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PMSG Based Wind Turbine Control Using MPPT and Pitch Angle Control at Variable Speeds

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ABSTRACT: It is essential to construct a PMSG-based wind turbine featuring MPPT and pitch angle controlling in order to improve performance and reliability. This control phenomenon enables the system to function more reliably and efficiently during erratic weather. Variable-speed wind turbines feature fixed-speed generation advantages include greater energy capture, operation at maximum power point, enhanced efficiency, and superior power quality. The power of the wind turbines is influenced by wind speed. However, wind power is accidental and unstable, and because of the nonlinear properties of the wind turbine, it is challenging to produce the maximum power in wind turbines. The voltage and power fluctuations produced by wind turbines are caused by the nature of the random variations in wind speed. The term MPPT (Maximum Power Point Tracking) control refers to a variety of research techniques used to monitor the wind turbine's peak power output.

KEYWORDS - Permanent Magnet Synchronous Generator (PMSG), Maximum Power Point Tracking (MPPT), Pitch Angle Control, Wind Energy Conversion System (WECS).

I.INTRODUCTION

Since the invention of electricity generation, people have consistently used a variety of resources, including coal, oil, gas, and other natural sources. The depletion of these sources' storage has started now as a result of their ongoing consumption. The effects of global warming have also increased significantly as a result of these processes. Thus, renewable energy sources are receiving increasing attention in the modern world, and wind is among the most efficient. The cleanest renewable energy source is wind power [1][2]. The potential of wind energy to replace traditional energy sources for power production is now the focus of research. Additionally, it will aid in lessening the impact of global warming.

The process of converting wind energy into electrical energy is known as a wind energy conversion system (WECS). Wind turbine, Control Method, Generator, and Power Converter are the components of WECS. There are various generator types employed in the conversion process, including Induction Generators (IG), Double-Fed Induction Generators (DFIG), and Permanent Magnet Synchronous Generators (PMSG) [3]. Due to its great efficiency and controllability, the PMSG is extensively employed in WECS. Permanent magnet materials are currently very sought-after for wind power generation due to their strong coercive field strength, temperature resistance, and inexpensive nature [4].

In comparison to fixed-speed generation, variable-speed wind turbines offer a number of benefits, including better power quality, enhanced energy capture, operating at maximum power, and improved efficiency [5][6]. However, there are issues with the gearbox that connects the wind turbine to the generator. The gearbox has problems and needs servicing on a regular basis. Using a direct-drive permanent-magnet synchronous generator can considerably increase the reliability of the variable-speed wind turbine (PMSG). Due to their self-excitation property, which enables high power factor and high efficiency operation, PMSG have attracted a lot of attention in wind energy applications.

The wind energy system captures wind energy and transforms it into electrical energy. The output power of a wind energy system fluctuates according to the wind speed. It is difficult to maintain the wind turbine's maximum power output for all wind speed circumstances because of its non-linear nature. The methods for tracking the wind turbine's peak power point, known as MPPT (Maximum Power Point Tracking) control, have been the subject of substantial research [7].

The three most widely used MPPT techniques are perturbation and observation (P&O) or hill climbing searching (HCS) [8], wind speed measuring (WSM) [10], and power signal feedback (PSF) [11]. The power output is observed after a little step-by-step perturbation of the rotor speed is applied in the P&O method, and the next small step-by-step perturbation of the rotor speed is then adjusted. The P&O algorithm monitors the power fluctuation and, in response, makes modifications to the relevant parameter, such as the duty cycle of the DC-DC converter to control the DC voltage or the current to regulate in order to change the rotor speed and track the MPP. According to this method, the control variable is perturbed in arbitrary small steps, and the decision for the subsequent perturbation is made after examining the changes in the power curve caused by the previous perturbation. Because of its simplicity and lack of the need for a mechanical speed sensor or anemometer during implementation, the P&O technique is a widely used MPPT algorithm. To maximize power for various wind speeds, a P&O-based MPPT algorithm is put into practice.

Whenever wind speed is above rated speed and a variety of regulating factors, including wind speed, generator speed, and generator power, may be chosen, pitch angle control is the most popular method for modifying the aerodynamic thrust of the wind turbine.

In order to control the turbine power at high wind speeds, a pitch angle control system was developed. This mechanism maintains power within certain bounds to safeguard the system and boost conversion effectiveness. Additionally, this technique enables the turbine to be stopped when the wind speed reaches a certain limit (cut-off speed). The blades are totally pitched in this scenario because no power will be generated [12].

The aerodynamic modeling of the turbine demonstrates that the characteristic of a turbine is substantially non-linear and mostly dependent on the wind speed. Following that, figure 1 [13] [14] illustrates how the power characteristic is represented as a function of wind speed. It illustrates how each turbine is defined by three different wind speeds: a starting wind speed (ws) from which the turbine generates power, a nominal wind speed (wn) from which the power generated by the turbine remains constant and equal to the rated speed, and a maximum wind speed (wmax) over which the turbine must shut down.

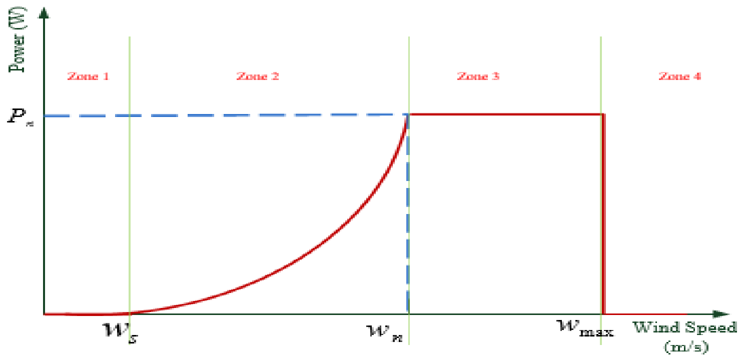

Figure 1The typical characteristics of the wind speed performance of a wind turbine

II.PROPOSED MODEL

The block diagram of the proposed model of Wind Energy Conversion Systems (WECS) is shown in Fig 2.

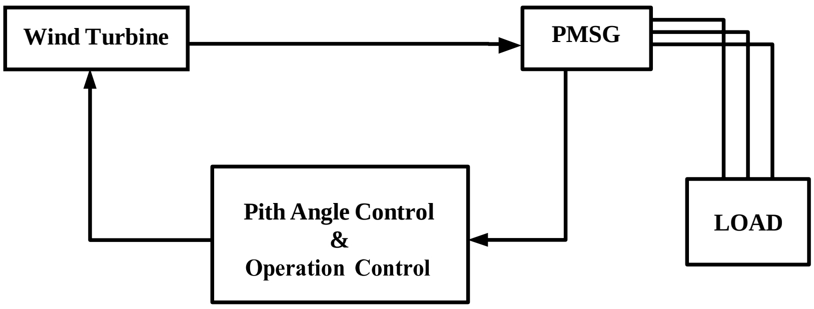

Figure 2 Block Diagram of PMSG based WECS

Wind Turbine Model

The following equation represents the kinetic energy store in wind as follows [6]:

$$E_c = \frac{1}{2} m v^2 \quad (1)$$

$$m = \rho v S \quad (2)$$

where,
m = air mass
v = wind speed
ρ = air density
S = surface area of the turbine
Thus, the wind power can be written as:

$$P_w = E_c = \frac{1}{2} m v^2 = \frac{1}{2} \rho S v^3 \quad (3)$$

After that wind turbine is used to convert the wind energy into mechanical torque. It can be determined from mechanical power at the turbine extracted from wind power. The power coefficient of the turbine (C_p) is applied. It is defined as the ratio between the mechanical power (P_m) and wind power (P_w). It is shown below:

$$C_p = \frac{p_m}{p_w}; C_p < 1 \quad (4)$$

The power coefficient is the function of pitch angle (β) and tip-speed (λ). Pitch angle is defined as the angle of turbine blade and tip speed is the ratio of rotational speed and wind speed [6]. The maximum value of power coefficient(C_p) is denoted as Betz's limit and equal to 0.593 theoretically. It means that the powerextracted from the wind turbine can be no longer than 59.3%.

The power coefficient(C_p) can also be expressed in terms of pitch angle (β) and tip-speed (λ) [7] as:

$$C_p(\lambda, \beta) = c_1(\frac{c_2}{\lambda_i} - c_3\beta - c_4)e^{-\frac{c_5}{\lambda_i}} + c_6\lambda \quad (5)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (6)$$

If we put the constant values as $c_1 = 0.5716, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21\ and c_6 = 0.0068$ then the characteristics of $C_p - \lambda$ curve is shown in Fig 3 for different values of β. The maximum value of C_p is attained for $\beta = 0\ and \lambda = 8.1$ [3].

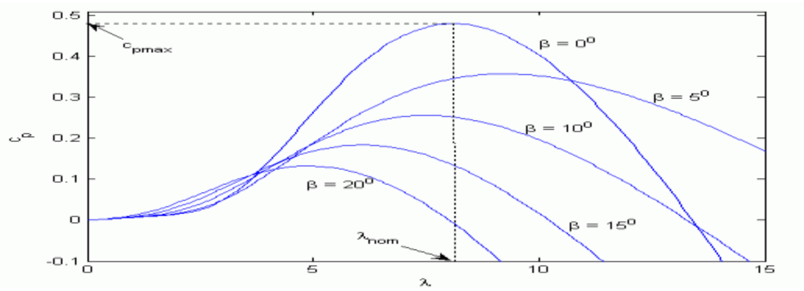

Figure 3 Cp - λ Curve

The following equations [6] express the mechanical output power and mechanical torque as shown below:

$$P_m = C_p(\lambda, \beta)\frac{\rho S}{2}v_{wind}^3 \quad (7)$$

$$T_m = \frac{P_m}{\omega} \quad (8)$$

where,
P_m = the mechanical output power
T_m = the mechanical torque
ρ = air density
S = surface area of the turbine
v_{wind} = velocity of wind
λ = the tip speed ratio
β = the pitch angle

III. CONTROL METHOD

This paper discusses the turbine blade pitch angle control and turbine operation control for getting an efficient wind power system.

Pitch Angle Control

By employing this control method, it is possible to keep the mechanical power input at its normal level while preventing an excessive increase in electrical power output. It frequently becomes active when there is a strong wind. In those circumstances, increasing generated power is not a viable option for controlling the rotor speed because doing so would overload the generator. Due to this, the rotor's aerodynamic efficiency is constrained, which helps to prevent the rotor speed from increasing. As a result, the blade pitch angle is adjusted. To harvest the least amount of electricity possible under this standard, the turbine blades are rotated away from the wind. Pitch angle control must be used whenever there is an imbalance between the amount of power produced and the amount of wind energy input in order to maintain the proper ratio between mechanical and electrical output. After the issue is fixed, the pitch angle once more maintains the ideal value for maximum power output [3]. For maximum power extraction, the turbine blades are also rotated with the wind.

As we previously discussed, the power coefficient, Cp, depends on the blade pitch angle and tip speed. Therefore, altering the would also alter the Cp, helping to manage both the generator output and rotational speed. We know that the maximum value of Cp is reached when the blade pitch angle, equals zero, which describes the circumstance in which pitch angle management is not necessary and denotes the state in which the turbine is working at terminal wind speed. However, this control mechanism must be used when the wind speed goes beyond the rated wind speed by a certain amount and the rotor speed goes over the rated value. To maintain the balance between input and output power, a mechanism will then be used to increase the value of pitch angle while decreasing the value of Cp. The Proportional-Integral (PI) control approach has been discussed for controlling pitch angle in this work.

This method of controlling pitch angle employs the difference between the rotor speed and a reference value of rotor speed to control the pitch angle. To compare the specified input rotor speed, a reference value is set. There is a discrepancy in signals observed whenever the rotor speed surpasses the reference value, which triggers the controller to work. The controller block, angle limit, and rate limiter block are placed after this error signal and are depicted in Figure 4 [3].

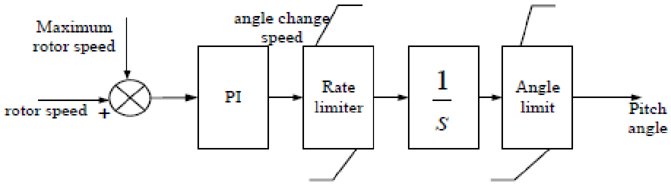

Figure 4 Pitch Angle Controller

If the rotor speed is lower than the referred value then the pitch angle controller will not work and it will give the value of β= 0 to the turbine for initiating maximum power output.

Operation Control

Even though the turbine is controlled by a pitch angle controller when it is windy, there must be a way to stop the entire operation if the cut-off speed is extended. In that case, the turbine must not run at all to prevent a major failure of the entire system. The cut-in speed that we used was 3 m/s, which is the speed at which the turbine will begin to produce usable electrical power. The range of (3-11) m/s is used to determine the running speed. The turbine is required to stop operating when the wind speed hits 11 m/s.

Thus, the cut-off speed specified in our suggested model is 11 m/s. Utilizing a user-defined MATLAB Function block where the predetermined requirements are met, this control approach is implemented in SIMULINK. In this block, the turbine was defined to operate between 3 and 11 m/s. Wind turbine won't produce any mechanical torque if the wind speed is less than 3 m/s or more than 11 m/s, hence Tm = 0. The generator won't produce any power as a result.

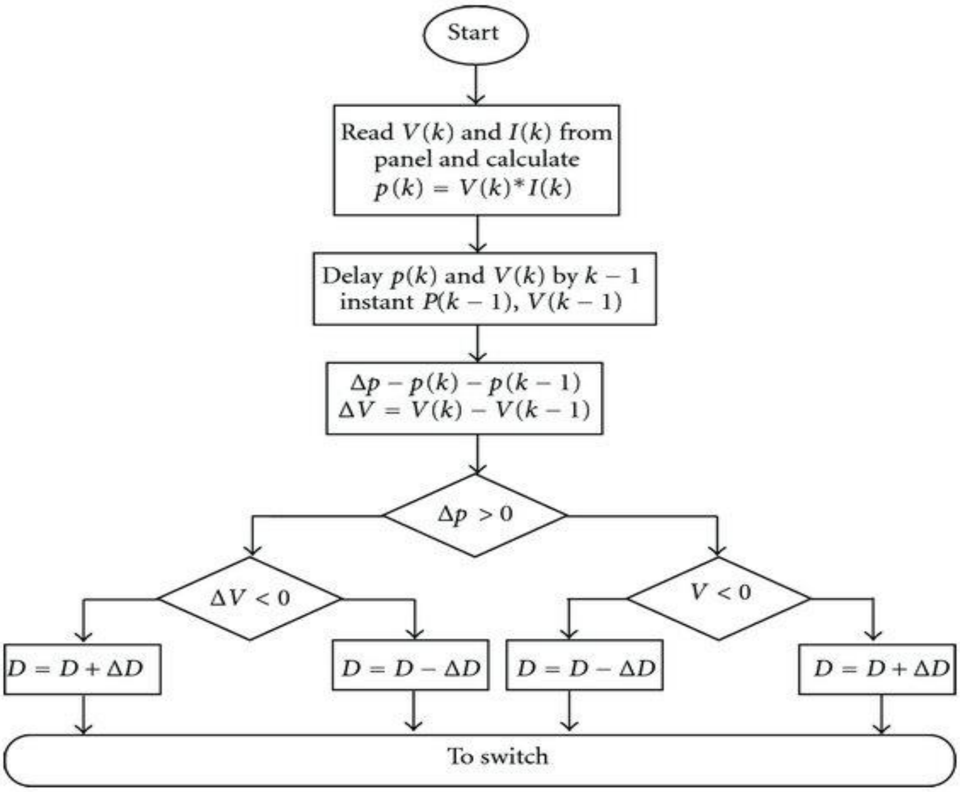

Figure 5 Perturb and Observe based MPPT algorithm

Maximum Power

Point Tracking

A sizable number of review publications claim that MPPT algorithms can be divided into four groups: indirect power controller (IPC), direct power controller (DPC), hybrid, and smart algorithms. Each group has advantages and disadvantages. Due to its many features, the perturb and observe (P&O) method has been used frequently during the past ten years in the WECS configuration. The produced step-sizes and tracking approach can be used to categorize P&O algorithms. The suggested MPPT controller's operation is demonstrated by the flow chart in Figure 5.

P&O algorithm tracks the MPP and adjusts a specific parameter, such as the duty cycle of the DC-DC converter to control the dc voltage, based on the observed power perturbation. It may also regulate current to control the rotor speed or to control voltage.

Being able to run at maximum power point (MPP) despite fluctuating wind speeds is a highly desirable attribute of wind turbine systems (WTS). By gaining the most energy from a wide variety of wind speed values, the MPPT algorithm allows the WTS to operate at its most efficient level.

IV.SIMULATION MODEL

The mathematical model of all necessary equipment's has been established so far. Now we need to implement it in simulation based study. For that MATLAB/SIMULINK software package is used where all the equipment's are successfully modeled with respective parameters. After that the performance of the proposed model was analyzed.

Wind Turbine SIMULINK Model

The Specifications of Wind Turbine are given in below table 1:

Table 1 Wind Turbine Parameters

arameter	Value
Mechanical Output Power	8.5 KW or 8.5e3 W
Base Power of the electrical generator	8.5e3/0.9
Base Wind Speed	6 m/s
Base Rotational Speed in pu	1 per unit

Pitch Angle Control SIMULINK Model

Figure 6 shows the simulation model of proposed pitch angle controller shown in figure 7. There is also a provision formanual control of pitch angle where we can manually input the value of β instead of pitch angle controller.

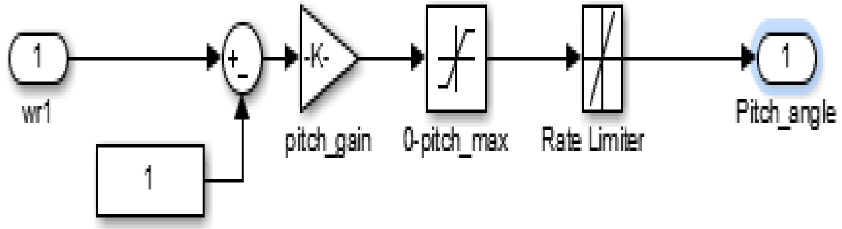

Figure 6 SIMULINK Model of Pitch Angle Control

Maximum Power Point Tracking SIMULINK Model

By using Perturb and Observe based MPPT algorithm shown in figure 5, this SIMULINK block is built. This algorithm is used to switch the IGBT in the block diagram. WECS subsystem shown in below figure 7.

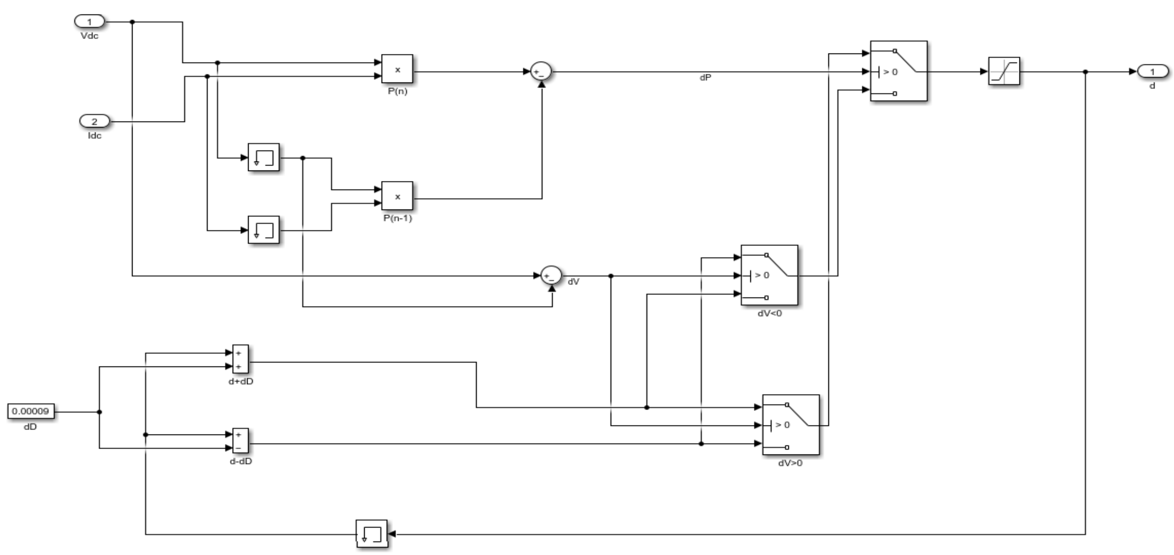

Figure 7 SIMULINK Model (sub system) of MPPT algorithm in WECS

Parking mode: When the wind speed is below cut-in speed, the turbine system creates less power than its internal consumption, so the turbine is maintained in parking mode. Generator-control mode: When the wind speed is above cut-in speed, the turbine system generates more power than its internal consumption, and the operation of the wind turbine may be separated into three modes: generator-control mode, pitch-control mode, and pitch-control mode. The mechanical brake is activated, and the blades are fully pitched out of the wind. In the generator control mode, the blades are pitched with the best angle of attack into the wind when the wind speed is between the cut-in and rated speed. In order to follow the MPP at various wind speeds, the turbine rotates at varied speeds. This is ccomplished by effective control of the generator.

Pitch-control mode: When the wind speed is higher than the rated speed but below the cut-out speed, the captured power is maintained at a constant level by the pitch mechanism to safeguard the turbine from harm while the system creates and sends the rated power to the grid. According to the wind speed, the generator speed is progressively adjusted to pitch the blades out of the wind.

DC-DC Boost Converter

It is used to increase the output power acquired by the PMSG. Normally, the PMSG produces 500V of DC voltage as its output voltage, but for convenience's sake, we often leave it set to produce 100V or 200V. The boost converter then raises this voltage. The Perturb and Observe method in the Wind Energy Conversion System has this restriction: The Boost Converter's capacitance is 6.6094e-04 F, the inductor's value is 4.5573e-05 H, and the load resistance ranges from 13.5 to 54 Ohm when run for an indefinite amount of time.

The Wind Turbine produces mechanical power for specified manual wind speeds in the stair generator; the PMSG uses this energy as input and produces electrical power as output. Then, using a universal diode-bridge, this AC power is transformed into DC. To track maximum power, we now use MPPT. After that, the IGBT switch is turned on using MPPT pulses. We may increase the generated power by employing a boost converter.

Complete Model of the System

By using the above Simulink blocks of Pitch controller and MPPT we construct a complete Simulink model of Wind Energy Conversion System. Fig. 8 shows complete model diagram of proposal implemented in MATLAB/ SIMULINK interface. Fig 8 shows complete model diagram of our proposal implemented in MATLAB/ SIMULINK interface.

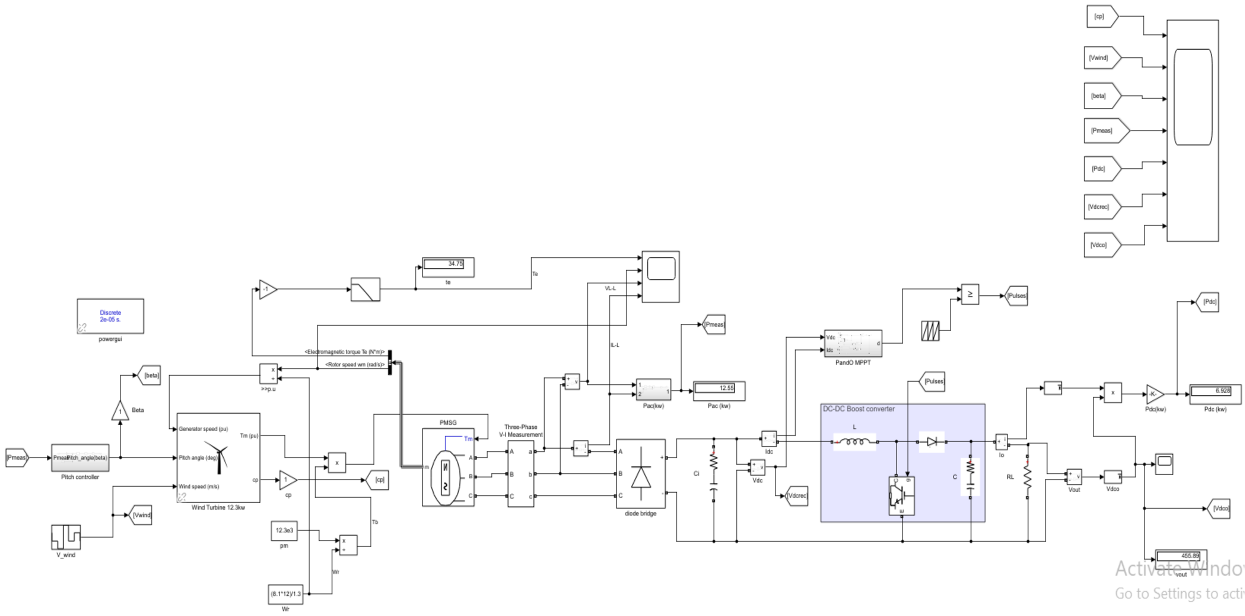

Figure 8 SIMULINK Model of PMSG based WECS

V.SIMULATION RESULTS

The following curves found from Scope1 shows the rotor speed of the generator both in pu value (Fig 9), actual value (Fig 9), the electromagnetic torque (Fig 11) for the base wind speed of 6 m/s. In Fig 9 and Fig 10, we see that the rotor speed initially fluctuates until it comes to stable state after 0.15 sec as expected the starting torque is higher than the running mechanical torque.

The following are the graphs obtained by the proposed model of complete Wind Energy Conversion system

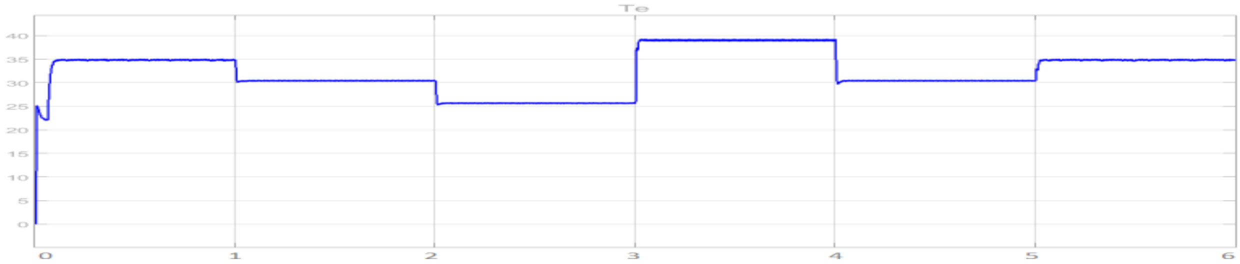

Figure 9 Electrical Torque of PMSG

Figure 10 Rotor Speed of PMSG

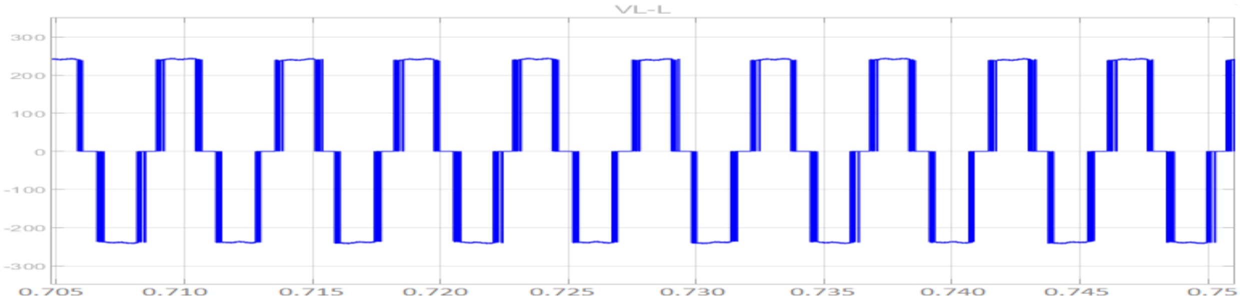

Figure 11 Line Voltage Waveform of PMSG

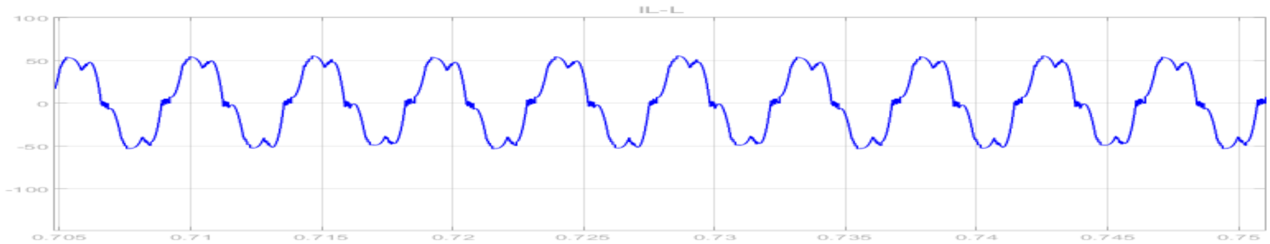

Figure 12 Line Current Waveform of PMSG

Figure 13 Power coefficient of Wind Turbine

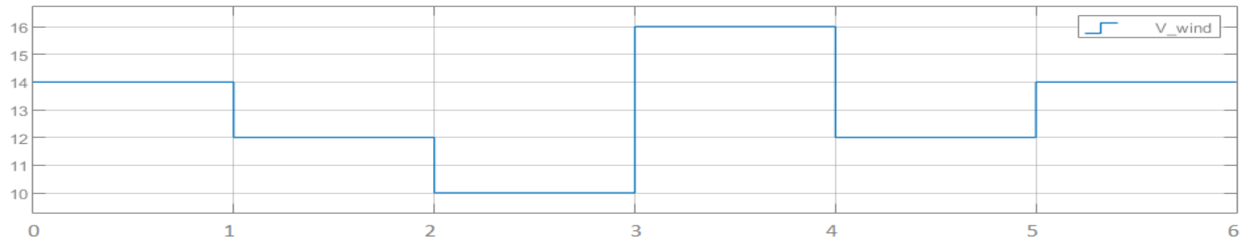

Figure 14 Variable Speeds of Wind Turbine (m/s)

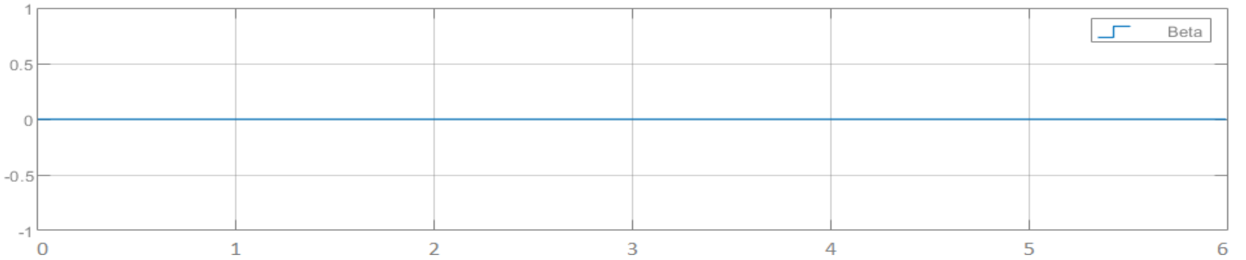

Figure 15 Pitch Angle (Beta)

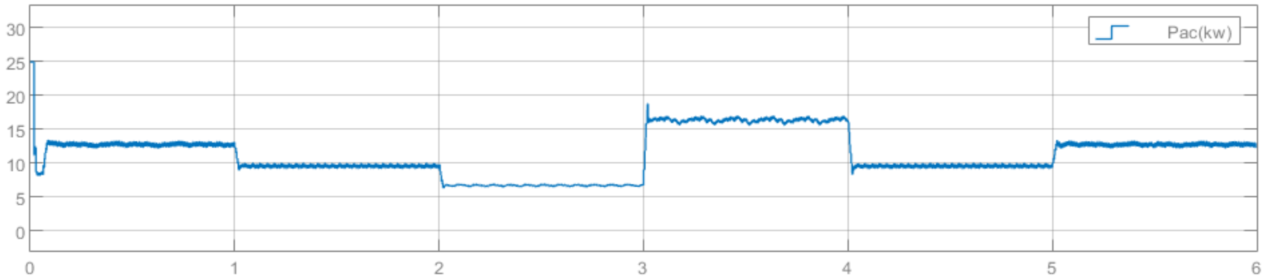

Figure 16 AC power generated by the PMSG

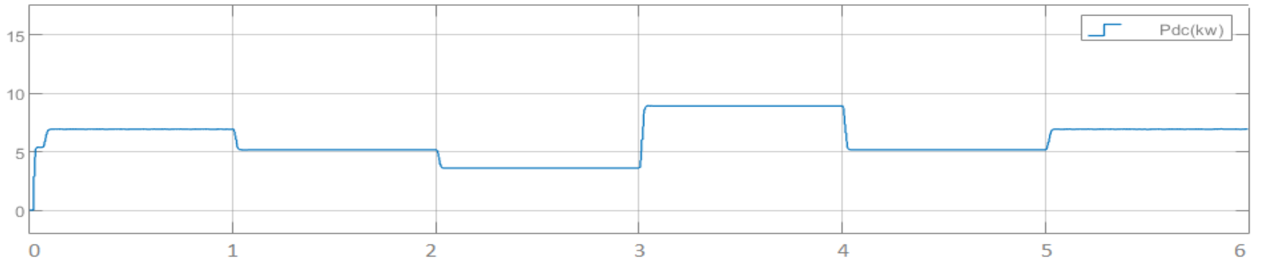

Figure 17 DC Power generated by DC-DC Converter

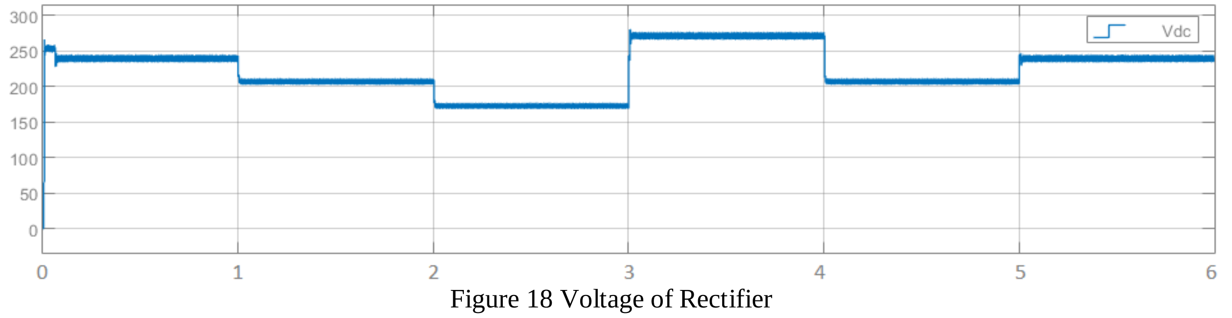

Figure 18 Voltage of Rectifier

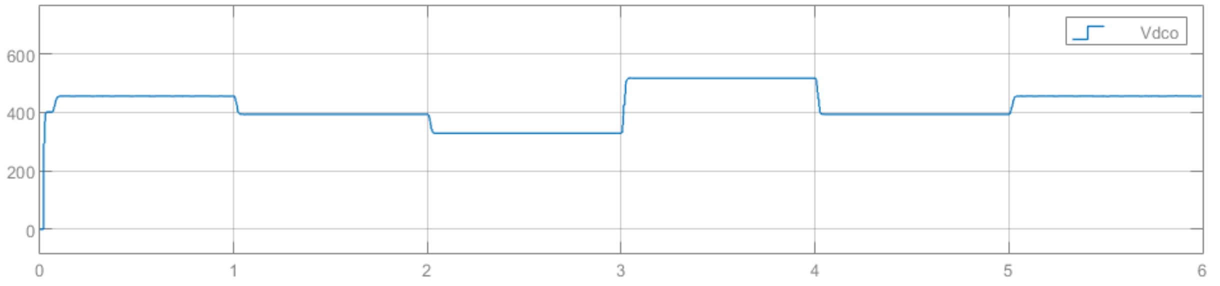

Figure 19 Output Voltage of DC-DC Converter

VI. CONCLUSION

This proposed system presents the pitch angle control of wind turbine systems to maximize power point tracking of wind turbines in nominal wind speed and protect wind turbines from damage for high wind speeds by using PI controller. From the simulation results of WECS it is observed that with pitch control technique the angle between wind direction and turbine blade is zero i.e. $\beta = 0$. The MPPT algorithms track the maximum power for varying wind conditions. Pitch control comes handy when speed increases more than rated speed, it will change pitch angle in such a way that it will rotate and constant speed to generate maximum power. The rotor speed is also controlled by using this pitch angle control.
Future research in MPPT should be in pursuit of more efficient hybrid technique, which is the combination of two or more existing method. As for example, Fuzzy logic control canbe used to find the optimal step size in Perturb and observe (P&O) method. To search maximum power point in the wind farm, multivariable P&O algorithm is very efficient.

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