can be appreciated that in order to extract the maximum amount of power from the incident wind, C_p should be maintained at a maximum. In order to achieve this objective, it can be appreciated from Fig. 4 that the speed of the generator rotor must be optimized according to instantaneous wind speed.

V. CONTROL OF WIND TURBINE

A: Mechanical Braking Control

A mechanism to physically turn the blades around their longitudinal axes is used. At low wind speed a control system will use this feature to maximize energy extracted from the wind. During the higher wind speed the torque or power can easily be limited to its rated value by adjusting the pitch angle β . In addition the axial aerodynamics forces are reduced. This method is almost always used with variable speed turbines in order to make operation at high wind speed possible and safety. The turbine's electronic controller checks the power output constantly. When the power output becomes too high the blade pitch mechanism is asked to immediately turn the blades slightly out of the wind. When the wind speed is less strong the blades are turned back, into the most effective position [19]. The complete system model of the pitch angle controller is shown in Fig. 9.

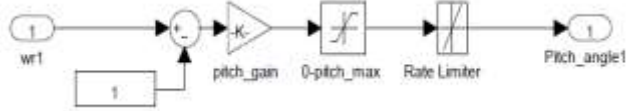


Fig.9. Pitch Angle Controller.

B: Electrical Braking Control

The braking chopper is composed of an IGBT switch a diode, a damp resistor and a PI controller for the duty cycle. The dc link voltage is maintained constant by dissipating the potential excess of power in the damp resistor. This linear control increases the duty cycle as a function of the over voltage amount. If the dc link voltage exceeds the maximum limit through the resistor R a short circuit will occur as shown in Fig.10.

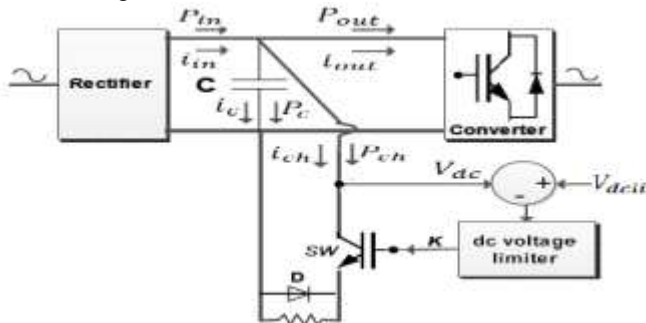


Fig.10. DC Bus model.

The braking chopper control loop is shown in Fig.11 [20]. To produce the duty cycle k, the error between the dc voltage V_{dc} and the limit dc voltage V_{dcli} is given to a PI controller. When $V_{dc} \leq V_{dcli}$ the braking chopper is off and no power is absorbed by the damp resistor, but when $V_{dc} \geq V_{dcli}$ the braking chopper becomes on and the damp resistor dissipates the power in excess keeping $V_{dc} = V_{dcli}$.

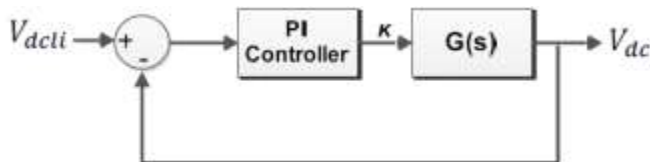


Fig.11.Braking chopper control loop

VI. RESULTS

In order to measure the performance of the control system for the variable speed wind turbine modelled with PMSG a set of step response simulations with deterministic wind speed are performed.

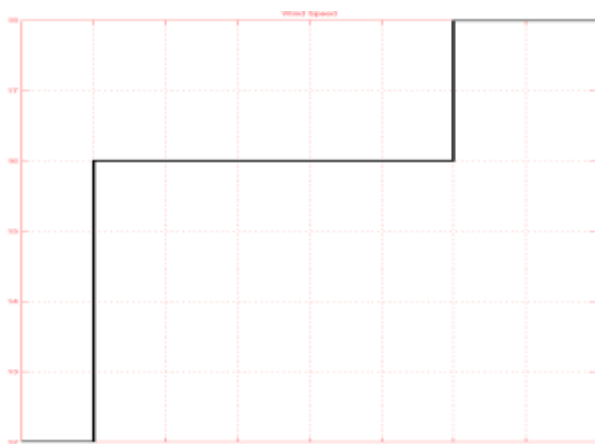


Fig.12. Wind Speed.

In Figure 12 and 13 different quantities of the turbine system, as wind speed, generator speed are shown for steps in wind for wind speed from 12 m/s up to 18 m/s. For a wind speed of 12 m/s the turbine works at rated conditions. As the wind speed is above its rated value (V_w , rated = 12 m/s), the pitch mechanism is active and limits the power and the speed to their rated values.

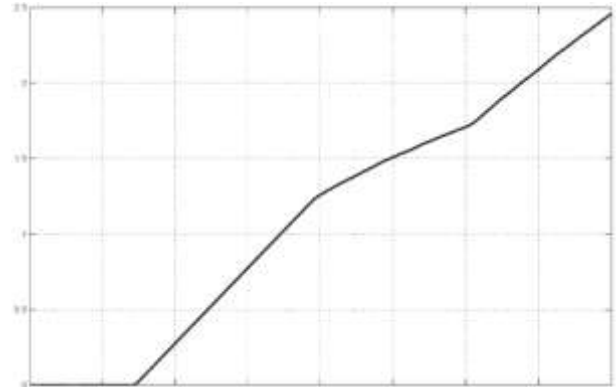
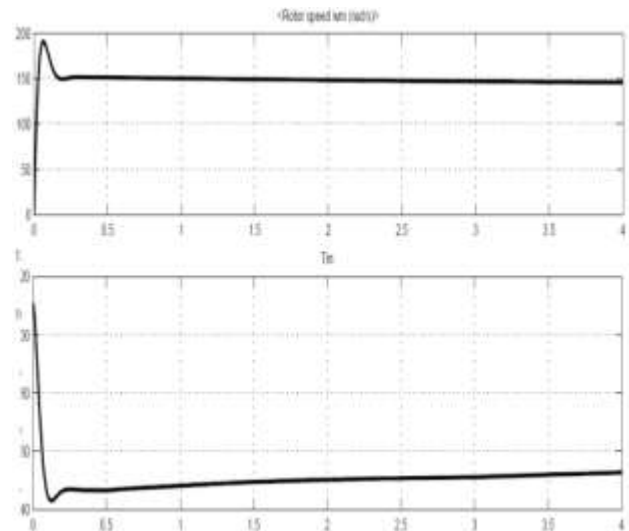


Fig.13. Pitch Angle.

Fig.14. Variation of Speed and Torque with time for stepped input.

It is observed from the fig.14, that the Torque and the Speed settles down after certain instant while simulation, this represents that the Mathematical Model is perfectly working for the parameters provided to it and also the Model generated has been executed as expected. Here the Torque is in the negative Y axis proving it that the machine is acting as a generator.



Real and Reactive power responses of permanent magnet synchronous generator are shown in fig.15. The output ac voltage remains constant at the rated value of 400 V (line-line) as shown in fig.16. From fig.16, it is observed that the output ac voltage is almost immune to fluctuations in the

wind speed. The rms value of output ac voltage may not give a clear picture of voltage waveform in the transient condition; hence instantaneous voltage is presented in fig.17.

From fig.17, it is seen that there is no significant rise in the voltage waveform during load transient. Following fig. 18, shows the graph for instantaneous line current. Also in fig. 19, we obtained the graph for three phase voltage produced by PMSG. From above simulation result, it can be established that with the help of PWM switching and passive LC filter, a satisfactory quality of voltage as well as current can be supplied to the load.

Fig.17. Instantaneous Output Voltage.

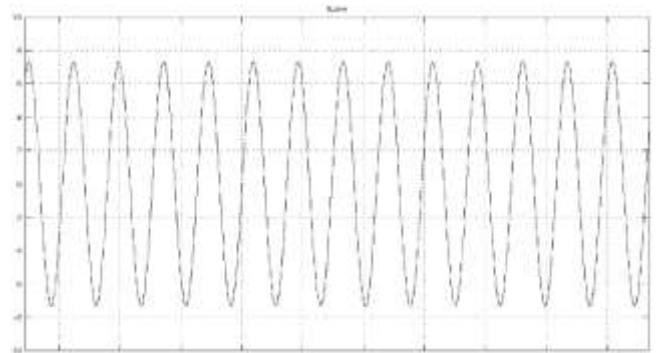


Fig.18. Instantaneous Output line Current.

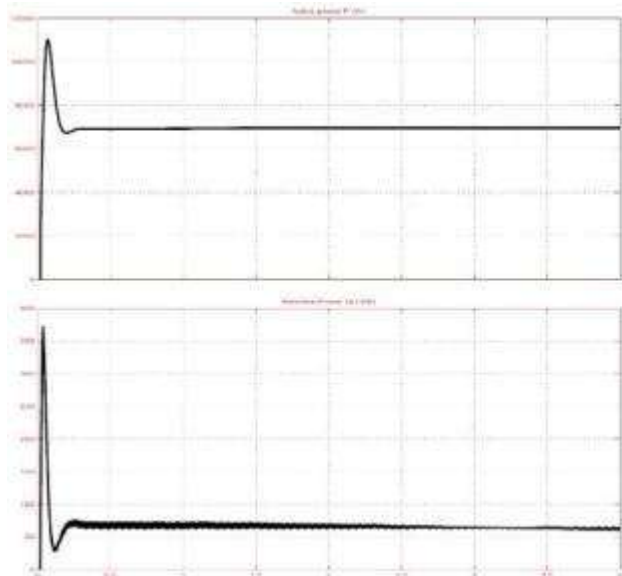


Fig.15. Active and Reactive Powers with time for stepped input

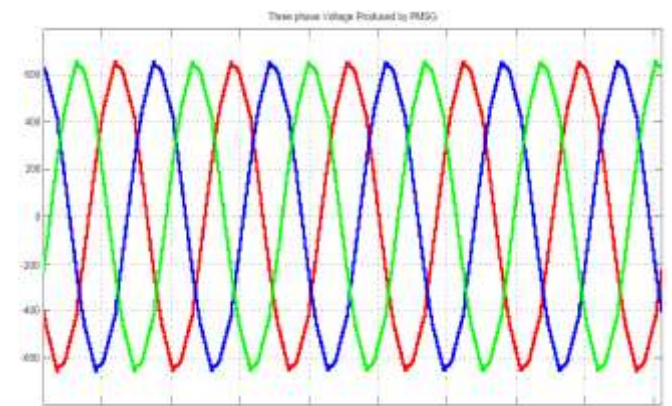


Fig.19. Three Phase Voltage produced by PMSG

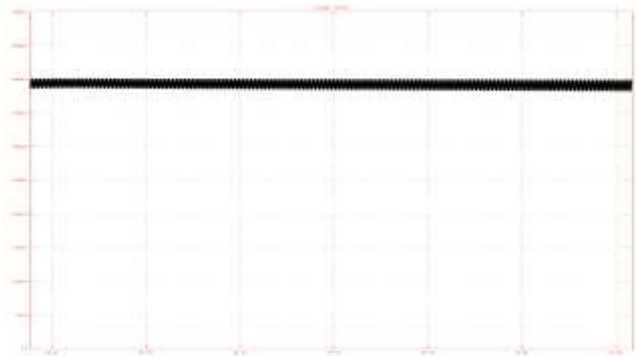
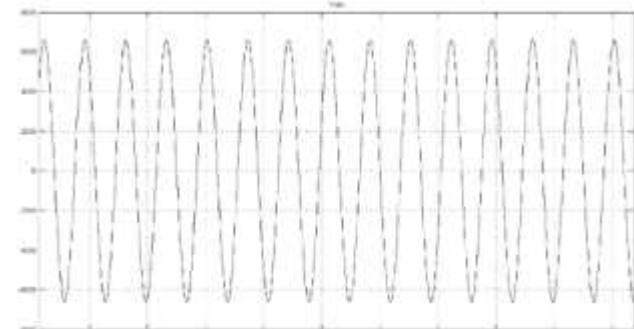


Fig.16. RMS Output Voltage (PCC Voltage).



The dynamic response of dc link voltage for the variation in load as well as in wind speed is presented in fig.20. Analysing the response of fig. 20, it can be ascertained that the performance of dc voltage controller both in transient as well as in steady state is quite satisfactory. Fig.21, shows the inverter output voltage in individual phases for variable speed and fig. 22 shows the three phase inverter output voltage in zoomed x-plane

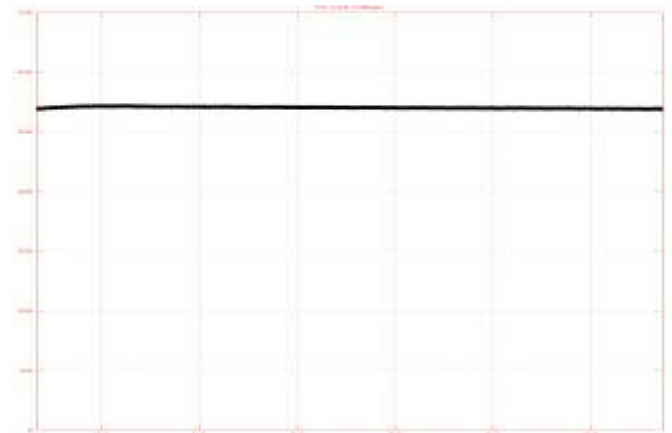


Fig.20. DC link Voltage.

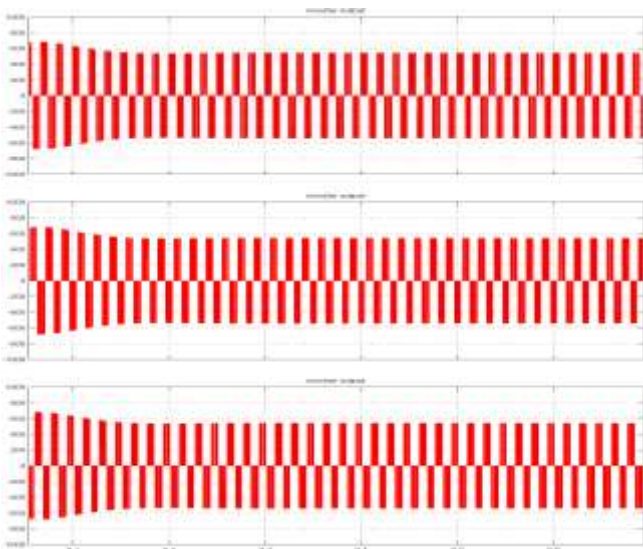


Fig.21. Inverter Output Voltage in individual Phases.

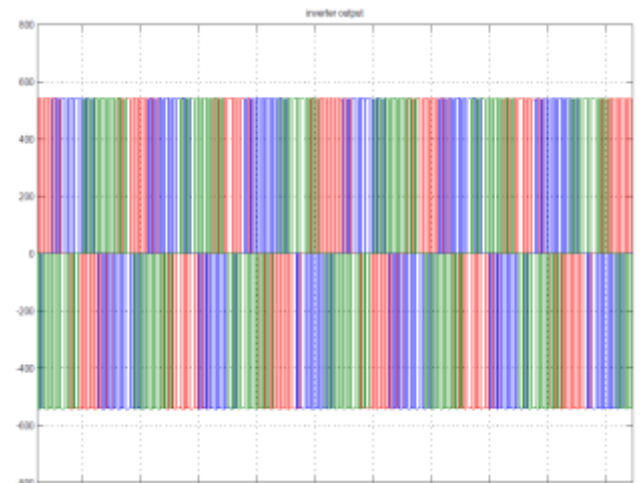


Fig.22. Inverter Output Voltage (Zoomed in X plane).

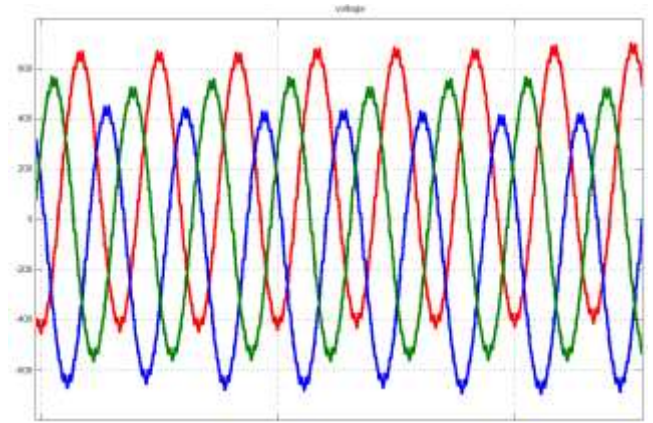
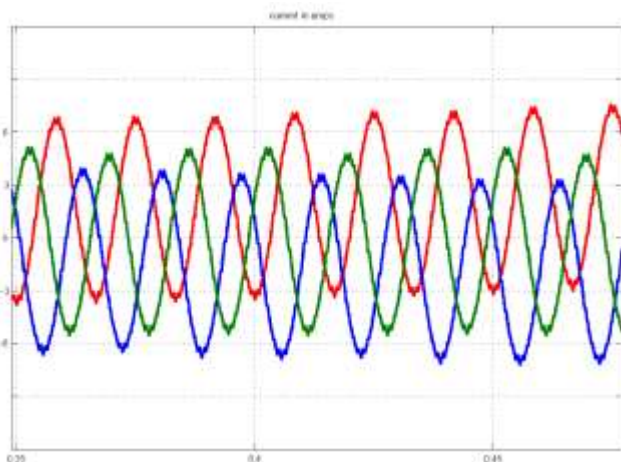


Fig.23. Three phase Currents for unbalanced load.

Fig.24. Instantaneous line voltage at PCC for unbalanced load.

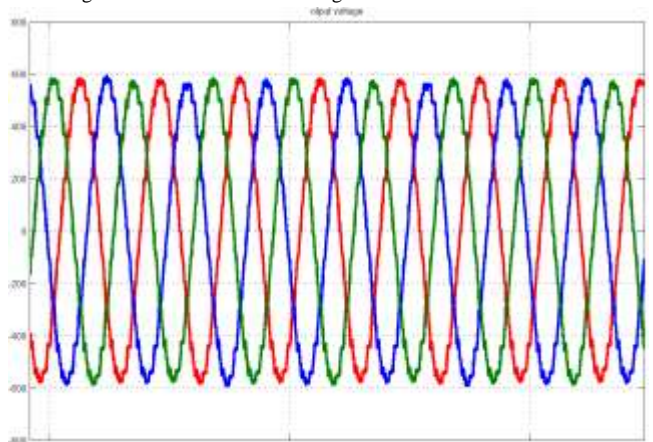


Fig.25. Instantaneous line Voltages at PCC after compensation.

Further consider the unbalanced load currents for three phase shown in above (fig. 23). Due to unbalanced load, the line voltage at PCC (fig. 24) also exhibits some unbalance behaviour. The voltage unbalanced factor (VUF), i.e., ratio of negative to positive sequence of the fundamental component is found to be 2.55% which is greater than permissible limit (i.e., 1%). To reduce VUF to an acceptable limit, the proposed PWM inverter control is applied and VUF is brought down to 0.4%, which is depicted in fig. 25. The basic parameters of the PMSG, and Wind turbine parameters are shown in following Table-I and Table-II.

Table-I
Parameters of PMSG

Parameters	Value and Units
Pole Pairs	5
Rated Speed	153 rad/s
Armature Resistance (R_s)	0.425 Ω
Magnetic Flux linkage	0.433 Wb
Stator Inductance (L_s)	8.4 mH

Rated Torque	55 Nm
Rated Power	8.5 Kw

Table-II

Parameters of Wind Turbine

Parameters	Value and Units
Air Density (ρ)	1.215 kg/m ³
Rotor Radius (R)	38
Rated Wind Speed	12 m/s
Maximum C_p (C_{pmax})	0.48

VII. CONCLUSION

The modelling of a variable speed wind turbine with a permanent magnet synchronous generator has been treated. The model has been implemented in MATLAB/Simulink. The generator has been modelled in the synchronously rotating $d-q$ reference frame, taking into account different simplifications. Moreover, the maximum power point tracking concept has been presented in terms of the adoption of the generator rotor speed according to instantaneous wind speed control strategies to regulate voltage of a variable speed wind turbine with a PMSG, are presented in this paper. We analysed that in PMSG connected wind turbine as the wind speed decreases from rated value generator speed, active power, current and voltage from wind generator decreases but as the wind speed increases beyond rated value the pitch mechanism is active and limits the power and the speed to their rated values and also it is observed that there is no variation in voltage and current at the generator terminal.

Also by controlling the modulation indices of the PWM inverter, and maintaining dc link voltage at its reference value, the inverter output voltage is maintained constant at their rated values. It is seen from the simulation results, that when there is a variation in wind speed and load the controller is unaffected and maintain the load voltage quite well. To reduce the effect of unbalanced load on the electrical torque of generator, first its effect is analysed, then a dc-dc converter (chopper) control scheme is proposed. It helps in maintaining the dc voltage constant and also acts as a dc-side active filter and reduces the oscillations in the generator torque which occur due to unbalanced load. To make the line voltage at PCC balanced under an unbalanced load condition PWM control is developed. The simulation results demonstrate that under steady state and dynamic conditions the performance of the controller is satisfactory and also it gives a good result under balanced as well as unbalanced load conditions.

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