Pitch Angle Control for Variable Speed Wind Turbine Using Particle Swarm Optimization Based Fuzzy Logic Controller

Adugna Tuli Negassa

A Thesis Submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Masters in Electrical Power and Control Engineering (Control Engineering)

Office of Graduate Studies

Adama Science and Technology University

September 2021

Adama, Ethiopia

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Declaration

I hereby declare that this Master Thesis entitled "**Pitch Angle Control for variable speed Wind Turbine Using Particle Swarm Optimization based Fuzzy Logic Controller**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources for the materials used in this document have been formally acknowledged by citations.

Adugna Tuli Negassa	____________________	____________________
Name	Signature	Date

Recommendation

I the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Pitch Angle Control for variable speed Wind Turbine Using Particle Swarm Optimization based Fuzzy Logic Controller**" prepared under my guidance by A**dugna Tuli Negassa** submitted in partial fulfillment of the requirements for the degree of Master's of Science in Electrical Power and Control Engineering (Control Engineering).

Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures.

Dr.Tefera T.Y (Assistant Professor)	________	________
Advisor	Signature	Date

Approval page

I the advisor of this thesis entitled "**Pitch Angle Control for variable speed Wind Turbine Using Particle Swarm Optimization based Fuzzy Logic Controller**" and developed by Adugna Tuli Negassa, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Tefera T.Y (Assistant Professor)	_______________	_______________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Adugna Tuli Negassa have read and evaluated the thesis entitled "**Pitch Angle Control for variable speed Wind Turbine Using Particle Swarm Optimization based Fuzzy Logic Controller**" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science Electrical Power and Control Engineering (Control Engineering).

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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ABSTRACT

Electricity is a basic demand, especially for developing countries where the scarcity of electricity exist. To allow people all over the world to use electricity, many possibilities need to be used, such as the promotion of wind energy and other energy sources that maintain the greenhouse effect. In today's energy system, wind power is developing gradually and, as we all know, it is the cleanest source of energy and has the least impact on the environment. The use of wind energy is difficult because its production is not linear, especially when the wind speed is higher than the rated speed. When the wind speed surpasses the rated speed, this thesis study provides the steadiness of the generator output power and the robustness of the proposed controller by controlling the pitch angle method. A complete mathematical model of the system's components is constructed to analyze the pitch angle control of a wind turbine. The controllers applied in this thesis are PID controller, fuzzy logic controller, and PSO-based fuzzy logic controllers. For implementation purposes, the relevant models are developed using the MATLAB/Simulink software tool. The maximum pitch angle obtained by the controllers; the PID controller is 14.8 degrees, the fuzzy logic controller is 12.5 degrees, and the PSO-Fuzzy controller is 12 degrees. The pitch angle deviates from 0 degrees to avoid the distraction of the wind turbine by turning away from the wind. As the pitch angle increases, the power coefficient decreases and causes the power drawn from the wind to decrease. As the power drawn from wind is decreased, the mechanical torque transmitted to the drive train will also decrease due to the ratio of the mechanical power divided by the rotor speed. This effect will reduce the stability of the output power of the generator during high wind speed. The rotational speed overshoot of the PID is MP 18.6167%, FLC is MP 18.214%, and PSO-FLC is MP 13.05% improved. The settling time of the PID is 310.5113second, FLC is 310.606second, and PSO-FLC is 309.234second. The rise time of the PID response is 8.7473second, FLC is 8.701second, and PSO-FLC is 8.1965second. The highest overshoot generator output power with PID controller reaches around 1.625MW which is 0.13% above the rated power, Fuzzy logic controller is 1.573MW (0.05%), and PSO-based fuzzy logic controller is 1.531MW (0.03%). In general PSO-based fuzzy logic controller shows better performance and better stability of the output power compared to other controllers used in this thesis work.

Keywords: *Pitch angle control, PID controller, Fuzzy Logic Controller, Particle Swarm Optimization, Wind turbine, PSO-based Fuzzy logic controller.*

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LIST OF ACRONYMS AND SYMBOLS

ANFIS	Adaptive Neural Fuzzy Inference System
AC	Alternating Current
CO2	Carbon dioxide
COA	Center of the Area
DFIG	Doubly-fed Induction Generator
EEP	Ethiopian Electric Power
FLC	Fuzzy Logic Controller
GW	Gigawatt
HAWT	Horizontal axis wind turbine
MW	Megawatt
MPPT	Maximum Power Point Technique
PSO	Particle swarm optimization
PMSG	Permanent Magnet Synchronous Generator
PI	Proportional-integral
PID	Proportional–Integral–Derivative
VAWT	Vertical axis wind turbine
WECS	Wind Energy Conversion System
e	Error
ce	Change of Error
Ge	Gain of Error
Gce	Gain of change of error
Gu	Gain of output
ω_r	Rotational speed
λ	Tip speed ration
cp	Power coefficient
β	Pitch angle
α	Angle of attack

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Most people do not have access to electricity, especially those who live in remote areas. Electricity is the best solution to improve and simplify human life and play its core value for industrialization and economic development. Wind turbines and solar cells that generate electricity for rural and remote areas are suitable solutions and help reduce grid costs. Electricity is the best-known energy carrier. An energy carrier may be a substance or framework that moves energy in a usable frame from one form to other. Electricity is one of the secondary energy produced by primary energy. Primary energy sources include fossil fuels (petroleum, natural gas, and coal), nuclear energy, and renewable sources of energy. But, a disadvantage of producing power from fossil fuels and nuclear fission is the adverse environmental impact, such as the greenhouse effect caused by the increase of the carbon dioxide (CO_2) concentration within the earth's environment and the nuclear waste problem [1]. Uranium and fossil fuel reserves are limited. The increasing concerns over environmental issues and the exhaustion of fossil fuel requested the explore of more feasible energy sources.

In africa wind energy and wave power resources are abundant and underutilized especially in the north and south. Sub-Saharan Africa has abundant wind potential, especially in the highlands of Chad, Ethiopia, and coastal regions. Currently,sub-Saharan Africa accounts for less than 1% of global installed wind power capacity [2]. Ethiopia is blessed with plenteous renewable energy resources, which can meet the demand of across the country electrification [3]. Ethiopia has high wind resource potential with 10GW of installation capacity [4]. In spite of all its available potential energy, Ethiopia is one of the lowest electricity consumption per capita in Africa and the majorities of the population lives in a rural area relied only on traditional biomass energy sources [5]. As reported by Ethiopian Electric Power (EEP); for the now installed capacity of 324MW consist of three wind farms Ashegoda 120MW (84 turbines), Adama I 51MW, AdamaII 153MW (102 turbines) which is the second wind farm in Africa next to Tarfaya wind farm in Morocco with 301MW [6]. It is important to mention that despite manageable shortcomings or problems,solar and wind turbine energy sources offer electrical energy with lower installation costs, and cost-effective operation compared with other energy sources.

These two alternate energies sources provide clean energy-free of environmental effects along with minimum cost and complexity compared to other energy sources mentioned above. So wind speed increase as the height above the ground increases. The wind energy available in the wind speed is extracted through the wind turbine. This energy is a nonlinear system as the energy extracted from the wind speed is proportional to the cube of wind speed [5]. As wind energy is renewable clean energy with brief development periods, it has the critical advantage of fast results.

Today, many nonlinear and complex systems need controllers to meet their best performance degree as much as it is possible. Fuzzy logic controller (FLC) is one of the controllers to model and simulate non-linear and complex systems, using human operators encounters and/or control engineer's information using the number of IF-THEN rules administering the plant under control [7]. In any case, this empirical information proposed may not be precise sufficient to construct an optimal system. Thus, this point requires to emerge for an optimization method to move forward the fuzzy controller performance. Particle swarm optimization (PSO) is one of the foremost significant swarm intelligence algorithms used to tune the parameters of fuzzy logic controllers due to the promising results that presented misusing the merits of these algorithms as search and optimization strategies.

1.2. Statement of the problem

Due to safety and environmental protection considerations, there is a high demand for electricity from renewable energy sources such as wind power. The difficult works in wind energy development are keeping up the stability of the power at the side running the wind turbine in a safe mode because of the nonlinearities of wind energy. When the blades of a wind turbine rotate, the wind speed around the blades continually changes in the upstream and downstream regions. Due to the variability of the wind speed, the energy of the wind is not efficient. When the wind speed is low, the power drawn from the wind is very small and some techniques; such as maximum power point tracking are needed to optimize the available power. At times, the wind speed is higher than the rated wind speed, causing harm to the wind turbine and unstable power output. Under conditions higher than the rated wind speed, if the pitch angle is not controlled, the wind turbine will not be able to protect itself from the influence of high wind speed, which will have a great impact on keeping the power stable and apply high stresses to wind turbines results in damage to the blades and other components of the wind turbine. To avoid the problems mentioned above, the control of the pitch angle must be applied and its robustness is necessary. So, for the efficient and reliable operation of wind turbines, automatic control is a key, interesting and challenging research topic. Since wind turbines are not linear, a perfect model of this system is difficult and can be represented as certain. Since energy efficiency and utilization are important issues, gearless permanent magnet synchronous generators are more popular than double-feed induction generators. The gearbox generates noise and vibration, needs lubrication, has no flexibility, and places a large load on the shaft.

The PID controller is usually used for the pitch angle control mechanism. However, PID controllers are effective for linear systems, not for complex nonlinear systems. A fuzzy logic controller is better than a PID controller as it is suitable for non-linear systems. The fuzzy logic controller also needs to modify the scale factor and membership function, because it cannot completely overcome the deficiencies of the PID controller, such as the ripple factor and when the power exceeding the rated output power. Particle swarm optimization is one of the optimization techniques used to optimize the scale factor of the fuzzy logic controller to obtain the best result. The proposed controller in this thesis work is to control the pitch angle of the wind turbine to stabilize the output power and reducing the damage of the wind turbine by the change of the wind speed. The work of this thesis is realized and simulated by MATLAB software.

1.3. Motivation

With the continuous growth of human demand for energy, the development of alternative and renewable energy sources has become an important factor in the supply of clean energy. All forms of renewable energy, from biofuels and hydroelectric energy to wind energy, geothermal and solar energy, have been explored and better in terms of the economic and real potential of renewable energy. The horizontal axis wind turbine industry has attracted more attention than vertical axis wind turbine due to its high efficiency. When the wind speed suddenly increases, the wind turbine will become unstable, and causing damage to the wind turbine costs much. To avoid damage to the wind turbine and stabilize the power when the wind speed is high, pitch angle control is the best method. Therefore, the PSO-based Fuzzy Optimization method, fuzzy logic controller, and traditional PID controller are used in this thesis for the pitch angle control method.

1.4. Objectives

1.4.1. General objectives

The main purpose of this thesis is to use the variable speed wind turbine pitch angle control based on the permanent magnet synchronous generator of the wind power conversion system to stabilize the wind turbine when the wind speed is higher than the nominal speed.

1.4.2. Specific objectives

The specific objectives of this thesis are the following:

- Mathematical modeling of the Aerodynamics, wind turbine, drive train, and Permanent Magnet Synchronous Generator.
- Design and simulate PID controller, fuzzy logic controller, and PSO tuning fuzzy logic controller.
- To compare the controllers specified in this thesis.
- To evaluate the impact of the extracted power from wind energy when there is a variety of wind speeds.
- To evaluate electrical output power in its rating steadiness.

1.5. Scope of the study

The scope of this thesis focuses on the mathematical modeling of wind turbines and MatLab simulation for pitch angle control techniques. The proposed particle swarm optimization algorithm is used to tune the scaling factor of the fuzzy logic controller only. This thesis presents PID controller, fuzzy logic controller and PSO-based Fuzzy Logic controller.

1.6. Limitation of the study

This thesis is limited to using MATLAB/Simulink to simulate the system. it is difficult to purchase components for real system implementation. With that comes the extra time and cost of implementing the actual prototype.

1.7. Significance of the study

Wind energy can't pollute the air like other energy that depends on the combustion of fossil fuels, such as coal or natural gas, which emanate particulate matter, nitrogen oxides,and sulfur dioxide causing human health issues and economic damages. Highly demanding energy is pushing to replace carbon-based fuels with renewable energies. In this transition of energy from fuel base to renewable energy, the improved efficiency of wind energy is necessary. Since there is no dominant technique to move forward the viability and efficiency of wind energy, numerous types of studies have been published. Particle swarm optimization (PSO) based research is one of them, whose primary advantage is that it can optimize numerous factors at the same time, reduce costs, reduce materials, improve efficiency, and make wind control more solid [7].

1.8. Thesis organization

This thesis presents five chapters:

Chapter One: Background of the thesis, statement of the problem, motivation, objectives, scope or delimitation of the study, and Significance of the study are presented in this chapter.

Chapter Two: Includes the basic theories of the wind turbine and literature review.

Chapter Three: Describes system modeling and mathematical modeling of the system.

Chapter Four: Presents results and discussions.

Chapter Five: Discuss the conclusions and recommendations.

CHAPTER TWO

2. BASIC THEORIES AND LITERATURE REVIEW

2.1. Introduction

In recent years, in terms of annual installed capacity, pitch-adjustable variable speed wind turbines have performed better than all other types of wind turbines. The fixed-speed wind turbine runs at a specific wind speed. If the wind speed is lower than this wind speed, it will not work; if the wind speed is high, it will try to reduce the rotational speed to match the fixed speed. The area above of cut-in and below the cut-out region is where variable speed wind turbines function. Variable-speed wind turbines have numerous points of interest over fixed-speed ones, such as higher energy outputs, higher conversion efficiency, lower component stress, and fewer power fluctuations[16] [17].

On variable speed wind turbines, output power and torque settings are used based on specific wind speed conditions. Torque control is used in areas with low wind speeds and when the wind speed surpasses the rated wind speed, pitch angle control is required [8]. The blade pitch angle control method is used to regulating the output power [10].

To generate electricity wind turbine uses the wind. Towers, anemometers, blades, nacelles, rotors, yaw motors, yaw drives, and generators are the main components of wind turbines. Wind turbines are partitioned into two groups based on the heading of the rotor [11].

- Horizontal axis wind turbine and
- Vertical axis wind turbine (VAWT).

1. **Horizontal Axis Wind Turbine (HAWT):**

HAWT is the most popular type of wind turbine, with the rotor shaft pointing in the direction of the wind to extract power [12].

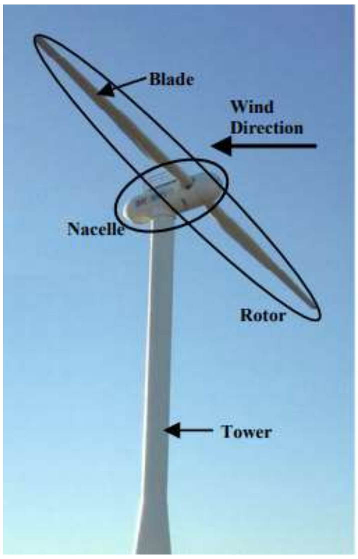

Figure 2.1 Double blade upwind Horizontal Axis Wind Turbine [12].

Figure 2.2 Three-blade Horizontal Axis Wind Turbine [13].

Advantageous:

HAWTs can get some greater wind speed, as it is located on the taller tower [14]. Because the blades move at an angle complementary to that of wind speed, drag forces are greatly reduced which causes the increment in the power output [14].

Disadvantageous:

The cost of installation is high and the noise generated can interfere with the operation of radar. Higher wind speeds and turbulence can damage the wind turbine structure.

Vertical Axis Wind Turbine (VAWT)

This type of wind turbine works close to the ground, and its blades rotate on an axis perpendicular to the ground. Darrieus VAWTs use lift forces generated by the wind, and the turn is many times greater than the hitting speed of the wind, resulting in a blade tip speed ratio greater than one (1) [7]. Darrieus VAWT is more efficient than Savonius VAWT because of the higher rotational speed but lower starting torque. Interestingly, the Darrieus wind turbine does not start automatically and requires a small electric motor to start the rotation [15].

Advantageous:

It is cheaper and easier to maintain, can be started at lower wind speeds, and produces very little noise. From any direction, it can receive wind, so it does not use a yaw mechanism. Heavy equipment such as generators and gearboxes are positioned close to the ground rather than in the nacelle, resulting in easier maintenance and a lighter tower.

Disadvantageous:

Placing the rotor on the ground will produce less power with the same amount of wind and capture area; poor self-starting capabilities; worse efficiency owing to higher drag forces; and complete rotor removal is necessary to repair bearings.

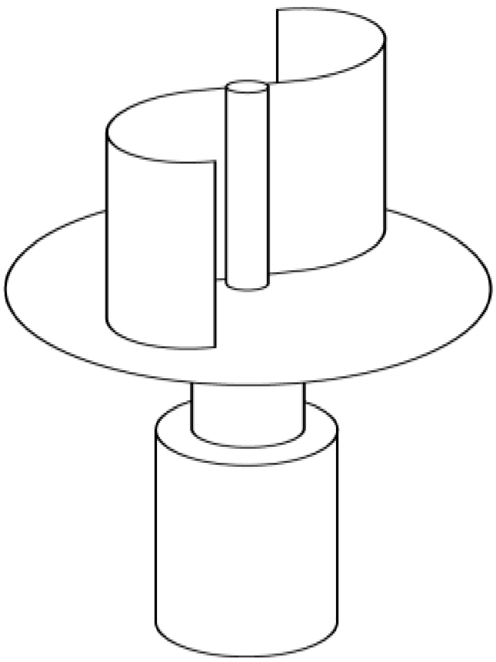

Figure 2.3 vertical axis wind turbine [16].

Table 2.1 Comparison between HAWT and VAWT

	HAWT	VAWT
Output power	Wide range	Narrow range
Starting	Self-starting	Need starting
Efficiency	Higher	Lower
Cost	Higher	Lower
Wind direction	Redirecting to the wind direction is necessary.	Redirecting to the wind direction is not necessary.
Generator and gearbox	At the top of the tower	At the ground level
Maintenance	Difficult	Easy

2.2. Variable speed wind turbine operation area

The relationship between the power output and the wind speed based on the specification of the parameters given in this thesis work is shown in figure 2.4 and divided into four regions.

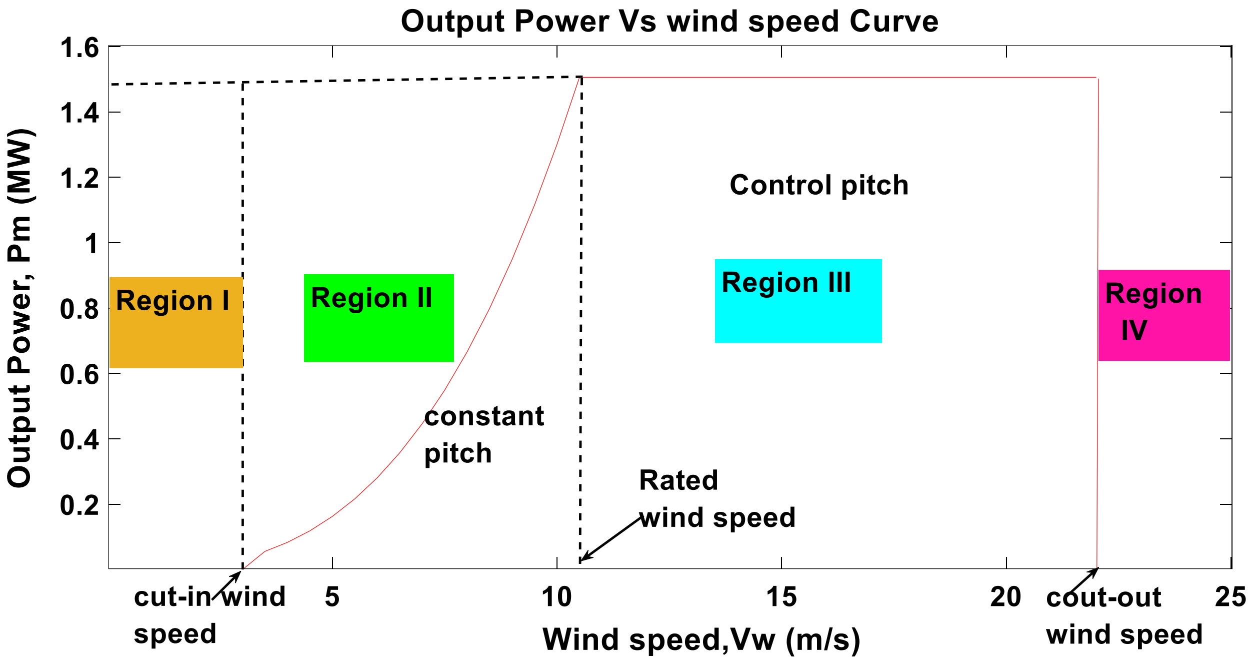

Figure 2.4 Ideal Output power vs wind speed curve

- **Region I** (<3m/s): It is below the cut-in wind speed region.

A wind turbine is not preferred to operate in the cut-in region for economic purposes [17].

- **Region II** (3m/s-10.5m/s): From cut-in wind speed to rated wind speed region.

The cut-in wind speed is the lowest wind speed to be captured to start generating electricity. More power is produced; as the wind speed increased until the rated wind speed is reached. The controllers used in this area are designed to capture as much wind energy as possible. This is accomplished by keeping the blade pitch relatively constant and changing the rotor speed with the generator torque [8], [18].

- **Region III** (10.5m/s-22m/s): between rated wind speed and cut-out wind speed.

Controlling pitch angle is required and maintains constant generator torque and power. To keep the output power within the rated range the rotor must turn away from the high wind stream. This is generally done by controlling blade pitch angles and maintaining generator torque constant. The pitch angle control also helps to reduce stress on the wind turbine [8].

- **Region IV** (>22m/s): above cut-out region.

Cut-out wind speed refers to the wind speed at which a wind turbine is expecting to shut down to avoid damage. The turbine control system generally monitors the wind speed, and if the cut-out wind speed is reached, the turbine braking system is actuated, and the turbine is shut down.

2.3. Control techniques of Wind Turbine

Pitch angle control, stall control, and active control are the three control techniques used by wind turbines. These control techniques can help the turbine; in maintaining the available power's stability as well as the wind turbine's safety.

2.3.1. Pitch angle control

The pitch angle control method helps turn in and out the angle of blades in response to different wind speed circumstances and adjusting the control system within the wind turbine's design specifications. Pitch angle controllers provide the advantage of keeping output power closer to rated power and reducing the aerodynamic load in high wind speed regions. Once the wind comes to the normal operating region, these blades are turned back into the wind. In the absence of this controller, the wind turbine will shut down if it exceeds a specific speed. The pitch angle of the wind turbine should change according to the wind speed to prevent the wind turbine from mechanical stress and structural damage[19], [20]. This control mechanism of blade pitch angle is effective and dominant.

2.3.2. Passive Stall control

In this method of control technique, the blades of the rotor are stalled or tighten onto the hub at a fixed angle. The angle is always constant, no mechanism to rotate the angles around their axis is needed [21]. The blades are aerodynamically designed to stop at higher wind speeds and the power input is limited near nominal value [21]. However, the rotor blades geometry is efficiently designed in such a manner that when the wind speed becomes too high, it generates turbulence on the back of the rotor blades, causing the blade to slow down. When the wind speed increases, the angle of attack will increase. Above a certain angle of attack (α) stall effect occurs, the torque produced can be limited approximately to its rated value[21], [22]. The output frequency of the wind turbines also needs to be constant despite varying winds [12].

2.3.3. Active control

This control method is the combination of both pitch control and passive stall control mechanism. These blades are pitched similar to the pitch-controlled turbine for low and medium speeds. Unlike that of a passive stall, there is no drop in the power at higher speed as the blade is rotated by few degrees in the opposite direction compared to that of pitch controlled [14]. One of the methods is to control the speed at which the generator shaft turns, which can be accomplished by adjusting the pitch and yaw so that a high-speed shaft operating at a constant speed to produce the required generator output frequency [12].

The maximum blade rotation can be in the range of 10-20rpm, and the gear ratio can be used to rotate the shaft at high speed with the speed required by the generator. Another method also used with vertical axis wind turbines for frequency control is to allow the wind turbine to run freely at any speed but within its rated value and to send voltage to the inverter [12]. This method has the advantage of having more operating conditions without the need for more complicated gearing [12]. A third way to control the output frequency of a generator is to use a double-fed induction generator, where the alternating field current is strictly controlled to the required output frequency by supplying a current through an electronic circuit that produces the correct frequency [12].

2.4. Pitch Angle control-related Works

Literature works related to this thesis area are:

Authors [24] **proposed, Pitch Control of Wind Turbine through PID, Fuzzy and adaptive Fuzzy-PID controllers.** They developed mathematical models of wind turbines and compared pitch angle controllers such as PID, Fuzzy, and adaptive Fuzzy-PID. The main objective of this research is to control the angle of pitch of the wind turbine blades at different wind speeds while keeping the power output constant [24]. Based on the simulation results, the adaptive FuzzyPID controller has the best performance. The overshoot is reduced from 32 percent (without the controller) to 11 percent with the PID controller. The overshoot of fuzzy logic is MP 0.5%, and the overshoot of adaptive fuzzy PID is MP 0.02%. In terms of rising time, the adaptive fuzzy-PID (0.63sec) is no better than another controller (fuzzy=6.81sec and PID=4.21sec); however, it does improve overshoot. The paper's shortcoming is that it does not represent the wind turbine system and instead uses the feedback signal from the actuator, which is inefficient for system control.

Authors [25] **proposed a control system design of adaptive wind turbine pitch angle using particle swarm optimization algorithm.** Using the PID controller, pitch angle adjustment is monitored, and the best value is determined using the PSO optimization method. A comparison was made between a PID controller, a PID tuned with PSO, and a PID tuned with fuzzy. When compared to PID tuned with fuzzy, the outcome of PID tuned with PSO parameter produces a more optimum response. However, the overshoot is high, resulting in a system response that exceeded the set-point value.

Authors [26] **presents Output power leveling for DFIG wind turbine systems using intelligent pitch angle control.**

In this article, an intelligent control method is used to adjust the blade pitch angle of a doubly-fed induction generator (DFIG) wind turbine. Use a fuzzy logic controller and neuro-fuzzy-based particle swarm optimization controller to obtain the required wind power generation position. The Neural Fuzzy Adaptive Inference System (ANFIS) controller is designed to use as few membership functions as possible to always maintain the rotor speed of the DFIG at the nominal value. The PI controller uses rotor speed as an input, while the fuzzy logic controller uses two inputs; generator power and rotor speed. Another proposed controller is the adaptive neuro-fuzzy inference system (ANFIS) particle swarm optimization controller, which uses a fuzzy inference system based on the fuzzy C (clustering) method. To provide improved clustering for the ANFIS controller, the FCM method clustering is updated by taking input from the classic fuzzy controller. The first fuzzy inference system was designed and optimized by optimizing the particle swarm. The ANFIS controller developed in different input scenarios and will be compared to traditional fuzzy logic controllers for a comprehensive evaluation [26].

Authors [27] **present Pitch Angle Control of Wind Turbine using Fuzzy Logic.** To regulate the pitch angle, PID and fuzzy-PI controllers are described, with generator power and wind speed as inputs and the output is pitch angle reference. The wind speed used as a reference is logically 62.83 m/s, which is not permitted since it will cause the blades in the wind turbine system to get damaged. The PID controller that controls the pitch angle controls the speed of the wind turbine rotor. The fuzzy logic controller takes as input the error signal and the rated power and wind speed of the generator. It is recommended that the initial PI controller of the controller use a power error signal model. At high wind speeds, the PI controller tries to prevent the rotation speed of the turbine from exceeding the rated speed of the wind. When the wind speed exceeds a certain level, the fuzzy logic controller gradually adjusts the pitch angle to limit the power output. When the turbine starts to spin faster than the nominal speed due to high wind speed, the fuzzy PI control tries to keep the power output within the nominal range.

Authors [28] **proposed Pitch Angle Control of Wind Turbine Using Adaptive Fuzzy-PID Controller.**Adaptive fuzzy-PID controller compared with traditional PID method for pitch angle of the turbine blades. Fuzzy tuning PID parameters gives an enhancement in the speed response of the wind turbine as compared with using PID controller only. Also, this intelligent method is suppressed the oscillation. PID controller emits to give lower rise time and delay time but with overshoot equal to MP 32.02% which lead to defect in the system performance. Fuzzy tuning PID controller made an enhancement in the transient response parameters as compared with conventional PID controller were, the reading ratio as a percentage for P.O.S, max time, rise time and settling time was 84.69%, 74.03%, 79.3% and 83% when using adaptive fuzzy-PID controller. The intelligent techniques are better than that of traditional control method where these techniques are used to attain the control process of pitch angle and to ensure the stabilization to the wind turbine output power. Pitch angle control based fuzzy Turing PID parameters improved the rendition of the system.

Authors [17]**, Proposed a particle swarm optimization technique for the wind turbine control system.** The controller's optimum parameters are calculated using the proposed particle swarm optimization technique [11]. The proposed Particle Swarm Optimization (PSO) and the conventional Particle Swarm Optimization (PSO) methods are presented in this paper (PSO).

The proposed PSO used a detailed algorithm with the fminsearch function. The fminsearch function is working on if the targeted or maximum iterations get is reached. If the maximum iteration is not reached the loop is returned to calculating the fitness function again. And they studied the stability analysis through the Lyapunov function. The Lyapunov function is $V(X) = X^T PX + \int_0^e f(e)de$ and using the Lyapunov stability condition $A^T P + PA = -Q$ the system satisfies the Lyapunov stability. Pitch servo is employed to tune the pitch angle according to the requirement of the system [17]. The wind profile is fed to the wind turbine system to acquire the output results using the proposed technique [17]. Compare these results with the results of traditional methods. The output power obtained using the proposed technology is higher than the output power obtained using a traditional technique. Rotor speed is within the rated limits, thus yielding the maximum power. The mechanical torque acquired through the proposed technique is very effective; in addition, the pitch angle is very efficient to regulate the output power, rotor speed, and torque for the system as compared to the conventional methodology. The PID controller optimization for the system is not much robust as the system is nonlinear.

CHAPTER THREE

3. SYSTEM MODELING

3.1. Materials

In this research work, the materials utilized are software such as MATLAB 2019b, Microsoft office 2016, Visio, and MathType equation. MATLAB is a computing software that consists of technical toolboxes and Simulink used for simulation and programming. Microsoft office is utilized for editing the thesis documentation. Microsoft Visio is used for block diagrams and flow charts. MathType is utilized for writing mathematical equations and equations in Microsoft workplaces word and PowerPoint presentation tools.

3.2. Methods

The method used in this thesis to perform the required tasks is shown in Figure 3.1. First, the related paper works with this thesis, and the literature is reviewed. After detailed studies, the modeling of the work is identified from different possibilities. The specification data of the generator, wind turbine and other are taken from a manufacturing company and some of the other specifications taken from the literature of similar size to the Adam I wind farm is using. After the mathematical modelling of the wind turbine, generator and actuator for pitch angle control from the rotor of the wind turbine take the speed as feedback. The collected data from the data specification of the wind turbine and PMSG with the same rated system analyzes how it relates to the model used in this thesis. The mathematical model of the system is carried out from the aerodynamics of generators. The controller's design is carried out and simulation is implemented to the MATLAB. The proposed controller is compared with the controller used in this thesis work, with results and discussion attached. Conclusions and suggestions of the recommendation are also added to the final paper, and the summary of the paper overflows as shown in Figure 3.1.

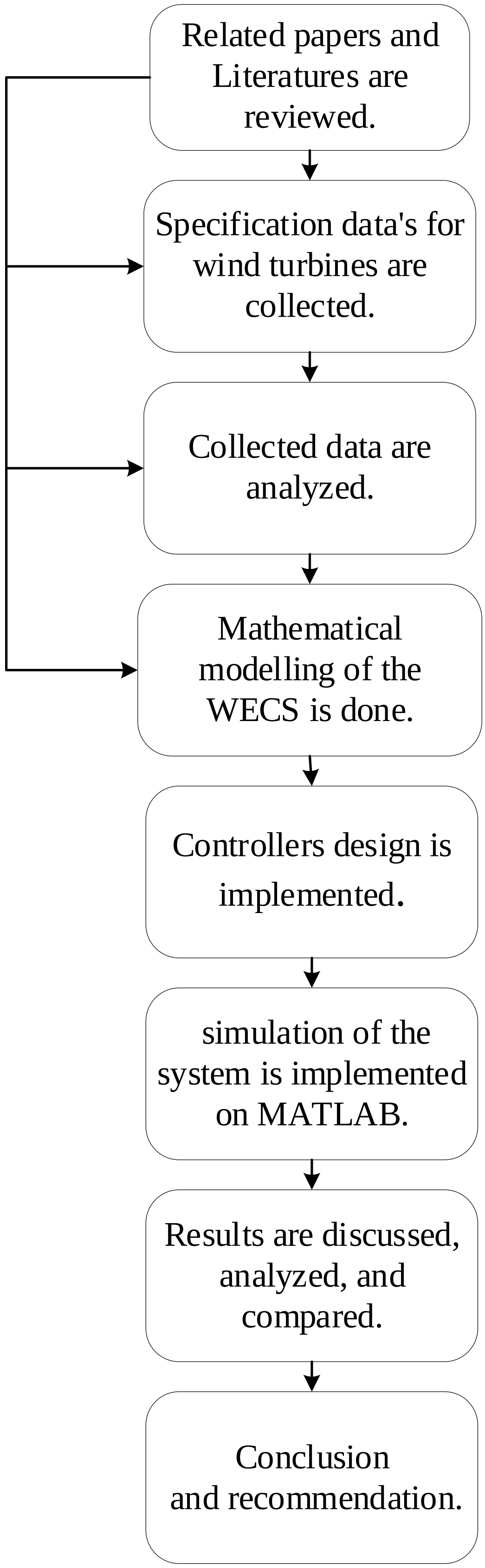

Figure 3.1 Research Methodology

3.3. Mathematical Modelling of the System

The wind energy conversion system is shown in the block diagrams below. Only a few of the components used to satisfy the study's requirements are described in detail. As this study focused on controlling the wind turbine's pitch angle, only the wind turbine, drive train, generator, and pitch controller (actuator) are discussed.

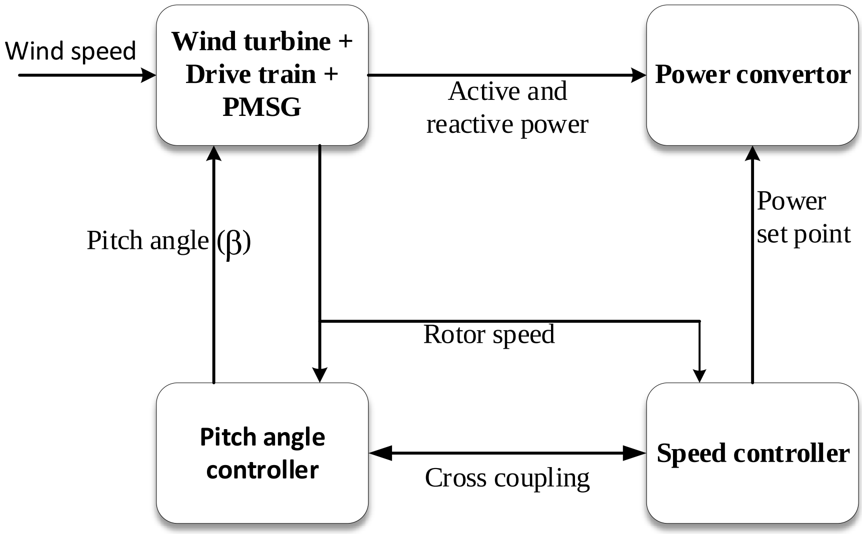

Figure 3.2 Block Diagram of Wind Energy Conversion System

3.3.1. Aerodynamics for wind turbine

Aerodynamics is the science describing the movement of the body in the air. Therefore, it is a branch of dynamics, which deals with the movement of air through the force acting on the object moving in the air or the object stationary in the air current. The airfoil is a surface designed to get the desired response from the air. Therefore, any part of the aircraft or object will convert air resistance into useful force [29].

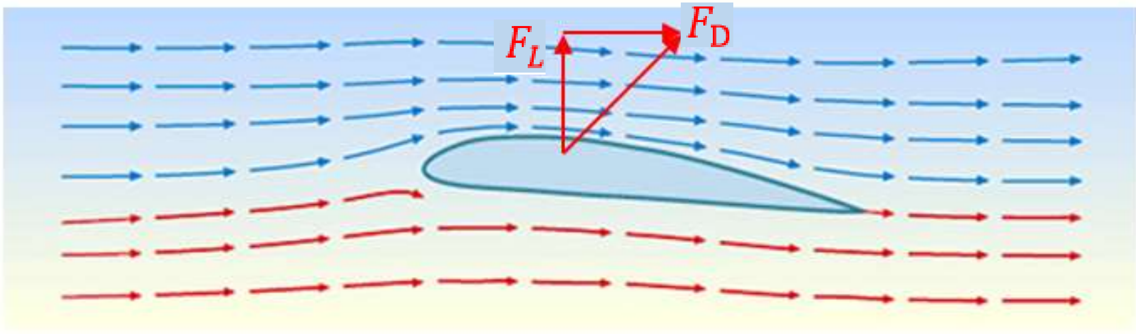

Figure 3.3 Streamlined flow around an airfoil [30].

Objects in the airstream are subjected to the forces from the airstream, lifting force (F_L), and drag force (F_D). The magnitude of these forces depends on the shape of the object, its direction to the airstream, and the speed of the wind [31]. Lift forces and Drag forces are perpendicular to each other and helping a wind turbine blade to rotate.

There are two reasons behind the rotation of wind turbine blades; Newton's third law and the Bernoulli effect. Newton's third law says that “every action has an equal and opposite reaction”. In the case of wind turbine blades, the action of the wind pushing air towards the blade results in a response of the blade deflecting or pushing. If the wind turbine has no pitch angle, the blades will be pushed back or downhill. But the positioning angle of the wind turbine causes the wind to deflect at the opposite angle pushes the blades away from the deflected wind.

Bernoulli's principle or Bernoulli's effect tells us that “air that moves faster has lower pressure, $V \propto \frac{1}{P}$”. The air moving around the wind turbine blades flows faster on the downwind side of the blades than on the upwind side of the blades. The downwind side of the blade has a larger curve, while the upwind side is relatively flat. Since the air moves faster on the side of the blade curved downwind, the pressure on the side of the blade is less. This pressure difference on opposite sides of the blade causes the blade to "lift" toward the curve of the wing [32].

The angle of the blade with respect to the plane of rotation is called the pitch angle. The angle of the blade with respect to the wind is called the angle of attack. The angle of attack is very important and complicated because it changes with the real speed of the wind and the speed of the blade (headwind) [32].

The angle of the attack in the pitch angle control mechanism decreases as the pitch angle increases. Components of the speed, the flow factor, and the rotational speed of the rotor will determine the angle of attack. Using the angle of attack, the force on the blade, the elements are calculated through the characteristics of the two-dimensional airfoil.

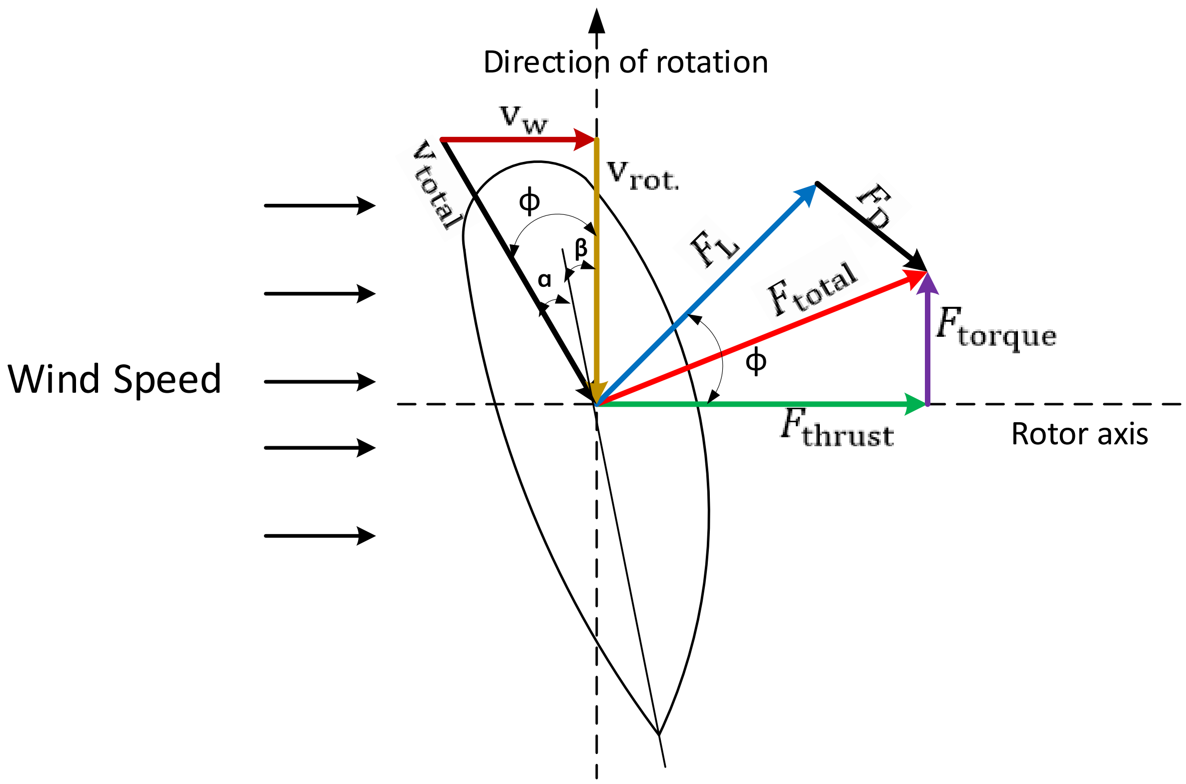

Figure 3.4 Aerodynamics forces [33].

where:

- F_L is a Lifting Force
- F_D is Dragging Force
- F_{torque} is Torque Force
- F_{thrust} is Thrust Force
- F_{total} is Total Force
- v_w is Wind Speed
- v_{total} is Total Speed
- $v_{rot.}$ is rotational Speed
- β is the pitch angle

- ϕ is a total angle
- α is the angle of attack

The inflow wind speed is v_w flows perpendicular to the rotor [34]. For the pitch angle control of a variable speed wind turbine, increasing the pitch angle β will cause the angle of attack α to decrease and result in a decrease in the lift force, resulting in a decrease in mechanical power output. The lift force (F_L) and drag force (F_D) components are converted together into a pair of axial thrust and torque forces, which are in the direction of the rotor. Ftorque generates a motor torque around the rotor axis. By varying the pitch angle β, the size and the direction of total force (F_{total}) components can be changed. The axial force Fthrust has no driving effect, but stresses the rotor blades and causes a thrust on the nacelle and tower [21].

A kinetic energy E of an object with mass m and velocity v under constant acceleration is equal to the work done W in moving that object from rest to a distance S under a force F.

$$E = W = F \times S \tag{3.1}$$

Newton's second law of motion is that;

$$F = ma \tag{3.2}$$

$$E = W = mas \tag{3.3}$$

From kinematics of solid motion

$$v^2 = u^2 + 2as \tag{3.4}$$

Assume the object's starting velocity is zero, $u = 0 m/s$

$$a = \frac{v^2}{2s} \tag{3.5}$$

Substitute equation (3.5) into equation (3.3).

$$E = \frac{mv^2 s}{2s} = \frac{1}{2}mv^2 \tag{3.6}$$

This kinetic energy formulation is based on the assumption that the solid's mass is constant. However, when we consider wind (moving air) as a fluid, both density and velocity may vary, therefore there is no fixed mass. Air density is assumed constant with altitude or temperature. The power of the wind is determined by the rate of change of kinetic energy.

$$P = \frac{dE}{dt} = \frac{d(\frac{1}{2}mv^2)}{dt} = \frac{1}{2}\frac{dm}{dt}v_w^2 \tag{3.7}$$

$\frac{dm}{dt}$, is the mass flow rate.

$$\frac{dm}{dt} = \rho A v_w \tag{3.8}$$

Substitute equation (3.8) into equation (3.7).

$$P = \frac{1}{2}\rho A v_w^3 \tag{3.9}$$

This is the power available in the wind.

where:

ρ air density

A Swept area

v_w Wind velocity

3.3.2. Wind turbine model

The difference between the upstream and downstream wind powers is the actual mechanical power Pm extracted by the rotor blades in watts is described in the equation (3.10).

$$Pm = \frac{1}{2}\rho A v_w(v_u^2 - v_d^2) \tag{3.10}$$

The swept area for the wind turbine is given as;

$$A = \pi R^2 \tag{3.11}$$

From the equation (3.10) and (3.11) the mechanical power extracted becomes;

$$Pm = \frac{1}{2}\rho\pi R^2 v_w(v_u^2 - v_d^2) \tag{3.12}$$

where:

R is the radius of the rotor

v_u is the upstream wind speed at the rotor blade inlet, and

v_d is the downstream wind speed at the exit of the rotor blades

These upstream and downstream wind speeds produce a blade tip speed ratio. v_w is the average of the input and output speeds of the turbine rotor blades [35].

$$v_w = \frac{v_u + v_d}{2} \tag{3.13}$$

Substitute equation (3.13) into equation (3.12).

$$P_m = \frac{1}{2}\rho\pi R^2 \left(\frac{v_u + v_d}{2}\right)(v_u^2 - v_d^2) \tag{3.14}$$

$$P_m = \frac{1}{2}\rho\pi R^2 (\frac{v_u}{2}\left(v_u^2 - v_d^2\right) + \left(\frac{v_d}{2}\left(v_u^2 - v_d^2\right)\right)$$

$$P_m = \frac{1}{2}\rho\pi R^2 (\frac{v_u^3}{2} - \frac{v_u v_d^2}{2} + \frac{v_d v_u^2}{2} - \frac{v_d^3}{2})$$

$$P_m = \frac{1}{2}\rho\pi R^2 (\left(\frac{v_u^3}{2} - \frac{v_u v_d^2}{2} + \frac{v_d v_u^2}{2} - \frac{v_d^3}{2}\right) * v_u^3)$$

$$P_m = \frac{1}{2}\rho\pi R^2 v_u^3 (\frac{1 - \left(\frac{v_d}{v_u}\right)^2 + \left(\frac{v_d}{v_u}\right) - \left(\frac{v_d}{v_u}\right)^3}{2}) \tag{3.15}$$

From the equation (3.15) we get the power coefficient C_p.

$$C_p = \frac{1 - \left(\frac{v_d}{v_u}\right)^2 + \left(\frac{v_d}{v_u}\right) - (\frac{v_d}{v_u})^3}{2} \tag{3.16}$$

The Tip Speed Ratio (TSR) of the wind turbine is the ratio of blade tip speed and wind speed.

$$\lambda = \frac{v_d}{v_u} \tag{3.17}$$

From equation (3.16) the power coefficient can rewrite as the following.

$$C_p = \frac{(1 + \frac{v_d}{v_u})(1 - (\frac{v_d}{v_u})^2)}{2} \tag{3.18}$$

Using the tips speed ratio λ power coefficient is given as;

$$C_p = \frac{(1+\lambda)(1-(\lambda)^2)}{2} \tag{3.19}$$

The power coefficient C_p of the wind turbine depends on the tip speed ratio λ and blade pitch angle β, and the mechanical power of the equation (3.15) can be written as;

$$P_m = \frac{1}{2}\rho\pi R^2 v_u^3 C_p(\lambda, \beta) \tag{3.20}$$

where,

P_m : Mechanical power

C_p : Power coefficient.

β: Blades pitch angle (degree).

λ: tip speed ratio

v_u: wind speed (m/s)

The rotor power coefficient, or power efficiency, is not a constant value; it varies with the wind turbine's tip speed ratio. When you differentiate power coefficient C_p to lambda λ, you get the maximum power coefficient by equating to zeros [35].

$$\frac{dC_p}{d\lambda} = \frac{d\left(\frac{(1+\lambda)(1-\lambda^2)}{2}\right)}{d\lambda} = 0 \tag{3.21}$$

From this equation, $\lambda_1 = -1$ or $\lambda_2 = \frac{1}{3}$ is obtained and substitute the values of the λ in the equation (3.19).

$$\lambda_1 = -1 \quad C_p = \frac{(1+\lambda)(1-\lambda^2)}{2} = \frac{(1+(-1))(1-(-1)^2)}{2} \quad C_p = 0$$

$$\lambda_2 = \frac{1}{3} \quad C_p = \frac{(1+\lambda)(1-\lambda^2)}{2} = \frac{(1+\frac{1}{3})(1-\frac{1}{3}^2)}{2} = \frac{16}{27} = 0.593$$

$$C_{p\,max} = 0.593$$

This indicates that the extracted wind energy converts no more than 59.3% of the kinetic energy of the wind into mechanical energy to rotate the rotor. This is the wind turbine's Betz limit. Even with the best-designed wind turbines, the real world is far below the Betz limit, with Betz values ranging from 0.35 to 0.45 [27], [28]. Because the wind will pass through the spaces between the blades when the rotor runs slowly and the minimum energy extraction is obtained. If the rotor rotates too fast, the rotating blades will act as a solid wall, blocking the flow of wind and limiting power extraction. To capture as much power as possible from the wind stream, the turbines must be configured to run with the best wind-to-tip speed ratio. Theoretically, the greater λ the better in terms of the generator's efficiency of operation [30].

However, there are drawbacks; high λ promotes erosion of the blades' leading edges due to the impact of the dust or sand in the air. This would need the employment of a specific erosion-resistant coating material, which might raise energy costs. Due to drag and tip loss, a higher λ can cause noise, vibration, and lower rotor efficiency, as well as the possibility of turbine failure due to excessive rotor speed. The power factor can be described by the tip speed ratio λ and the pitch angle β as the following equation (3.22) [36],[37].

$$C_p(\lambda, \beta) = c_1 \left(c_2 \frac{1}{\lambda_i} - c_3\beta - c_4 \right) e^{-\frac{c5}{\lambda_i}} + c_6\lambda \qquad (3.22)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+\beta} - \frac{0.035}{1+\beta^3} \qquad (3.23)$$

In the case of power control, the power coefficient C_p is the most essential parameter. It is a non-linear function whose value is different for each type of turbine and is indirectly a function of the wind speed, as the tip speed of the wind turbine is depends on the rotor speed, radius, and wind speed power coefficient is depends on the pitch angle and tip speed ratio. For this thesis, the following values are used [9],[37].

$c_1 = 0.5176,\ c_2 = 116,\ c_3 = -0.4, c_4 = 5, c_5 = -21, c_6 = 0.0068.$

The tip speed relationship is also described in terms of the relationship between wind speed and rotor speed.

$$\lambda = \frac{R\omega_r}{V_w} \qquad (3.24)$$

The rotor torque is obtained also from the rotational speed.

$$T_m = \frac{P_m}{\omega_r} \tag{3.25}$$

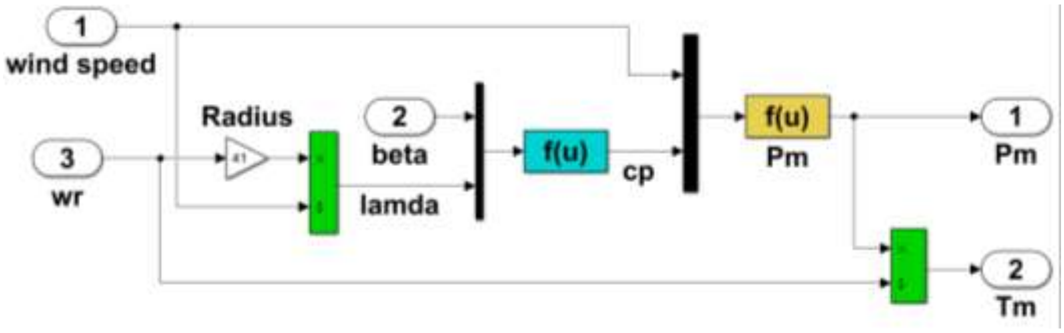

Figure 3.5 Wind turbine model

3.3.3. Drive Train Model

Blade pitch mechanism with the rotor, blade hub, rotor shaft, and gearbox with a breaker and a generator constitute the transmission system of the wind turbine power generation system, which converts the torque or rotation of the blades into energy. Due to the use of multi-pole PMSG, no gearbox is used, and the drive train is modeled as a lumped mass model. The rotation speed can be calculated using the following equation [36].

$$\sum T = J\alpha = J\frac{d\omega}{dt} \tag{3.26}$$

$$T_m - T_e - T_{Damping} = J\frac{d\omega_r}{dt} \tag{3.27}$$

$$T_{Damping} = B_s * \omega_r \tag{3.28}$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_m - T_e - B_s * \omega_r) \tag{3.29}$$

where:

ω_r is the rotational speed.

J is the moment inertia of the rotor and generator.

T_m is the mechanical torque of the shaft.

T_e is electromechanical torque.

B_s Damping coefficient.

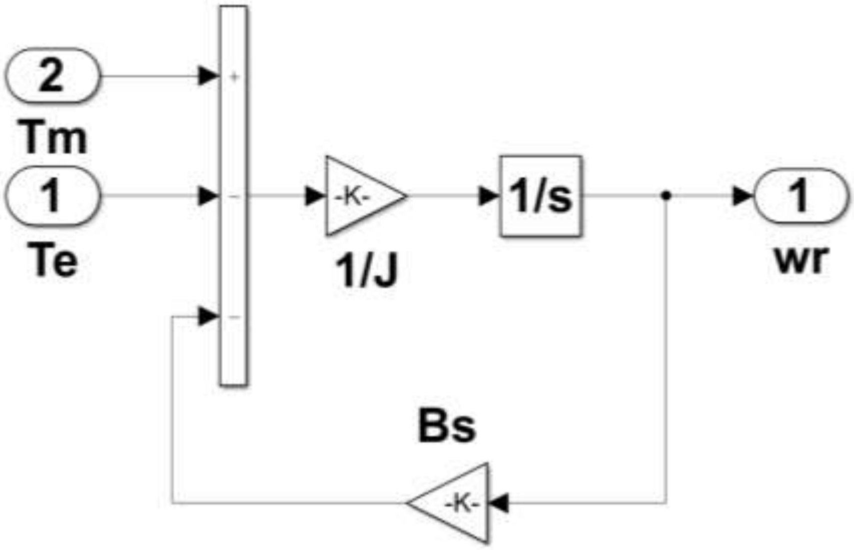

Figure 3.6 Drive train model.

3.3.4. Permanent Magnet Synchronous Generator (PMSG) Model

Double Feed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) are the two most widely used generators in wind energy conversion systems (PMSG). PMSG provides various advantages over DFIG, including the capacity to operate without a gearbox, cheaper maintenance costs, and the capacity to extract maximum power from variable speed, among others. As a result, PMSG was chosen for this thesis based on its benefits. The dynamic model of PMSG is derived from a two-phase synchronous reference frame, where the q-axis is 90° in front of the d-axis concerning the direction of rotation. Using a phase-locked loop (PLL), the synchronization between the d-q rotating reference frame and the ABC-three-phase frame is kept up [14], [38]. The generator equation is projected onto the reference d-q axis coordinate system, which rotates synchronously with the magnetic flux so that the generator control system can be easily constructed using the generator dynamic model. The cross-sectional view of the PMSG is shown in the following figure 3.7 with 3_phase and 2_poles.

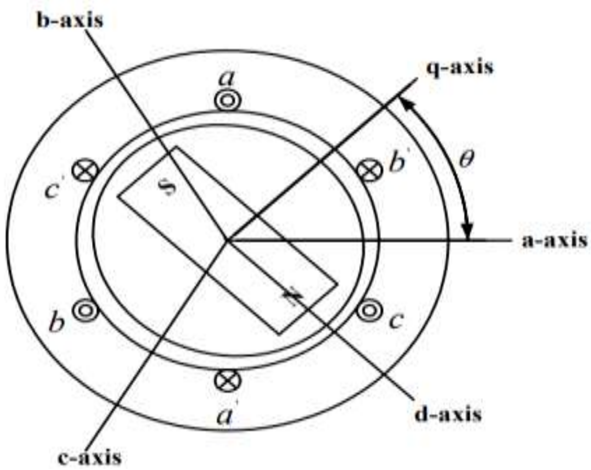

Figure 3.7 Permanent magnet synchronous motor [39].

The electrical dynamic equation of the PMSG in terms of the phase variables is shown as the following.

$$v_{as} = R_s I_{as} + \frac{d\lambda_{as}}{dt} \tag{3.30}$$

$$v_{bs} = R_s I_{bs} + \frac{d\lambda_{bs}}{dt} \tag{3.31}$$

$$v_{cs} = R_s I_{cs} + \frac{d\lambda_c s}{dt} \tag{3.32}$$

where:

$[v_{as}, v_{bs}, v_{cs}]$, $[I_{as}, I_{bs}, I_{cs}]$ and R_s are phase voltage, phase current, and resistance of 3-phase (a, b, and c) stator side.

$[\lambda_{as}, \lambda_{bs}, \lambda_{cs}]$ are phase flux linkages provided by the 3-phase currents and permanent magnets and described as the following equations.

$$\lambda_{as} = L_{aa} I_{as} + L_{ab} I_{bs} + L_{ac} I_{cs} + \lambda_{ra} \tag{3.33}$$

$$\lambda_{bs} = L_{ab} I_{as} + L_{bb} I_{bs} + L_{bc} I_{cs} + \lambda_{rb} \tag{3.34}$$

$$\lambda_{cs} = L_{ac} I_{as} + L_{cb} I_{bs} + L_{cc} I_{cs} + \lambda_{rc} \tag{3.35}$$

where:

$[L_{aa}, L_{bb,}, L_{cc}]$ are self-inductance and $[L_{ab}, L_{bc}, L_{ac}]$ are mutual inductance.

$[\lambda_{ra}, \lambda_{rb}, \lambda_{rc}]$ are the rotor flux linkage from a permanent magnet.

$$\lambda_{ra} = \lambda_r \cos\theta \tag{3.36}$$

$$\lambda_{rb} = \lambda_r \cos(\theta - \frac{2\pi}{3}) \tag{3.37}$$

$$\lambda_{rc} = \lambda_r \cos(\theta + \frac{2\pi}{3}) \tag{3.38}$$

Inductance is a function of θ because the stator self-inductance is maximized when the q-axis of the rotor is aligned with the phase axis. The mutual inductance is greater when the q axis is between them [39]. Using the park's transformation the 3-phases (a,b,c) are transformed into the d-q frame. By this transformation, the time-varying AC quantities are transformed into the DC variables which are free from time-varying. From the inverse park's transformation, the following equation 3.39 is obtained. Y represents any of the following variables (voltage, current, and flux linkage) [39].

$$\begin{bmatrix} Y_{qs} \\ Y_{ds} \\ Y_{os} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} Y_{as} \\ Y_{bs} \\ Y_{cs} \end{bmatrix} \tag{3.39}$$

where;

Y is voltage or current.

With this transformation, the voltage equation of the dq-axis can be expressed as.

$$v_{ds=R_s I_d s} + L_d \frac{d(I_{ds})}{dt} - \omega_{ge} I_{qs} L_q \tag{3.40}$$

$$v_{qs=R_s I_{qs}} + L_q \frac{d(I_{qs})}{dt} + \omega_{ge} I_{ds} L_d + \omega_{ge} \lambda_r \tag{3.41}$$

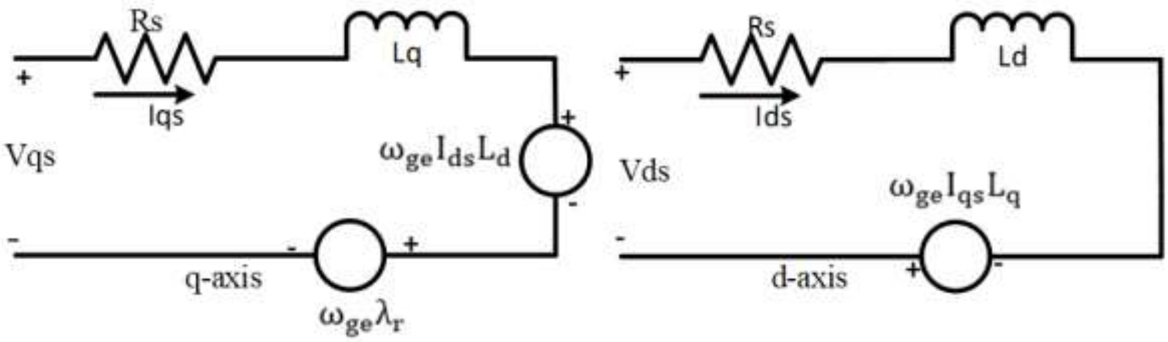

Figure 3.8 d-q axis equivalent circuit.

Input power can be derived as the following equation.

$$P_{in} = \begin{bmatrix} v_{as} & v_{bs} & v_{cs} \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} \equiv \frac{3}{2} \begin{bmatrix} v_{qs} & v_{ds} \end{bmatrix} \begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} \qquad (3.42)$$

$$P_{in\ dq} = \frac{3}{2}\left(v_{qs} I_{qs} + v_{ds} I_{ds}\right) \qquad (3.43)$$

The PMSM's electromagnetic torque can be characterized as follows;

$$T_e = \frac{3}{2} p(\lambda_r I_{qs} - (L_{ds} - L_{qs}) I_{qs} I_{ds}) \qquad (3.44)$$

where:

p is the number of poles.

In this thesis from the specification of PMSG $L_{ds} = L_{qs}$, then electrical torque is;

$$T_e = \frac{3}{2} p \lambda_r I_{qs}$$

And generator Output Power is $P_e = Te\omega_{ge}$

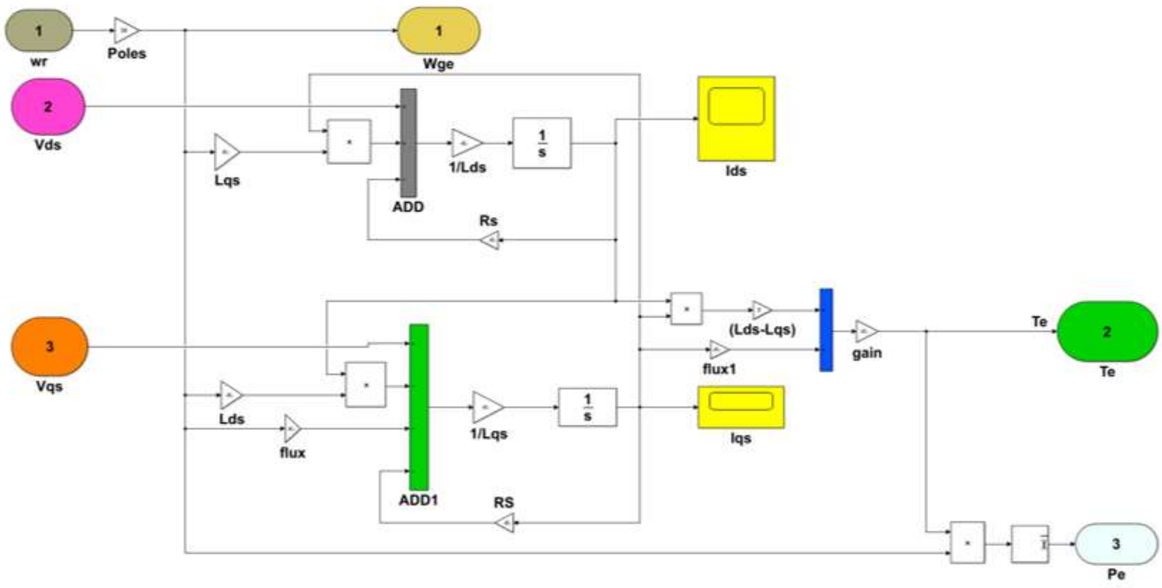

Figure 3.9 Permanent magnet synchronous generator

3.3.5. Pitch Actuator

A pitch actuator controls the rotation of the blades along their longitudinal axis in a pitch angle controlled wind turbine. The pitch control system reduces the angle of attack and spins the blades or pitches out of the wind when the wind speed exceeds the rated value. As pitch actuators, electric or hydraulic devices are used. Electric pitch angle control is mostly used, and the servo motor adjusts each blade individually. The pitch actuator modeling equation is given as the following equation below [28].

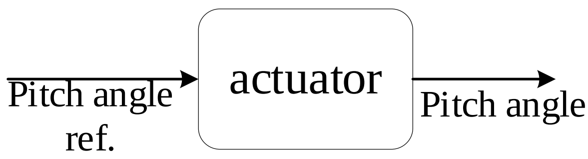

Figure 3.10 Pitch Actuator Gain

$$\frac{d\beta}{dt} = (\beta_{ref} - \beta)/\tau_c \tag{3.45}$$

where:

β_{ref} Reference pitch angle

β Measurement of pitch angle

τ_c, is time constant

$$\tau_c \frac{d\beta}{dt} = \beta_f - \beta \tag{3.46}$$

$$\tau_c \frac{d\beta}{dt} + \beta = \beta_f \tag{3.47}$$

Take Laplace transform

$$\tau_c s\beta(s) + \beta(s) = \beta_{ref}(s) \tag{3.48}$$

$$(\tau_c s + 1)\beta(s) = \beta_{ref}(s) \tag{3.49}$$

$$\beta(s) = \frac{1}{1+\tau_c s}\beta_{ref}(s) \tag{3.50}$$

Assuming $\tau_c = 0.05\text{sec}$ equation (3.50) can be written as a first-order transfer function [28].

$$\frac{\beta(s)}{\beta_{ref}(s)} = \frac{1}{1+0.05s} \tag{3.51}$$

3.4. Controllers Design

The controller must be built appropriately to maintain the system's stability and performance since the wind energy conversion system is extremely nonlinear. An actuator in the pitch angle controller keeps the rotor blade in the appropriate position. The control signal or information is provided by the hydraulic or electrical actuator's controller. The maximum power point tracking control approach is used to achieve maximum power production below the rated wind speed. Maximum power point tracking systems are controlled in a variety of ways. Tip speed ratio control is one way for improving output power by adjusting rotational speed to get the optimal tip speed ratio.

$$\omega_{ref} = \frac{\lambda_{op} * V_w}{R} \tag{3.52}$$

where,

ω_{ref} Reference rotational speed.

λ_{op} optimum tip speed ratio.

V_w, wind speed.

R, rotor radius.

The power coefficient reaches its maximum value at the optimal tip speed ratio, and the power captured by the turbine blade reaches its maximum value at certain speeds, while the pitch angle remains unchanged. As a result, the tip speed ratio must be kept at optimum to collect maximum energy when the wind speed is less than the rated speed [39]. The other control mechanism for maximum power point tracking is the optimum torque control technique.

$$\lambda = \frac{\omega_r * R}{V_w} \tag{3.53}$$

$$V_w = \frac{\omega_r * R}{\lambda} \tag{3.54}$$

Mechanical power equation can be written as:

$$P_m = \frac{1}{2}\rho\pi R^2 \left(\frac{\omega_r * R}{\lambda}\right)^3 C_p(\lambda, \beta) \tag{3.55}$$

At some value of the tip speed ratio λ_{op} maximum power coefficient C_{p-max} is obtained which can optimize the extracted power $P_{m\ opt}$. Equation (3.55) can be written as:

$$P_{m\ opt} = \frac{1}{2}\rho\pi R^2 \left(\frac{\omega_r * R}{\lambda_{op}}\right)^3 C_{pmax}(\lambda, \beta) \tag{3.56}$$

$$P_{m\ opt} = \frac{1}{2}\rho\pi R^5 \frac{{\omega_r}^3}{{\lambda_{op}}^3} C_{pmax}(\lambda, \beta) = \frac{\frac{1}{2}\rho\pi R^5 C_{pmax}(\lambda, \beta)}{{\lambda_{op}}^3} . {\omega_r}^3 \tag{3.57}$$

Equation (3.57) can be put as the following equation (3.58) in terms of K_{opt}.

$$P_{m\ opt} = K_{opt}. {\omega_r}^3 \tag{3.58}$$

The relationship between mechanical power and torque is given in the equation (3.25).

$$T_{m\ opt} = \frac{P_{m\ opt}}{\omega_r} = \frac{K_{opt}.{\omega_r}^3}{\omega_r}$$

$$T_{m\ opt} = K_{opt}. {\omega_r}^2 \tag{3.59}$$

By measuring the mechanical torque to its optimum value the extracted power output is obtained. But the control mechanism operated in this thesis is when the wind speed is higher than the nominal speed. The pitch angle control system is used to limit the power output and protect the wind turbine when the wind speed exceeds the rated wind speed. In this thesis, various control approaches of the pitch angle control method are used to stabilize the power and reduce the mechanical stress of the wind turbine.

3.4.1. PID Controller

The PID controller is a feedback-based control loop that is commonly utilized in industrial control systems and a variety of applications that require control [40]. The three parameters of a proportional–integral–derivative (PID) controller are proportional, integration, and derivative are varied to get the desired response. Proportional is used for fast-rising time responses, Integral is used for minimizing errors, and Derivative is also used for minimizing errors, reducing overshoot, and undershoot in PID controllers [41].

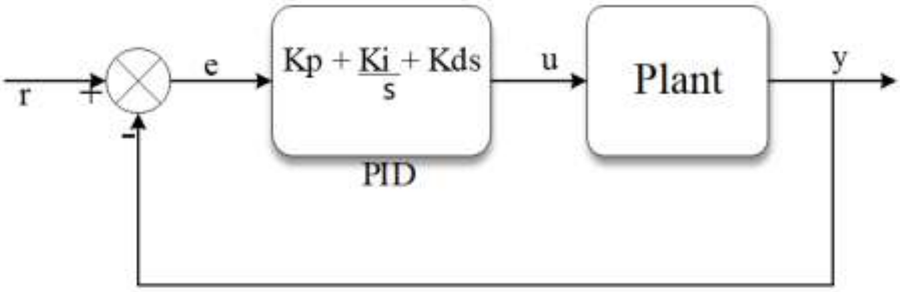

Figure 3.11 PID controller working mechanism.

$$e(t) = y(t) - r(t) \quad (3.60)$$

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t) \quad (3.61)$$

On a closed-loop system, the impacts of the PID controller parameters are given in the table below.

Table 3.1 Effects of the PID parameters on the closed-loop response [40],[41].

Closed-loop Response	Rise time	Settling time	overshoot	Steady-state error	stability
Proportional (increasing)	Decrease	Increase	Small increase	Decrease	Degrade
Integral (increasing)	Small decrease	Increase	Increase	Large decrease	Degrade
Derivative (increasing)	Small decrease	Decrease	Decrease	Minor change	improve

After the PID controller settings have been determined by trial and error, auto-tuning is carried out to obtain the optimum result response.

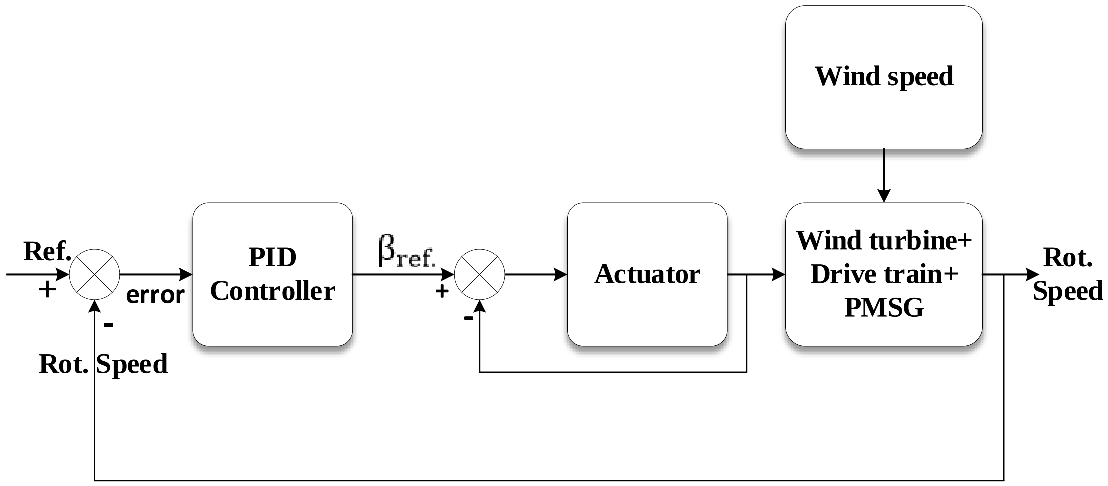

Figure 3.12 PID Controller Block Diagram.

The PID controller is used to calculate the difference between the actual rotational speed and the reference rotational speed (set-point). The PID parameters correct the error sent to the PID controller. The pitch actuator is to change the control signal from the PID controller to convert to the rotational. The pitch angle of an actuator is updated and compared regularly to β_{ref}.

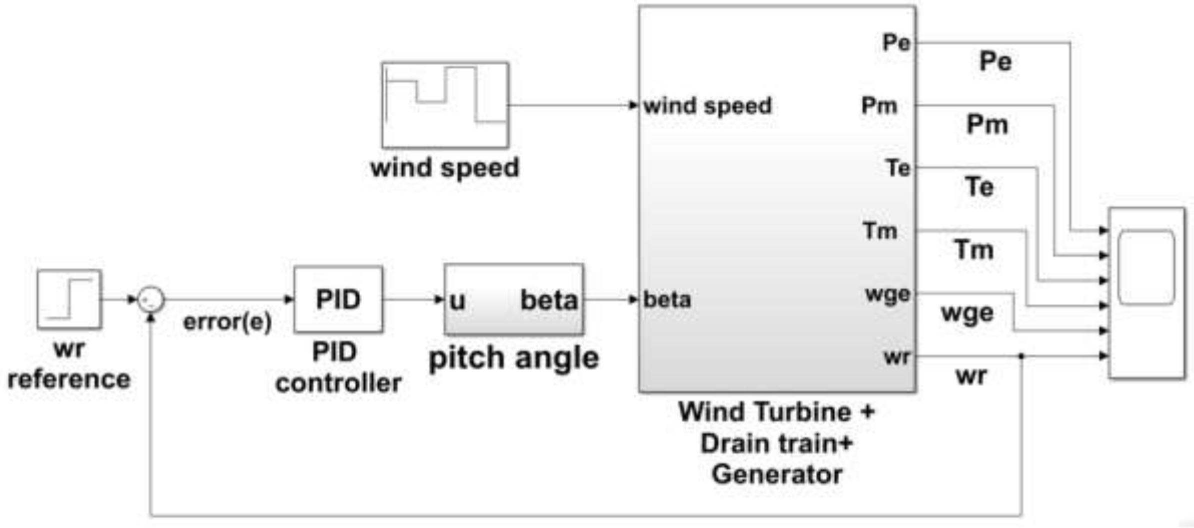

Figure 3.13 Simulink of PID controller.

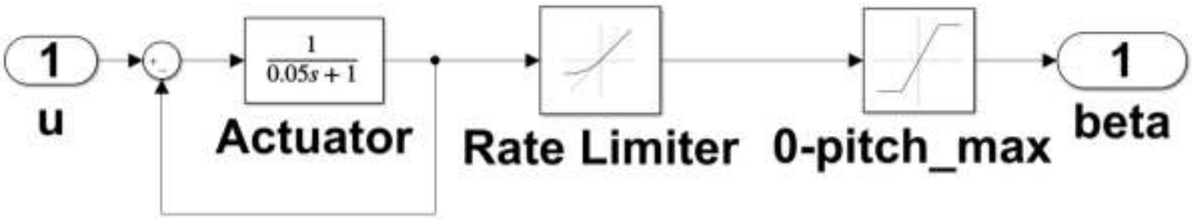

Figure 3.14 Pitch angle

Rate limiter: It can be a block, limiting the first derivative of the signal passing through it, and the output change will not surpass the desired limit [42].

$$\text{rate} = \frac{u(i)-y(i-1)}{t(i)-t(i-1)} \quad (3.62)$$

$$\text{rate} = \frac{u(i)-y(i-1)}{\Delta t} \quad (3.63)$$

where:

$u(i)$ and $t(i)$ are the input and time at the current step.

$y(i-1)$ and $t(i-1)$ are the output and time of the previous step.

Rising slew Rate (R): Limits the derivative of the increasing input signal.

Falling response rate (F): The derivative limit of the falling input signal.

If the rate is greater than the rising a slew rate parameter (R) the output obtained is as the following equation [42], [43].

$$y(i) = \Delta\mathrm{t}.\mathrm{R} + \mathrm{y}(\mathrm{i} - 1) \qquad (3.64)$$

If the rate is greater than the falling a slew rate parameter (F) in the output obtained is similar to the following equation.

$$y(i) = \Delta\mathrm{t}.\mathrm{F} + \mathrm{y}(\mathrm{i} - 1) \qquad (3.65)$$

If the rate is between the rising slew rate (R) and the falling slew rate (F), the change in output equals the change in input.

$$\mathrm{y}(\mathrm{i}) = \mathrm{u}(\mathrm{i}) \qquad (3.66)$$

Saturation block: The saturation limiter block produces an output signal that is the upper and lower limit of the input signal value. The upper and lower limits are indicated by the upper and lower limit parameters. When the input signal is within the range indicated by the lower and upper limit parameters, the input signal passes is unaltered. When the input signal exceeds these limits, the signal will clip to the upper or lower limit [44], [45].

Table 3.2 function of saturation block

Input	**output**
LL ≤ Input value < UL	Input Value
Input Value < LL	LL
Input Value > UL	UL

3.4.2. Fuzzy Logic Controller

It is too difficult to regulate nonlinear and complicated systems using a conventional controller like a PID controller. In recent years, fuzzy logic techniques have gained acceptance as the best tools for dealing with nonlinearity, uncertainty, unpredictability, modeling, and control of complex systems for which there are no simple mathematical explanations. The crucial advantage of fuzzy logic is that it does not require an accurate model description. Fuzzy logic control solves non-linear systems problems with the limited input information. It interprets system behavior as a set of IF-THEN rules based on human common sense information. The design of a rule-based fuzzy logic controller may be divided into three stages.

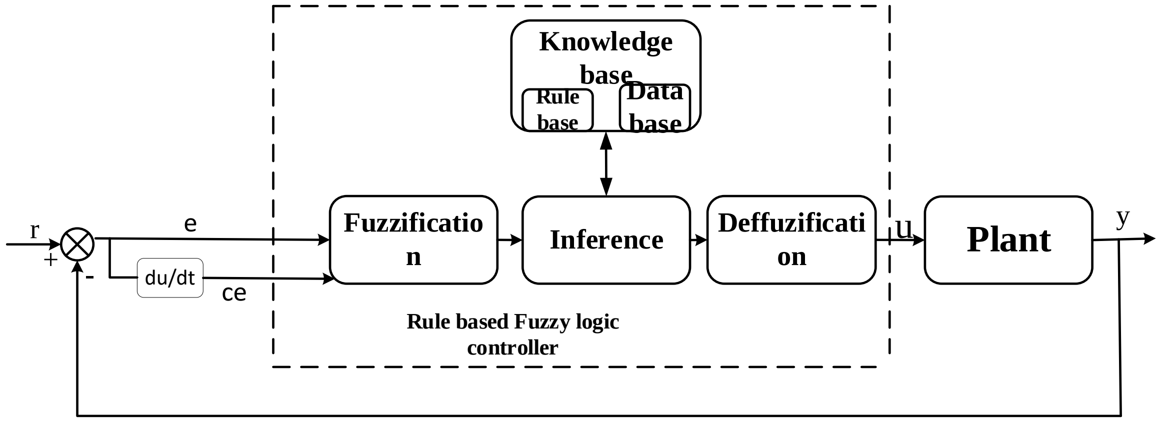

Figure 3.15 Design of Rule-Based Fuzzy Logic Controller

i. Fuzzification

Determining the membership functions for the control and converting crisp values to fuzzy values and this process is called fuzzification.

ii. Fuzzy Inference System

A fuzzy inference system (fis) or the rule base is used to maps the inputs to the outputs of the system. To build a fuzzy logic reasoning rule, a fuzzy inference system, also known as a rule base is used. Mamdani and Sugeno are the two fuzzy inference systems. Their difference is; Mamdani uses the defuzzification method to get the crisp output and Sugeno uses a weighted average to calculate the crisp output. In this thesis, Mamdani fuzzy inference system is used.

iii. Deffuzification

The process of conversion of a fuzzy set into a real number (crisp value) is called defuzzification. Several methods have been developed to generate real values as outputs [24]. In this paper centroid, defuzzification method is used. This centroid defuzzification method is used to determine the center of the area (COA) of the fuzzy set and return the corresponding crisp value.

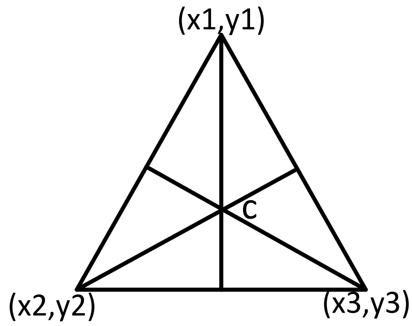

Figure 3.16 Centroid of the Triangle

Centroid formula, $$c = [\left(\frac{x_1+x_2+x_3}{3}\right), (\frac{y_1+y_2+y_3}{3})] \quad (3.67)$$

As the membership function applied in this thesis is triangular; the centroid of a triangle is the center of the triangle, which can be determined as the point of intersection of all the three medians of a triangle.

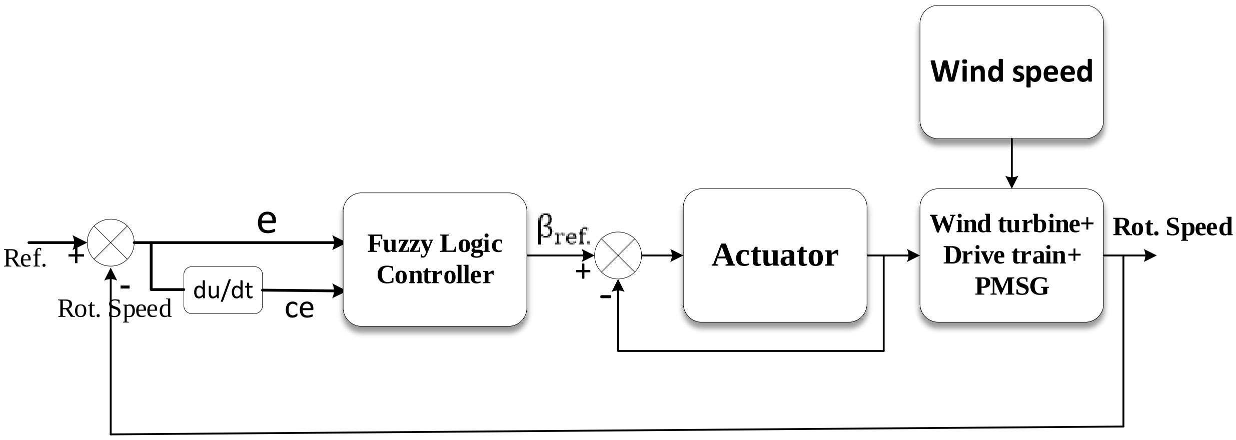

Figure 3.17 Fuzzy Logic Controller Block Diagram.

FLC's input variables are an error and derivative of the error. Error is the difference between the actual and reference rotational speeds. The reference pitch angle is the controller's output.

Constructing a fuzzy logic controller with Rule Base

The inference rule for the Fuzzy logic controller is based on the relationship between the rotor speed's two inputs (error and change in error) and the corresponding output (reference pitch angle). The language variables for the fuzzy logic controller used here are Negative Big (NB), Negative Small (NS), Zero (ZO), Positive Small (PS), and Positive Big (PB). The rule base for the fuzzy logic controller is given in the following table.

Table 3.3 Fuzzy Logic Controller Rule base.

e \ Ce	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NS	NS	ZO	PS
ZO	NS	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

For example: If error(e) is Negative Big (NB) and change of error(ce) is PS then Beta ref. (Bref) is NS. A fuzzy logic controller is designed on MatLab after the rule base is formulated.

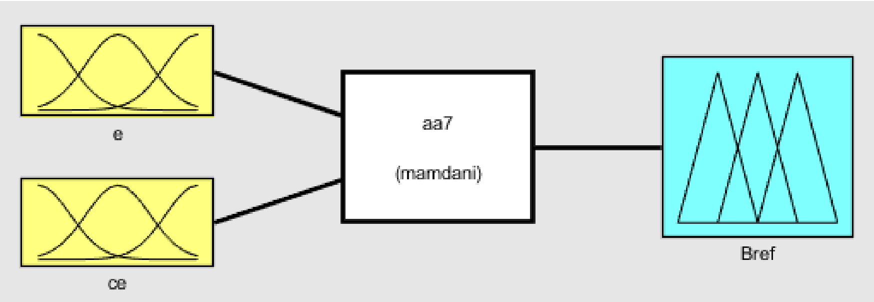

Figure 3.18 Fuzzy Logic Designer

For the input and output variables, the following membership function in the range of [-1 1] is designed as the following figure below.

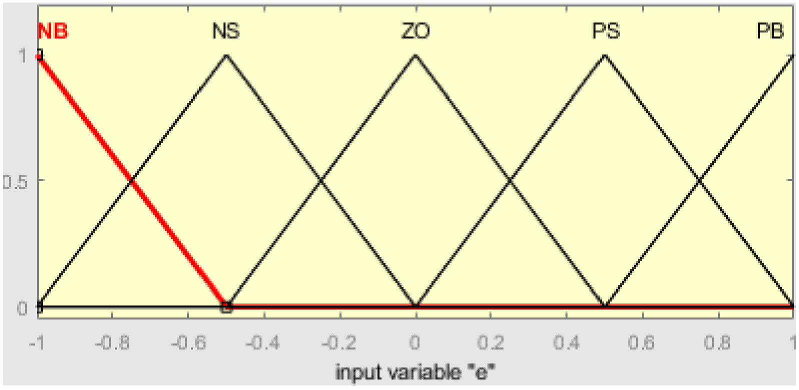

Figure 3.19 Membership functions of the error (e)

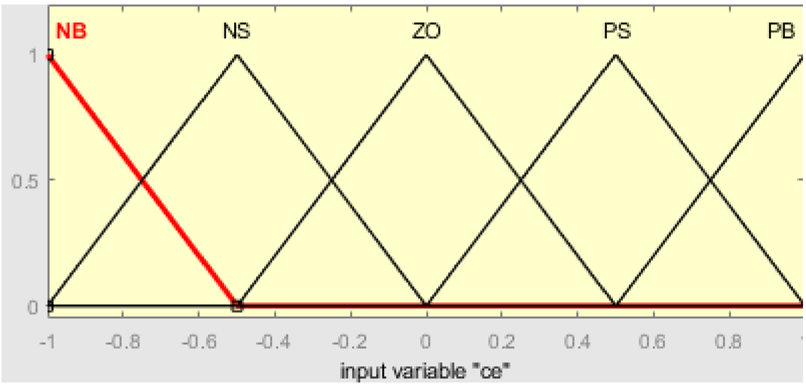

Figure 3.20 Membership functions of the change of the error (ce)

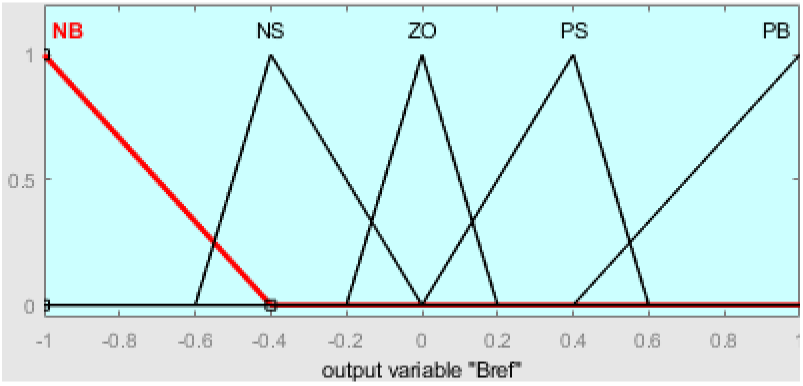

Figure 3.21 Membership functions of the output (Bref)

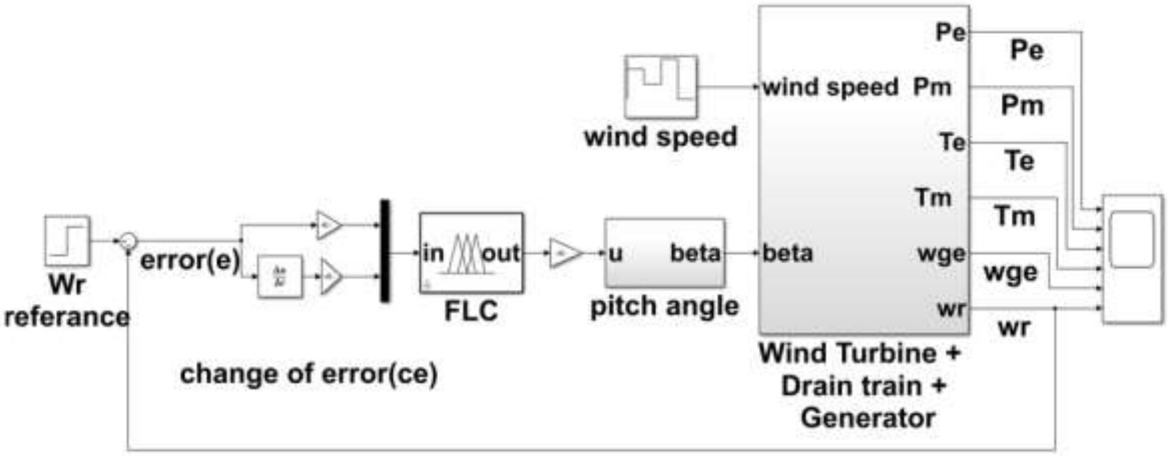

Figure 3.22 Simulink of Fuzzy Logic Controller

3.4.3. PSO based fuzzy logic controller block diagram

Particle Swarm Optimization (PSO) is the basic Swarm Intelligence-based methodologies. The swarm's qualities in swarm intelligence include no central control or distributed control, and the capacity to adapt to environmental changes. The PSO algorithm was inspired by simulations of animal social behavior such as bird flocking, and fish schooling [19].

Advantageous:

Simple for implementation.
Few algorithm parameters.
Efficient in global search.
There are few parameters to adjust.
Robust.
Have short computational time.

Disadvantages

Slow convergence (weak local search ability).
It is difficult to determine the initial design parameters [23].

Applications of particle swarm optimization:

- Training of neural networks (Identification of Parkinson's disease, Extraction of rules from fuzzy networks, Image recognition).
- Optimization of electric power distribution networks.
- Structural optimization (Optimal shape and sizing design, Topology optimization).
- Process biochemistry.
- System identification in biomechanics [19].

Fuzzy Logic controllers and PSOs are useful in modeling and maintaining intelligent and automated control systems. Each system has its own set of benefits, such as Fuzzy Logic's nonlinearity and explicit knowledge expression and PSOs' global and local search approach [46]. An FLC has several parameters that can be modified to vary the controller's performance. Among them are:

- Scaling factors for each variable.
- Fuzzy sets representing the meaning of linguistic values.
- Adjust the membership functions. Making the membership function thinner.
- Design of the rule base [46], [47].

From these above-listed controller performance parameters, only tuning of the scaling factors of fuzzy logic controllers is explored in this thesis. Only by adjusting the scale factor can real-time control be achieved. Therefore, it is best to use a self-adjusting scale factor when using fuzzy control [48]. The tuning of the scale factor of the fuzzy logic controller is similar to that of the fuzzy PID type controller type. The corresponding; proportional control, integral control, and derivative control components of a PID type fuzzy controller can be analyzed. The difficulty in choosing relative scale factors is the main disadvantage of all these PID-type FLC designs. Similarly, the dynamic behavior of the fuzzy controller depends on this appropriate choice [48].

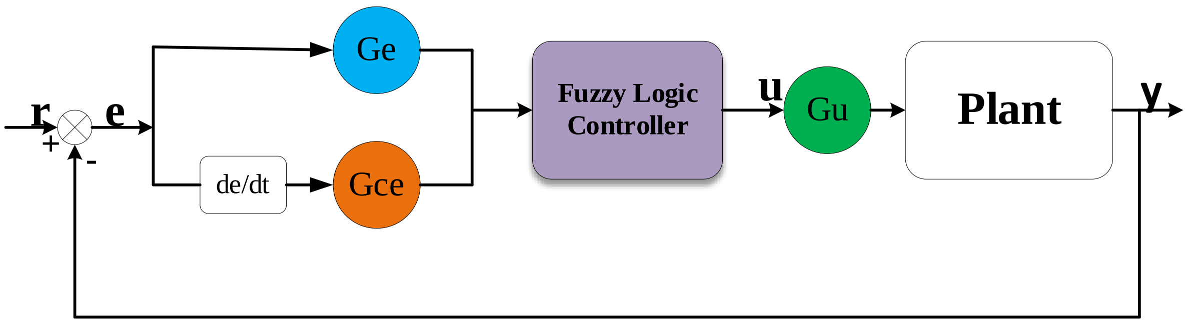

Figure 3.23 Input and Output gains

where;

G_e and G_{ce} are the input gains.

G_u is the output gains.

Gain Tuning

Because the scaling gain is frequently used for fuzzy controller tuning, it's crucial to understand what occurs when these scaling gains are tuned.

i. Input scaling gains

G_e and G_{ce} are the gains for the error and change of error input of the fuzzy logic controller. The choice of the scaling gains G_e and G_{ce} results on the horizontal axis of the membership function by $\frac{1}{G_e}$ and $\frac{1}{G_{ce}}$ respectively. The scaling gains effects are seen as the following[48].

- If G_e = G_{ce}=1, the membership function doesn't change.

- If G_e and G_{ce} <1, the membership functions are uniformly spread out by the factor of $\frac{1}{G_e}$ and $\frac{1}{G_{ce}}$ respectively.
- If G_e and G_{ce} >1, the membership functions are uniformly contracted by the factor of $\frac{1}{G_e}$ and $\frac{1}{G_{ce}}$ respectively.

ii. Output scaling gains

G_u is the output gains of the membership function of the fuzzy logic controller. Output scaling gain has the following effects.

- If $G_u = 1$, there are no changes on the output membership functions.
- If $G_u < 1$, the membership functions are all uniformly contracted by a factor of $\frac{1}{G_u}$.
- If $G_u > 1$, the membership functions are all uniformly spread out by a factor of $\frac{1}{G_u}$.

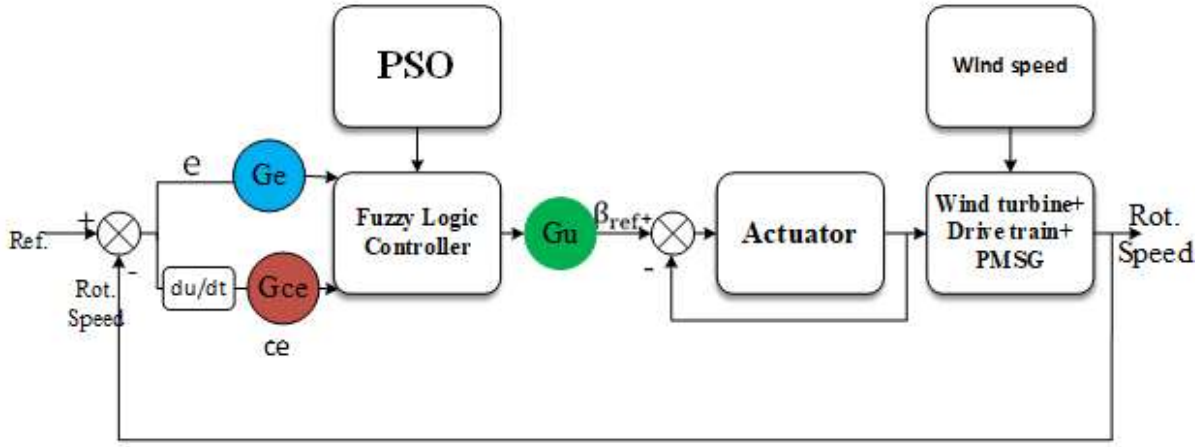

Figure 3.24 Particle Swarm Optimization based Fuzzy logic controller block diagram

Objective function

For the non-linear optimization of fuzzy logic controller design time-domain analysis is used. The trapezoidal integration rule is used for the evaluation of the performance index. The trapezoidal rule works by approximating the region under the graph of the function as a trapezoid and calculating its area [49].

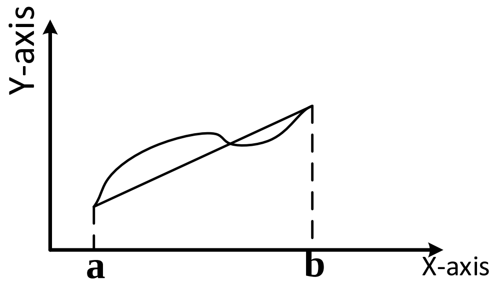

Figure 3.25 Trapezoidal rule

$$\int_a^b f(x)dx \approx (b-a) * \frac{1}{2}(f(a) + f(b)) \tag{3.67}$$

Based on this performance index the objective considered in this thesis for PSO based fuzzy logic controller is:

$$\mathbf{obj} = \frac{\mathbf{1}}{\mathbf{2}} * (\mathbf{t}(\mathbf{i}-\mathbf{1}) - \mathbf{t}(\mathbf{i})) * (|\mathbf{e}(\mathbf{i}-\mathbf{1})| + |\mathbf{e}(\mathbf{i})|) \tag{3.68}$$

Time (t) and error (e) are used as an output from the Simulink model and retrieve from it.

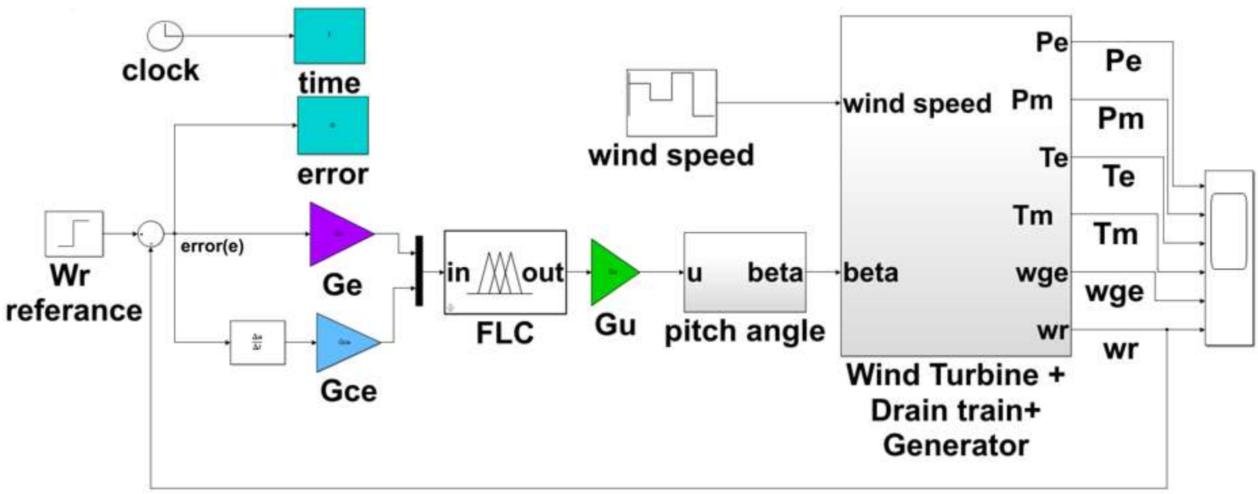

Figure 3.26 Simulink model of PSO-based FLC

The conversion factor from the tuning scaling factor is shown in figure 3.27 and the value of the gains obtained are put in table 3.4.

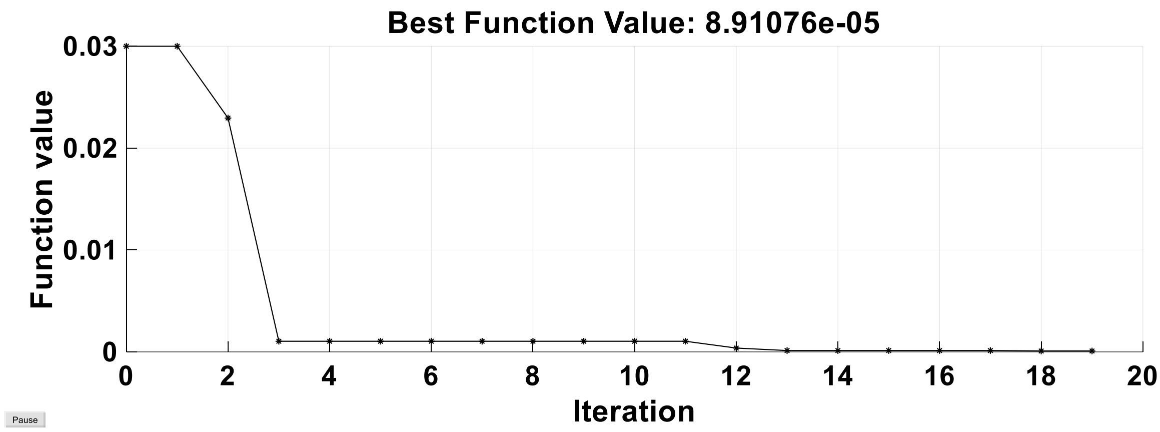

Figure 3.27 fitness value for the objective function

Table 3.4 Tuned value of scaling factors of FLC using PSO

Gains	Randomly given value	Tuned value
Ge	0.05	0.15
Gce	0.005	1.826364182095297
Gu	0.05	6.132789220969585

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

This chapter analyzes and discusses the results of the PID controller, the fuzzy logic controller, and the proposed PSO-based fuzzy controller. After studying the mathematical modeling of the PMSG-based variable speed wind turbine, each component was modeled in MATLAB/Simulink to evaluate the system and its related results. To verify the validation of the proposed method, the simulation was performed for a 1.5-MW PMSG wind power system. Wind turbine parameters and PMSG are listed in the appendix. The wind speed profile is considered as a disturbance for the wind turbine in this thesis is a stepped change model for simulation and controller robustness considerations.

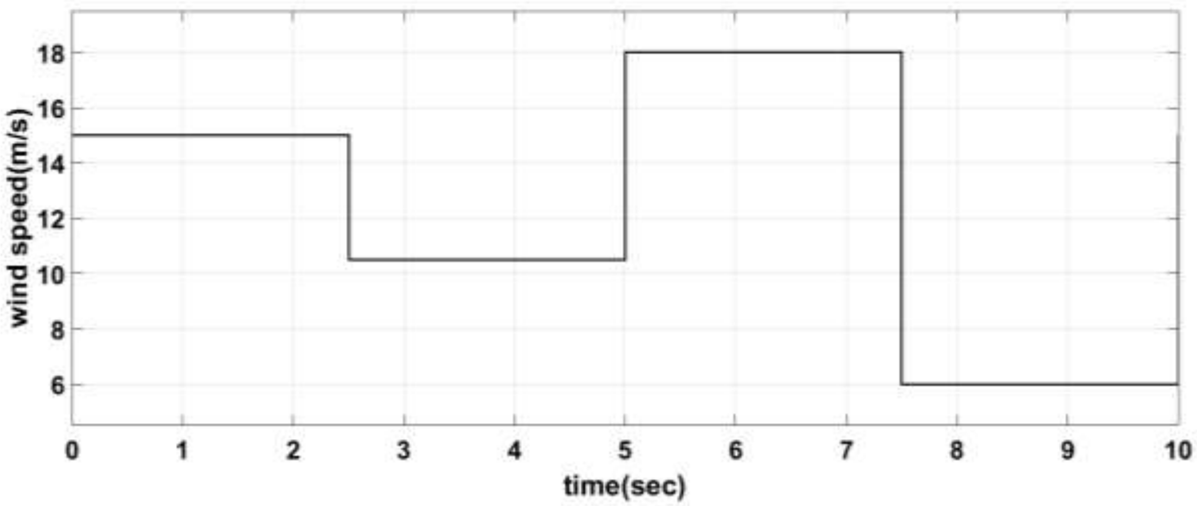

Figure 4.1 Wind Speed model

In this model, the wind speed has different speed ranges from 6m/s to 18m/s. The change of this wind speed on this wind model is to show the performance of the controller. When the wind speed increases or decreases, the controller controls the pitch angle to protect the wind turbine. The simulation of the PID controller result is obtained by comparing the rotational speed with the set-point rotational reference speed which is 17.3rpm and PID parameters are adjusted offline. For fuzzy logic controller and PSO-based fuzzy controller error, and change of the error are given to the inputs.

4.1. Pitch angle response result

The pitch angle range for this research work is, from 0 to 15degrees. The following results are obtained for PID, fuzzy logic controller, and PSO-Fuzzy logic controller.

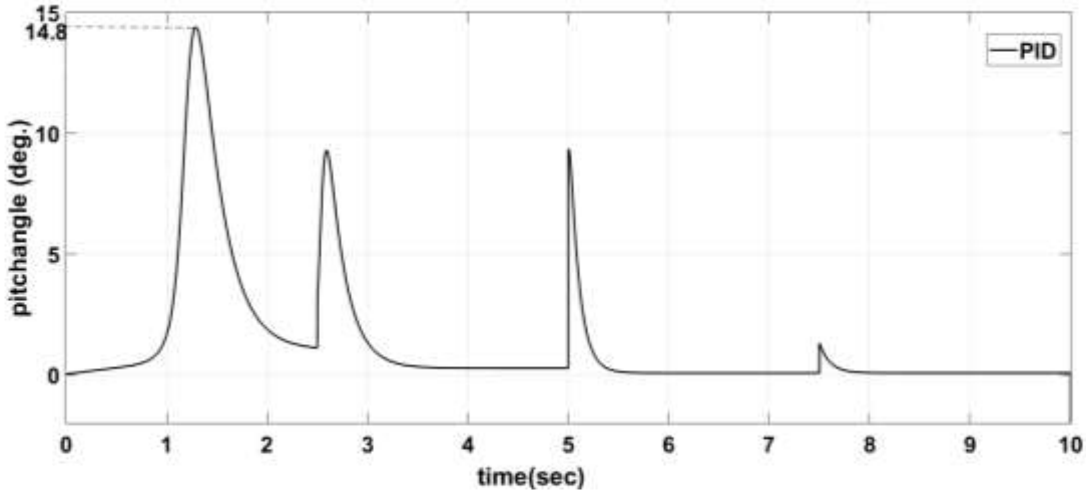

Figure 4.2 Response of pitch angle, PID Controller

The viability control of the pitch angle on the changes of the wind speed is continuous. The maximum pitch angle of the PID controller reaches about 14.8degrees. The pitch angle of the controller is high, the first disturbance is 15m/s, and it also decreases when the wind speed decreases.

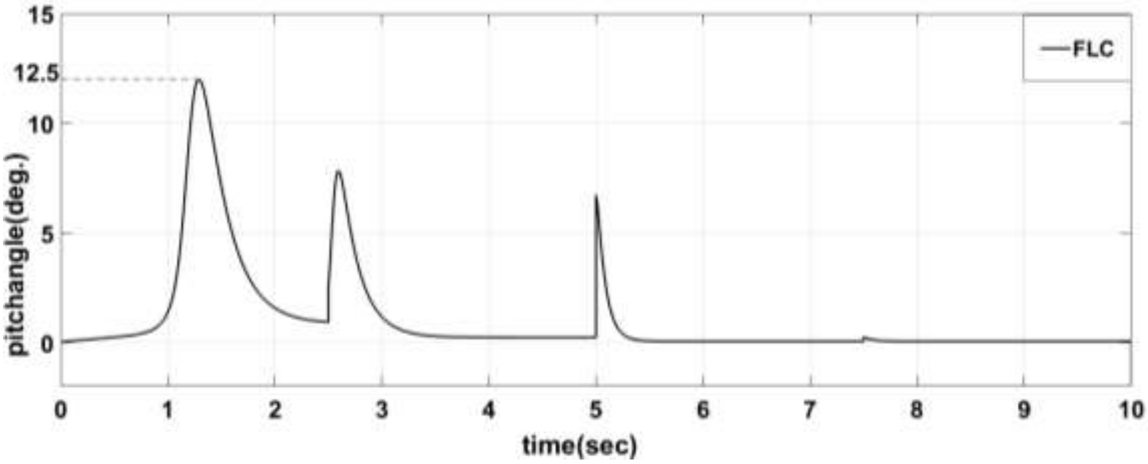

Figure 4.2.3 Response of pitch angle, FLC

The maximum pitch angle of the fuzzy logic controller reaches approximately 12.5degrees.

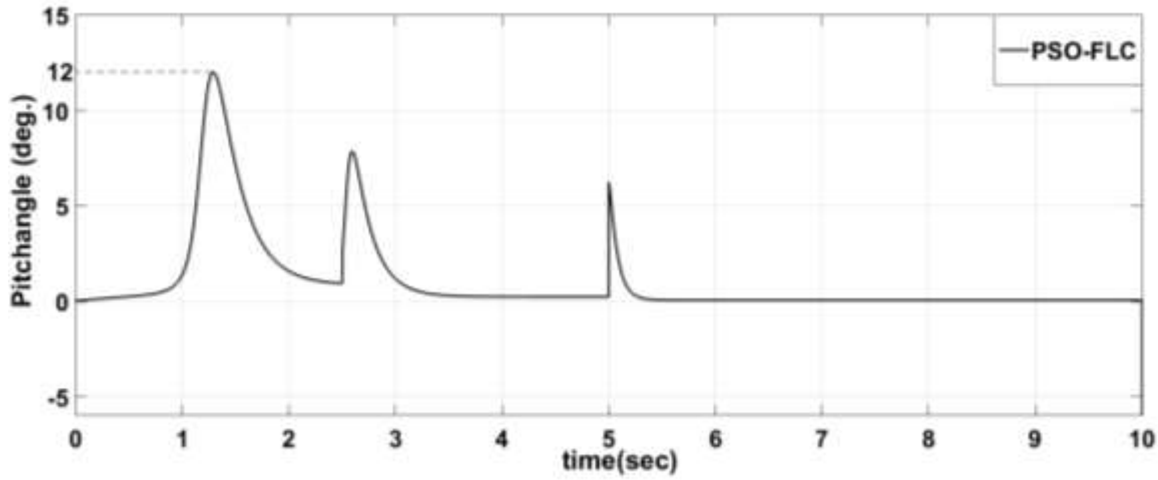

Figure 4.4 Response of pitch angle, PSO-FLC

The maximum pitch angle of the PSO-based fuzzy logic controller reaches approximately 12 degrees. At 7.5seconds, when the wind speed drops to 6m/s, the pitch angle response has been constant or unchanged.

4.2. Rotor speed response result

The rotor output is used for pitch angle control. The speed of the rotor is directly proportional to the wind speed.

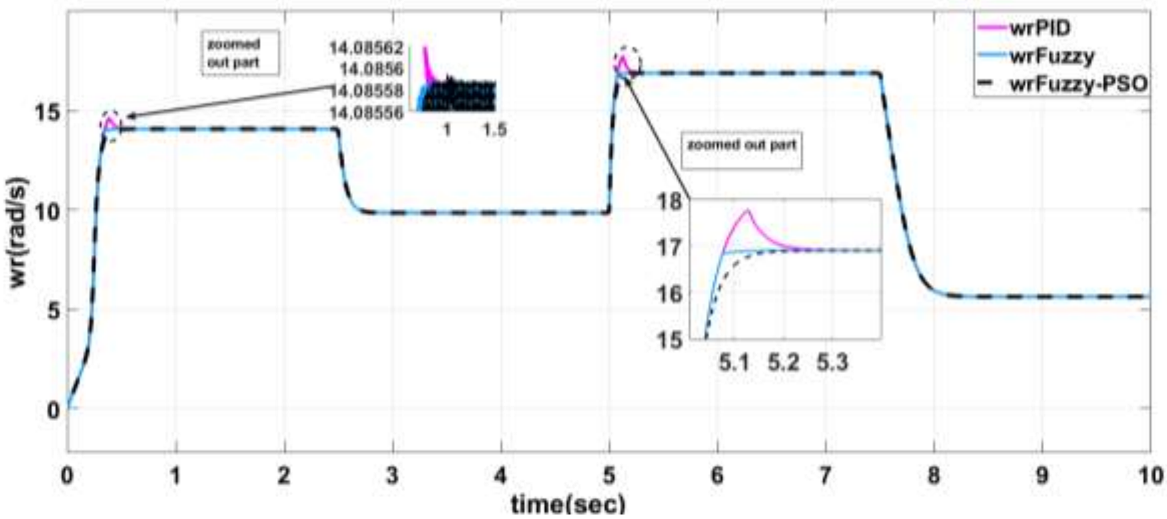

Figure 4.3 response of the rotational speed

Even if the speed is taken after the wind speed, due to the inertia of the wind turbine, it takes some time to respond quickly. According to the time domain specification obtained from the response, the results in Table 4.1 below are obtained.

Table 4.1 Time-domain performance

PID

```
>> stepinfo(out.wrPID)

ans =

  struct with fields:

        RiseTime: 8.7473
    SettlingTime: 310.5113
     SettlingMin: 1.7900
     SettlingMax: 5.9233
       Overshoot: 18.6167
      Undershoot: 0
            Peak: 5.9233
        PeakTime: 202
```

Fuzzy

```
>> stepinfo(out.wrFuzzy)

ans =

  struct with fields:

        RiseTime: 8.701
    SettlingTime: 310.606
     SettlingMin: 1.7800
     SettlingMax: 5.7886
       Overshoot: 18.214
      Undershoot: 0
            Peak: 5.7886
        PeakTime: 201
```

Fuzzy_PSO

```
>> stepinfo(out.wrFuzzy_PSO)

ans =

  struct with fields:

        RiseTime: 8.1965
    SettlingTime: 308.234
     SettlingMin: 1.8841
     SettlingMax: 5.6470
       Overshoot: 13.05
      Undershoot: 0
            Peak: 5.123
        PeakTime: 288
```

In the PID controller, the system overshot response is 18.6167%, which is greater than for the fuzzy controller (18.214%) and the PSO-based fuzzy controller (13.06%). The PID controller has a rise time of 8.7473sec, the Fuzzy logic controller has a faster rise time with 8.701sec and the PSO-based fuzzy logic controller is 8.1965sec.

4.3. Mechanical power result

The mechanical power response of the wind turbine is shown in Figure 4.4 below.

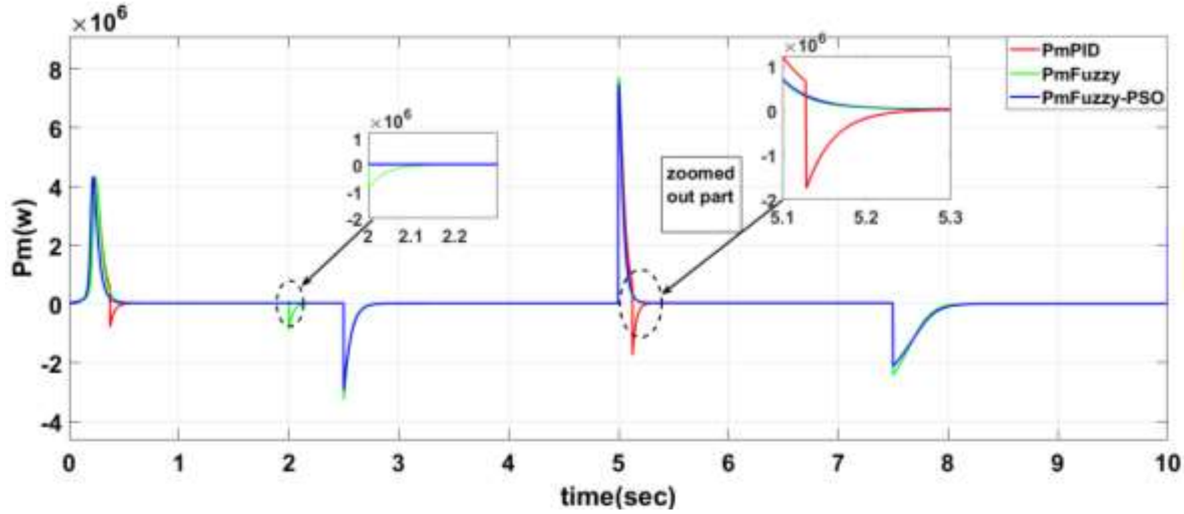

Figure 4.4 The response of mechanical power

The mechanical power response of the wind turbine shows that the PID controller is not stable at startup and when increasing from 10.5m/s to 18m/s. The instability of the mechanical power has a great influence because the torque is obtained from the mechanical power divided by the rotor speed, which is provided to the drive train and affects the entire system. In the fuzzy logic controller, the energy drawn from the wind drops in about 2 seconds suddenly. This shows that even if the fuzzy logic controller's performance is better than that of the PID controller, there is a fluctuation in the fuzzy logic controller at the time 2second.

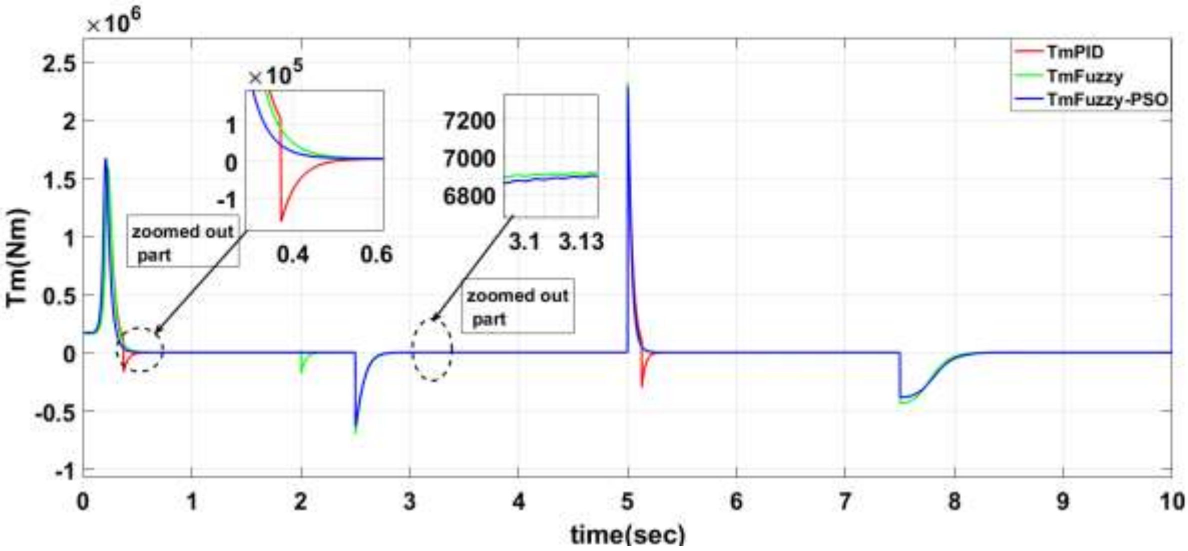

Figure 4.5 The response of Mechanical torque

The mechanical power is drawn from the wind speed and the rotational torque is directly proportional. The PID controller has a large ripple factor at the time 0.4 seconds and 5.2 seconds, while the fuzzy logic controller also has a ripple factor of approximately 2 seconds, which leads to wind turbine fatigue. This wind turbine fatigue causes damage to the wind turbine but is eliminated in the PSO-fuzzy logic controller.

4.4. Generator output power response

The electrical power changes with the rotational speed and the resulting response is shown in Figure 4.6.

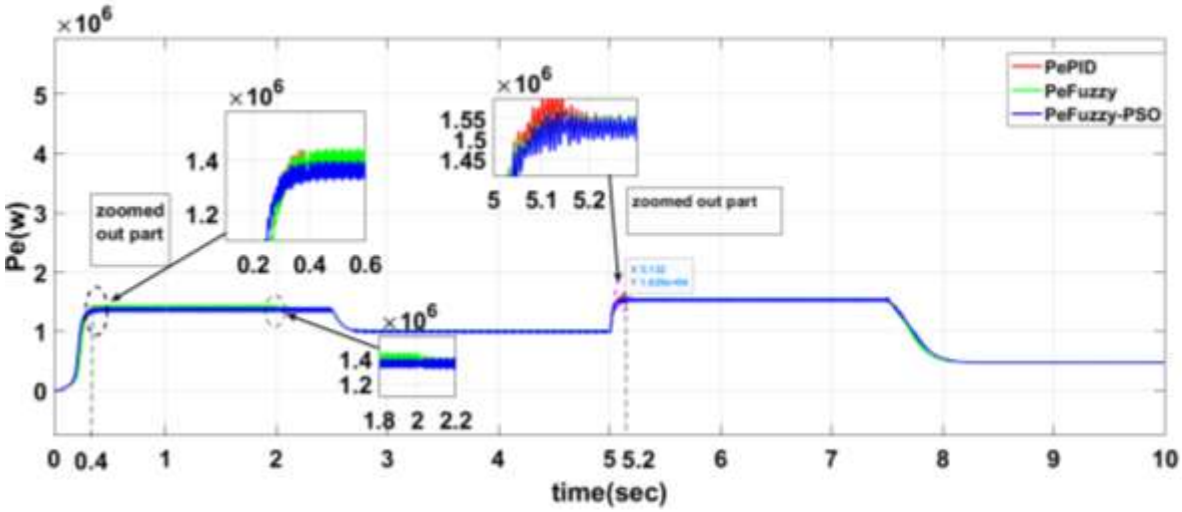

Figure 4.6 The response of the generator Output Power

When the wind speed is higher than the rated speed, the generator output power tries to reach the nominal value of 1.5 MW power. When the wind speed is higher than the rated speed, the generator runs at full load. At t = 5.132 seconds, the generator output power obtained from the PID controller is 1.625MW, while the fuzzy logic controller is 1.573MW. The proposed PSO-based fuzzy logic controller has a maximum generator power of 1.531MW, which is an improvement compared to PID and fuzzy logic controllers. The maximum power change of the PID controller above the rated power is 0.125 MW, and the fuzzy logic controller is 0.052 MW. For the proposed controller the maximum change above the nominal power is 0.031MW, which shows that in the presence of disturbance, it is a good disturbance rejection and good tracking of the generator rated value.

4.5. Discussions of the results

Using the dynamic model of the wind helps to understand the behavior of the wind system. However, in this thesis work, as it is only for simulation purposes the wind speed is modeled as the figure 4.1. The variable of wind speed makes the system non-linear, which also becomes a problem in calculating the ideal parameters of the controller. This is why a controller is used to adjusts according to the variable changes of the system variables. The proposed controller PSO-based fuzzy logic controller adjusts its control response according to wind conditions and provides stability to the system.

The Controller system used affects the pitch angle to limit the wind energy. The power extracted from the wind is related to the cubic speed of the wind and the power coefficient. As the wind speed increases, the angle of inclination increases, causing the blade head to turn away from the direction of the wind. When the wind speed increases, the extracted power increases by a cubic ratio, but as the pitch angle increases, the power coefficient decreases, and when the power coefficient decreases, the extracted power is decreased. The power coefficient is maximum at 0 degrees.

The response of the Fuzzy controller and PSO-Fuzzy controller to the pitch angle is slower than that of the PID controller, indicating that it has better adaptability to changes in wind speed. At the time of 7.5 sec, when the wind speed is reduced from 18 m/s to 6 m/s, the PSO-Fuzzy logic controller has not changed from the previously obtained pitch angle. The smallest minimum pitch angle has a high power coefficient resulting in high mechanical power. When the wind speed decreases the pitch angle decreases also to turn back the blades.

PID controller has a poor overshoot, and rise time than other controllers. PID controller overshoot is 18.6167%, the rise time is 8.7473sec. The settling time of the Fuzzy logic controller (310.606sec) is greater than the PID controller settling time (310.5113sec). Even if the performance of the Fuzzy logic controller is better than that of the PID controller, it will take longer to stabilize. Using the PSO-Fuzzy logic controller greatly improves the system overshoot, which is 13.05%. It has also improved settling time (308.234sec) and rise time (8.1965sec). The peak time for the PSO-Fuzzy logic controller to reach the peak is longer than other controllers.

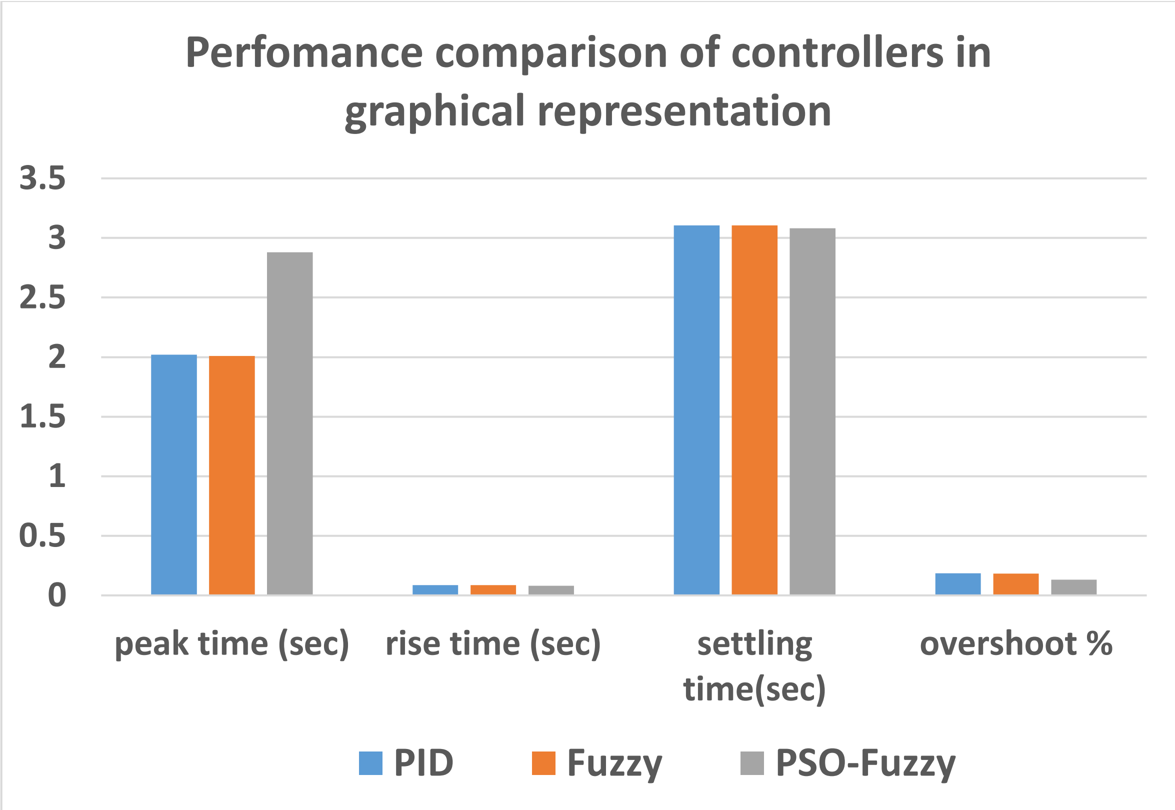

Figure 4.7 Graphical representation of the dynamic performance parameters

The proposed PSO-Fuzzy logic controller has better performance, as shown in figure 4.7 irrespective of the peak time.

Mechanical torque is generated by the wind on the rotor, which is transmitted to the generator through the drive train. The main point of the drivetrain is to transmit the mechanical torque while supporting all the other loads that follow the torque. From the extracted power, we can obtain the mechanical torque which is transmitted to the drive train is divided by the rotor speed. There are some fluctuation factors in mechanical power and mechanical torque for PID controller and Fuzzy Logic controller. The power drawn from the wind has good stability in the PSO-based fuzzy logic controller.

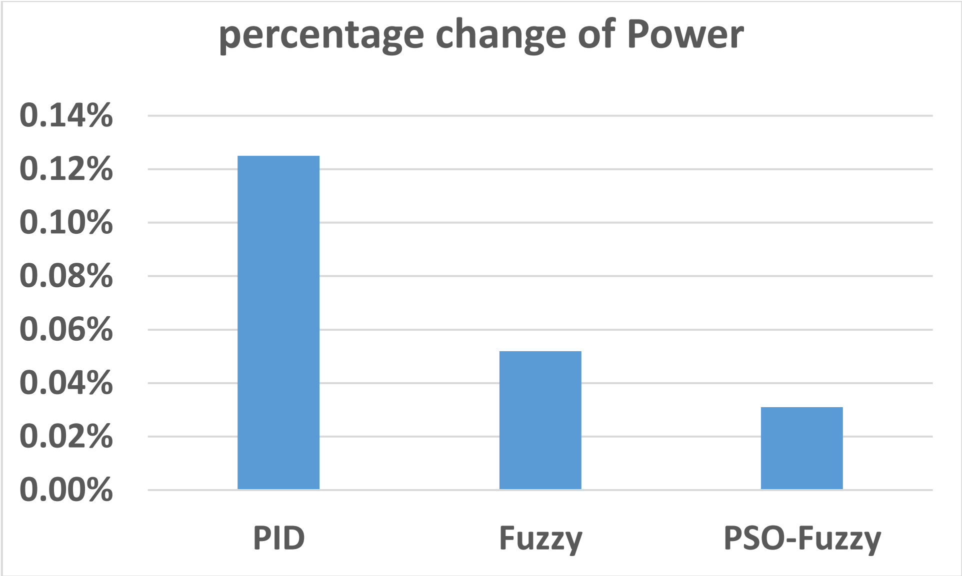

Figure 4.8 Graphical representation of the electrical output power

The maximum generator overshoot output power of the PID controller reaches 1.625MW, and the fuzzy logic controller also reaches 1.573MW. The proposed controller PSO-based fuzzy logic controller (1.531MW) shows higher output power stability than other controllers. In the proposed controller, the change in output power greater than the rated power (1.5MW) is only about 0.03% much less than the other controllers.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Since the relationship between the wind speed and the output power of the wind turbine rotor is a cubic relation, a small variation of the wind speed results in a large deviation in the output power. This in turn will cause such as system vibration, mechanical fatigue, and speed acceleration to exceed the generator's rated speed. Pitch angle control is the method of controlling the movement of the blade and has an impact on aerodynamic loads, to obtain a lower peak torque and lower fatigue load. In this research work, PID controller, fuzzy logic controller, and PSO-based fuzzy logic controller are applied to pitch angle control. PID controller has a good response in a stable state but is difficult in sudden changes of the wind speed. PSO_Fuzzy logic controller based on the tuning of the scaling factors results in a better control response in different wind speed variations. For wind speeds lower than the rated speed, the initial pitch angle is set to the optimized value at pitch angle degree ($\beta = 0$). But for the wind speed above rated speed, the pitch angle must be changed according to the wind speed, to secure the wind turbine from mechanical overload and structural damage. For a wind speed of 15 m / s, the pitch angle of the wind turbine reaches about 14.8 degrees. For the fuzzy logic controller and the PSO fuzzy logic controller, the pitch angle is smaller than that of the PID controller, which is 12.5 degrees and 12 degrees, respectively.

The dynamic speed performance of the wind turbine with PID controller, the rise time is 8.7473sec, the settling time is 310.5113sec, and the overshoot is 18.6167%. The fuzzy logic controller improves the PID controller's rise time by 8.701sec, the settling time by 310.606sec, and the result of overshoot by 18.214%. The PSO-based fuzzy logic controller output rise time result is 8.1965sec, the settling time is 308.234sec, and the overshoot is 13.05%. Fuzzy logic controller based on PSO based on time-domain specifications and disturbances (step changes in wind speed) is more robust than PID and fuzzy logic controllers. When the wind speed changes with the pitch angle control, the received power from the wind also changes. When the wind speed is 18m /s, the maximum value of the PSO-based fuzzy logic controller is 1.531MW, which is not much higher than the nominal value compared to other controllers. The maximum change in output power of the PID controller is 0.13%, the fuzzy logic controller is 0.05%, and the PSO-Fuzzy logic controller is 0.03%. Therefore, using the proposed PSO-based fuzzy logic controller, a more stable output power response is achieved through the pitch angle control of the wind turbine. In general, the PSO-Fuzzy logic controller has a smaller overshoot when disturbances occur, so it is very effective to control the pitch angle of the wind turbine under various wind speeds reduces the transient effect of the controller, thereby reducing the power consumption of the actuator. The simulation results of the PID controller, Fuzzy logic controller, and PSO-based fuzzy controller show that the performance of the PSO-based fuzzy controller is better.

5.2. Recommendation

In addition to the scale factor, the fuzzy controller can be further improved by optimizing the width of the fuzzy logic controller. Another possibility for further work is to analyze and compare the output responses of different types of controllers (such as GA-based Fuzzy logic controllers and GA-PID controllers). Online training algorithm, such as multilayer perceptual artificial neural network, is recommended for additional improvements through pitch angle control to be more effective in terms of power stability and lower peak torque.

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Appendix

Table 0.1 datasheet for Gold-wind GW 82/1500 wind turbine model [50].

Wind turbine	**Values**
Rated power	1.5MW
Cut-in wind speed	3m/s
Rated wind speed	10.3m/s
Cut-out-wind speed	22m/s
Rotor	**Values**
Diameter	82m
Swept area	5,325.0m^2
Number of blades	3
Rotor speed	17.3rpm
Gear Box	**Values/description**
Type	Direct drive
Ratio	-
Generator	**Values/description**
Generator type	PMSG
Rated Power	1.5MW
Rated Voltage	720 V
Poles	36
Rated rotor speed	17.3 rpm
Stator resistance R_s	0.08Ω
q-axis inductance =d-axis inductance ($L_{qs} = L_{ds}$)	41mH
Rated Frequency	50/60 Hz
Rated Output	620/690v
Flux φ	1.53Wb

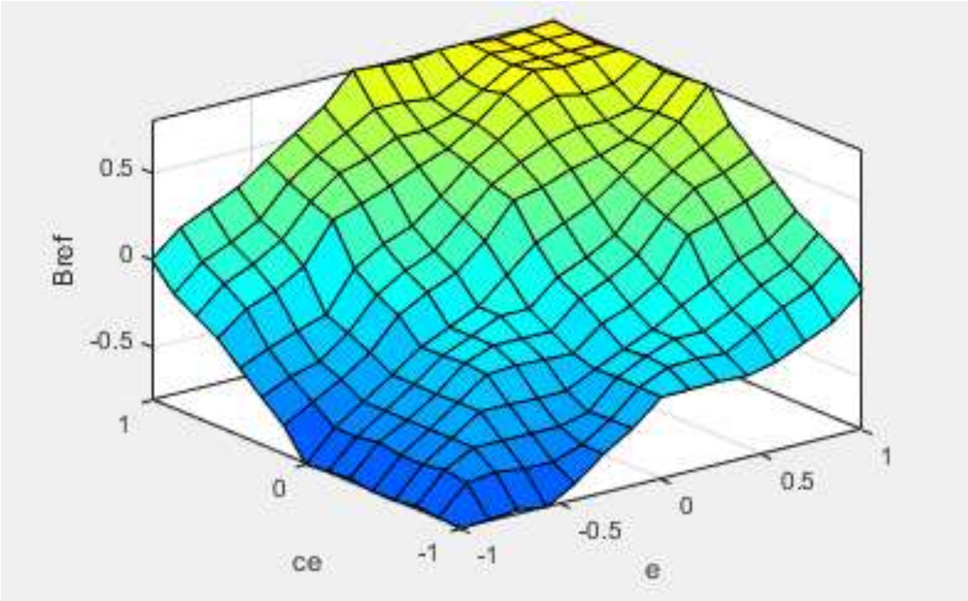

Figure 0.1 Surface Viewer of the Fuzzy logic rules

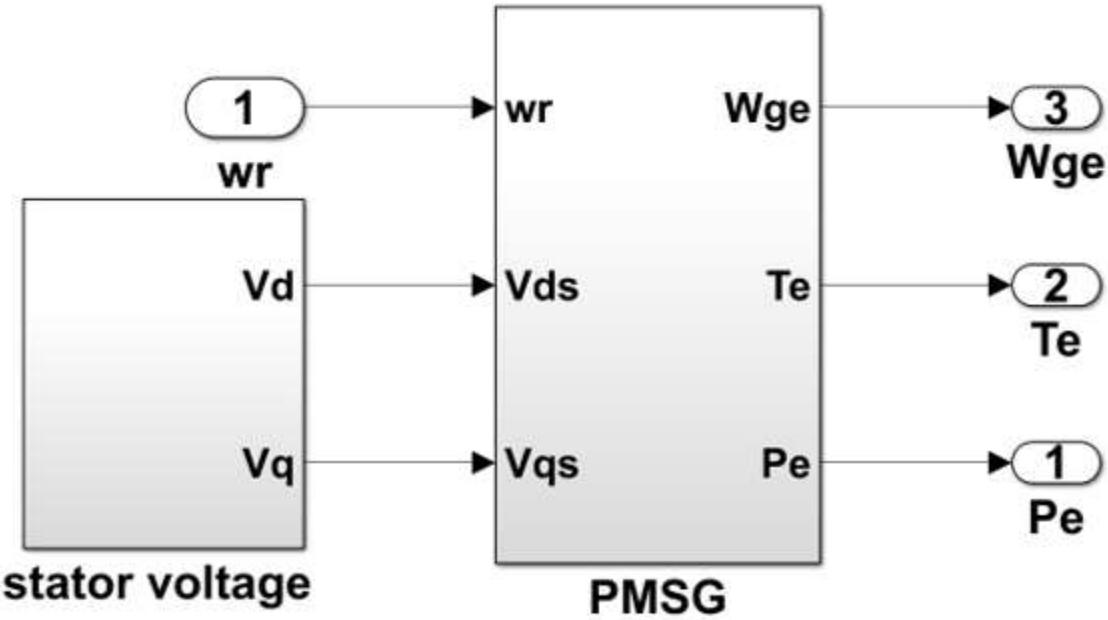

Figure 0.2 conversion of Vabc-Vdq

Matlab code of PSO-tuning gains of Fuzzy Logic Controller

```
function Tune_PSO_Fuzzy

rng default % Initialize the random number generator

options = optimoptions('particleswarm');

options.PlotFcn= 'pswplotbestf';

options.SwarmSize= 20;

nvar= 3;

LB= [0.15 0.15 0.15];

UB= [15 15 15];

    [x,fval]= particleswarm(@EvalObj,nvar,LB,UB,options)

% Measures a performance index from the simulink model

function obj= EvalObj(x)

simulink_model= 'fuzzypso';

load_system(simulink_model);

gains= get_param(simulink_model,'modelworkspace');

gains.assignin('Ge', x(1));

gains.assignin('Gce', x(2));

    gains.assignin('Gu', x(3));

% Simulates the simulink model to get the outputs

simOut= sim(simulink_model,'SaveOutput','on');

t= simOut.find('t');
```

```
e= simOut.find('e');

% Calculate a performance index

n= length(e);

ae= abs(e);

for i= 2:n

   stepsize= t(i)-t(i-1);

   obj= 0.5*stepsize*(ae(i-1)+ae(i)); % IAE

end
```

Matlab code for power vs wind speed

```
clear all

clc

vcin = 3 ; % cut-in speed

vnom = 10.5; % normal speed

vcout = 22; %cut_out speed

step = 0.5;

v = step : step : 22;

P = zeros(1, length(v));

index = 1;

for v1 = step : step : vcin

P(index) = 0;

index = index + 1;

end

for v2 = vcin+step : step : vnom

r = 41; % in meters, indicates the blade length

A = pi * (r^2);

Raw = 1.225; % Air Density, in kg/m³

P(index) = 0.5 * A * (v2^3) * Raw ; % Cubic relation

index = index + 1;

end
```

```
Prated = P(index-1);
for v3 = vnom+step : step : vcout
P(index) = Prated;
index = index + 1;
end
plot(v,P/(10^6),'r');
title ('Output Power- wind speed Curve')
xlabel('Wind Velocity (m/s)')
ylabel('Output Power (MW)')
```