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A Novel Approach to Maximize Performance and Reliability of PMSG Based Wind Turbine: Bangladesh Perspective

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ABSTRACT: *The goal of this work is to design a PMSG based wind turbine with pitch angle and turbine operational control strategy. This control phenomena helps to run the system with higher efficiency and reliability in turbulent weather conditions. The proposed model considers the wind speed as low value i.e., 6 m/s because of wind flow characteristics in Bangladesh. Though the onshore regions offer speed not more than 4-5 m/s, the value is taken higher than this value as this paper focuses on offshore regions of Bangladesh. The model of proposed system is implemented in MATLAB/SIMULINK software for verifying the described design and control methods. The simulation results proved the sustainability of the model.*

KEYWORDS *-MATLAB/SIMULINK, Operation Control, Permanent Magnet Synchronous Generator (PMSG), Pitch Angle Control, Wind Energy Conversion System (WECS).*

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I INTRODUCTION

Since the dawn of generating electricity people have been continuously utilizing various resources such as coal, oil, gas and other natural sources. Due to constant consumption of the sources, the reduction of storage of these sources now has begun. Also, these phenomena have risen the impact of global warming in a large scale. So, the new era of world is focusing more on renewable energy sources and wind is one of the most effective one. Wind energy is the purest form of renewable energy [1, 2]. The power of wind is now being the subject of research and it has the capability of replacing the conventional energy sources for power production. It will also help to reduce the effect of global warming. Bangladesh is a small country with limited natural resources. Among the several renewable sources, wind is one of the considerable sources for electricity generation. By using the potential of wind effectively, it can reduce the power crisis problem in Bangladesh.

The wind power system exists are of various types. Some of them are connected to the power grid and some are independent of grid system [3]. This nature depends on the purpose of use of wind power.

Wind energy is converted into electrical energy which is commonly known as Wind Energy Conversion System (WECS). WECS consists of Wind turbine, Control Method, Generator and Power converter. There are several types of generator used in the conversion process such as Induction Generator (IG), Double-Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generator (PMSG) [4]. The PMSG is vastly used in WECS because of its high efficiency and controllability [5]. Now-a-days the permanent magnet materials with high coercive field strength, temperature resistance and economical nature makes it highly desirable for wind power generation [3].

The proposed model of PMSG based WECS includes a wind turbine, drive train, PMSG and control mechanism.

The control strategy used in this paper for maximizing the performance and efficiency of a PMSG based WECS is categorized into two parts. Firstly, the blade pitch angle control of the wind turbine. It will enable the turbine to operate in wind speed which is higher than the rated wind speed. Without pitch angle control this would have not been possible. Secondly, there is a method for turbine operation control in such a range of wind speed that whenever the wind speed exceeds a certain upper limit the turbine will shut down. Otherwise the generator will lost control on its rotor speed hence will create several damage to the entire system.

A simulation based study is always necessary for better understanding of a topic before implementing it practically. This paper uses MATLAB/SIMULINK Software for designing the simulation model and also analyze the overall performance of proposed approach.

II MATHEMATICAL MODEL

The block diagram of the proposed model is shown in Fig 1. In this section the mathematical model of these blocks has been discussed.

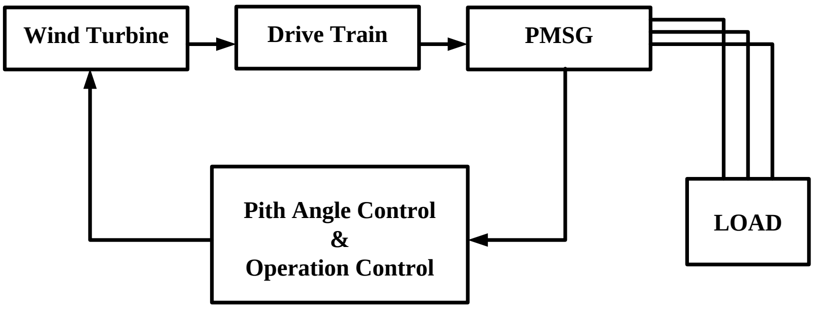

Fig 1. Block Diagram of PMSG based WECS

1.1 Wind Turbine Model

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

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

$m = \rho v S$ (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:

$P_w = E_c = \frac{1}{2}mv^2 = \frac{1}{2}\rho S v^3$ (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:

$C_p = \frac{P_m}{P_w}; C_p < 1$ (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 power extracted 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:

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

$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$ (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 2 for different values of β. The maximum value of C_p is attained for $\beta = 0\ and \lambda = 8.1$ [3].

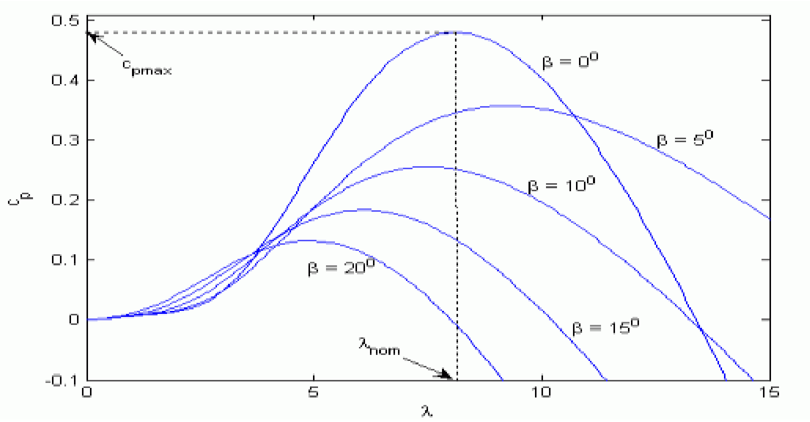

Fig 2. C_p - λ Curve

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

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

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

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

1.2 Drive Train Model

Drive train is considered as a mechanical system of a wind turbine comprising of turbine, generator and gear box [3]. The gear box converts the low speed of wind turbine into the desired speed of generator turbine. The mathematical model of two-mass drive train is expressed as follows[8] :

$$2H_t\frac{dw_t}{dt} = T_m - T_s \quad (9)$$

$$\frac{1}{w_{ebs}}\frac{d\theta_{sta}}{dt} = w_t - w_r \quad (10)$$

$$T_s = K_{ss}\theta_{sta} + D_t\frac{d\theta_{sta}}{dt} \quad (11)$$

where,

H_t = Inertia constant of the turbine
θ_{sta} = Shaft twist angle
w_t = Angular speed of the wind turbine
w_r = Rotor speed of generator
w_{ebs} = Electrical base speed
T_s = Shaft torque
K_{ss} = Shaft stiffness
D_t = Damping Coefficient

1.3 Generator Model

Permanent magnets are broadly used in synchronous machines with the advantages of simple rotor design without field windings, slip-rings and excitation system. The PMSG is becoming very popular for its compact size, high power density, high reliability and robustness. As our study is based on offshore wind power installation, the gearless PMSG generator becomes more suitable than geared double-fed induction generator or induction generator [3]. The equivalent circuit of PMSG based WECS is shown in Fig 3 [9] . This model is created in *d-q* synchronous reference frame.

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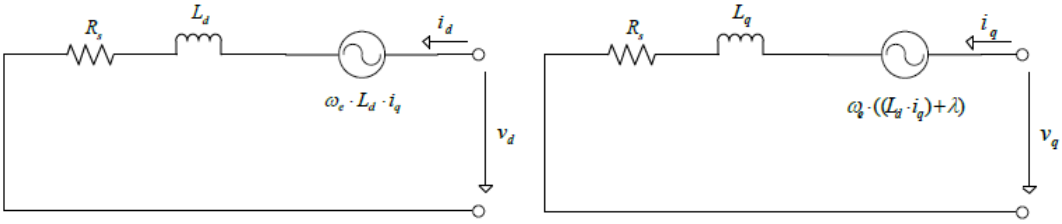

(a) *d-axis* equivalent circuit **(b) *q-axis* equivalent circuit**

Fig 3. Equivalent Circuit of PMSG in *d-q* reference frame

The voltage equations of PMSG can be written as [10] :

$$\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p w_r i_q \quad (12)$$

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p w_r i_d - \frac{\lambda p w_r}{L_q} \quad (13)$$

The electromagnetic torque is written by the following equation [6] :

$$T_e = 1.5\rho[\lambda i_q + (L_d - L_q) i_d i_q \quad (14)$$

where,
L_d = d − axis inductance
L_q = q − axis inductance
R = resistance of the stator winding
i_d = d − axis current
i_q = q − axis current
v_d = d − axis voltage
v_q = q − axis voltage
w_r = angular velocity of rotor
λ = amplitude of flux induced
p = number of pole pairs

The dynamic equations are given by [11],

$$\frac{d}{dt} w_r = \frac{1}{J}(T_e - F w_r - T_m) \quad (15)$$

$$\frac{d}{dt} \theta = w_r \quad (16)$$

where,
J = inertia of rotor
F = friction of rotor
θ = rotor angular

III CONTROL METHOD

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

3.1. Pitch Angle Control

This control strategy is applied to control the mechanical power input at the nominal value and also prevent the electrical power output becoming so high. It is usually active in the condition of high wind speed. In those situations, the rotor speed can't be controlled by increasing the generated power because this would make the overloading of the generator. That's why the blade pitch angle is modified for limiting the aerodynamic efficiency of the rotor which helps to control the rotor speed to become high. In this criterion, the turbine blades are turned away from the wind for minimum power extraction. Whenever there is an unbalance between power output and input wind energy the pitch angle control method must be implemented in order to keep the balance between mechanical input and electrical output. After the clearance of fault, the pitch angle again retains its optimum value for maximum power output [3]. Then again the turbine blades are turned with the wind for maximum power extraction.

As we discussed earlier, power coefficient, C_p is function of tip-speed, λ and blade pitch angle, β. So modifying the β would also modify the C_p and therefore it will help to control the rotational speed as well as the generator output. We know that the maximum value of C_p is attained when blade pitch angle, β is zero which defines the condition when pitch angle control is not required which means the turbine is operating at the nominal wind speed. But when the wind speed exceeds the rated wind speed by some extent where the rotor speed exceeds its rated value then this control method must be applied. Then the value of pitch angle β will be increased by some mechanism to decrease the value of C_p to maintain the balance between input and output power. In this paper, Proportional-Integral (PI) control method has been discussed for pitch angle control.

This method of pitch angle control uses the difference rotor speed and a reference value of rotor speed to control the pitch angle. A reference value is set to compare the given input rotor speed. Whenever the rotor speed exceeds the reference value there is a difference in signals found which causes the controller to operate. This error signal is followed by the controller block, angle limit and rate limiter block which is shown in Fig 4 [3].

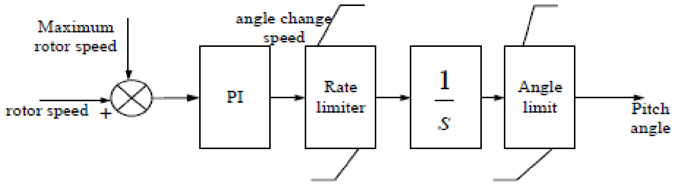

Fig 4. Pitch Angle Controller

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.

3.2. Operation Control

Though we use pitch angle controller to control the turbine in windy condition, there must be a method for shutting down the complete operation in the case of extension of cut-off speed. Then the turbine must not operate at all otherwise it will create a massive disaster of the whole system. We have taken the cut-in speed as 3 m/s i.e., the speed at which the turbine will start to generate reasonable electrical power. The running speed is defined in the range of (3-11) m/s. After the wind speed reaches 11 m/s the turbine must shut down its operation. So, 11 m/s is the cut-off speed defined in our proposed model. This control strategy is implemented in SIMULINK by using User-defined MATLAB Function block where the certain criteria are achieved. In this block we defined the turbine to operate under (3-11) m/s. If the wind speed is lower than 3 m/s or greater than 11 m/s the turbine will not produce any mechanical torque i.e., $T_m = 0$. Therefore, there will be no output power from the generator.

IV SIMULATION MODEL

The mathematical model of all necessary equipments 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 equipments are successfully modeled with respective parameters. After that the performance of the proposed model was analyzed.

4.1. Wind Turbine SIMULINK Model

Fig 5 shows the wind turbine model implemented in MATLAB/Simulink interface.

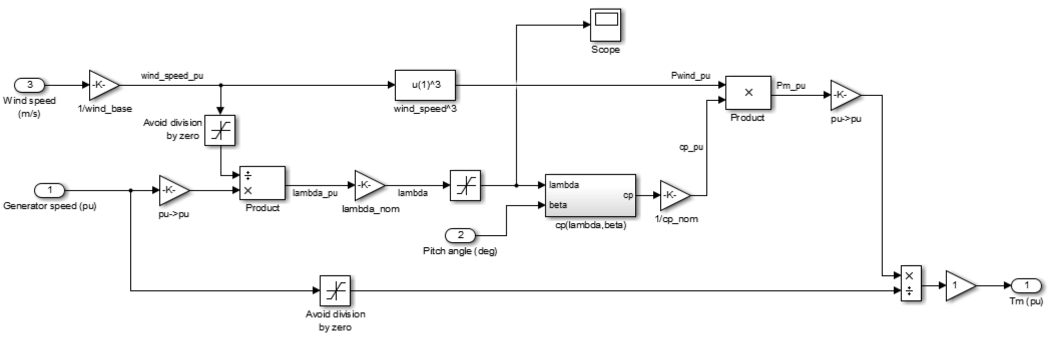

Fig 5. SIMULINK Model of Wind Turbine

The Specifications used for these model are listed in the Table I [12].

Table I: Wind Turbine Parameters

Parameter	Value
Mechanical Output Power	10 KW or 10e3 W
Base Power of the electrical generator	10e3/0.9
Base Wind Speed	6 m/s
Maximum Power at base wind speed	0.8
Base Rotational Speed in pu	1

4.2. Drive Train SIMULINK Model

Fig 6 shows the two-mass drive train model implemented in MATLAB/SIMULINK.

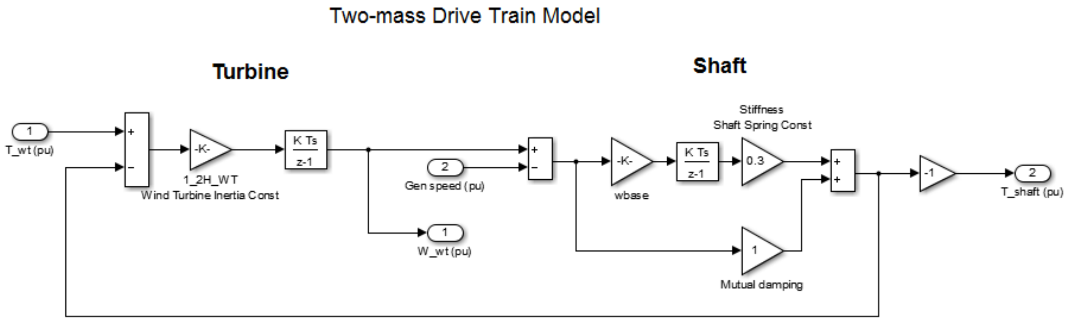

Fig 6. SIMULINK Model of two-mass drive train

The Specifications used for this model are listed in the Table II.

Table II: Drive Train Parameters

Parameter	Value
Inertia at the turbine	4
Shaft Stiffness	0.3
Damping Coefficient	1

4.3. PMSG SIMULINK MODEL

The Permanent Magnet Synchronous Generator (PMSG) block is found in the Simulink Library. The specifications used in this PMSG model are listed in the Table III [13].

Table III: Generator Parameters

Parameter	Value
Rating	10 KW
Base Rotor Speed	155 rad/sec
Stator phase resistance	0.425 ohm
Armature inductance	0.000835 H
Flux linkage	0.53333
Number of Poles pair	5

4.4. Pitch Angle Control SIMULINK Model

Fig 7 shows the simulation model of proposed pitch angle controller. There is also a provision for manual control of pitch angle where we can manually input the value of β instead of pitch angle controller.

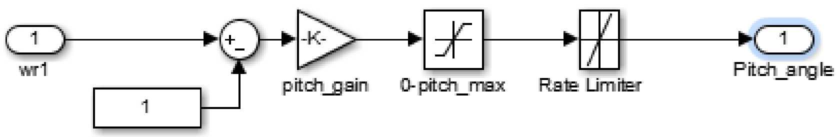

Fig 7. SIMULINK Model of Pitch Angle Controller

4.5. Complete Model of the System

Fig 8 shows complete model diagram of our proposal implemented in MATLAB/ SIMULINK interface.

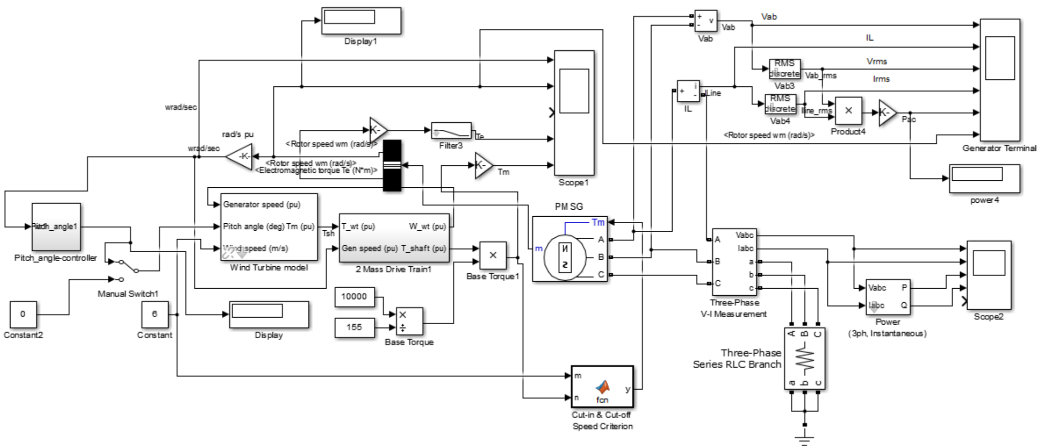

Fig 8. SIMULINK Model of PMSG based WECS

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 10), the electromagnetic torque (Fig 11) and mechanical torque (Fig 12) 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. In Fig 11 and Fig 12, after some fluctuations both electromagnetic and mechanical torque become stable after 0.14 sec. As expected the starting torque is higher than the running mechanical torque.

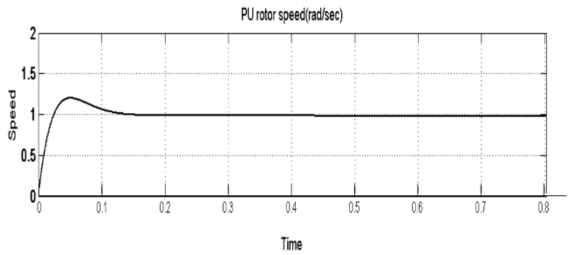

Fig 9. Rotor Speed in pu value

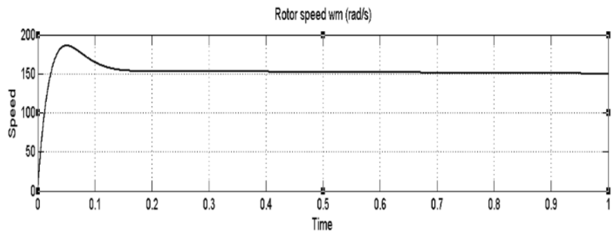

Fig 10. Rotor Speed in actual value

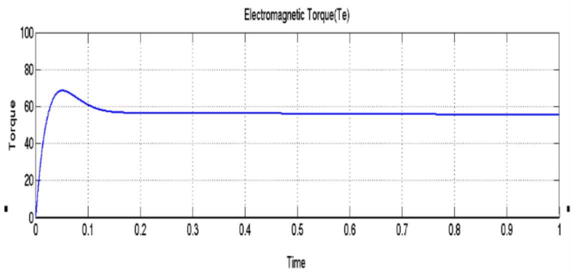

Fig 11. Electromagnetic Torque, T_e

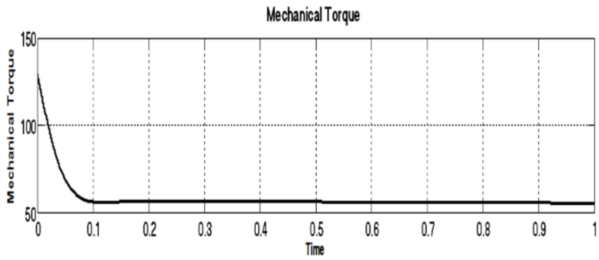

Fig 12. Mechanical Torque, T_m

The following waveforms found from Scope2 displays the Phase Voltage (Fig 13), Line Current (Fig 14), RMS Phase Voltage (Fig 15), RMS Line Current (Fig 16), AC power (Fig 17). From Fig 17, the time taken for staring the machine initially produces no power until 0.04 s. Then the power rises above the rated value and after 0.25 s it comes to the steady-state condition.

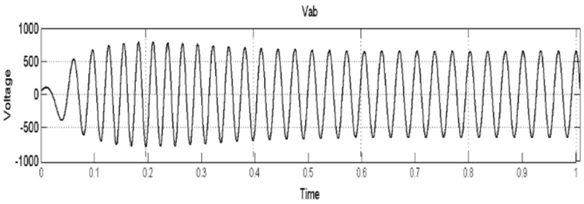

Fig 13. Phase Voltage

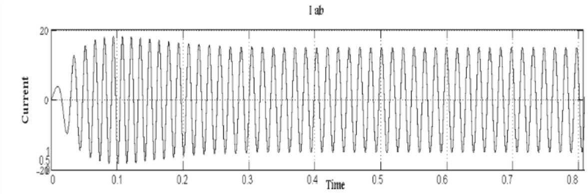

Fig 14. Line Current

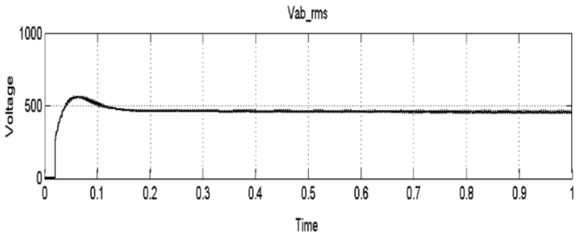

Fig 15. RMS Phase Voltage

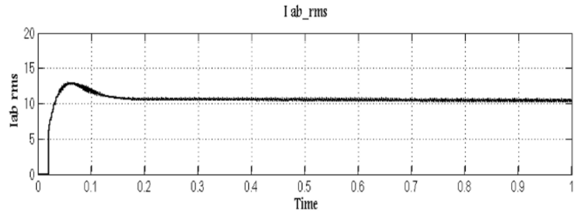

Fig 16. RMS Line Current

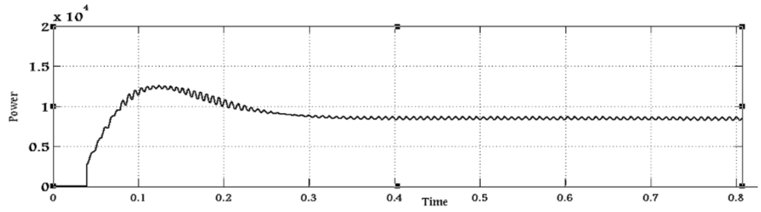

Fig 17. AC Power Output

Three-phase voltage, current, active power and reactive power is shown in Fig 18, Fig 19, Fig 20 and Fig 21 respectively.

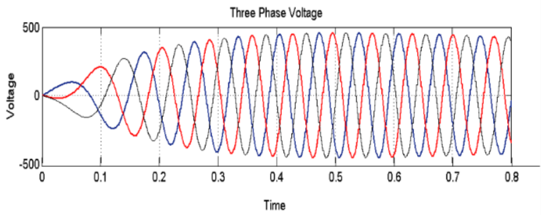

Fig 18. Three-phase Voltage

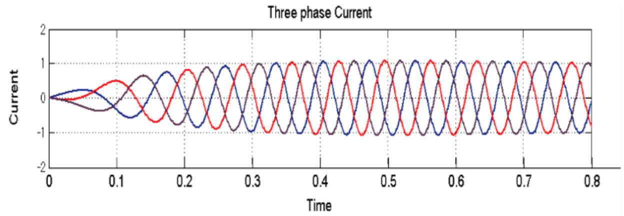

Fig 19. Three-phase Current

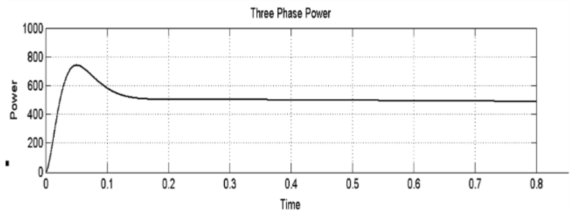

Fig 20. Three-phase Active Power

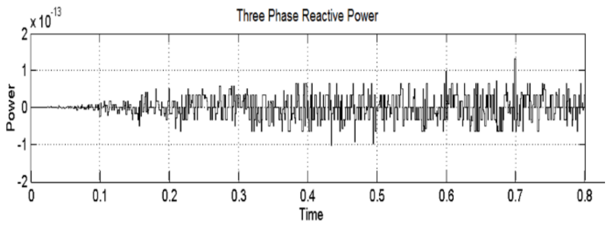

Fig 21. Three-phase Reactive Power

The following tables shows the variation of rotor speed and output power with respect to the variation of wind speed with Pitch angle control (Table IV) and without Pitch angle control (Table V). From these tables, we see that when we will use the pitch angle control strategy the wind turbine will be able to run up to 11 m/s. In that case the rotor speed and power remains under controllable range. If the pitch angle controller is not used then the turbine is unable to run at more than 8 m/s wind speed. So the proposed control approach helps the system to run with extended wind speeds (8-11 m/s).

Table IV: Variation of Rotor Speed, Output Power and Pitch angle with respect to Wind Speed with Pitch Control

Wind Speed (m/s)	Rotor Speed (rad/s)	Power (w)	Pitch Angle (rad)
2	0	0	0
3	137.6	7104	0
4	140.7	7267	0
5	145.7	8063	0
6	151.5	8130	0
7	155.4	8789	1.198
8	156.7	8882	5.474
9	159.4	9197	9.756
10	162.2	9697	9.756
11	164.2	9570	9.757
12	0	0	0

Table V: Variation of Rotor Speed, Output Power and Pitch angle with respect to Wind Speed without Pitch Control

Wind Speed (m/s)	Rotor Speed (rad/s)	Power (w)	Pitch Angle (rad)
2	0	0	0
3	137.5	6700	0
4	140.6	7553	0
5	145.7	8084	0
6	151.6	8383	0
7	157.7	9029	0
8	163.2	9567	0
9	167.8	9961	0
10	171.2	11200	0
11	173.2	10950	0

As soon as the wind speed exceeds its base value (6 m/s), the pitch angle, β starts increasing so that the power coefficient, C_p decreases and keep the rotor speed and output power in desired limit. But after crossing the wind speed of 11 m/s the rotor speed become so high that the turbine must be shut down in order to prevent further damage. That's why the rotor speed as well as the output power becomes zero at wind speed more than 11 m/s shown also in the Table IV. This operation control of wind turbine is graphically represented in Fig 22. From this figure, we can see that how much of rotor speed we can control by using pitch angle controller.

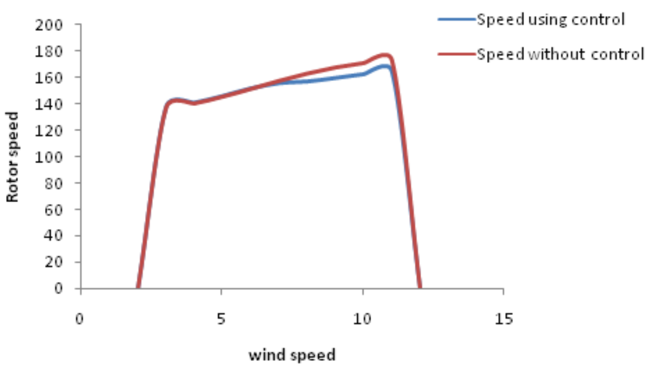

Fig 22. Rotor Speed With and Without Pitch Angle Control

VI CONCLUSION

This paper has established a complete model of PMSG based wind turbine by considering the weather conditions in Bangladesh. There are two control strategies named pitch angle control and operation control of turbine explained here. The results shows that by applying these control methods, system efficiency and reliability can be achieved to a good extent.

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