Pitch Control of Wind Turbine using PID and Fuzzy Logic Controllers.

By

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ABSTRACT

As wind power becomes more widely used in the supply of electricity, research and development on wind turbine power generation increases for the purpose of enhancing the wind turbine ability to generate power for a wider range of operating conditions. Wind turbines can operate within a specific range of wind speeds; wind direction as well is a critical factor for the wind turbine power generation efficiency. For that reason, controllers were developed in recent years to increase the ability of the wind turbine to work outside of its design requirements with the best possible efficiency. Blade pitch angle is the main parameter involved in the control process of the wind turbine, as changing the blade angle of attack with the wind can help control the flow separation on the blade and hence increase the efficiency of the wind turbine and increase the generated power along wider range of wind speeds.

This thesis proposes an updated angle of pitch control approach based on fuzzy logic control to deal with the wind turbine's nonlinear dynamics while also reducing blade loads. A mathematical representation of a wind turbine pitch control system is constructed and evaluated using two controllers: PID and Fuzzy. After comparing the two proposed solutions, the computer simulation results demonstrate that the Fuzzy controller performs well since it governs both the pitch mechanism and the fluctuations and unusual off-design conditions linked with it.

DECLARATION

I certify that this thesis is an original report of my research work, written by me. The experimental work is entirely my own work, the collaborative contributions have been indicated clearly and acknowledged. Due references have been provided for all supporting literature and resources.

I further declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification.

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Name of student: Neela Tripura Sundari

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I certify that I have read this thesis. In my opinion it is/is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Master of Engineering (Electrical and Electronics). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/fully (please circle).

Signature of Principal Supervisor...

Print name of Principal Supervisor...

Date...

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I would like to express my sincere gratitude to all those who have contributed to the completion of this project on "Pitch Control of Wind Turbine using PID and Fuzzy Logic Controllers".

I would like to convey my profound appreciation to my supervisor, Dr. Amin Mahmoudi for his outstanding mentorship, assistance, and motivation for the whole of this research endeavour. His profound understanding and specialized knowledge have played a crucial role in determining the course and excellence of this project.

I would like to express my gratitude to the staff members and administration of Flinders University for their administrative support and help, which greatly aided the completion of this research project.

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1. INTRODUCTION

1.1 Background

Due to the effects of climate change, environmental degradation, and a severe lack of energy, efforts have been made globally to reduce the use of fossil fuels, with a particular emphasis on clean and renewable energy sources. The method of wind energy systems has demonstrated that wind energy is a practical way to meet human needs for energy on a daily basis without posing any risks or depleting the environment. Furthermore, using wind power to provide clean energy and lower costs makes sense.

Wind energy, unlike gas and coal, is highly dependent on the climate and seasons. Wind speed and direction have a significant role in wind turbine efficiency. Wind power systems convert wind energy into electricity. Wind energy is unstable, resulting in varying mechanical strains on wind power systems (Baburajan, 2017).

Kinetic energy can be transformed into electrical power with the aid of wing turbines. According to (Bauer, 2023), as of 2020, large number of wind farms, with each included hundreds and maybe even thousands of wind turbines generated successfully more than 650 GW of electrical power, with installations per year reaching up to 60 GW. Wind turbines are emerging as an increasingly important electrical power source, with many nations using wind turbines to cut energy costs and usage of fossil fuels. Mentioned in (Evans, Strezov, & Evans, 2009) research, wind offers minimum relative greenhouse-gas emissions, minimum requirements of water consumption, and the minimum environmental impact when compared to other sources such as photovoltaic, hydromechanical, geothermal, coal burning, and gas turbines energy. The main function of smaller wind turbines is battery charging and to power distant equipment like warning traffic signals. Larger turbines may be beneficial to regional power generation and sell surplus electricity again to the energy company via the electrical grid (Righter, 2011).

Wind turbine has two sorts of models: vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). Horizontal axis turbines are the most common for wind power systems. The vast bulk of wind power generated now originates from massive triple-bladed horizontal-axis wind turbines (HAWT), with blades facing the wind.

These turbines must be facing the wind, with the low-speed rotor shaft and the generator located inside the nacelle at the top of the tower. A basic wind vane guides small turbines. However, bigger turbines often employ a wind sensor in conjunction with a yaw mechanism. Most include a drivetrain that converts the low-speed revolution of blades into a faster spin appropriate for powering an electrical generator (Righter, 2011). Vertical-axis wind turbines (VAWTs) feature a main rotor shaft positioned upwards. One benefit of this layout is that the turbine has no requirement to be directed at the wind to be efficient, which is useful in areas where the wind direction varies greatly. It is also advantageous to embed the turbine inside a building since it is intrinsically limited in steering. In addition, the generator and transmission may be situated close to the surface, with a direct-drive from the rotating part to the transmission mounted on ground surface, resulting in easier maintenance. Nevertheless, these layouts generate far fewer electricity when aggregated over an extended period, and this can be considered as a big disadvantage of the VAWT (Barnard, 2014).

Figure 1 – Difference between Horizontal & Vertical Axis wind turbines in construction

Moving on to the dynamics of a wind turbine, due to high inertia, control dynamics need gradual speed changes. In windy conditions, controlling the speed using a power converter becomes challenging. Pitch control is a quick way to manage power flow, especially at high speeds.

Figure 2 depicts the model under discussion. The output of the generator may be adjusted to match the requested power. The wind turbine manages its aerodynamic power using a pitch-able blade. The dashed line shows how much angle of pitch may be altered. A mechanism (e.g., drivetrain) connects the high- and low-speed shafts. The turbine blades drive the low-speed shaft, generating aerodynamic power. The electric generator loads the high-speed shaft with electricity (Muljadi & Butterfield, 2000).

Figure removed due to copyright restriction.

Figure 2 – Variable speed wind turbine physical system description (Muljadi & Butterfield, 2000)

1.2 Problem Statement

This research aims to investigate the performance of a wind-turbine generator with variable speed and pitch control under turbulent conditions. The objectives are to model the wind turbine aerodynamic model along with the generator and drivetrain models, and then design two types of controllers that can achieve a steady state generator output during wind speed changes. Comparison between the two controllers is required prior to selecting the best control methodology.

1.3 Research objective

1.3.1 Wind turbine studies

Fixed-speed wind turbines (FSWTs) are commonly used to enhance the lifetime and safety of wind turbines. They operate at the same generator and rotor speeds without taking speed of the wind into consideration. Nevertheless, FSWT is difficult to optimize wind power over a large range of wind speeds. The variable-speed wind turbine (VSWT) was designed to improve wind turbine efficiency across a large range of wind speeds (Baburajan, 2017). SIMULINK offers mathematical models for wind turbines, including aerodynamics, drive-train, generator, torque controller, and pitch controller. To begin the investigation, a thorough grasp of all wind turbine components is necessary. Theoretical mathematics equations are necessary prior to building the simulation models.

1.3.2 Pitch controller studies

Various pitch control solutions have been shown to enhance wind turbine performance. Research by Muljadi and Butterfield (2000) demonstrated that a well-tuned PID controller can help wind turbines follow their planned power production. To further improve performance and reliability, exploring non-linear pitch control approaches like fuzzy logic algorithms is crucial due to the inherent nonlinearities of wind turbines. More research is needed to understand and compare different pitch control mechanisms, such as PID, fuzzy logic, and gain tuning, which will aid in the implementation and prediction of control techniques.

1.4 Organization of thesis

The thesis is structured as follows: Chapter 2 includes a literature review about wind turbines in general and mechanisms and strategies of wind turbine pitch control. The next chapter focuses on the wind turbine model in which different parts of the wind turbine assembly are modeled. The fourth chapter includes the design of pitch controllers, where two different controller architectures are modeled: PID & Fuzzy logic controller. chapter five offers the results of the assembled models, and discussions about results and comparisons between both controllers are presented in sixth chapter,
and finally, a conclusion in seventh & final chapter.

2. LITERATURE REVIEW

2.1 Wind turbine

Wind turbines extract electrical power from the wind and modulate it for grid delivery. Traditional horizontal-axis wind turbines consist of the following components:

- The rotating part, that accounts for roughly 20 percent of the wind turbine price, contains the blades that transform energy from the wind into mechanical rotation.
- The generator, accounting for 34 percent of price of the wind turbine, comprises a generator that produces electricity, control devices, and a drivetrain (e.g., planetary transmission), that converts low-speed input rotation into rapid rotation to generate power.
- The main tower and rotary tilt mechanism make up around 15 percent of the wind turbine's price.
- In an emergency, the brake uses mechanical, electrical, or hydraulic forces to stop the rotor.
- The pitch controller starts the machine at cut-in wind speeds and shuts it off at cut-out wind speeds to offer protection and maximize the power delivery time of the turbine. Turbines cannot function over 55 mph due to potential damage from high winds. Pitch adjusts wind turbine blades to manage rotor speed and keep it below the operating limit of 55 mph.

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Figure 3 – Main components of variable speed horizontal axis wind turbine (Bauer, 2023)

As an example, a 1.5 MW rated-power wind turbine (from the type that is usually utilized in the US) incorporates a tower that is around 80 m in height. The rotating mechanism (blades and nose cone) is approximately 80 m in diameter. The housing of the generator (called the Nacelle), measures around15.24 m in length and its weight may exceed 300 thousand kg (Bauer, 2023).

2.1.1 Advantages

Wind turbines, like solar panels, are considered the cheapest forms of renewable power. Prices for wind turbines reduced as technology improved. Furthermore, no market can compete with wind power currently (although this can change in future), as wind is a natural resource that is available for free, with the majority remaining untapped. The primary expense of small wind-turbines is the purchasing and assembly procedure, that typically ranges between $48,000 and $65,000 for each assembly. Most of the time, the entire quantity of energy extracted exceeds the price of the turbine assembly & purchase (Rueter, 2021).

2.1.2 Drawbacks

The harmful effects of wind power involve an impact on animals, which could be mitigated if proper measures are utilized, such as locating wind turbines away from sensitive locations, screening from landscape features and painting the blades black to help deter birds from colliding with them. Wind energy is erratic and not a stable source of power. It is available only when the wind blows, not when electricity is required. Turbines could be erected on hills or mountains to enhance their accessibility to wind. Nevertheless, this restricts their placement options. Wind turbines contain flickering lights that alert pilots to prevent crashes. People in residential areas near wind farms, particularly in regions without electricity, have objected that the flickering lights are a nuisance kind of light-pollution (Hosansky, 2011).

2.2 Wind turbine pitch control architectures

The pitch control allows you to enhance the amount of wind energy captured by your turbine. To begin, use an electronic controller to continuously monitor the turbine's power production. When wind speed exceeds the operating limitation, a signal is sent to the pitch control mechanism, causing the rotating blades to spin a little away from wind and adjust the angle of attack with incoming air. When the wind dies down, these rotating blades are redirected again into it. Wind turbines using such control systems are referred to as pitch controlled.

2.2.1 PID control architecture

Turbine rotor speed may be adjusted using Proportional, Integral, and Derivative gain combinations to maximize power output without relying on wind speed estimates. The traditional PID controller is a linear controller that uses the proportion (P), integration (I), and differential (D) of the error deviation as input variables for the control function. The output acts on the regulated target (T).

2.2.2 Fuzzy logic control architecture

Some research employs fuzzy logic and particle swarm optimization to obtain optimal control of wind turbines, without calculating wind speed. In (Ramírez, Haber, Peña, & Rodríguez, 2004), fuzzy-logic control approaches are utilized to improve blade pitch-control of the turbines that are supplying the grids. Another paper (Muljadi & Butterfield, 2000) explains control for individual blade pitch using the feed-forward machine learning in sophisticated double-bladed wind turbines. Another author (Opie, 2018) investigates a multivariable design strategy for controlling huge wind turbines. This multivariable design strategy controls output power while running at varying speeds, allowing for optimal power extraction at various wind speeds.

2.2.3 Performance comparison of proposed architectures

At the start of the research, a conventional PID controller was used. However, its performance was subpar due to oscillations causing damage to the wind turbine's pitch actuator servos. Although oscillations are minimized by 7% of their initial value, using a single set of PID settings reduces robustness. To increase the system's robustness and reduce oscillations, dynamic PID parameters were used, which means that the system continuously changes PID gains by learning from the system response.

Furthermore, the fuzzy logic and gain scheduling approaches are utilized to optimize PID settings. The fuzzy pitch controller was tested and found to provide good control with minimal oscillations and overshoot. However, the steady error is too great, potentially leading to low power output efficiency. Fuzzy logic and gain scheduling optimized PIDs outperform other algorithms in terms of resilience and performance (Baburajan, 2017).

2.3 Research gaps

Previous research cited in this paper have some gaps that need to be addressed during the work on this thesis. The first gap that needs to be addressed was the generator model, as most of the papers tended to model the generator mathematically using the ideal Newton's laws modelling equations, which does not consider some parameters such as the electrical load on the generator, the resistance/impedance of the transmission lines and the internal resistance and inductance of the generator itself. To improve on this point, a physical generator model in Simscape was used in this study, with the addition of grid load and transmission lines. Another gap was in the PID tuning method, with previous research opting for outdated tuning methods such as Ziegler-Nichols PID tuning methodology or trial & error methods. In Simulink, an automatic tuning algorithm was used in this thesis which depends on optimization techniques that ensures giving the best gain prediction for the required system speed and robustness. The final gap was in the pitch angle membership in fuzzy logic design, where most of the thesis opt for a smaller range of pitch angle between -10 to 20 degrees, which can have a negative effect on the logic during the fuzzification process. To address this gap, a larger range will be utilized with more input combination probabilities.

3. METHODOLOGY

3.1 Wind Turbine Model

3.1.1 Aerodynamic model

The aerodynamic mathematical model converts wind power to mechanical rotation and rotates triple bladed turbines. The function used is provided as follows.

$$P_t = \frac{1}{2} C_p A \rho v^3 ---------------------[1]$$

Where, P_t is the turbine power, A is the rotor area, ρ is the air density, v is the wind speed, and C_p is the power coefficient. The later can be computed with the aid of equation (2):

$$C_p = c_1 \left[c_2 \frac{1}{\beta} - c_3 \varphi - c_4 \varphi^x - c_5 \right] \times e^{\left(-c_6 \frac{1}{\beta}\right)} ------ [2]$$

Where, coefficients c_1 to C_6 and x are empirical constants for various wind turbine types, φ is the blade pitch angle and β is a parameter computed using the following formula:

$$\beta = \frac{1}{\left(\frac{1}{\lambda + y_2 \varphi} - \frac{y_1}{1 + \varphi^3}\right)} --------------[3]$$

Where, y_1 & y_2 are empirical constants with the values of 0.035 and 0.08, respectively, according to (Baburajan, 2017), and λ is the tip speed ratio (TSR) and can be calculated as follows:

$$\lambda = \frac{\omega R}{v} ----------------------[4]$$

Where, ω is the speed of the rotor, and R is the length of the blade. This model for the wind turbine aerodynamics mentioned in equation (1) was implemented in Simulink as shown in figure (4). The power coefficient subsystem represented by equation (2) is shown in figure (5). In figure (5), the Beta subsystem block contains the model representation of equations (3) and (4), where rotor speed, wind speed and pitch angle are utilized to calculate tip speed ratio and hence calculate the β parameter, which in turn is used in the power coefficient calculation process. The parameters used while modelling the aerodynamic wind turbine model according to (Baburajan, 2017) are shown in Table (1).

Table 1 – Aerodynamic model parameters

Parameter	c_1	c_2	c_3	c_4	c_5	c_6	ρ	x	$R(m)$
Value	0.5	116	0.4	0	5	21	1.225	0	35

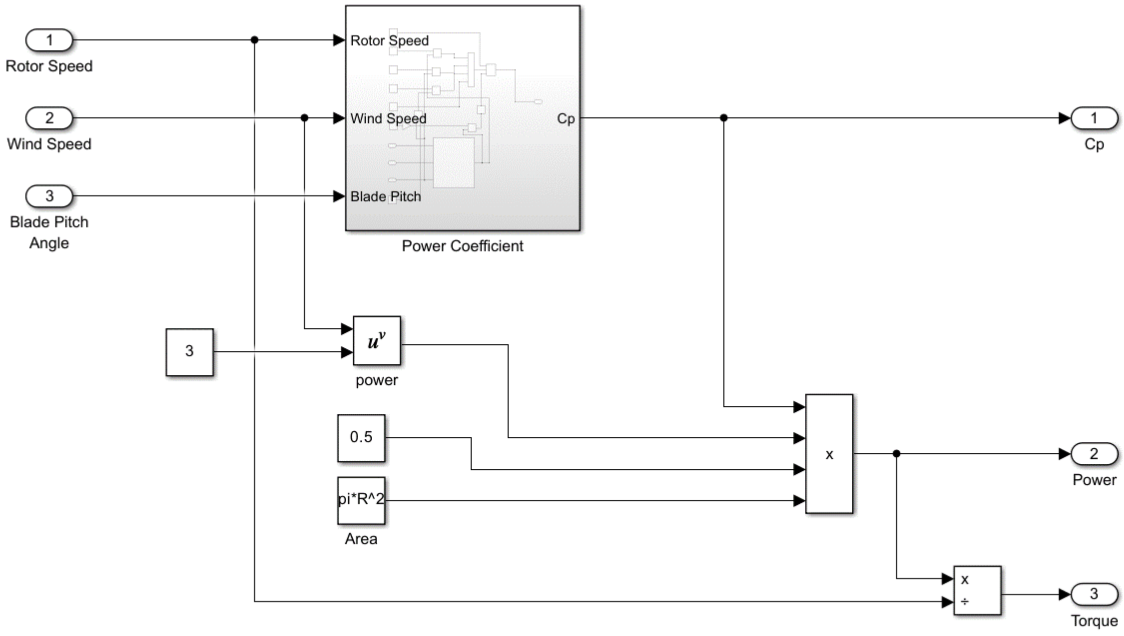

Figure 4 – Wind turbine aerodynamics mathematical model

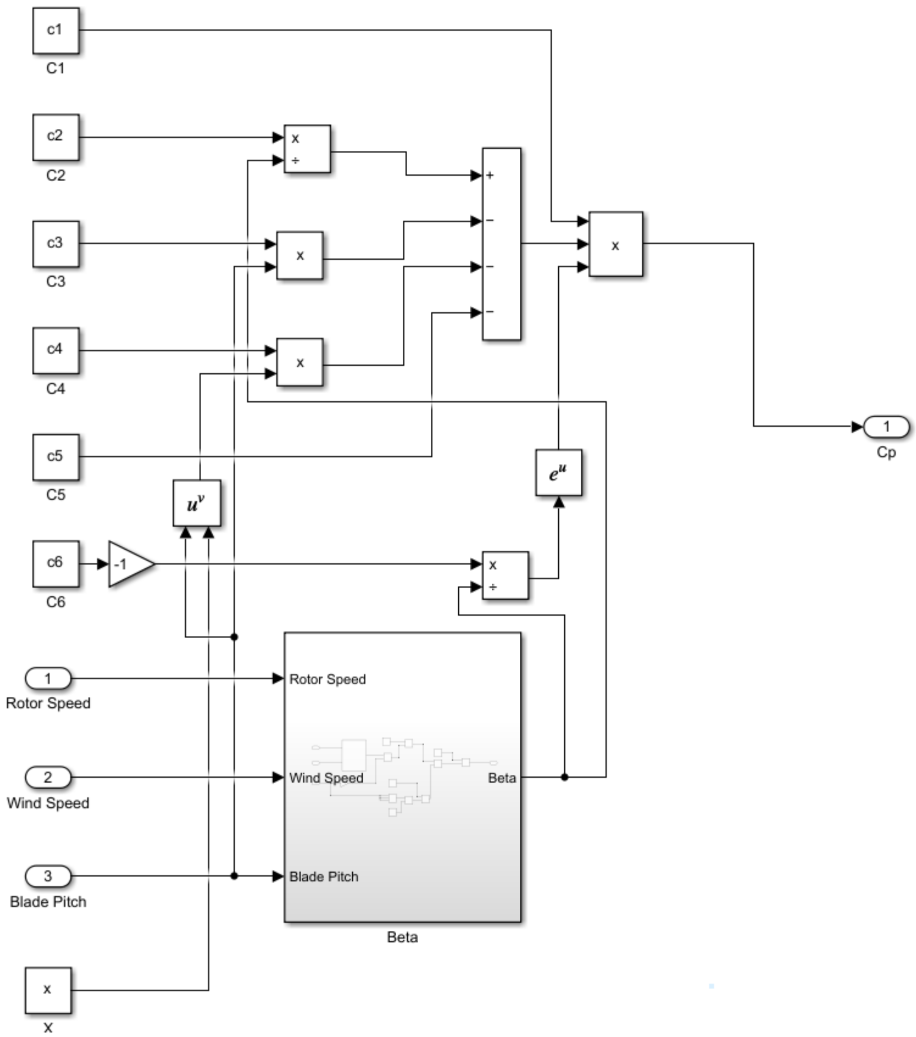

Figure 5 – Power coefficient calculation subsystem

3.1.2 Drive-train model

Newton's 2nd law of motion states that:

$$\sum T = J\frac{d\omega}{dt} = J\frac{d^2\theta}{dt^2}$$

Where, J is the wind turbine moment of inertia, θ and ω are the angle and angular speed of the drivetrain. Applying this general law, the dynamical representation of the drivetrain can be represented by the differential equations (5) and (6):

$$J\frac{d^2\theta}{dt^2} = T_i - \left(K\theta + B\frac{d\theta}{dt}\right) - - - - - - - - [5]$$

$$\frac{d\theta}{dt} = \omega - - - - - - - - - - - - - - - - - - [6]$$

Where, T_i is the input torque, K is the stiffness coefficient and B is the damper coefficient. Taking Laplace transform for equation (5):

$$Js^2\theta = T_i - K\theta - Bs\theta - - - - - - - - - [7]$$

Rearranging equation (7):

$$\frac{\theta}{T_i} = \frac{1}{Js^2 + Bs + K} - - - - - - - - - - - [8]$$

Equation (8) gives the transfer function of the drivetrain and is modeled in Simulink as shown in figure (6). Drivetrain model parameters were obtained from previous literature (Baburajan, 2017) as shown in Table (2).

Table 2 – Drivetrain model parameters

Parameter	$\boldsymbol{B}$ $(\boldsymbol{N.m.s/rad})$	$\boldsymbol{J}$ $(\boldsymbol{kg.m^2})$	$\boldsymbol{K}$ $(\boldsymbol{N.m/rad})$
Value	2	0.75	2000

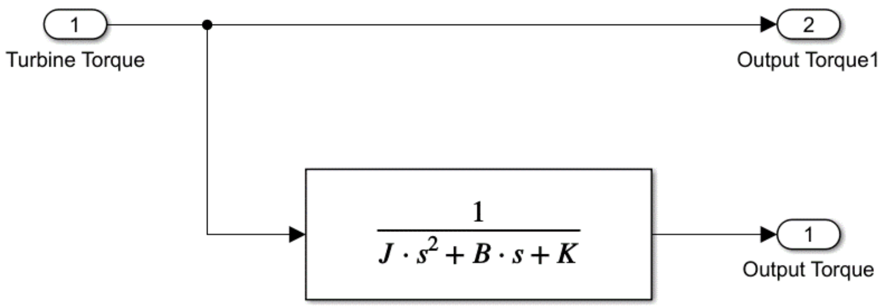

Figure 6 – Drivetrain model

3.1.3 Generator model

The generator model is built based on the Asynchronous Machine block in Simulink. This block models asynchronous induction generator. The block takes the mechanical torque as input and gives three-phase electrical power as output, along with physical signal outputs such as generator shaft speed and electromechanical torque.

A three-phase voltage/ampere measurement block is added to calculate the output voltage and current from the generator and using these values to calculate the output electrical power. Figure (7) shows the layout of the generator model in Simulink. Table (3) shows the parameters used in the generator model.

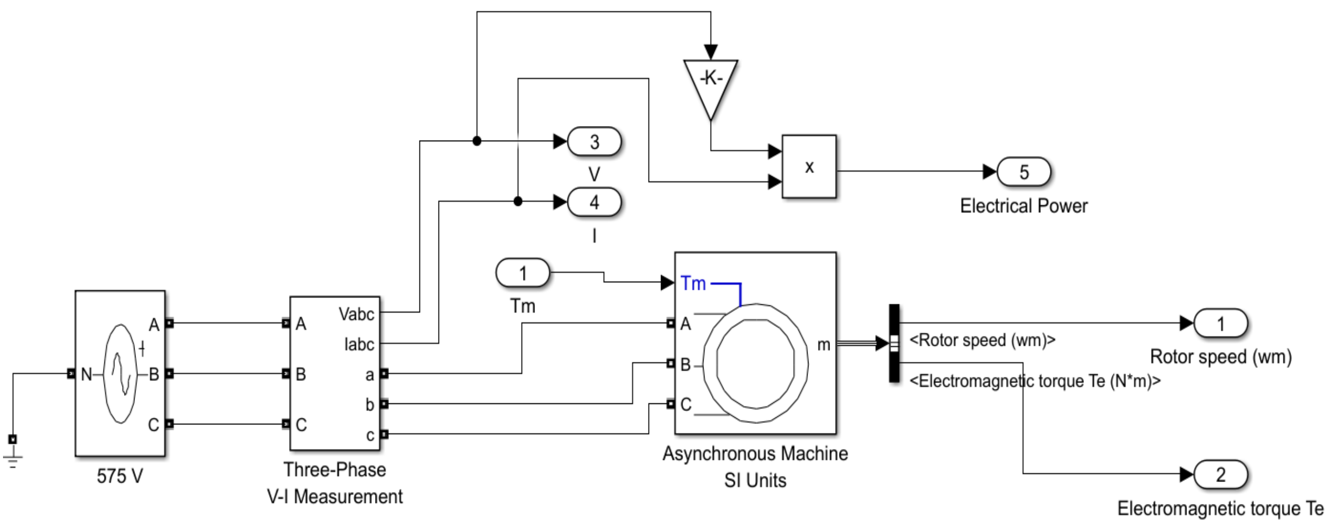

Figure 7 – Generator model

The generator is modelled in SIMULINK as an asynchronous machine as shown in figure (7), with the main input to the machine is the torque output from the drive train. The Asynchronous machine block gives an output physical three-phase electrical signal (A, B & C), which passes through a

Voltage/Ampere measurement block to measure the three-phase parameters, before it is supplied to the grid (represented by an AC load block). The Asynchronous machine block gives measured outputs for the generator rotational speed and electromagnetic torque.

Table 3 – Generator model parameters

Parameter	Value
Nominal Power (kW)	100
Nominal Voltage (V_{rms})	575
Nominal Frequency (Hz)	50
Stator Resistance (Ω)	0.5968
Stator Inductance (H)	0.0003495
Rotor Resistance (Ω)	0.6258
Rotor Inductance (H)	0.005473
Mutual Inductance (H)	0.0354
Inertia Constant (s)	0.05
Friction Factor	0.005879
Pairs of poles	2

3.2 Pitch controllers' design

3.2.1 Conventional PID Pitch Controllers

The traditional PID controller can be defined as a linear controller that uses the proportional (P), integration (I), and differential (D) of the error as input variables for the control block. The output is then applied to the controlled target. The concepts are depicted in Figure (8). Also, equation (9) represents the PID controller mathematically.

$$C(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d(e)}{dt} - - - - - - - - [9]$$

Where, $e(t)$ is the error between the actual state and demand state (setpoint).

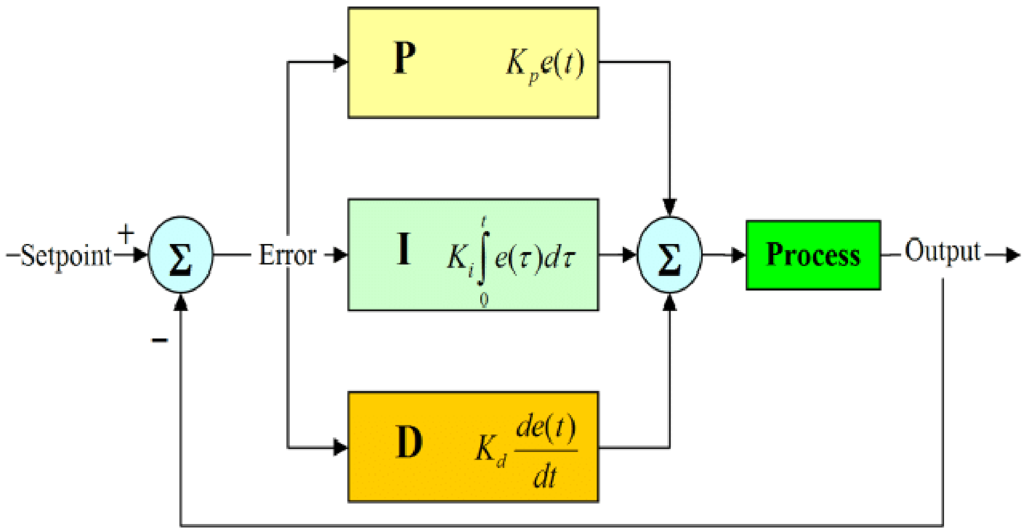

Figure 8 – PID Controller basic architecture

The continuous system PID block in Simulink is used to model the PID controller. With the auto tuning ability in Simulink, the controller was tuned for least settling time and maximum robustness using the PID tuning tool. The tuned controller has the final gains shown in table (4)

Table 4 – PID Controller Gain Values

Parameter	Value
K_p	-5245.8041
K_i	-10661.6187
K_d	-81.7046
Filter Coefficient (N)	41.8694

3.2.2 Fuzzy logic Pitch Controllers

A fuzzy control framework is an automation system built around fuzzy logic - a mathematical technique that evaluates analog input data in terms of logical parameters with continuous values between 0 and 1, as opposed to traditional or digital logic, which works on discrete amounts of 1 or 0. Fuzzy logic is commonly utilized for machine control. The word "fuzzy" alludes to the reality that the logic used may cope with things that cannot be represented as "1" or "0" but instead as "partially 1."

While genetic algorithms and neural networks may have efficacy to fuzzy logic in many cases fuzzy logic stands out for its ability to convey solutions in a manner understandable to humans. This feature facilitates leveraging expertise in controller design streamlining the automation of tasks currently carried out by humans. Fuzzy logic systems excel at emulating decision making processes, capable of handling vague information akin to how humans rely on experience and intuition rather than precise data. This adaptability enables the creation of control systems that can adjust to changing circumstances and uncertainties like operators would enhancing the intuitiveness and alignment with human knowledge, in automation processes.

The fuzzy logic controller that will be used here will take two inputs, which are the error between the demand and computed generator shaft speed, and the derivative of this error. The controller will give a single output, which is the pitch control angle. First step was to create a distribution function for the two inputs and the output, Gaussian distribution function was selected and the distributions for the inputs and output are shown in figures 9 to 11 (Hájek, 1998).

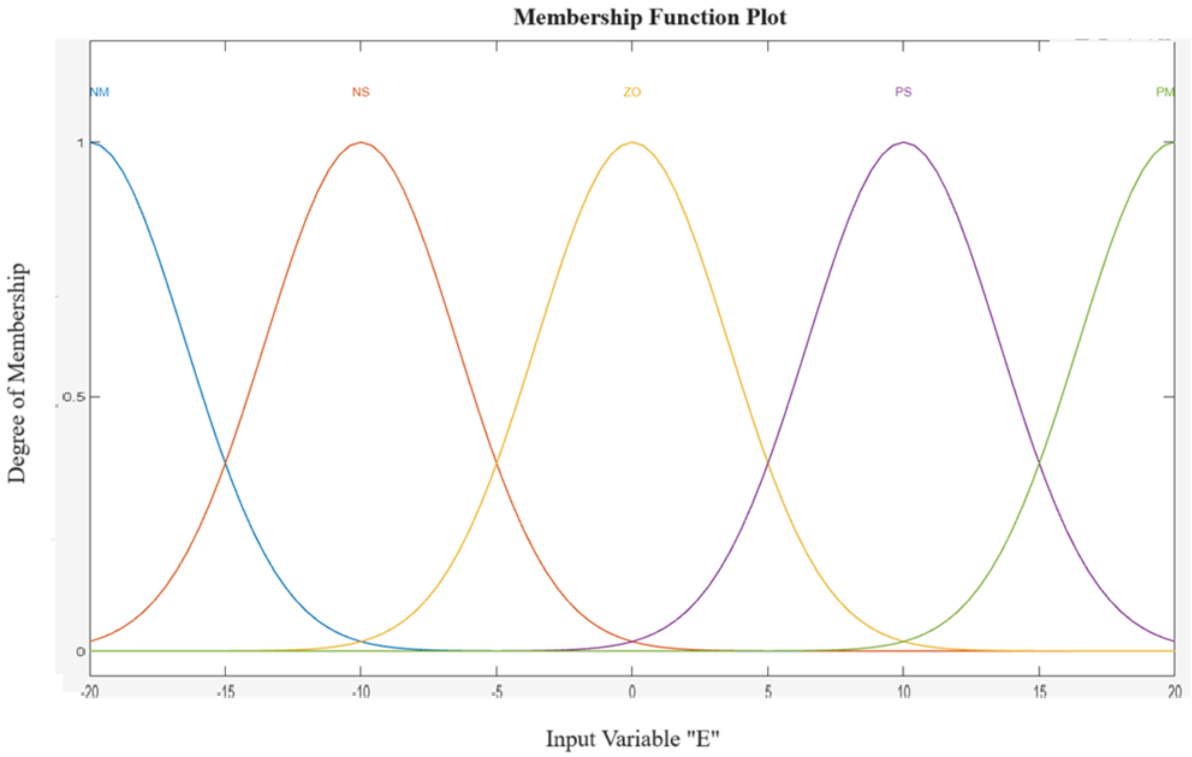

Figure 9 – Input one "error" (E) membership function

A membership function is a technique that is used to solve practical control problems with the aid of experience learning instead of knowledge. In Fuzzy logic controllers, membership function defines fuzziness properties (All the information in a fuzzy set), regardless of the type of the fuzzy sets being discrete or continuous. As shown in figures 9, 10 and 11, membership functions are represented graphically.

Also, in figures 9, 10 and 11, there are five distributions: Negative medium (NM), Negative Small (NS), Zero (ZO), Positive small (PS) and positive medium (PM). These are the different values for each of the input parameters.

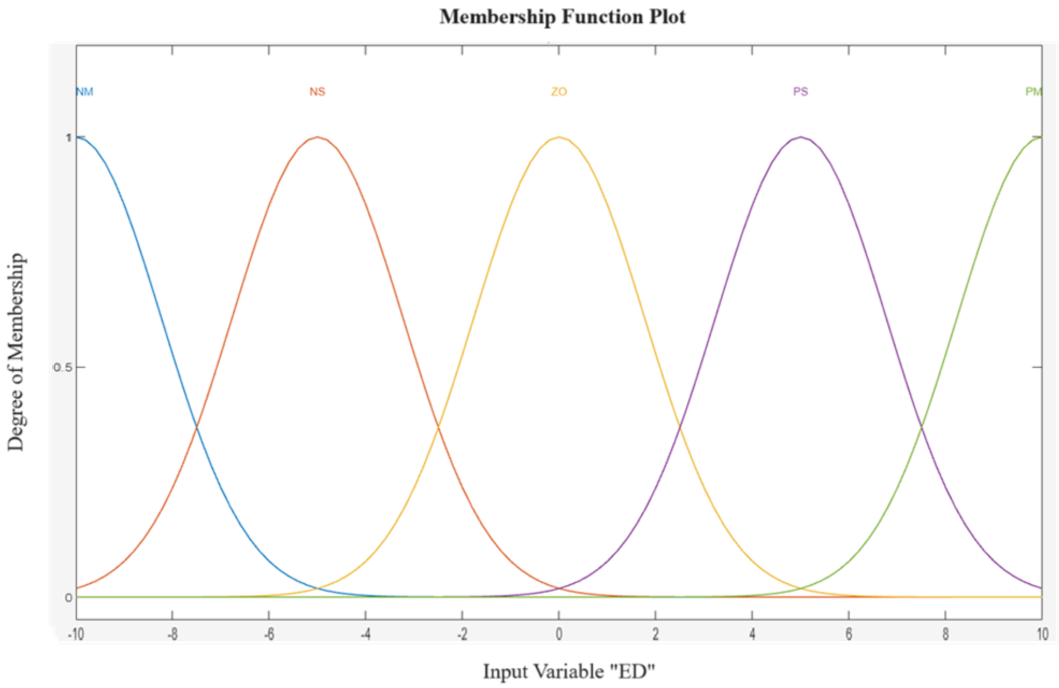

Figure 10 – Input two “error derivative” (ED) membership function

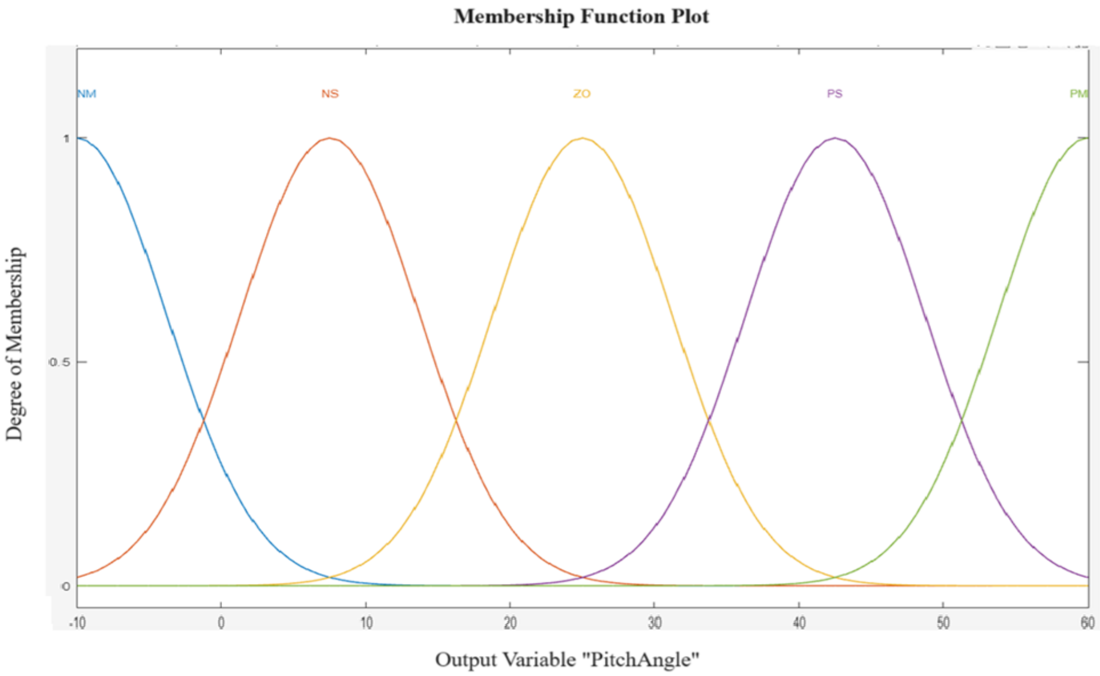

Figure 11 – Output “pitch control angle” membership function

Next step was to create the rules for the fuzzy controller. Twenty-five rules were calculated for the controller based on 5 different values for each input parameter: negative medium, negative small, zero, positive small and positive medium. The output values are also based on the same 5 values and the output distribution rules based on the input combinations are shown in Table (5). The rule surface is shown in figure (12), and the rule distribution is shown in figure (13).

Table 5 – Fuzzy logic rules

Error (E)	Error Derivative (ED)				
	NM	**NS**	**ZE**	**PS**	**PM**
NM	PM	PM	PS	NM	NM
NS	PM	PS	ZO	NS	NM
ZE	PM	PS	ZO	NS	NM
PS	PM	PS	ZO	NS	NM
PM	PM	ZO	NS	ZO	NM

(Note: Negative medium (NM), Negative Small (NS), Zero (ZO), Positive small (PS) and positive medium (PM)).

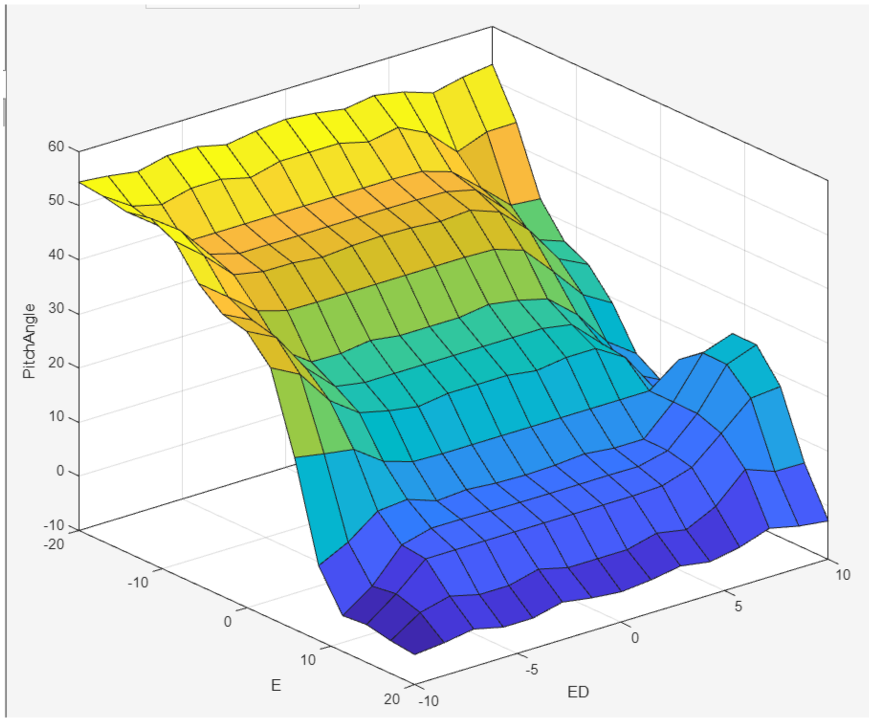

Figure 12 – Fuzzy rule surface

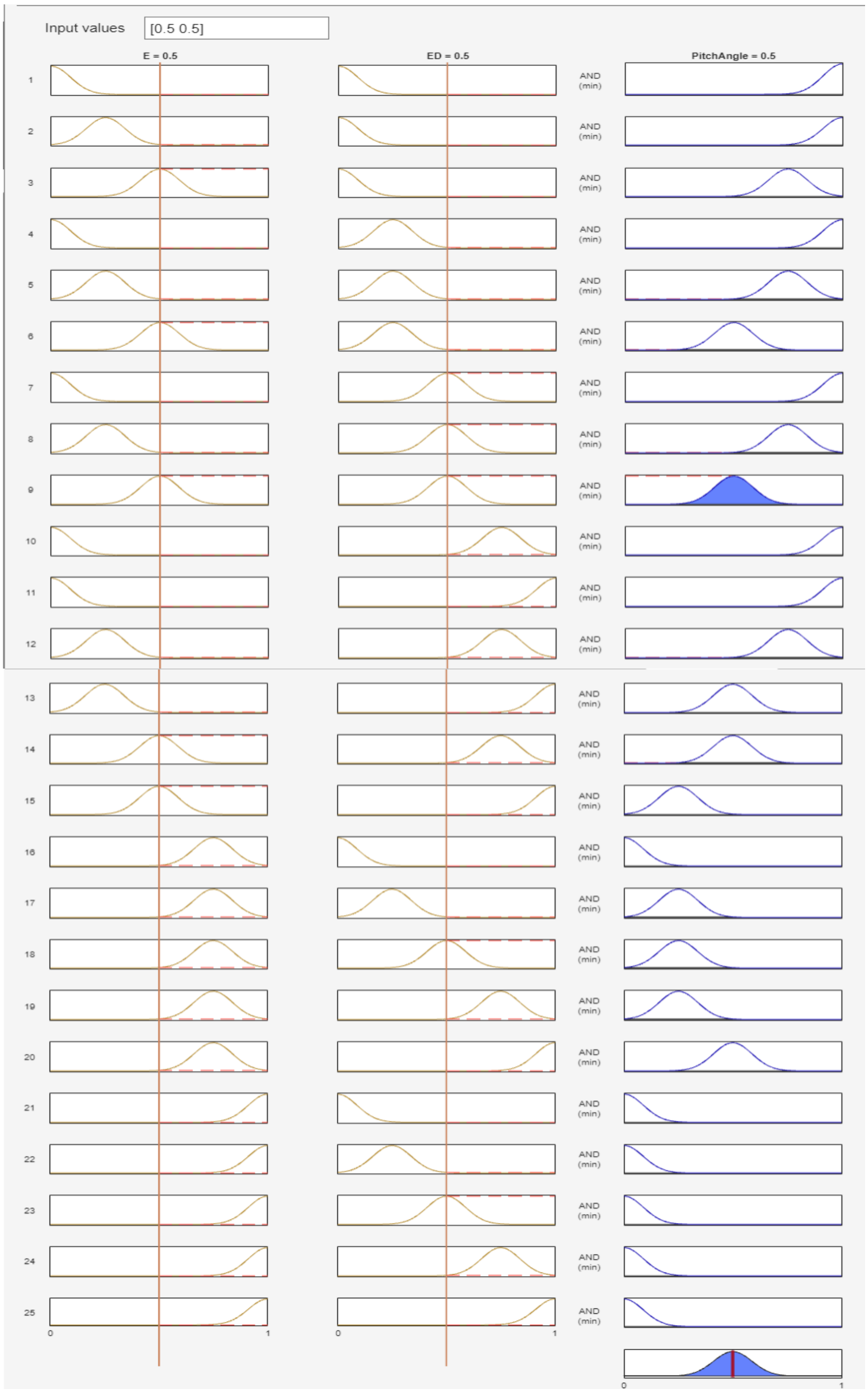

Figure 13 – fuzzy rule distribution

The diagram shows a table depicting the distribution of rules in fuzzy logic systems. Each row represents a rule and explains how the input variables x1 and x2 undergo processing through their corresponding membership functions. The "firing rate" column indicates the strength of activation, for each rule based on the inputs while the output column demonstrates the action resulting from the activated rule. This table serves as a component of a fuzzy logic controller, where all rule outputs are integrated to determine the ultimate decision or control action. The visual presentation allows for observation of how different input values influence the activation and outcomes of individual fuzzy rules.

4. RESULTS

4.1 Conventional PID Control Results

The models discussed in the methodology section were assembled to create the PID controlled wind turbine pitch. The assembled model used a rated rotor speed of 2.2 rad/s and a step input of wind speed. The original wind speed value was 15 m/s, and the step value was 35 m/s. A rate limiter was inserted for the pitch PID controller output to maintain the rate of change of blade pitch angle between 0.6 degrees in either direction. The complete model is shown in figure (14).

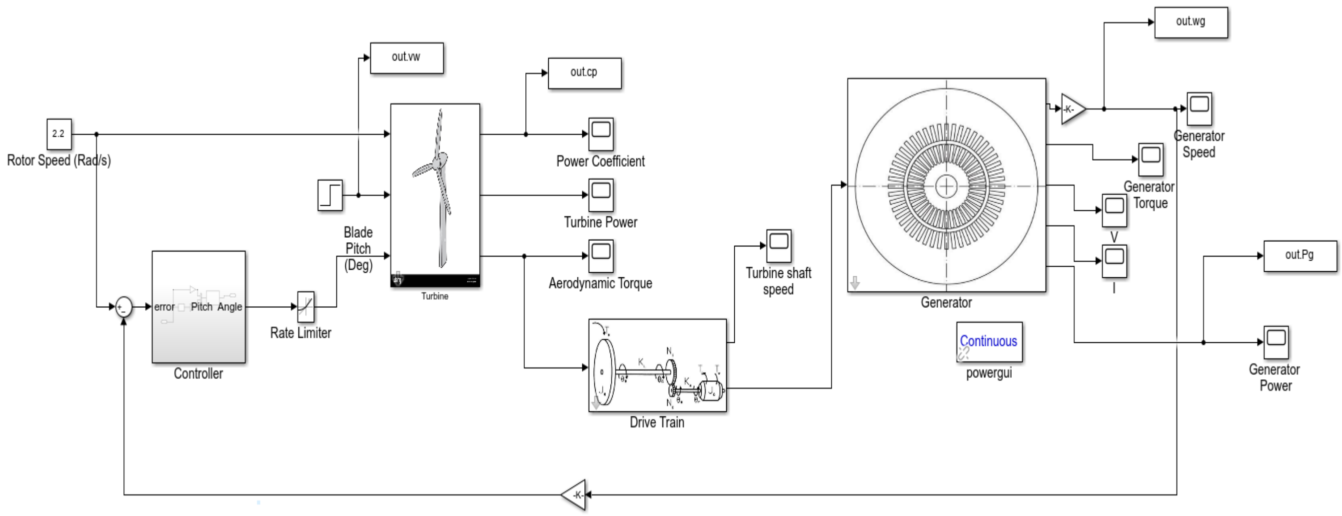

Figure 14 – Complete PID Pitch Controller Model

The simulated output from the model is shown in figure (15). The above figure shows the wind speed step input, middle figure shows the generator shaft speed, and the lower figure shows the electrical power from the generator.

It can be observed that once the wind speed is stepped up to reach a value beyond cut off speed, the controller reacts by changing the blade pitch angle, and hence decreasing the generator shaft speed to maintain the power generation. Extracted electrical Power also increased because the controller attempts to maximize the output power without violating the speed operational range of the turbine.

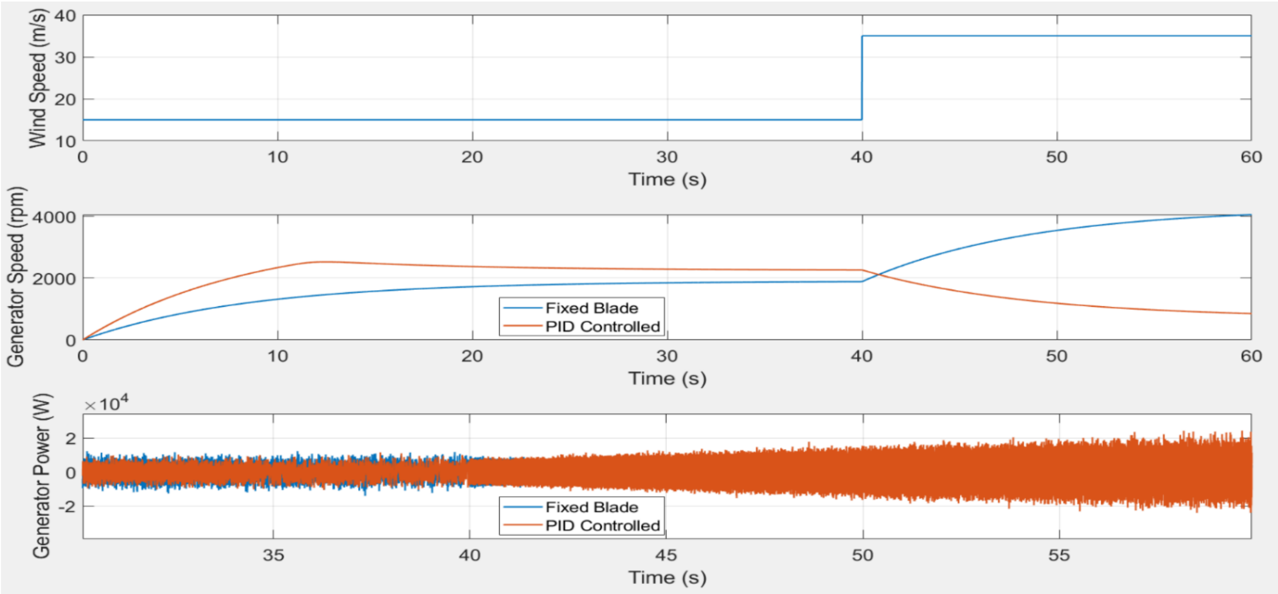

Figure 15 – PID Control model outputs

4.2 Fuzzy Logic Controller Results

The fuzzy logic-controlled wind turbine pitch model is similar, with the change of controller block only. The PID control block was replaced with the fuzzy control subsystem shown in figure (16). The fuzzy logic controller block takes two inputs: the error and its derivative, and outputs the pitch angle.

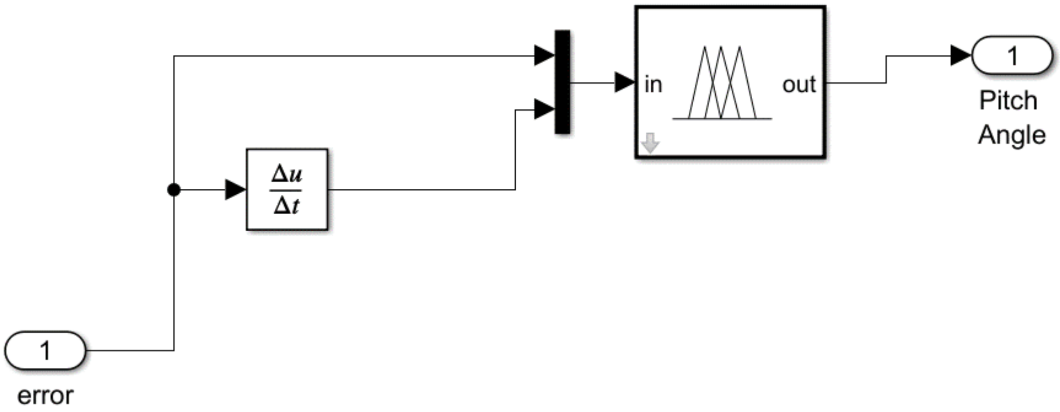

Figure 16 – Fuzzy wind turbine pitch controller subsystem

The resulting simulation of the fuzzy logic controller pitch angle model with a step input of 15 m/s wind speed resulted in the step response shown in figure (17) for the generator shaft speed. The generator shaft speed stabilized without any overshoot (unlike PID controller) on the selected rated rotor speed.

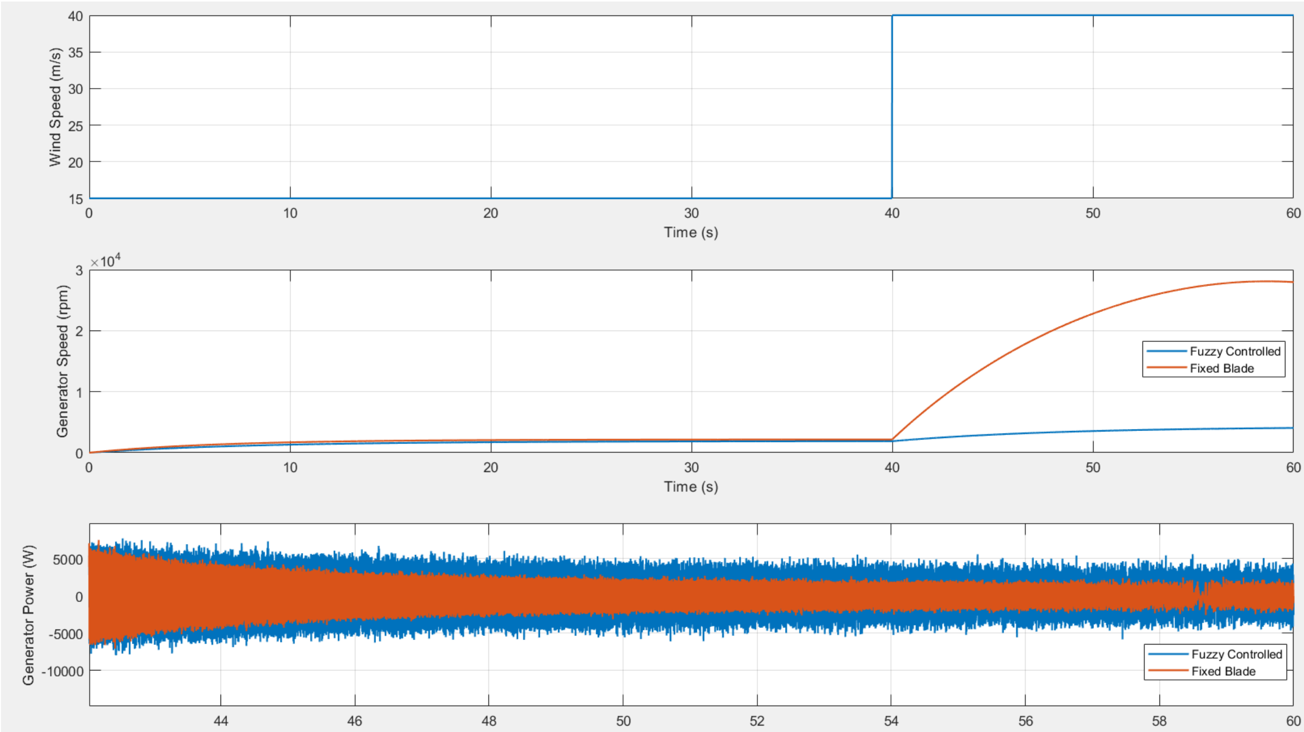

Figure 17 – Fuzzy Logic Control model outputs

5. DISCUSSION

From the results obtained, a comparison between the performance of the two selected controllers (PID & fuzzy logic) can be discussed. Table (6) shows the main performance parameters and their values for the system step response for each controller.

Table 6 – Performance comparison between PID & Fuzzy logic

Parameter	PID Controller	Fuzzy Logic Controller
Delay time (s)	3	2.2
Rise time (s)	8	14
Settling time (s)	34	29
Percentage overshoot (%)	4.5	0
Steady state error	0	0.018

The fuzzy logic controller demonstrated better performance regarding settling time and overshoot. However, the steady state error was present by a very small value in the case of fuzzy logic controller, meanwhile PID controller gave a 0 steady state error, which is the main advantage of the classical controller type. Step responses for both controllers are shown in figure (18) below, where the differences in performance mentioned are very clear.

The non-linearity of the system effect is very clearly visible in the case of the PID controller, as percentage of overshoot is visible, with longer time needed for signal rise and settling. This is the main reason why a fuzzy logic controller was proposed for the control of such a system. Fuzzy logic controller proved in this research that it has an enhanced ability to control non-linear systems such as wind turbine blade pitch angle control. Also, by observing the result of the fuzzy logic controller, it can be clearly concluded that the controller is able to reach a steady state generator shaft speed, and hence a steady state generator output power by manipulating the wind turbine blade pitch angle, and with the best performance possible, and this was the main requirement from the system design. Furthermore, the fuzzy logic controller showed less vulnerability to sudden wind speed changes, unlike PID controller.

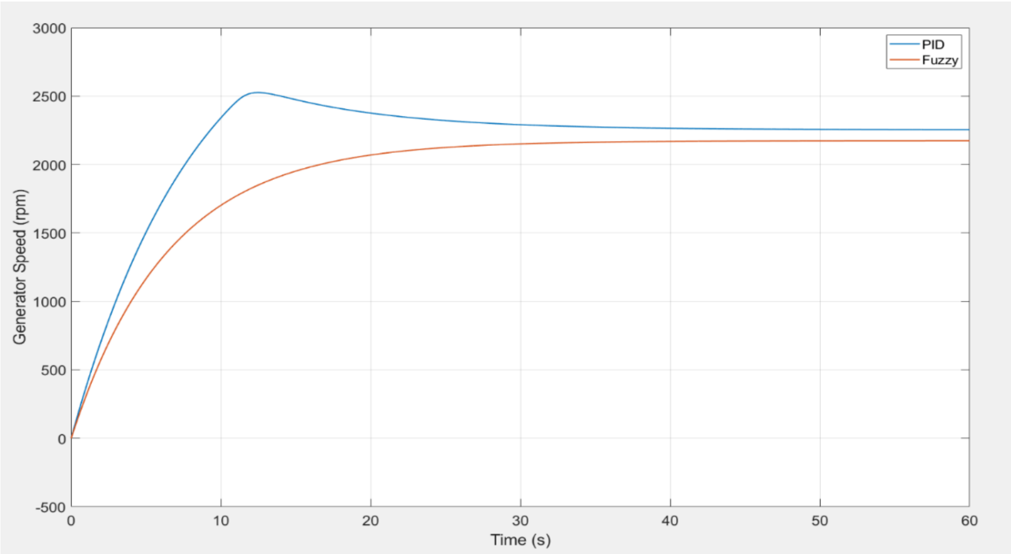

Figure 18 – Step response of both controller types

The project's main aim was to design a controller for wind turbine blade pitch angle that can regulate the generator speed around a preselected value, and hence regulate and increase the generator power outcome. Table (7) shows the generator output for the two controller cases in addition to the uncontrolled case. The table shows the performance of each system in wind speed within the design limits and when the wind speed is off design limits. It is observed that both PID and fuzzy controllers enhanced the power generation ability, especially in off-design wind conditions when the wind speed reaches cut off speed and hence the fixed blade model power output drops significantly.

Table 7 – Effect of controllers on generated power

Wind Speed (m/s)	Generator Power kW		
	Uncontrolled	PID Controlled	Fuzzy Controlled
15	4.24	15	15.8
40	2.58	10.7	11.4

By observing figures (15), (17) and (18), it can be clearly observed that the main project aim was met. The project objectives were mainly around designing two different controllers for the wind turbine blade pitch angle and conducting a comparison between the performance of the two controllers prior to selecting the best controller. Due to the non-linearity of the system, fuzzy logic controller gave better performance in previous research as shown in the literature review and introduction sections; and that was proved by observing figure (18), which shows the fuzzy logic giving the steady state solution without being projected to any percentage overshoot, and with better time delay, settling time and rise time. Also, by comparing the outcome with the results of previous work in literature, the same point can be proved.

6. CONCLUSION

In this study, a mathematical representation of a wind turbine pitch control system was constructed and modeled using traditional PID and fuzzy logic controllers in MATLAB/Simulink. The responses regarding time domain requirements for step input were evaluated with traditional PID and fuzzy logic controllers. Although the PID controller delivers a response with a reduced steady state error and rise time, it has a longer delay time, rise time, and a peak overshoot of 4.55%, causing adverse effects on the system performance. To address these issues, a fuzzy logic controller is recommended for usage. The results show that this controller improves performance and generates smooth responses.

The investigation shows that the fuzzy logic controller responds rather quickly to step input. This technology is far superior for controlling the pitch mechanism and ensuring the consistency of wind turbine power generation.

7. FUTURE WORK

In the future, machine learning methodologies such as artificial neural networks (ANN) or principal component analysis (PCA) can be utilized to regulate the pitch angle of wind turbines and analyze their performance against PID and fuzzy logic controllers. For the PID controller, optimization algorithms such as genetic algorithm (GA), particle swarm (PSO) or Stochastic gradient descent (SGD) could be implemented to reach the optimum proportional, integral, and derivative controller gains. For the fuzzy controller, other forms of membership functions could be utilized and tested for the error and error derivative inputs and also the pitch angle output. Single pitch control can be utilized in conjunction with the Fuzzy controller to boost the system's overall efficiency.

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APPENDICES

PID Controller Code

```
clc
close all

%Run model
vi = 1;
out = sim('WindTurbineControl.slx');
out2 = sim('WindTurbine_unControlled.slx');

%Simulate output
subplot(3,1,1)
plot(out.vw.Time, out.vw.Data, 'LineWidth',1.3), grid on
xlabel('Time (s)'), ylabel('Wind Speed (m/s)')
set(gca,'fontsize',15)
subplot(3,1,2)
plot(out2.vw.Time, out2.wg.Data, 'LineWidth',1.3), hold on
plot(out.vw.Time, out.wg.Data, 'LineWidth',1.3), grid on
xlabel('Time (s)'), ylabel('Generator Speed (rpm)')
legend('Fixed Blade','PID Controlled')
set(gca,'fontsize',15)
subplot(3,1,3)
plot(out2.vw.Time(80000:end,1), out2.Pg.Data(80000:end,1), 'LineWidth',1.3), hold on
plot(out.vw.Time(80000:end,1), out.Pg.Data(80000:end,1), 'LineWidth',1.3), grid on
xlabel('Time (s)'), ylabel('Generator Power (W)')
legend('Fixed Blade','PID Controlled')
set(gca,'fontsize',15)
```

Fuzzy Controller Code

```
clc
close all

%Run model
out = sim('WindTurbineControl2.slx');
out2 = sim('WindTurbine_unControlled.slx');

%Simulate output
subplot(3,1,1)
plot(out.vw.Time, out.vw.Data, 'LineWidth',1.3), grid on
xlabel('Time (s)'), ylabel('Wind Speed (m/s)')
subplot(3,1,2)
plot(out2.vw.Time, out2.wg.Data, 'LineWidth',1.3), hold on
plot(out.vw.Time, 3.1884*out.wg.Data, 'LineWidth',1.3), grid on
xlabel('Time (s)'), ylabel('Generator Speed (rpm)')
legend('Fuzzy Controlled','Fixed Blade')
subplot(3,1,3)
plot(out2.vw.Time(20000:end,1), out2.Pg.Data(20000:end,1), 'LineWidth',1.3), hold on
plot(out.vw.Time(200000:end,1), out.Pg.Data(200000:end,1), 'LineWidth',1.3), grid on
xlabel('Time (s)'), ylabel('Generator Power (W)')
legend('Fuzzy Controlled','Fixed Blade')

figure
plot(out.vw.Time, 3.1884*out.wg.Data, 'LineWidth',1.3), grid on
xlabel('Time (s)'), ylabel('Generator Speed (rpm)')
set(gca,'fontsize',15)
```

Comparison plots of the two controllers

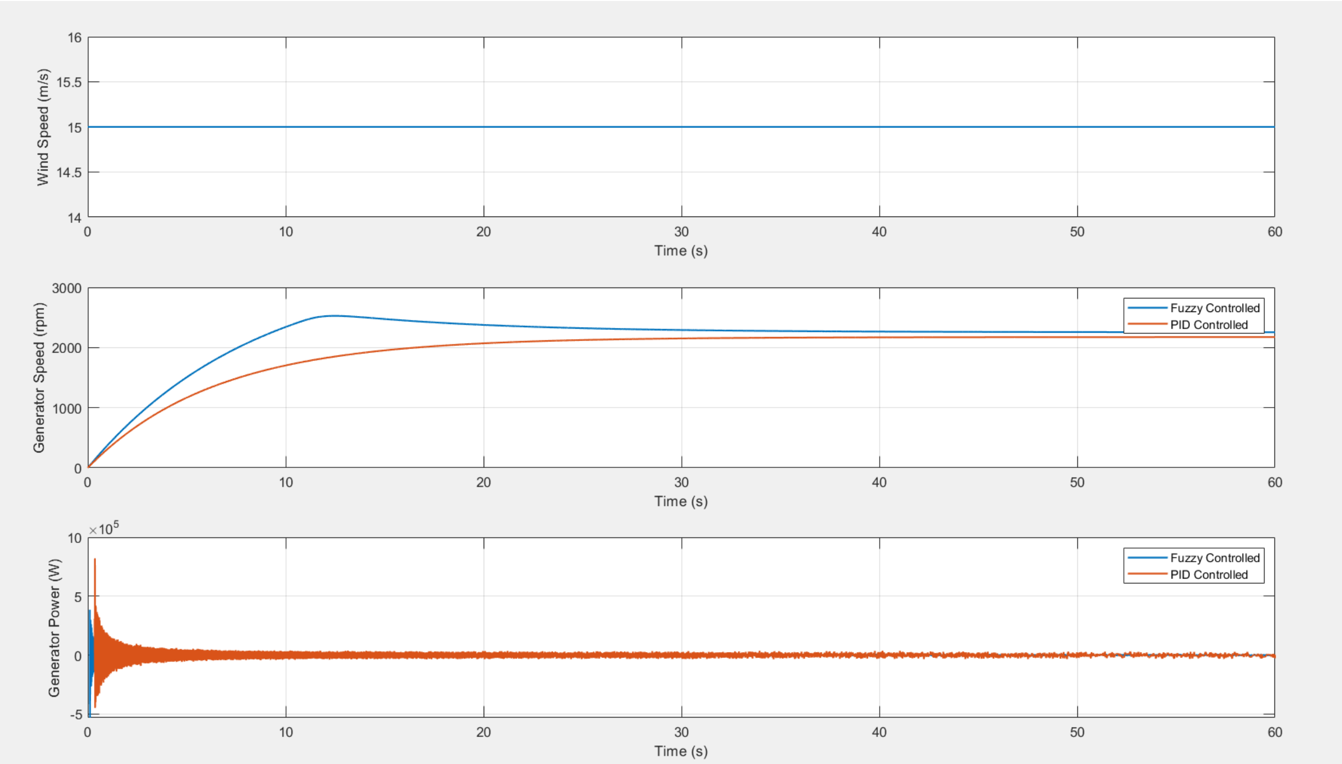

Figure 19 – Response of PID & Fuzzy controllers to constant wind speed input

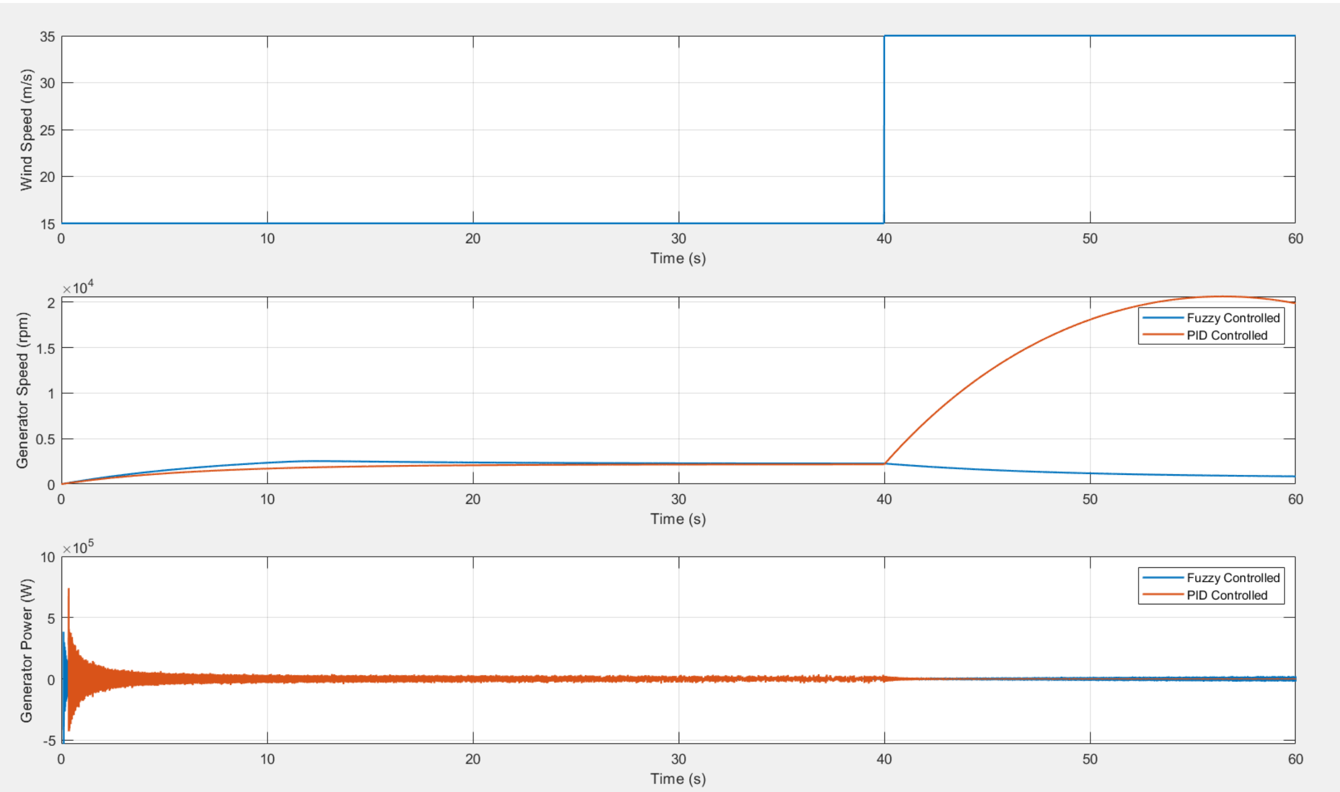

Figure 20 – Response of PID & Fuzzy controllers to Step wind speed input

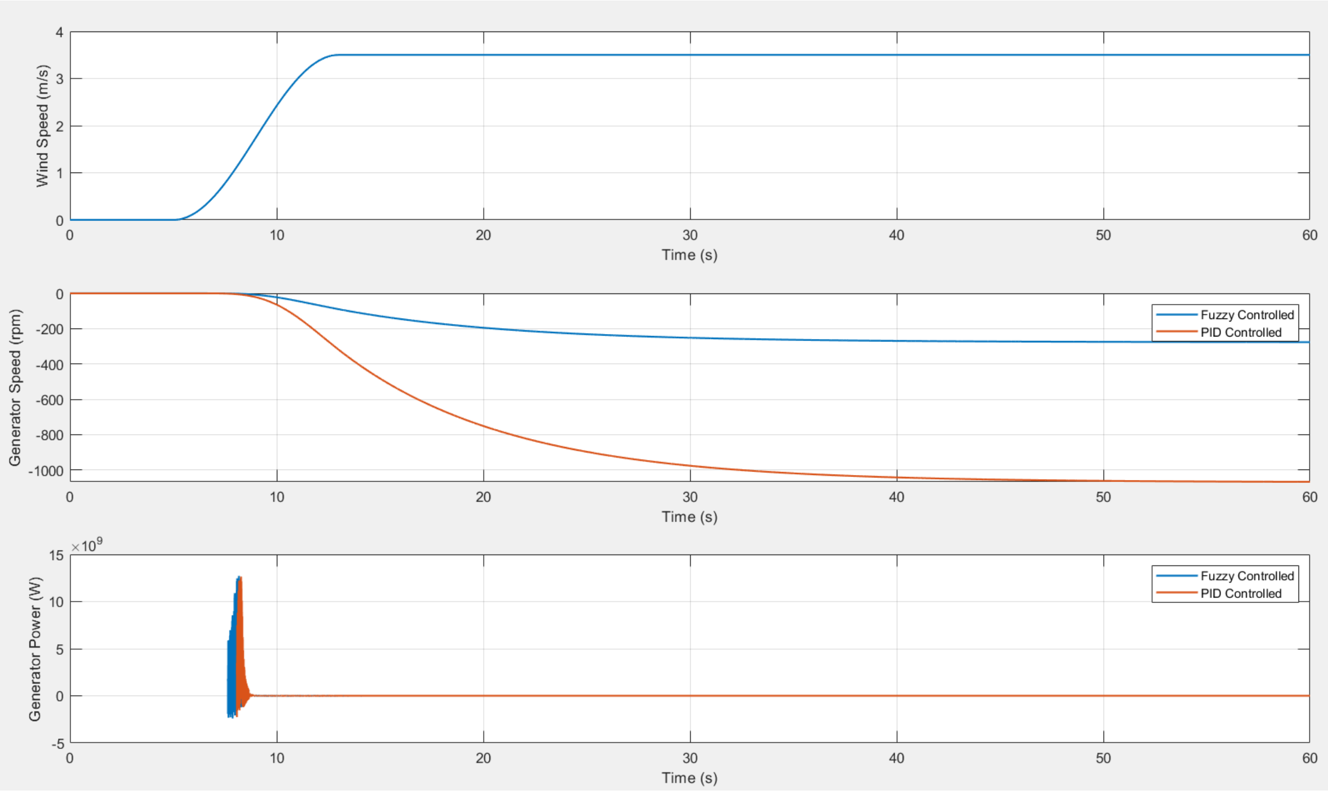

Figure 21 – Response of PID & Fuzzy controllers to gust wind speed input

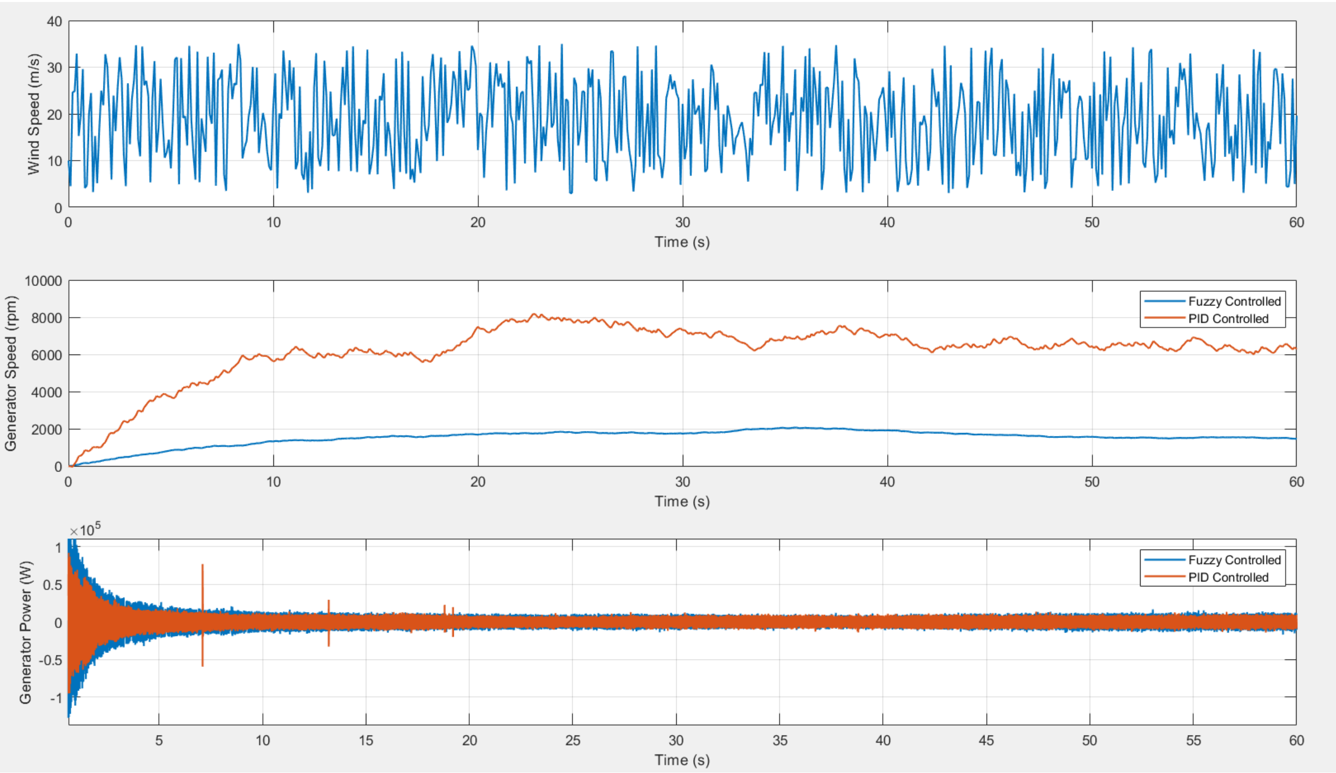

Figure 22 – Response of PID & Fuzzy controllers to random wind speed input