Scholars Journal of Engineering and Technology
OPEN ACCESS
Abbreviated Key Title: Sch J Eng Tech
ISSN 2347-9523 (Print) | ISSN 2321-435X (Online)
Journal homepage: https://saspublishers.com/journal/sjet/home

Maximum Performance from Wind Power System Using Fuzzy Logic Controller

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| **Received:** 17.03.2019 | **Accepted:** 28.03.2019 | **Published:** 30.03.2019
DOI: 10.36347/sjet.2019.v07i03.003

Abstract **Original Research Article**

This paper describes fuzzy logic controller applied to the wind power system. The wind power system is modeled using Matlab and a fuzzy logic control is designed for the control of this system. The generated controller was combined with the wind power system and the control was realized with the fuzzy logic controller. The theory of Fuzzy-PID control and PID control were applied to the control of generator speed and blade pitch angle. The pitch angle control system was simulated using test the control strategy and performance evaluation of the system. To test the controller's performance, a wind profile has been simulated. Wind power system of fuzzy logic control was designed to increase the efficiency output obtained from wind energy. Wind turbine is the main sources for the system maximum perform as a backup power source. Therefore, continuous energy supply needs energy storing devices.
Keywords: Wind power, performance, Fuzzy, controller.

INTRODUCTION

Depending on the advancing technology nowadays, the countries' needs for electrical energy also increase. Due to the limited number of fossil fuels used in the production of electricity, and due to their decreasing day by day, studies on the generation of electricity by using renewable energy sources continue at a great pace. One of the studies carried out in this production of electrical energy from wind systems. In this context, studies on simulation, modeling and control of wind systems and optimization of energy are studied. Renewable energy sources offer limitless resource and environment friendly operation compared to conventional energy sources. There are several forms of renewable energy such as solar energy, wind energy, geothermal energy, tidal energy, hydro energy and bioenergy wind turbines are become more popular with a growing interest in renewable energy resources. It is thought that this interest would be alive as environmental concerns are present and also a need for electricity increases. In parallel with technological developments and the demand for electricity, both the capacity of wind turbine is grown and their control methods employed are enhanced and changed [1].

For many centuries the wind and the water falls was used to turn the wind and water mills to grind corn or transporting water, but after discovering the fossil sources such as coal and oil, these sources are missing in progressively, until man found that fossil fuels have caused various hazards in particular the environmental aspect. Face to these problems man was confronted to the reduction in consumption of fossil sources on one side and the development of sustainable sources on the other side many researchers have made significant contributions to wind energy technology [2].

The main reasons for this success are the eco friendliness and the steady improvement of the technology, together with the continuous increase in the power output of a single wind turbine. Recently, fuzzy logic has been extensively used in the fields of energy engineering applications and there are many studies available in the literature. Nowadays, artificial intelligence methods are muchmore popular in engineering sciences. Fuzzy logic (FL) concept, an artificial intelligence method, was introduced by adeh. FL modelling provides good solutions for controlling of the ambiguous, time-varying, complex and ill-defined systems, encountered in the dailylife [3].

In literature; M. Sarvi, Sh. and Abdi, S. Ahmadi [12] have proposed the maximum power point tracking control scheme based on particle swarm optimization fuzzy logic for wind turbine PMSG system. The maximum wind power was captured by adjusting the rotor speed of the PMSG. The rotor speed varies according to the wind speed and the wind turbine generator was operated by adjusting the duty cycle of the boost converter and increases the efficiency of wind energy conversion system. Jogendra Singh Thongam and Mohand Ouhrouche [13] have proposed MPPT controllers to extract maximum power from the wind using various types of generators such as Permanent Magnet Synchronous Generator (PMSG), Squirrel Cage Induction Generator (SCIG) and Doubly Fed Induction Generator (DFIG). They have used three main control methods to track the maximum power namely tip speed ratio (TSR) control, Power signal feedback (PSF) control and hill-climb search control (HCS). E. Koutroulis and K. Kalaitzakis [14] have proposed the Maximum power tracking system for wind energy conversion applications. The output voltage and current of the wind generator was determined to monitor the output power of wind generator. Based on the result of comparison between successive wind power values, the dc-dc boost converter was adjusted directly. Y. Izumi *et al*. [15] has proposed a control method for tracking maximum power in a wind energy conversion system using online parameter identification. Bipin Biharee Srivastava and Er. Sudhanshu Tripathi [16] have proposed the fuzzy logic MPPT controller to track the maximum power from the wind generation system.

The maximum power is achieved based on the rotor speed of the wind system which consists of wind turbine. The wind turbine was connected with transmits the power into AC grid through the converter. The generator side converter controls the torque of the grid side inverter controls the voltage in the dc link and the grid for steady operation. The online parameter identification was used to determine the optimum torque of it varies due to wind turbulence, parameter error and other unexpected conditions. The parameter identification was achieved by the use of weighted least square method and it was appropriate for practical systems [4].

Wind Turbine

A wind turbine is a machine for converting the kinetic energy in wind into mechanical energy. Wind turbines can be separated into two basic types based on the axis about which the turbine rotates. Turbines that rotate around a horizontal axis are more common. Vertical axis turbines are less frequently used. Wind turbines can also be classified by the location in which they are used as Onshore, Offshore and aerial wind turbines. The use of environment friendly renewable energy sources are getting popular today. Because of high renewable energy potential of countries, renewable energy systems are also getting more attention by end users. The efficiency of a wind turbine is depending on meteorological and geographical conditions [5]. Therefore, the wind power system was designed on the data of wind availability in the city of Karaman, Turkey. The wind power system a 5 kW wind turbine. Fig. 1 shows the wind turbine views.

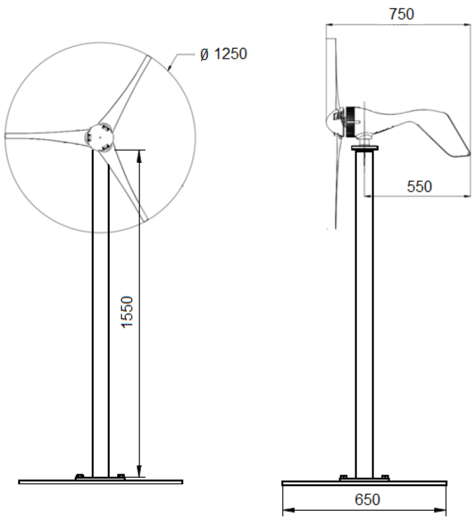

Fig-1: Turbine views and dimensions

Shown in Fig. 2, the availability of wind is determined by the average daily wind speed in September, Karaman at 10 m altitude. And shown in Fig. 3, the availability of wind is determined by the average daily wind power in September, Karaman at 10 m altitude.

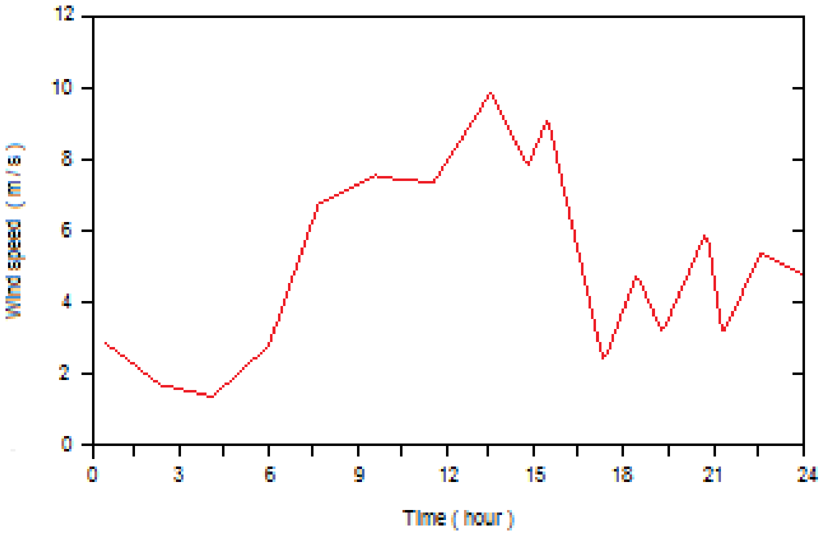

Fig-2: Daily wind speed in September

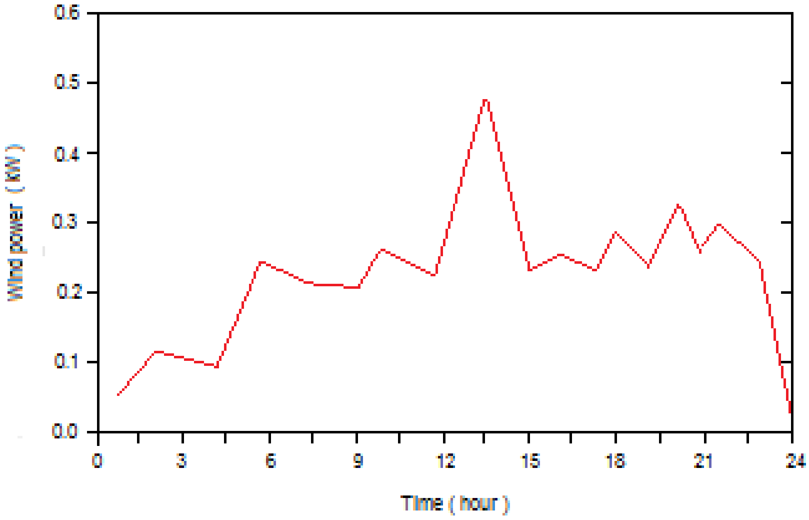

Fig-3: Daily wind power in September

The wind turbine system is installed in Karaman, Turkey. The analysis of this system, considered the geographical and meteorological conditions of Karaman 41^0 33′ north latitude, 28^0 59' east longitude. The annual monthly in 2018 years of wind speed data in this region can be seen in Fig. 4.

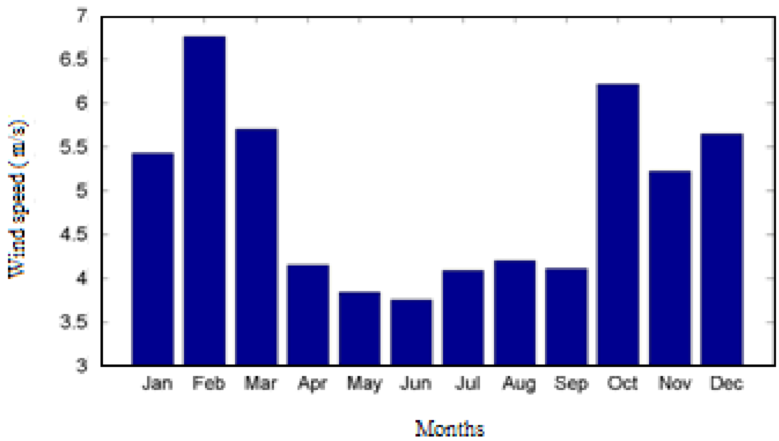

Fig-4: Monthly average wind speed of Karaman

Pitch control

Pitch controlling, wind turbines have adjustable blade on the rotor hub.When the wind speed exceeds the rated value, the pitch controller will reduce the angle of attack, turning the blades (pitching) gradually out of the wind. The pressure difference in front and on the back of the blade is reduced, leading to a reduction in the lifting force on the blade. The operating principle of the pitch control is illustrated in the Fig.5. The pitch angle of one of the wing angles in the nacelle part containing the wings of the wind turbine Fig.9 also seen. In order for the wings to rotate more efficiently, the pitch angle should be controlled to be optimal. Pitch angle is the angle between the axial of wind direction and the chord line. This angle is made by turning the axis of rotation of the blade counterclockwise or clockwise.

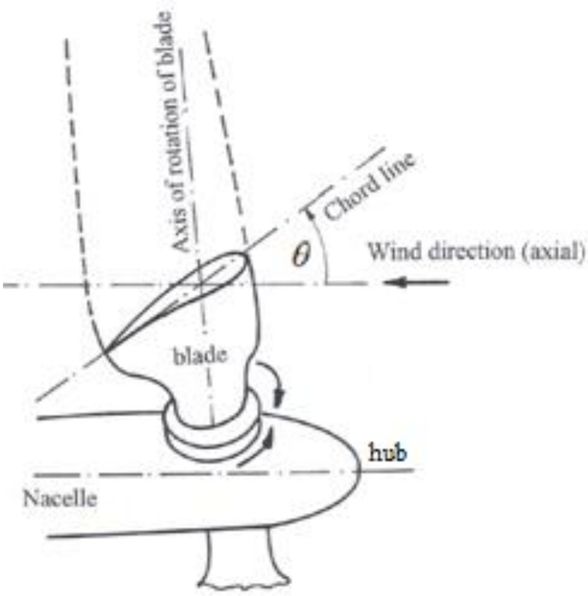

Fig-5: Pitch angle of blade in wind turbine

Wind Energy Conversion System

To design a mobile wind energy system with a required capacity, it is a must to properly size the system components. The energy flow route of the system is given at Fig. 6 [6].

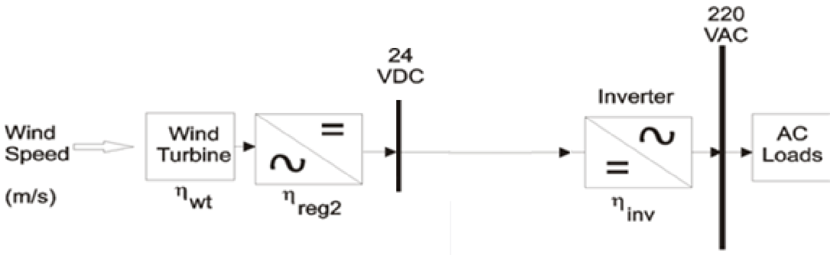

Fig-6: Energy flow of the wind power system

The wind power supply system should meet the following specific requirements; The electric input parameters should be compatible with the electric output parameters, especially taking in to account: The wide range of variation of the electric output parameters of the wind generator, due to the variation of wind speed.The reduced range of variation of the accumulator batteries load unload electric parameters, this mode having to be controlled by means of a charge controller. Compatibility in various operating modes of the load by interconnecting adequate interfaces (both for the DC part and for the AC part). Providing part of the necessary electric energy by converting the mechanical energy from the wind. Usually Pb batteries are used, but also Ni-Cd or Ni-Fe, dedicated to applications in the area of renewable energy sources.Unit for power conditioning that can be a DC/DC converter (for DC loads) and/or inverters [7]. Output power of a wind turbine is expressed by the following equation (1), which determines the power-speed characteristic of a wind turbine

$$Pw = \frac{1}{2} Cp\,(\lambda , \theta).\, \rho .\, A.v^{3} \qquad (1)$$

where *Cp* is the performance coefficient determined by the aerodynamic laws, (ρ) the air density, *A* the swept area of the turbine bladesand *v* the wind speed (m/s). The performance coefficient depends on both the pitch angle (θ) and the tip speed ratio (λ). If the pitch angle increases, the Cp will be decreased and as a result, the turbine mechanical power will be reduced. Thus, to achieve the maximum power point tracking, the pitch angle should be fixed. The tip speed ratio is calculated by using blade tip speed and wind speed upstream of the rotor, as in the following equation (2) :

$$\lambda = \frac{W_t . R}{v} \quad (2)$$

where *R* is the blade radius, *Wt* is the rotational speed and λ is the tip speed ratio.The relationship between performance coefficient (*Cp*), pitch angle (θ) and tip speed ratio (λ) is established by the *Cp* - λ approximation (3) for different blade pitch angles.(B. B. Srivastava, Er. S. Tripathi, 2014),

$$Cp = (0.44\text{-}0.16.\ \theta).\sin\left(\frac{\pi\ (\lambda-3\ )}{15-0.3\ \lambda}\right) - 0.00184(\lambda-3).\theta \quad (3)$$

Tansfer function for Pitch control as in the following equation (4) :

$$G(s) = \frac{\theta(s)}{\theta_{ref}} = \frac{e^{-\tau s}}{T_\theta s+1} \quad (4)$$

Where, θ is definited the actual pitch angle, θ_{ref} is definited the pitch angle for the reference, T_θ is the time constant , τ as the delay time. The parameters of the wind generation system used in this paper are given in Table 1.

Table-1: Wind turbine parameters

Wind turbine type	Vertical axis
Rotor diameter	100 mm
Weight	16 kg
Cut-in	2 m/s
Cut-off	50 m/s
Nominal power	5 K W
voltage	12-24 V
Start-up wind speed	2 m/s
Rated wind speed	13 m/s
Survival wind speed	50 m/s
Wind wheel diameter	1.25 m
Blades quantity	3
Blade material	Fiber
Generator	Three-phase alternating current
Working temperature	-20°C /+40°C

Equation (5) shows the estimation of average daily energy consumption.

$$E_d = \sum_{i=1}^{n} I_n V_n D_n \quad (5)$$

Where I_n, V_n, and D_n are the current, voltage and duty cycle of each appliance used during the day, respectively and E_d shows the total energy demand for the system. As shown in Table 2, the average daily energy consumption of the system is calculated as 4264 Wh according to equation (5).

Table-2: Calculated energy consumption of the wind power system

Appliance	Quantity	Power [W]	Consumption / Day [hours]	Consumption / Day [Wh]
Air Conditioner	1	550	5*	2700
Refrigerator	1	60	10*	600
TV	1	50	2*	100
Lamp	5	100	5*	500
Heater	1	1300	0.28	364
Total	9	2060	22.28	4264

* Discontinous time

Fuzzy-PID Controller

In wind energy conversion systems, one of the operational problems is the changeability and discontinuity of wind. In most cases, wind speed can fluctuate rapidly. Hence, quality of produced energy becomes an important problem in wind energy conversion plants. Several control techniques have been applied to improve the quality of power generated from wind turbines. Pitch control is the most efficient and popular power control method, especially for variable-speed wind turbines. It is a useful method for power regulation above the rated wind speed. PID controller loop is shows in Fig. 7.

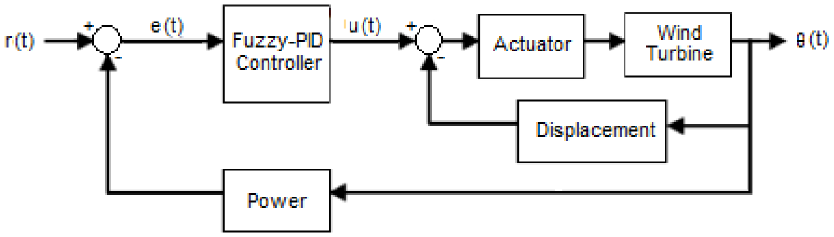

Fig-7: Fuzzy-PID control system

The control error as in the following equation (6):

$$e(t) = r(t) - \theta(t) \quad (6)$$

Where $e(t)$ is control error, $r(t)$ is referans pitch angle and $\theta(t)$ is pitch angle.

The control gains and input parameters as in the following equation (7) :

$$u(t) = Kp\, e(t) + Ki \int_0^T e(t)\, dt + Kd \frac{d\, e(t)}{dt} \quad (7)$$

Where $u(t)$ is control action and control gains are Kp, Ki, Kd.

Fuzzy controller can summarize the experiences to form fuzzy relations, through fuzzy reasoning and fuzzy decision, drive implementing agencies to implement the corresponding action. Have the advantage of fast dynamic response, robustness etc. and so is suitable to nonlinear multivariable systems. But on the whole fuzzy controller is equivalent to a nonlinear PD controller, the lack of integral action, will cause the system steady-state error. Therefore, fuzzy controller and PID controller can be used together. Early in the control fuzzy controller is selected to achieve system's rapid response. When the error reaches a certain level (error < 10 %), the PID control system is cut in quickly to reduce the steady-state error. Improve overall system performance. The software that was used, was divided into two main parts: control and power generation. Both, coded in the software environment on the Arduino with adaptions of code from [8].

The algorithm, which is illustrated in Fig. 8, is based on sensors that contributes to control the wind turbine. The algorithm starts with reading the input values, wind speed, wind angle and wind turbine angle. The error between the two latter variables, along with the rate of change of the error, is sent to be fuzzified, to be understood by the wind turbine. Once that is done, the fuzzy rules belonging to the fuzzified values are applied. This leads to the defuzzification process, which means that the gain parameters of the PID controller are tuned. The output from the calculations made in the controller, is a PWM signal that is sent to the H-bridge. The H-bridge determines the direction of the DC-motor and the corresponding PWM signal [9].

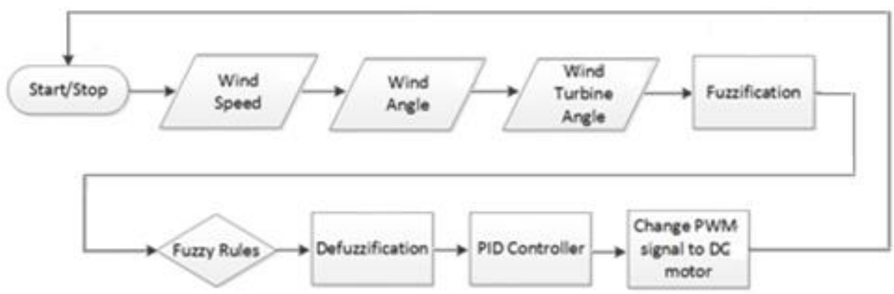

Fig-8: Algorithm flowchart of the control system

Self-tuning Fuzzy-PID controller is auto-adaptive controller that is used to determine Kp, Ki and Kd parameters of PID controller. Mamdani's fuzzy inference method is used the system with two inputs and one output.The controller uses the error and the rate of change of error as its inputs while Kp, Ki and Kd are outputs respectively. Fig.9 shows the Kp, Kd and Ki gains. Fuzzy control theory is an automatic control theory based on fuzzy set theory, To develop a control system with classical Fuzzy Logic Control (FLC) theory, following steps have been to be adopted: (i) fuzzification: the operation directed towards determining the inputs and output membership functions; (ii) setting up the rules, (iii) defuzzification: the operation directed towards converting the fuzzy result of the rules into output signal.

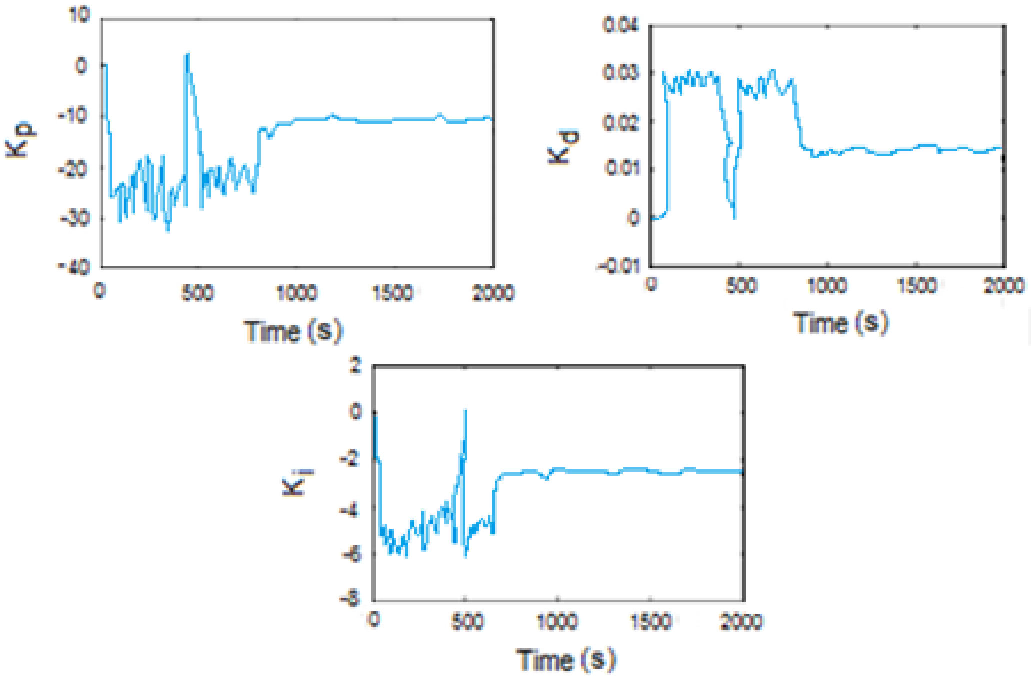

Fig-9: Kp, Kd and Ki gains for wind power

In this paper, the fuzzy logic controller is present to track the maximum power from the wind by using the rotor speed of the wind. Fuzzy logic is the best controller to track the maximum power point. The inputs of the fuzzy controller are the error between the actual rotor speed and the estimated rotor speed and change in this error. Output of the fuzzy controller is the duty cycle of the boost converter. By adjusting the duty cycle of the boost converter the maximum power will be achieved. An FLS comprises of three basic blocks, namely, Fuzzification, Inference system and Defuzzification as shown in Fig. 10 [10].

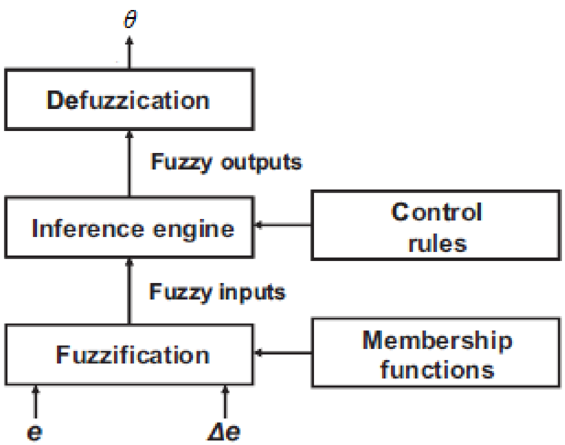

Fig-10: Fuzzy Logic System

At first, the various terms are selected to form the fuzzy rules. Based on these terms, the different rules are formed. The linguistic terms used here are: 1. Error (Very Negative, Negative, Small Negative, Zero, Small Positive,

Positive, Very Positive) 2. Derivative of error (Negative, Zero, Positive). Shown in Fig. 4a and b, the triangular membership functions (MFs) are applied for the fuzzification. "IF-THEN" rules are designed for the fuzzy inference engine. For defuzzification, the center of the gravity method and appropriate MFs illustrated in Fig. 11, are used.

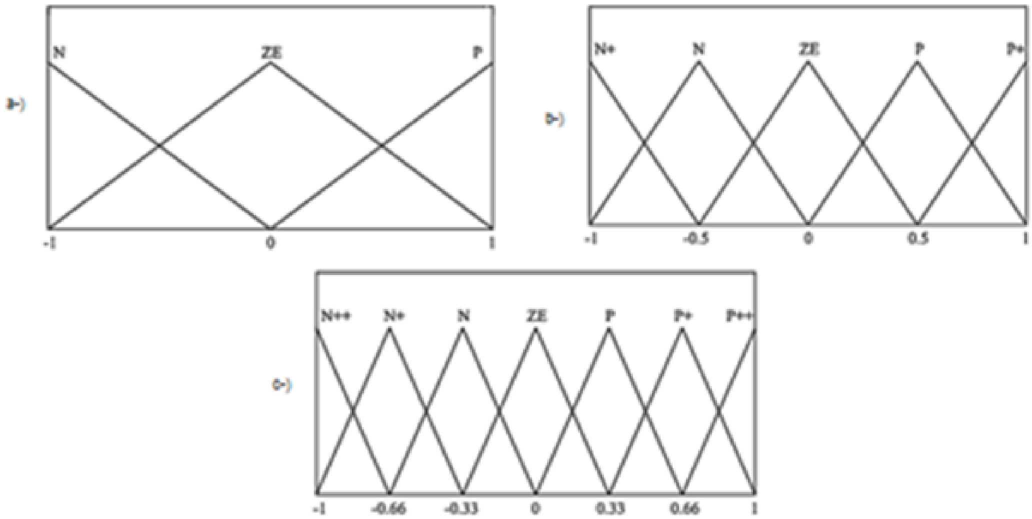

Fig-11. a-) The first input membership functions, b-) the second input membership functions c-) the output membership functions

In the study fuzzy controller, totally 21 rules are formed and it shown in table 2. If the error is positive and change in error is negative then the duty cycle will be positive. The rules process is called as fuzzification. The defuzzification is performed which converts the fuzzified value into defuzzified value. It gives the final output value. The defuzzification is shown in Fig. 12.

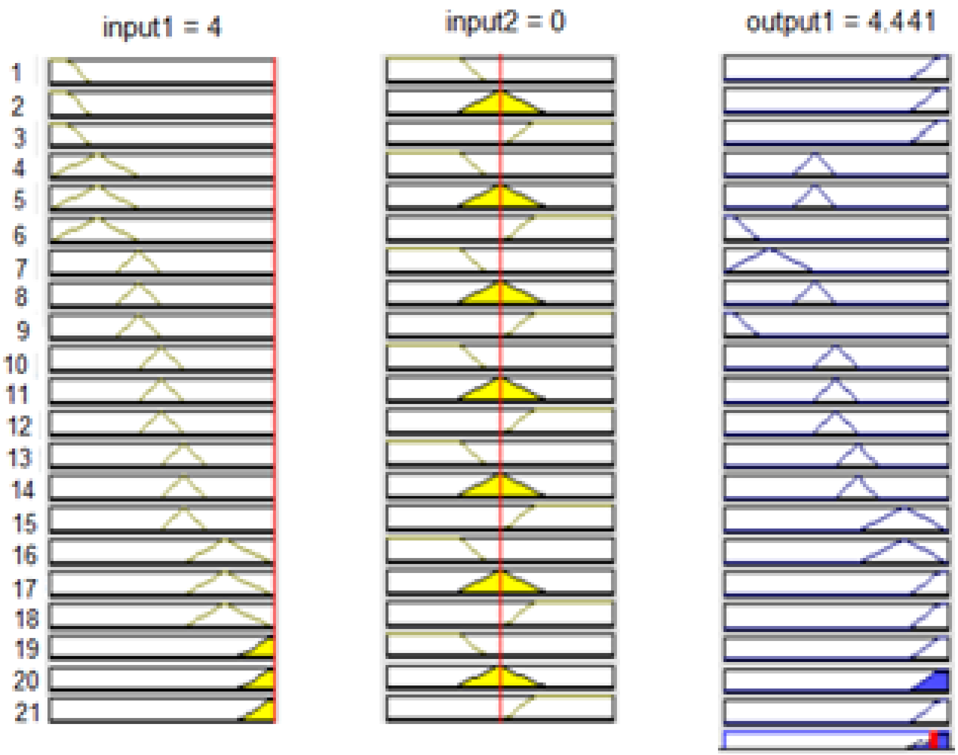

Fig-12: Defuzzification

In the Matlab/Simulink, Simulation of the Fuzzy-PID controller is done for the regulation of output power value Pr = 5 KW. A test simulation is performed on a wind energy conversion system is shown in Fig. 12 with the parameters as described in Table 3.

Table-3: Wind energy convertion system parameters

Output Power	5 kW
Wind Speed	10 m/s
Output Power Voltage	220 Volt
Output Power Frequency	25 Hz
Gear Box Ratio	4

Fig.13 shows simulation of the Fuzzy-PID controller in the Matlab/Simulink environment

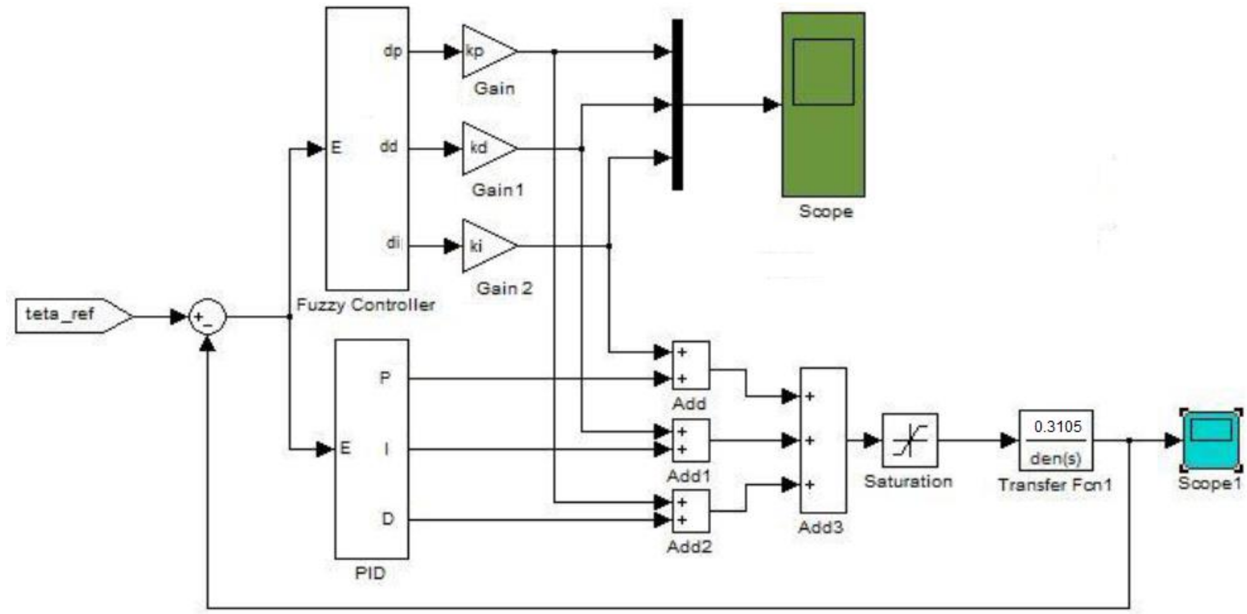

Fig-13: Fuzzy-PID controller simulink model

Below are some of the codes in this study with Matlab14a.

M-File software codes

```
c l e a r a l l , c l o s e a l l , c l c
% Maximum Performance
%Made by : B.Cirak
%Date : 2018−10−29
% Ca l cul a t i on o f t r a n s f e r func t i on o f PID c o n t r o l l e r
s = t f ( ’ s ’ ) ; % f r equency laplce domain
%PID values :
Ki = 0 . 2 ;
Kp = 1 . 8 ;
Kd = 2 . 3 ;
%DC motor values
J = 0 . 0 0 0 0 789 ;
K = 42.3*10ˆ −2;
 R = 35 ;
L = 0 . 0 0 6 14 ;
f = 0 . 1 249 ;
%Trans f e r func t i on o f the plant
Gplant = K/ ( (R+L* s ) *( J* f * s )+Kˆ2)
%Trans f e r func t i on o f the PID c o n t r o l l e r
F = (Kp + Ki/ s + Kd* s ) ;
%Trans f e r func t i on o f the c l o s e d loop system
```



```
Cloop = feedback (F*Gplant , 1 )
f i g u r e
s t ep (Cloop )
legend ( ’PID−c o n t r o l l e r ’ )
g r id on
```

The electronic system has mainly two subsystems illustrated in Fig. 14. The first subsystem consists of four sensors that sends signals to the other subsystem, which includes an Arduino. The Arduino sends signals to the DC-motor, via an H-bridge, controlling the turbine mechanism [11].

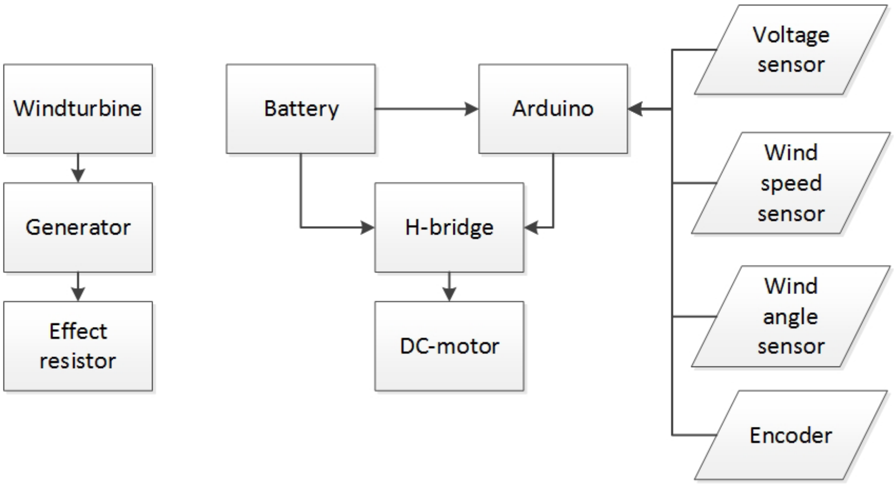

Fig-14: Block diagram of the system and ardunio

Below are some codes in this work with ardunio

Some of Ardunio codes

```
% Maximum Performance
%Made by : B.Cirak
%Date : 2018−10−29
*/
//−−−−−−−−−−−−−−−−−−−−−−−−−PID−−−−−−−−−−−−−−−−−−−−−−−−
double Input , Output , Se tpo int ;
//Gain parameters
double Kp = 1 . 8 ;
double Ki = 0 . 2 ;
double Kd = 2 . 3 ;
// i n i t i a t e PID c o n t r o l l e r
PID myPID(&Input , &Output , &Setpoint , Kp, Ki , Kd, DIRECT) ;
//−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−−
//−−−−−−−−−−−−−−−−−−Fuzzy PID−−−−−−−−−−−−−−−−−−−−−−−−
double e r r o r = 0 ;
double de = 0 ;
double l a s tEr r o r = 0 ;
unsigned long fuzzyTime ;
unsigned long lastTime ;
double PB = 3 7 ;
double PS = 1 8 ;
double ZO = 0 ;
double NS = −1 8 ;
double NB = −2 5;
//Gain values in the d i f f e r e n t membership f u n c t i o n s
double KpPB = 1 ;
double KpPS = 1 ;
double KpZO = 0 ;
double KpNS = −1;
double KpNB = −1;
```

double KiPB = 0 . 1 3 ;
double KiPS = 0 . 0 64 ;
double KiZO = 0 ;
double KiNS = −0.064;
double KiNB = −0.13;
double KdPB = 3 ;
double KdPS = 2 ;
double KdZO = 0 ;
double KdNS = −2;
double KdNB = −3;
//−−−

Simulation Results

This paper did simulation and data analysis based on the meteorolycal data and actual data between 1-30 days on September of 2018 of a wind turbine in Karaman. Using Matlab combined with Labview , took every 10 minutes as a sampling time interval and set ± 20 % to be the acceptable range of the error. Fig. 15 illustrates typical and characteristic curves of wind speed. The value of the wind speed is 10 m/s respectively.

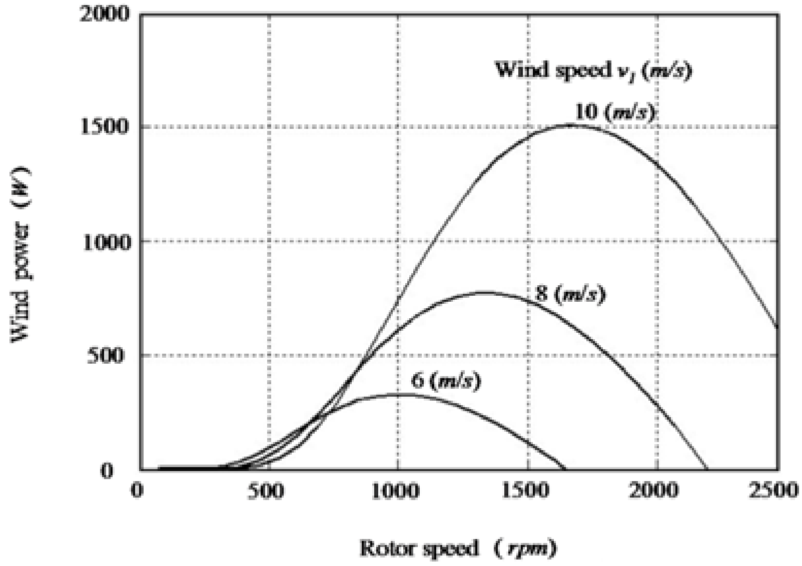

Fig-15: Corelation of wind speed, rotor speed and wind power values

Fig 16 illustrates Coleration of between Cp (performance coefficent) and λ (Tip speed ratio) in characteristic different values of pitch angle (θ).

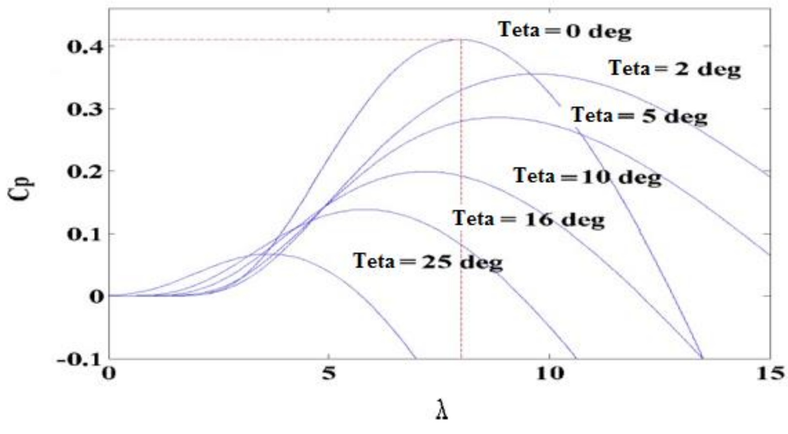

Fig-16: Coleration of between Cp (performance coefficent) and λ (Tip speed ratio) in different values of pitch angle (θ)

Fig. 17 illustrates characteristic curves of values that is Coleration of between Torque and Rotor speed and Output Power.

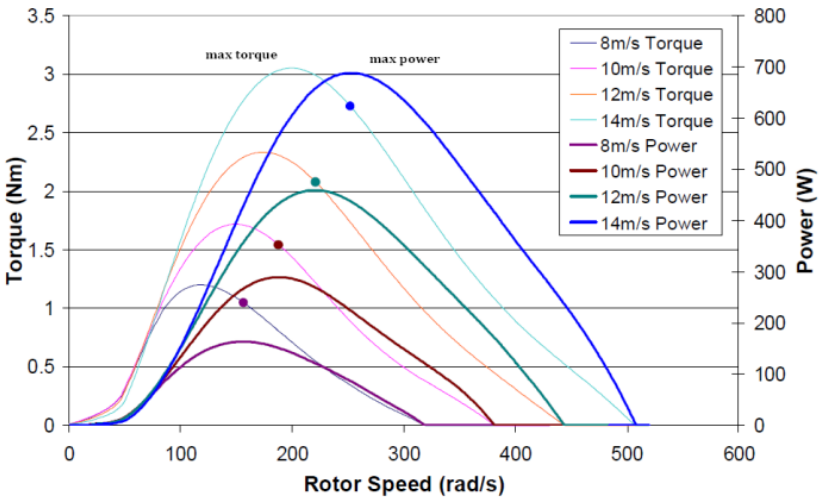

Fig-17: Coleration of between Torque, Rotor speed and Output Power

Table-4: Comparision of PID and Fuzzy-PID controller simulation results

Parameters	PID	Fuzzy-PID
Settling time (s)	1.7	0.5
Rise time (s)	1.9	0.68
Delay time (s)	1.8	0.6
Overshoot (%)	0.1	0.3
Steady state error	0	0

The unit step response of wind turbine pitch control system is shown in Fig. 18. Time domain specifications are observed from the response graphs and tabulated in Table 4. With PID controller, we observed more rise time (1.9sec) and less settling time (1.7sec) compared to conventional PID controller and a very little overshoot (0.1%).With Fuzzy-PID controller, we observed more rise time (0.68 sec) and less settling time (0.5sec) compared to conventional PID controller and a very little overshoot (0.3%). Hence the Fuzzy - PID gives a better control for the pitch angle of the wind turbine system. With Fuzzy -PID controller, compared to both conventional PID and fuzzy logic controller no overshoot (only 0.03%). This is because the damping coefficient after adding an Fuzzy-PID controller is greater than 2 value which results in system being over damped and hence no overshoot. However, the performance is not better in terms of rise time when compared to conventional PID controller.

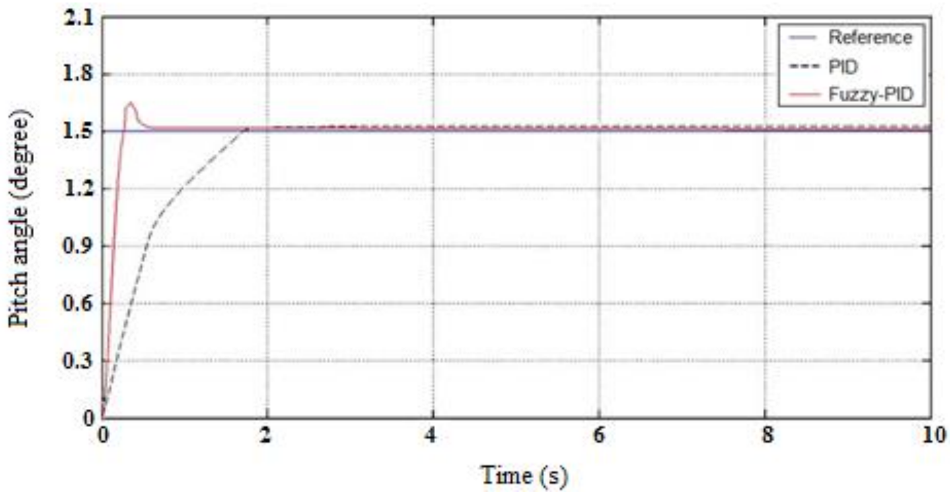

Fig-18: Comparision of unit step response of wind turbine pitch controllers

Table-5: Comparison of PID and Fuzzy-PID controller simulation results

Parameters	PID	Fuzzy-PID
Settling time (s)	35	17
Rise time (s)	1.9	0.68
Delay time (s)	12	5
Overshoot (%)	11	1
Steady state error	0	0

The unit step response of wind turbine power control system is shown in Fig. 19. Time domain specifications are observed from the response graphs and tabulated in Table 5. With PID controller, rise time (1.9sec), delay time (12s) and less settling time (35sec) compared to conventional PID controller and overshoot (11%).With Fuzzy- PID controller, more rise time (0.68 sec), delay time (5s) and less settling time (17sec) compared to conventional PID controller and a very little overshoot (1%). Hence the Fuzzy - PID gives a better control for the output power of the wind turbine system.The compared to both conventional PID and fuzzy logic controller difference overshoot (10%). Fuzzy-PID controller is greater than 10 value which results in system being over damped and hence the performance is better in terms of rise time when compared to F uzzy-PID controller.

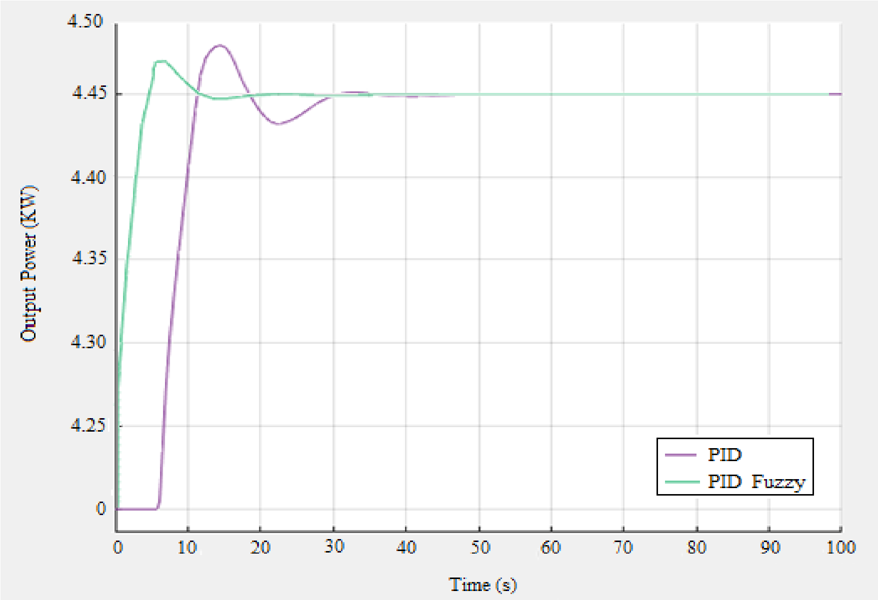

Fig-19: Comparision of tuning performance system

Fig. 19 gives the comparison between fuzzy- PID controller and a simple PID controller, when the wind speed is above the rated wind speed, the generator's output power can be maintained constant near the rated power through the blade pitch angle adjustment. Besides, PID and PID-Fuzzy logic controller outputs according to 4.450 kw power value of the system created.The study with PID controller is shown as blue lines on the graphics and PID coefficients respectively are Kp =1.2, Kd = 0.003, Ki = 0.001.

CONCLUSION

In this study, the wind turbine pitch control system mathematical model and simulated with PID and Fuzzy-PID controllers using Matlab. The PID controller produces the response with lower delay time and rise time, it has oscillations with a peak overshoot of 0.1%, which causes the damage in the system performance. To suppress these oscillations fuzzy logic controller is proposed to use. The PID gains are tuned by using fuzzy logic concepts, the results showed that this design can effectively suppress the steady state error to zero and the system has minimum delay time (0.6 seconds), quick settling time (0.5 seconds) and better stability. Fuzzy-PID controller gives relatively fast response for unit step input. It is much better to realize the control of pitch system and to guarantee the stability of wind turbine output performance of the power. Maximum performance tracked from the wind using Fuzzy-PID controller. The maximum output power from the wind is 4.450 KW is evaluated using Fuzzy-PID controller. The simulation results of fuzzy-PID controller have been compared with the simulation results of the conventional PID controller. When the wind turbine controlled with classic PID, increase in Ki parameter is caused overshoot. And run time is too long as Ki parameter decreases. The simulation results represent that shows the dynamic and steady state performances. Some advantages of using fuzzy controller are quick response, limit insensitivity and universal control algorithm.

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