

Pitch Angle Control of a Wind Turbine for Maximizing Power Transfer Capability Using Adaptive Model Predictive Control



Betelihem Mulugeta Munkka

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 Master's in
Electrical Power and Control Engineering (Control Engineering)

Office of Graduate Studies

Adama Science and Technology University

September, 2024

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled “**Pitch Angle Control of a Wind Turbine for Maximizing Power Transfer Capability Using Adaptive Model Predictive Control**” 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 of materials that are used for this thesis have been duly acknowledged through citation.

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RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “**Pitch Angle Control of a Wind Turbine for Maximizing Power Transfer Capability Using Adaptive Model Predictive Control**” prepared under my guidance by Betelihem Mulugeta Munkka Submitted in partial fulfillment of the requirements for the degree of Master of Science in Control Engineering. Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

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APPROVAL PAGE

I, the advisor of the thesis entitled **“Pitch Angle Control of a Wind Turbine for Maximizing Power Transfer Capability Using Adaptive Model Predictive Control”** and developed by Betelihem Mulugeta Munkka, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Prof. Gang Gyoo Jin

Advisor

Signature

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We, the undersigned, members of the Board of Examiners of the thesis by Betelihem Mulugeta Munkka have read and evaluated the thesis entitled **“Pitch Angle Control of a Wind Turbine for Maximizing Power Transfer Capability Using Adaptive Model Predictive Control”** and examined the candidate during open defense. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Masters in Electrical Power and Control Engineering.

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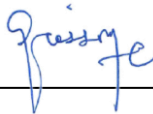
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LIST OF ACRONYMS

DFGs	Double-Fed Induction Generator
EKF	Extended Kalman Filter
EMF	Electro Motive Force
FLC	Fuzzy Logic Controller
HAWT	Horizontal Axis Wind Turbine
LTI	Linear Time Invariant
MATLAB	Matrix Laboratory
MHC	Moving Horizon Control
MOM	Middle of Maximum
MPC	Model Predictive Controller
MPPT	Maximum Power Point Tracking
PID	Proportional Integral Derivative
PMSG	Permanent Magnet Synchronous Generator
RHC	Receding Horizon Control
SCIGs	Squirrel Cage Induction Generators
TSR	Tip Speed Ratio
VAWT	Vertical Axis Wind Turbine
WECS	Wind Energy Conversion System

LIST OF SYMBOLS

N	Prediction Horizon
T_s	Sample Time
M	Control Horizon
Q and R	Weights
P_{mec}	Mechanical Power
λ	Tip Speed Ratio
β	Pitch Angle
ω_r	Rotor Angular Speed
V_{wind}	Wind Speeds
H_{tur}	Wind Turbine Moment of Inertia Constant
θ_{sta}	Shaft Twisting Angle
K_{ss}	Shaft Stiffness
D_t	Damping Coefficient

ABSTRACT

Nowadays, wind energy has emerged as a critical renewable source of energy because of its sustainability and scalability. However, the inherent variability of wind speed presents challenges to the power transmission capacity of the turbines. These variations can be characterized by sudden and unpredictable changes in wind speeds. Wind turbines face dynamic operating conditions and a non-linear connection between wind speed and output power; this too diminishes efficiency and transmission capacity, especially during volatile wind conditions. To solve these problems, it requires designing a controller for pitch angle. By modifying the angle of the turbine blades, the pitch angle controller can regulate the output power and improve the transmission capacity of the turbines. In order to optimize power transfer capacity and enhance system performance, this thesis designed PID controllers, model predictive controllers, and an adaptive model predictive controller (MPC). To support this control strategy, a thorough mathematical model was developed that includes every component of the wind turbine system, with the aim of studying how the pitch angle is regulated. MATLAB/Simulink software was applied to build the entire analysis, modeling, and simulation. The outcomes of the simulation indicate that the highest pitch angle for MPC is 0.785 radians, and the adaptive MPC is 0.76 radians. To optimize the generator speed and turbine's power extraction, the pitch angle must be adjusted as wind speeds drop between rated and cut-in values. This ensures maximum efficiency and energy extraction from the wind, while maintaining the pitch angle at 0 radians ensures maximum power extraction after wind speeds exceed the optimal value. The rotor speed settling time of PID is 4.712 sec; MPC is 4.601 sec; and adaptive MPC is 4.523 sec. The rise time of PID is 2.875 sec; MPC is 2.783 sec; and adaptive MPC is 2.675 sec. With PID, the maximum overshoot generator power output is 1.511 MW; this implies 0.733% above the rated speed. For MPC, the maximum generator power output overshoot is 1.5053, which implies 0.353% above the rated speed; and for adaptive MPC, the maximum power overshoot is 15023, which implies 0.153% above the rated wind speed. The simulation's outcomes research validates that the adaptive MPC controller performs well in both dynamic and steady-state conditions while monitoring maximum power.

Keywords: MPC Controller, Wind Turbine, Pitch Angle Control, Dynamic Modeling, MPPT.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Our modern world is powered by energy, which is the ability to work. We use it for transportation, heating and lighting our houses, and powering the manufacturing operations that make the items we use. Energy sources are divided into two categories: renewable and non-renewable (Wadim Strielkowski, 2021). The usage of non-renewable sources of energy has resulted in a significant increase in environmental pollution, causing a notable increase in environmental pollution in recent years, which poses a serious global problem. An enormous amount of the power utilized in industrial operations comes from non-sustainable sources, which has a tremendous influence on nature and all living things, including people. (Kukuh Mukti Wibowo¹, 2019). Due to the increased attention that renewable energy sources have received as a way to both mitigate environmental issues and meet the expanding global energy demand, these factors have contributed to the expansion of sustainable energy. These days, more is being done to advance technology in order to efficiently transform renewable energy sources into usable electrical energy sources. Since wind energy has a far lower environmental pollution effect than non-sustainable energy sources, it's one of the renewable energy sources that can help with the pollution problem in the environment. Since wind energy can be produced via wind turbines and is a clean, sustainable energy source that can keep up with the world's expanding power demands, it has been receiving more attention globally (Zinmickas, Gecevičius, & Markevičius, 2016.).

Wind turbines are used to collect the wind's available energy, resulting in a nonlinear system in which the energy is gained is proportional to the wind's velocity. Controllers are necessary for many complex and nonlinear systems to function well. Various strategies are employed, contingent on the wind turbine's operating position. The purpose is to keep the structure's burdens to a minimum once the rated power has been produced, which entails keeping power output at minimal levels until the wind speed threshold is met.

The efficiency of wind turbine depends on a number on a number of factors, including the design of the blades, the direction of the turbine, and the control strategy used to operate it. There has

already been an increase in the system's share of wind power generation (Kukuh Mukti Wibowo¹, 2019). However, the inherent inconsistency of wind speeds presents challenges to the power transmission ability of the turbines and damages them. These variations can be characterized by sudden and unpredictable changes in wind speeds. When wind speeds fall below the optimal range, the power transmission capacity suffers. Conversely, when wind speeds exceed the rated range, the turbines themselves are at risk of damage resulting from mechanical stress and overloading.

To address these issues, it is essential to develop a pitch angle control method and design a dynamic model that can regulate the power output, and ensuring the reliable operation of the wind turbine. Adjusting the pitch angle of the wind turbine helps stabilize the turbine system and optimize power production. Pitch angle control is primarily used to modify power output: increasing the pitch angle reduces the turbine's rotation speed in strong winds, limiting the amount of power it can produce. Conversely, lowering the pitch angle during low winds enables the wind turbine to capture more wind energy. Conventional controllers often struggled to adapt to these dynamic conditions, limiting power capture at low speeds and potentially causing damage at high wind speeds. In contrast, Adaptive MPC offers a robust solution for controlling the pitch angle of wind turbines. This approach excels at predicting wind turbine behavior and remains effective amidst changing wind conditions. By continuously adjusting the control input based on actual system behavior and changes in operating conditions, adaptive MPC optimizes the pitch angle to maximize power transfer capability.

By utilizing a dynamic model and solving an optimization challenge at each time step, the adaptive MPC algorithms ascertain the optimal pitch angle control inputs that diminish a predefined cost function while sustaining system constraints, resulting in efficient and effective management of power transfer capability (Gbadega, 2021). A wind turbine system's dynamic model was created, including the wind turbine generator, drivetrain, and grid connection. This model incorporated an aerodynamic model, a mechanical model, and an electrical model. This method proved crucial for wind turbines operating in dynamic environments, offering benefits such as improved wind power integration. With MATLAB software, the entire system is implemented and simulated.

1.2 Statement of Problem

Although many researchers have studied in the context of power generation, due to the complexity of wind energy conversion systems, control of pitch angle still needs additional improvement. The complex systems of wind energy conversion, characterized by sudden and unpredictable changes in wind speeds, pose challenges for the power transmission capacity of the turbines. The ever-changing nature of wind introduces dynamic operating conditions, demanding continuous adaptation from wind turbines. This challenge is amplified by the non-linear correlation between power production and wind speeds, where small wind variations can cause disproportionate fluctuations in power generation. These complexities significantly compromise the efficiency and stability of power transmission, especially during periods of volatile wind conditions. Traditional control strategies, such as PID controllers, have limitations in handling the nonlinear, time-varying dynamics of wind turbines and maximizing power capture at changing wind conditions. Therefore, to address this problem, this thesis work resulted in the development of an adaptive model predictive controller (MPC) to control the pitch angle of wind turbines that exhibits exceptional capability to predict wind turbine behavior and remains robust in the face of changing wind conditions. The planned control strategy was based on a dynamic model of a wind turbine that maximizes the power output of the turbine and handles nonlinear and time-varying wind conditions. A dynamic model creates a mathematical model that accurately predicts a wind turbine's response to changes in wind speed and direction. These advanced tools help make wind turbines more efficient and reliable.

1.3 Objectives of the Study

1.3.1 General Objectives

The general objective of this study is to design an adaptive model predictive controller (MPC) for pitch angle control of wind turbines to maximize power transmission capacity.

1.3.2 Specific Objectives

- ❖ To obtain the mathematical models for wind turbines, drive trains, and permanent magnet synchronous generators.
- ❖ To design an adaptive MPC controller for the wind turbine's pitch angle.
- ❖ To create a MATLAB/Simulink model that implements the overall control system.

- ❖ To analyze the effectiveness of the designed controller and compare its performance with that of the traditional PID controller.

1.4 Scope of the Study

This study's scope is to examine the meticulous mathematical modeling of wind turbines. Adaptive MPC is designed to optimize the transmission capacity of wind turbines. To evaluate the effectiveness of the proposed control approach, simulations are conducted comparing its performance to that of the conventional PID controller. For this, MATLAB/SIMULINK is used.

1.5 Limitation of the Study

This research work is constrained by utilizing Simulink or MATLAB to simulate the system and represent how the system's various components interact with each other. This is because it is challenging to get the parts needed to put an actual system into place. It also necessitates devoting more time and funds to developing the authentic implementation of the prototype.

1.6 Motivation of the Study

The increasing global demand for energy and the need for clean, sustainable sources of power resulted in the development of alternative and renewable energy sources. Renewable energy encompasses various forms: biofuels, hydroelectric energy, wind energy, solar energy, and geothermal energy. These sources of energy have been extensively researched and improved in terms of their monetary variability and actual potential. Among the different kinds of wind turbines, the horizontal axis wind turbine (HAWT) industry has gained more attention due to its high efficiency. Sudden wind speed changes, especially above-rated wind speeds, can indeed challenge wind turbine power transmission capacity, demanding grid integration solutions and control strategies to ensure stable and efficient power delivery. To mitigate this problem, developing a new pitch angle controller and designing a dynamic model are essential to managing the complex system of wind turbines. Therefore, the aim of this study was to build a model predictive controller that is adaptable (MPC) capable of predicting wind turbine behavior and remaining robust to changing wind conditions.

1.7 Significance of the Study

Wind power is a fresh, sustainable power source that creates electricity without releasing greenhouse gases or adding to their pollution. It is cost-effective, economically viable, and

reduces reliance on imported fossil fuels. Wind energy also empowers countries to generate their own electricity, enhancing national security and reducing vulnerability to global energy market fluctuations. Today, the wind energy industry significantly contributes to job creation and economic growth. This indicates that the requirement for wind energy products has gone up from time to time. It leads to an increasing demand for high-efficiency wind energy control systems. So, developing control mechanisms for pitch angle and mathematical modeling of wind turbines plays a big role in maximizing power transmission capacity and wind energy production. This study proposed dynamic modeling and an adaptive model predictive controller (MPC), which have the ability to adapt to complex wind conditions and enhance the performance of wind turbine systems.

1.8 Thesis Organization

There are six chapters in this thesis:

Chapter Two: This chapter discusses the conceptual framework and relevant literature on pitch angle control.

Chapter Three: The underlying physics and mathematical models that underpin the operation of any wind turbine are introduced in this chapter.

Chapter Four: This section develops PID and Adaptive MPC strategies for pitch angle of VSWTs.

Chapter Five: This section outlined the simulation findings and included a detailed assessment of the reported outcomes.

Chapter Six: This thesis concludes with a summary and recommendations for next study paths.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of the Chapter

This chapter thoroughly examines two important segments. The primary segment discusses wind turbines, their components, kinds, wind speed operating regions, and wind turbine control mechanisms. The second segment includes a review of relevant work.

2.2 Theoretical Background

In wind energy conversion systems, wind turbine blade pitch angle control is essential because it enables operators to precisely adjust the angle at which the blades face the incoming wind. This allows operators to maximize energy capture by making the most of the available wind resource, protect the structural integrity and longevity of the turbine by limiting loads and stresses during high wind conditions, and dynamically adjust the turbine's speed and power output to maintain safe and efficient operation. Pitch angle control is a critical innovation that is propelling technological advancements in wind energy conversion. It is based on the principles of aerodynamic and control theory and allows operators to precisely manipulate the blade's angle of attack to optimize energy capture, reduce mechanical strain on components, and minimize power output fluctuations. These abilities are especially useful for variable-speed wind turbines, which can dynamically adjust their pitch under a variety of operating conditions to maximize power extraction from the wind resource while improving overall efficiency, reliability, and stability of electricity generation (Sarkar, 2020).

2.2.1 The Parts of a Wind Turbine

Wind turbine is a combination of mechanical and electrical components that work together to turn wind energy into useful power. The parts are divided into three categories: control system, electrical, and mechanical.

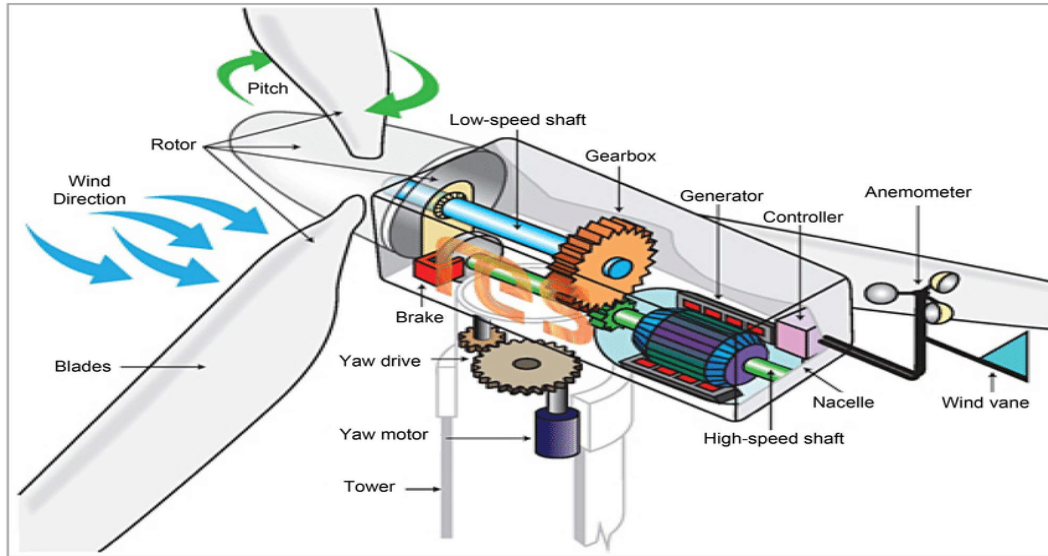


Figure 2.1 Parts of a wind turbine (Anudipta Chaudhuri, 2022)

2.2.1.1 Mechanical Parts

Wind turbine mechanical elements play a significant role in the transformation of energy. The mechanical command accommodates the introduction of work into the system by enabling a mass to revolve and sending it to the required position so that it can communicate with the electrical mechanisms. Among the main mechanical elements of wind turbines are the following:

Rotor: Rotors are key spinning parts found in wind turbine systems, responsible for gathering wind kinetic energy and translating it into mechanical power. The rotor's major components are the aerodynamically constructed blades, which are positioned on the rotor hub and allow the entire assembly to spin, transferring rotational mechanical energy to the main shaft. The blade design, length, and material composition all have an impact on the rotor's capacity to harvest as much power as possible from the wind.

Main Shaft (Low-Speed Shaft): The primary shaft, frequently referred to as a shaft operating at low speed, is a crucial component within a set of wind turbines. For power conversion, it sends the rotor's mechanical energy to the gearbox. It rotates at a relatively modest pace, usually between 10 and 30 revolutions per minute, to capture maximum wind energy. Designed with high-strength steel, it ensures unhindered blade rotation and efficiently transmits power to the gearbox, turning the kinetic energy of the wind into electrical power.

Gearbox: A wind turbine system's gearbox is an essential component that connects the rotor's low speed spinning in response to the generator's high-speed demands. By enhancing mechanical power transfer, wind energy is transformed into electrical energy. For optimum efficiency and dependability, the gearbox needs exact ratios, lubrication, and cooling systems since malfunctions might result in expensive repairs.

Nacelle: The nacelle is an important enclosure on a wind turbine tower because it protects key mechanical components such as the gearbox, yaw drive, bearing, anemometers, wind vanes, cooling systems, and control systems. It guarantees the turbine's efficiency and power generating capabilities while safeguarding it from harsh environment conditions, ensuring its dependability and lifespan.

Anemometer: An anemometer is an instrument used to gauge wind direction and velocity. It's normally situated on the wind turbine's nacelle and is often installed on a short pole or boom to collect precise wind data.

Tower: The tower holds up the nacelle and rotor, raising the wind turbine to a height where it can catch higher and more constant wind speeds.

2.2.1.2 Electrical Components

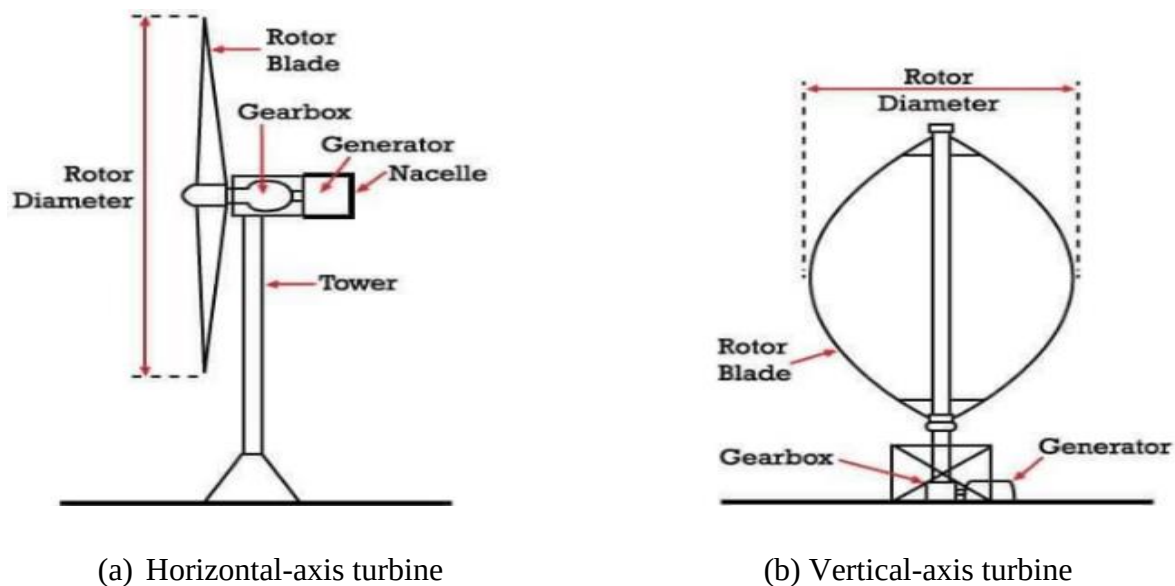
Generators: In a wind turbine system, the generator is the main electrical component that transforms the rotational mechanical force derived from the turbine's drivetrain into usable electrical force. It usually consists of a rotor and a stator, with the rotator rotating inside the stator to provide an electrical current. Several generator types are utilized in wind-power generators: doubly fed induction generators (DFIGs), synchronous generators (SGs) using wound rotors or permanent magnets, and squirrel cage induction generators (SCIGs). The power outputs of these generators range from kilowatts to megawatts.

Power Converter: A wind turbine system's power converter is an essential electrical component that transforms the output voltage and frequency variation of the generator into a consistent, grid-compatible form. In order to convert AC to D and then return to AC at the necessary transmission voltage and frequency, power electronics such as rectifiers, inverters, and transformers are used. In addition, it maintains grid stability by regulating the flow of both active and reactive electricity, as well as the speed and torque of the turbine.

Transformer: The generator of a wind generator effectively converts mechanical energy into electrical energy; however, the electricity is first generated at a low voltage. To overcome this, for effective transmission over a long distance, a transformer raises this voltage to a very high level. This critical phase, which transitions from low-voltage generation to high-voltage transmission, guarantees little energy loss and enables wind farms to efficiently power residences and commercial buildings.

2.2.2 Kinds of Wind Turbine

Depending on how their axis is oriented, wind turbines may be classified into two categories: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT).



(a) Horizontal-axis turbine

(b) Vertical-axis turbine

Figure 2.2 Horizontal-axis and vertical-axis wind turbines (O. Apata*, 2020).

Horizontal Axis Wind Turbines: A horizontal-axis wind turbine spin axis is aligned parallel to the earth, as shown in Figure 2.2 (a).

Vertical Axis Wind Turbines: The vertical-axis wind turbine's spin axis is oriented perpendicular to the earth. The turbine rotor uses curved airfoils that are passionate vertically. As shown in Figure 2.2 (b), the electrical system and gearbox are often buried close to the turbine's base.

Based on the rotor's rotational speed, wind turbines may alternatively be categorized as variable speed and fixed speed wind turbines.

Fixed-Speed Wind Turbines: These turbines revolve at virtually persistent speeds, which are controlled by elements like the generator’s pole count, gear ratio, and grid frequency. This fixed-speed operation limits system efficiency to a restricted range of wind speeds, and the turbine produces wildly erratic power production, which can disrupt the grid. However, the fixed-speed design enables easier and more durable mechanical systems (Dr. Srikanth Narasimalu, 2017).

Variable-Speed Wind Turbines: Variable speed wind turbines increase energy conversion efficiency by constantly adjusting the turbine’s rotating speed to meet wind speeds. This maintains the ideal tip speed ratio between wind and blade tip speed. The wind turbine generator is linked to the utility grid via power converter technology (Atif Iqbala, 2019) (Dr. Srikanth Narasimalu, 2017).

Table 2.1 Comparative of fixed-speed and variable-speed wind turbines

Speed Mode	Merits	Demerits
Fixed-Speed	Straightforward, dependable, and sturdy Low expense and maintenance	Comparatively poor efficiency of energy conversion Elevated mechanical tension Significant variations in grid electricity
Variable-Speed	High efficiency of energy conversion Enhanced quality of power Decreased tension in the machinery	Increased expenses and losses as a result of using converters More intricate control mechanism

2.2.3 Wind Turbine System Operating Regions

Features of a wind turbine’s power output can be represented through a graph illustrated by plotting the connection between wind speed and produced energy. This connection is usually separated into four operational areas, each defined by the three key wind speed thresholds depicted below.

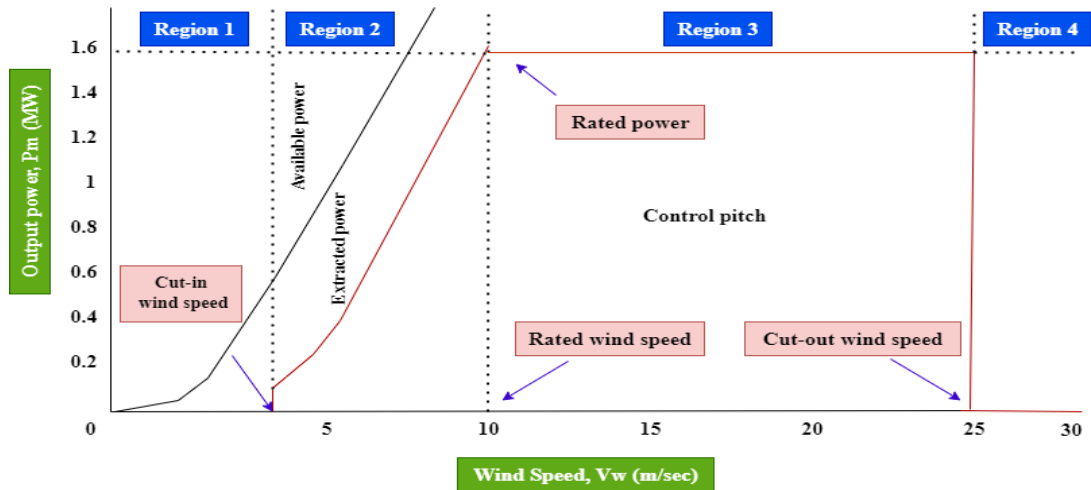


Figure 2.3 Characteristics of output power and wind speed.

Region I (below cut-in speed): This region is below the cut-in wind speed threshold for a wind turbine's operation. In this low-wind regime, the available wind energy is insufficient to generate a meaningful amount of electricity generated by wind turbines.

Region II (cut-in to optimal speed): This is the most important region, spanning wind speed from the cut-in to the rated speed. In this range, the power output increases cubically with the wind speed, making it ideal for efficient and profitable operation. The turbine's control system works to maximize wind energy extraction, adjusting parameters like blade pitch and rotor speed to optimize energy capture.

Region III (optimal speed): This is the range of wind speeds wherein the turbine performs optimally and generates the maximum amount of desired power. Wind turbine control systems are critical in this region. Even though wind speeds may steadily increase inside this region, the control systems adjust the turbine's operation (such as blade pitch) to maintain that steady maximum power generation. This guarantees safe and efficient operation and maintains the turbine's design capacity.

Region IV (above cut-out region): This region encompasses wind speeds that exceed the turbine's rated speed. In this region, the wind speeds become too high for safe operation, as the immense aerodynamic and structural loads could potentially damage the turbine. To protect the investment, the control systems of the turbine will automatically shut down the machine until the winds calm down to a safe level.

2.2.4 Control Techniques for Wind Turbine

The wind rotates the blade because of the air flowing over its surface. Air moving away from the wind travels more quickly than air moving against the wind on the surface. As a result, the blade is pulled to spin by a lift force. The angle at which the blade strikes the air determines how much force and torque the turbine produces. As such, it is a practical means of controlling the amount of electricity that is harvested. Passive stall, pitch control, and active stall are the three types of aerodynamic techniques used to regulate how much power wind turbines capture (Divyansha Pandey1, 2020).

Passive-Stall Control: Passive stall-controlled wind turbine blades are positioned at an appropriate angle at which the rotor hub is attached. This angle enables the turbine to collect maximum power when wind speeds are below or equivalent to the nominal value of the design. However, as wind speed rises above the normal threshold, the high wind generates turbulence on the rear side of the blades, limiting lifting force and finally resulting in the stall phenomenon. This natural stall effect decreases the turbine's rotational speed, functioning as a built-in limitation to avoid damage in strong winds without the need for sophisticated pitch adjustment devices. The blades must be meticulously built with an optimal aerodynamic profile to provide a gradual, predictable stall as wind speeds surpass the nominal optimal range (Divyansha Pandey1, 2020).

Active-Stall Control: Active stall turbines have adjustable-pitch blades that may cause the stall phenomena either by increasing wind speeds or by actively rotating the blades towards the wind, lowering their angle of attack wind speeds reach the rated value. This active pitch control enables the turbine to maintain its nominal power output by restricting the amount of power collected from high winds, rather than depending exclusively on the natural stall effect, as passive-stall turbines with fixed blade angles accomplish (Divyansha Pandey1, 2020).

Pitch Control: In order to change the wind turbines as part of the design parameters and to turn the blades in and out in response to varying wind speed conditions, the regulation of the pitch angle technique is used. The benefits of pitch angle controllers include reducing the aerodynamic load in areas with strong wind speeds and maintaining output power nearer to rated power. These blades are reoriented into the wind once they reach the typical working range. If a wind turbine reaches a specific speed without this controller, it will shut down. It is necessary

for the wind turbine's pitch angle to change in response to wind speed in order to prevent mechanical stress and harm to the structure (Dereje, 2021).

2.3 Review of Related Works

This segment comprises a review of the literature on pitch angle control systems related to this proposed work. Many researchers have performed several studies and research applications in the field of wind turbine technology pitch angle control. Most of the studies focus on providing an improvement from time to time in the efficiency of the controllers and extracting maximum power from wind energy.

Authors (Smail, 2017) ,have proposed “Pitch control of wind turbine through PID, fuzzy and adaptive fuzzy-PID controllers”. They proposed a pitch angle control technique based on adaptive fuzzy-PID control to deal with the nonlinear features of wind turbines, reduce loads on wind turbine blades, and improve performance at different wind speeds. It develops a computational model of the wind turbine pitch angle control system and tests it with three controllers, such as PID, fuzzy, and adaptive fuzzy-PID. The simulation outcomes demonstrate that the adaptive fuzzy-PID controller performs the best, regulating the pitch system and handling disruptions and ambiguous elements related to the system. However, the main shortcoming of the paper is the ineffective use of an actuator feedback signal instead of representing the wind turbine system, which may not be able to accurately estimate the forces on the blades. As a result, the controller may not adjust the pitch angle quickly enough to reduce these forces. This can lead to over speeding of the wind turbine, which can damage the components and even cause the wind turbine to fail.

Authors (A. Musyafa', 2020) ,have proposed “Pitch angle control of variable low rated speed wind turbine using fuzzy logic controller”. The paper focused on maximizing the mechanical power of the wind turbine by optimizing the pitch angle control of the turbine blades with different wind speeds in low rated wind speed environment. The study develops defuzzification using Mamdani method and middle of maximum method (MOM), constructs a wind turbine prototype, and optimizes FLC for desired performance. It also demonstrates that the use of a fuzzy logic controller (FLC-2) enhances wind turbine performance, particularly in low rated wind speed areas, compared to FLC-1 and FLC-2. However, in this study, the controller it used to improve the desired performance of the FLC-2 controller still has limitations in terms of

average power, standard deviation, and uncertainty, and the study also does not consider the influence of external factors like turbulence.

Authors (Atif Iqbala, 2019) ,have proposed “Efficacious pitch angle control of variable-speed wind turbine using fuzzy based predictive controller”. The study offers a fuzzy based predictive controller for wind turbine pitch angle management in order to maximize power production and system stability. In comparison to typical PI controllers, the suggested controller successfully avoids loading effects while increasing power extraction by integrating fuzzy logic with predictive control. The shortcoming of this study is that it necessitates manual adjustment of fuzzy sets, linguistic variables, and fuzzy rule. This manual modifying technique can be subjective and time-intensive. The absence of defined design approaches for fuzzy based predictive controllers may impede their wind spread adoption and make replicating the control approach across diverse wind turbine system challenging.

Authors (Sakly, 2018), have proposed “Smoothing wind power fluctuations by particle swarm optimization-based pitch angle controller”. The study demonstrates how PSO-based control techniques might enhance wind turbine performance. The study proposes using PSO-based pitch angle management to reduce power fluctuations and improve wind energy integration in the grid. This study lacks a precise model of the wind turbine system, making it difficult to adjust the pitch angle for maximum performance. Additionally, being single input single output (SISO) controllers, they may struggle with managing complex relationship between control variables.

Author (Kandula, 2022), has proposed “Mechanical modeling of wind turbine speed and pitch angle for different speed profiles”. The paper presented a mechanical model of a wind turbine, utilizing different wind speed profiles for simulation and observation. It investigates the workings of speed and pitch control in wind turbines, with a focus on the pitch controller that adjusts the attack angle of the rotor blades. It explores the use of individual pitch control as a method to overcome the variation of wind speed across the rotor blades and optimize the amount of collected data. But the paper does not provide a detailed examination of the performance and efficiency of the wind turbine system under different wind speed profiles, and it’s limited to a specific type of generator and may not be applicable to other types of wind turbine systems. Additionally, the author does not consider the impact of external factors, such as environmental conditions or grid integration, on the effectiveness of the wind turbine system.

Authors (Ismail, 2017), have proposed “Fuzzy logic pitch control of variable speed wind turbine”. They proposed the design of an efficient wind turbine pitch controller using fuzzy logic. The paper presents a mathematical model of the wind turbine and simulation utilizing MATLAB/SIMULINK software based fuzzy logic controllers, which allow for the evaluation and testing of control methods and are capable of superior control performance than traditional PID controllers. The use of fuzzy control rules based on expert knowledge and experience helps to characterize the dynamic behavior of the fuzzy system and achieve fast response and minimum error. But the paper did not thoroughly investigate the effect of different wind conditions and variations in wind speed on the performance of a fuzzy logic controller, which could limit the adaptability and robustness of the control system.

In general, the literature reviewed discusses and examines different controller techniques and settings aimed at enhancing wind turbine power output and efficiency. Many controllers face specific challenges when regulating the blade pitch angle of wind turbines. These challenges include limited responsiveness to variations in wind conditions, difficulties in efficiently handling multiple constraints, failure in presenting the system state with explicit consideration for future behavior, and possible challenges in managing intricate interactions between various control variables because they are single-input, single-output controllers.

To address this problem, this thesis proposes the development of an adaptive model predictive controller (MPC). This controller takes into account a number of operating restrictions, including turbine load limitations, rotational speed limits, and maximum and minimum pitch angles. The suggested control strategy considered the complex system of variable-speed wind turbines in its optimization. It was able to predict wind turbine behavior and optimize control inputs, maximizing power output, improving the entire performance of the system, and enhancing efficiency based on the design of a dynamic model.

CHAPTER THREE

METHODOLOGY AND SYSTEM MODELING

3.1 Overview of the Chapter

This chapter explains the ingredients and techniques for gathering and analyzing data that are utilized to finish this research project. It also covers acquiring the mathematical models of the wind turbine, concepts of maximum power extraction, drive train, permanent magnet synchronous generator, and pitch actuator.

3.2 Materials

This thesis achieves its objectives by utilizing a range of software technologies. These included MATLAB 2023a, Microsoft Office Word 2021, draw.io, and Math Type 7.0 for equations. MATLAB, a robust software with a technical toolbox, served as the platform for programming, simulations, and technical analysis. To write the thesis records, Microsoft Office Word is utilized. Flow charts and block schematics are created with draw.io. Math Type 7.0 is applied for creating algebraic equations and formulas.

3.3 Methods

To meet the above-mentioned objectives of this thesis work, the following formal methodologies are followed:

Literature review: This thesis work commences with a comprehensive review of existing literature on controlling the pitch angle in wind turbines with varying speeds. This involved delving into the work of various researchers, extracting key information, and critically evaluating them. The review aimed to gain a thorough understanding of the concept, identify gaps in previous research, and formulate potential solutions to address those identified shortcomings.

Data collection: In this work, data are extensively collected from various sources for the layout of the controller for pitch angle in a wind turbine system with variable speed. These are from books, research papers, journals, simulation tools, and online searches. Subsequently, the obtained information was carefully analyzed and researched.

Data analysis: Using the collected data and reviewed literature, the system is rigorously analyzed using MATLAB software.

Design of Controller: In this study, two controllers are designed and implemented to manage the angle of pitch of a variable-speed wind turbine system. The PID controller serves as a benchmark, and an adaptive MPC functions as the primary controller.

Conclusion and recommendation: Following a thorough analysis of the designed system, the thesis culminated in a comprehensive conclusion and insightful recommendations regarding upcoming works in the field.

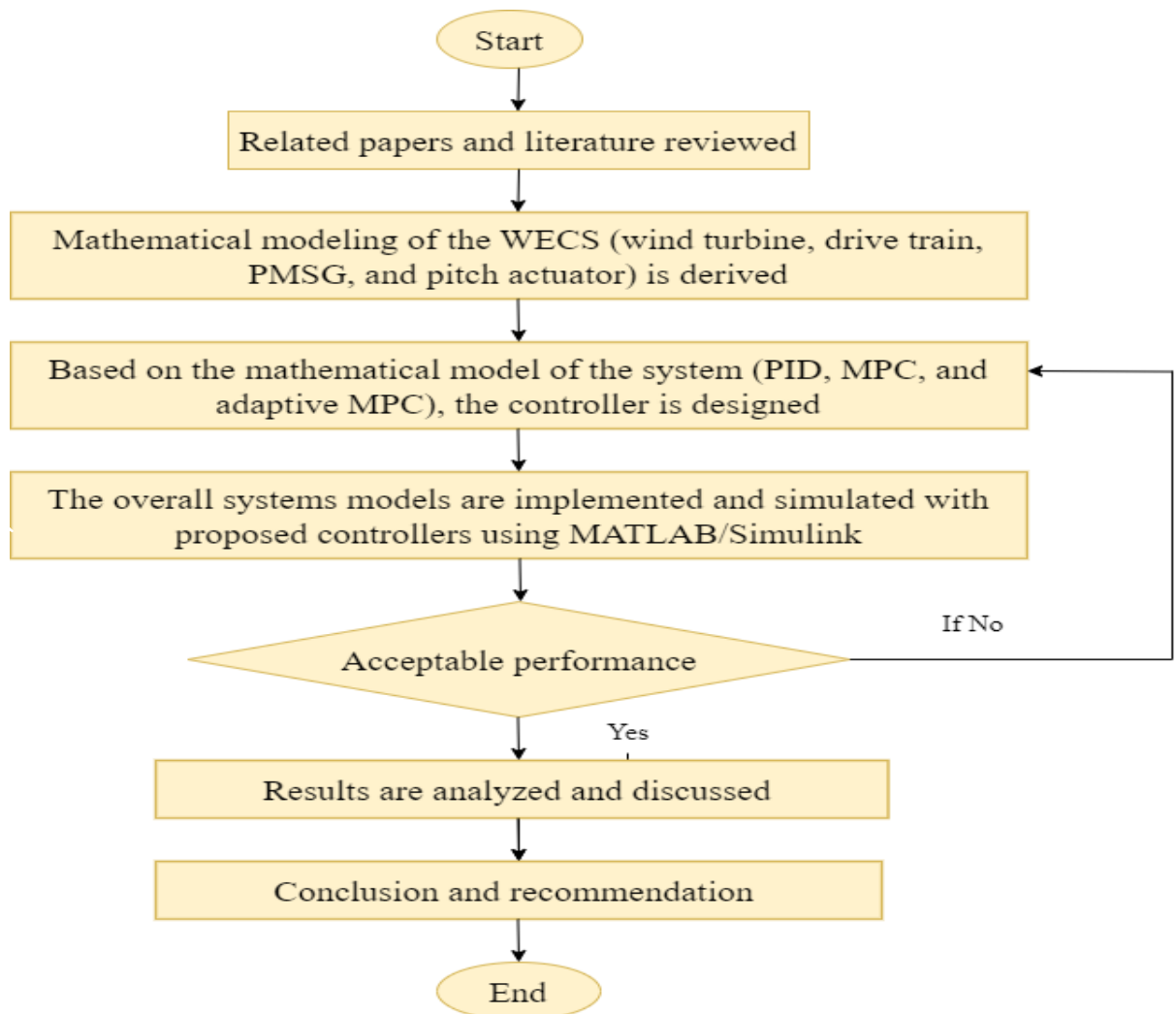


Figure 3.1 Block diagram of research methods

3.4 Diagram of a System Block

Figure 3.2 shows the block diagram of a variable speed wind turbine's angle of pitch control system. The design of the suggested control system utilized a dynamic model of a wind turbine, specifically chosen for its suitability for the adaptive MPC. The components that were employed to meet the requirements of the study are only partially mentioned. These are the pitch actuator, wind turbine, driving train, and generator (PMSG), because the goal of this study was to adjust the turbine's angle of pitch.

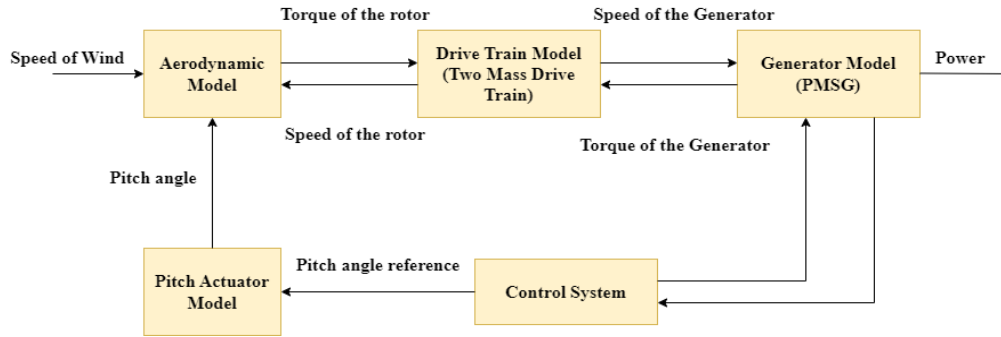


Figure 3.2 Block diagram of a wind turbine control system

3.5 Dynamic Modeling of the System

Dynamic models of wind turbines are mathematical representations that describe the behavior and performance of the turbine under varying operating conditions. The turbine's dynamic reaction to variations in wind speed, control inputs, and other parameters is simulated and analyzed using these models. This analysis aims to understand and optimize the behavior of wind turbines, enhance their performance, maximize the transmission capacity of the turbine, and guarantee their safe and dependable operation, which represents the key goal of dynamic modeling. Dynamic model of wind turbines typically includes the following features:

3.5.1 Wind Turbine Aerodynamic Modeling

The science that explains how the body moves in the air is called aerodynamics. Consequently, it is a branch of dynamics that studies air movement due to force operating on motionless objects in air currents. The purpose of the airfoil's surface is to induce the desired reaction in the air. Consequently, air resistance will be transformed into usable force by any component of the aircraft or object. The following figure shows airfoil-encircling streamline flow.

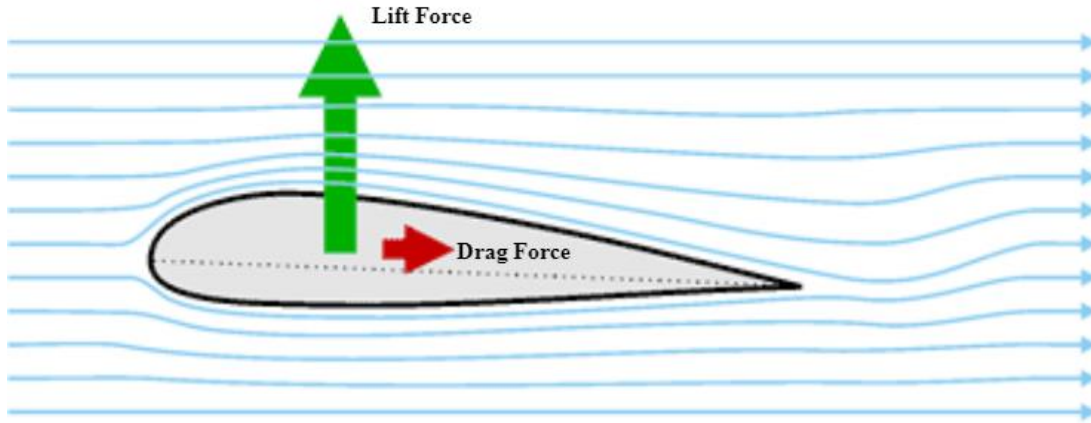


Figure 3.3 Airfoil-encircling streamline flow

Airstream-derived forces, lifting force, and drag force all affect objects in the airstream. These forces' magnitude is determined by the object's direction relative to the airstream and wind speed. Lift and drag forces, which are perpendicular to one another, aid in the rotation of a turbine blade (TAYMANS, 2018).

The work W needed to move an item with mass m and velocity v from rest to distance S under a force F is equal to its kinetic energy E . This energy is expressed in terms of constant acceleration.

$$\Delta K = W = F \times \Delta S \quad (3.1)$$

$$F = m \times a_{cc} \quad (3.2)$$

$$\Delta K = W = m a_{cc} \Delta s \quad (3.3)$$

From kinematics of solid motion; square of velocity equation and reorder it a small.

$$v^2 = v_0^2 + 2a_{cc}\Delta s \quad (3.4)$$

$$a_{cc}\Delta s = \frac{v^2 - v_0^2}{2} \quad (3.5)$$

Integrate aequations (3.3) and (3.5)

$$\Delta K = m \left(\frac{v^2 - v_0^2}{2} \right) = \frac{1}{2} m v^2 - \frac{1}{2} m v_0^2 \quad (3.6)$$

Since the force of motion is called kinetic energy, an object at rest has zero kinetic energy ($v_0 = 0$).

$$\Delta K = \frac{1}{2} m v^2 \quad (3.7)$$

The pace at which the kinetic energy of the wind flowing through a wind turbine's rotor changes determines how much electricity it can produce.

$$P = \frac{dE}{dt} \quad (3.8)$$

$$P = \frac{1}{2} v^2 \frac{dm}{dt} + m v \frac{dv}{dt} \quad (3.9)$$

Given that mass flow rate is determined via:

$$\frac{dm}{dt} = \rho A V \quad (3.10)$$

For steady speed $\frac{dv}{dt} = 0$. Thus, the power may be represented as follows in terms of mass flow rate and speed V :

$$P = \frac{dE}{dt} = \frac{1}{2} v^2 \frac{dm}{dt} = \frac{1}{2} \rho A v^3 \quad (3.11)$$

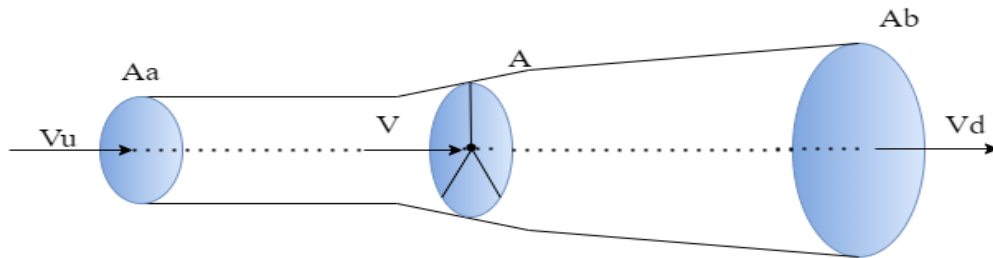


Figure 3.4 Airfoil through an actuator disc

By using the airflow as an example of an indestructible flow, we can express the continuity of the mass conversion equation as follows:

$$\frac{dm}{dt} = \rho A_u V_u = \rho AV = \rho A_b V_d \quad (3.12)$$

Where: ρ air density (kg / m^3), A_u area of cross section as it gets closer to the turbine, A_b cross sectional area of the air stream after the turbine, V_u upstream wind velocity, V the turbine blades air velocity, and V_d after the air passes the turbine, its downstream wind velocity (m/s). There is a slowdown in the air velocity as it moves through the disc ($V_u - V_d$). Therefore, the force that the actuator disc creates on the incident airflow is equal to the overall speed decreasing times the mass flow rate:

$$F_d = \frac{dm}{dt} \Delta V = \rho AV (V_u - V_d) \quad (3.13)$$

The effort put into the wind stream can be expressed as:

$$dE = F_d dx \quad (3.14)$$

$$P = \frac{dE}{dt} = F_d \frac{dx}{dt} = F_d V \quad (3.15)$$

Substituting Equation (3.15) into Equation (3.13) gives.

$$P = \rho AV^2 (V_u - V_d) \quad (3.16)$$

Applying the law of conservation of energy yields the power

$$P = \frac{\Delta E}{\Delta t} = \frac{\frac{1}{2} m V_u^2 - \frac{1}{2} m V_d^2}{\Delta t} \quad (3.17)$$

Substitute mass flow rate in Equation (3.17) and rearrange it a bit $dm / dt = \rho AV$.

$$P = \frac{1}{2} \rho AV (V_u - V_d) \quad (3.18)$$

Equating equation (3.16) and equation (3.18)

$$P = \rho AV^2(v_u - v_d) = \frac{1}{2} \rho AV(v_u - v_d) \quad (3.19)$$

$$V = \frac{1}{2}(v_u + v_d), v_u \neq v_d \quad (3.20)$$

This indicates that wind velocities at the rotor may be calculated using the mean wind speeds upstream and downstream. The energy that the turbine captures from the wind.

$$P_{wind} = \frac{1}{2} \rho AV(v_u^2 - v_d^2) \quad (3.21)$$

Substituting Equation (3.20) into Equation (3.21) yields

$$P_{wind} = \frac{1}{2} \rho A \cdot \frac{1}{2}(v_u + v_d)(v_u^2 - v_d^2) \quad (3.22)$$

Rewriting Equation (3.22) gives

$$\begin{aligned} P_{wind} &= \frac{1}{4} \rho A [v_u(v_u^2 - v_d^2) + v_d(v_u^2 - v_d^2)] \\ &= \frac{1}{4} \rho A (v_u^3 - v_u v_d^2 + v_d v_u^2 - v_d^3) \end{aligned} \quad (3.23)$$

Let take as $z = \frac{v_d}{v_u}$

$$P_{wind} = \frac{1}{4} \rho AV_u^3 (1 - z^2 + z - z^3) \quad (3.24)$$

Equation (3.24) demonstrates that the power extracted via the turbine is proportional to the cube of the upstream velocity and depends on the ratio of air velocities, Z between downstream and upstream. When the turbine (highest extracted energy) is not there, the wind velocity V_u remains constant. In other words, the cross-sectional areas A , A_a , and A_b are equal and the $\frac{dV_u}{dt}$ terms go to zero. The whole power can be written as follows:

$$P_{total} = \frac{1}{2} \rho AV_u^3 \quad (3.25)$$

The outcomes of Equation (3.25) resemble those obtained for a turbine that can extract energy. Expressions for the power collected at the turbine from Equation (3.24) and the total amount of wind available from Equation (3.25) respectively, are available. Consequently, the optimal power coefficient of a wind turbine.

Where power coefficient is expressed as: - $C_p = \frac{P_{wind}}{P_{total}}$

which means;

$$C_p = \frac{\frac{1}{4} \rho A V_u^3 (1 - z^2 + z - z^3)}{\frac{1}{2} \rho A V_u^3} \quad (3.26)$$

$$C_p = \frac{1}{2} (1 - z^2 + z - z^3) \quad (3.27)$$

We will apply calculus to obtain the derivative of Equation (3.27) with respect to Z , set it equal to zero, and solve for an in order to get the maximum points at which the turbine operates at its most efficient.

$$\frac{dC_p}{dt} = \frac{1}{2} (0 - 2z + 1 - 3z^3) \quad (3.28)$$

We got a value $z = -1$ & $z = \frac{1}{3}$

So, we used second ' Z ' value for ' Z ' because it had more practical significance. This value demonstrated that the speed downstream ought to be equal to one-third of the wind speed upstream to maximize the power from the turbine. To determine the highest level of power coefficient factors by inserting Equation ($z = \frac{v_d}{v_u} = \frac{1}{3}$) into Equation (3.28).

$$C_p = \frac{1}{2} (1 - \frac{1}{9} + \frac{1}{3} - \frac{1}{27}) \quad (3.29)$$

$$C_p = \frac{1}{2} \left(\frac{27 - 3 + 9 - 1}{27} \right) = \frac{32}{54} = 0.59259 = 59.26\% \quad (3.30)$$

This observation aligns with the Betz limit, which signifies the theoretical maximum conversion power coefficient of wind kinetic energy into rotor rotation at 59.3%. The wind turbine's maximum power coefficient is always going to be less than the Betz factor in practical situations. Thus, for the sake of simulation, the extractable electricity from the wind is provided by:

$$P_{mec} = \frac{1}{2} C_p(\lambda, \beta) \rho A v_{wind}^3 \quad (3.31)$$

The power coefficient isn't fixed value. It fluctuates based on the turbine's tip speed ratio, which compares the speed of the blade tip with the wind. Drawing on past research, this formula captures the power coefficient's dependence on both blade pitch angle and tip speed ratio.

$$C_p(\lambda, \beta) = Y_1 \left(\frac{Y_2}{\lambda_i} - Y_3 \beta - Y_4 \right) e^{-Y_5/\lambda_i} + Y_6 \lambda \quad (3.32)$$

The value of Y_1 to Y_6 are depends on the kind of turbine. These are coefficients are used in the calculation of the power coefficient (C_p), which represents how efficiently the wind turbine catches available power from the wind (Miguel Carpintero-Renteria, 2020). In this thesis work we worked on variable-speed wind turbine, so the value of Y_1 to Y_6 are:

$Y_1 = 0.5176, Y_2 = 116, Y_3 = 0.4, Y_4 = 5, Y_5 = 21$ and $Y_6 = 0.0068$ these coefficients are essential for determining the turbine's performance and ensuring it operates efficiently across varying wind speeds. The maximum value of C_p (reached at $\beta = 0$ degrees and $\lambda = 8.1$ is approximately). (Miguel Carpintero-Renteria, 2020).

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\left(\frac{-21}{\lambda_i} \right)} + 0.0068\lambda \quad (3.33)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{1 + \beta^3} \quad (3.34)$$

The tip speed relationship has been used to represent the interaction between wind speed and rotor speed.

$$\lambda = \frac{\text{tip speed}}{\text{wind speed}} = \frac{\omega_r R}{V_{wind}} \quad (3.35)$$

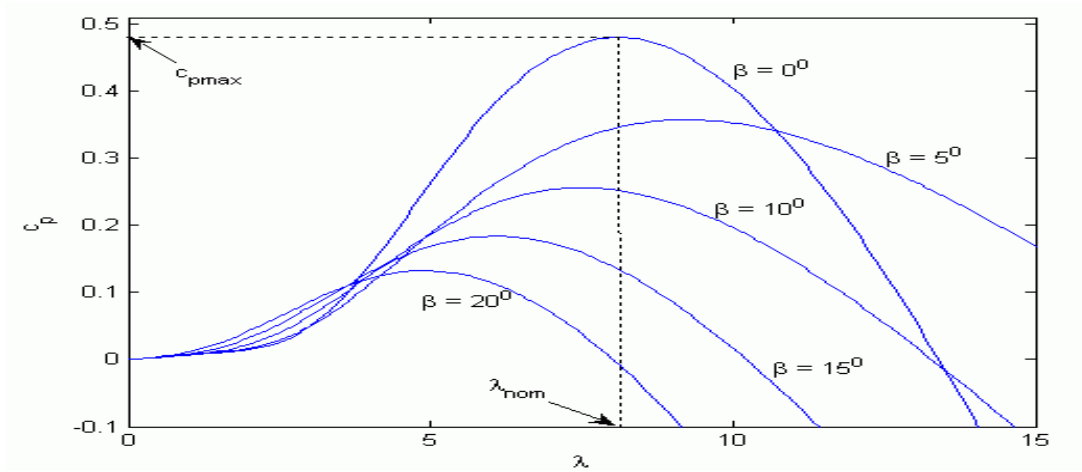


Figure 3.5 C_p variation with tip speed (λ) for different pitch angle (β) (Miguel Carpintero-Renteria, 2020)

The turbine mechanical torque can be expressed as:

$$T_{mec} = \frac{P_{mec}}{\omega_r} = \frac{1}{2} C_p (\lambda, \beta) \rho \pi R^2 \frac{V_{wind}^3}{\omega_r} \quad (3.36)$$

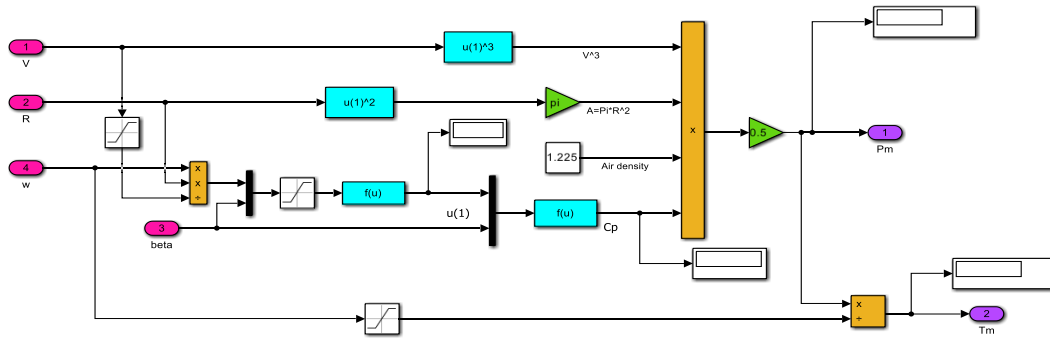


Figure 3.6 Simulink model of the wind turbine model

3.5.2 Principles of Maximum Power Extraction

Several Maximum Power Point Tracking (MPPT) algorithms have been employed for wind turbines with varying speeds in wind turbine control. This thesis focuses on using tip speed ratio (TSR) control. Determining the operational point at which the power coefficient is at its optimum is necessary to increase power harvesting from wind-powered machines. This optimal occurs at a specific value of the tip speed ratio; this represents the relationship between wind

speed and blade tip speed, but the optimal varies somewhat depending on the operating conditions, allowing us to identify and maintain the maximum power points (MPPs) effectively. Variable-speed turbines utilize various MPPT systems that manage parameters depending on turbine design to adapt their operating point and track changing wind conditions, effectively maintaining an optimal range for power extraction. Therefore, to enhance power at a variable-speed turbine, tip speed ratio control is a powerful tool for boosting power production through the use of speed of rotation adjustments to get the ideal TSR. In addition, adjusting the angle of pitch is important for optimizing power capture across diverse wind conditions for wind turbines with varying speeds. While increasing the angle of pitch generally reduces input power and vice versa, the specific effect depends significantly on factors like wind speed, tip speed ratio, and turbine design. Variable-speed turbines utilize sophisticated control systems that dynamically adjust the pitch angle along with other parameters like rotor speed to maintain the optimal operating point for maximum power extraction at each wind speed.

$$\lambda = \frac{\omega_{ref} R}{V_{wind}} \quad (3.37)$$

$$\omega_{ref} = \frac{\lambda_{Topt} V_{wind}}{R} \quad (3.38)$$

$$V_{wind} = \frac{\omega_{ref} R}{\lambda} \quad (3.39)$$

Since it is impossible to determine wind speed precisely, it's preferable to compute the optimum power as follows neglecting monitoring wind speed (Liejiang Wei, 2019).

$$P_{mec} = \frac{1}{2} \rho \pi R^2 \left(\frac{\omega_{ref} R}{\lambda_{opt}} \right)^3 C_{\rho-opt} (\lambda, \beta) \quad (3.40)$$

Where: λ_{Topt} and $C_{\rho-opt}$ denotes the optimal values for the power coefficient and tip speed ratio, in that order.

$$C_{\rho-opt} = C_{\rho} (\lambda_{Topt}) = C_{\rho max}$$

The maximum power is obtained $P_{mec opt}$. Equation (3.40) can be written as

$$P_{mec\ opt} = \frac{1}{2} \rho \pi R^2 \left(\frac{\omega_{ref} R}{\lambda_{opt}} \right)^3 C_{\rho\ max}(\lambda, \beta) \quad (3.41)$$

$$P_{mec\ opt} = \frac{1}{2} \rho \pi R^5 \frac{\omega_{ref}^3}{\lambda_{T\ opt}^3} C_{\rho\ max}(\lambda, \beta) \quad (3.42)$$

Where optimal tip speed ratio is expressed as $K_{opt} = \frac{1}{2} \frac{\rho \pi R^5 C_{\rho\ max}(\lambda, \beta)}{\lambda_{T\ opt}^3}$ So, rewrite Equation

(3.42) in terms of optimal tip speed ratio.

$$P_{mec\ opt} = K_{opt} \omega_{ref}^3 \quad (3.43)$$

Equation (3.43) shows how mechanical torque and power relate to one another.

$$T_{mec\ opt} = \frac{P_{mec\ opt}}{\omega_{ref}} = \frac{K_{opt} \omega_{ref}^3}{\omega_{ref}} = K_{opt} \omega_{ref}^2 \quad (3.44)$$

Optimizing the power output of a wind turbine is largely dependent on the pitch angle control mechanism. The pitch setting must be modified to its ideal value when wind speeds exceed the rated capacity. This guarantees that we maximize wind energy harvesting without going above the turbine's power generating capability. The adaptive model predictive control (MPC) approach was used within this study to optimize the angle of pitch under various wind scenarios. This method enhances the wind turbine system's overall performance and captures energy.

3.5.3 Mechanical Model

A mechanical modeling of a wind turbine is the mathematical representation of the mechanical components within the turbine. The models help us understand and predict how wind turbines perform, optimize their performance, and integrate them efficiently into power systems.

3.5.3.1 Drive Train Model

The drive train of a wind generator, often referred to as a power train, transfers the rotational momentum that the rotor captures to the generator, which generates energy. Although the rotor is an essential part of the drive train since it starts the rotation, it is not a part of the motor unit itself. A gearbox, a rotor, a generator, and a speed shaft serve as the drive train. The driving train model is mass-based and is classified into four types: single-mass drive train models

(lumped drive trains), two-mass drive train models, models of three-mass drive trains, and six-mass train models. Since two-mass models are the most often used and may be employed without scarifying accuracy for wind turbine transmissions, the turbine rotor in this thesis work is derived as a dual-mass drive train. The dual-mass power train model, complete with a connecting shaft and all shaft and inertia components, is shown in Figure 3.7 (Hitesh Kumawat, 2020).

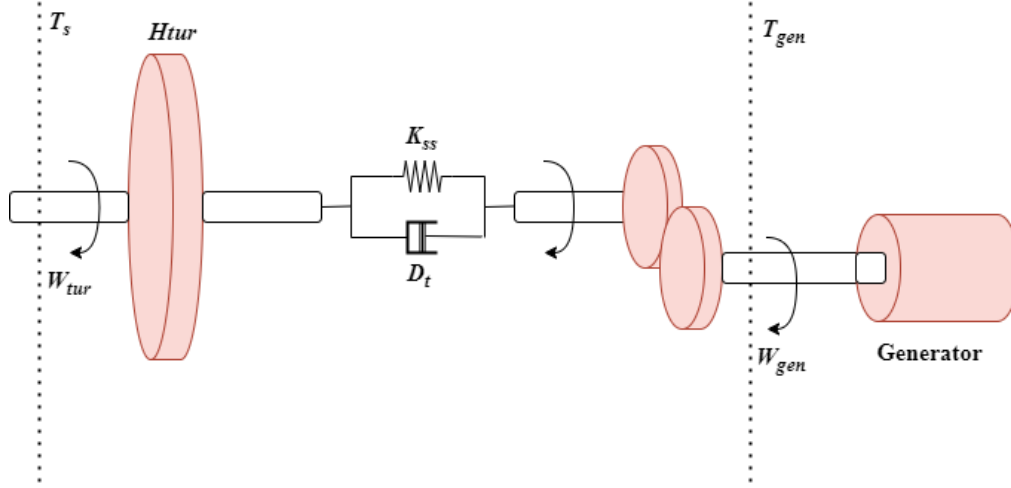


Figure 3.7 Dual-mass drive train model

On the generator side, the drive train's dynamic equation is:

$$2H_{tur} \frac{d\omega_{tur}}{dt} = T_m - T_s \quad (3.45)$$

$$\frac{1}{\omega_{ebs}} \frac{d\theta_{sta}}{dt} = \omega_{tur} - \omega_{gen} \quad (3.46)$$

$$T_s = K_{ss} \theta_{sta} + D_t \frac{d\theta_{sta}}{dt} \quad (3.47)$$

Where: H_{tur} is wind turbine moment of inertia constant, T_s is shaft torque, T_{gen} is generator torque, θ_{sta} is shaft twisting angle, ω_{ebs} is electrical base speed, K_{ss} is stiffness of the shaft, and D_t is damping coefficient.

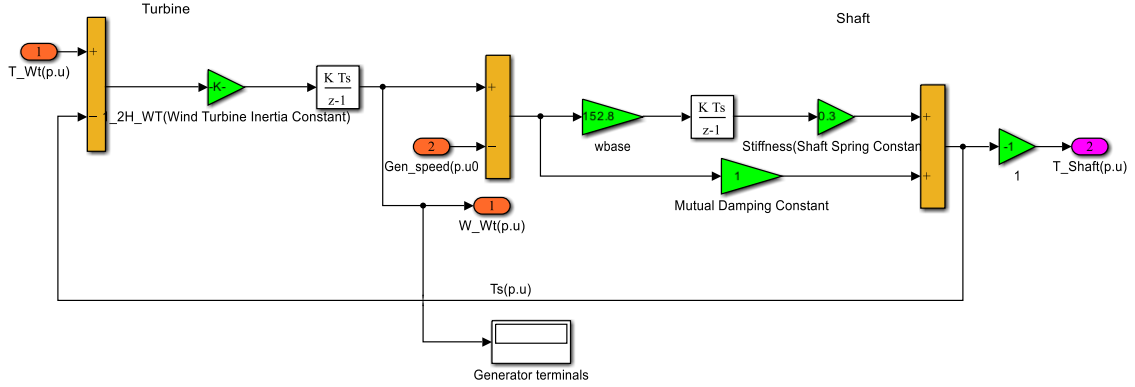


Figure 3.8 Simulink model of the dual-mass drive train

3.5.4 Permanent Magnet Synchronous Generators (PMSG)

Generators rely on the basis of electromagnetism to turn mechanical energy into electrical energy. They consist of a rotating part (the rotor) that generates a changing magnetic field and a stationary housing (the stator) containing wire coils. The rotor can serve as either an electromagnet or a permanent magnet to create a revolving field of magnets, which is crucial for inducing electricity in the stator. The wind turbine generators in this thesis utilize the permanent magnet synchronous generator PMSG.

In the context of wind turbines, a permanent magnet synchronous generator (PMSG) is a type of generator that is growing in prominence. In order to create machines, manage algorithms, and analyze the dynamic and stable properties of WECS, a thorough computational simulation of the PMSG is necessary (Venkata Yaramasu¹ ✉, 2017).

3.5.4.1 The 3-Phase Natural abc Stationary Reference Frame Used in PMSG Modeling

Prior to creating the mathematical representation of the Permanent Modeling Synchronous Magnet (PMSG), several assumptions are made about the model as follows:

- ❖ The effects of magnetic saturation are neglected;
- ❖ The losses caused by hysteresis and eddy current are disregarded;
- ❖ The effect of damping in the magnet and in the rotor are negligible;
- ❖ There is a sinusoidal reverse force of electromotive (EMF) generated in the windings of the stator.

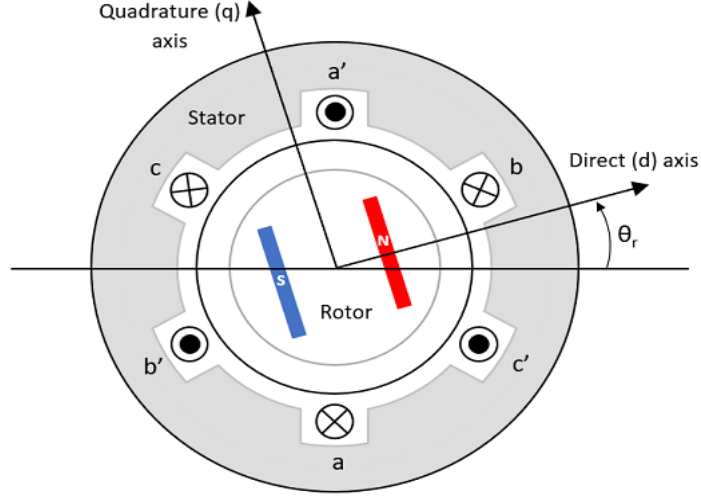


Figure 3.9 Interior part of a permanent magnet synchronous motor (PMSM)

The stator voltage equation of the permanent magnet synchronous machine in its natural reference frame in three phases (ABC) provides the basis for dynamic modeling (Hailemariam, 2019).

$$v_{as} = r_s i_{as} + \frac{d\tilde{\lambda}_{as}}{dt} \quad (3.48)$$

$$v_{bs} = r_s i_{bs} + \frac{d\tilde{\lambda}_{bs}}{dt} \quad (3.49)$$

$$v_{cs} = r_s i_{cs} + \frac{d\tilde{\lambda}_{cs}}{dt} \quad (3.50)$$

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \tilde{\lambda}_{as} \\ \tilde{\lambda}_{bs} \\ \tilde{\lambda}_{cs} \end{bmatrix} \quad (3.51)$$

Where: i_{as}, i_{bs}, i_{cs} and v_{as}, v_{bs}, v_{cs} are the three-phase stator's instantaneous a, b, c voltages and currents, r_s each stator winding phase's resistance, and $\tilde{\lambda}_{as}, \tilde{\lambda}_{bs}, \tilde{\lambda}_{cs}$ are the flux linkages that are brought about by the PMs and the three-phase AC currents; they may be expressed more fully as follows:

$$\tilde{\lambda}_{as} = L_{aa}I_{as} + L_{ab}I_{bs} + L_{ac}I_{cs} + \tilde{\lambda}_{ra} \quad (3.52)$$

$$\tilde{\lambda}_{bs} = L_{ab}I_{as} + L_{bb}I_{bs} + L_{bc}I_{cs} + \tilde{\lambda}_{rb} \quad (3.53)$$

$$\tilde{\lambda}_{cs} = L_{ac}I_{as} + L_{cb}I_{bs} + L_{cc}I_{cs} + \tilde{\lambda}_{rc} \quad (3.54)$$

$$\begin{bmatrix} \tilde{\lambda}_{as} \\ \tilde{\lambda}_{bs} \\ \tilde{\lambda}_{cs} \end{bmatrix} = \begin{bmatrix} l_{aa} & l_{ab} & l_{ac} \\ l_{ba} & l_{bb} & l_{bc} \\ l_{ca} & l_{cb} & l_{cc} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} \tilde{\lambda}_r \cos(\theta_r) \\ \tilde{\lambda}_r \cos(\theta_r - \frac{2\pi}{3}) \\ \tilde{\lambda}_r \cos(\theta_r + \frac{2\pi}{3}) \end{bmatrix} \quad (3.55)$$

Where: $\tilde{\lambda}_r$ denotes the rotor flux linkage, l_{aa}, l_{bb}, l_{cc} and $l_{ab}, l_{ac}, l_{ba}, l_{bc}, l_{ca}, l_{cb}$ are three-phase's self and mutual inductances, respectively. Both the mutual and self-inductances are functions of θ_r . The inductances are all time-varying parameters as a result.

3.5.4.2 PMSG Modeling in the DQ-axes Synchronously Rotating Reference Frame

In 1929, R.H. Park developed the dq0 Park's transformation, a mathematical transformation that attempts to simplify the study of synchronous machinery models (Hailemariam, 2019). Phase quantities, which include flux linkages, stator, voltages, and currents in three-phase systems like PMSGs, fluctuate with time. Park's transformation converts the AC quantities into DC quantities that are time-independent by projecting the phase quantities onto a rotating reference frame within two axes.

The following is a matrix representation of the transformation from abc to dq0.

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r - \frac{4\pi}{3}) \\ -\sin(\theta_r) & -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r - \frac{4\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad (3.56)$$

The inverse of Park transformation is as follows:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos(\theta_r) & -\sin(\theta_r) & \frac{\sqrt{2}}{2} \\ \cos(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\theta_r - \frac{4\pi}{3}) & -\sin(\theta_r - \frac{4\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{0s} \end{bmatrix} \quad (3.57)$$

The machine's terminal voltage was transformed from its natural *abc* three-phase coordinate its corresponding $\alpha\beta 0$ stationary reference frame, as indicated Equation (3.58), by applying the Clark transformation in Equation (3.51) and Equation (3.55).

$$\mathbf{v}^s = R\mathbf{i}^s + L \frac{d\mathbf{i}^s}{dt} + \lambda_r \omega_e \begin{bmatrix} -\sin \theta_r \\ \cos \theta_r \end{bmatrix} \quad (3.58)$$

A three-phase system has neither zero-sequence voltages nor currents, three-wire system because in this case, the PMSG, so that v_0 and i_0 can be eliminated from the equation. After that, we can express PMSG's voltage function in the dq-axes reference frame is as follows. After determining the formula for the salient pole PMSG's stator terminal voltage in the *dq0* rotating frame with L_d and L_q inductance. (Fitzgerald, 2015) applied again Park transformation in equation (3.60).

$$\begin{aligned} v_{ds} &= R_s i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_e L_q i_{qs} \\ v_{qs} &= R_s i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_e L_q i_{ds} + \omega_e \lambda_r \end{aligned} \quad (3.59)$$

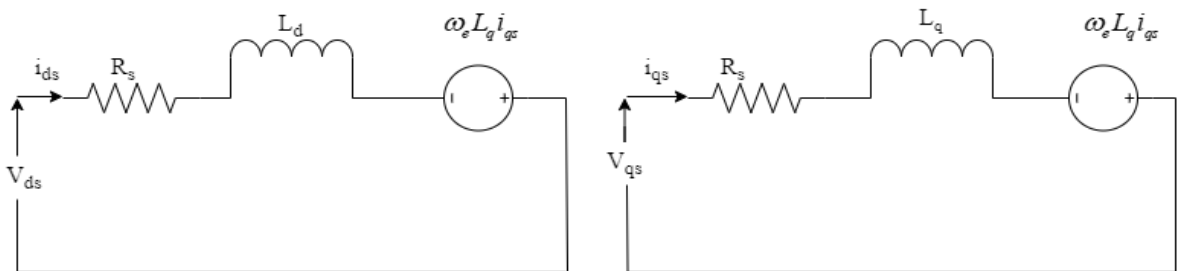


Figure 3.10 Comparable circuits for dq-axes in a PMSG

3.5.4.3 A PMSG's Power and Torque

The input of electrical power of any PMSG may be stated inside the 'abc' frame of reference as follows:

$$P_{abc} = \begin{bmatrix} v_{as} & v_{bs} & v_{cs} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = v_{as}i_{as} + v_{bs}i_{bs} + v_{cs}i_{cs} \quad (3.60)$$

Or expressed as in dq-axes reference frame as follows:

$$P_{qd} = \frac{3}{2} \begin{bmatrix} v_{qs} & v_{ds} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} = \frac{3}{2} (v_{qs}i_{qs} + v_{ds}i_{ds}) \quad (3.61)$$

In generating mode, the machine converts active power to electrical power, which is stated as:

$$P_e = \frac{3}{2} (e_d i_{ds} + e_q i_{qs}) \quad (3.62)$$

Where e_d and e_q are the back electromotive forces (EMFs) within the reference frame of the dq-axes, it is able to be stated as:

$$e_d = -\omega_e L_q i_{qs} = -\omega_e \lambda_{qs} \quad (3.63)$$

$$e_q = \omega_e L_d i_{ds} + \omega_e \lambda_r = \omega_e \lambda_{ds} \quad (3.64)$$

The dq-axes stator flux linkage is denoted by λ_{ds} and λ_{qs} , which may be found via:

$$\begin{cases} \lambda_{ds} = -L_{ls} i_{ds} + L_{dm} (I_f - i_{ds}) = -(L_{ls} + L_{dm}) i_{ds} + L_{dm} I_f = -L_d i_{ds} + \lambda_r \\ \lambda_{qs} = -(L_{ls} + L_{qm}) i_{qs} = -L_q i_{qs} \end{cases} \quad (3.65)$$

Equation (3.64) and Equation (3.65) were substituted into Equation (3.63) to obtain active power.

$$P_e = \frac{3}{2} ((-\omega_e \lambda_{qs})(i_{ds}) + (\omega_e \lambda_{ds})(i_{qs})) = \frac{3}{2} \omega_e (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (3.66)$$

By using the above equation developed electromagnetic torque by PMSG can be expressed as follow:

$$T_e = \frac{P_e}{\omega_g} \quad (3.67)$$

Where $\omega_e = \frac{p}{2} \omega_g$, p poles, and ω_g the rotor's mechanical rotational speed.

$$T_e = \frac{P_e}{\omega_g} = \frac{\frac{3}{2} \omega_e (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})}{\omega_g} = \frac{\frac{3}{2} \left(\frac{p}{2} \omega_g \right) (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})}{\omega_g} = \frac{3}{2} \left(\frac{p}{2} \right) (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (3.68)$$

Equation (3.66) is substituted into Equation (3.69)

$$T_e = \frac{3}{2} \left(\frac{p}{2} \right) (\lambda_r i_{qs} + (L_q - L_d) i_{qs} i_{ds}) \quad (3.69)$$

The inductances, L_d and L_q for non-salient pole PMSG are almost equal. Under this situation, the electromagnetic torque equation may be written as follows:

$$T_e = 1.5 \left(\frac{p}{2} \right) \lambda_r i_{qs} \quad (3.70)$$

The electrical angular speed rotor ω_e is governed by motion equation:

$$\omega_e = \frac{P}{JS} (T_e - T_m) \quad (3.71)$$

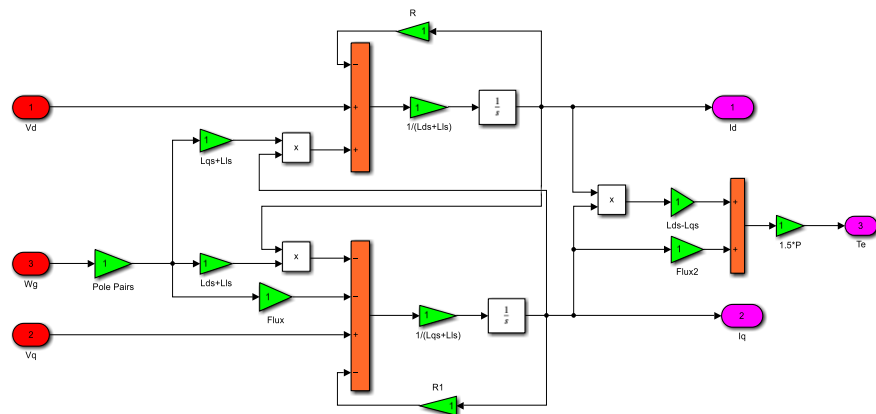


Figure 3.11 Simulink model of the permanent magnet synchronous generator (PMSG)

3.5.5 Pitch Actuator Model

Pitch actuators, which rotate turbine blades along their length, are a key control element for managing power output and addressing the complex relationship between wind speed and power generation.

Pitch actuator can be controlled using either hydraulic or electric systems. Electric actuators offer individual blade control through servo motors. A dynamic model for hydraulic pitch actuators describes how the pitch controller's instructions β_d , the measured blade angle β , the system's response time interact τ_c . The following is the equation for pitch servo modelling:

$$\frac{d\beta}{dt} = -\frac{1}{\tau_c}\beta + \frac{1}{\tau_c}\beta_d = \frac{1}{\tau_c}(\beta_d - \beta) = \frac{(\beta_d - \beta)}{\tau_c} \quad (3.72)$$

$$\tau_c \frac{d\beta}{dt} = \beta_d - \beta = \tau_c \frac{d\beta}{dt} + \beta = \beta_d \quad (3.73)$$

By taking Laplace transformation of Equation (3.73) would yield

$$(\tau_c s + 1)\beta(s) = \beta_d(s) \quad (3.74)$$

$$\beta(s) = \frac{1}{1 + \tau_c s} \beta_d(s) \rightarrow \frac{\beta(s)}{\beta_d(s)} = \frac{1}{1 + \tau_c s} \quad (3.75)$$

Pitch control response is contingent upon the pitch actuator's time constant. In this thesis, we assume medium wind turbines, which are often between 0.001- 0.2 seconds. (K.Vijaya Lakshmi and P.Srinivas, 2017).

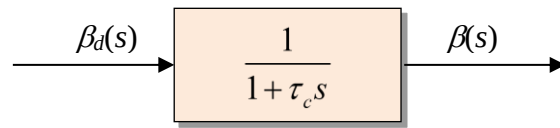


Figure 3.12 Block diagram of the pitch actuator gain.

The time constant value of ($\tau_c = 0.001\text{sec}$)

$$\frac{\beta(s)}{\beta_d(s)} = \frac{1}{1 + 0.001s} \quad (3.76)$$

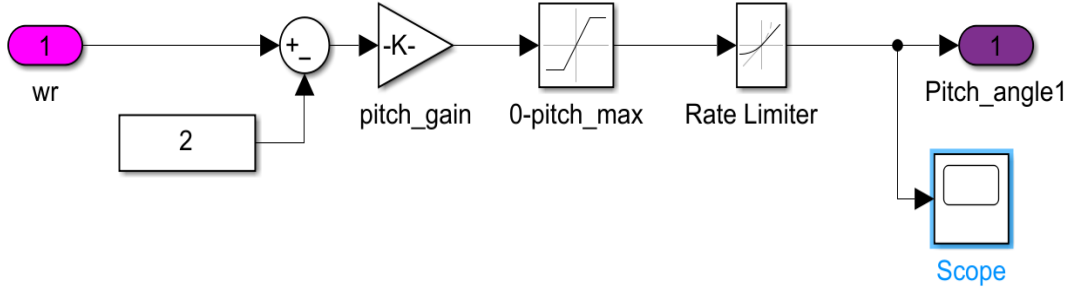


Figure 3.13 Simulink model of the pitch actuator model

3.5.6 Linearized Wind Energy Conversion System

Wind energy conversion systems are inherently nonlinear due to various factors. But the system needs to be linearized around operational points in order to apply linear control methods. The wind turbine's dynamic equation can be subjected to the Taylor series to produce this linearized model.

$$\frac{d\omega_{ref}}{dt} = \frac{1}{J} (T_e - F\omega_{ref} - T_m) \quad (3.77)$$

Where: T_e electrical torque of generator, J inertial of rotor, T_m mechanical torque, and F friction of rotor.

We use the assumption that the rotor's friction is negligible in Equation (3.77). As a result, we disregard it and can be stated as follows:

$$T_e - T_m = J \frac{d\omega_r}{dt} \quad (3.78)$$

Taking the mechanical torque of wind turbine $T_m = f(\beta, \omega, V_{wind})$

By applying Taylor series to Equation (3.78) it can be provided as follows at operating point:

$$\Delta T_m = \frac{\partial f}{\partial \beta} \Delta \beta + \frac{\partial f}{\partial \omega} \Delta \omega + \frac{\partial f}{\partial V_{wind}} \Delta V_{wind} \quad (3.79)$$

$$\Delta T_e - \Delta T_m = J \Delta \omega \quad (3.80)$$

By taking Laplace transformation of Equation (3.79) and Equation (3.80) would yield

$$J \Delta \omega s = \alpha \Delta V_{wind}(s) + \gamma \Delta \omega + \delta \Delta \beta \quad (3.81)$$

Where: $\alpha = \frac{\gamma}{J}$

$$\Delta \omega = \left[\frac{\alpha}{J} \Delta V_{wind}(s) + \frac{\delta}{J} \Delta \beta \right] \frac{1}{s - a} \quad (3.82)$$

In order to keep the system aerodynamically stable, choosing an operating point is crucial. These linear coefficients are provided by:

$$\alpha = \left. \frac{\partial T_m}{\partial V_{wind}} \right|_{opt}, \delta = \left. \frac{\partial T_m}{\partial \beta} \right|_{opt}, \text{ and } \gamma = \left. \frac{\partial T_m}{\partial \omega} \right|_{opt}$$

Where: α , δ , and γ are linearization coefficients and ΔV_{wind} , $\Delta \omega$, and $\Delta \beta$ represents a deviation from the operating point of $\Delta V_{wind-opt}$, $\Delta \omega_{opt}$, and $\Delta \beta_{opt}$.

We determined Equation (3.82) was that the plant is a first order system,

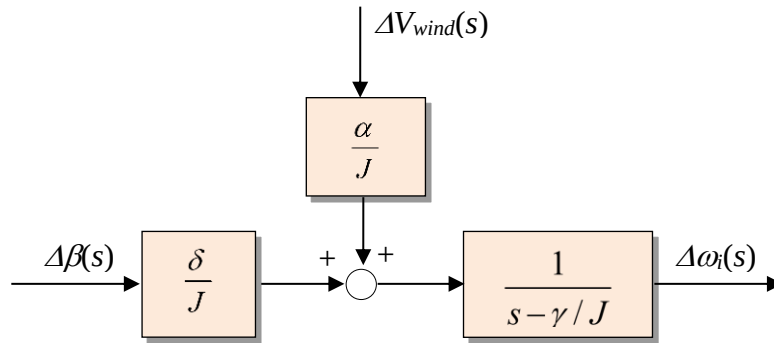


Figure 3.14 Block diagram of the linearized wind energy conversion system.

CHAPTER FOUR

CONTROLLER DESIGN

4.1 Overview of the Chapter

This chapter explains the control methods that are being used at work. The wind energy conversion system (WECS) is a highly nonlinear and uncertain system; for this reason, it is important to design an efficient and reliable controller. So, the adaptive model predictive control (MPC) method is offered for regulating the angle pitch of wind turbines. To provide a benchmark for performance comparison, this chapter also includes the PID controller's design.

4.2 Introduction

The controller's design aims to provide a wind energy conversion system with steady, quick response times, and effective work. By optimizing turbine operation across various wind speeds, the controller maximizes power at modest speeds and regulates output at elevated speeds to prevent overloading. It also ensures quick response times and steady operation for smooth system function. Additionally, they are essential in preventing damage to the turbine by putting safety measures in place and keeping an eye on variables like wind speed and mechanical stresses. This results in decreased mechanical stress on the turbine during high wind speeds, enhanced efficiency throughout a larger wind speed range, and higher power collection at low wind speeds.

4.3 PID Controller as a Benchmark

The PID controller is a linear control method that utilizes proportional (P), integral (I), and derivative (D) terms to produce an output that acts on the controlled goal (B. Zahra, 2017). The PID controller's output in the time domain, which represents the signal of control supplied to the plant, is determined by:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \quad (4.1)$$

where K_p , K_i and K_d are the proportional, integral and derivative gains, respectively. Taking the Laplace transform in Equation (4.1) gives the transfer function as

$$U(s) = (K_p + \frac{K_i}{s} + K_d s)E(s) \quad (4.2)$$

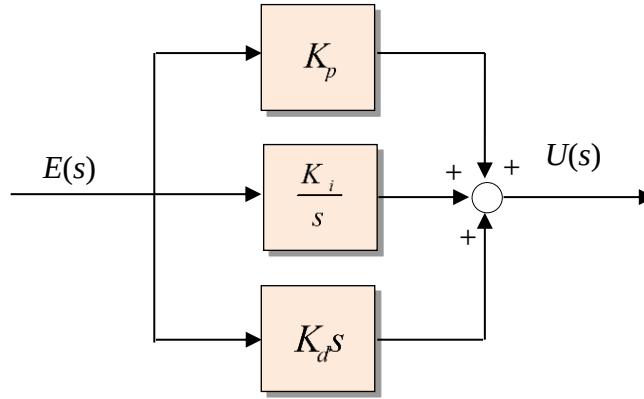


Figure 4.1 Shows the structure of the PID controller

4.3.1 The Pitch Angle Controller Design

The PID controller calculates the distinction between the current and the rotating speed reference (setpoint). The PID parameters correct errors transmitted to the PID controller. A rotational signal is produced from the PID controller's control signal by the pitch actuator. An actuator's pitch angle is frequently updated and compared to β_d .

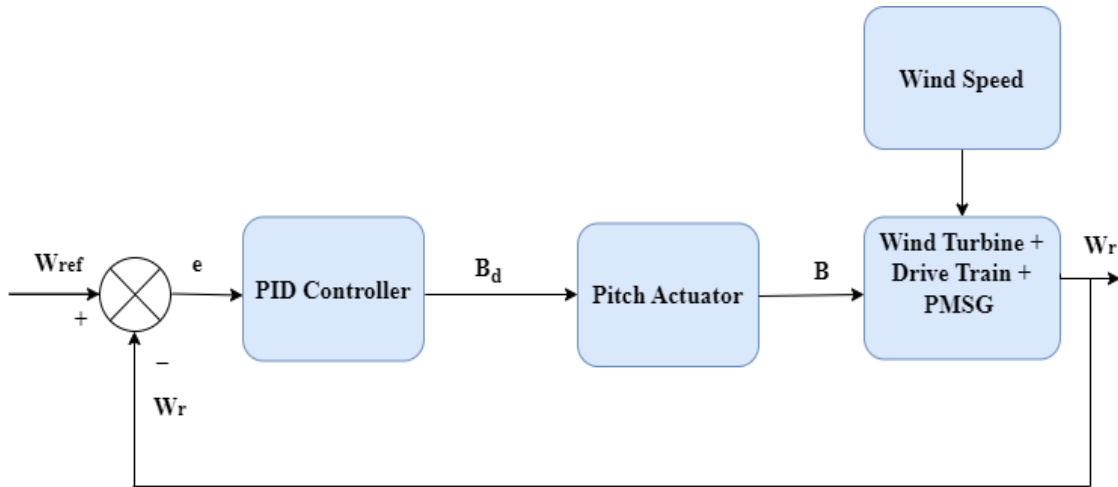


Figure 4.2 Wind energy conversion using the PID controller

From Equation (4.2) we can the forward transfer function of the closed-loop system.

$$G(s) = C(s)G_p(s) \quad (4.3)$$

where $C(s)$ and $G_p(s)$ are the PID controller transfer function and the linearized transfer function of wind turbines, respectively, in that order.

$$C(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_p s + K_i + K_d s^2}{s} \quad (4.4)$$

$$G_p(s) = \frac{\gamma}{T_\beta s + 1} \quad (4.5)$$

In order to let the Hurwitz closed-loop characteristic equation be stable, we need to choose the controller gains K_p , K_i and K_d properly. That's $1 + G_c(s)G_p(s)$ is the Hurwitz polynomial and the criteria of the design should be met.

4.4 Adaptive Controller

The wind energy conversion system (WECS) can present challenges for PID controllers due to system's nonlinearity and uncertainty. Because wind turbine dynamics and wind conditions fluctuated to a great extent, PID control may have difficulty in efficiently regulating such a system. Alternative control techniques, such as the adaptive model predictive controller (MPC), have been developed to overcome these difficulties.

Adaptive control is a control method that has a mechanism for parameter adjustments as well as configurable parameters. Adaptive control is used when a system's parameters or dynamics are uncertain or change over time. This is because it allows the controller to adjust its behavior to maintain optimal performance in the face of these variations.

4.5 Adaptive Model Predictive Control (MPC)

MPC is the most effective model-based management technique to minimize an objective function and maximize control inputs. The goal function is well-defined based on present and predicted system factors and is evaluated using a clear model to forecast future system outputs. This section describes current practices in MPC, computational, and design practices.

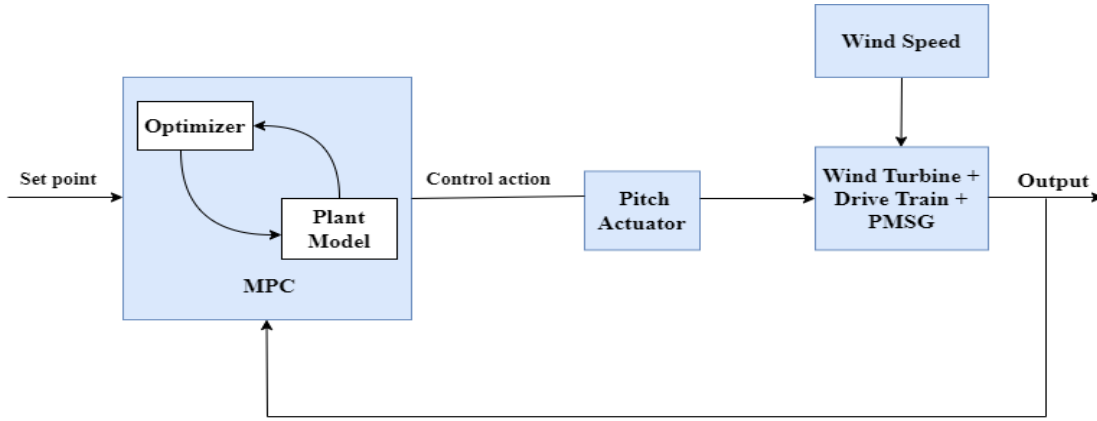


Figure 4.3 Wind energy conversion using model predictive control (MPC) system

A wind turbine is a system of non-linear multi-parameter couplings, and the model predictive controller (MPC) is capable of managing nonlinear problems and multi-input multi-output (MIMO) mechanisms that might exist interrelationships between what they put in and take out. Therefore, MPC has the benefit of being a multivariable controller that concurrently regulates the output by accounting for all system variable interactions. The capacity of the controller to manage both states and control constraints is another benefit. Constraints are crucial to the control system since breaking them might have unfavorable effects. Moreover, MPC can increase controller performance by incorporating future reference information into the control issue through its preview feature.

4.5.1 Working Principle of MPC

A computational representation of the dynamic system being managed is utilized in model predictive control to anticipate the system's model output, $y_m(k+i)$, across a period of time referred to as the forecast horizon, N_p . For each forecast step, the quantity of steps corresponds to the forecast horizon's size, and the sample time that is selected is 'i'. A control horizon's, N_c worth of control inputs is determined by minimizing a control input phase with weights, $u(k+i)$, and a cost estimate of the error between the anticipated outcomes and reference/set point values, $r(k+i)$. In this sequence, the amount of control action considered at each control step equals the prediction horizon length. The control activities necessary to move the system and model to the benchmark values are represented by this configuration of control inputs. At

both the mode and the process, just the first element of the control input sequence is applied since the system measurement and reference values are updated constantly at subsequent sampling instants.

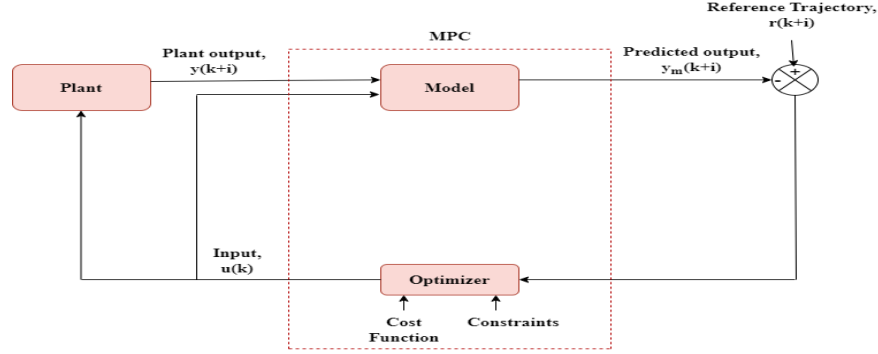


Figure 4.4 The operating principle of MPC

Model predictive control (MPC) plays a crucial role in optimizing wind turbine performance. it utilizes a mathematical model to forecast future wind behavior and continuously modify the angle of pitch of the turbine blades within a defined time frame. This optimization process considers critical constraints, such as the lowest and highest allowable angles of pitch or the rate at which the blades can change position. Additionally, MPC takes into account the entire wind turbine system dynamics to maximize power generation in a safe and efficient manner. By continuously updating control inputs based on model predictions, MPC ensures that the wind turbine operates at its peak potential in diverse wind circumstances.

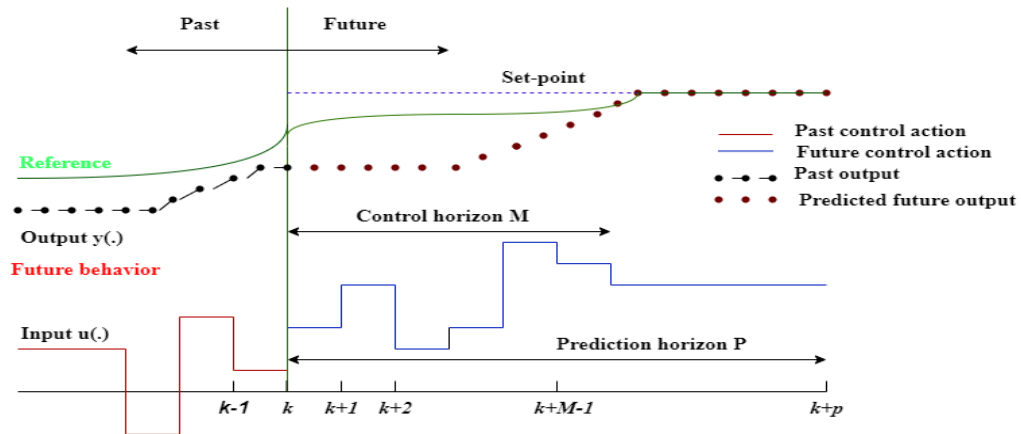


Figure 4.5 The basic concept of MPC

4.5.1.1 Prediction

The state space of wind energy conversion system is expressed as:

$$\dot{\omega}_r = -\frac{N}{J_r} T_{tw} + \frac{1}{J_r} T_r \quad (4.6)$$

$$\dot{\omega}_g = \frac{1}{J_g} T_{tw} - \frac{1}{J_g} T_g \quad (4.7)$$

$$\dot{T}_{tw} = k_d N \omega_{wr} - k_d \omega_g - \left(\frac{N^2 D_t}{J_r} + \frac{D_t}{J_g} \right) T_{tw} + \frac{N D_t}{J_r} T_r + \frac{D_t}{J_g} T_g \quad (4.8)$$

$$T_{tw} = k_d \beta_{tw} + D_t (N \omega_r - \omega_g) \quad (4.9)$$

$$\begin{aligned} \dot{x}_w(t) &= A x(t) + B_u u(t) + B_v \delta v(t) \\ y_w(t) &= C x(t) \end{aligned} \quad (4.10)$$

$$x_w = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} \delta \omega_r \\ \delta \omega_g \\ \delta T_{tw} \\ \delta T_g \\ \delta \beta \end{bmatrix} \in R^5 \quad \text{the state vector, } u_w = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} \delta T_{gr} \\ \delta \beta_d \end{bmatrix} \in R^2 \text{ is the control input,}$$

$$\text{and } y_w = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \delta \omega_g \\ \delta P_e \end{bmatrix} \in R^2 \text{ is the measured output.}$$

Where ω_r rotor speed, N gear ratio, J_r rotor ratio, T_{tw} the drive train torsional torque, T_r turbine torque, ω_g generator speed, J_g generator inertia, T_g generator torque, k_d is shaft stiffness, D_t damping coefficients, β pitch angle, β_{tw} shift twist angle, and P_e the generator power.

$$A = \begin{bmatrix} \frac{L_\omega}{J_r} & 0 & -\frac{N}{J_t} & 0 & \frac{L_\beta}{J_r} \\ 0 & 0 & \frac{1}{J_g} & -\frac{1}{J_g} & 0 \\ k_d N + \frac{N D_t}{J_r} L_\omega & -k_d & -\left(\frac{N^2 D_t}{J_r} + \frac{D_t}{J_g} \right) & \frac{D_t}{J_g} & \frac{N D_t}{J_{tr}} \\ 0 & 0 & 0 & -\frac{1}{\tau_t} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{\tau_c} \end{bmatrix} \quad (4.11)$$

$$B_u = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{\tau_t} & 0 \\ 0 & \frac{1}{\tau_c} \end{bmatrix}, B_v = \begin{bmatrix} \frac{L_v}{J_r} \\ 0 \\ 0 \\ \frac{ND_t}{J_r} \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & T_g & 0 & \omega_g & 0 \end{bmatrix} \quad (4.12)$$

The system is MIMO, and its dynamics vary with average wind speed. The prediction model consisting linearized model the WECS dynamics as follows:

$$\begin{aligned} x(i+1) &= A_d x(i) + B_{du} u(i) + B_{dd} d(i) \\ y(i) &= C_d x(i) + D_d u(i) \end{aligned} \quad (4.13)$$

Equation (4.10) is used to derive an enhanced state space representation. This enhanced representation was then used to design the MPC. Suppose that a new state variable is defined as:

$$z(i) = \begin{bmatrix} \Delta x(i) \\ y(i) \end{bmatrix} \quad (4.14)$$

The state equation is rewritten as:

$$\begin{aligned} x(i+1) &= A_d x(i) + B_{du} u(i) + B_{dd} d \\ x(i) &= A_d x(i-1) + B_{du} u(i-1) + B_{dd} d \\ x(i+1) - x(i) &= A_d (x(i) - x(i-1)) + B_{du} (u(i) - u(i-1)) \end{aligned} \quad (4.15)$$

Applying the expression $\Delta x(i) = x(i) - x(i-1)$, $\Delta u(i) = u(i) - u(i-1)$, state increments are expressed as:

$$\Delta x(i+1) = A_d \Delta x(i) + B_{du} \Delta u(i) \quad (4.16)$$

Similarly, using the state and input increments, the output equations is defined as follows:

$$y(i+1) = y(i) + C_d A_d \Delta x(i) + C_d B_{du} \Delta u(i) \quad (4.17)$$

The augmented system designed as:

$$\begin{bmatrix} \Delta x(i+1) \\ y(i+1) \end{bmatrix} = \begin{bmatrix} A_d & 0 \\ C_d A_d & 1 \end{bmatrix} \begin{bmatrix} \Delta x(i) \\ y(i) \end{bmatrix} + \begin{bmatrix} B_{du} \\ C_d B_{du} \end{bmatrix} \Delta u(i) \quad (4.18)$$

Equation (4.18) can be written using the new state, the augmented expression, as

$$z(i+1) = Az(i) + B\Delta u(i) \quad (4.19)$$

The output equation can be written as:

$$y(i) = Cz(i) \quad (4.20)$$

Where $A = \begin{bmatrix} A_d & 0 \\ C_d A_d & 1 \end{bmatrix}$, $B = \begin{bmatrix} B_d \\ C_d B_{du} \end{bmatrix}$, $C = \begin{bmatrix} (0)_{\text{size of } x(k)} & 1 \end{bmatrix}$

Equation (4.19) means that the augmented system is influenced by previous states and changes in control signal.

The control horizon (N_c) is the number of forecast control actions calculated explicitly by the controller. This control actions determine the system's forecast trajectory:

$$\Delta U = \Delta u(i), \Delta u(i+1), \Delta u(i+2); \dots \dots \Delta u(i+N_c) \quad (4.21)$$

Where ΔU represents the change in the control input (pitch angle adjustment) at each time step i represents the current time step, n represents the forecast horizon of the MPC (number of future time steps considered), T represents the transpose operation (converts the row vector to a column vector).

An additional parameter known as the forecast horizon (N_p) refers to duration of the optimization window. The following can be used to represent the predicted states:

$$z(i+1|i), z(i+2|i), z(i+3|i), \dots \dots z(i+N_p|i) \quad (4.22)$$

It prefers for the control horizon to be less than or equal to the prediction horizon. It is necessary to compute anticipated plant production using upcoming state variables. The variables that reflect the future state are as follows: $z(i+1|i), z(i+2|i), z(i+3|i), \dots; z(i+ny|i)$.

At $(i+1|i)$,

$$\begin{aligned} z(i+1|i) &= Az(i) + B\Delta u(i) \\ y(i+1|i) &= Cz(i+1|i) \end{aligned} \quad (4.23)$$

At $(i+2|i)$,

$$\begin{aligned} z(i+2|i) &= Az(i+1|i) + B\Delta u(i+1|i) \\ z(i+2|i) &= A(Az(i) + B\Delta u(i)) + B\Delta u(i+1) = A^2z(i) + AB\Delta u(i) + B\Delta u(i+1|i) \\ y(i+2|i) &= Cz(i+2|i) = C(A^2z(i) + AB\Delta u(i) + B\Delta u(i+1|i)) \end{aligned} \quad (4.24)$$

At $(i+3|i)$,

$$\begin{aligned} z(i+3|i) &= Az(i+2|i) + B\Delta u(i+2|i) \\ z(i+3|i) &= A(A^2z(i+1|i) + AB\Delta u(i) + B\Delta u(i+1|i)) + B\Delta u(i+2|i) \\ z(i+3|i) &= A^3z(i+1) + A^2B\Delta u(i) + AB\Delta u(i+1|i) + B\Delta u(i+2|i) \\ y(i+3|i) &= Cz(i+3) = C(A^3z(i+1|i) + A^2B\Delta u(i) + AB\Delta u(i+1|i) + B\Delta u(i+2|i)) \end{aligned} \quad (4.25)$$

$$\begin{aligned} z(i+N_p|i) &= A^{N_p}z(i) + A^{N_p-1}B\Delta u(i) + A^{N_p-2}B\Delta u(i+1) + \dots + A^{N_p-N_c}B\Delta u(i+N_c-1) \\ y(i+N_p|i) &= Cz(i+N_p|i) \end{aligned} \quad (4.26)$$

In general, the output prediction vector is defined as:

$$V = Pz(i) + H\Delta U \quad (4.27)$$

$$\begin{bmatrix} v(i+1|i) \\ v(i+2|i) \\ v(i+3|i) \\ \vdots \\ v(i+N_p|i) \end{bmatrix} = \begin{bmatrix} NL \\ NL^2 \\ NL^3 \\ \vdots \\ NL^{N_p} \end{bmatrix} z(i) + \begin{bmatrix} NM & 0 & 0 & \dots 0 \\ NLM & NM & 0 & \dots 0 \\ NL^2M & NLM & 0 & \dots 0 \\ NL^3M & NL^2M & NM & \dots 0 \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ NL^{N_p-1}M & NL^{N_p-2}M & NL^{N_p-3}M & NL^{N_p-N}M \end{bmatrix} \Delta u \quad (4.28)$$

$$\text{Where;} \quad V = \begin{bmatrix} v(i+1|i) \\ v(i+2|i) \\ v(i+3|i) \\ \vdots \\ \vdots \\ \vdots \\ v(i+N_p|i) \end{bmatrix}, \quad P = \begin{bmatrix} NL \\ NL^2 \\ NL^3 \\ \vdots \\ \vdots \\ \vdots \\ NL^{N_p} \end{bmatrix}, \quad \Delta U = \begin{bmatrix} u(i) \\ u(i+1) \\ u(i+2) \\ \vdots \\ \vdots \\ \vdots \\ u(i+N_c-1) \end{bmatrix} \text{ and}$$

$$H = \begin{bmatrix} NM & 0 & 0 & \dots 0 \\ NLM & NM & 0 & \dots 0 \\ NL^2M & NLM & 0 & \dots 0 \\ NL^2M & NLM & NM & \dots 0 \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ NL^{N_p-1}M & NL^{N_p-2}M & NL^{N_p-3}M \dots & NL^{N_p-N_c}M \end{bmatrix}$$

4.5.1.2 Constraints

Constraint integration is one of the factors that make model predictive controllers (MPCs) noteworthy. Operational restrictions, such as limited size and control capacity, affect all systems and practices. A lot of the time, these limitations are implemented on purpose and are suggested being as strict as feasible in order to preserve energy, minimize resource usage, or just make a certain item smaller. In controlling the angle of pitch of wind turbines for maximizing power transmission capacity, the controller is accomplished by modifying the turbine blades pitch angle. In a practical case, $u(i)$ is pitch angle reference for the blades at each time step, rate of pitch angle change constraint $\Delta u(i)$, and $y(i)$ is the output power. For safe and effective functioning, limitations such as the lowest and highest pitch angles and the rate of change are essential. Through deliberate manipulation of the pitch angle reference within these limitations, the MPC optimizes wind power output while maintaining turbine safety. Constraint on input control signal $u(i)$, constraint about the rate of input (increment of the input signal) $\Delta u(i)$, and constraint on the output signal can be expressed as follows

$$\begin{aligned} u_{\min} &\leq u(i+j) \leq u_{\max}, \\ \Delta u_{\min} &\leq \Delta u(i) \leq \Delta u_{\max}, \\ y_{\min} &\leq y(i+j) \leq y_{\max} \end{aligned} \tag{4.29}$$

Where $j=1,2,3, \dots$

Pitch angle constraint:

Input constraints are represented as:

$$\beta_{\min} \leq \beta(i+j) \leq \beta_{\max} \quad (4.30)$$

where the minimum pitch angle ($\beta_{\min}$) prevents blade stall at low wind speeds and the maximum pitch angle ($\beta_{\max}$) ensures safety by avoiding excessive loads at high wind speeds.

Rate change of pitch angle constraint:

$$\Delta\beta_{\min}(i) \leq \Delta\beta(i) \leq \Delta\beta_{\max} \quad (4.31)$$

This constraint restricts the speed at which the blades may be adjusted to avoid harm from sudden movements.

Output power constraint:

$$y_{\min} \leq y(i+j) \leq y_{\max} \quad (4.32)$$

Output variable (power transmission capacity).

4.5.1.3 Optimization

A predictive control scheme is designed by analyzing the forecast output and the upcoming signal of control as modifiable variables. This anticipation is labeled in the optimization pane. The intended reference signals are created by converting the anticipated outputs using the MPC. In order to solve this problem, a cost estimate with a deviation between the signal of reference and the anticipated state depending on the process restriction must be minimized. This optimization produces a sequence of inputs (Δu), which are utilized to calculate anticipated outputs for the reference path. The output forecast at time of sample k is produced based on the anticipated horizon's size.

An optimization problem has two components, which are:

Objective function: this function prioritizes maximizing power transmission capacity while taking control effort and other factors into consideration. A common form is as follows:

$$\min_{\Delta U} J = \frac{1}{2} \int_0^{\infty} \left((R_s - Y)^T Q (R_s - Y) + \Delta U^T R \Delta U \right) dt \quad (4.33)$$

Where: J objective function to be minimized, R_s is the desired speed (set point), Q and R are the weighing matrices of the output errors and input increments.

Decision variables: the optimization process looks for the best values for these components. They represent the systems or situation's variables that can be controlled. The decision variable for wind turbine pitch angle control MPC is: w represents the change in pitch angle each temporal step i within the forecast horizon. This is the control input that the MPC controller can use to influence the turbine's behavior.

4.5.1.4 Adaptation Mechanism

The adaptation mechanism in adaptive model predictive control (MPC) allows the controller to adjust its prediction model or control parameters in real-time based on observed data and system conditions. This adaptation is crucial for maintaining optimal performance and robustness in the face of uncertainties, instabilities, and changes in system dynamics. There are various key aspects of the adaptation mechanism; from these, this thesis focused on the extended Kalman filter (EKF) of parameter estimation within the adaptive model predictive controller.

Extended Kalman Filter (EKF) is an algorithm utilized for the estimation of the state of a system with nonlinear dynamics. It's a popular choice because it provides a good balance between computational efficiency and accuracy for a variety of purposes, such as wind turbine control systems. EKF equations for controlling the wind turbine's pitch angle, assuming a simplified linear time invariant (LTI) model. This approach offers a balance between complexity and effectiveness for many wind turbine control applications.

$$\begin{aligned} x(i+1) &= Ax(i) + Au(i) + v(i) \\ y(i) &= Cx(i) + Du(i) + w(i) \end{aligned} \quad (4.34)$$

Where: $x(i)$ state vector at time step i (e.g., rotor speed, rotor speed deviation), $u(i)$ control input (change in pitch angle) at time step i , $v(i)$ measurement noise affecting sensor readings, $w(i)$ process noise representing wind speed variations and other uncertainties A , B , C , and D constant

matrix system representing the linear relationships between state, control input, and measurement. Extended Kalman Filter (EKF) equations:

Prediction Step (at time step i):

❖ Predicted State Estimate:

$$\hat{x}(i+1|i) = A(i)\hat{x}(i|i) + B(i)u(i) \quad (4.35)$$

Where: $P(i+1|i)$ is predicted state matrix of covariance, Q noise covariance matrix in the process, representing the uncertainty associated with the process noise $v(i)$.

$$\hat{y}(i) = C(i)\hat{x}(i+1|i) \quad (4.36)$$

Correction Step (upon receiving a new measurement at time step i):

❖ Kalman gain

$$K(i+1) = P(i+1|i) \hat{C} [C P(i+1|i) + R]^{-1} \quad (4.37)$$

Where: $K(i+1)$ Kalman gain, R measurement noise covariance matrix, representing uncertainty associated with the sensor measurements $w(i)$.

❖ Updated state estimate:

$$\hat{x}(i+1|i+1) = \hat{x}(i+1|i) + K(i+1)(y(i) - C\hat{x}(i+1|i)) \quad (4.38)$$

Where: $\hat{x}(i+1|i+1)$ updated state estimate after correction using the latest measurement $y(i)$.

4.5.2 Model Predictive Control (MPC) Design Parameters

Model predictive control design parameters are the key elements that define how the controller operates and achieves its goal. These parameters influence the capability of the controller to optimize control actions, handle uncertainties, and ensure safe and efficient operation.

$$\min_{u,x} J(\mathbf{x}, \mathbf{u}; \mathbf{N}, \mathbf{M}) = \frac{1}{2} \int_0^{\infty} ((R_s - Y)^T Q (R_s - Y) + \Delta U^T R \Delta U) dt \quad (4.39)$$

Where: N forecast horizon and M control horizon.

$$\text{s.t } x(i+1) = Ax(i) + B_u u(i) + B_v d(i)$$

$$x(i) \in x, \forall i \in [0, N] \text{ and } u(i) \in u, \forall i \in [0, M]$$

4.5.2.1 Sampling Time

Sampling time (T_s) determines the rate at which the control mechanism is carried out by the controller over time t . If it's excessively large, the controller will be unable to respond to the disturbance quickly enough. And if it is small, the controller can respond much faster to disturbances, but it incurs an excessive computational load. The aim is to find the appropriate equilibrium between execution and computational effort. This thesis work took $T_s=0.1$ second (10 Hz).

4.5.2.2 Prediction Horizon

The prediction horizon (N) specifies how many future time steps are considered when making predictions in the control algorithm. An extended forecast period enables the controller to be able to predict and react to variations in wind speed and other variables. Typically, the prediction horizon is determined by the anticipated wind dynamics and the turbine's response time. MPC, frequently stated as receding horizon control (RHC) or moving horizon control (MHC), is a commonly used method for controlling dynamical systems (taken 15-time steps).

4.5.2.3 Control Horizon

The control horizon (M) defines the quantity of upcoming inputs for control (pitch angle adjustment) that the MPC has to explicitly calculate and optimize. The rest of the input remains constant. Each control move on the control horizon can be considered an independent variable that has to be calculated by the optimizer. The computations are reduced as the control horizon decreases. Although a control horizon of 1 can be chosen, it may not result in the best maneuver. Increasing M increases the controller's aggressiveness and computational effort, but it can also lead to improved predictions. For optimal results, set M to 10–20% of the prediction horizon N with $0.1N \leq M \leq 0.2N$ (taken=5-time steps)

4.5.2.4 Weights (Q and R)

In the optimization process of control, weighting matrices are used to rank state variables and control inputs in order of importance. Tuning and optimization can determine the appropriate values for Q and R . A higher power deviation weight in Q prioritizes power generation, which may result in faster but less smooth pitch adjustments. Conversely, a higher R value penalizes aggressive pitch variations, promoting smoother control but potentially sacrificing some power output. If $Q \gg R$, reducing the difference between desired and predicted values is more important than penalizing input. If $R \gg Q$, minimizing control effort is preferred.

CHAPTER FIVE

SIMULATION RESULTS AND DISCUSSION

5.1 Overview of the Chapter

The outcomes of the PID, model predictive controller (MPC), and adaptive model predictive controller (MPC) are examined and discussed in this chapter. MATLAB/Simulink is used to model each component and assess the system's performance in chapters three and four, where the computational framework of the system and controller design were established. In order to confirm that the suggested approach is validated, a 1.5-MW PMSG for power generation simulation was executed. Details of the whole system parameters are included in the appendix.

5.2 Wind Speed

The speed of the wind is highly unpredictable; it fluctuates rapidly from 0 m/s to 25 m/s, which presents a major challenge for wind turbine regulator mechanisms. To assess controller performance, the wind model generates varying wind speeds. A variable speed wind turbine's operational range is shown in Figure 5.1. This range is usually separated into three regions: the cut-in region (3 m/s -11.8 m/s), the rated region (11.8 m/s-25 m/s), and the cut-out region (above 25 m/s). The controller automatically modifies the turbine blade's pitch angle in response to variations in wind speeds. This critical function maximizes power output at moderate wind speeds while shielding the turbine from harm during powerful gusts.

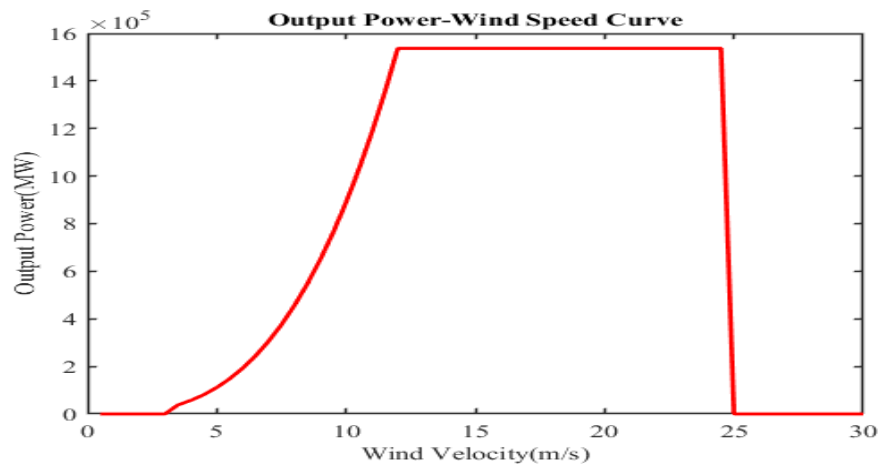


Figure 5.1 Output power vs. wind speed

The generated power of a wind turbine is directly correlated with the wind speed cube. The power graphical representation shows the relationship between wind speed and electrical power generation. Low wind speeds result in little power generation since there is not enough wind energy. The turbine produces more electricity as the wind speed rises. The rated power, also known as the turbine's maximum power output, is the greatest energy that may be obtained from wind; however, there is a limit.

5.3 Results of Pitch Angle Response

This simulation study uses a pitch angle range of 0 to 0.8 radians. The outcomes are attained for model predictive controllers (MPCs) and adaptive model predictive controllers.

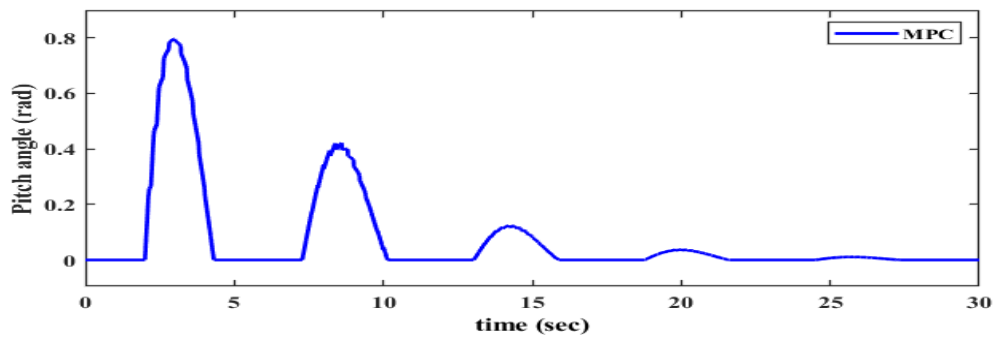


Figure 5.2 MPC controller-based pitch angle response

In strong wind conditions, as illustrated in Figure 5.2, the pitch angle becomes crucial for managing turbine performance. If power generation were to increase, it could overwhelm the generator, making it difficult to control rotor speed. Therefore, the blade pitch angle is adjusted to decrease the rotor's aerodynamic efficiency, which helps regulate the rotor's elevated speed. In this scenario, the turbine blades are turned away from the wind to minimize power extraction. When there is an imbalance between mechanical energy input and electrical energy output, pitch angle adjustments are employed to restore balance. Once the wind speed stabilizes at its rated level, the pitch angle is reset to zero to optimize power output. The maximum pitch angle shows 0.785 radians in (2.5 sec to 4.5 sec), reflecting the controller's rapid response to rising wind speeds, which is essential for preventing excessive power generation during high wind conditions. As the timeline progresses, particularly between 5 sec to 10 sec, the pitch angle exhibits fluctuations, indicating ongoing adjustments to adapt to changing wind speeds. However, the MPC does not consistently react to smaller variations in wind speed, suggesting

that its performance may be less effective in managing minor fluctuations, which could impact overall turbine efficiency.

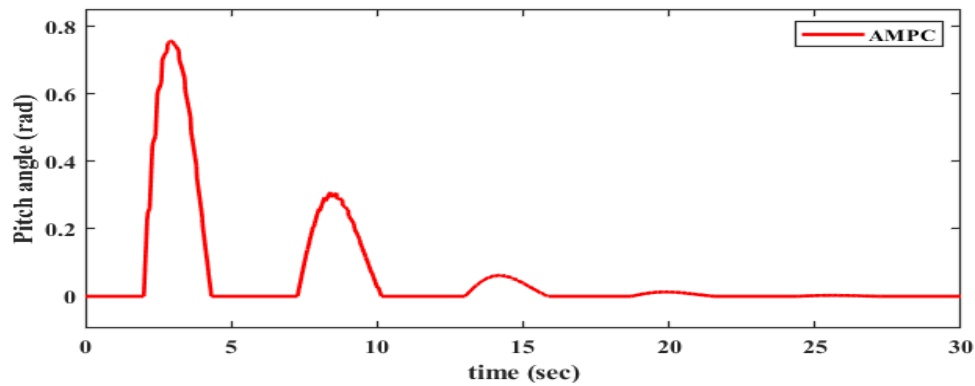


Figure 5.3 Adaptive MPC controller based-pitch angle response

The adaptive MPC controllers show a maximum pitch angle of 0.76 radians. At 22.5 seconds, the response of the pitch angle approaches 0 radians as the wind speed approaches the specified level. This adjustment represents the controller's capacity to minimize pitch angle when wind speed falls within the specified range, optimizing energy capture and enabling the turbine to operate safely while maximizing power production. The controller's adaptive feature makes it more sensitive to variations in wind speed, which improves the turbine's overall performance.

5.4 Results of Mechanical Power Response

Mechanical power response describes how the output power of a mechanical system, such as a wind turbine or generator, fluctuates in response to other variables.

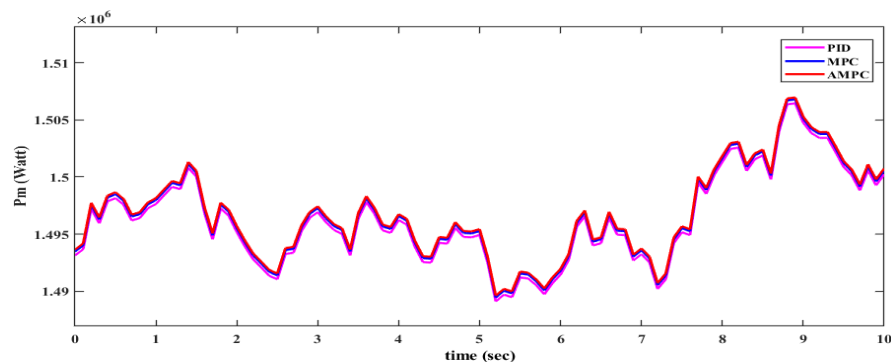


Figure 5.4 PID, MPC, and adaptive MPC controllers based mechanical power response

From Figure 5.4, the PID controller can be used to adjust pitch angle in order to maintain the appropriate mechanical output, but it has limited adaptability to changing wind conditions. MPC controllers outperform PID controllers, especially when dealing with disturbances and changing wind conditions, because they can anticipate and respond to these changes. The adaptation mechanism constantly evaluates the plant characteristics as wind conditions changed. Thus, adaptive MPC provided good and effective performance for system response.

5.5 Results of Rotor Speed Response

In this thesis, we consider that the wind turbine operates at a nominal rotational speed of 16 rpm (1.674 rad/sec). The PID controllers exhibits a slower response to rapid wind speed fluctuations, resulting in rotor speed overshoot and oscillations before settling at the desired operating point. Excessive rotor speed, reaching up to 1.87 rad/sec (17.86 rpm), could negatively impact power output and increase turbine loads. MPC controllers offers improved performance by predicting wind conditions, reducing overshoot, and limiting rotor speed to approximately 1.8 rad/sec (17.19 rpm). Adaptive MPC further enhances control by adapting to dynamic wind conditions, surpassing both PID and MPC in terms of stability and disturbance rejection.

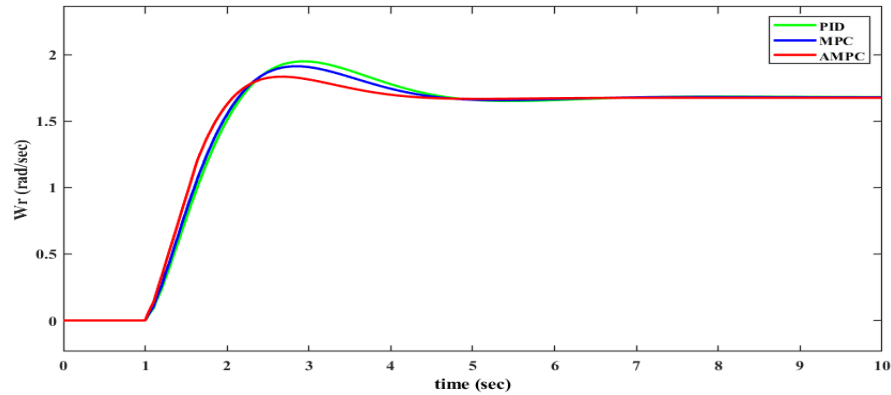


Figure 5.5 PID, MPC, and adaptive MPC controllers based rotor speed response

5.6 Results of Generator Torque Response

The wind turbine generator had at rated torque of 896057.35 Nm required to produce a rated mechanical power output of 1.5MW. This high torque value is necessary to efficiently convert the available wind energy into electrical energy at the generator's rated operating point. At this level of torque, the generator can efficiently harness the kinetic energy from the wind, ensuring optimal performance and maximizing energy conversion.

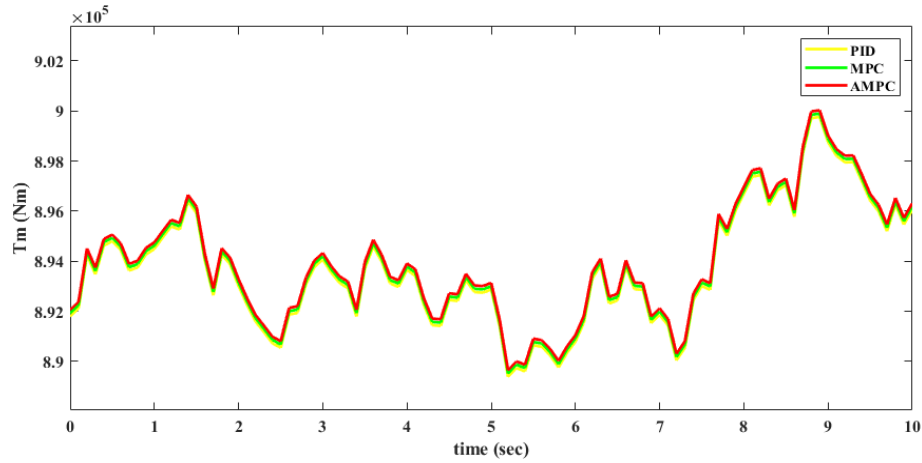


Figure 5.6 PID, MPC, and adaptive MPC controllers based generator torque response

5.7 Results of the Generated Power Response

The generator aims to produce the power of 1.5MW of power when the wind speed surpasses its rated value. The power output of the wind turbine generator utilizing the PID controller was 1.511 MW, which is 0.733% above the rated speed, but it was 1.5053 when using a typical MPC, which is 0.353% above the rated speed. However, the suggested system, which combines adaptation mechanisms with a model predictive controller, produced a maximum generating power output of 1.5023 MW, which is 0.153% above the rated speed, outperforming both the PID controller and the model predictive controller. The PID controllers has a maximum power change of 0.11 MW over rated, the MPC controllers 0.053 MW, and the adaptive MPC controllers 0.012 MW, which indicates that the adaptive MPC controllers performs well in tracking the generator's rated value and rejecting disturbances. Its responses are illustrated in the below figures:

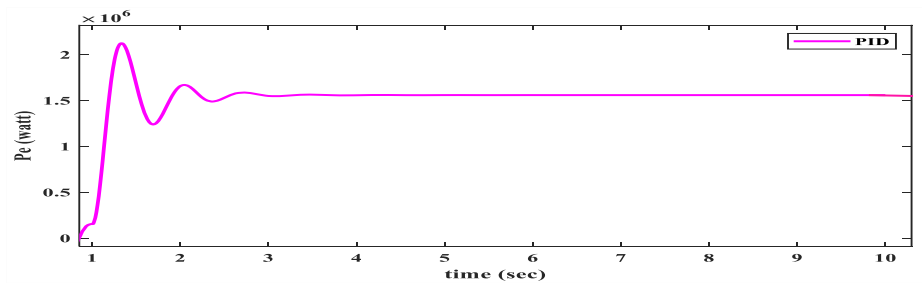


Figure 5.7 PID controllers based generated power response

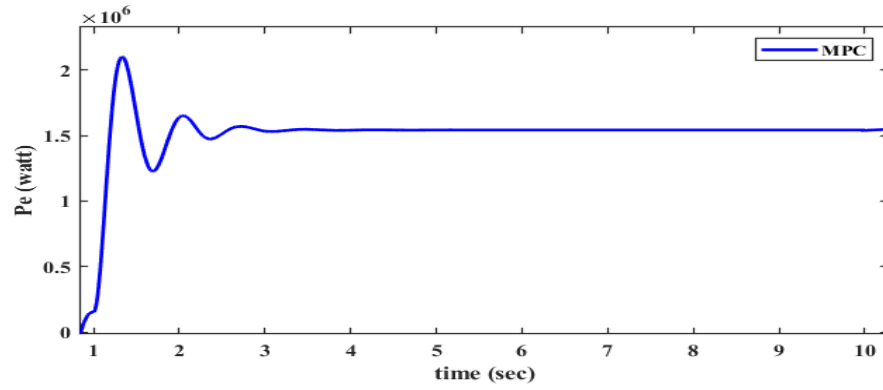


Figure 5.8 MPC controllers based generated power response

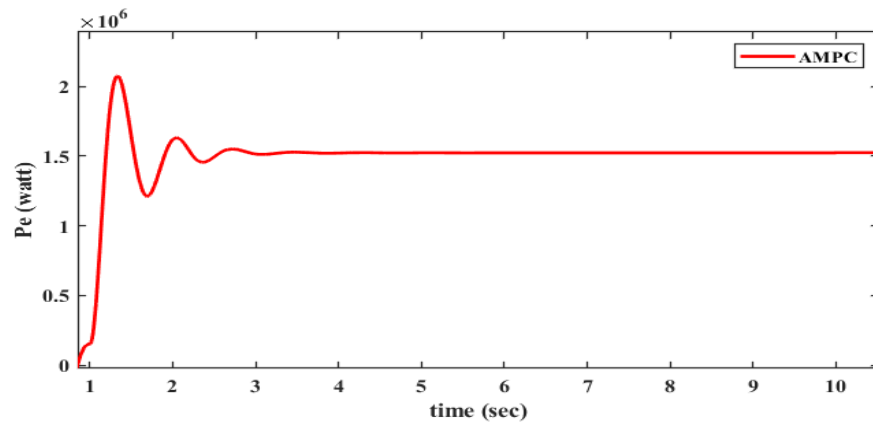


Figure 5.9 Adaptive MPC controllers based generated power response

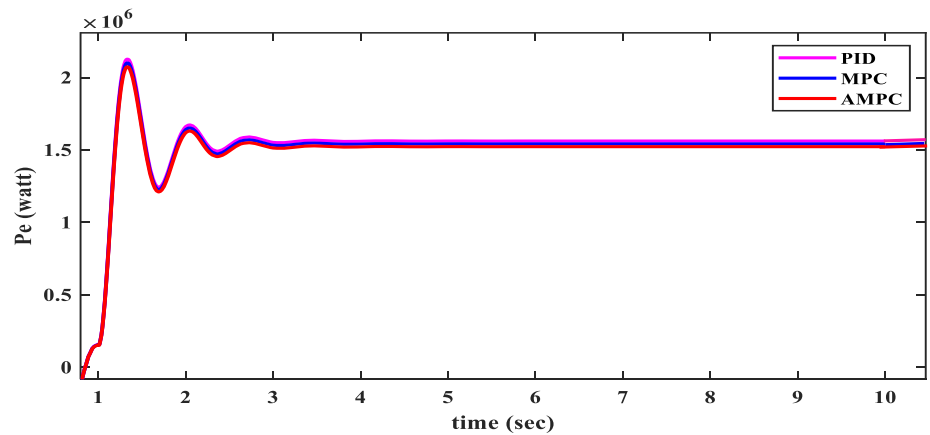


Figure 5.10 PID, MPC, and adaptive MPC controllers based generated power response

The pitch angle control system is a critical component for maximizing the power transmission capacity of wind turbines. By continuously monitoring rotor speed and dynamically adjusting

the blade pitch, this system maintains the turbines at their optimal, rated operating point, where the generator and drivetrain can convert the captured wind energy into electrical power as efficiently as possible. While traditional PID controllers can struggle with this task due to the system's highly nonlinear aerodynamics, more advanced adaptive controllers like MPCs are better able to estimate changing parameters and adapt their gain accordingly. This enhanced adaptive capability allows the wind turbine to track rapid wind fluctuations, avoid efficiency-robbing overload conditions, and keep the rotor operating at the precise rated speed required to extract and transmit the maximum available power from the wind source.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The research presented in this study has focused on developing dynamic modeling and advanced pitch angle control strategies to maximize the power transfer capability of wind turbine systems, which face significant challenges because of the volatile characteristics of wind speed. The ever-changing and unpredictable nature of wind introduces highly dynamic operating conditions that require continued adaptation, further exacerbated by the disproportionate oscillations in power generation caused by small variations in wind speed, severely compromising the efficiency and stability of power transmission, particularly during periods of volatile wind conditions. By dynamically adjusting blade pitch, wind turbines extract maximum power while mitigating the impact of fluctuating wind speeds. This control strategy is crucial for optimizing energy capture, protecting turbine components, and ensuring stable operation. This thesis investigates three types of controllers: PID, model predictive controller (MPC), and adaptive model predictive controller (MPC) to manage pitch angle of wind turbines. Simulations have shown that the adaptive model predictive controller (MPC) approach is proficient at dynamically defining the maximum power point of the wind energy system and adjusting the wind turbines' tip speed ratio under varying wind speeds. This adaptive controller is able to effectively regulate the system to work around its highest power coefficient value, minimizing the deficit of captured wind energy compared to traditional PID and MPC control strategies.

To optimize the generator speed and turbine's power extraction, the pitch angle must be adjusted as wind speeds drop between rated and cut-in values. This ensures maximum efficiency and energy extraction from the wind, while maintaining the pitch angle at 0 radians ensures maximum power extraction after wind speeds exceed the specified value. The power output of a wind turbine generator utilizing a PID controller was 1.511 MW, which is 0.733% above the rated speed, but it was 1.5053 when using a typical model predictive controller (MPC), which is 0.353% above the rated speed. However, the suggested system, which combines adaptation mechanisms with a model predictive controller, produced a maximum generating power output of 1.5023 MW, which is 0.153% above the rated speed, outperforming both the PID controller and the model predictive controller.

6.2 Recommendation

Future work should concentrate on applying sophisticated wind modeling and forecasting techniques to enhance the prediction capabilities of the adaptive model predictive controller (MPC), investigating alternative adaptation mechanisms, and addressing computational efficiency for real-time implementation. These research avenues may be explored in order to further optimize the adaptive MPC technique, which will maximize power transfer capabilities and guarantee dependable and effective wind turbine performance under a variety of operating circumstances.

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APPENDIXES

APPENDIX A1:

Table A1: GW 70/1500 Wind turbine specifications (htt)

Parameters	Values
Rated Power	1500kW
Cut-in Wind Speed	3m/s
Rated Wind Speed	11.8m/s
Cut-out Wind Speed	25m/s
Rotor speed	16rpm
Air density	1.225kg/m ²
Maximum power coefficient	0.48
Diameter	70m
Swept Area	3886m ²
Number of blades	3
Rated voltage	690V
Stator phase resistance Rs	0.08ohm
Armature inductance	0.00041H
Frequency	50/60 Hz
Shaft Stiffness	0.3
Damping Coefficients	1

APPENDIX A2:

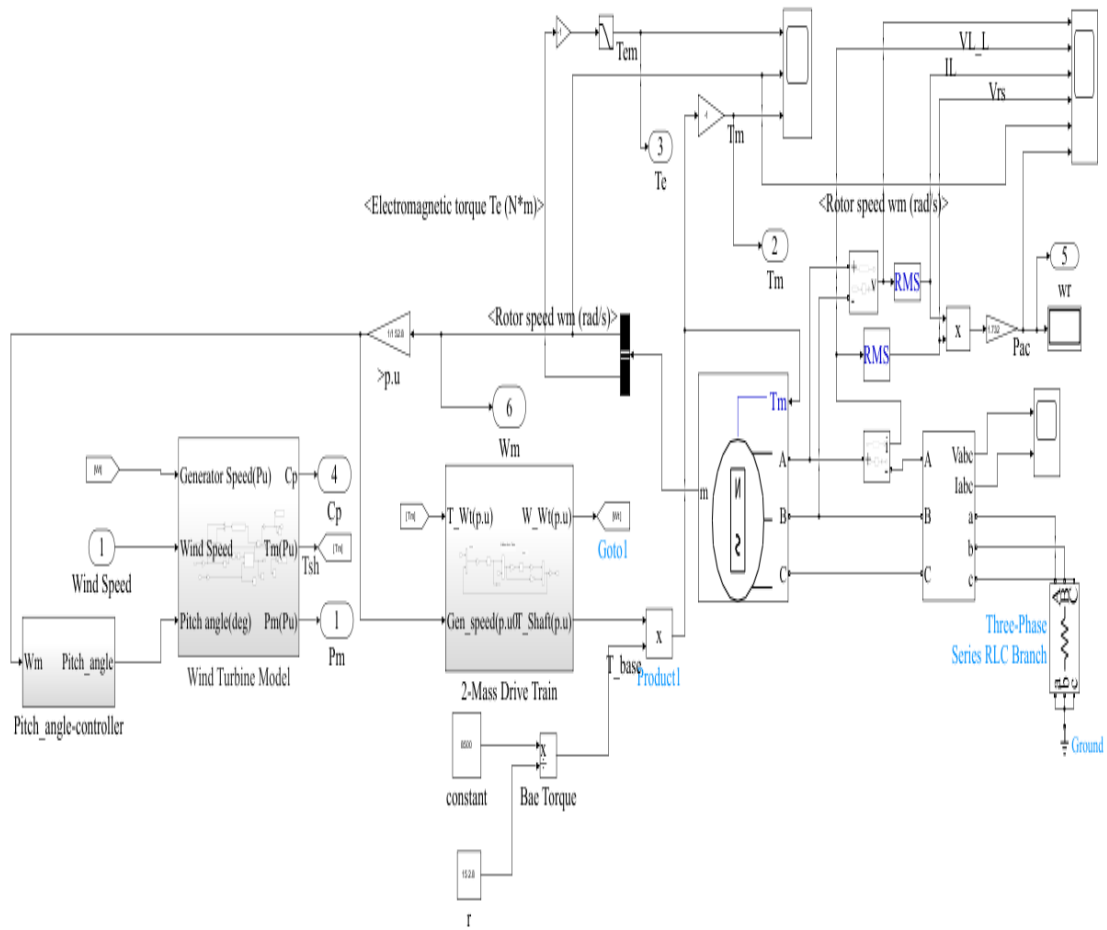
Table A2: MPC controller specification

Parameters	Values
Prediction Horizon	15-time steps
Control Horizon	5-time steps
Maximum Constraint	0.8 radians
Minimum Constraint	0 radians

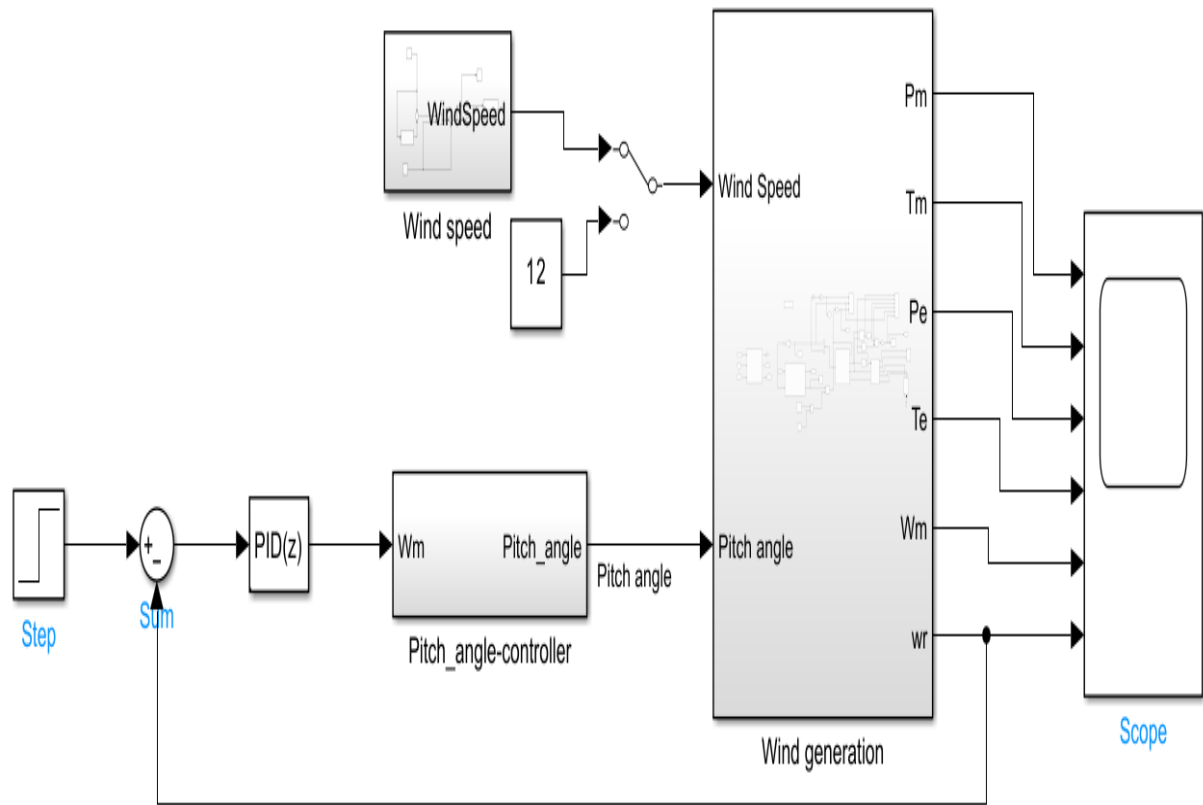
APPENDIX B: MATLAB code for output power vs. wind speed

```
clear all
clc
vcin=3;% cut-in speed
vnom=11.8;% normal speed
vcout=25;% cut-out speed
step=0.5;
v=step:step:30;
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=35.5;% in meters, indicates the blade length
    A=pi*(r^2);
    Raw=1.225;% Air density,in kg/m^3
    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)')
```

APPENDIX C



APPENDIX D



APPENDIX E

