Pitch Angle Control for Optimal Power of Horizontal Axis Variable Speed Wind Turbines Using Fuzzy Tuned PID Controller

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Abstract. Energy is the firewood for development of a country. An increased access to electricity boosts chances for industrial development and improves quality of health and education. Renewable energies have a large potential to maintain sustainable energy. Wind turbine is a system which is used to change kinetic energy that exists in airstream into Mechanical Energy. The system is complex, unstable and highly nonlinear involving some random wind speed. Because of this reason, the output power from the system is fluctuated and also the mechanical part of the turbine become structurally overloaded as well as damage itself physically at strong wind condition. Pitch control is the most popular and extensively used practical technique to Control the output Power especially, when the wind velocity is beyond the rated value. It is considered as the most competent and common power regulation method. This paper suggests optimal power control method through pitch angle control of Horizontal-axis variable speed wind turbine system to extract constant energy between rated and maximum wind speed using a Fuzzy tuned PID controller. The Performance of the proposed controller is evaluated by simulation results for 1.5 MW Wind Turbine using MATLAB ™/SIMULINK. After implementing and validating, the results obtained shows that the performance of the proposed controller was much better than the conventional PID and Fuzzy controllers.

Keywords: Horizontal-axis variable speed wind turbine · PMSG · Pitch angle and Fuzzy-PID controller

1 Introduction

Wind is one of the most gifted renewable energy sources for generating electricity due to its cost attractiveness compared with other types of energy resources [1]. It is Environment Friendly. According to Global Wind Energy data, Currently, around 743 GW of wind power capacity worldwide, this helping us to remove over 1.1 billion tonnes of CO2 worldwide. And also, the installed capacity of wind power is growing at an average rate of 53% year over the year 2020 [3].

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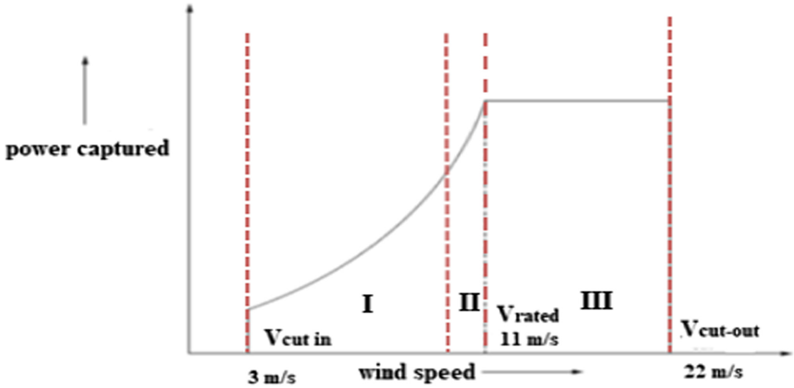

Fig. 1. Power Captured vs. wind speed characteristic

In recent years, Pitch adjusted VSWT have become the dominating type of yearly installed wind turbines. The process and control mechanisms of variable speed wind turbine differs along the wind speed range. Figure 1 shows a characteristic of Power captured to wind speed curve. In Region one, the system is in partial load and the objective is to maximize the captured Energy. The change between low and high wind speed Region is exposed by region two. The 3rd region is named full load region. In this region, the objective is to control the turbine at its rated power and to keep the turbine components within safety limits. Unceasing turning of turbine higher than the rated speed will yield high aerodynamic torque such that the mechanical structure of turbine may get hurtle or damaged. To overcome this problem and limit the aerodynamic power captured in region three, many pitch angle control approaches can be proposed. Practically, PID based pitch angle controllers are often used for power regulation.

In this paper work, a Fuzzy tuned PID method is suggested for optimal power condition through pitch control of wind power system under various wind speed conditions.

2 Mathematical Modeling

2.1 Aerodynamic Model

In this system, the wind turbine blades structurally designed in different shape and number. It extracts the kinetic Energy in the wind and converts in to Mechanical Energy.

In Fig. 2, the mass flow rate is constant for upstream, on the rotor and downstream of the blade. Mathematically expressed as follows:

$$A_0 V_0 = A_1 V_1 = A_2 V_2 \quad (1)$$

Then,

$$m = PA_0V_0 = PA_1V_1 \tag{2}$$

Where m is mass flow rate, p is pressure difference, A is area and V is velocity of air.

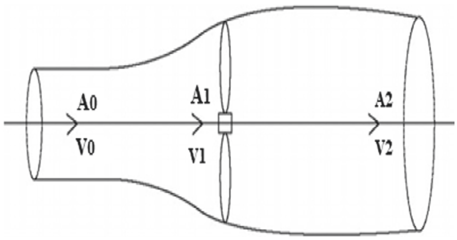

Fig. 2. Airstreams around a turbine [5, 20]

Assume, all the air particles are moving at the same direction and speed before bear upon the rotor blades of the wind turbine.

The kinetic energy stored in the wind can be stated as follows:

$$E = \frac{1}{2}mv^2 \tag{3}$$

But, the total mass of the particles expressed as follows:

$$m = \rho Avt = \rho\pi R^2 vt \tag{4}$$

Sub. (4) into (3) then, the kinetic energy become:

$$E = \frac{1}{2}\rho\pi R^2 v^3 t \tag{5}$$

2.2 Captured Power by Wind Turbines

The harvested Power in the moving air is proportional to the cube of the wind Velocity:

$$P_w = \frac{dE}{dt} = \frac{1}{2}mv2 = \frac{1}{2}\rho Av3 = \frac{1}{2}\rho\pi R^2 v^3 \tag{6}$$

According to Betz limit, a wind turbine can extract maximum 59.3% of power stored in wind energy [13]. This fraction is defined by the power coefficient of the turbine, (Cp). Consequently, the Mechanical power is mathematically expressed by

$$P_m = P_w c_p(\lambda, \beta) \tag{7}$$

Substitute (6) into (7), then we have

$$P_m = \frac{1}{2}\rho A v^3 c_p(\lambda, \beta) = \frac{1}{2}\rho \pi R^2 v^3 c_p(\lambda, \beta) \tag{8}$$

The rotor torque T_a, can be computed as:

$$\mathrm{T}_a = \frac{P_m}{\omega_m} \tag{9}$$

Substitute (8) into (9), then we have

$$\mathrm{T}_a = \frac{\frac{1}{2}\rho \pi R^2 v^3 c_p(\lambda, \beta)}{\omega_m} \tag{10}$$

Then,

$$\lambda = \frac{\omega_m R}{V} \tag{11}$$

Now, C_p can be defined as a function of λ, β:

$$C_p(\lambda, \beta) = c_1\left(c_2 \frac{1}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{12}$$

Where:

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

the values of a wind turbine constants (c_1–c_6) depend on the design of the wind turbine. For this work, we take the following value $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = -21$, $c_6 = 0.0068$ [8]. This power coefficient governs the efficiency of the turbine to convert the kinetic energy contained in the wind to Mechanical Energy. Figure 3 shows the relationship between C_p, λ and β.

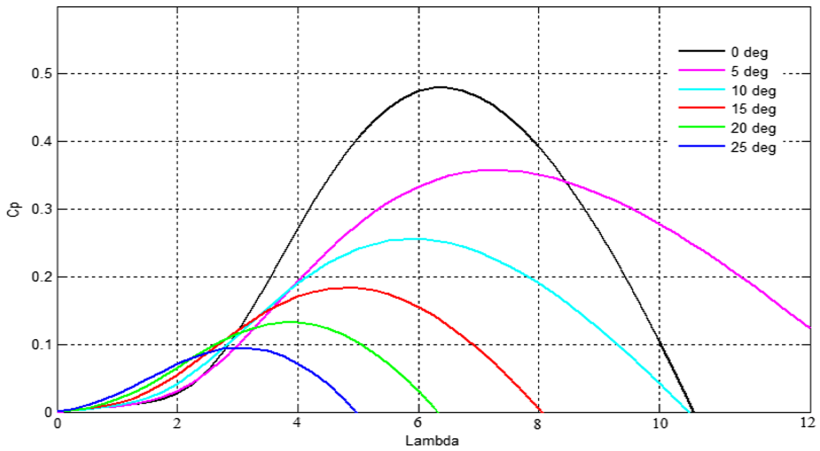

Fig. 3. Cp Vs TSR at different β angles

2.3 Drive Train

The fundamental dynamic equation is described by:

$$\frac{d(w_r)}{dt} = \frac{1}{J}(T_m - Bm * w_r - T_e) \tag{13}$$

$$\frac{d(\theta)}{dt} = w_r \tag{14}$$

Where J is Combined inertia of rotor & generator, Bm is combined viscous friction of rotor & generator, θ is angular position of rotor and T_m is mechanical torque (Table 1).

Table 1. Wind turbine data set

WTG Version	**GW 1.5/77**
Wind turbine nominal power (MW)	1.5
Number of wind turbines	34
Wind turbine inertia constant (H(s))	4.32
Rotor diameter (m)	77
Wind turbine rotor radius(m)	37.3
Tower height(m)	65
Cut-in wind speed	3 m/s
Rated wind speed	11m/s
Optimal speed ratio (λ_{opt})	6.14
Maximum Power coefficient ($C_{p,max}$)	0.45
Cut-out wind speed	22 m/s
Swept area	4649m^2
Number of blades	3
Power control	Collective pitch control/rotor speed control

2.4 Permanent Magnet Synchronous Generator

The mathematical model of a PMSG was developed both in three phase and two reference frames (dq synchronously rotating reference frame) by using Park and clark transformation techniques. Some parameters of the generators like magnetic saturation, eddy current and hysteresis effect, damping effect are neglected [4, 6] (Fig. 4).

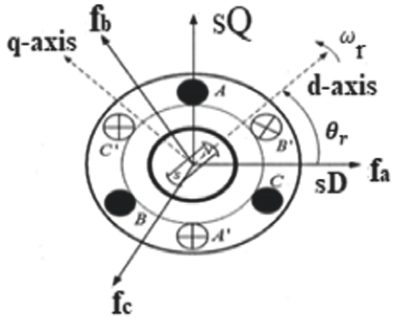

Fig. 4. Cross-section view of the PMSM [6]

2.4.1 Modeling PMSM in the Dq-Axes Synchronously Rotating Reference Frame

In the 3-phase systems like PMSMs, the phase quantities are time varying quantities. This makes our system complex. So, by applying Park's transformation, we can transform from 3-phase in to dq synchronously rotating reference frame.

$$\begin{bmatrix} X_{ds} \\ X_{qs} \\ X_{0s} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_r) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ -\sin(\theta_r) & -\sin\left(\theta_r - \frac{2\pi}{3}\right) & -\sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} X_{as} \\ X_{bs} \\ X_{cs} \end{bmatrix} \tag{15}$$

In Eq. (15), $X_{(abc)s}$ represent stator voltages, currents or flux linkages of the AC machines. Since, the system is under balanced conditions, $X_{0s} = 0$, the voltage equation of the PMSM in the dq-axis reference frame become like this [6]:

$$V_{ds} = R_s i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_r i_{qs} L_q \tag{16}$$

$$V_{qs} = R_s i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_r i_{ds} L_d + \omega_r \lambda_r \tag{17}$$

where V_{ds}, V_{qs}, i_{ds}, and i_{qs}, are the instantaneous stator voltages and current in the dq-axis reference frame respectively. Whereas, L_d and L_q are the d-axis and q-axis inductances respectively.

2.4.2 Power and Torque Analysis

The power in dq-axis is written as follows:

$$P_{dq} = \frac{3}{2}\left(i_{qs}V_{ds} + i_{ds}V_{qs}\right) \tag{18}$$

The torque produced by the PMSM (Table 2)

$$\mathrm{T}_e = \frac{3}{2}P\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) \tag{19}$$

$$\mathrm{T}_e = \frac{3}{2}P\left(\lambda_r i_{qs} - \left(L_d - L_q\right)i_{ds}i_{qr}\right)$$ Where, P is number of poles

Table 2. Generator data set

Generator Type	**PMSG, 1.5 MW, 620 V, 12.7 Hz, multi - pole (non-salient pole)**
Rated Mechanical Power	1.5MW
Rated Apparent Power	1.6 MVA
Generator inertia	35000(J(kg.m²))
Rated Power Factor	0. 97
Speed Range	9-17.3 rpm
Rated rotor speed	17.3
Shaft stiffness (pu)	0.3
Number of Pole Pairs	44
Rated Rotor Flux Linkage	1.48
Stator Winding Resistance	0.006Ω
d axis Synchronous Inductance	0.395mH
q axis Synchronous Inductance	0.395mH
Rated current	680 A
Static friction	0.01
Viscous damping	1.5

2.5 Actuator

The Actuators model defines the dynamic behavior between a pitch demand ($\boldsymbol{\beta_d}$) from the pitch controller and the pitch angle ($\boldsymbol{\beta}$). This is written mathematically as follows:

$$\frac{\mathrm{d}\beta}{\mathrm{dt}} = \frac{\beta_\mathrm{d} - \beta}{\tau_\beta} \tag{20}$$

By applying Laplace transforms, we get

$$\beta_d(s) = \tau_\beta s \beta(s) + \beta(s) = \beta(s)(\tau_\beta s + 1) \tag{21}$$

Then, the transfer function of the actuator is

$$\frac{\beta(s)}{\beta_d(s)} = \frac{1}{(\tau_\beta s + 1)} \tag{22}$$

$$\frac{\beta(s)}{\beta_d(s)} = \frac{1}{(0.01s + 1)} \tag{23}$$

Many authors used different values of time constant τ_β based on their logic. But, for this work we used small amount of time constant (τ_β = 0.01) to increase the control effort.

3 Controller Design

3.1 Conventional Controller (PID)

Correcting the pitch angle of the blades as shown in Fig. 5, brings an operative means of regulations (limiting the operation of the turbine in strong wind velocity). In conventional system, PID controller with pitch servos are in use to set the blades into the ideal position. In normal operation, blade pitch adjustments with rotational speeds of approximately 5–10°/s are expected [23]. The conventional blade pitch angle control approaches are shown in Fig. 5.

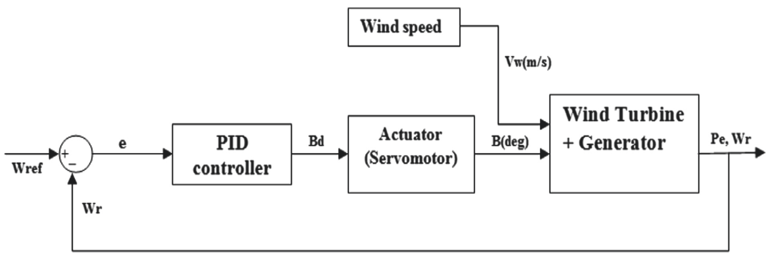

Fig. 5. Wind energy conversion system with PID controller

3.2 Fuzzy Logic Controller

Complex physical systems are very difficult to model by an accurate and precise mathematical equation. This is due to the complication of the system structure, uncertainty, nonlinearity, randomness, etc. Fuzzy logic control solves non-linear systems problem by requiring little prerequisite knowledge of inputs and crisp mathematical description of the system. In case of wind turbine, the wind velocity is a changing quantity this makes the system output unpredictable and nonlinear (Fig. 6, Table 3).

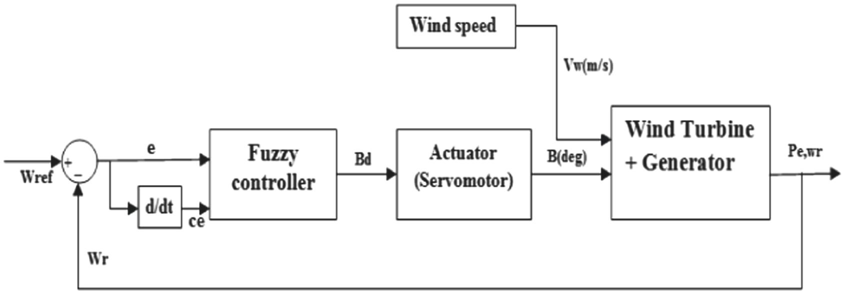

Fig. 6. Wind energy conversion system with Fuzzy controller

Table 3. Fuzzy logic controller rule base.

Bd		Error					
		nvb	nb	nm	ns	ze	p
Change in error	nb	PVL	PL	PVB	PB	ZE	ZE
	ns	PVL	PVVB	PB	PS	ZE	ZE
	ze	PL	PVB	PB	PS	ZE	ZE
	ps	PVL	PVVB	PB	PS	ZE	ZE
	pb	PVL	PL	PVB	PB	ZE	ZE

3.3 Fuzzy Tuned PID Controller

Conventional PID controller is the simplest and robust controller but its function is limited based on the application area (plant). In this work, PID itself can't control the overall system because the system is highly nonlinear. Which means the gains of the PID controller are not regularly tuned for the nonlinear plant with random parameter variations. In addition to this, PID controller is offline controller. To solve this problem, we have used Fuzzy tuned PID controller which can able to tune automatically the gains (K_p, K_I, K_D) of the PID controller with the supervision of fuzzy controller online over wider range of operating conditions [18, 19] (Fig. 7).

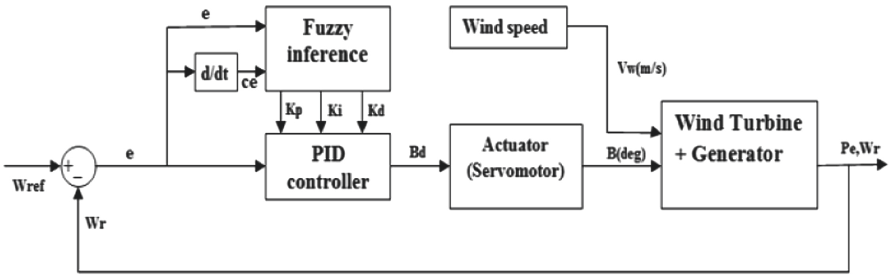

Fig. 7. Wind energy conversion system with Fuzzy Tuned PID controller

The rule base for each parameter have been carried out & shown in the tables below (Tables 4, 5 and 6).

Table 4. Rule base for Kp.

K_p		error							
		NL	NVVB	NVB	NB	NM	NS	ZE	PO
Change in error	NB	NEL	NVVL	NVVL	NVVL	NVVB	NVVB	ZE	ZE
	NS	NVVL	NVVL	NVVL	NVL	NVVB	NVB	ZE	ZE
	ZE	NVVL	NVL	NVL	NVL	NVB	NVB	ZE	ZE
	PS	NVL	NVL	NVL	NL	NVB	NB	ZE	ZE
	PB	NVL	NL	NL	NL	NB	NB	ZE	ZE

Table 5. Rule base for Ki.

K_i		error							
		NL	NVVB	NVB	NB	NM	NS	ZE	PO
Change in error	NB	NL	NL	NVB	NVB	NB	NB	ZE	ZE
	NS	NL	NVB	NVB	NB	NB	NM	ZE	ZE
	ZE	NVB	NVB	NB	NB	NM	NS	ZE	ZE
	PS	NVB	NB	NB	NM	NM	NS	ZE	ZE
	PB	NB	NB	NM	NS	NS	ZE	ZE	ZE

Table 6. Rule Base for Kd.

K_d		error							
		NL	NVVB	NVB	NB	NM	NS	ZE	PO
Change in error	NB	PM	PS	PS	ZE	NS	NS	ZE	ZE
	NS	PS	PS	ZE	NS	NS	NM	ZE	ZE
	ZE	PS	ZE	NS	NS	NM	NM	ZE	ZE
	PS	ZE	NS	NS	NM	NM	NB	ZE	ZE
	PB	NS	NS	NM	NM	NB	NB	ZE	ZE

4 Result and Discussion

4.1 Uncontrolled Wind Turbine

In Fig. 8, the dynamic performances of the system without controller have been study under variable wind speed and uniform wind direction to compare the validity of the proposed method.

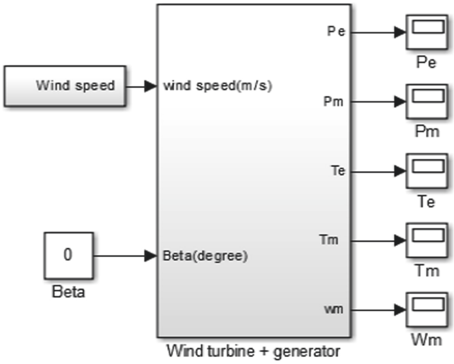

Fig. 8. Simulation diagram of uncontrolled system under different wind speed

The simulation result in Fig. 9 Shows as, the extracted power mainly depends on the magnitude of the velocity of the wind. Once the wind velocity is goes beyond rated wind speed, the torque and captured power go up above rated valued. This leads very big fatigue loads to the components of the turbine and this results a short fatigue life.

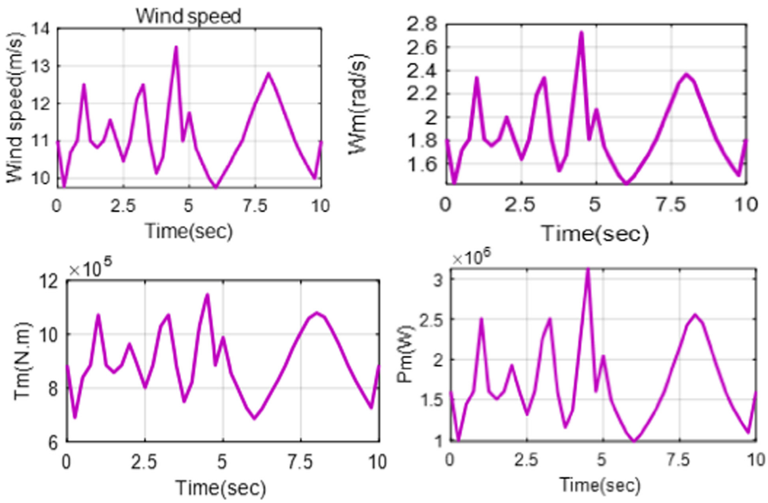

Fig. 9. Uncontrolled system response under variable wind speed

4.2 The Conventional PID Controller of Wind Turbine

In this simulation diagram, the gains of the PID controller are auto tuned based on the inflow wind speed velocity (Fig. 10).

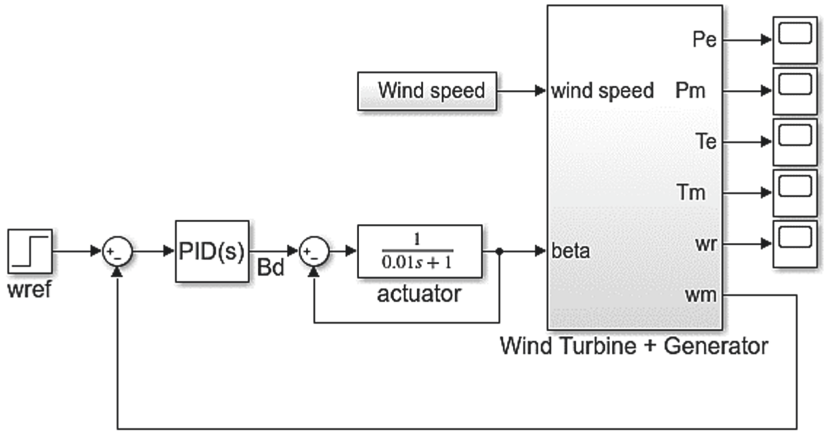

Fig. 10. Simulation diagram of overall system with PID controller

The results obtained from the simulation are depicted in Fig. 11 below. System with PID controller perform batter compared with uncontrolled system. However, still there is power and torque above rated values. This means there is power and torque ripples. This makes the system under pressure and give an impact on wind turbine system.

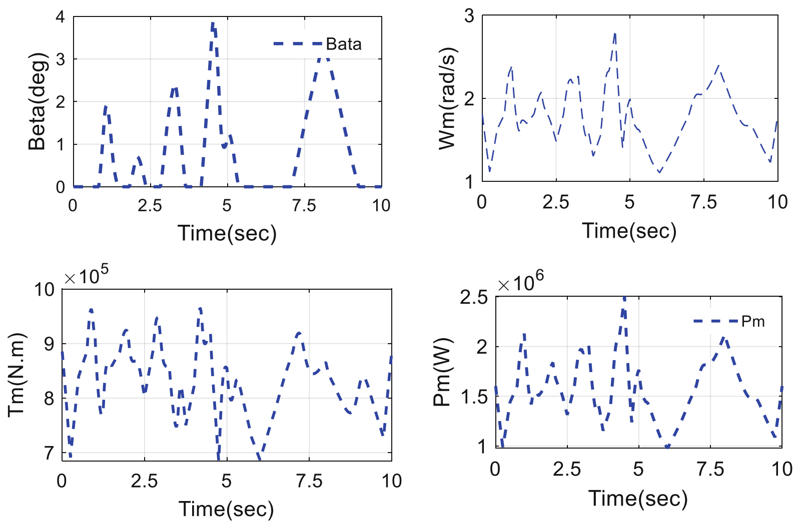

Fig. 11. Simulation results of overall system using PID controller

4.3 The Fuzzy Controller Design of Wind Power System

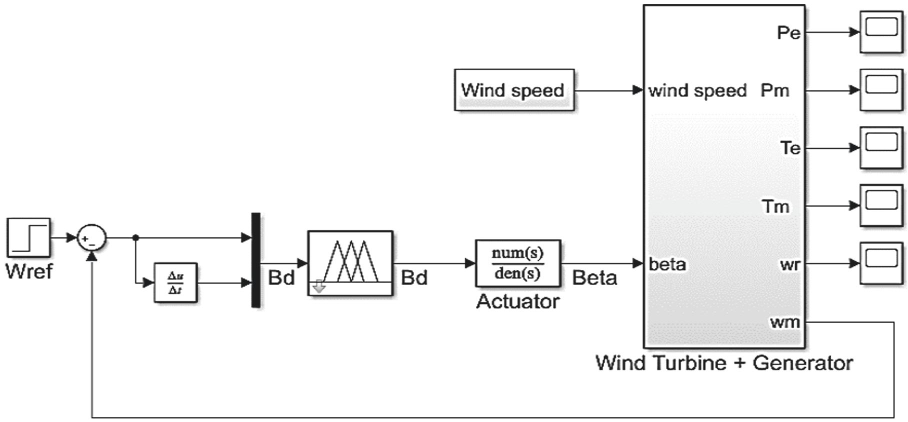

Fig. 12. Simulation diagram of overall system with fuzzy controller

The inputs/output membership function, the rule editor and the simulated results of overall system using Fuzzy controller are shown as follows (Figs. 12 and 13).

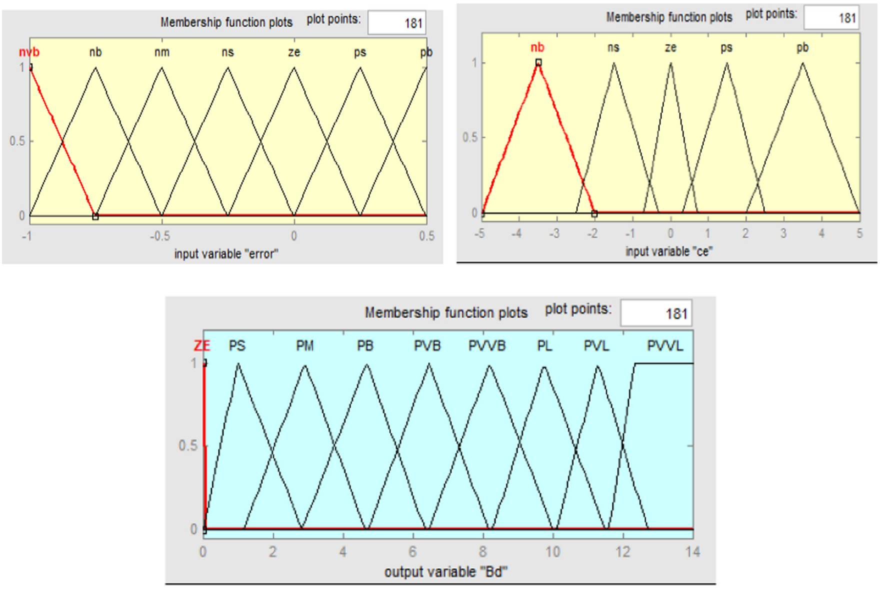

Fig. 13. Input/output fuzzy membership function

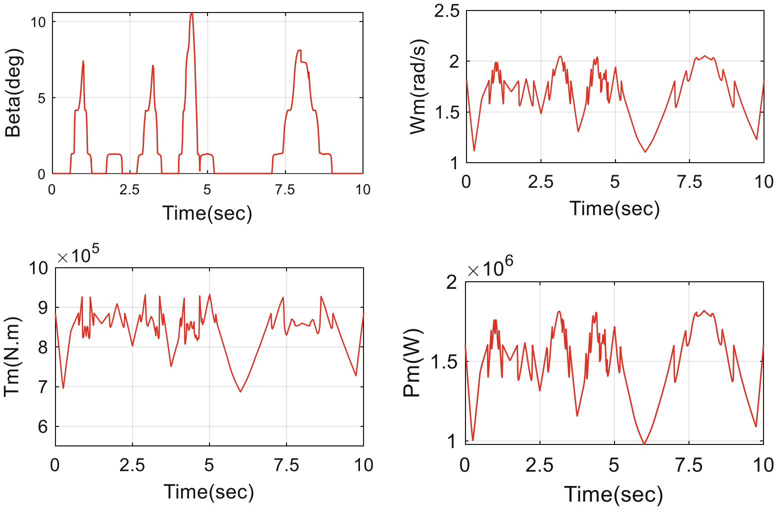

Fig. 14. Simulation results of overall system using Fuzzy controller.

From the above results, system with fuzzy controller perform batter compared with system with PID controller. The time taken to reach rated value of rotor speed, torque and output power are very small compared with PID controller. However, there is still a problem in power and torque values. Due to variable nature of the wind, there is torque ripples. This makes the system under pressure and give an impact on wind turbine system. This tells as, the system needs further improvement (Fig. 14).

4.4 The Fuzzy Tuned PID Controller

This research proposed fuzzy to tune the gains of the main controller (PID controller). In this simulation diagram, the gains of the PID controller are auto tuned under the inflow wind speed (Fig. 15).

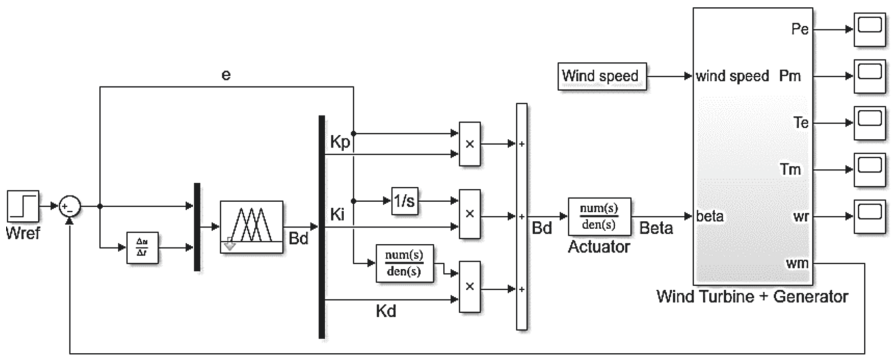

Fig. 15. Simulation diagram of overall system with fuzzy tuned PID controller

The inputs/output membership function, the rule editor and the simulated results of overall system using Fuzzy tuned PID controller are shown as follows (Fig. 16 and 17).

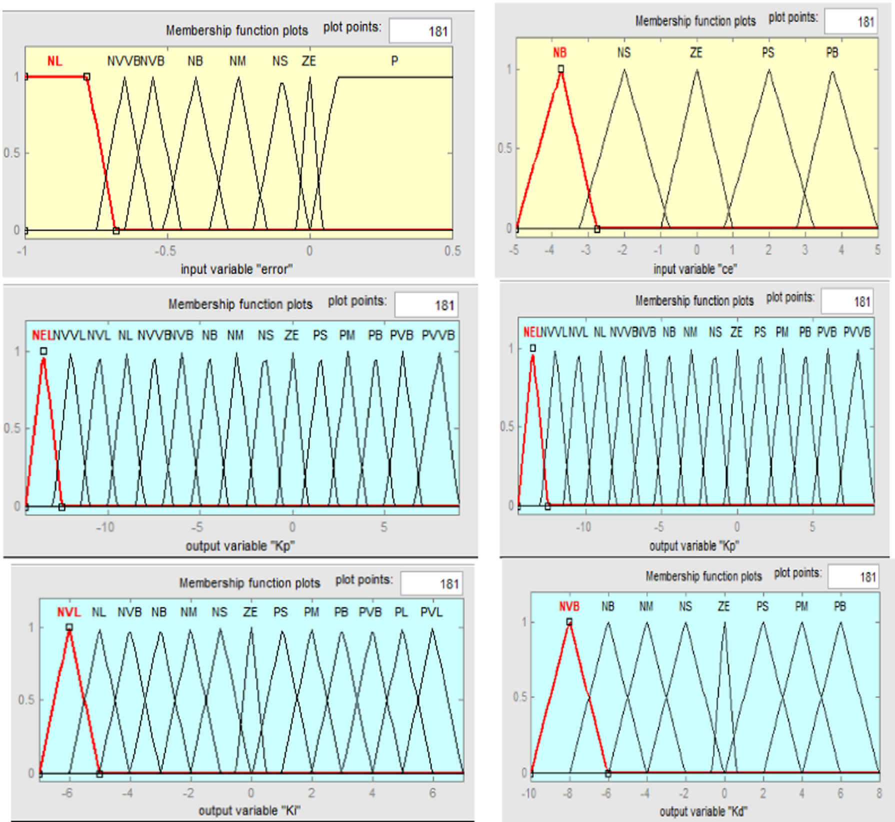

Fig. 16. The inputs/output membership function of fuzzy logic controller

The result obtained from the proposed controller are much better than PID and fuzzy controllers in terms of regulation or limiting. The time taken to reach rated value of rotor speed, torque and output power are very small compared with PID and fuzzy controller. With this controller, we can able to regulate the output power to the rated value up to cutoff wind speed value (22 m/s). The comparison between the proposed controller and the other two controllers are clearly stated in Sect. 4.5 below.

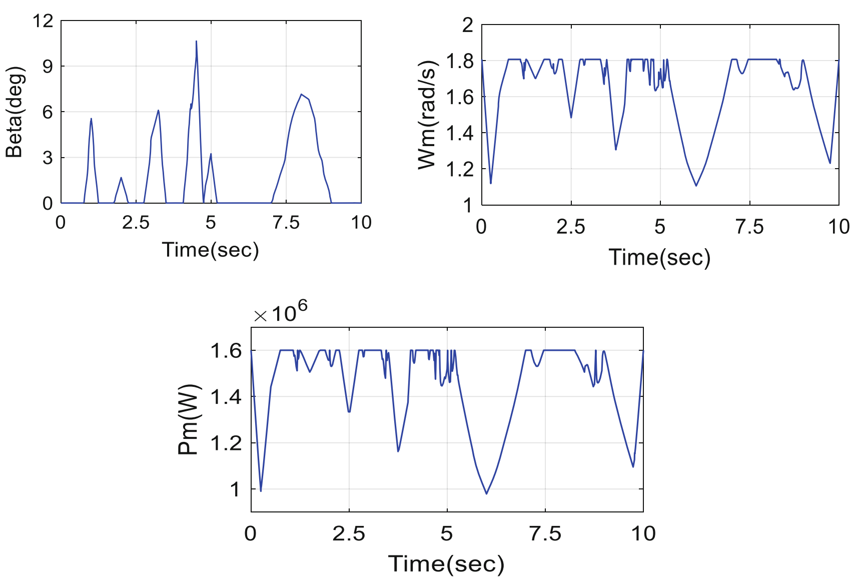

Fig. 17. Simulation results of overall system using fuzzy tuned PID controller

4.5 The Comparison of Control Systems

The performances of each controller under different wind speed are shown in Fig. 18. Standing from this result, the proposed controller has better performance compared to the other controllers. Table 5, illustrates the characteristics of each controller in detail (Tables 7, 8 and 9).

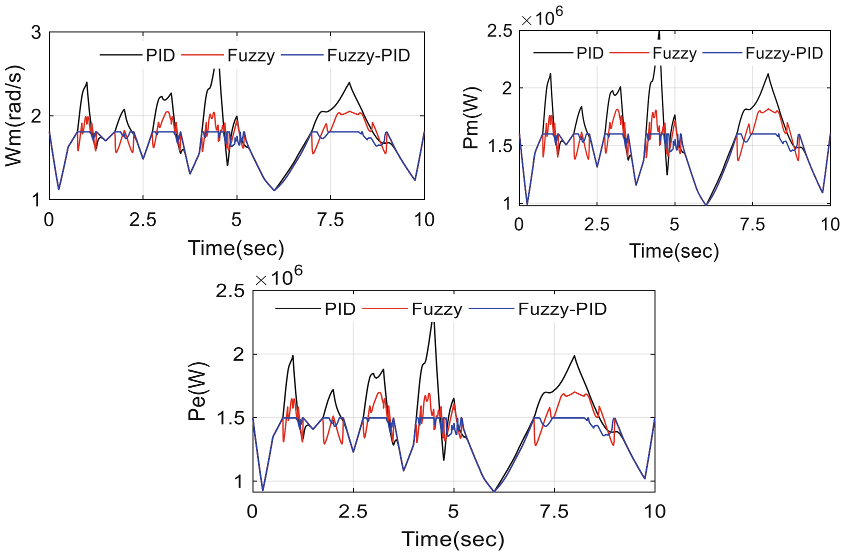

Fig. 18. Simulation results of overall system under different controllers

Table 7. Performance of PID, Fuzzy and Fuzzy-PID controller in case of below rated wind speed.

Power optimization (maximum power tracking)							
V_w (m/s)	ʎ	C_p	β^{o}	w_m(rad/s)	Electrical power (w)		
					PID	Fuzzy	Fuzzy-PID
3	1.675	0.45	0	0.1347	935.8	935.8	935.8
4	2.233	0.45	0	0.2394	4375	4375	4375
5	2.791	0.45	0	0.3741	$1.911 * 10^4$	$1.911 * 10^4$	$1.911 * 10^4$
6	3.349	0.45	0	0.5387	$6.415 * 10^4$	$6.415 * 10^4$	$6.415 * 10^4$
7	3.907	0.45	0	0.7333	$1.655 * 10^5$	$1.655 * 10^5$	$1.655 * 10^5$
8	4.465	0.45	0	0.9577	$3.487 * 10^5$	$3.487 * 10^5$	$3.487 * 10^5$
9	5.024	0.45	0	1.212	$6.312 * 10^5$	$6.312 * 10^5$	$6.312 * 10^5$
10	5.582	0.45	0	1.496	$1.018 * 10^5$	$1.018 * 10^5$	$1.018 * 10^5$
11	6.14	0.45	0	1.811	$1.5 * 10^6$	$1.5 * 10^6$	$1.5 * 10^6$

Table 8. Performance of PID and Fuzzy controller in case of above rated wind speed.

V_w (m/s)	ʎ	C_p	PID			Fuzzy		
			β^o	w_m	Power (w)	β^o	w_m	Power (w)
11.48	5.884	0.293	1.52	1.72	$1.42 * 10^6$	1.67	1.743	$1.405 * 10^6$
11.75	5.748	0.257	1.14	2	$1.65 * 10^6$	1.88	1.532	$1.512 * 10^6$
12	5.629	0.235	1.46	2.017	$1.71 * 10^6$	3.6	1.822	$1.454 * 10^6$
12.42	5.438	0.217	3.03	2.14	$1.77 * 10^6$	6.35	1.755	$1.543 * 10^6$
12.52	5.404	0.214	1.54	2.4	$1.99 * 10^6$	6.96	1.936	$1.512 * 10^6$
12.8	5.277	0.205	1.98	2.4	$1.98 * 10^6$	8.37	1.825	$1.51 * 10^6$
13.5	5.003	0.186	3.64	2.827	$2.34 * 10^6$	10.5	1.696	$1.4 * 10^6$

Table 9. Performance of Fuzzy-PID controller in case of above rated wind speed.

V_w (m/s)	ʎ	C_p	Fuzzy-PID		
			β^o	$w_m(rad/s)$	Power(w)
11.48	5.884	0.293	1.18	1.78	$1.47 * 10^6$
11.75	5.748	0.257	1.8	1.81	$1.495 * 10^6$
12	5.629	0.235	4.1	1.811	$1.5 * 10^6$
12.38	5.456	0.218	6.8	1.811	$1.5 * 10^6$
12.42	5.438	0.217	7	1.811	$1.5 * 10^6$
12.52	5.404	0.214	7.22	1.811	$1.5 * 10^6$
12.8	5.277	0.205	8.36	1.811	$1.5 * 10^6$
13.5	5.003	0.186	10.1	1.811	$1.5 * 10^6$

5 Conclusions

We start this work by modeling the system (pitch controlled HAVSWT) with some assumptions. It has been shown that the system is nonlinear & also the outputs are mainly depended on the aerodynamic torque and rotor speed of the shaft. To control this system under different wind condition, we proposed Fuzzy tuned PID controller. To compare the efficiency of the anticipated controller, we use conventional PID & Fuzzy controller. The simulation is done by using MATLAB/SIMULINK. Results obtained from simulation illustrates that fluctuations of output power and Mechanical Torque is very high in conventional controller (PID). In case of Fuzzy controller, the output reaches target value after 1.15 s. But, due to quick change of the value of change of error there are still some fluctuations in both outputs. However, when a fuzzy tuned PID is used, the power output reaches target value very quickly (before 1.15 s) and fluctuation gets reduced. Numerically, at 13.5 m/sec wind velocity by using conventional PID controller we get 2.827 rad/s angular velocity and $2.34 * 10^6$ output power, when the controller is replaced by fuzzy controller, we get 1.696 rad/s angular velocity and $1.4 * 10^6$ output power. Finally, when we use the proposed controller, we get 1.811 rad/s angular velocity and $1.5 * 10^6$ output power. Based on this result, the proposed controller has better performance than other two controllers.

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