Modeling and Simulation of Wind Turbine Driven Permanent Magnet Generator with New MPPT Algorithm

R. Bharanikumar[1] A.C. Yazhini[2] A. Nirmal Kumar[3]

Abstract – This paper presents Maximum Power Point Control for variable speed wind turbine driven permanent-magnet generator. The wind turbine generator is operated such that the rotor speed varies according to wind speed to adjust the duty cycle of power converter and maximizes Wind Energy Conversion System (WECS) efficiency. The maximum power point for each speed value is traced using Maximum Power Point Tracking (MPPT) algorithm. The rotating speed of permanent-magnet generator should be adjusted in the real time to capture maximum wind power. The system includes the wind-turbine, permanent-magnet generator (PMG), three-phase rectifier, boost chopper, inverter and load. The control parameter is the duty cycle of the chopper. PMG is made to operate at variable speed to achieve good performance. The entire WECS model consists of wind turbine model, PMG model and power converters model. The MATLAB / SIMULINK are used for simulation and the results are compared with laboratory setup.

Keywords – PMG, rectifier, boost chopper, inverter, wind turbine, MPPT.

I. NOMENCLATURE

ρ	- *Air density*
A	- *Area swept by the blades*
I_q,I_d	- *q - axis, d -axis current, respectively*
X_q,X_d	- *Reactance of q -axis , d - axis, respectively*
δ	- *Power Angle*
p	- *Differential Operator (d/dt)*
T_e	- *Electromagnetic Torque produced*
V	- *Velocity of the Wind*
λ	- *Tip Speed Ratio*
ω_t	- *Turbine Speed*
T_g	- *Generator Torque*
V_{abc}	- *Phase Voltages*
R_{abc}	- *Phase Resistances*
λ_{abc}	- *Flux Linkages in the phases*
β	- *Pitch Angle*
G	- *Gear ratio*
C_p	- *Power Coefficient*

II. INTRODUCTION

Consumption of energy based on fossil fuels is considered to be the major factor for global warming and environment degradation. The utilization of naturally occurring renewable energy sources as an alternative energy supply has been assuming more importance of less Power generation utilizing solar rays, geothermal energy, wind force and wave force has became a reality.

The paper first received 8 July 2009 and in revised form 21 April 2010.
Digital Ref: Digital Ref: A170701235

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Research on performance improvement of and cost reduction in such non–conventional energy conversion systems is being accorded the highest priority [8].Wind power generation has a strong connection to rotating machinery and hence its practical application is most promising. Wind generator control methods have already been proposed to efficiently utilize the wind power which is prone to fluctuation every moment**.** The induction type machine has the advantages of robustness, low cost and maintenance-free operation. However, they have the drawbacks of low power factor and need for an AC excitation source. Permanent magnet generator is chosen so as to eliminate the drawbacks of induction generator. Boost chopper circuit with a single switching device is the choice for power control that provides an improved efficiency [9].

For analysis of the above wind generator system, the generator and boost chopper are represented by their equivalent circuits. Performance characteristics such as generated output power and DC output voltage are expressed as functions of the duty cycle of chopper and shaft speed of generator. The power generated varies with load with the peak occurring at certain load. Therefore, the optimum duty cycle for maximum power can be deduced by differentiating the output power with respect to duty cycle. The validity of the technique for arriving at the maximum power is confirmed in the simulation study. In the present analysis, the value of each part is calculated on the basis of the rotational speed observed by the rotation sensor. Considerations of the characteristics of the wind mill are not necessary, because the torque is a function of the generator speed and characteristics of the wind mill are reflected in the rotational speed [8].

III. COMPONENTS OF WIND ELECTRIC SYSTEMS

The basic components of a wind electric system analyzed herein are shown in Fig 1. A step-up gear box and a suitable coupling connect the wind turbine to the Permanent Magnet Generator (PMG). The generated power of continuously varying frequency is fed to local load through suitable power converters, to ensure constant voltage and constant frequency. 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 voltage is then regulated to obtain constant voltage by controlling the duty ratio of a DC/DC boost converter. The DC voltage is inverted to get the desired AC voltage and frequency employing a PWM inverter. The duty ratio, δ controls the Boost chopper output voltage.

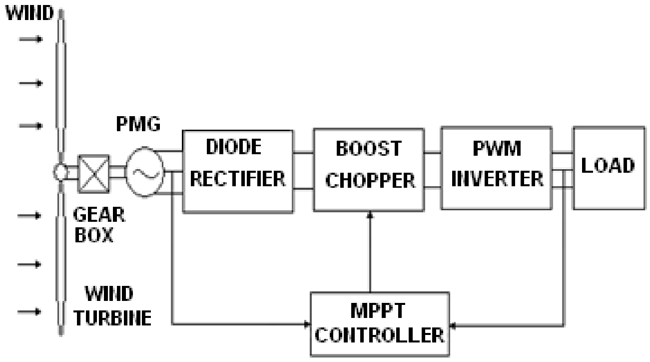

Fig. 1: Block diagram of wind electric generator system

IV. THEORETICAL ANALYSIS

A. Wind turbine model

There are two types of wind turbines namely vertical axis and horizontal axis types. Horizontal axis wind turbines are preferred due to the advantages of ease in design and lesser cost particularly for higher power ratings.

The power captured by the wind turbine is obtained as

$$P = \frac{1}{2}\pi\rho R^3 V^2 C_p \quad (1)$$

where the power coefficient C_p is a nonlinear function of wind velocity and blade pitch angle and is highly dependent on the constructive features and characteristics of the turbine. It is represented as a function of the tip speed ratio λ given by [2].

$$\lambda = \frac{R\omega_t}{V} \quad (2)$$

It is important to note that the aerodynamic efficiency is maximum at the optimum tip speed ratio. The torque value obtained by dividing the turbine power by turbine speed is formed obtained as follows:

$$T_t(V,\omega_t) = \frac{1}{2}\pi\rho R^2 C_t(\lambda) V^3 \quad (3)$$

where $C_t(\lambda)$ is the torque co-efficient of the turbine, given by

$$C_t(\lambda) = \frac{C_p(\lambda)}{\lambda} \quad (4)$$

The power co-efficient C_p is given by [3]

$$C_p(\lambda) = \left(\frac{116}{\lambda 1} - (0.4*\beta) - 5\right)0.5e^{\frac{-16.5}{\lambda 1}} \quad (5)$$

where

$$\lambda_1 = \frac{1}{\left(\frac{1}{(\lambda + 0.089\beta)} - \frac{0.035}{\beta^3 + 1}\right)} \quad (6)$$

B. Permanent Magnet Generator Model

Permanent Magnet Generator provides an optimal solution for varying-speed wind turbines, of gearless or single-stage gear configuration. This eliminates the need for separate base frames, gearboxes, couplings, shaft lines, and pre-assembly of the nacelle. The output of the generator can be fed to the power grid directly. A high level of overall efficiency can be achieved, while keeping the mechanical structure of the turbine simple.

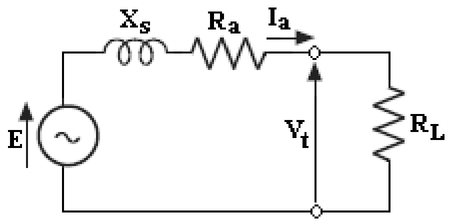

Fig. 2: Equivalent circuit of PM generator for one phase

Generated emf / phase ,

$$E = Vt + Ia(Ra + jXs) = Vt + IaZs \quad (7)$$

where

$$Zs = \sqrt{Ra^2 + Xs^2}$$

The rotor reference frames of the voltages are obtained as

$$V_q = -(R_S + L_q p) I_q - \omega_r L_d I_d + \omega_r \lambda_m \quad (8)$$

$$V_d = -(R_S + L_d p) I_d + \omega_r L_q I_q \quad (9)$$

The expression for the electromagnetic (EM) torque in the rotor is given by

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P_n}{2}\right)\left[\left(L_d - L_q\right) I_q I_d - \lambda_m I_q\right] \quad (10)$$

The relationship between the angular frequency of the stator voltage (ω_r) and the mechanical angular velocity of the rotor (ω_m) is obtained as follows:

$$\omega_r = \frac{P_n}{2}\omega_m G \quad (11)$$

$$p\omega_r = \frac{P_n}{2J_g}(T_m - T_e) \quad (12)$$

$$p\theta = \omega_r \quad (13)$$

Torque developed by the turbine T_t released to the input to the generator T_m is expressed as

$$T_m = \frac{T_t}{G} \quad (14)$$

C. Rectifier Model

A three-phase diode bridge rectifier converts the AC generated output voltage, which will be varying in magnitude and also in frequency, into DC. The average output voltage of the three phase diode rectifier is obtained [5] as follows:

$$Vdc = \frac{3Vm}{\pi} \quad (15)$$

and the average and RMS load currents are given by

$$Idc = \frac{Vdc}{Rl} \quad (16)$$

$$C\ Irms = \frac{Vrms}{Rl} \quad (17)$$

D. Boost Chopper

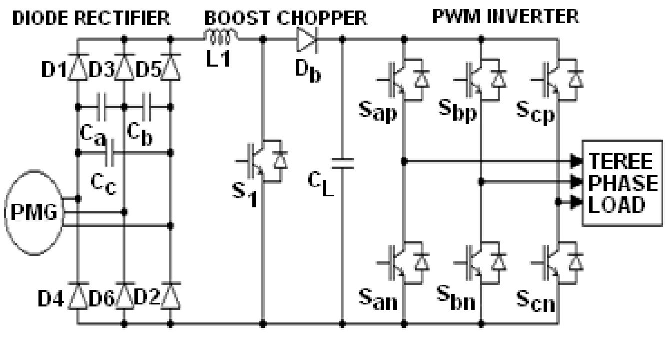

Fig. 3: Circuit diagram of boost chopper and PWM inverter

The conversion of rectified DC voltage to any specified DC output voltage can be carried out employing a DC–DC converter or chopper circuit. Fig 3 shows the circuit diagram of boost chopper and PWM inverter.
The boost chopper output voltage is obtained [8] as

$$V_o = V_s \frac{T}{(T - T_{on})} \quad (18)$$

$$V_o = \frac{V_s}{(1-\delta)} \quad (19)$$

where δ=Duty ratio of the chopper
Table 1 shows the change of duty ratio of chopper with respect to wind velocity. As the wind velocity changes the duty ratio of chopper is adjusted in order to provide a constant output.

Table 1: Change of Duty Ratio of Chopper with respect to Wind Velocity

S.NO.	Wind Velocity in m/s	Duty Ratio δ
1.	4	0.8618
2.	5	0.8272
3.	6	0.7926
4.	7	0.7581
5.	8	0.7235
6.	9	0.689
7.	10	0.6544
8.	11	0.6198
9.	12	0.8583
10.	13	0.5507
11.	14	0.5162
12.	15	0.4816

E. PWM Inverter Model

For providing electric power to industrial applications in the form of AC, the DC output of Boost Chopper is inverted in a three – phase ac voltage [1]. The most efficient of controlling the output voltage is to incorporate pulse width modulation control with in the inverters. In this method, a fixed dc input voltage is supplied to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of inverter devices. In the inverter output voltage of 2π radians, each control signal has duration of π radians. The period T has been divided into six intervals. During each interval the switches receive control signals.

A switch conducts and carries current in the direction of its diode when the control signal is present and the switch is forward biased. The switch will always be forward biased, except when its antiparallel diode conducts and thus reverse biases the switch by its voltage drop. In any case, either the switch or its antiparallel diode will be in conduction during the presence of the control signal and the current will be flowed in either direction. During the interval I, the switch diode pairs S_{ap}, S_{cp} and S_{bn} are in conduction. Hence, terminals A and C are connected to positive terminal of DC source and terminal B is connected to the negative terminal of the DC source.

Gating signals for PWM Inverter devices are generated employing a Sinusoidal Pulse Width Modulation Technique (SPWM), by comparing a sinusoidal reference signal with a triangular carrier wave. Fig. 4a, 4b and 4c shows the PWM pulses generated for phase a, phase b and phase c legs in three phase inverter. In this method of PWM, the harmonic content can be reduced using several pulses in each half cycle of output voltage. The width of each pulse is varied proportional to the amplitude of a sine wave evaluated at the centre of the same pulse. The frequency of reference signals f_r determines the inverter output frequency f_0 and its peak amplitude controls the modulation index M and this in turn the rms output voltage, V_0. The number of pulses per half cycle depends on the carrier frequency. By varying the modulation index, the rms output voltage can be varied.

If δ_m is the width of the m^{th} pulse and p is the number of pulses, then the rms output voltage is obtained as:

$$V_{ac} = V_{in} \left(\sum_{m=1}^{2pul} \frac{\delta_m}{\pi} \right)^{\frac{1}{2}} \quad (20)$$

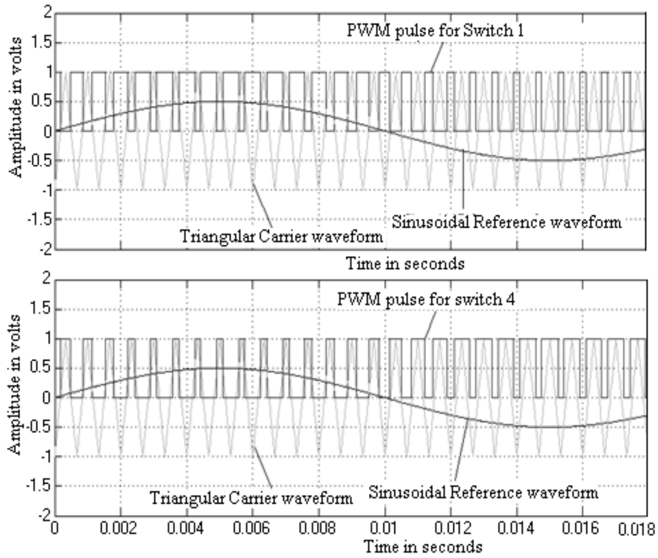

Fig. 4 a: PWM pulse generation for Phase A leg in three phase inverter

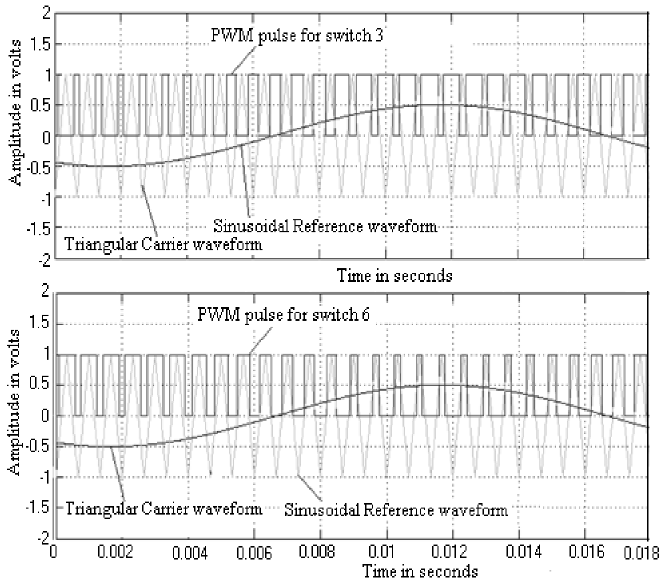

Fig. 4 b: PWM pulse generation for Phase B leg in three phase inverter

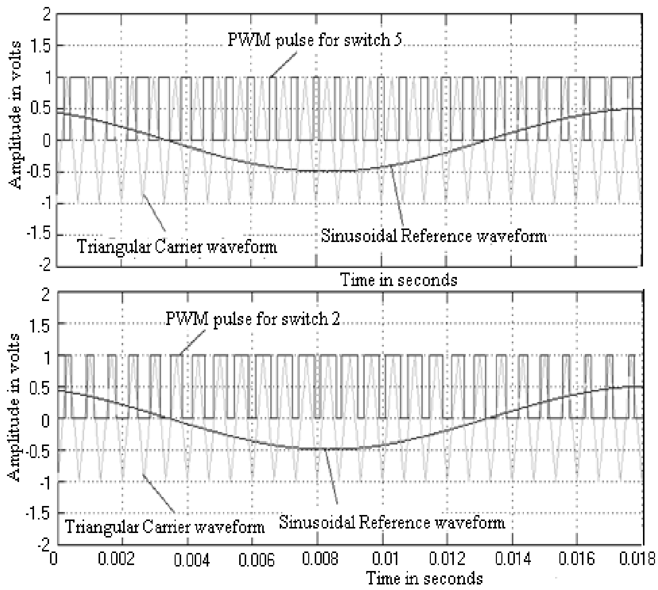

Fig. 4 c: PWM pulse generation for Phase C leg in three phase inverter

F. Maximum Power Point Tracking

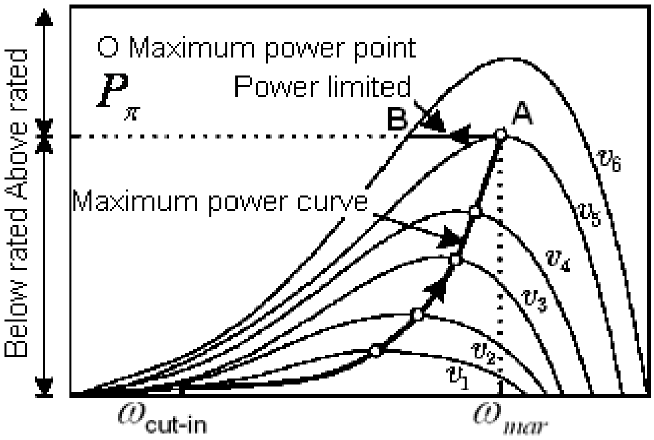

Fig. 5: Optimum Power Point tracked.

For variable speed operation, each wind velocity has a maximum power point. Fig.5 shows the optimum power point tracked in the power characteristics curve of wind turbine. To operate the WECS at maximum power point, the controller requires both voltage and current inputs. This increases the number of controller blocks [4], [7].

To improve the efficiency and to reduce the number of controller blocks, the control algorithm is developed with only one input – the current input. This controller generates appropriate firing angle to the boost chopper, and as a result, maximum power point is tracked. The optimized current is used as reference so as to obtain the maximum generated output power from the wind turbine generator for various wind velocities. The proposed MPPT control algorithm is represented in Fig. 6.

From the current reference we are finding out the flux components that are given by equation (21).

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = R \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + p \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} \quad (21)$$

The flux linkage in the previous matrices is expressed by the following equation

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} = L_q \begin{bmatrix} i_{dst} \\ i_{qst} \end{bmatrix} + K_e \begin{bmatrix} \cos\theta_m \\ \sin\theta_m \end{bmatrix} \quad (22$$

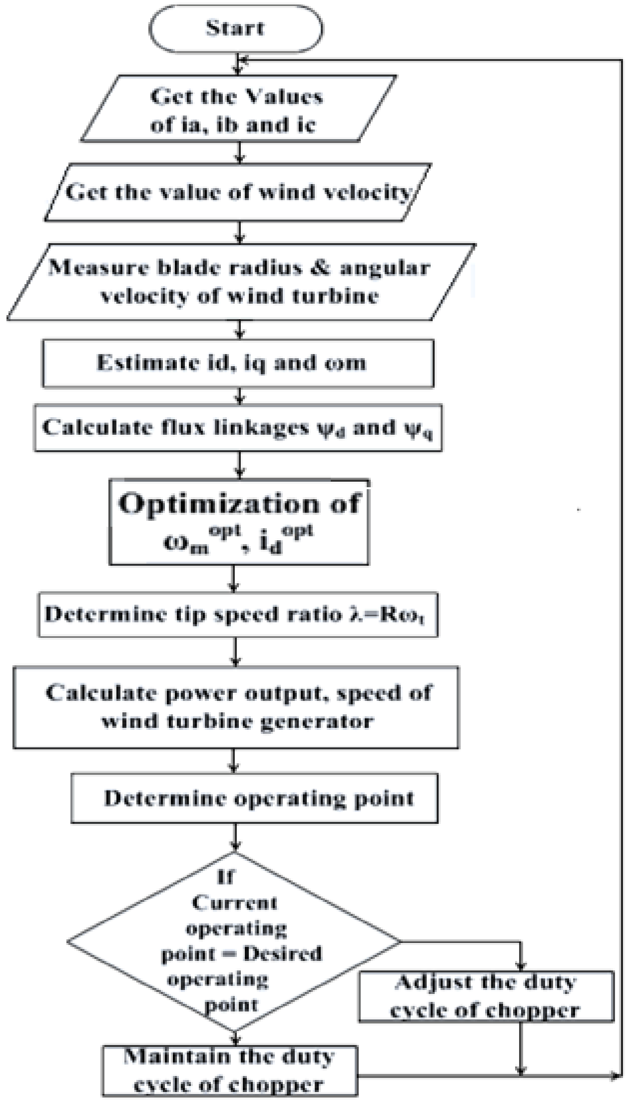

Fig. 6: MPPT algorithm with current feedback

The Fig. 7 shows the MATLAB/SIMULINK model of flux linkage estimator which converts the direct axis and the quadrature axis current in to the equivalent flux linkage.

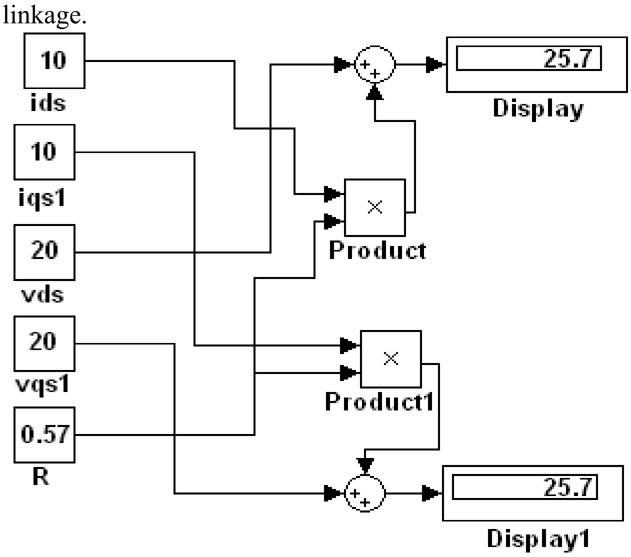

Fig. 7 : Flux Linkage Estimation

In the MPPT algorithm as shown in Fig. 5 the values of i_a, i_b and i_c is taken as input and i_d , i_q and ω_m are calculated using the equations (23),(24) and (25),

$$i_d = (2/3)(i_a \sin\theta + i_b \sin(\theta - \omega t) + i_c \sin(\theta + \omega t)) \quad (23)$$

$$i_q = (2/3)(i_a \cos\theta + i_b \cos(\theta - \omega t) + i_c \cos(\theta + \omega t)) \quad (24)$$

$$\omega_m = \frac{2\omega_r}{p_n G} \quad (25)$$

The value of flux linkages are obtained by using equations (26) and (27),

$$\psi_d = v_{ds} + Ri_{ds} \quad (26)$$

$$\psi_q = v_{qs} + Ri_{qs} \quad (27)$$

The optimized speed is given by equation (28),

$$\omega_m{}^{opt} = \sqrt{((c_r{}^3 - k_0)3k_2 + k_1{}^2)) - k_1{}^2(v * \frac{1}{3k_2})} \quad (28)$$

Tip speed ratio (λ) and power output are obtained from the equations (1) and (2), given in the wind turbine model. For a particular wind velocity, the current operating point is determined by using the power-speed relationship and the desired operating point is determined by using the optimized value. If current operating point is equal to desired operating point then the duty cycle of chopper is maintained as the same otherwise the duty cycle of chopper is adjusted to make to make both operating points equal and again the process is repeated.

V. MATLAB IMPLEMENTATION

Fig. 8 shows the overall simulation model of Wind Energy Conversion System. This model is simulated in MATLAB/SIMULINK for various wind velocities.

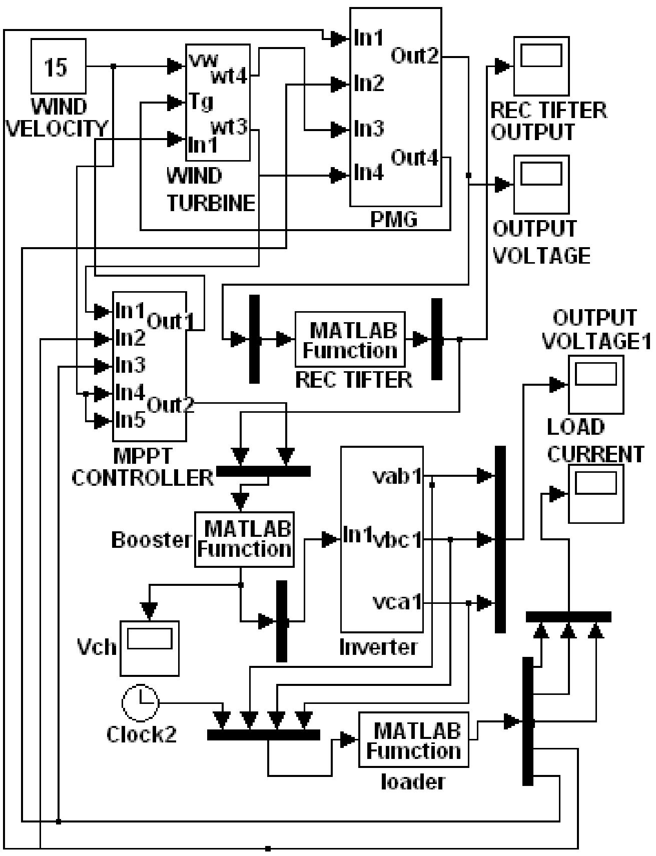

Fig. 8: MATLAB model of Wind Energy Conversion System

VI. RESULTS

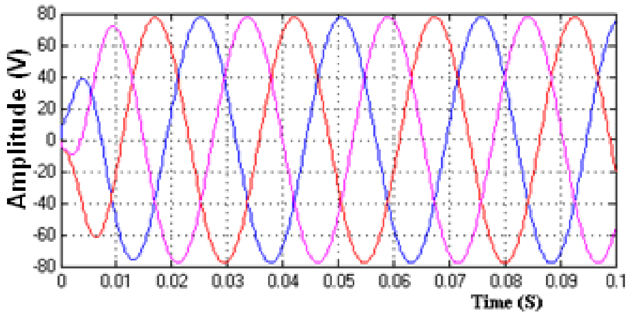

Fig. 9: PMG output voltage curve for the wind velocity of 10 m/s

Fig 9 shows the Permanent Magnet Generator output voltage. This AC voltage is rectified into DC using a rectifier.

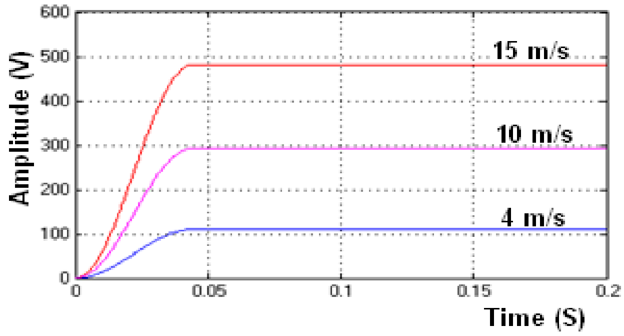

Fig. 10: Rectifier output voltage for wind velocity of 10m/s.

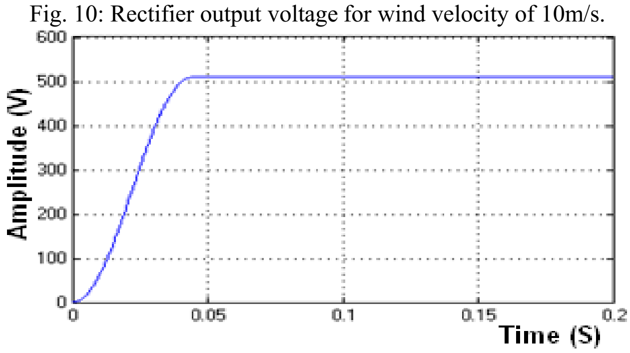

Fig. 11: Boost Chopper Output Voltage

Fig 10 shows the diode rectifier output voltage for wind velocity of 10m/s. The DC output is given to boost chopper unit. Fig 11 shows the boost chopper output voltage for different values of wind velocity. The chopper output voltage is 508 volt constant. This is given to SPWM inverter.

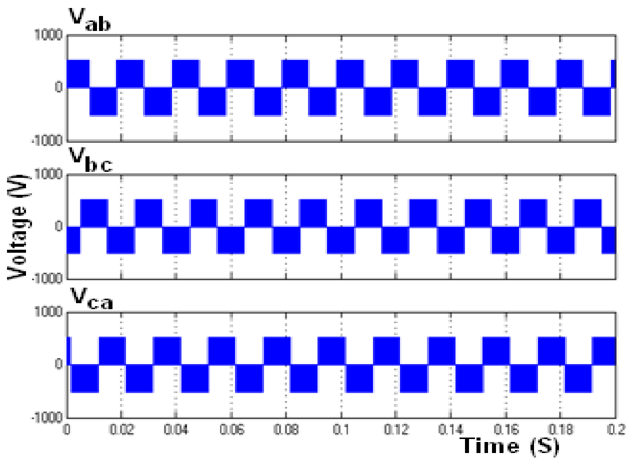

Fig 12: SPWM Inverter Output Voltage

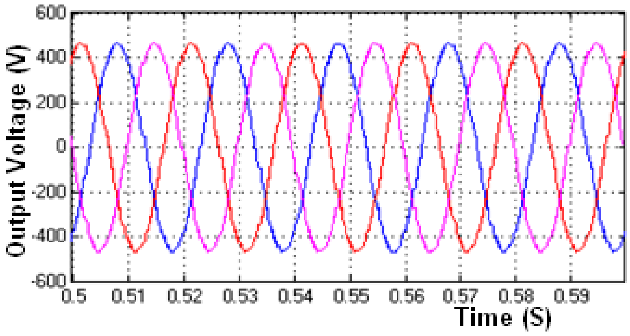

Fig. 13: Sinusoidal Output Voltage of SPWM Inverter

Figs 12 and 13 show the inverter output voltage of 415Volt AC is constant for that all wind velocities. This is given to load.

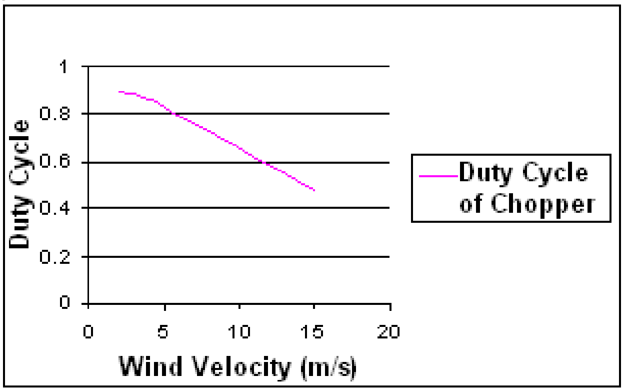

Fig 14: Duty cycle variation for variation in wind velocity

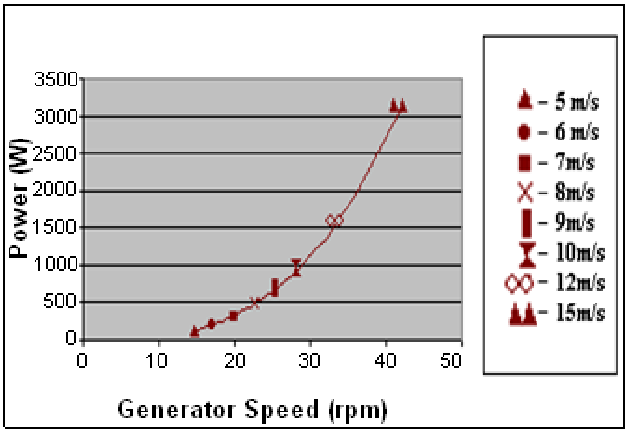

Fig 15: Maximum Power Point Tracking

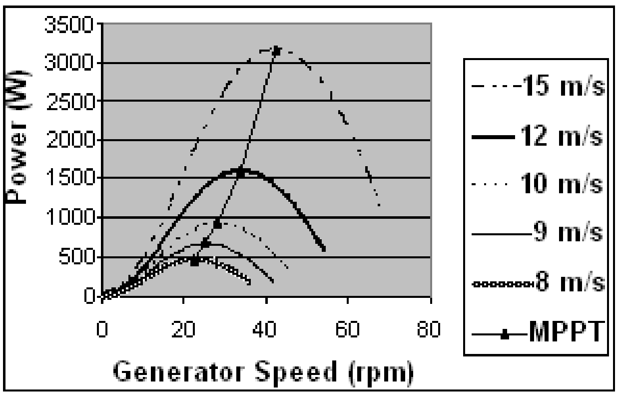

Fig. 16: Optimum Power Trajectory

Fig. 14 shows the variation in duty cycle for different values of wind velocity. As the wind velocity is varied, the duty cycle of chopper varies accordingly to maintain operation of WECS at maximum power point.

Fig 15 shows the maximum power point tracked for different values of wind velocity.

Fig 16 shows the optimum power trajectory. The maximum power point for various wind velocities are tracked in the graph.

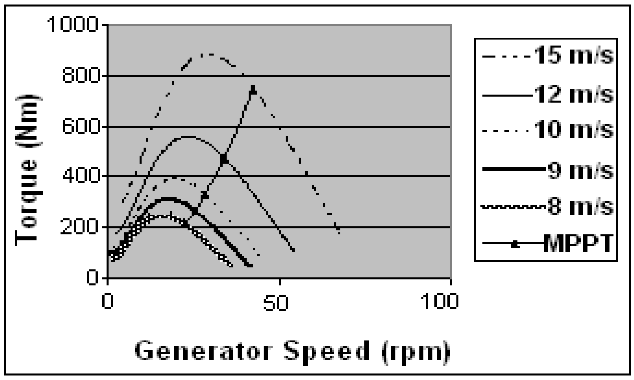

Fig. 17: Optimum Torque Trajectory

Fig 17 shows the Optimum Torque Trajectory of the wind turbine generator model. From the above two figures the maximum power and torque points for each wind velocity can be determined.

VII. Conclusion

The variable-speed wind energy conversion system using a permanent magnet generator has been discussed in this paper and the optimal control strategy of PMG maximizing the generated power was proposed. The optimum current value that maximizes output power is determined and used as reference for MPPT algorithm. Also MPPT control is achieved without a wind speed sensor. The control algorithm is made simple from other existing algorithms by this current reference. The system configuration is also simple, but the operation of wind turbine generator is optimized. Simulation study on a Wind Energy Conversion System employing MATLAB/SIMULINK model is the core coverage in this paper.

Appendix

PMG - 0.75kW, 380V, 1000rpm
Converter unit -500V, 10A
Load - 3 phase, 415V, 10A

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BIOGRAPHIES

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