Model Predictive Based Control of Wind Turbine Blade Pitch Angle

Getacho Edossa Guduma

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

July, 2023

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Declaration

I declare that this thesis Master entitled **"Model Predictive Based Control of Wind Turbine Blade Pitch Angle"** is my own work and has not been submitted to any university for similar purpose. All sources for the materials used in this document have been formally acknowledged by citations.

Getacho Edosa Guduma	____________________	____________________
Name of student	Signature	Date

Recommendation

I the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled, **“Model Predictive Based Control of Wind Turbine Blade Pitch Angle”** prepared under my guidance by **Getacho Edossa Guduma**. Submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power and Control Engineering (Control Engineering). Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures.

Dr. Endalew Ayenew	__________________	__________________
Advisor	Signature	Date

Approval Sheet

I the advisor of this thesis entitled, **"Model Predictive Based Control of Wind Turbine Blade Pitch Angle"** and developed by **Getacho Edossa Guduma**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Endalew Ayenew	____________________	________________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Getacho Edossa Guduma, have read and evaluated the thesis entitled "**Model Predictive Based Control of Wind Turbine Blade Pitch Angle"** and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science Electrical Power and Control Engineering (Control Engineering).

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Acknowledgments

First of all, I would like to thank the omnipotent God, for his help in each path of my life. May glory for his name! And then, I would like to thank my Advisor Dr. Endalew Ayenew for his guidance, valuable support, useful comments, and supervision from the beginning to the completion of this thesis.

I also want to thank my entire family for their love, encouragement, and all the sacrifices they have made for me. I thank Samara University for the scholarship. Adama science and Technology University department of power and control Engineering staff has the great role for my success.

Table of Contents

List of Table

List of Figures

List of Acronyms

Abbreviations	Description
MPC	Model predictive controller
PID	Proportional integral derivative
IEC	International Electromechanical commission
MIMO	Multi-input multi-output
EECP	Ethiopian Electric Power Corporation
PAC	Pitch Angle Control

Abstract

The utilization of wind energy has become increasingly crucial in the energy composition of numerous countries and is projected to continue expanding in the forthcoming years. Wind turbine control has evolved into a crucial element within contemporary wind turbine systems. However, wind energy has emerged as a promising and sustainable source of power generation, but the intermittent and unpredictable nature of wind presents significant challenges for efficient and reliable operation of wind turbines. When the strong wind appears, power fluctuation is occurred, this leads to damage many materials. Accurately predicting and effectively managing the output power of wind turbines is crucial to mitigate the adverse impacts caused by excessive power fluctuations on both the wind turbine itself and the power grid. It is essential to ensure proper planning and control measures are in place to maintain stable and reliable operation. Since the wind turbines are nonlinear systems, the blade pitch angle plays a crucial role in capturing the maximum energy from the wind and ensuring safe turbine operation. This thesis developed a control strategy that maximizes energy extraction from the wind while maintaining the structural integrity of the turbine. Model predictive control (MPC) has chosen as the foundation for this approach due to its ability to handle complex and uncertain dynamics inherent in the wind turbines. To investigate the regulation of the pitch angle in a wind turbine, a comprehensive mathematical model encompassing all the system's elements has constructed. To facilitate simulation, the MATLAB software tool is utilized to develop the pertinent models. The MPC controller achieves a maximum pitch angle of 1.57 radians or 90 degrees. In the case of wind speeds ranging between the cut-in and rated speed, the pitch angle needs to be adjusted based on the prevailing wind speed. When the wind speed reached at nominal values, the pitch angle maintained at 0 radian. The generator speed settling time of PI is 1.3461 sec and rise time is 0.0806 sec. The generator speed settling time of MPC is 1.1995 sec and rise time is 0.0803 sec. The highest overshoot generator output power for PI is 5.035 MW which means 0.70% above the rated speed. The highest overshoot generator output power for MPC is 5.0145 MW which means 0.29% above the rated speed. In general, the MPC controller shows the higher quality stability of output power.

Keywords: *MPC controller; wind turbine; blade Pitch angle.*

CHAPTER ONE

1 INTRODUCTION

1.1 Background of the Study

Wind power is an environmentally friendly and lasting means of generating electricity that possesses the capacity to fulfill a substantial proportion of global energy demands. The distribution of electricity in our country especially in rural area is infant. The best way to enhance and simplify human life while also fostering industrialization and economic growth is through the use of electricity. Rural and distant locations can benefit from using solar and wind power to create electricity, which lowers grid prices. The percentage of wind power generation in the system has already been rising. The world is currently shifting its energy usage toward green energy (renewable energies). Because of the rise in global energy demand as well as environmental concerns, using wind energy to generate electricity is becoming an increasingly appealing energy option. The emission of gases into the atmosphere from the combustion of fossil fuels, such as carbon dioxide, is responsible for the phenomenon of global warming. The utilization of wind energy for electricity production does not rely on fossil fuels. Ethiopia possesses plentiful renewable energy resources, which have the potential to fulfill the entirety of the country's electricity requirements (Hailu & Kumsa, 2021). Despite having access to ample energy resources, Ethiopia's power consumption rates in Africa are among the lowest. Additionally, the majority of its population resides in rural areas and depends solely on traditional biomass energy sources (Albagoury, 2016).

It is important to recognize that despite occasional challenges or limitations, solar and wind energy resources provide electricity with lower installation expenses and more economically viable operation compared to other energy sources. The utilization of wind to generate mechanical or electrical energy is known as wind energy or wind power. Wind turbines are employed to capture the accessible energy from the wind, creating a nonlinear system where the energy obtained is directly related to the velocity of the wind. Many nonlinear and complicated systems today require controllers in order to perform to their highest level. Several tactics are used, depending on the operating point at which the wind turbine is functioning. The goal is to keep the loads acting on the structure to a minimum once the rated power is obtained, which involves maintaining the power generation at nominal levels until the cut-off wind speed is reached. IEC-64100's (ICE) (Commission & others, 2005) for designing wind turbines is a set of design criteria used to ensure that the wind turbine is appropriately developed. The effectiveness of wind turbines relies on various elements, such as blade design, turbine orientation, and the control approach implemented to manage its functioning. The proportion of wind power generation within the system has already been increasing. Nevertheless, due to the unpredictable nature of wind energy, its erratic variations lead to power imbalances within the system and pose a risk to the frequency stability of the power grid. Wind turbines employ two levels of control: a slow control level, which focuses on power regulation, and a quick control level, involving a frequency converter and rotor current controller. To tackle these concerns, an inquiry was carried out regarding the active power control of a wind turbine with two degrees of freedom. This control method, based on the small signal approach, effectively mitigated torque fatigue in the wind turbine tower by simultaneously regulating the rotor speed and pitch angle. (Singh et al., 2018)

A crucial element of wind turbine control involves modifying the blade pitch angle, which represents the angle between the blade chord line and the plane of rotation. This angle significantly influences the turbine's ability to harness energy from the wind. Generally, the pitch angle should be fine-tuned to optimize the turbine's power output while minimizing the loads on the blades. The main drawback they have in the wind turbine control is impossibility to take into account system constraints. The majority of control systems for wind turbines are traditional proportional integral derivative (PID) controllers with added band pass and/or notch filters to boost the damping of particular structural modes. (Bossanyi, 2000). Nevertheless, conventional control methods have restrictions when it comes to managing the nonlinear and ever-changing dynamics of wind turbines. Additionally, they fail to offer optimal solutions for intricate control challenges.

In addition to recently developed improved control algorithms, model predictive controllers will undoubtedly play an intriguing role in the control of large wind turbines in the future. (Maciejowski, 2002). MPC (Model Predictive Control) has garnered growing interest in recent times for its capacity to address intricate control issues and accommodate diverse constraints on control inputs and outputs. Specifically in the realm of wind turbine blade pitch angle control, MPC leverages a model of the wind turbine system to forecast the turbine's future behavior and optimize the blade pitch angles accordingly. MPC has shown promising results in improving the power capture efficiency and reducing the loads on the wind turbine blades. In comparison to PID control, MPC displays superior speed tracking control capability. It also excels at handling restrictions and forecasting system dynamics during the course of its operational state. (Mayne, 2014)

The objective of this research is to create a resilient and efficient MPC controller capable of managing the nonlinear and ever-changing dynamics of wind turbine systems while adhering to different constraints on control inputs and outputs. The evaluation of the proposed controller will involve utilizing a high-fidelity simulation model of a wind turbine system, and the obtained results will be compared with alternative control strategies to showcase the effectiveness of the suggested approach.

1.2 Statement of the Problem

The increasing need for electricity derived from sustainable energy sources, like wind power, is motivated by escalating concerns for safety and environmental preservation. Due to the nonlinearities of wind energy, ensuring the stability of power while operating the wind turbine in a secure mode poses a significant challenge in the advancement of wind energy. The wind speed around a wind turbine's rotating blades is constantly fluctuating both upstream and downstream. When the wind speed surpasses the designated threshold, certain components of wind turbines are susceptible to damage, leading to unstable power output. In highly windy conditions, wind turbines frequently halt power generation and initiate shutdown procedures as a safety precaution. This shutdown not only results in significant power losses but also has an impact on the economic value of the wind turbine project, particularly when the wind speed exceeds the nominal level. Without proper pitch angle control, the wind turbine is unable to safeguard itself against the adverse effects of high wind speeds, especially those surpassing the rated wind speed.

The wind turbine rotor is subjected to a highly nonlinear aerodynamic load, which poses significant challenges in maintaining stable power output and exposes the wind turbine to elevated stresses. The strains incurred may lead to harm in both the blades and other parts of the wind turbine. The aim of this thesis is to enhance the efficiency of wind power systems by concentrating on the control of the wind turbine blade pitch angle. The suggested control approach seeks to modify the pitch angle of the blades based on alterations in wind speed and direction, while simultaneously meeting diverse constraints imposed on control inputs and outputs. Traditional control strategies, such as PID control used for wind turbine blade pitch angle control have limitations in handling the nonlinear and time-varying dynamics of wind turbines. This may lead to below optimal performance and magnified mechanical stress on the turbine components, causing accelerated wear and tear. Therefore, advanced control strategies such as model predictive control (MPC) are investigated as a potential solution to this problem.

1.3 Motivation

Wind turbines offer a promising solution to address a substantial portion of the world's energy requirements and facilitate the transition towards a low-carbon economy. However, in order to fully harness the potential of wind energy, it is crucial to enhance the performance and dependability of wind power systems, which heavily rely on effective control strategies for regulating wind turbine operations. When wind speed increases rapidly, wind turbines can become unstable and repairing any resulting damages can be costly. To mitigate these risks and ensure power stability in high wind conditions, pitch angle control emerges as the optimal approach. Hence, there is a pressing need for advanced control strategies, such as model predictive control (MPC), to optimize the performance and reliability of wind power systems by effectively managing the pitch angle of wind turbines.

1.4 Objectives

1.4.1 General Objective

The primary aim of this thesis is to develop a control system based on model predictive techniques for the regulation of wind turbine blade pitch angle by considering system constraint.

1.4.2 Specific Objective

- Analyze the mathematical modeling of wind turbine, including aerodynamics, wind train, pitch angle and generator.
- Ascertain the highest power output achievable to guarantee the durability of the wind turbine.
- Design the MPC pitch angle controller.
- Evaluate electrical output power in the performance of MPC and compare it with that of the PI controller.

1.5 Scope of the Study

This thesis centers around regulating the pitch angle of wind turbine blades, particularly within horizontal axis wind energy conversion systems. These systems can be divided into different operational zones based on varying wind speeds. The first zone, associated with low wind speeds, does not provide enough energy to rotate the turbine effectively. In region two, the wind speed range lies between the cut-in wind speed and the rated wind speed, initiating the extraction of energy from the wind by the turbine. On the other hand, in region three, the wind speed surpasses the rated wind speed, necessitating a dependable controller to govern the turbine speed and avert mechanical harm. The cutoff or shutdown region signifies wind speeds at which the turbine ceases power generation. The emphasis of the thesis is on formulating a model predictive controller, implemented solely through MATLAB simulation without practical execution.

1.6 Limitation of the study

The scope of the thesis study will be confined to the mathematical design and simulation of the system using MATLAB code. The primary objective is to showcase the interplay between the various components of the system. This is owing to the fact that actual deployment of the system is challenging due to the increased time and cost involved.

1.7 Significance of the study

Like conventional energy sources such as coal and natural gas, which emit harmful pollutants and pose health and economic risks, wind energy offers the advantage of being environmentally friendly, as it does not contribute to air pollution. The findings of this study hold potential benefits for both the Ethiopian Electric Power Corporation (EEPCO) and the factory involved. Additionally, this study's outcomes can serve as valuable academic references for BSc and MSc students. Furthermore, the findings can assist local wind farms in reassessing their power extraction and control methods, as well as taking necessary measures to address any shortcomings. The analysis will also be relevant for future wind farm projects, aiding in their optimal design and layout.

1.8 Thesis Organization

There are five chapters in this thesis:

Chapter One - Covers the thesis background, problem statement, motivation, objectives, study scope, and study significance.

Chapter Two - Comprises fundamental theories of the wind turbine and a review of relevant literature.

Chapter Three - Provides an explanation of the system methodology and the mathematical modeling of the system.

Chapter Four - Showcases the findings and discussions of the research.

Chapter Five - Dedicated to the discussion of the study's conclusions and recommendations based on the findings.

CHAPTER TWO

2 BASIC THEORY AND LITERATURE REVIEW

2.1 Theoretical background

Controlling the pitch angle of wind turbine blades is a crucial element in wind energy conversion systems as it plays a vital role in maximizing energy generation and prolonging the lifespan of wind turbines. The pitch angle refers to the angle between the blade's plane of rotation and the plane of the incoming wind. By manipulating the pitch angle, operators can manage the turbine's speed and power output, ensuring its protection against potential damage during high wind conditions (Hamoodi et al., 2020a). The concept of blade pitch angle control is grounded in principles of aerodynamics and control theory. The adjustment of the pitch angle impacts the angle of attack of the blades, which directly influences the generation of lift and drag. Variable-speed wind turbines operate within a range that extends beyond the cut-in threshold and below the cut-out threshold. Variable-speed turbines provide numerous benefits in comparison to fixed-speed turbines, including heightened energy generation, improved conversion efficiency, reduced strain on components, and diminished power fluctuations (Sarkar et al., 2020).

Wind turbines harness the power of the wind by utilizing rotor systems equipped with aerodynamic blades, which in turn rotate a shaft. This shaft spins within a generator, generating electricity as a result. Furthermore, through turbine control, it becomes possible to optimize the utilization of wind power by maximizing the extraction of energy from the wind, or alternatively, by limiting the extraction during periods of intense wind. Modern turbines depend on complex control systems to maximize capability and ensure safe operation. Variable speed wind turbines operate in the region between the cut-in and cut-out thresholds. They offer several advantages compared to fixed speed turbines, including increased energy production, improved conversion efficiency, reduced stress on components, and fewer fluctuations in power. (Iqbal, Ying, Saleem, Hayat, & Mateen, 2020). Various sources have discussed the utilization of traditional control methods in wind turbines; see for example (Bossanyi, 2000).

2.2 Wind

Wind turbines capture the energy from the wind to generate electricity. The variations in wind turbine velocity can be classified into different categories, either based on geographical factors or temporal fluctuations. Geographical categorizations can be divided into two main types: coastal, which includes bodies of water such as oceans and gulfs, and continental, which refers to land that is situated far from water and deep inland. Typically, wind speeds are higher in coastal areas compared to inland regions. Additionally, the wind patterns in these areas tend to exhibit a greater consistency, primarily blowing from a specific direction as influenced by intricate weather systems, rather than from other directions.

• Yearly and seasonal fluctuations, such as El Nino and storms during the fall season, etc.

• Synoptic and diurnal fluctuations refer to the movement of extensive weather systems and the contrast between day and night.

• Turbulence arises from the interaction of airflow with surface friction and variations in temperature.

In this thesis study, the constant or slowly changing mean wind speed incorporates annual, synoptic, seasonal, and diurnal variations, modeled as a constant, step function, or ramp. The focus of dynamic modeling is solely on the turbulent wind, while other dynamic aspects of wind are not considered.

Wind shear, which refers to the turbulence induced by rough terrain, is not included in the design modeling. The roughness of the terrain affects the friction between the surface and the wind, resulting in slower wind speeds near the ground compared to higher elevations. As a result, the rotor experiences varying wind speeds as it rotates from top to bottom, creating a time-correlated effect that depends on the rotor's rotation speed.

2.3 Wind turbine

Wind turbines are mechanisms that harness the kinetic energy of wind motion to produce electrical power. They comprise essential components, such as a rotor, generator, control system, and tower. The rotor, consisting of multiple blades, captures the kinetic energy of the air mass and transfers it to the connected electrical generator. Typically, wind turbines are mounted on tall towers to maximize their ability to capture wind energy. The conversion of aerodynamic power to electrical energy involves two distinct processes. In the beginning, the aerodynamic energy present in the wind undergoes a conversion process to mechanical power, which is then further transformed into electrical power.

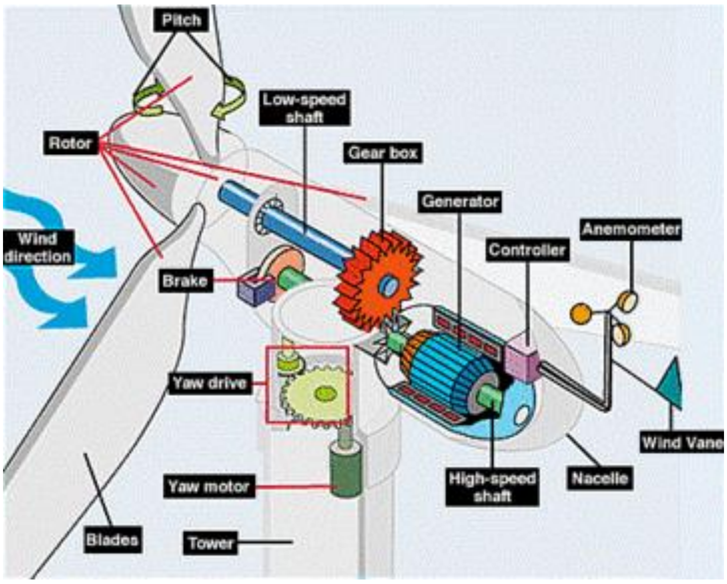

Figure 2.1 Wind turbine components (Burton et al., 2011)

Wind turbines can be either onshore or offshore. Onshore wind turbines are located on land and are typically smaller than offshore wind turbines. Offshore wind turbines are located in bodies of water and can be much larger than onshore turbines. Wind turbines have several advantages over other forms of energy generation. Wind turbines represent a sustainable and environmentally friendly energy source as they produce no greenhouse gas emissions and have minimal environmental impact. Additionally, they are considered a clean and renewable source of energy. However, they also have some disadvantages, including their leaning on wind as a source of energy, their potential impact on wildlife, and their visual impact on the landscape.

Wind turbines consist of various key components, such as anemometers, rotors, blades, towers, nacelles, yaw motors, yaw drives, and generators. The tower acts as the primary support structure for the wind turbine, ensuring that the rotating blades are positioned at an optimal height to capture an abundant amount of wind energy. The yaw mechanism enables the rotor blades to align with the direction of the wind. The gearbox plays a crucial role in transforming the slower rotational speeds of the wind turbine into higher speeds on the electrical generator side. With the wind turbine driving its shaft, the electrical generator produces electricity, which is regulated according to specifications through suitable control and monitoring techniques.

Rotor Blades - The operating principle of wind turbine rotor blades is akin to that of aircraft wings. Similar to wings, one side of the blade is curved while the other remains flat. As the wind moves along the curved edge, it accelerates, resulting in a pressure disparity on opposite sides of the blade. This pressure difference propels the blades forward as the air endeavors to balance the pressures, thereby initiating rotation. Commonly, rotor blades for wind turbines are constructed using lightweight and resilient composite materials like fiberglass or carbon fiber reinforced plastic. The main goal of blade design is to optimize the capture of wind energy and enable its efficient transfer to the rotor hub. As a result, the rotational movement of the rotor hub drives the generator, resulting in the production of electricity. The design and production of rotor blades capable of withstanding the intense forces exerted by wind and weather conditions are crucial for ensuring the secure and dependable operation of wind turbines. Therefore, rotor blades undergo rigorous testing and certification before they are installed in wind turbines.

Nacelle – The wind turbine nacelle, positioned atop the turbine tower, serves as a protective housing for the mechanical elements of the turbine, including the generator, gearbox, and control systems. Its purpose is to shield these components from the elements and maintain their optimal functioning. Additionally, the nacelle incorporates sensors and control systems that enable automatic adjustments to blade pitch and yaw, maximizing the turbine's wind energy capture. In most modern wind turbines, a hub connects the nacelle to the three blades. As wind flows over the blades, they rotate, causing the hub to rotate as well, thereby driving the generator housed within the nacelle to produce electricity. The nacelle holds great significance as a crucial component of a wind turbine, necessitating regular maintenance and inspection to ensure safety and peak performance.

Tower – A wind turbine tower is a raised structure specifically designed to offer stability and assistance provided to the blades and other elements of a wind turbine. Its purpose is to elevate the rotor blades to an optimal height where they can harness the desired wind speeds. Typically, wind turbine towers are constructed at heights ranging from 50 to 100 meters above the ground or water surface. The tower needs to be tall enough to place the turbine's blades in the path of strong and consistent winds, which are typically found at higher elevations. The tower is designed to be rugged and able to withstand the forces of wind and other weather conditions. It is also designed to be easily assembled and installed, as the tower is typically constructed on-site and assembled piece by piece. The tower plays a crucial role in a wind turbine system by offering vital support to the blades and other equipment required for its operation. It also houses the machinery and electronics that control the turbine's operation and collect data on its performance.

The categorization of wind turbines is primarily determined by the placement of the rotation axis. Based on this factor, two common categorizations in the field of wind turbines are horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). Additionally, wind turbines can be categorized based on the torque delivery mechanism to the rotating shaft, which can be either lift or drag, depending on the airflow across the rotor surface.

2.3.1 Horizontal Axis Wind Turbine (HAWT)

In a horizontal-axis wind turbine (HAWT), the main rotor shaft is positioned horizontally to align with the wind direction. The rotor shaft of the wind turbine holds the blades, which are specifically designed to rotate around this axis in response to the force of the wind. Horizontal-axis wind turbines are extensively used and serve as the dominant type of wind turbine utilized in present times, offering a range of sizes and designs. Large-scale HAWTs can produce several megawatts of electricity, while smaller turbines can be used for residential or small-scale commercial applications. To achieve optimal efficiency, this particular turbine variant often incorporates features such as wind sensors and servo motors, enabling the alignment of the rotor blades with the wind direction. To mitigate potential risks and damage caused by high wind speeds, the turbine is equipped with a brake mechanism to reduce the rotational speed of the rotor shaft. Notably, the prominent advantages of Horizontal Axis Wind Turbines (HAWTs) stem from their elevated towers, which expose them to stronger winds with increased wind shear, ultimately leading to higher power output. The design of the HAWT facilitates its ability to orient itself according to the wind direction. As the wind blows, the aerodynamic configuration generates lift, inducing rotation in the rotor blades. HAWTs exhibit optimal performance in regions characterized by reliable and moderate to high wind speeds. However, these turbines have certain drawbacks. In extreme wind conditions, a brake mechanism is necessary to reduce the rotation speed of the rotor blades, and an additional system is needed to enable the blades to align with the wind direction. Moreover, due to their tall stature, wind turbines have the capacity to alter the visual aesthetics of the surroundings. Furthermore, maintaining wind turbines is challenging, and substantial structures are essential to support the large blades, gearbox, and generator components. (Manerikar et al., 2021)

Figure 2.2 A wind turbine with a horizontal axis and three blades. (Burton et al., 2011)

2.3.2 Vertical axis wind turbine (VAWT)

A vertical axis wind turbine (VAWT) distinguishes itself from the traditional horizontal axis wind turbines (HAWT) by having a vertically oriented main rotor shaft instead of a horizontal one. In VAWTs, the rotor shaft is aligned perpendicular to the wind direction. Furthermore, essential components such as the generator and gearbox are positioned closer to the ground. Vertical axis wind turbines (VAWTs) provide various advantages compared to horizontal axis turbines. One notable advantage is their omnidirectional capability, allowing them to generate power regardless of the wind direction. This makes them ideal for urban and suburban environmental where the wind is often turbulent and changes direction frequently. VAWTs also have a lower profile than HAWTs, which makes them easier to install in areas with height restrictions or limited space. They are also generally quieter and less visually overbrearing than HAWTs. However, VAWTs also have some disadvantages. They generally have lower efficiency than HAWTs, meaning they generate less power for the same wind speed. They also require a more complex mechanical design, which can increase maintenance costs. (Lenz & others, 2019)

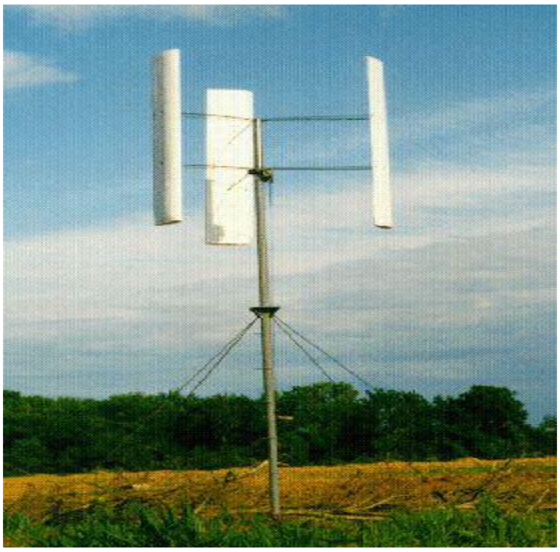

Figure 2.3 Vertical Axis Wind Turbine (Burton et al., 2011)

Regards to speed wind speed divided into two: Constant wind speed and variable wind speed

2.3.3 Fixed speed wind turbine

A wind turbine operating at a fixed speed, alternatively known as a constant-speed turbine or steady-speed wind turbine, maintains a consistent rotor speed regardless of the wind velocity. In these turbines, the rotor and synchronous generator are directly linked, resulting in a wind turbine system with a constant rotational velocity. The generator generates electricity at a fixed frequency determined by the rotational speed, typically set at 50 Hz or 60 Hz depending on the geographical location. Constant velocity wind turbines' main advantage is that they are simple. Compared to variable velocity wind turbines, they often require less electronic components and are more affordable to construct and maintain. They are also very reliable and have been used in wind power projects for many years. They are made to operate at their most effective level under specific wind conditions. (SN et al., 2016).

However, there are certain disadvantages to fixed velocity wind turbines. They are less efficient than variable velocity turbines, especially when there is little wind. This is due to the fixed rotor speed, which prevents them from capturing as much wind energy as turbines with variable speed. Fixed speed turbines are also more sensitive to grid disturbances, which can cause voltage and frequency fluctuations.

2.3.4 Variable speed wind turbine

A variable speed wind turbine, also known as a pitch-controlled or variable-pitch wind turbine, exhibits the ability to adjust its rotor speed in response to varying wind speeds. These turbines employ pitch control systems on the rotor blades, allowing for the modification of their angle of attack as the wind speed changes. This adaptive feature enables the turbine to harness a greater amount of wind energy and operate with improved efficiency across a broader range of wind speeds. In recent years, variable-speed wind turbines have emerged as the predominant choice among installed wind turbines. Their design prioritizes the attainment of optimal aerodynamic efficiency across diverse wind conditions. The primary advantage of variable speed wind turbines lies in their enhanced efficiency. By matching the rotor speed to the wind speed, they can capture more energy from the wind and operate with greater effectiveness across a wider spectrum of wind velocities. Additionally, they demonstrate heightened resilience to grid disturbances and possess the capacity to offer grid support functions, a crucial aspect for the seamless integration of wind power into the electricity grid.

By regulating a predetermined value corresponding to the maximum power coefficient, the tip speed ratio λ is effectively maintained at a constant level. Unlike a fixed-speed system, a variable-speed system ensures a relatively steady generator torque while adapting the generator speed to accommodate changes in wind conditions. The electrical system of a variable-speed wind turbine is more complex than that of a fixed-speed wind turbine. The variable-speed setup improves energy capture, resulting in reduced mechanical stress and enhanced power quality within the wind turbine system.

However, variable speed wind turbines are more complex and expensive to manufacture and maintain than fixed speed turbines. They require more electronic components and discerning control systems, which can increase their cost and complexity. They also require more maintenance due to the additional mechanical and electrical components. (SN et al., 2016)

2.4 Variable speed wind turbine operation area

The operational range of a variable speed wind turbine refers to the range of wind speeds within which the turbine can operate efficiently and generate electricity. In a variable speed wind turbine, the rotor velocity is adjusted to align with the wind speed, effectively maximizing the turbine's power generation capacity.

The operation area of a variable speed wind turbine is typically divided into three regions:

Cut-in region: This represents the zone characterized by wind speeds that are insufficient for power generation by the turbine. Within this range, the turbine remains inactive, and the rotor speed is deliberately maintained at a low level to prevent any harm to the turbine components.

Rated region: This indicates the area where the wind speed lies within the optimal range for the turbine to generate power at its intended capacity. In this zone, the rotor speed is precisely adjusted to match the wind speed, thereby maximizing the power produced by the turbine.

Cut-out region: This represents the range where the wind speed exceeds the safe operating limits of the turbine. Within this area, the rotor speed is modified to restrict the power output of the turbine, safeguarding its components against potential damage. The precise boundaries of these regions are contingent upon the unique configuration of the wind turbine and can fluctuate based on factors such as blade length, generator size, and control methodology. The operational range of a variable speed wind turbine holds significant significance in wind farm planning and operation, as it impacts the capacity factor and energy generation of the turbine.

2.5 Model Predictive Control (MPC)

MPC, also referred to as rolling horizon control, originated in the 1960s and draws inspiration from established control algorithms like dynamic matrix control (DMC) and generalized predictive control (GPC) that are extensively employed in industrial system control. MPC belongs to a category of controllers that leverage an explicit and identifiable model for direct utilization.

MPC, which stands for Model Predictive Control, typically encompasses three stages: prediction modeling, rolling optimization, and feedback correction. It is an advanced control technique employed to regulate intricate systems with numerous variables. By employing a precise dynamic model of the system, MPC utilizes current output measurements and model-based output predictions to anticipate future output values. These predicted outputs are then employed to determine suitable adjustments in the control input variables. (Seborg et al., 2016)

The primary aim of MPC is to calculate a trajectory for the future manipulated variable u in order to optimize the future performance of the plant output y. (Wang, 2009) . Within a constrained time frame, optimization is conducted by utilizing the plant information available at the beginning of the time window.

MPC provides various significant benefits:

- ✓ The process model demonstrates the interconnected relationships, both dynamic and static, between input, output, and disturbance variables.
- ✓ The constraints affecting both the inputs and outputs are systematically considered and accounted for.
- ✓ The calculation of the control input and the optimum set points can be done simultaneously.
- ✓ Precise model predictions offer timely indications of potential issues.

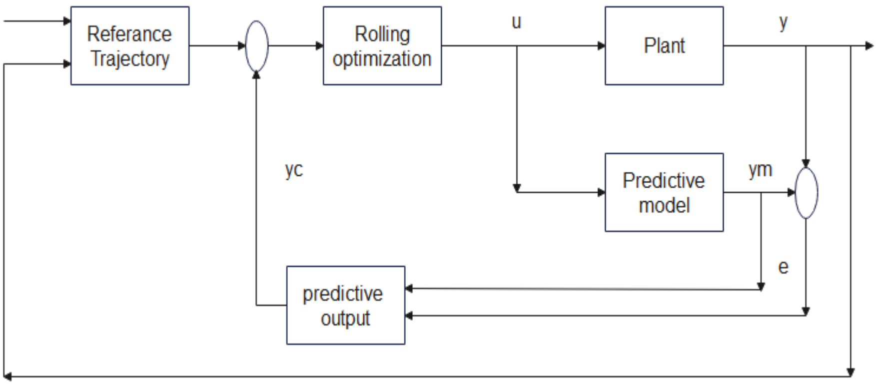

Figure 2.4 Block diagram of MPC(Vazquez et al., 2014)

MPC computations rely on present measurements and future projections of the output. Its aim is to generate a series of control actions (changes in manipulated inputs) that steer the predicted response towards the desired set point in an optimal manner.

MPC systems are designed using the mathematical representation of the plant, primarily in the form of a state space model. (Wang, 2009) Hence to predict the future output and states, current states, output and input information are used.

MPC is a type of optimal control technique in which a new optimal control input is designed each time in a time horizon depending on the current situation of the system. These present information and predicted output values determine optimized control input which can be used in the next prediction.

The overall design objective can be summarized as: (Seborg et al., 2016)

i. Preventing input and output constraints violation.

ii. Track the set point for some outputs while keeping the other outputs within predetermined range.

iii. Preventing excess input variables movement.

iv. During no sensor or actuator is available for closed loop control, control as many processes variables as possible.

One notable characteristic of MPC is its receding horizon approach, which involves calculating a predefined number of control moves (Nc) at each sampling point, but executing only the first move. Then, based on updated measurements, another set of Nc control moves is determined, with only the initial move being applied. This iterative procedure continues until a stable response is attained.

The MPC predictions are mainly using the system's dynamic model as a basis. This model can be either state space model or transfer function model.Top of Form

2.6 Control Technique of wind turbine

Wind turbines are engineered to achieve optimal efficiency at a specific wind speed, resulting in maximum output. However, if the wind speed surpasses this threshold, the excess energy goes unused. Nonetheless, it is essential to safeguard the rotor from potential damage. Wind turbines are intricate devices that necessitate sophisticated control methods for effective and safe operation. Here are some common control techniques used in wind turbines:

2.6.1 Stall Control

Wind turbine stall control is a technique employed to regulate the power generated by a wind turbine by intentionally stalling its blades. When the wind speed surpasses a specific limit, the blades may rotate at excessive speeds, resulting in potentially damaging power output. To mitigate this risk, wind turbines incorporate stall control systems that enable adjustments to the blade angle, reducing lift and subsequently decreasing rotational speed. Stall-regulated machines require the regulation of torque speed and the incorporation of an appropriate speed characteristic into the rotor's aerodynamics. As the wind speed rises, the flow angles over the blade sections become sharper, while the rotor speed remains consistent. This causes the blades to experience increased stall, which effectively limits the power output to acceptable levels without requiring additional active control. To maintain a near-constant speed, the implementation of stall control involves linking the generator to the grid. In this setup, the grid serves as a substantial flywheel, assisting in stabilizing the turbine's speed irrespective of variations in wind speed (Kulka, 2004a). As the angle remains fixed, there is no requirement for rotating the angles around their axis using a mechanism. However, as the wind speed increases, the angle of attack also increases. Once the angle of attack surpasses a specific threshold (α), the stall effect takes place, and the torque generated is limited to approximately its rated value. (Kulka, 2004a)

Stall control is a complex procedure, involving both aerodynamic and electrical aspects. In essence, a stall-regulated wind turbine maintains a nearly constant speed in strong winds, preventing excessive power generation, all without requiring any adjustments to the rotor's geometry.

2.6.2 Pitch Angle Control

The control of wind turbine pitch angle is crucial in capturing wind energy effectively. It entails adjusting the angle of attack of the blades to optimize performance and ensure the safe functioning of the turbine across varying wind conditions. The pitch angle, which refers to the angle between the blade chord line and the plane of rotation, determines the turbine's ability to extract power from the wind. The pitch angle control system is responsible for regulating the blade pitch angle, maintaining the optimal angle of attack, and preventing the turbine from either over-speeding or stalling during high winds.

Pitch regulation involves rotating the wind turbine blades around their longitudinal axis, known as pitching, to manage the power extracted by the rotor. Unlike stall regulation, pitch regulation requires modifying the rotor's geometry by adjusting the blade pitch. This process involves the utilization of an active control system that detects blade position, measures output power, and provides instructions for the required blade pitch adjustments. The pitch angle control system needs to be responsive to rapid changes in wind speed and direction to ensure optimal turbine performance and prevent any potential damage. In modern wind turbine, the pitch angle control system is often integrated with other control systems, such as the yaw control system, which controls the turbine's orientation to the wind.

Similar to stall regulation, the objective of pitch regulation is to manage the power output during high wind speeds. Another approach, known as active stall regulation, utilizes blades that can be pitched across the entire span. However, in active stall regulation, the blades are pitched in the opposite direction compared to the typical fine pitching, where the leading edge of the airfoil sections faces into the wind. This approach utilizes the pitch system as a primary safety mechanism, similar to the conventional fine pitch solution, but also takes advantage of stall regulation characteristics to minimize pitch activity for power limitation. Through the utilization of pitch angle controllers, it is possible to keep the output power closer to the rated power while simultaneously decreasing the aerodynamic load in areas characterized by high wind speeds (Mughal & Guojie, 2015).

2.6.3 Active Control

This control approach combines pitch control and passive stall control mechanisms. During low and medium wind speeds, the blades are pitched similarly to those in a pitch-controlled turbine. However, unlike passive stall control, there is no reduction in power at higher speeds. Instead, the blades are rotated a few degrees in the opposite direction compared to the pitch-controlled configuration (Rehman et al., 2018).

Vertical axis wind turbines also employ an additional method for frequency management, which involves, enabling the turbine to operate unrestricted at any speed within its rated range while supplying voltage to the inverter. This approach provides the benefit of accommodating a wider range of operating conditions without the need for intricate gearing systems (Rehman et al., 2018).

2.6.4 Yaw control

Wind turbine yaw control involves the act of aligning the rotor blades of a wind turbine to face directly towards the oncoming wind. This is a vital factor as the energy generation capacity of a wind turbine relies on the speed and direction of the wind it encounters. By continuously adjusting the yaw angle of the rotor blades, a wind turbine can ensure optimal operation, leading to the maximization of its energy output.

Apart from optimizing energy production, yaw control also serves to minimize strain on the components of the wind turbine. When the rotor blades are not aligned with the wind, they can be subjected to uneven forces and vibrations, leading to potential long-term damage. By maintaining proper alignment between the rotor blades and the wind, yaw control plays a vital role in promoting the safe and efficient operation of the wind turbine.

2.7 Review of related work

The interest of researchers has been drawn towards the control of wind turbine systems at various points in time. They have explored diverse types of controllers and mechanisms to study the optimal extraction of power from wind turbines. Wind turbines are complex systems with multiple variables, which makes a model-based control design approach an appropriate tool. This approach allows for the systematic development of controllers to effectively tackle the challenges of multi-variable control.

Authors (Ben Smida & Sakly, 2019), proposed smoothing wind power fluctuation by PSO-based pitch angle control. The paper demonstrated the potential of PSO-based control strategies in improving wind turbine performance. By applying PSO-based pitch angle control, the paper aims to smooth out power fluctuations and enhance the integration of wind energy into the grid. The gap of this research work is, it does not typically incorporate a detailed model of the wind turbine system, which can limit their ability to accurately optimize the pitch angle for optimal performance. Also, it operates as single-input-single-output controllers and may struggle to manage complex interactions between different control variables effectively.

Authors (Iqbal, Ying, Saleem, Hayat, & Mehmood, 2020), combined two powerful control techniques, Fuzzy Logic and Predictive Control, to develop a control strategy for pitch angle control in variable-speed wind turbines. This integration allows for improved control performance and adaptability to varying wind conditions. The weakness of this research work is, since it requires manual tuning of fuzzy sets, linguistic variables, and fuzzy rules. This manual tuning process can be subjective and time-consuming. The lack of standardized design methods for Fuzzy-Based Predictive Controller (FBPCs) may hinder their wider adoption and make it difficult to replicate the control strategy across different wind turbine systems.

Authors (Sarkar et al., 2020) discussed method involves optimizing the blade pitch angles in real-time to regulate the power output and reduce the fatigue loads on the blades, thereby increasing the overall lifetime of the turbine. The paper presents a method to mitigate the loads on the blades of a floating offshore wind turbine through individual blade pitch control (IBPC). The authors reflect the behavior of a floating wind turbine using IBPC using a model-based method. The simulations show how the proposed control technique effectively reduces loads on the blades and controls the turbine's production of electricity. The study only considers IBPC for load mitigation and power regulation, and other control strategies may be needed to address other challenges faced by floating wind turbines, such as wave-induced motions and dynamic positioning.

Authors (Maknunah et al., 2019) proposed a novel method for using a particle swarm optimization (PSO) algorithm to optimize the pitch angle of wind turbines. To improve energy production and minimize turbine damage, the authors propose the implementation of an adaptive control system capable of adjusting the pitch angle in real-time according to the prevailing wind speed. The paper stands out for its notable strength in employing a PSO technique to optimize the control system. The algorithm is effective in enhancing the wind turbine's performance and is well-suited to the issue. Additionally, the control system's adaptability enables it to react to shifting wind conditions, which is crucial for real-world applications. However, there are a few areas where the paper could be improved. The authors do not provide a clear explanation of the specific performance metrics used to evaluate the effectiveness of their approach. Additionally, while the results are promising, the authors do not compare their approach to other optimization algorithms or control strategies. This limits the ability to assess the relative effectiveness of the proposed approach.

Authors (Yuan et al., 2020) suggested approach to make the control system more resilient to periodic loads, which are known to be a significant cause of fatigue damage to wind turbine blades. The article is well-structured and provides a clear introduction to the problem, along with a detailed explanation of the proposed control design methodology. The authors start by presenting the mathematical model of a wind turbine and then develop a multivariable control system that takes into account the dynamics of both the wind turbine and the wind disturbances. The control system is based on a combination of feedback and feedforward control, and is designed using robust control theory to ensure stability and performance under uncertain operating conditions. The proposed control design methodology is innovative and shows great potential for improving the reliability and durability of wind turbines. However, the proposed approach may require significant computational resources to implement in practice, which could be a limitation in certain applications.

Authors (Lasheen & Elshafei, 2016) addressed the issue of wind turbine control, which is a crucial factor in the efficient operation of wind turbines. The authors have provided a detailed introduction to the concept of wind turbine collective-pitch control and have presented a comprehensive review of the related literature. The methodology used in this research involves the use of fuzzy logic-based predictive control for collective-pitch control of a wind turbine. The results obtained through simulation studies are presented in detail and demonstrate the effectiveness of the proposed method in controlling the collective pitch angle of the wind turbine. The authors have compared their results with those obtained from a conventional PI controller and have demonstrated that the fuzzy predictive control method offers improved performance. However, some aspects of the methodology, such as the choice of the input variables and the membership functions used in the fuzzy system, could be elaborated further.

Authors (Zhang et al., 2008) discussed a comprehensive overview of the pitch control system and its constituent elements, such as the fuzzy-PD controller, pitch actuator, pitch angle sensor, and wind speed sensor. The authors describe how the fuzzy-PD controller utilizes fuzzy logic to dynamically adjust the proportional and derivative gains of the PD controller based on real-time feedback of wind speed and pitch angle. Additionally, the authors present simulation results comparing the performance of the fuzzy-PD control method with a conventional PID control method. The simulation results demonstrate that the fuzzy-PD control method outperforms the PID control method by effectively reducing wind turbine oscillations and maintaining a more stable power output. However, it is worth noting that as a conference paper, it may lack the level of detail and comprehensiveness typically found in a full research article.

Generally, when it comes to controlling the blade pitch angle of wind turbines, other controllers face certain challenges. These include not explicitly accounting for future behavior when presenting the system state, difficulties in effectively handling multiple constraints, limited responsiveness to fluctuations in wind conditions, and potential struggles in managing complex interactions between different control variables due to being single-input-single-output controllers. In contrast, the Model Predictive Control (MPC) controller addresses these challenges by considering various operational constraints such as maximum and minimum pitch angles, rotor speed limits, and turbine load limits. Through active optimization of the pitch angle, the MPC controller ensures that the turbine operates within these limits, thus minimizing the risks of mechanical failures and potential accidents.

CHAPTER THREE

3 METHODOLOGY OF THE THESIS

3.1 Introduction

To achieve the goals of the thesis, the subsequent methods and techniques will be employed.

Literature Review: The thesis requires a comprehensive understanding of prior research in relevant areas to identify previous achievements and areas for improvement in multiple aspects. The work of this thesis is necessarily based on what has already been done by other scholars related to this selected topic. Thus, it is crucial to examine the contributions of these scholars and gather essential information pertaining to the topic. Different literatures have referred from different available sources such as journals, books, internet, etc. Consequently, the literature review encompasses studying, articles, books, journal papers, simulation tools, and conducting online research on the implementation of model predictive controllers for wind turbines, particularly in wind turbine farms.

Data Collection: The effectiveness of research relies on obtaining the necessary data, which can be accomplished through various data collection methods. These methods include examining data from existing wind turbine farms, analyzing data from previous studies relevant to the thesis, and conducted interviews with relevant stakeholders when necessary.

Data Analysis: In order to develop a proposed design and achieve greater performance efficiency, the obtained data and studied literature are analyzed.

System Model and Design: The system design and modeling will be done. Because of the limited time available to complete the thesis and the lack of materials, the system implementation in hardware is not carried out. The interaction of different part of a system will be shown in MATLAB software environment and the output is to be examined.

Conclusion and Recommendation: After assessing the designed system, the thesis will come to a conclusion by making implicit recommendations and further work to be done on the area.

Ethical consideration: Every step of this thesis takes ethical thought into account. Anyone who is familiar with wind turbines and their controlling mechanisms can be participant.

The participation of peoples in this study is fully voluntary. This study takes full account of integrity, care, openness, confidentiality, competency, legality, and objectivity.

3.2 Materials

- The simulation and testing of the system model in the thesis will be carried out using MATLAB. This software is a general-purpose computing tool that include a wide range of toolboxes and suitable for numerical solution and graphical user interface design.
- Block diagrams and figures are created using Microsoft Visio.
- To write the equations and formula Math type will be used. Math type is an interactive equation editor for creating mathematical expressions.

3.3 Mathematical modeling of the system

The block diagrams below depict the wind energy conversion system, with a select few components highlighted and thoroughly explained to meet the study's objectives. The main focus of this research is the control of the wind turbine's pitch angle. Consequently, the analysis focuses exclusively on providing a detailed examination of the wind turbine, drive train, generator, and pitch controller (actuator).

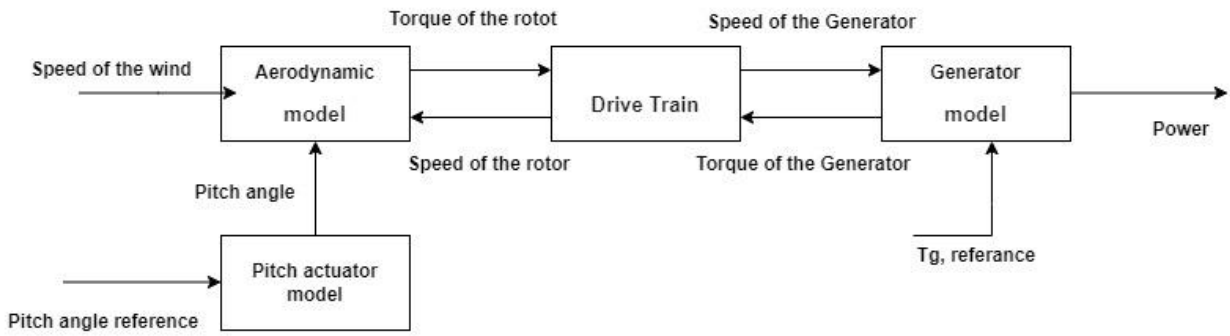

Figure 3.1 Block diagram of the dynamic model of wind turbine(Gosk, 2011)

3.3.1 Aerodynamics for wind turbine

The initial stage involves constructing an aerodynamic model for the wind turbine, as this model largely accounts for the nonlinearity observed in its behavior. The study of aerodynamics plays a vital role in both the design and operation of wind turbines. It involves the study of the motion of air and the forces that act on objects as they move through it. In the case of wind turbines, the objective of aerodynamics is to maximize the energy output of the turbine while minimizing its structural loads and the associated maintenance costs. Here are some key aspects of aerodynamics for wind turbines. In a wind turbine, lift and drag forces play important roles in converting wind energy into mechanical energy. Lift force is generated by the aerodynamic shape of the turbine blades and acts perpendicular to the direction of the wind flow. This force helps to lift the blades and create rotational motion.

The magnitude of the lift force generated by the blades relies on factors such as the angle of attack, air density, and the square of the wind velocity. The drag force is caused by the friction between the turbine blades and the air. It acts parallel to the direction of the wind flow and works against the rotation of the blades, reducing the turbine's efficiency. The drag force of the blades is determined by the product of the wind speed squared and the drag coefficient. To achieve optimal energy generation from a wind turbine, it is essential to strike a balance between the lift and drag forces. Ideally, the blade design should aim to maximize the lift force while minimizing the drag force. This can be achieved through careful considerations of the blade shape, angle of attack, and surface texture. (Amano & Sundén, 2014)

The pitch angle denotes the orientation of the blade relative to the plane of rotation. It establishes the angle of attack, which signifies the blade's alignment concerning the wind. The angle of attack is a pivotal and complex factor that fluctuates in a specific manner based on the wind speed and blade velocity.

In the mechanism controlling the pitch angle, the attack angle decreases when the pitch angle increases. The angle of attack is impacted by the velocity, flow factor, and rotational speed of the rotor. By taking into account, the angle of attack and the applied force on the blade, the characteristics of the two-dimensional airfoil are computed. In a wind turbine featuring variable speed, increasing the pitch angle results in a reduction of the angle of attack, lift force, and mechanical power output. Modifying the pitch angle allows for adjustments in both the magnitude and direction of the total force components. (Kulka, 2004b)

The work, represented by W, needed to displace an object from a state of rest over a distance S, utilizing a force F, is equal to the kinetic energy, denoted as E, of an object with mass m and velocity v when subjected to constant acceleration.

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

Based on the basic principles of momentum theory, we can utilize the following equations to represent the kinetic energy of an air mass with a mass m that is moving at a velocity v:

$$E = \frac{1}{2}mv^2 (Nm) \tag{3.2}$$

The determination of the volume, denoted as V, that moves across a defined cross-sectional area A can be established by the following equation;

$$V = vA \tag{3.3}$$

Where:

V - volume flow (m^3 / s),

v- velocity of air passing through A (m/s),

A - cross-sectional area (m^2).

$$M = \rho V = \rho vA \tag{3.4}$$

Where:

M - mass flow (kg / s),

ρ - air density kg / m^3

The rate of change of kinetic energy significantly impacts the power generated by the wind.

$$P = \frac{dE}{dt} = \frac{d(\frac{1}{2}mv^2)}{dt} = \frac{1}{2}\frac{dm}{dt}v^2 \tag{3.5}$$

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

$$\frac{dm}{dt} = \rho Av \tag{3.6}$$

We may determine how much energy passes through cross-sectional area A each second by substituting Equation 3.6 into 3.5. This energy has a power dimension.

$$P = \frac{1}{2}\rho v^3 A(W) \tag{3.7}$$

Regarding wind turbines:

$$P_{wind} = \frac{1}{2}\rho v_{wind}^{3} \pi R_{Rotor}^{2} \quad (3.8)$$

The purpose of the wind turbine is to convert the energy of the wind into mechanical torque. The power coefficient is characterized as the proportion between the power extracted from the rotor and the power contained within the wind.

$$C_p = \frac{P_m}{P_w}, \; C_p < 1 \quad (3.9)$$

The power coefficient, pitch angle, and tip-speed ratio are interrelated. The tip-speed ratio signifies the ratio of rotational speed to wind speed, whereas the pitch angle pertains to the angle of the turbine blade. The Betz limit establishes an upper limit for the power coefficient, representing the theoretical highest efficiency achievable by a wind turbine. The Betz limit is 59.3% and is achieved when the rotor extracts one-third of the power available in the wind. However, depending on a number of variables such the rotor design, wind speed, and tip speed ratio, real-world wind turbines often have driven power coefficients in the range of 30–50%. (Heier, 2014)

To maximize the electricity generation from the wind flow, it is necessary to configure the turbines to function at the ideal tip-speed ratio. Theoretically, a higher tip-speed ratio leads to improved efficiency in the generator's operation. Nonetheless, the existence of drag and tip loss can give rise to problems like vibration, noise, reduced rotor efficiency, and potentially turbine failure caused by excessive rotor speed. The calculation of the power coefficient involves the utilization of the tip-speed ratio and the pitch angle in the provided equation (Rashid et al., 2018).

$$C_p(\lambda, \theta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\theta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \quad (3.10)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \quad (3.11)$$

The coefficients remain constant:

$C_1 = 0.5176,\; C_2 = 116,\; C_3 = 0.4,\; C_4 = 5,\; C_5 = 21,\; C_6 = 0.0068.$

The highest possible value is achieved when C_p ($C_{p\max} = 0.48$) is attained for $\beta = \theta = 0$ *and* λ = 8.1.

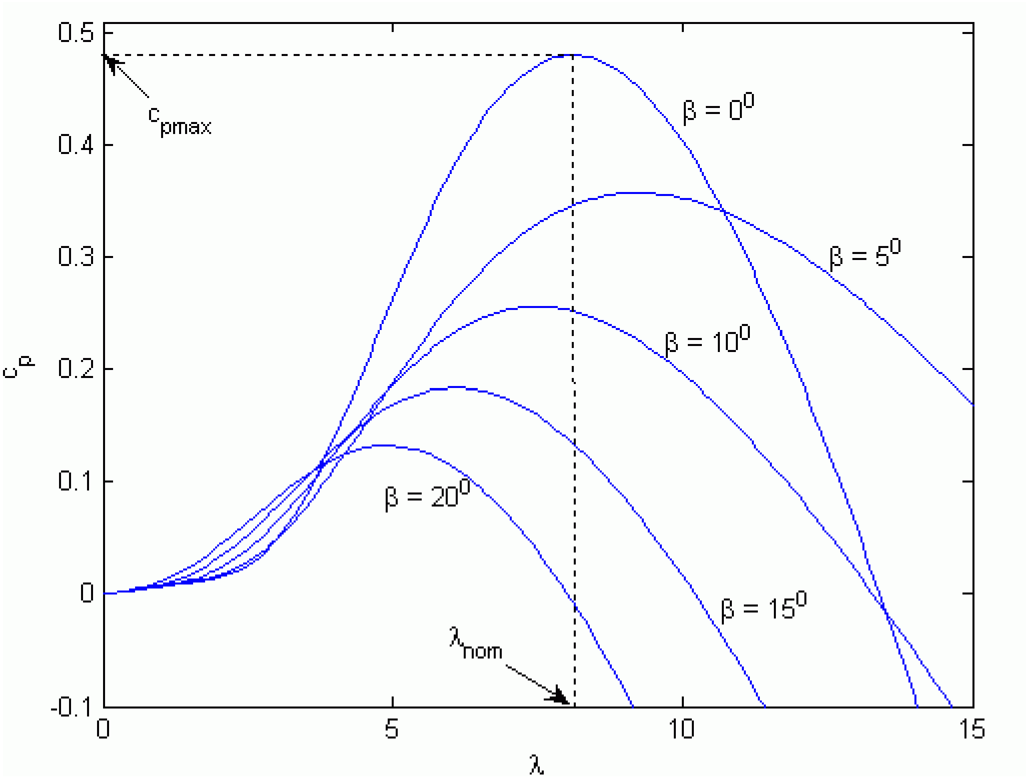

Figure 3.2 Power coefficient vs tip speed ration

The tip speed ratio provides further insights into the correlation between wind speed and rotor speed. These coefficients are determined by the pitch angle of the blades and the tip speed ratio.

$$\lambda = \frac{R\omega_r}{V_r} \tag{3.12}$$

Where:

R - blade length (m)

ω_r , - blade rotor angular speed (rad/s)

V_r - effective wind speed at the rotor plane (m/s).

The rotational speed yields the mechanical torque.

$$T_r = \frac{P_r}{\omega_r} \tag{3.13}$$

Where: $P_r = \frac{1}{2}\pi\rho R^2 V^3 C_p(\lambda,\theta)$

$$T_r = \frac{\frac{1}{2}\pi\rho R^2 V^3 C_p(\lambda,\theta)}{\omega_r} \tag{3.14}$$

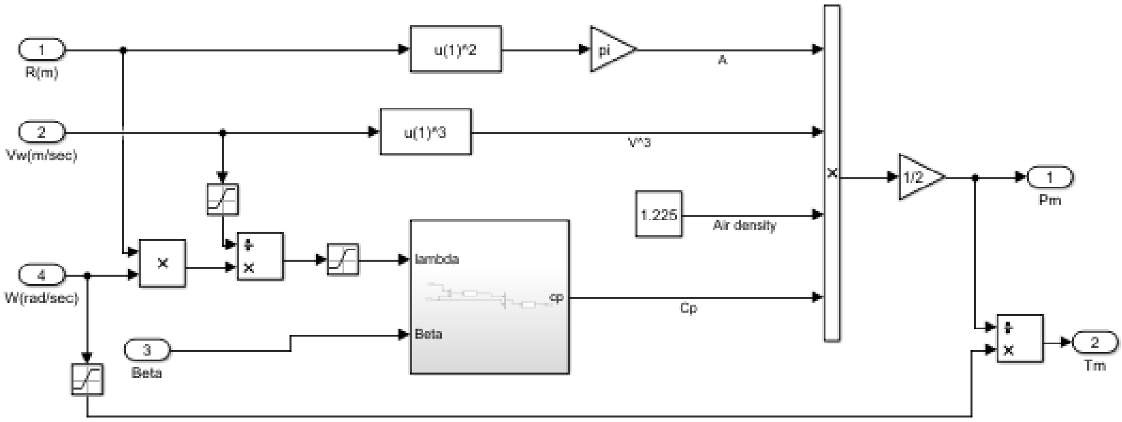

Figure 3.3 Simulink model of wind turbine

3.3.2 Drive train model

The drive train plays a vital role in wind turbines by transferring the mechanical energy generated by the rotating blades to the electrical generator. It encompasses various components such as the rotor, low-speed shaft, gearbox, high-speed shaft, generator, bearings, and couplings. The generator receives power from the rotor through a system involving two shafts and a gearbox. The rotor-side shaft, known as the LSS (Low-Speed Shaft), is flexible, while the generator-side shaft, referred to as the HSS (High-Speed Shaft), is rigid. In a state of equilibrium, the effect of this disparity is negligible, and thus,

$$\omega_r - \frac{\omega_g}{N_g} = 0$$

$$\phi_r - \frac{\phi_g}{N_g} = 0$$

Where:

N_g - gear ration

ϕ_r - angular position of the rotor shaft

ϕ_g - angular position of the generator shaft

However, in the temporary condition, those relationships are altered by the torsion that one of the drivetrain shafts experiences. The equations above have the form

$$\omega_r - \frac{\omega_g}{N_g} = \Delta\dot{\omega} \quad (3.15a)$$

$$\phi_r - \frac{\phi_g}{N_g} = \Delta\phi \quad (3.15b)$$

Where; $\Delta\phi \neq 0, \Delta\omega \neq 0, \Delta\omega = \Delta\dot{\phi}$

According to (Larsen & Mogensen, 2006) the equations that establish the relationship between those quantities are as follows.;

$$\dot{\omega}_r = \frac{P_r}{J_r \omega_r} - \frac{Ks}{J_r}\Delta\phi - \frac{Ds}{J_r}\omega_r + \frac{Ds}{J_r N_g}\omega_g \quad (3.16)$$

$$\dot{\omega}_g = -\frac{T_g}{J_g} + \frac{Ks}{J_g N_g}\Delta\phi + \frac{Ds}{J_g N_g}\omega_r + \frac{Ds}{J_g N_g^2}\omega_g \quad (3.17)$$

$$\Delta\dot{\phi} = \omega_r - \frac{\omega_g}{N_g} \quad (3.18)$$

Where, J_r is rotor inertia, J_g is generator inertia, K_s is drive train spring constant, D_s is drive train dampening constant, ω_r is speed of the rotor, ω_g is speed of the generator.

3.3.3 Pitch angle actuator model

The wind turbine's pitch angle refers to the adjustment or alignment of the rotor blades to enhance the turbine's effectiveness across varying wind conditions. When the wind speed surpasses the rated value, the pitch control system decreases the angle of attack and adjusts the blade orientation to deflect the wind. By manipulating the blade's pitch angle, the turbine can regulate the quantity of wind energy captured and converted into mechanical power. A wind turbine's pitch angle performs a variety of tasks, including power control, wind speed regulation, turbine protection, efficiency optimization, noise reduction, and easier start-up and shut-down procedures. Wind turbines can function effectively, safely, and adapt to variable wind conditions by modifying the pitch angle. Electric or hydraulic devices are employed as pitch actuators. According to (Thomsen, 2006) the dynamics of the system are represented by a simplified model that can be described using the following First-order linear model.

$$\dot{\theta} = -\frac{1}{\tau_\theta}\theta + \frac{1}{\tau_\theta}\theta_r \qquad (3.19)$$

Where:

θ_r - Pitch angle reference

θ - Pitch angle measurement

τ_θ - Time constant

3.3.4 Generator model

The generator plays a vital role in a wind turbine as it transforms the mechanical energy produced by the rotor blades into electrical energy, which can be harnessed or transmitted. In order to regulate the rotational speed and power generation of the wind turbine, an asynchronous generator is employed, capable of delivering the necessary torque. According to (Larsen & Mogensen, 2006), such a generator can be properly modeled by a simple first-order system,

$$\dot{T}_g = -\frac{1}{\tau_T}T_g + \frac{1}{\tau_T}T_{g,r} \qquad (3.20)$$

Where:

τ_T - time constant of the generator,

$T_{g,r}$ -reference value for the actuator's output.

3.3.5 State space model

By consolidating all the preceding equations, the following set is obtained

$$\dot{\omega}_r = \frac{P_r}{J_r \omega_r} - \frac{Ks}{J_r} \Delta\phi - \frac{Ds}{J_r} \omega_r + \frac{Ds}{J_r N_g} \omega_g$$

$$\dot{\omega}_g = -\frac{T_g}{J_g} + \frac{Ks}{J_g N_g} \Delta\phi + \frac{Ds}{J_g N_g} \omega_r + \frac{Ds}{J_g N_g^2} \omega_g$$

$$\Delta\dot{\phi} = \omega_r - \frac{\omega_g}{N_g} \tag{3.21}$$

$$\dot{\theta} = -\frac{1}{\tau_\theta} \theta + \frac{1}{\tau_\theta} \theta_r$$

$$\dot{T}_g = -\frac{1}{\tau_T} T_g + \frac{1}{\tau_T} T_{g,r}$$

Defining the state and input vector as

$$x_1 = \omega_r,\ x_2 = \omega_g,\ \ x_3 = \Delta\phi,\ \ x_4 = \theta,\ \ x_5 = T_g$$

$$u_1 = \theta_r,\ u_2 = T_{g,r}$$

The given Equations (3.21) can be reformulated in the form of a state space representation.

$$\dot{x}_1 = \frac{T_r}{J_r} - \frac{Ds}{J_r} x_1 + \frac{Ds}{J_r N_g} x_2 - \frac{Ks}{J_r} x_3 \tag{3.22}$$

$$\dot{x}_2 = \frac{Ds}{J_g N_g} x_1 + \frac{Ds}{J_g N_g^2} x_2 + \frac{Ks}{J_g N_g} x_3 - \frac{x_5}{J_g} \tag{3.23}$$

$$\dot{x}_3 = x_1 - \frac{x_2}{N_g} \tag{3.24}$$

$$\dot{x}_4 = -\frac{1}{\tau_\theta} x_4 + \frac{1}{\tau_\theta} u_1 \tag{3.25}$$

$$\dot{x}_5 = -\frac{1}{\tau_T} x_5 + \frac{1}{\tau_T} u_2 \tag{3.26}$$

3.4 Controller Design

To ensure system stability and optimal performance, it is crucial to design the controller properly. The pitch angle controller employs an actuator to ensure the proper alignment of the rotor blade. The controller of the hydraulic or electrical actuator facilitates the transmission of the control signal or information. Various methods can be employed to manage systems that track maximum power points. One such approach is tip speed ratio control, which adjusts the rotational speed to achieve the desired tip speed ratio, thereby enhancing power output.

The controllers are designed such that they can operate in wind speeds above 14 m/s.

3.4.1 PI controller design

A Proportional-Integral (PI) controller is a widely used feedback control technique in diverse industrial applications. It combines proportional and integral control actions to enhance system performance and stability.

A PI controller's objective is to control a process variable (PV) to a desired setpoint (SP) by modifying a control variable (CV) in response to feedback data. The controller provides the necessary control action in an effort to reduce the error between the PV and SP.

The error between the PV and SP is precisely proportional to the proportional control action. The strength of this action and factors affecting the stability and response time of the controller are determined by the proportional gain (Kp).

The integral control action is directly proportional to the accumulation of the error over time. It assists in reducing the impact of disturbances or system biases and eliminating steady-state mistakes. The strength of the integral action and the controller's capacity to remove offset or bias are both influenced by the integral gain (Ki). Overshoot or instability can arise from a Ki value that is too high, while sluggish reaction or the inability to eliminate steady-state faults might result from a value that is too low.

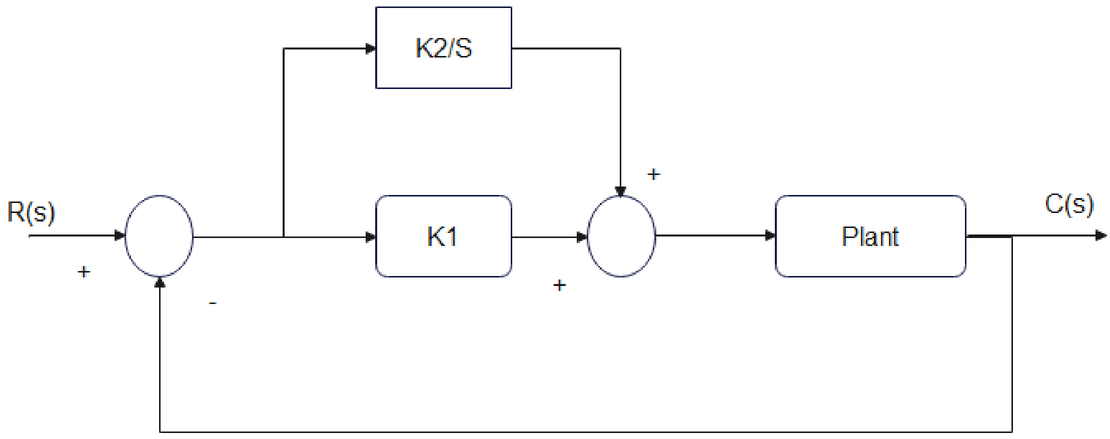

Figure 3.4 Block diagram of the PI controller

Where, k1=kp and k2=ki.

3.4.2 MPC design

3.4.2.1 Discretization

The calculated continuous time state space model is discretized because the buck converter duty ratio in this project is controlled by a discrete MPC. For this purpose, a discretization method known study as zero order hold (ZOH) is used.

The discrete system can be denoted as:

$$\begin{aligned} x(k+1) &= A_d x(k) + B_d \begin{bmatrix} u(k) \\ d \end{bmatrix} \\ x(k+1) &= A_d x(k) + B_{du} u(k) + B_{dd} d \end{aligned} \tag{3.27}$$

Where, $A_d = e^{A_c * T_s}$, $B_d = \int_0^{T_s} e^{A_c * \tau} B_c d\tau = \begin{bmatrix} B_{du} & B_{dd} \end{bmatrix}$

Hence, the output is also discretized as:

$$y(k) = C_d x(k) + D_d u(k) \tag{3.28}$$

Where, $C_d = C_c = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix}$, $D_d = D_c = \begin{bmatrix} 0 & 0 \end{bmatrix}$

A_C and B_C are continuous time state and input matrices, and they are explained in Appendix II.

From Equations (3.27) and (3.28), an augmented state space representation will be enhanced. It will be progressed used for MPC design. Suppose a novel state variable is defined as:

$$z(k) = \begin{bmatrix} \Delta x(k) \\ y(k) \end{bmatrix} \tag{3.29}$$

Using the new state variables vector, the state space expression is rewritten in the following equations.

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

$$
\begin{aligned}
y(k) &= C_d x(k) + D_d u(k) \\
y(k+1) &= C_d x(k+1) + D_d u(k+1) \\
y(k+1) - y(k) &= C_d (x(k+1) - x(k)) \\
y(k+1) &= y(k) + C_d A_d \Delta x(k) + C_d B_{du} \Delta u(k)
\end{aligned}
$$

In compact form, $\begin{bmatrix} \Delta x(k+1) \\ y(k+1) \end{bmatrix} = \begin{bmatrix} A_d & 0 \\ C_d A_d & 1 \end{bmatrix} \begin{bmatrix} \Delta x(k) \\ y(k) \end{bmatrix} + \begin{bmatrix} B_{du} \\ C_d B_{du} \end{bmatrix} \Delta u(k)$,

And using the new state,

$$z(k+1) = Az(k) + B\Delta u(k) \tag{3.30}$$

The output also can be written as:

$$y(k) = Cz(k) \tag{3.31}$$

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

Equation (3.30) gives a state variable that is molded by the previous states and the change of the control signal.

The control horizon (Nc) is defined as the number of parameters employed to establish the anticipated control trajectory. The future control trajectory can be represented as:

$\Delta u(k)$, $\Delta u(k+1)$, $\Delta u(k+2)$, ... $\Delta u(k+N_C)$

Another parameter is called prediction horizon, Np, defined as the length of the optimization window. The predicted states can be denoted as:

$z(k+1|k)$, $z(k+2|k)$, $z(k+3|k)$, ... $z(k+N_P|k)$

From the Equation (3.30), the states predicted for Np number of predictions are given by:

$$
\begin{aligned}
&z(k+1|k) = Az(k) + B\Delta u(k) \\
&z(k+2|k) = Az(k+1|k) + B\Delta u(k+1) \\
&z(k+3|k) = Az(k+2|k) + B\Delta u(k+2) \\
&. \\
&. \\
&z(k+N_P|k) = A^{N_P} z(k) + A^{N_P-1} B\Delta u(k) + A^{N_P-2} B\Delta u(k+1) + \ldots + A^{N_P-N_C} B\Delta u(k+N_C-1)
\end{aligned}
$$

And also, from Equation (3.31), the predicted outputs are shown below:

$$
\begin{aligned}
&y(k+1|k) = Cz(k+1|k)\\
&y(k+2|k) = Cz(k+2|k)\\
&y(k+3|k) = Cz(k+3|k)\\
&.\\
&.\\
&y(k+N_p|k) = Cz(k+N_p|k)
\end{aligned}
$$

In compact matrix form, the output, Y, can be written as:

$$Y = Ez(k) + F\Delta U \tag{3.32}$$

Where, $Y = \begin{bmatrix} y(k+1|k) \\ y(k+2|k) \\ \vdots \\ y(k+N_P|k) \end{bmatrix}$, $\Delta U = \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ \vdots \\ \Delta u(k+Nc-1) \end{bmatrix}$

$$E = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^{N_p} \end{bmatrix} \quad and \quad F = \begin{bmatrix} CB & 0 & \cdots & 0 \\ CAB & CB & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{N_P-1}B & CA^{N_P-2}B & \cdots & CA^{N_P-N_C}B \end{bmatrix}$$

3.4.2.2 Cost function and optimization

Given the knowledge of the final value, optimal control is implemented through fixed final state optimization to minimize the discrepancy between the set point value and the predicted state output. It can be written as:

$$J = \frac{1}{2}\int_0^\infty ((R_S - Y)^T Q(R_S - Y) + \Delta U^T R \Delta U)dt \tag{3.33}$$

Where, R_S is the desired speed (set point) and Y is a vector containing the NP number of output predictions. Q and R are the weighting matrices of the output error and input increment.

MPC is a type of controller in which various constraints can be applied for better control performance. In this project there are three constraints are defined:

i. Constrain on input control signal, u
ii. Constraint on the increment of the input signal, Δu
iii. Constraint on the output, y

The input constraint is bounded by a specific range established by the minimum and maximum values of the converter's duty ratio (that means $u_{\min}$ and $u_{\max}$, respectively). The predicted input signals can be expressed as:

$$
\begin{aligned}
&u(k) = u(k-1) + \Delta u(k) \\
&u(k+1) = u(k) + \Delta u(k+1) \\
&u(k+2) = u(k+1) + \Delta u(k+2) \\
&. \\
&. \\
&u(k+N_C-1) = u(k-1) + \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ \vdots \\ \Delta u(k+N_C-1) \end{bmatrix} \\
&u(k+N_C-1) = u(k-1) + \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \Delta U
\end{aligned}
$$

Let set constraint on the last predicted control signal and deriving an inequality constraint equation is shown below.

$$
\begin{aligned}
&u_{\min} \le u(k+N_C-1) \le u_{\max} \\
&u_{\min} \le u(k-1) + \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \Delta U \le u_{\max} \\
&u_{\min} - u(k-1) \le \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \Delta U \le u_{\max} - u(k-1) \\
&u_{\min} - u(k-1) \le \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \Delta U \\
&\begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \Delta U \le u_{\max} - u(k-1) \\
&-\begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \Delta U \le -u_{\min} + u(k-1)
\end{aligned}
$$

From the last two expressions, a compact form is written as:

$$M_1 * \Delta U \le N_1 \tag{3.34}$$

Where, $M_1 = \begin{bmatrix} -\begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \\ \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_C} \end{bmatrix}$, $N_1 = \begin{bmatrix} -u_{\min} + u(k-1) \\ u_{\max} - u(k-1) \end{bmatrix}$

The increment of the input signal, Δu, is taken to be in the range of $\Delta u_{\min}$ and $\Delta u_{\max}$. The restrictions starting with the first increment and continuing through the last one is described below.

$$\Delta u_{\min} \le \Delta u(k) \le \Delta u_{\max}$$
$$\Delta u_{\min} \le \Delta u(k+1) \le \Delta u_{\max}$$
$$\Delta u_{\min} \le \Delta u(k+2) \le \Delta u_{\max}$$
$$\Delta u_{\min} \le \Delta u(k+N_C-1) \le \Delta u_{\max}$$

These can be represented in a condensed matrix format as:

$$\begin{bmatrix} \Delta u_{\min} \\ \Delta u_{\min} \\ \vdots \\ \Delta u_{\min} \end{bmatrix}_{N_C \times 1} \le \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ \vdots \\ \Delta u(k+N_C-1) \end{bmatrix}_{N_C \times 1} \le \begin{bmatrix} \Delta u_{\max} \\ \Delta u_{\max} \\ \vdots \\ \Delta u_{\max} \end{bmatrix}_{N_C \times 1}$$

$$\Delta U_{\min} \le \Delta U \le \Delta U_{\max}$$
$$\Delta U_{\min} \le \Delta U \quad , \quad \Delta U \le \Delta U_{\max}$$
$$-\Delta U \le -\Delta U_{\min} \quad , \quad \Delta U \le \Delta U_{\max}$$

Where, $\Delta U_{\min} = \begin{bmatrix} \Delta u_{\min} \\ \Delta u_{\min} \\ \vdots \\ \Delta u_{\min} \end{bmatrix}_{N_C \times 1}$, $\Delta U_{\max} = \begin{bmatrix} \Delta u_{\max} \\ \Delta u_{\max} \\ \vdots \\ \Delta u_{\max} \end{bmatrix}_{N_C \times 1}$

Again, in simplified form,

$$M_2 * \Delta U \le N_2 \tag{3.35}$$

Where, $M_2 = \begin{bmatrix} -I_{N_C \times N_C} \\ I_{N_C \times N_C} \end{bmatrix}$, $N_2 = \begin{bmatrix} -\Delta U_{\min} \\ \Delta U_{\max} \end{bmatrix}$

Similarly, the output is set to be in between $Y_{\min}$ and $Y_{\max}$

$$Y_{\min} \le Y \le Y_{\max}$$

From equation (3.31)

$$Y_{\min} \le Ez(k) + F\Delta U \le Y_{\max}$$
$$Y_{\min} - Ez(k) \le F\Delta U \le Y_{\max} - Ez(k)$$
$$-F\Delta U \le -Y_{\min} + Ez(k) \quad , \quad F\Delta U \le Y_{\max} - Ez(k)$$

In compact simplified form,

$$M_3 * \Delta U \le N_3 \tag{3.36}$$

Where, $M_3 = \begin{bmatrix} -F \\ F \end{bmatrix}$, $N_3 = \begin{bmatrix} -Y_{\min} + Ez(k) \\ Y_{\max} - Ez(k) \end{bmatrix}$

The expressions refined in Equations (3.34), (3.35) and (3.36) are summarized in a single equation as:

$$M * \Delta U \le N \tag{3.37}$$

Where, $M = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}$, $N = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix}$

Due to constraints exist, the optimization problem becomes:

$$\min_{\Delta U} J = \frac{1}{2} \int_0^{\infty} ((R_S - Y)^T Q(R_S - Y) + \Delta U^T R \Delta U) dt \tag{3.38}$$

Such that, $M * \Delta U \le N$

Hence, Hamiltonian equation is required for optimization.

$$H = \frac{1}{2}(R_s - Y)^T Q(R_s - Y) + \frac{1}{2}\Delta U^T R \Delta U + \lambda^T (M * \Delta U - N) \tag{3.39}$$

R_s is the set point (the final speed of the motor). Since Y is determined in equation (3.35),

$$H = \frac{1}{2}(R_S - Ez(k) - F\Delta U)^T Q(R_S - Ez(k) - F\Delta U) + \frac{1}{2}\Delta U^T R \Delta U + \lambda^T (M * \Delta U - N)$$

The necessary conditions for optimization are

$$0 = \frac{\partial H}{\partial \Delta U} \quad , \quad 0 = \frac{\partial H}{\partial \lambda} \tag{3.40}$$

Using Equation (3.34),

$$\frac{\partial H}{\partial \Delta U} = F^T QF\Delta U - F^T Q(R_S - Ez(k)) + R\Delta U + M^T \lambda = 0$$

$$(F^T QF + R)\Delta U - F^T Q(R_S - Ez(k)) + M^T \lambda = 0$$

$$\frac{\partial H}{\partial \lambda} = M * \Delta U - N = 0$$
$$M * \Delta U = N$$
$$M^T M * \Delta U = M^T N$$
$$\Delta U = (M^T M)^{-1} M^T N$$

Since the constraint is inequality constraint, finding the optimal value of ΔU is difficult. So, a MATLAB built in function, quadprog, is used.

$$\Delta U = quadprog(\gamma, \beta, M, N) \qquad (3.41)$$

Where, $\gamma = F^T * Q * F + R$, $\beta = -F^T * Q * (R_S - E * x)$

ΔU is a matrix of size $N_c \times 1$ which consists optimal control signal values (in our context, the duty ratio of the converter). But MPC is optimization technique where the first value of ΔU is applied on the system to determine the dynamics of the system. Hence, the optimal control increment value that is applied is given by:

$$\Delta u(k) = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}_{1 \times Nc} \Delta U \qquad (3.42)$$

And the applied control is:

$$u(k) = u(k-1) + \Delta u(k) \qquad (3.43)$$

This optimal control signal is applied in equation (3.36) to find the new state values x(k+1). This process continues until desired set point is reached. For better optimization result, considering values of N_C and N_p is very crucial.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

In this chapter, the results and discussions of both the MPC controller and the PI controller are examined and presented. After studying mathematical model of the system, each element was subjected to modeling in order to evaluate the system and its respective outcomes. A simulation was conducted for a 5-MW wind power plant to validate the efficacy of the proposed strategy. Although efforts have been made to obtain correct control performance.

4.1 Wind speed

The wind speed varies across different ranges, spanning from 0 to 24m/s. The controller's efficacy is illustrated by the response to changes in wind speed within this wind model. As depicted in Figure 4.1, which showcases the operational range of a variable speed wind turbine, this range is typically divided into three regions: the Cut-in region, the Rated region, and the Cut-out region.

Cut –in- where the speed is too low for turbine, from 3m/s to 14m/s.

Rated region- This is the wind speed range within which the turbine operates optimally to generate power at its rated output, spanning from 14m/s to 24m/s.

Cut-out region: This refers to the zone where the wind speed exceeds the safe operational limits of the turbine, specifically surpassing 24m/s.

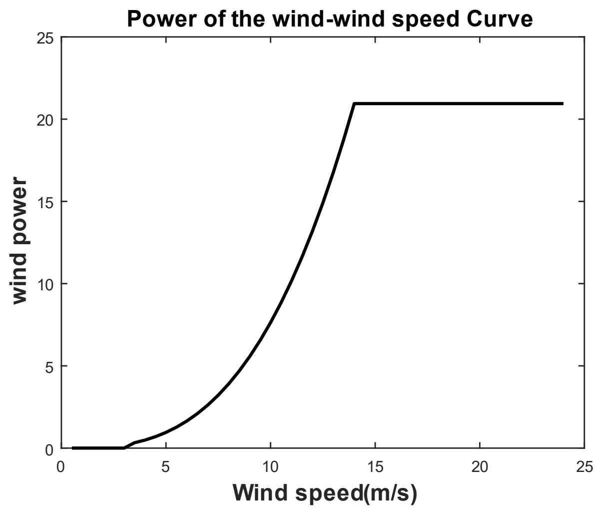

Figure 4.1 Wind Power Vs wind speed

The generated power of a wind turbine is directly proportional to the cube of the wind speed. This correlation between wind speed and the electrical power output is illustrated through the power curve. When wind speeds are low, the power output remains minimal due to insufficient wind energy. As the wind speed escalates, the turbine's power output also rises. However, there exists a threshold for the maximum power that can be harnessed from the wind, referred to as the rated power or the turbine's maximum power output.

4.2 Open loop response system

An open-loop system is one that does not feed the output back into the input for control purposes in control systems engineering. In other words, there is no feedback or mechanism for system adjustment. An open-loop system's response is completely based on its input and the features of the system itself. It does not take into account the actual output or the desired output.

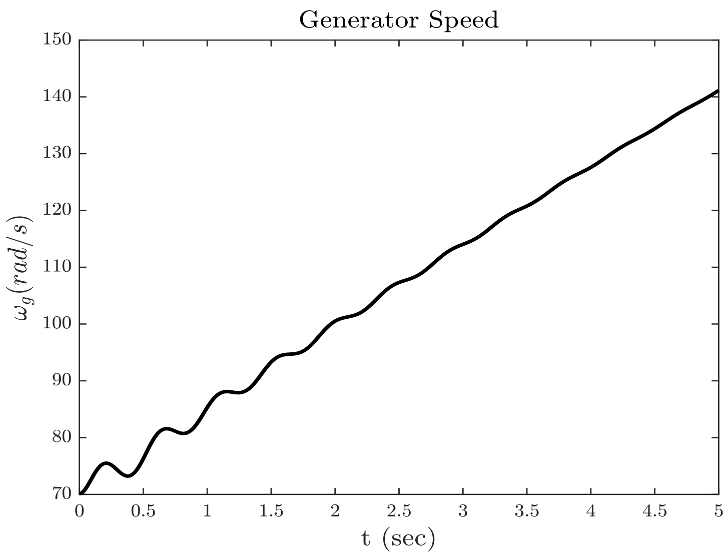

Figure 4.2 Open loop response of speed of the generator.

The behavior of the system is generally anticipated and adheres to a predetermined mathematical model or transfer function. Figure 4.2 illustrates the response of the generator's speed in an open-loop system. As the generator's velocity is determined by the multiplication of the gear ratio and rotor speed, an elevation in wind speed leads to a swift escalation in the generator's velocity. The reference value for the generator's speed is set at 122 rad/s to generate electrical power of 5 MW. The response indicates that the speed of the generator reaches 140 rad/s.

$$P_g = \omega_g * T_g \tag{4.1}$$

Where, P_g is generated power, ω_g is speed of the generator and T_g is Torque of the generator. When the speed of the wind is very high under uncontrolled condition the speed of the generator is increasing. That mean it is not fully loaded. With the increase in speed, the generator's torque exceeds the predetermined torque limit within the system.

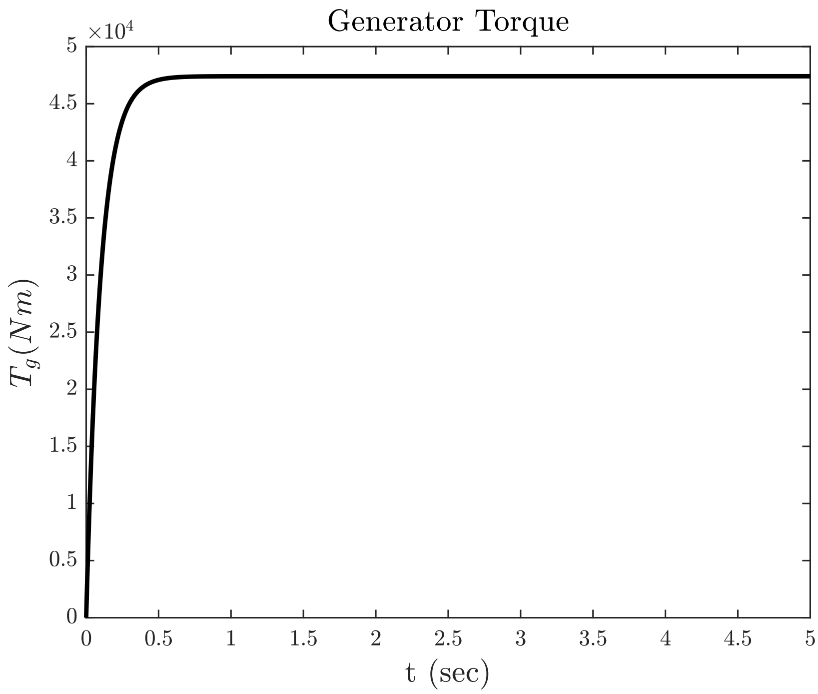

Figure 4.3 Open Loop response of torque of the generator.

The rated torque is 40983 Nm but under the open loop system the response shown that torque reached around 47402.97 Nm, that means it is above the rated value. Also speed of the generator is increasing up to 140 rad/s. At this point the output power will be around 6.6 MW. The power production of the turbine rises when the wind speed surpasses the rated threshold. When the wind reaches its rated speed, the power generation achieves the turbine's maximum capacity. If the wind speed continues to escalate, the power output will correspondingly increase. Hence, it is necessary to implement a control system to manage the power output and maintain it within the prescribed 5 MW threshold.

4.3 MPC results

The simulations provide evidence that the system is functioning correctly. A noticeable deviation in the reference tracking of electric power can be observed in the mid region. This deviation is primarily attributed to the emphasis placed on tracking the generator speed. In the mid region, the generated power is strongly correlated with the rotor rotational speed. When the blade pitch angle θ is at its optimal value (which remains fixed in this case), the ideal value of the tip speed ratio λ (calculated using a characteristic curve) should correspond to an optimal value of electric power (achieved through an optimal value of the power coefficient).

4.3.1 MPC optimized controller output

The desired or targeted outcome that is actively managed or governed by control mechanisms is referred to as the controlled output system. It shows the outcome or behavior of the system that is consciously managed to satisfy particular demands or objectives. The system's output is constantly monitored by the control loop, which also compares it to a desired reference point or set point and modifies the system's inputs or parameters to keep the output within the intended range. There are two controller output for this thesis work. These are theta reference and torque of the generator reference. The controller output-controlled generator outputs like speed of the generator, torque of the generator, and so on. The theta reference controlled the system at 0 radian.

Figure 4.4 illustrates the behavior of the pitch angle reference. The utmost pitch angle is 1.57 radian or 90 degrees, while the minimum pitch angle is -0.017 radian or -1 degree. The pitch angle reference controlled the system at 0 radian to produce the rated power as our controller objectives.

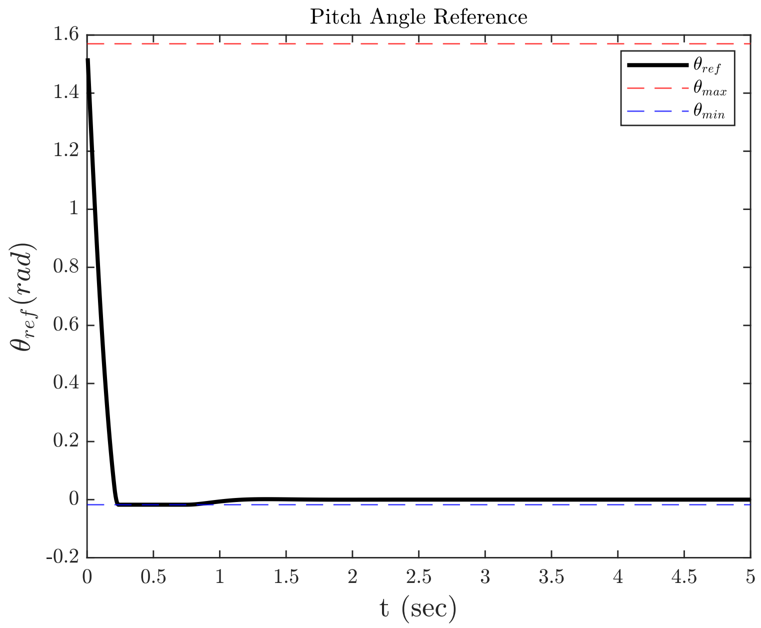

Figure 4.4 Response of controller output theta reference, MPC Controller

The second controller output is generator torque reference. The refence torque is 40983 Nm to produce the expected output power.

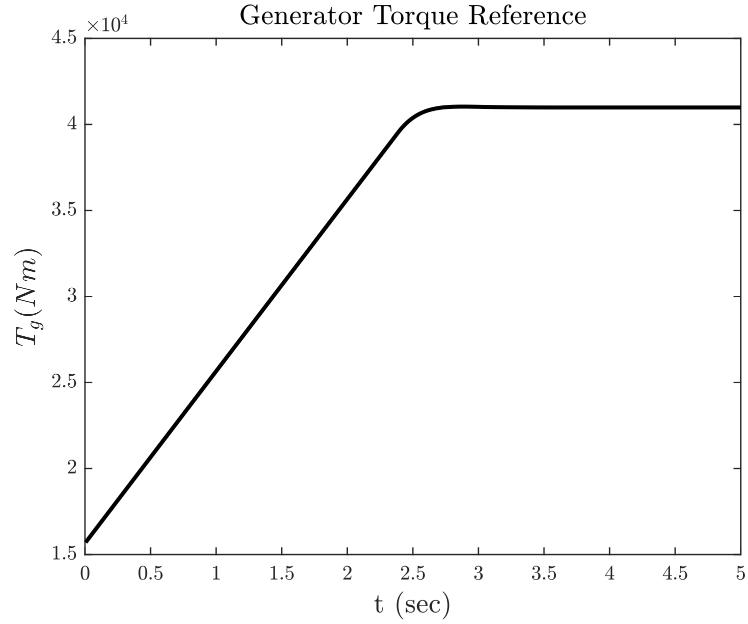

Figure 4.5 Response of the contoller output Torgue of the genererator reference, MPC controller

4.3.2 Speed of the generator response result

The PI controller exhibits a significant overshoot in the generator speed, reaching up to 140 rad/s. The system exhibits a comparatively low transient response. However, the steady state response is relatively smooth, reaching approximately 125 rad/s, which exceeds the rated value. This high generator speed can lead to power imbalance issues.

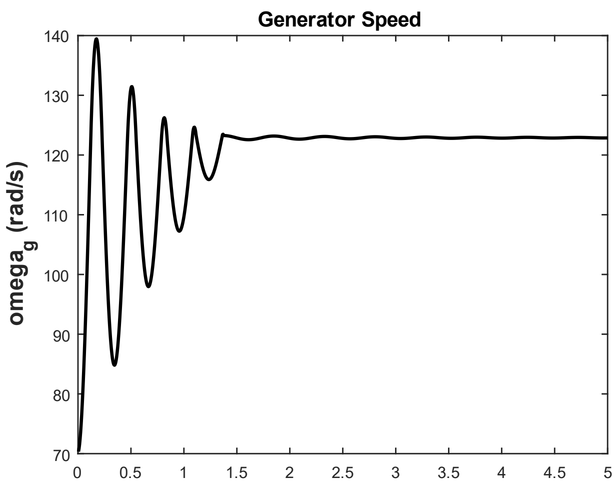

Figure 4.6 Response of generator's speed, PI controller

In the MPC controller, the generator operates at the rated speed of 122 rad/s. It starts initially at 70.0534 rad/s. The velocity of the generator is calculated by multiplying the rotor speed with the gear ratio.

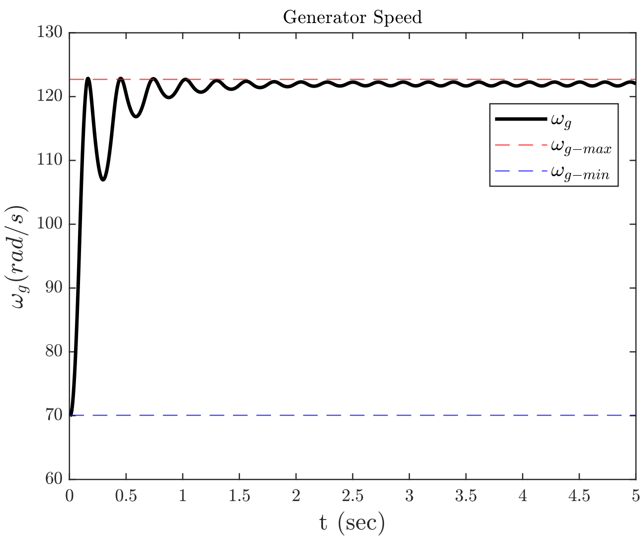

Figure 4.7 Response of speed of the generator, MPC controller

According to the results, the generator initially operated at a speed of 70.0534 rad/s, signifying the minimum velocity in the cut-in range. Conversely, the rated speed of the generator is documented as 122 rad/s.

4.3.3 Torque of the generator response result

Torque of the generator at rated is 40983 Nm, to produce 5 MW power.

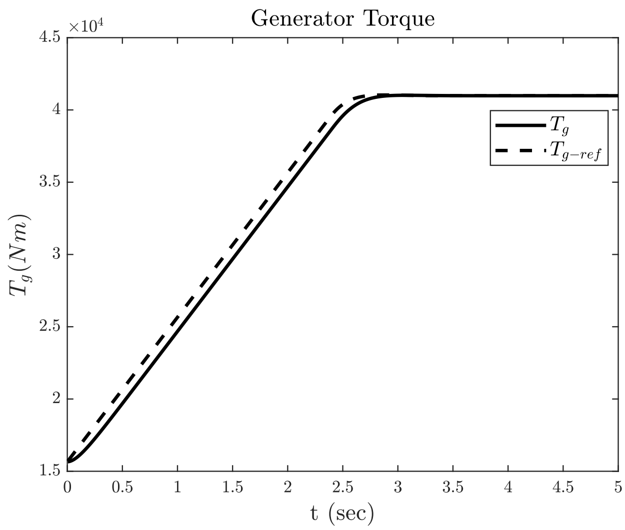

Figure 4.8 Response of torque of the generator related to torque reference, MPC controller

The result shown that torque of the generator output reaches the torque of the reference rated.

4.3.4 Pitch angle response result

During extremely high wind speeds, the pitch angle maintains a constant value of 1.57 radians. Within the wind speed range from cut-in to rated speed, the pitch angle fluctuates between its minimum and maximum values. As the wind speed reaches the rated level, the pitch angle gradually approaches 0 radians.

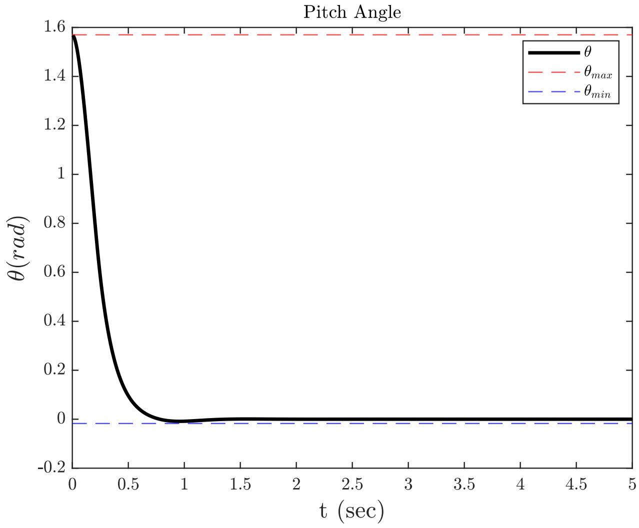

Figure 4.9 Response of pitch angle, MPC controller

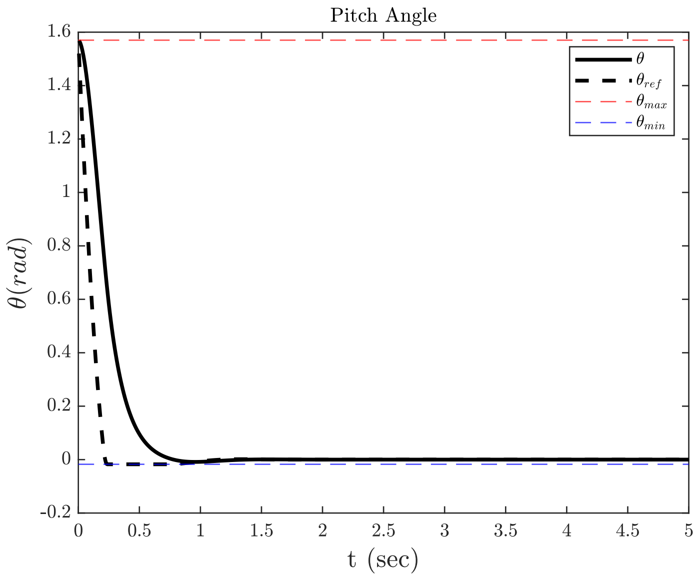

Figure 4.10 Response of pitch angle related to pitch angle reference, MPC controller

4.3.5 Generated power response result

The generated power is determined by the product of the generator speed and the generator torque. In the PI controller, the response shown that, it has the high oscillation between cut-in point to the rated point. Also, the settling max is 5.035 MW.

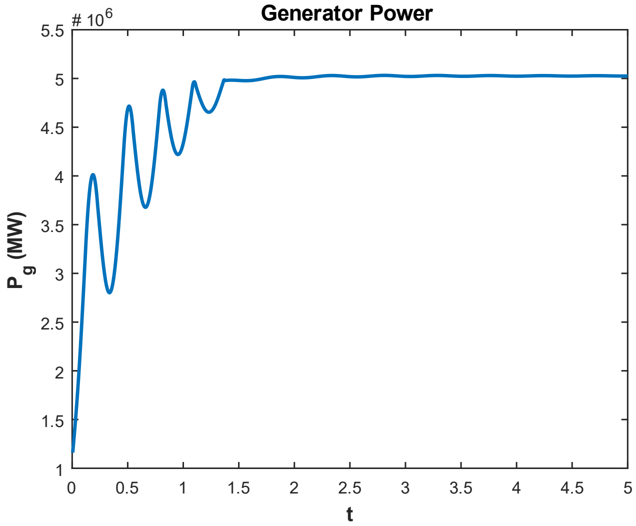

Figure 4.11 Response of the generated power, PI controller

In MPC controller, the generated power follow the torque of the generator and it has small oscillation in starting point. Also, the settling max is 5.0145 MW.

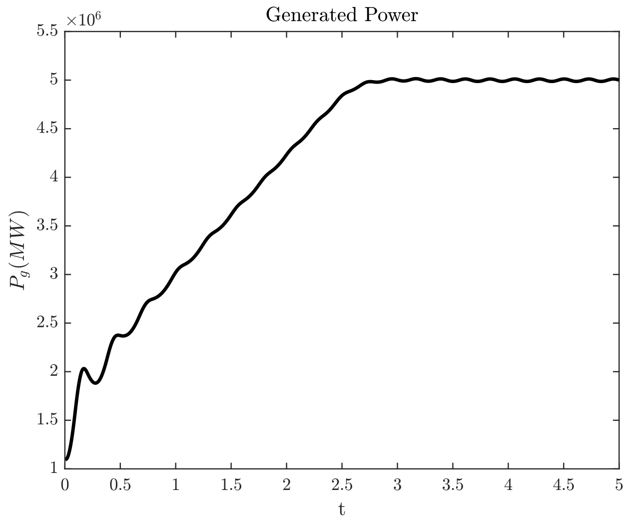

Figure 4.12 Response of the generated power, MPC controller

CHAPTER FIVE

5 CONCLUSION AND RECCOMANDATION

5.1 Conclusion

Even a slight disparity in wind speed can result in a substantial disparity in the output power of the wind turbine, owing to the cubic correlation between wind speed and power production. This, in turn, can result in the acceleration of the generator speed beyond its rated limit, causing system vibration, mechanical wear, and fatigue. The control method employed to govern the movement of the blades, referred to as pitch angle control, directly influences the aerodynamic forces. This research study investigates the utilization of Model Predictive Control (MPC) for pitch angle control. Various models representing different systems associated with wind turbines are presented, providing a comprehensive overview of the wind turbine pitch angle control system using MPC.

In this research study, the essential components of an MPC-based pitch angle control system are examined, including the mathematical model, prediction horizon, control objectives, and constraints. To ensure optimal turbine performance, a predetermined optimized value of 1.57 radians is assigned to the pitch angle for wind speeds below the rated speed. However, in the wind speed range between the cut-in and rated speed, adjustments to the pitch angle are necessary, taking into account the wind speed, to prevent mechanical overload and structural damage to the wind turbine. Once the wind speed reaches nominal levels, the pitch angle is maintained at 0 degrees.

The thesis work compares the output power controlled by a PI controller and an MPC controller. The highest overshoot in generator output power for the PI controller is 5.035 MW, which corresponds to a 0.70% increase above the rated speed. On the other hand, the highest overshoot in generator output power for the MPC controller is 5.0145 MW, indicating a 0.29% increase above the rated speed. Overall, the MPC controller demonstrates superior stability and performance in controlling the output power.

5.2 Recommendation

In addition to employing the MPC controller, further enhancements can be achieved by combining it with another controller. An additional area of potential future investigation involves examining and contrasting the output responses of different controller types, including adaptive controllers and robust controllers. To enhance power stability through pitch angle control, it is recommended to explore online training techniques, such as multilayer perceptron artificial neural networks. Additionally, efforts can be directed towards hardware implementation of the proposed technique, allowing for practical application and real-world testing.

Acknowledgements: This research thesis was founded by Adama Science and Technology University under the grant number ASTU/SM-R/719/23, Adama, Ethiopia.

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Appendix I

Table 1 NREL offshore 5-MW baseline wind turbine (Jonkman et al., 2009)

Parameter	Symbol	Units	Value
Nominal Power	P_e, nom	MW	5
Rated generator speed	$\omega_{g,\max}$	rad/s	122
Cut-in generator speed	$\omega_{g,\min}$	rad/s	70.0621
Drive train spring const.	K_s	$N.m/rad$	$867.637*10^6$
Drive train dampening const.	D_s	$N.m/(rad/s)$	$6.251*10^6$
Generator inertia (w.r.t. HSS)	J_g	$kg.m^2$	534.116
Rotor inertia (w.r.t. LSS)	J_r	$kg.m^2$	$3.8768*10^7$
Blade radius	R	m	63
Gear ration	N_g	-	97
Maximum blade pitch	$\theta_{\max}$	$radian$	1.57
Minimum blade pitch	$\theta_{\min}$	$radian$	-0.017
Maximum generator torque	$T_{g,\max}$	$N.m$	40983
Minimum generator torque	$T_{g,\min}$	$N.m$	0
Rho	ρ		1.225
Number of blade	-	-	3

```
% Wind speed Vs Power wind
clear all
% clc
vcin=3;
vnom=14;
vcout=24;
step=0.5;
v=step:step:24;
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=63;
    pi=3.14;
    A=pi*R^2;
    rho=1.225;
    P(index)=0.5*A*v2^3*rho;
    index=index+1;
end
Prated=P(index-1);
for v3=vnom+step:step:vcout
    P(index)=Prated;
    index=index+1;
end
```

% **PI controller**

```
Clear all
rho=1.225;
R=63;
Ng=97;
Jr=3.8768e7;
Jg=534.116;
Ks=867.637e6;
Ds=6.215e6;
tau_theta = 0.15;
tau_T = 0.1;
kp1 = para(1); ki1 = para(2);
kp2 = para(3); ki2 = para(4);
R = 63;
wg_ref = 122; Tg_ref = 40980;
xm = [0.7222  70.05 0 1.57 1.5656e+04]';
Tg_set = 40980
buf = []; Pe = []; t = 0; h = 0.05; Y = []; Ys = [];
e1 = 0; z1 = 0; e2 = 0; z2 = 0; ee1 = 0; ee2 = 0;
theta_set = 0;
for i = 1:200
wr_ref = lambda_ref*v/R;
   wg_ref = wr_ref*Ng;
   e1 = Tg_set - xm(5);
   z1 = z1 + 0.5*h*(e1 + ee1); ee1 = e1;
   Tg_ref = kp1*e1 + ki1*z1;
   e2 = theta_set - xm(4);
   z2 = z2 + 0.5*h*(ee2 + e2); ee2 = e2;
   theta_ref = kp2*e2 + ki2*z2;
   if theta_ref < -0.0157
      theta_ref = -0.0157;
   elseif theta_ref > 1.57
      theta_ref = 1.57;
   end
```

```
    if Tg_ref < 0
        Tg_ref = 0;
    elseif Tg_ref > 47800
        Tg_ref = 47800;
    end
    ui = [theta_ref; Tg_ref];
    xm = RK4(@nonlin_model, t, xm, ui, h, v); t = t+h;
    if xm(2) >= 122.22
        xm(2) = 122.22;
    end
    Pg = xm(2)*xm(5);
    Pe = [Pe; t xm(2)*xm(5)];
    buf = [buf; t, xm' ui' Pg];
end
wr = buf(:, 2); wg = buf(:, 3); sigma = buf(:, 4); theta = buf(:, 5);
Tg = buf(:, 6); Pg = buf(:, 9); Tg_ref = buf(:, 8); t = buf(:, 1);
theta_ref = buf(:, 7);
figure(1)
subplot 321, plot(t, wr, 'k')
subplot 322, plot(t, wg)
subplot 323, plot(t, theta, 'k', t, theta_ref, 'k--')
subplot 324, plot(t, sigma)
subplot 325, plot(t, Tg, 'k', t, Tg_ref, 'k--')
subplot 326, plot(t, Pg)

function xdot = nonlin_model(t, x, u, para)
rho=1.225; R=63;
Ng=97;
v = para;
Jr=3.8768e7;
Jg=534.116;
Ks=867.637e6;
Ds=6.215e6;
tau_theta = 0.15;
```

```
tau_T = 0.1;

lambda=(x(1)*R)/v;
lambda_t=1/(1/(lambda^(-1) + 0.12*x(4)) - 0.035/((1.5*x(4))^3 + 1));
lambda_t=1/(1/(lambda + 0.08*x(4)) - 0.035/(x(4)^3 + 1));

Cp = @(lambda, lambda_t, theta) 0.5176*(116/lambda_t - 0.4*theta - 5)*exp(-
21/lambda_t)+0.0068*lambda;
Pr=0.5*rho*3.14*R^2*v^3*Cp(lambda, lambda_t, x(4));
xdot = zeros(5, 1);
xdot(1) = Pr/(Jr*x(1))-Ds/Jr*x(1)+Ds/(Jr*Ng)*x(2)-Ks/Jr*x(3);
xdot(2) = Ds/(Ng*Jg)*x(1)-Ds/(Ng^2*Jg)*x(2)+Ks/(Ng*Jg)*x(3)+1/Jg*x(5);
xdot(3) = 1*x(1)-1/Ng*x(2);
xdot(4) = -1/tau_theta*x(4)+1/tau_theta*u(1);
xdot(5) = -1/tau_T*x(5)+1/tau_T*u(2);
end
```

Appendix II

```
rho=1.225;
R=63;
Ng=97;
v=14;
Jr=3.8768e7;
Jg=534.116;
Ks=867.637e6;
Ds=6.215e6;
tau_theta = 0.15;
tau_T = 0.1;
Ac = [-1/tau_theta 0; 0 -1/tau_T];
Bc = [1/tau_theta 0; 0 1/tau_T];
Cc = [1 0; 0 1];
Dc = [0 0; 0 0];
% discretization
Ts = 0.005; t = 0;
[Ad Bd Cd Dd] = c2dm(Ac, Bc, Cc, Dc, Ts);
%% augmented system
A= [Ad zeros(size(Ad, 1), size(Cd, 1)); Cd*Ad eye(size(Cd, 1))]; B= [Bd; Cd*Bd];
C= [zeros(size(Cd, 1), size(Ad, 1)), eye(size(Cd, 1))]; D= 0;
Np = 10; Nc= 5;
[F, phi]= F_phi(A, B, C, Np, Nc);
ys = [0; 40983];
Rs= reshape(ys*ones(1, Np), 2*Np, 1);
phi'*phi; phi'*F;
rw = [1000; 1e5]; qw = [20; 1e3];

R = diag(reshape(rw*ones(1, Nc), 2*Nc, 1));
Q = diag(reshape(qw*ones(1, Np), 2*Np, 1));
E= phi'*Q*phi + R;
% constraints
deltaUmax = [0.05; 100]; deltaUmin = -deltaUmax;
u_max = [1.57; 47402.97]; u_min = [-0.0175; 1.5656e+04];
```

```
y_max = [1.57; 47402.97]; y_min = [-0.0175; 1.5656e+04];
M1 = [eye(2*Nc); -eye(2*Nc)];
beta1 = [reshape(deltaUmax*ones(1, Nc), 2*Nc, 1);
        reshape(-deltaUmin*ones(1, Nc), 2*Nc, 1)];
m2 = zeros(2*Nc);
for j = 1:Nc  % row number
        for i = 1:Nc  % coloumn number
                if i <= j
                        m2(2*j-1:2*j, 2*i-1:2*i) = eye(2);
                end
        end
end
M2 = [m2; -m2];
M3 = [phi; -phi];
M = [M1; M2; M3];
% initials
xi = [0.7222 70.0534 0 1.5700 1.5656e+04]';
xm = [1.57 1.5656e+04]'; y = Cd*xm;
u = [1.57; 1.5656e+04]; z = [zeros(2, 1); y]; xm_old = xm;
buf = []; Pe = []; t = 0; h = 0.005; u_old = 0; buf2 = [];
for i = 1:1000
        G = phi'*Q*(F*z - Rs);
        beta2 = [reshape((u_max-u)*ones(1, Nc), 2*Nc, 1);
                reshape((-u_min+u)*ones(1, Nc), 2*Nc, 1)];
        beta3 = [reshape(y_max*ones(1, Np), 2*Np, 1)-F*z;
                reshape(-y_min*ones(1, Np), 2*Np, 1)+F*z];
        beta = [beta1; beta2; beta3];
        deltaU = QPhild(E, G, M, beta);
        u = u + deltaU(1:2);
        xi = RK4(@non_model, t, xi, u,h); t = t+h;
        xm = xi(4:5, 1); y = xm;
        z = [xm-xm_old; y]; xm_old = xm; u_old = u;
        Pe = [Pe; t xi(2)*y(2)];
        buf = [buf; t, xm' u' deltaU(1:2)'];
        buf2 = [buf2; t xi'];
```

```
end
t = buf(:, 1); theta = buf(:, 2); Tg = buf(:, 3);
theta_ref = buf(:, 4); Tg_ref = buf(:, 5);
delta_thetaref = buf(:, 6); deltaTg_ref = buf(:, 7);
wg = buf2(:, 3);
Pe = Pe(:, 2);
plot(t, theta, 'k', t, theta_ref, 'k--', 'linewidth', 2), title 'Pitch Angle', hold on
ylabel('$\theta (rad)$','FontSize',14,'FontWeight','bold')
yline(1.57, 'r--'), yline(-0.0175, 'b--'), xlabel('t (sec)','FontSize',14,'FontWeight','bold')
legend '$\theta$' '$\theta_{ref}$' '$\theta_{max}$' '$\theta_{min}$'
figure(2)
plot(t, theta_ref, 'k', 'linewidth', 2), title 'Pitch Angle Reference', hold on
ylabel('$\theta_{ref} (rad)$','FontSize',14,'FontWeight','bold')
yline(1.57, 'r--'), yline(-0.0175, 'b--'), xlabel('t (sec)','FontSize',14,'FontWeight','bold')
legend '$\theta_{ref}$' '$\theta_{max}$' '$\theta_{min}$'
figure(3)
plot(t, theta, 'k', 'linewidth', 2), title 'Pitch Angle', hold on
ylabel('$\theta (rad)$','FontSize',14,'FontWeight','bold')
yline(1.57, 'r--'), yline(-0.0175, 'b--'), xlabel('t (sec)','FontSize',14,'FontWeight','bold')
legend '$\theta$' '$\theta_{max}$' '$\theta_{min}$'
figure(4)
subplot 221, stairs(t, wr), title '\omega_r'
subplot 222, stairs(t, Tg_ref), title 'Tg_{ref}'
subplot 223, stairs(t, deltawr), title '\Delta\omega_{g-ref}'
subplot 224, stairs(t, delta_Tg_ref), title '\DeltaT_{g-ref}'

function xdot = non_model(t, x, u)
rho=1.25; R=63;
Ng=97; %Ng=85;
V=14, Jr=3.8768e7; Jg=534.116;
Ks=867.637e6; Ds=6.215e6;
tau_theta = 0.15; tau_T = 0.1;
theta = x(4);
lambda=(x(1)*R)/v;
lambda_t=1/(1/(lambda^(-1) + 0.12*x(4)) - 0.035/((1.5*x(4))^3 + 1));
```

```
Cp = @(lambda_t, theta) 0.22*(116/lambda_t - 0.6*theta - 5)*exp(-12.5/lambda_t);
 Pr=0.5*rho*R^2*v^3*Cp(lambda_t, theta);
xdot = zeros(5, 1);
xdot(1) = Pr/(Jr*x(1))-Ds/Jr*x(1)+Ds/(Jr*Ng)*x(2)-Ks/Jr*x(3);
xdot(2) = Ds/(Ng*Jg)*x(1)-Ds/(Ng^2*Jg)*x(2)+Ks/(Ng*Jg)*x(3)-1/Jg*x(5);
xdot(3) = 1*x(1)-1/Ng*x(2);
xdot(4) = -1/tau_theta*x(4)+1/tau_theta*u(1);
xdot(5) = -1/tau_T*x(5)+1/tau_T*u(2);
end
```