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Closed Loop Control of Permanent Magnet Synchronous Generator Wind Turbine for Standalone System along with MPPT Control

A. Suyampulingam* V. Subbiah and R. Neelaveni****

Abstract : In this paper, the closed loop control of a wind energy system with sensor-less maximum power point extraction scheme, using PI controller is presented. In practice, the electrical energy generated by a permanent magnet synchronous generator coupled wind turbine is supplied to the load using a circuit which consists of a rectifier, boost converter and a load. The rectified output is controlled by boost converter by adjusting the duty ratio of converter as per the maximum power extraction algorithm. The algorithm changes the rotating speed of the permanent magnet synchronous generator so that Cp (power Coefficient) of the wind turbine reaches its maximum value. The proposed system has been simulated using MATLAB/SIMULINK under varying wind conditions and results obtained.

Keywords : Maximum Power Point Tracking, Wind Energy Extraction, Boost convertor, PMSG.

1. INTRODUCTION

In the advent of serious concerns surrounding the sustainability and the ecological footprint of conventional energy sources, renewable energy sources such as wind energy systems have been fast gaining momentum. In developing countries like India with a high wind potential, the development of distributed generation and advancements in power electronics devices has led to a higher penetration of wind technology. DC micro-grids are localized stand-alone systems involving hybrid renewable energy sources like solar power and wind power technologies. Wind power depends mainly on geographical conditions and weather conditions. Therefore, it is necessary to develop a system capable of generating maximum power under these constraints.

Nowadays, permanent magnet synchronous generators (PMSGs) are used in wind turbine because of its advantages: better reliability, less maintenance, high power to weight ratio, self-excitation capability leading to high power factor and high efficiency operation. The absence of the dc excitation does away with the slip rings and associated brushes, leading to lesser weight, lower cost, and fewer mechanical components resulting in higher reliability.

There are many remote communities throughout the world where the electricity grid is not available. These communities are supplied with conventional energy sources. It is well known that these conventional sources are very expensive and go to depletion. Since these communities are affluent in wind energy, stand-alone wind energy systems can be considered as an effective way to supply power to the loads. It is one of the practicalities for self-sufficient power generation which involves using a wind turbine with battery storage system to create a stand-alone system for isolated communities located far from a utility

* Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India *a_suyampulingam@cb.amrita.edu*

** Department of Electrical and Electronics Engineering, PSG College of Technology, Coimbatore.

grid. Wind energy supply systems are among the most interesting, low cost, and environmental friendly for supply power to remote communities which are affluent in wind energy resource.

Maximum power can be extracted from the available wind power, which varies continually withchange in the wind speed throughout a day, by adjusting the rotor speed of PMSG according to the wind speed variation. So, most recent papers try to achieve sensor less maximum power extraction from available wind power because these mechanical sensors leads to inaccurate measurements due to mechanical parts consideration.

Power electronics have an important role for controlling electrical characteristics of wind turbines. DC-DC converters have been used for modifying the electrical load in order to maximize energy generation, on its various topologies: buck, boost and buck boost [11]. Input of the DC-DC converter is connected to bridge rectifier and a bulky capacitor (DC link), and output is connected to the load.

The scheme with a proper control algorithm to modify duty-cycle of DC-DC converter for maximum energy generation is known as Maximum Power Point Tracking (MPPT). The converter is used to change the apparent DC bus voltage seen by the generator. Thus by controlling the Duty Cycle of the converter the terminal voltage of the PMSG is adjustable in order to maximize the power production.

For maximum power transfer in all wind speeds, the converter must be able to reduce PMSG terminal voltage in low wind speeds, and increase in high wind speeds. Thus, the recommended converter for this type of application must have boost voltage characteristics.

The closed loop control of converter can be obtained by varying the duty ratio of it based on the error between reference voltage and dc actual output voltage. The maximum output can be obtained by tuning the PI controller.

2. SYSTEM OVERVIEW

The block diagram of the proposed system is shown in Fig.1. The proposed system consists of a wind turbine that converts the wind power in the wind to mechanical power in the rotor shaft; the mechanical power in the shaft is then converted to electricity using a permanent magnet synchronous generator (PMSG). The voltage generated by the permanent magnet machine is rectified using a three-phase uncontrolled rectifier, which converts the AC voltage generated by the PMSG to a DC voltage.

The rectified DC output voltage is increased depending on the wind conditions by changing the duty ratio of the boost converter. The generated output power and DC output voltage are maximized in functions of boost chopper'sduty ratio and the generator rotational speed. The electric energy generated from the generator has characteristics by the condition of the load with the peak point.

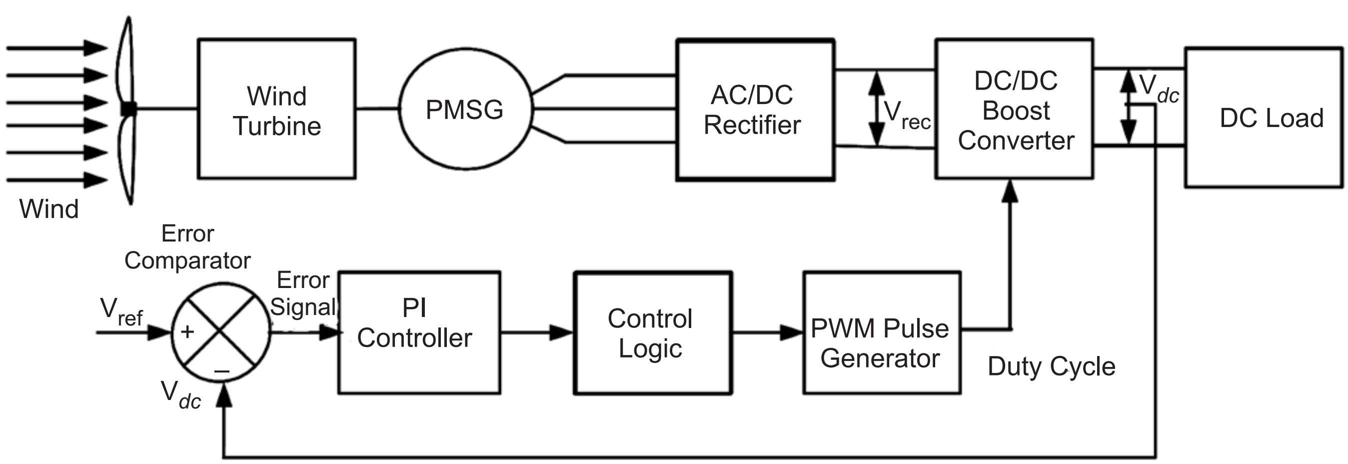


Figure 1: System Overview

3. WIND TURBINE CHARACTERISTICS

Depending on the aerodynamic characteristics, the wind power captured by the wind turbine can be expressed as

$$P = \frac{1}{2}\rho\pi R^2 v_{wind}^3 \tag{1}$$

Where, ρ is the air density (kg/*m*3), R is the radius of wind turbine blade (*m*), v_{wind} is the wind speed(*m*/*s*). It is not possible to extract all the kinetic energy of wind, so it extracts a fraction of the power of wind as shown in (2) as the power coefficient C*p*.

$$P_m = \frac{1}{2}C_p(\lambda,\beta)\rho\pi R^2 v_{wind}^3 \tag{2}$$

Where P*m* is the mechanical power of the wind turbine. The maximum power coefficient is 0.59 which is also known as Betz limit. It can be expressed in terms of tip speed ratio λ and pitch angle β. If ω_m is the rotor speed, the tip speed ratio λ is expressed as shown in (3).

$$\lambda = \frac{\omega_m R}{v_{wind}} \tag{3}$$

Assuming a constant wind speed v_{wind}, the tip speed ratio,λ varies proportionally to the rotor speed $\omega_{m.}$

The generic equation is used to model the power coefficient $C_p = C_p(\lambda, \beta)$, based on the modeling turbine characteristics described in (4),[6]:

$$C_p(\lambda\lambda\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)\exp^{\left(\frac{21}{\lambda_i}\right)} + 0.0068\lambda \tag{4}$$

The characteristic function C_p *vs* λ for various values of the pitch angle β, is illustrated in Fig. 2.The maximum value of C_p is achieved for β = 0°. This particular value λopt results in the point of optimal efficiency where the wind turbine captures the maximum power [6]. In this work, a typical small-sized three-bladed horizontal-axis wind turbine generator with no blade pitch angle control is considered, so that β = 0° at all times.

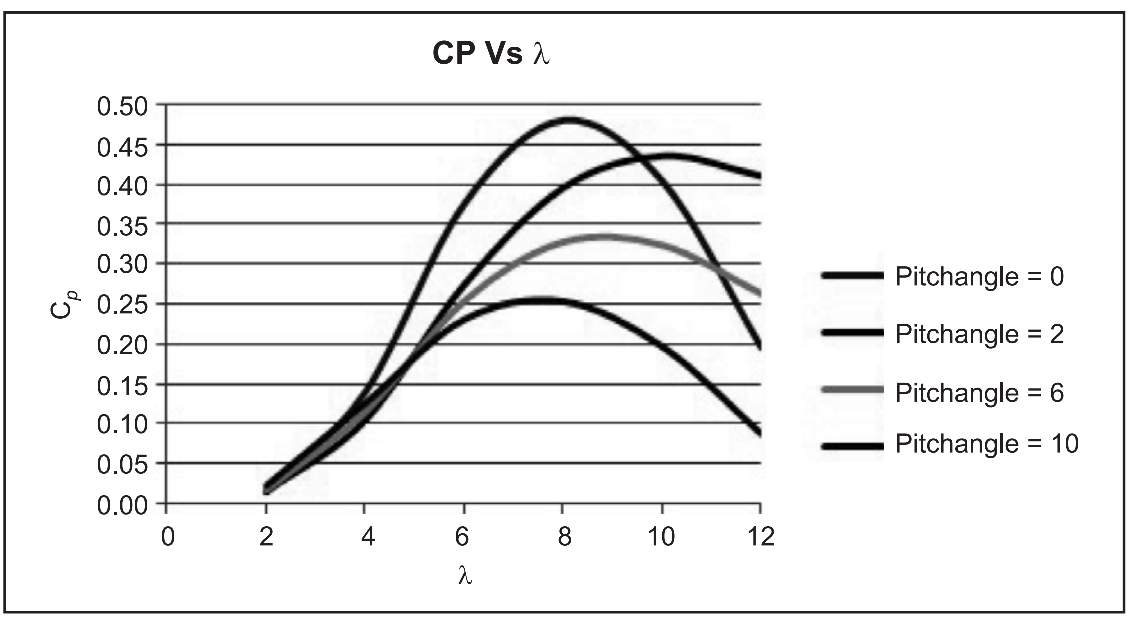


Figure 2: CP Vs λ for various pitchangle

If the tip speed ratio λ is maintained at its optimal value λopt, the power coefficient is at its maximum value $C_{p\,max} = C_p(\lambda opt)$, the maximum power of the wind turbine will be:

$$P_m^{opt} = \frac{1}{2} C_{p\max} \rho\pi R^2 v_{\text{wind}}^3 \tag{5}$$

On the other hand, the speed ratio assumed to be maintained at the optimum value, we obtain the optimum speed rotor:

$$\lambda_{\text{opt}} = \frac{\omega_m R}{v_{\text{wind}}} \Rightarrow \omega_{\text{opt}} = \frac{\lambda_{\text{opt}} v_{\text{wind}}}{R} \tag{6}$$

Thus, for each wind speed v_{wind}, there is a maximum rotor speed ω_{opt} which made a maximum power recovered from the wind turbine.

4. MODELING OF PMSG

In Permanent Magnet Synchronous Generators(PMSG), as the field winding of synchronous machines is replaced by permanent magnets,it has the advantages of compact size, the higher power density,the loss reduction, high reliability and good robustness.In addition, the simple design of the rotor without field windings, no slip rings and no excitation system also increases the efficiency of the machine [12].

The dynamic model of PMSG can be represented in the Park's system using the following equations(7), [8]:

$$V_d = -R_s i_d - L_d \frac{di_d}{dt} + \omega L_q i_q$$

$$V_q = -R_s i_q - L_q \frac{di}{dt} - \omega L_d i_d + \omega\lambda_m \tag{7}$$

The expression of electromagnetic torque in the rotor is given by (8):

$$T_e = \frac{3}{2} p[(L_d - L_q) i_q i_d - \lambda_m i_q] \tag{8}$$

$$\omega_m = p\omega$$

where p is the number of pole pair, λ_m is the magnetic flux, L_d is the direct axis inductance, L_q is the quadrature axis inductance , R_s is the stator resistance and ω is the electrical angular frequency.

If the rotor is cylindrical, $L_d \approx L_q \approx L_s$ so:

$$T_e = -\frac{3}{2} p\lambda_m i_q \tag{9}$$

The torque and induced voltage of PMSG given by(10) :

$$T_e = K_t I_a$$

$$E = E_e \omega \tag{10}$$

where I_a is the stator current, K_t is the torque constant and K_e is voltage constant of generator.

The relation between the induced voltage and terminal voltage of the generator is

$$E_2 = V_2 + (I_a L_s \omega)^2 \tag{11}$$

Where V is the terminal voltage per phase and L_s is the inductance of stator winding of generator.

The output voltage of the rectifier is expressed as in(12)

$$V_{\text{rec}} = 2.34 \text{ V} \tag{12}$$

The output voltage of the boost converter is:

$$V_{dc} = \frac{1}{1-D} V_{\text{rec}} \tag{13}$$

Where D is the duty ratio of the boost converter.

By substituting the value of V_{rec} from (12)the expression of Vdc becomes as in (14)

$$V_{dc} = \frac{1}{1-D}\frac{3\sqrt{6}}{\omega}\sqrt{k_e^2 - \left(\frac{T_e L_s}{k_t}\right)^2} \tag{14}$$

So the torque is determined by the rotor speed and wind speed: a specific value of the voltage is estimated for a specific rotor speed and wind speed.

Now, for a given value of rotor speed, voltage can be obtained and applied to the system. By applying this control strategy, speed and voltage vary continuously until they reach their equilibrium. In this case, the maximum power of wind energy is achieved.

Hence, the voltage optimal value is reached by varying the duty ratio D of the boost converter as follows:

$$D = \frac{V_{dc} - V_{dc}\_opt}{V_{dc}} \Rightarrow \frac{\omega_{m-}\omega_{m\_opt}}{\omega_m} \tag{15}$$

In this proposed method the duty cycle, D of the boost converter is varied by adjusting the difference between the reference dc voltage and actual dc voltage by tuning the PI controller to obtain the maximum voltage.

Specifications of permanent magnet synchronous generator used:

Table 1

Parameters for PMSG

Parameter name	*Value*
Rated output power	0.5KW
Rated mechanical speed	500 rpm
Number of poles	12
Rated Voltage	200V
Stator winding resistance Rs	0.17Ω
Stator leakage inductance	0.0011H
Peak line-to-neutral back emf constant Km	565V/krpm

5. CLOSED LOOP CONTROL LOGIC

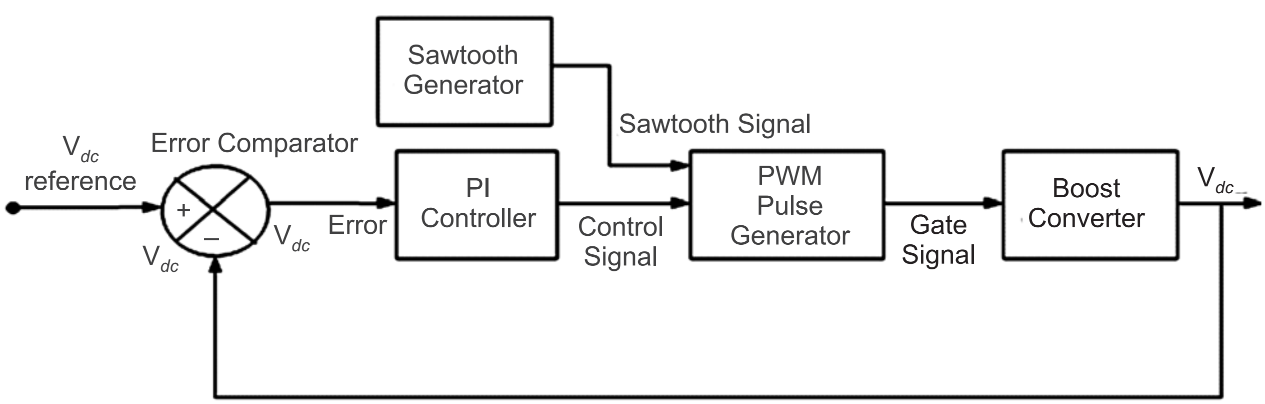


Figure 3: Control logic for PWM Pulse

The control logic is required to obtain the closed loop control operation of the system is shown in Fig.3. This control provides the necessary gate pulses with variable duty ratio to the boost converter to get maximum voltage. The pulse width modulated (PWM) signal is generated by comparing the error signal of dc output voltage with saw tooth carrier signal. The error signal is obtained by subtracting the actual dc output voltage with reference dc voltage which is given as the input of PI controller. The PI controller is tuned by selecting the appropriate value of K_P and K_I to obtain the maximum output voltage depending on the wind velocity.

6. SIMULATION RESULTS

The PMSG based wind turbine is modelled and simulated using MATLAB/SIMULINK.. The output of the generator is rectified and given as input to boost convertor, which is simulated for the different wind velocities and the Simulink model is shown in Fig. 4.

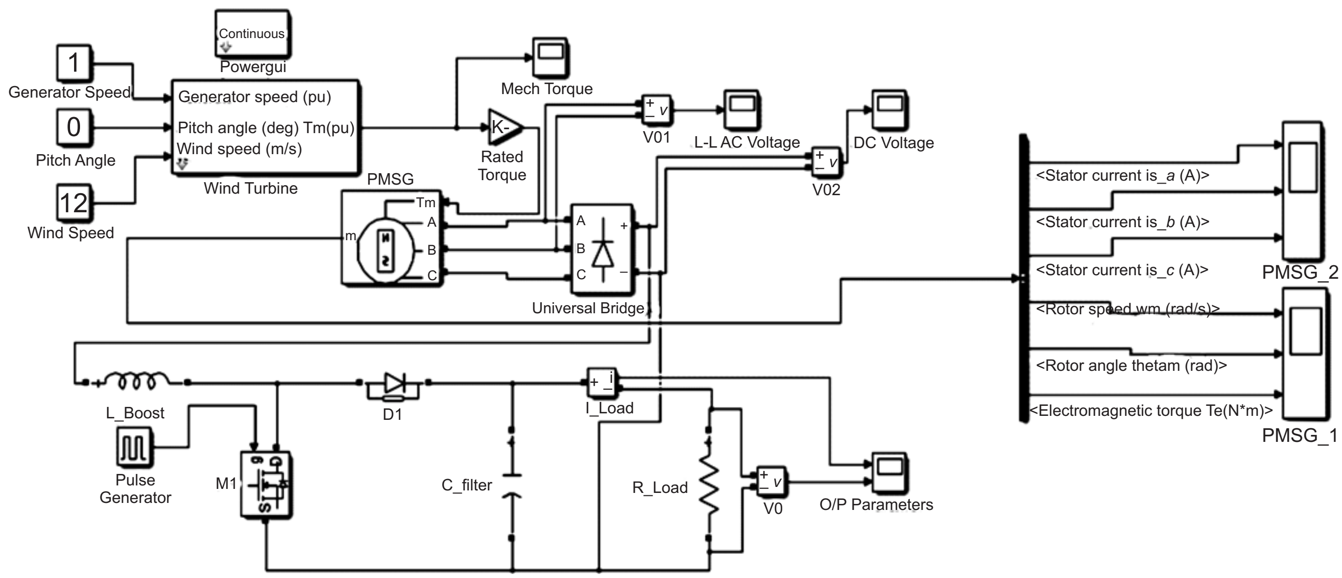


Figure 4: Simulink Model

The rectified DC voltage and output voltage of boost convertor values for various wind velocities for the duty ratio of 0.5 is shown in Table 2. It is observed that output voltage is higher than rectified voltage.

Table 2
Output Voltage for various wind velocities

S.No	*Wind Velocity*	*Rectified Voltage*	*Boost Voltage*
1.	12	140	282
2.	8	20	35
3.	6	17	33

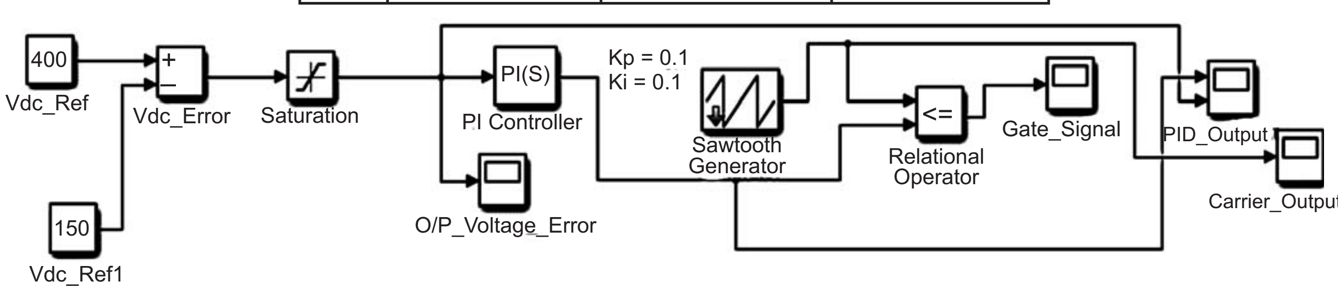


Figure 5: Simulation of Proposed Control Logic

The proposed control logic for generation of PWM pulses that triggers gate of boost convertor is implemented in SIMULINK is shown in Fig.5. The PWM pulses generated with $K_p = K_i = 0.01$ is shown in Fig.6

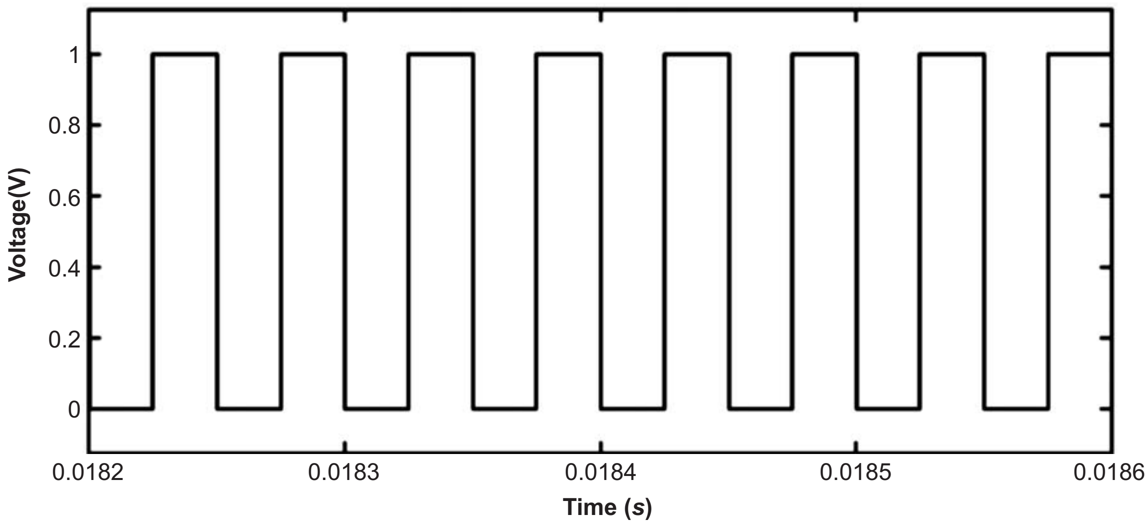
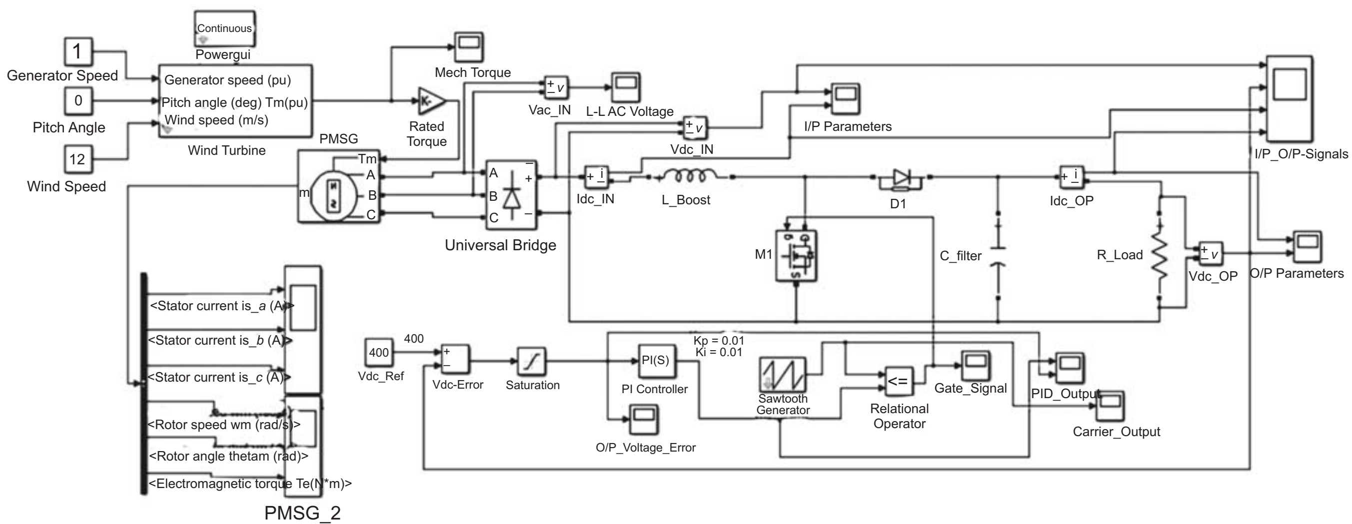


Figure 6: Gate Pulses



Figire 7: Closed loop System

The closed loop system of PMSG based wind turbine is modelled with proposed control logic with PI controller, which can be tuned for maximum power tracking and simulated using MATLAB/SIMULINK is shown in Fig.7. The DC output voltage, the output power of the generator,rotor speed, load current and electro-magnetic torque of the generator is observed for various values of K_p and K_i of PI controller. The observed various parameters of system for $K_p = K_i = 0.01$ is shown in Fig. 8(*a,b,c,d*).

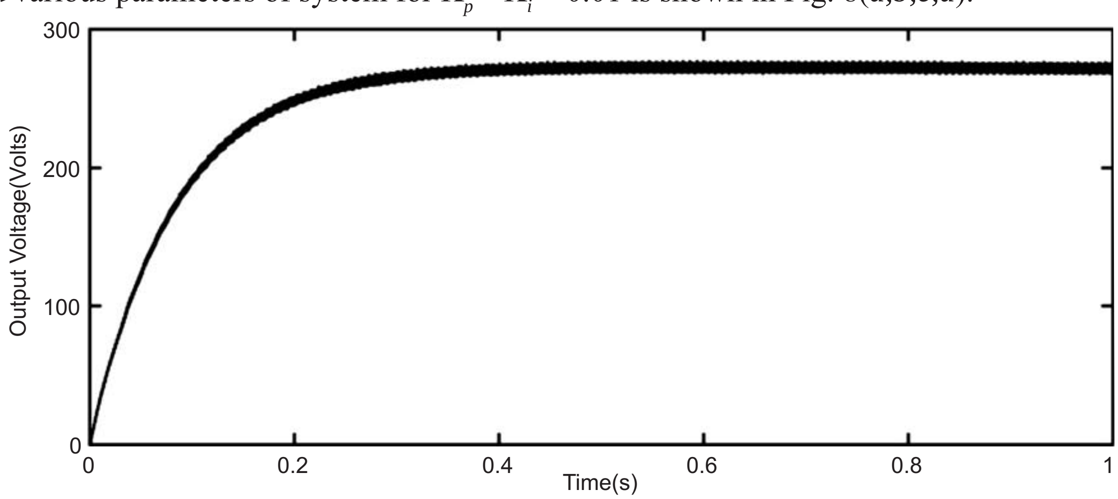


Figure 8: (*a*) Output Voltage

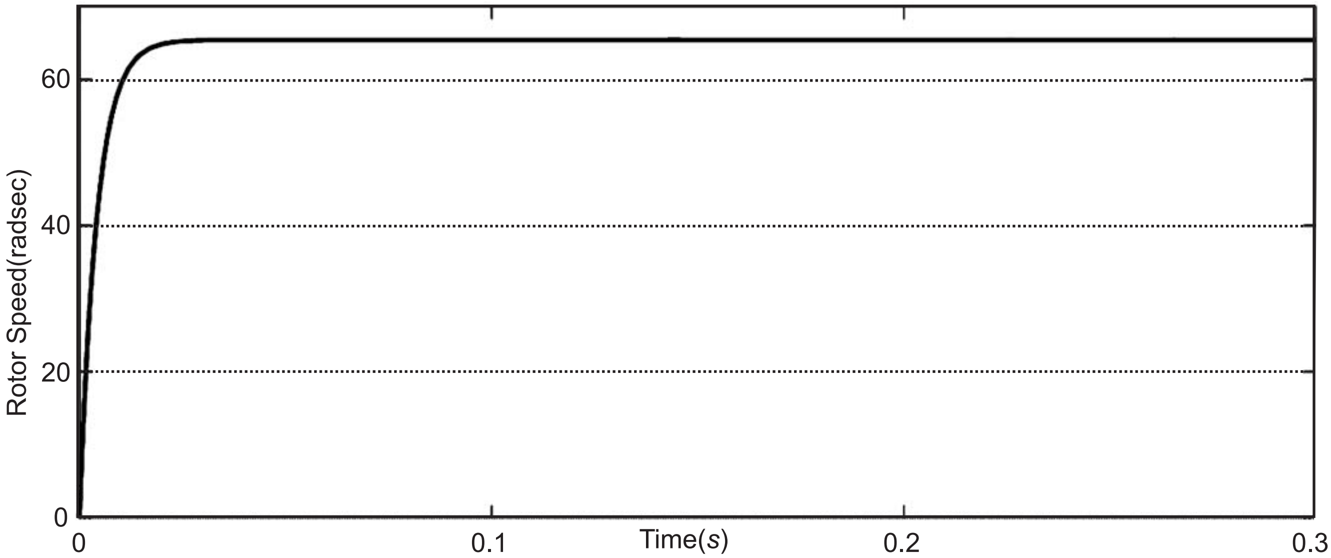


Figure 8: (*b*) Rotor Speed

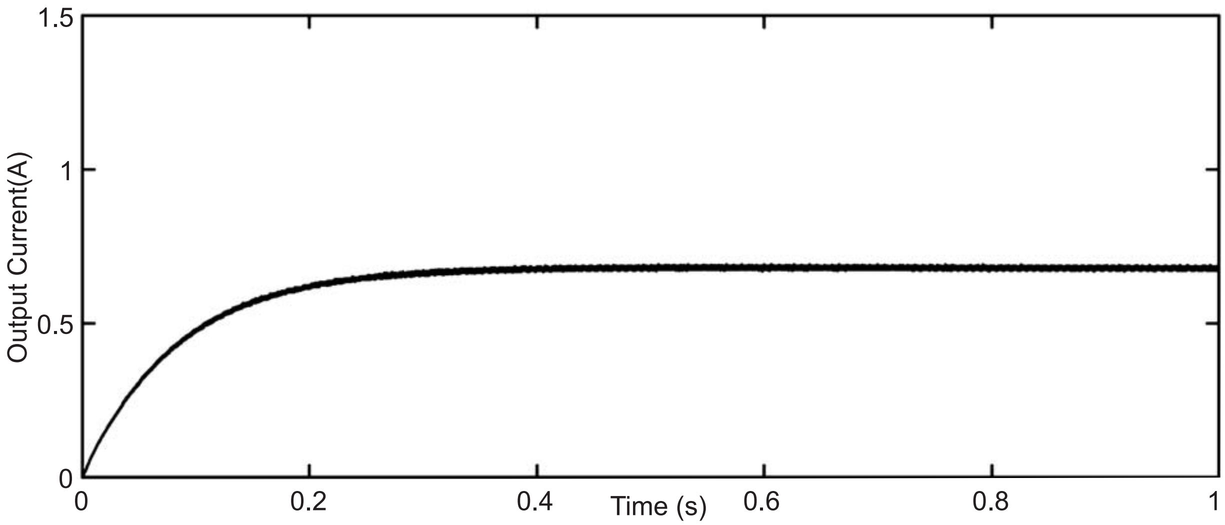


Figure 8: (*c*) Load Current

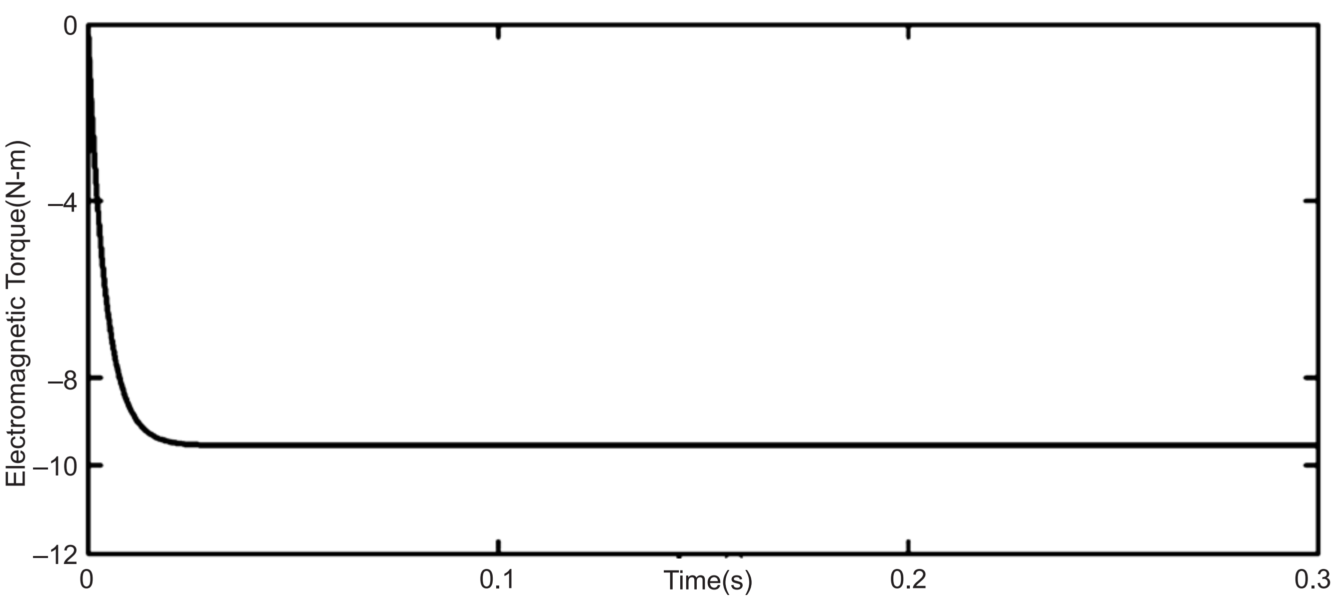


Figure 8: (*d*) Electro-magnetic Torque

The output power delivered to the load is observed for various duty cycle of convertor which is shown in Fig. 9.

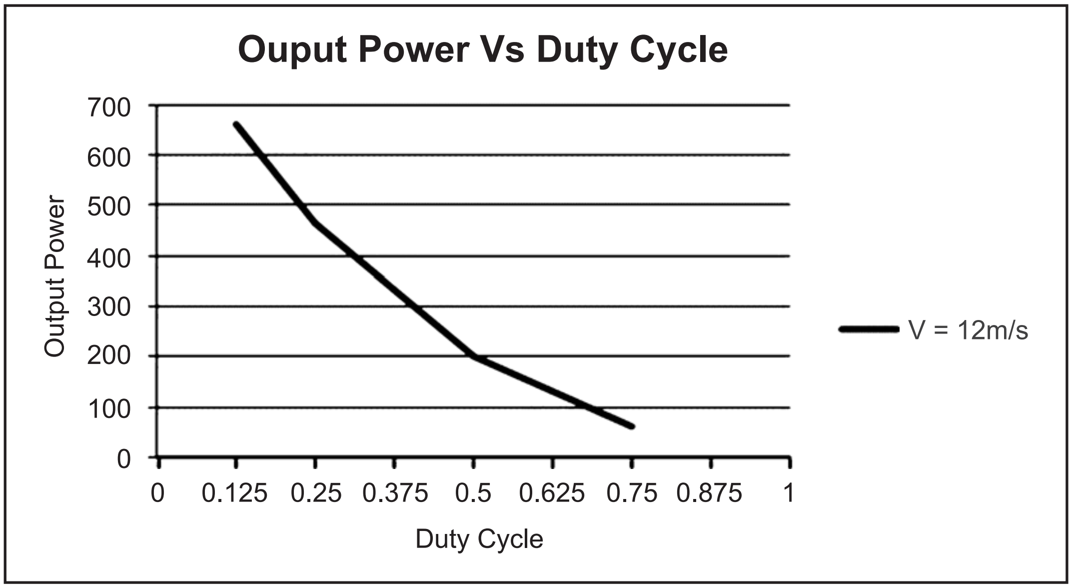


Figure 9: Output Power

The rectified DC voltage and output DC voltage across the load for various duty cycle is measured and shown in Fig.10.

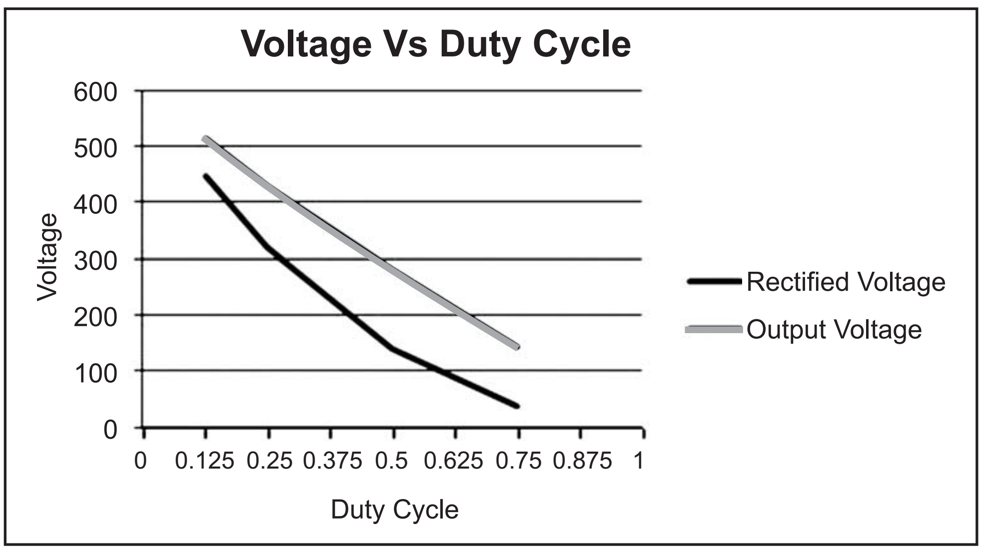


Figure 10: Output Voltage

The output voltage across the load is observed for various duty cycle and shown in Fig. 11.

From the observation it is seen that output voltage and power are increasing, with increasing wind velocity by adjusting duty ratio values of the convertor. The K_p and K_i values of PI controller are tuned so that the steady state error is reduced. It also reduces the settling time of the system.

7. CONCLUSION

The closed loop control of PMSG connected with wind turbine has been simulated and the output of generator is rectified and boosted, so that the maximum power is extracted from the wind turbine. The duty ratio of the boost convertor is adjusted by tuning the parameter of PI controller to obtain the required output voltage as wind speed increases. It is observed that the settling time and steady state error is reduced.

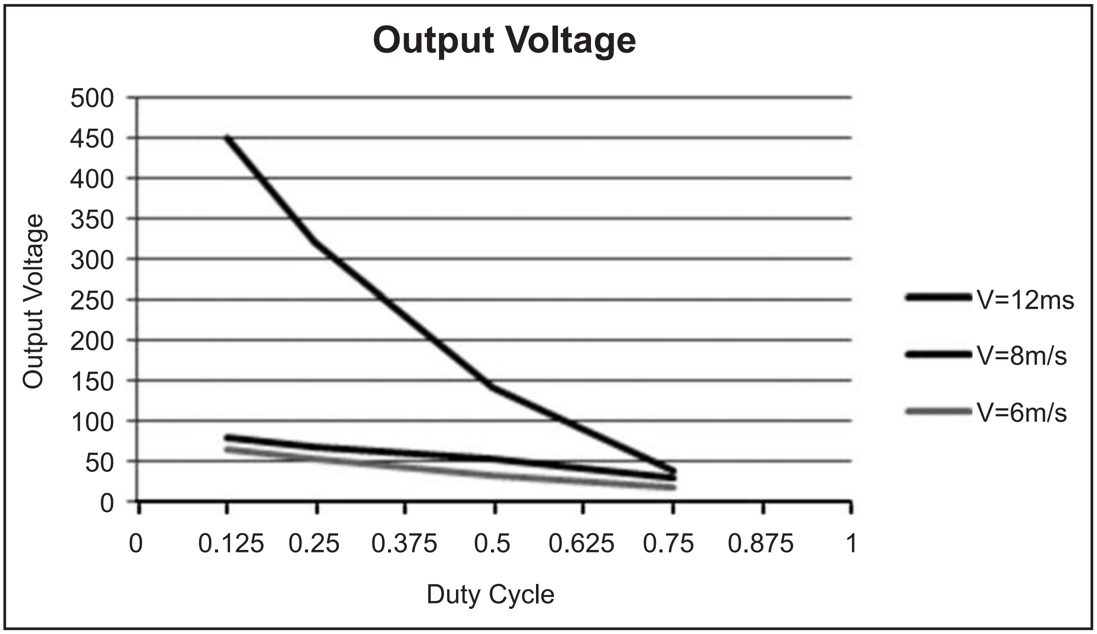


Figure 11: Output Voltage in function of wind velocity

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