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FUZZY LOGIC PITCH CONTROL OF VARIABLE SPEED WIND TURBINE

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Abstract - *Control plays an important role in modern wind energy conversion systems (WECS). The pitch control system is one of the most widely used control techniques to regulate the output power of a wind turbine. In this paper, efficient wind turbine pitch controller is designed to achieve an optimal angle of wind incident. By controlling the pitch angle in high wind speeds, aerodynamic load and generated power by the rotor are adjusted. MATLAB/SIMULINK is used to simulate the pitch angle control system to evaluate and test the control methods. Fuzzy Logic Controller for the variable speed wind turbine is used to regulate the wind turbine pitch. Simulations show that the fuzzy logic controller is capable of achieving better control performances than the conventional PID controller.*

***Key Words*: PID Control, Fuzzy Logic Control, Variable Speed Wind Turbine, Pitch Control System, Wind Turbine Model**

1. INTRODUCTION

Wind energy is one of the most attractive energy resources used for power generation around the world since the 20th century. It is virtually pollution-free, reproducible and resourceful as a result of which a great deal of research has been focused on the development of wind power. It is expected by 2050, global demand for wind energy will grow up to 3 times, according to forecast, and 15 to 20 percent of the global demand for energy will be fulfilled from renewable energy resources. It is an inexhaustible supply of clean energy and promotes a low carbon economy as compared to other sources like nuclear power and fossil power that causes hazards to the planet. Hence wind energy has emerged as one of the most preferred sources for electricity production.

The energy needs of the emerging economies are quite high like India, China and Brazil as they are competing with the already high demand from the developed countries. In 2016, China added 19.3 GW of wind power capacity to its total electricity produced capacity. China is forecast to have 250GW of wind capacity by 2020. As of March 2017, the total installed wind capacity in India was 32.17 GW. As of 2015, the countries ranked by total installations were China, United States, Germany, India, Spain and United Kingdom [8].

1.1. VARIABLE SPEED WIND TURBINE

Wind turbine system is a high order, strongly coupled, non-linear, multivariable system. Pitch-adjusting variable-speed wind turbines are the dominating type of installed wind turbines. As shown in Fig-1, variable speed wind turbines offer improved energy capture as the range of speed of the wind under which the maximum power is generated is increased. In modern power control techniques, power is kept at a rated value by controlling pitch angle β. This angle is defined as the angle between the pitch rope and its rotating shaft. Rotor speed must be controlled either by regulating the generator torque or manipulating the blade pitch angles.

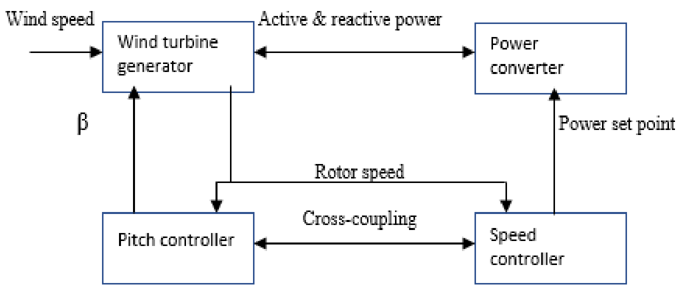

Fig- 1: Structure of a Variable Speed Wind Turbine

1.2. POWER IN THE WIND

The speed of the wind is crucial for the energy, a wind turbine can convert into electricity. The energy content in the wind varies with the third power of the average wind speed. The power (P) conversion in a wind turbine is given by,

$$P = 0.5\rho A C_p V^3 \quad (1)$$

where, ρ is the mass density of the air, A is the area swept by rotor blades. V is the wind speed, Cp is the non-dimensional power coefficient. For a variable speed wind turbine, the objective is to operate near maximum efficiency, where the power can be expressed as,

$$P_{target} = 0.5\rho A\, C_{target} (R/TSR_{target})^3\, \omega^3 \quad (2)$$

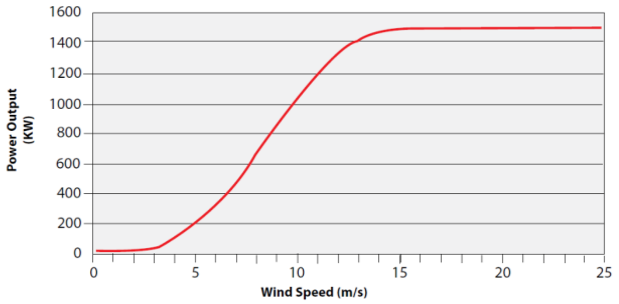

Fig- 2: Power vs. Wind Speed of a Wind Turbine

where, R = rotor radius (at blade tip) and ω is the rotational speed of the blade. The Tip-speed ratio (TSR) is defined as the ratio between the blade tip speed and wind speed υw,

$$\lambda = \Omega R / \upsilon w \quad (3)$$

where Ω is the turbine rotor speed and R is the radius of the wind turbine blade [12].

1.3. PITCH ANGLE CONTROL FOR WIND TURBINE

The most commonly used method to control the power is to adjust the pitch angle of the turbine blades. With the changes from fixed pitch, whole leaf variable pitch and variable speed constant frequency three stages. Moving towards wind-turbine development, variable pitch control technologies have way more advantages. The aim of pitch control is to achieve an optimum angle of wind incident to the pitch. When the wind speed is higher than the permissible level, pitch rotates in an appropriate direction with respect to the wind speed in order to decrease the effect of wind. The rate of pitch angles in an urgent case is considered as 10° to 20°.

Pitch control prevents imposing the wind power that is higher than the tolerable limit of the equipment. The Cp (λ, β) characteristic gives us a power coefficient that depends on λ and β. The advantages of this type of control is that there is good power control, assisted start up and emergency stop. With the increase in pitch angle, the wind turbine rotor power coefficient decreases and this in turn can be controlled by the pitch angle and hence output power can be limited [11].

2. WIND TURBINE SYSTEM MODEL

The block diagram of wind turbine system model is shown in Fig-3. Modern wind turbine generator systems are systems with a horizontal axis of rotation, a high speed asynchronous generator, a wind wheel consisting of three blades and a gear box. The pitch actuator is used to turn the blades along their longitudinal axis. The dynamic behavior between the pitch demand β_d from the pitch controller and measuring the pitch angle β is described by the actuator model [15].

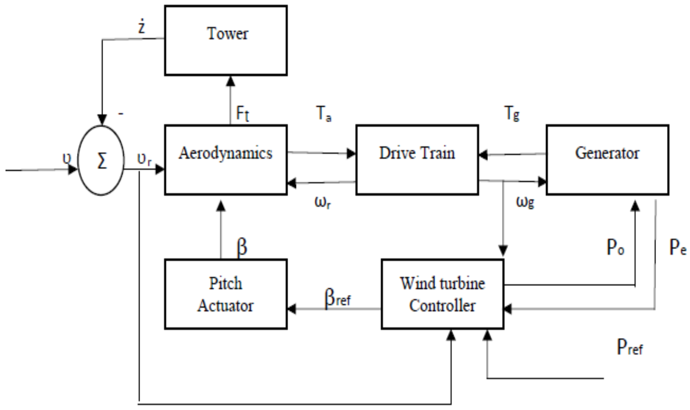

Fig- 3: Block diagram of a wind turbine model

The change in pitch angle is given by,

$$d\beta / dt = (\beta_d - \beta) / T_\beta \quad (4)$$

$$T_\beta . d\beta / dt = \beta_d - \beta \quad (5)$$

$$T_\beta . d\beta / dt + \beta = \beta_d \quad (6)$$

Applying Laplace transforms,

$$T_\beta . \beta s + \beta = \beta_d \quad (7)$$

$$\beta . (T_\beta s + 1) = \beta_d \quad (8)$$

$$\beta / \beta_d = 1 / (T_\beta s + 1) \quad (9)$$

This is the required transfer function of the pitch actuator model. T_β is the value of time constant of pitch actuator and can be calculated from initial parameters of the wind turbine [7] shown in Table-1. The drive train model of wind turbine consists of blade pitching mechanism, a rotor shaft, a hub with blades and a gear box with generator.

The structure of the model is illustrated in Fig-4. The gear box inertia is typically much smaller (by a factor of 1/30) than the generator inertia, which means that it will have no dynamic influence on the low frequencies.

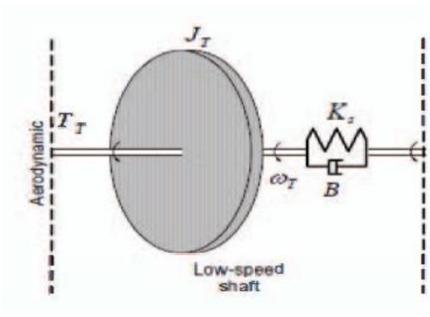

Fig- 4: Drive Train Dynamics

Table -1: Parameters of the wind turbine

Rated generator power, P_e	1000 KW
Rated generator speed, W_g	1500 rpm
Rated turning speed of rotor, W_t	20 rpm
Wind turbine blade radius, R	35 m
Reference pitch angle, β_d	0 to 90 deg
Rate of change of pitch angle	0.6 deg/ sec
Control accuracy of pitch angle	0.3 deg
Damping coefficient, B	2 N.m./ rad /sec
Drive-train inertia, J_t	0.75 N.m2

The parameters to be considered while modeling the drive train are given in Table-2 [15].

Table -2: Mechanical Model Parameters of Drive Train

Parameter	Description	Parameter	Description
J_T	Wind turbine inertia [kg.m2]	w_T	Wind turbine shaft speed (rad/s)
J_G	Generator inertia [kg.m2]	W_g	Generator shaft speed (rad/s)
K_s	Stiffness Coefficient [N.m/rad]	$Ø_T$	Wind turbine shaft angle (rad)
B	Damper Coefficient [N.m/rad/sec]	$Ø_g$	Generator shaft angle (rad)
T_T	Wind turbine torque [N.m]	1:n_{gear}	Gear ratio
T_G	Generator electromechanical torque [N.m]		

The dynamics of drive-train are described as follows by differential equations,

$$J_T \cdot d/dt\,(w_T) = T_T - (K_s\,\delta Ø + B\,\delta w) \quad (10)$$

$$d/dt\,(\delta Ø) = \delta w \quad (11)$$

By Newton's second law of motion,

$$J.\,dw / dt = T - Bw \quad (12)$$

Applying Laplace transform on both sides,

$$J.\,Ws = T - BW \quad (13)$$

$$J.\,Ws + BW = T \quad (14)$$

$$W\,(Js+B) = T \quad (15)$$

$$W/T = 1/(Js+B) \quad (16)$$

This is the required transfer function. It is a first order transfer function of drive train.

It can also be written as,

$$W/T = (1/B) / ((J/B)\,s + 1) \quad (17)$$

Substituting values for J and B from the initial parameters of the wind turbine;

$$W/T = 0.5/(0.375\,s + 1) \quad (18)$$

This is the mathematical model of the wind turbine [15]. This model has been derived from the above analysis. The simulation is done using MATLAB/ SIMULINK software.

3. FUZZY LOGIC CONTROL

This control strategy is used in various control system these days that include flight control systems, dishwashers, and to really complex processes such as waste water treatment. In this type of control, the parameters are fixed. They have the advantages of being very robust, can be easily modified and they can use multiple input and output sources. The Fig-5 illustrates the diagram of the fuzzy controller [16].

FLC incorporates a rule-based approach (IF X AND Y THEN Z), to solving a control problem instead of modelling a system mathematically. It first converts a measured signal x (error signal) into a set of fuzzy variables. This is called fuzzification [15]. The membership values are created. After which we specify a rule table which has been designed to regulate the speed and finally determine the procedure for defuzzifying the result.

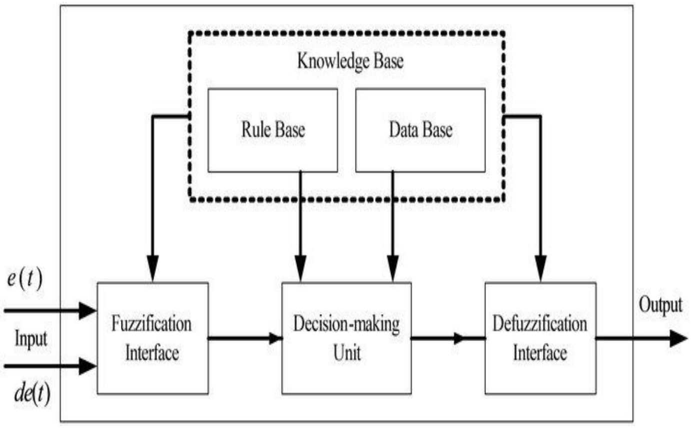

Figure-5: Principle Diagram of a Fuzzy Controller

The main objective of using fuzzy control is to improve the speed and captured energy of the wind turbine. When compared to PID controllers that are mostly used these days, fuzzy controllers are non-linear state controllers with robust features. They perform better control characteristics. While developing a control system with Fuzzy Logic Control (FLC), following steps should be followed:

A. Fuzzification

In this operation, we determine the input and output membership functions. This process involves measuring the values of input variables and performing a scale mapping that transfers the range of input variables into corresponding universe of discourse. This means this function converts input data into suitable linguistic values which are viewed as labels of fuzzy sets. Two inputs are defined namely, error and change in error. The three parameters of PID controller are automatically adjusted. The three outputs are Kp, Ki and Kd [9].

Membership functions are also defined and we use Gaussian membership functions for both inputs and outputs. We get the solution of fuzzy by the method of weighted average. The variable universe of discourse for the system, pitch error (e) and change in error (ec) is taken as { -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5}. This set is divided into seven levels, the linguistic values of the 7 fuzzy sets are taken as {Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, Positive Big} [17]. The inputs (error and change in error) and outputs (Kp, Ki and Kd) with Gaussian membership functions are shown in Fig-6 and Fig-7. the seven linguistic variables are {NB, NM, NS, ZO, PS, PM, PB}. The selected universe is { -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5}.

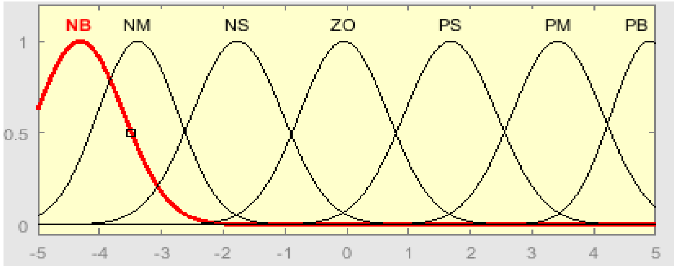

Figure-6: Membership Functions of error (e) and change in error (ec)

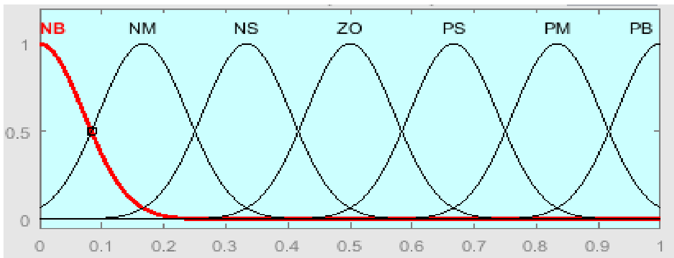

Figure-7: Membership Functions of Kp, Ki and Kd

B. Fuzzy Rule Base

Fuzzy control rules are a summary of expert knowledge and experience accumulated. These set of linguistic based rules characterizes the dynamic behavior of a fuzzy system. A fuzzy control rule is a fuzzy conditional statement in which the antecedent is a condition in its application domain and the consequent is a control action for the system.

The accuracy of the output depends on the formation of rules. The expert knowledge is usually of the form: If (a set of conditions are satisfied) Then (a set of consequences can be inferred). Accordingly, in the present pitch control design, the fuzzy controller has 49 fuzzy rules for each parameter based on the input and output membership functions. Fuzzy control rules are expressed by the fuzzy conditional statement: If E and EC then U [3]. The fuzzy rules represent the knowledge level and abilities of humans who adjusts the system so that there is fast response and minimum error. The Tables 3, 4 and 5 show the rule base for Kp, Ki and Kd.

Table -3: Rule Base for Kp

e	ec						
	NB	***NM***	***NS***	***ZO***	***PS***	***PM***	***PB***
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

All these rules drawn into the table constitutes a fuzzy control rule table. Optimum response of the pitch control system is derived from an effective rule base. These rules are formed based on checking frequently the output response.

Table -4: Rule Base for Ki

e	Ec						
	NB	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table -5: Rule Base for Kd

e	Ec						
	NB	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NS	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PS	PS	PS	PB

C. Defuzzification

Defuzzification is the process of converting a fuzzy set in to a real number. It is required to defuzzify the fuzzy control action (that is the output) inferred from the fuzzy control algorithm. Several methods have been developed to generate real values as outputs. It is the process of interpreting the membership degrees of the fuzzy sets into a specific real value. For this fuzzy control design under study, Centroid Defuzzification method is employed [15].

4. CONTROLLER DESIGN

In this chapter, various control technique designs are discussed. Initially, PI controller and the conventional PID controller are designed to study the response of the wind turbine to the applied pitch control. Then, Fuzzy logic controller is applied and analyzed for better system performance. The Fig-8 illustrates the simulation block diagram of the wind turbine for pitch control system.

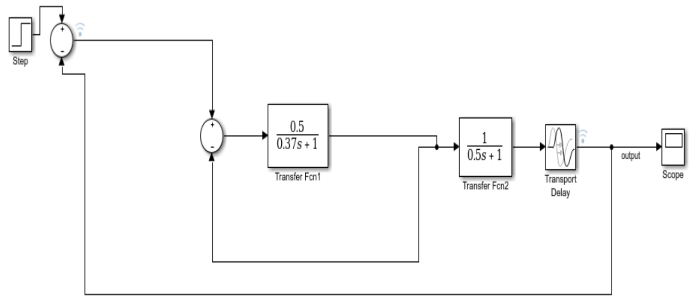

Fig-8: Simulation block diagram of wind turbine with no Pitch Controller

This case can also be considered in which the pitch controller is a proportional controller with Kp=1 (no controller). It has no impact on the process and hence considered as the same effect without a controller. There is a peak overshoot, high rise time and more settling time observed for this system with no pitch controller. By controlling the pitch angle, the output power can be limited as the wind turbine rotor power coefficient decreases with the increase of pitch angle.

In the second case, a PI controller is used for pitch control. The value of the constant (proportional gain) is 10 and the value of the integrator factor of PI controller is a small value of .002. The block diagram of pitch control system with PI controller is shown in Fig-9.

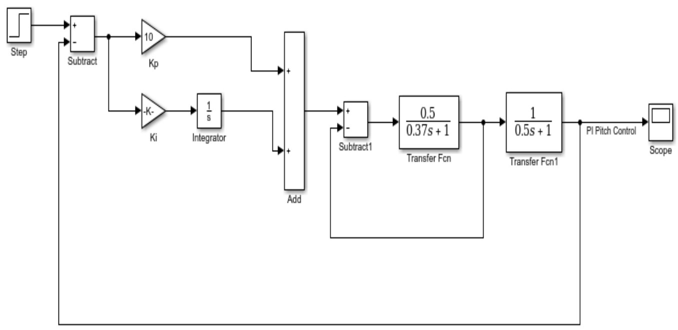

Fig-9: Simulation block diagram of Pitch Control System with PI Controller

PID controllers are the most widely used industrial controllers as it is simple and has robustness. Many of the complex control systems employ PID controller as its main control element. In Fig-10, a PID module is shown. It is a linear controller and it generates the control action u(t) depending on the control error, e (t) [9].

$$e(t) = r(t) - c(t) \tag{19}$$

The linear combination of proportional, integral and derivative of the error signal is the PID control action.

u (t) = Kp e (t) + Ki e(t) dt + Kd (de (t) / dt)   (20)

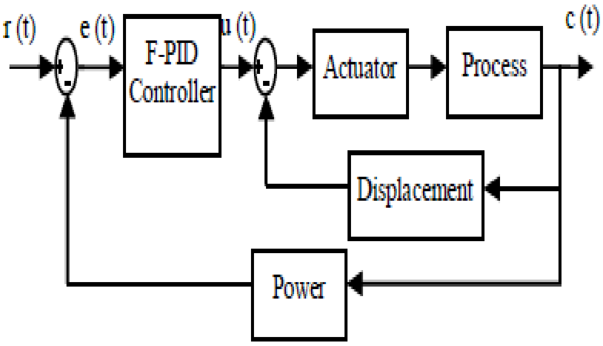

Fig-10: Closed Loop Pitch Control System

The values of these three parameters can be changed (Kp, Ki and Kd) to improve the control effect. The proportional control produces the action that is directly proportional to the input control system. But, here, the steady state error cannot be completely eliminated. The integral link is used to eliminate the steady state error which was present in the proportional control and this is done without the use of large controller gains.

While using PID, the output of the derivative control depends on the rate of change of error signal. The derivative action is similar to the high pass filter. The Simulink model of the wind turbine pitch control system with conventional PID controller is shown in Fig-11.

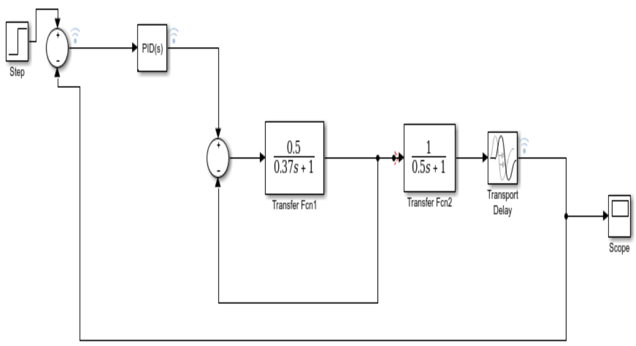

Fig-11: Simulation block diagram of PID Controller for Pitch Control System

The Simulink model of the pitch control system of wind turbine with fuzzy logic controller is shown in Fig-12.

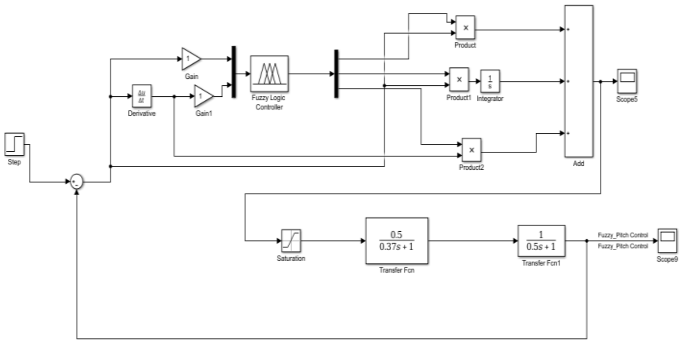

Fig -12: Simulink block diagram model of Fuzzy Controller for Pitch Control System of Wind Turbine

5. SIMULATION AND RESULTS

From the response graph of the pitch control system with PI controller, the Y-axis represents the pitch angle in degrees, while the X-axis represents the time in seconds. The unit response curve is shown in Fig-13. We observe a considerable rise time and high overshoot of 15.6%.

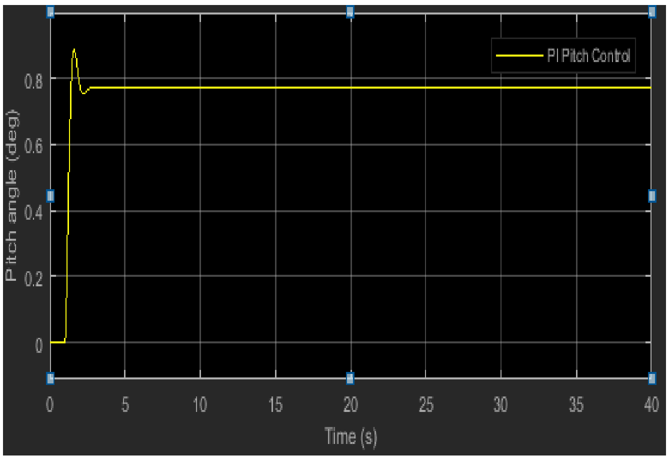

Fig-13: Unit step response of Pitch Control System with PI Controller

The unit step response of the pitch control system using PID controller is illustrated in Fig-14. With this PID controller, the system produces a decent response when compared to the PI controller. The overshoot is reduced to about 11.7%. Also, we observe more rise time and less settling time than the previous case of a PI controller.

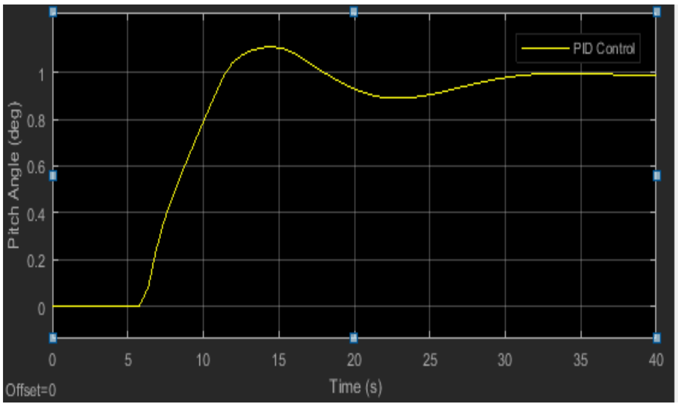

Fig-14: Unit step response of Pitch Control System with PID Controller

The unit step response of pitch control system with fuzzy controller is plotted and illustrated in Fig-15. With fuzzy controller based wind turbine pitch control system, we observe high rise time; there is almost zero overshoot (0.505%) and less settling time (21 secs).

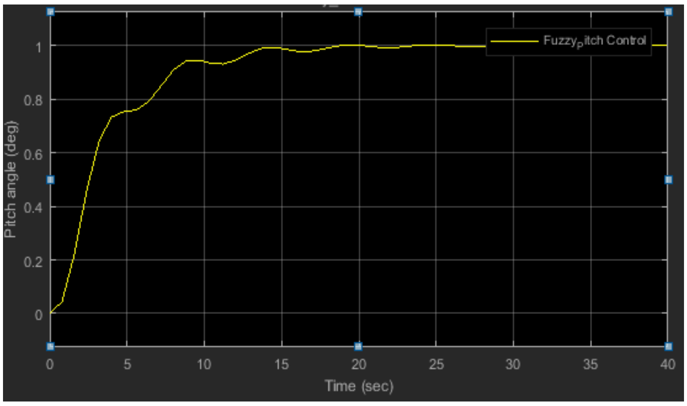

Fig-15: Unit step response of Pitch Control System with Fuzzy Controller

Fig-16 illustrates the comparison between a fuzzy controller and a conventional PID controller for pitch control system. By using fuzzy controller, the system response has improved considerably with an almost zero percent overshoot. The steady state accuracy and the stability of the system has been improved substantially with the fuzzy controller. While simulating the wind turbine system model of the pitch control system, fuzzy controller exhibited a fast response with almost no overshoot.

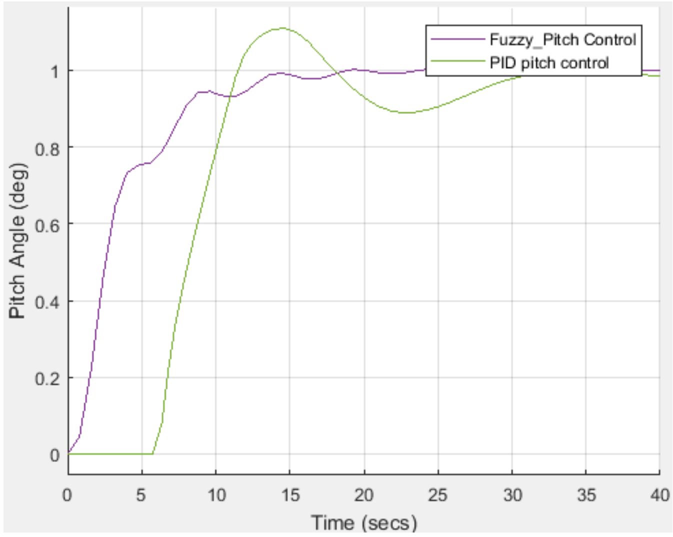

Fig-16: Comparison of unit step response of wind turbine pitch control system using fuzzy and PID controllers

Table-6 tabulates the time domain specifications of pitch control system for unit step input using PI, PID and Fuzzy controllers. The Fuzzy controller is able to produce a considerably better and smooth response for pitch control system of the wind turbine. As seen in the different controller cases, the system overshoot is reduced at the expense of the higher rise time of the system.

Time Domain Specifications	PI Controller	PID Controller	Fuzzy Controller
Rise Time (sec)	3.1 secs	4.29 secs	6.81 secs
Settling Time (sec)	29 secs	27 secs	21 secs
Peak Overshoot	15.69%	11.79%	0.50%

Table -6: Comparison of time domain specifications of pitch control system for unit step input using PI controller, PID controller and Fuzzy controller

6. CONCLUSION

The pitch angle control strategy using different controllers such as PI, PID and Fuzzy controller has been proposed. On the basis of the different characteristics of PI, general PID and fuzzy control techniques, the pitch control system of the wind turbine was designed and simulated to achieve optimum response. The mathematical model of the wind turbine system was first developed and then designed using Matlab/Simulink software. After which it was simulated using various control techniques. It is seen that the fuzzy controller produces an overall smooth response and can suppress the oscillations.This technique is more efficient to realize the control of pitch system to ensure the stability of wind turbine output power.

From the analysis, we can conclude that fuzzy controller gives a relatively faster response for unit step input.

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