PSO-Based Super-Twisting Sliding Mode Controller MPPT Algorithm Design for Pitch Angle Control of Wind Turbine Based PMSG

Oliyad Dribssa

A Thesis Submitted to

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

Sep, 2024

Adama, Ethiopia

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DECLARATION

I declare that this thesis entitled PSO-Based Super-Twisting Sliding Mode Controller MPPT algorithm design for Pitch Angle Control of Wind Turbine based PMSG is my own work and has not been submitted to any university for similar purpose. The references used in this proposal are duly recognized by proper citations.

_Oliyad Dribssa_____	_______________	__19/09/2024_________
Name of student	Signature	Date

RECOMMENDATION OF ADVISOR

I, the advisor of this Thesis, hereby certify that I have closely advised the student while developing this thesis and read the draft thesis entitled "PSO-Based Super-Twisting Sliding Mode Controller MPPT Algorithm design for Pitch Angle Control of Wind Turbine based PMSG'' prepared under my guidance by Oliyad Dribssa. Therefore, I recommend the submission of the thesis to the department for further review and evaluation.

01-Sept. 2024
Tefera Terefe Y. (PhD)
Associate Prof., ASTU, EPCE

Dr. Tefera Terefe		19/09/2024
Advisor	Signature	Date

APPROVAL SHEET

I here certify that the recommendation and suggestion given by the thesis review committee are appropriately incorporated into the final thesis PSO-Super-Twisting Sliding Mode Controller MPPT Algorithm design for Pitch Angle Control of Wind Turbine based PMSG by Oliyad Dribssa.

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Dr. Tefera Terefe__	_______________	____19/09/2024_________
Advisor	Signature	Date

APPROVAL OF BOARD OF REVIEWERS

We, the under signed, members of the Board of Reviewers of the proposal open defense by Oliyad Dribssa have read and evaluated the thesis PSO-Based Super-Twisting Sliding Mode Controller MPPT Algorithm design for Pitch Angle Control of Wind Turbine based PMSG and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Masters of Science in control system engineering.

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

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Office of Postgraduate Studies, Dean	Signature	

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Oliyad Dribssa

Table of Contents

LIST OF FIGURES

APPENDICES FIGURES

LIST OF TABLES

APPENDICES TABLES

LIST OF ABBREVIATION AND ACRONYMS

DFIG	Double Fed Induction Generator
FLC	Fuzzy Logic Controller
HAWTs	Horizontal Axis Wind Turbines
IAE	Integral Absolute Error
MPC	Model Predictive Controller
MPPT	Maximum Power Point Tracking
PA	Pitch Actuator
PI	Proportional Integral
PID	Proportional Integral Derivatives
PMSG	Permanent Magnet Synchronous Generator
PSO	Particle Swarm Optimization
PAC	Pitch Angle Controller
SG	Synchronous Generator
SMC	Sliding Mode Controller
ST	Supper Twisting
STA	Super Twisting Algorithm
STSMC	Super-Twisting Sliding Mode Controller
TSR	Tip Speed Ratio
VAWT	Vertical Axis Wind Turbine
VSWT	Variable Speed Wind Turbine
WECS	Wind Energy Conversion System
WRSG	Wound Rotor Squirrel Cage Generator
WT	Wind turbine

LIST OF SYMBOLS

$C_p(\lambda,\beta)$	Conversion coefficient of power from wind to mechanical power
$C_{p\,opt}$	Optimal conversion coefficient of power
P_m	Mechanical Power
P_e	Electrical Power
λ	Tip Speed Ratio
β	Pitch Angle
T_m	mechanical torque
ω_m	Rotor or Mechanical Speed
$\omega_{m(opt)}$	Optimal Rotational Speed
$P_{m(\max)}$	Maximum Mechanical Power
λ_{opt}	Optimal Tip Speed Ratio
T_g	Generator Torque
T_d	Damping Torque
D_t	Damping Coefficient
ω_m	Rotor Or Mechanical Speed
J_t	Total Moment of Inertia
J_g	Generator Rotational Inertias
T_e	Electromagnetic Torque
$P_{m(max)}$	Maximum Mechanical Power
$T_{m(opt)}$	Optimal Mechanical Torque
β_D	Reference Pitch Demand Angle
τ_c	Time Constant of Pitch Actuator
$V_{ds,}$	Instantaneous Stator Voltage in d - axis
V_{qs}	Instantaneous Stator Voltage in q - axis

i_{ds}	Instantaneous Stator current in d - axis
i_{qs}	Instantaneous Stator current in q - axis
L_q	Inductances in q- Axis
L_d	Inductances in d- Axis
λ_m	Peak or Maximum Phase Flux Linkage

ABSTRUCT

Wind turbine system has gained significance in nearly all engineering domains due to the increased attention of researchers in this method. A wind turbine (WT) transfers kinetic energy from the wind into mechanical energy, which is subsequently utilized to create electricity. WT systems are highly nonlinear, unstable, and complicated, with frequent unpredictable wind speed fluctuations, which brings the challenging task in maintaining the power output of the WTs and the permanent Magnet Synchronous Generator (PMSG) output. To address those challenges, this thesis proposes a pitch angle control scheme based on the PMSG to regulate output power and maintains mechanical or rotor speed under variable speed WT. The imbalance of the power might cause deviation on the rotor speed from its nominal, thus maintaining the pitch angle by the deviation of actual rotor speed with its nominal will overcome these problems. Mathematical models of the system are analyzed and stability of the system is maintained using Lyapunov theorem. This thesis provides Super-Twisting Sliding mode controller (STSMC) designed to track the error between the rated and the actual rotor speed, it regulates mechanical power and rotor speed of WTs by adjusting the pitch angle using the actuator. The system also provides PI controllers to track maximum power point tracking (MPPT) by using the deviation of the mechanical speed fed to generator and the reference speed which keeps system at rated speed 1.5MW. The Particle swarm optimization (PSO) algorithms based for STSMC is applied, parameters of the STSMC are tuned using PSO and results satisfactory with the settling time of 0.3814 sec with undershoot of 1.942% and has overshoot of 19.880%. under constant speed. The dynamics model and controllers' system are implemented in MATLAB/Simulink environment. The performances of STSMC are conducted by comparing to conventional methods SMC and PID controllers under variable as well as constant wind speed. As a result, the proposed controller scheme verifies STSMC's superiority over the two controllers based on the response time of the system, has better convergence, less overshoot and settling time and robustness.

Keywords: *WECS, STSMC, MPPT, PMSG, pitch angle, optimization, VSWT*

CHAPTER ONE

1. INTRODUCTION

1.1 Background

In recent years, there has been growing concern about environmental pollution and the potential for an energy crisis. As a result, they are developing new technologies that use renewable energy sources. In addition to solar, hydropower, and tidal energy, wind power can be used as an environmentally beneficial energy source. To reduce the climate change's impact and rely less on fossil fuels, we need to increase use of wind energy. Wind energy becomes much more known in the last ten years, and it is now a serious competitor to traditional energy sources. Wind energy is becoming increasingly popular in power systems worldwide due to environmental and economic benefits. It is estimated that by 2020, "up to 12% of the world's electricity will be generated by wind power". (Chavero-Navarrete et al., 2019)

Ethiopia's government has a long-term aim to increase resource use by integrating independent power producers, the Transformation Plan (GTP) and National Growth outlines plans to build and connect 800MW of wind farms to the national grid within the next three to five years. The country's first wind facility's 51,000KW Adama I wind farm, which was built in 2011, and the second one is the 120MW Ashegoda wind farm, which launched in October 2013. Ethiopia's biggest wind farm, the 153-megawatt Adama II, opened in May 2015, providing the total 324MW of installed wind capacity. In this study Adama-I Wind Farm is focused because of it uses the permanent magnet synchronous generator to produce electricity, The farm's elevation spans between 1741 and 2173 meters. It comprises 34 turbines, each producing 1.5 MW, and has a nominal capacity of 51 MW. Ethiopia aims to expand its power system capacity in order to generate more renewable energy which result the demand for electrical energy will increase.(*Ethiopia Is Set to Become the Wind Capital of Africa*, n.d.)

Most researches in generation of wind power focus on synchronous or asynchronous machines. Because of its numerous advantages, the PMSG is the preferred type of synchronous generators. The benefits of PMSG, such as reduced size, cost, and maintenance requirements, they have been widely used and researched in most wind power systems (Derbel & Zhu, 2019).

Figure (1.1) below depicts the generator types, which shows that the classification of different types of generators. Most used generators on wind turbine systems are PMSG and DFIG. In this thesis PMSG will be employed in wind turbine due to it provides increased energy storage, high performance and reliability, self-excitation features, and straightforward reactive power control.

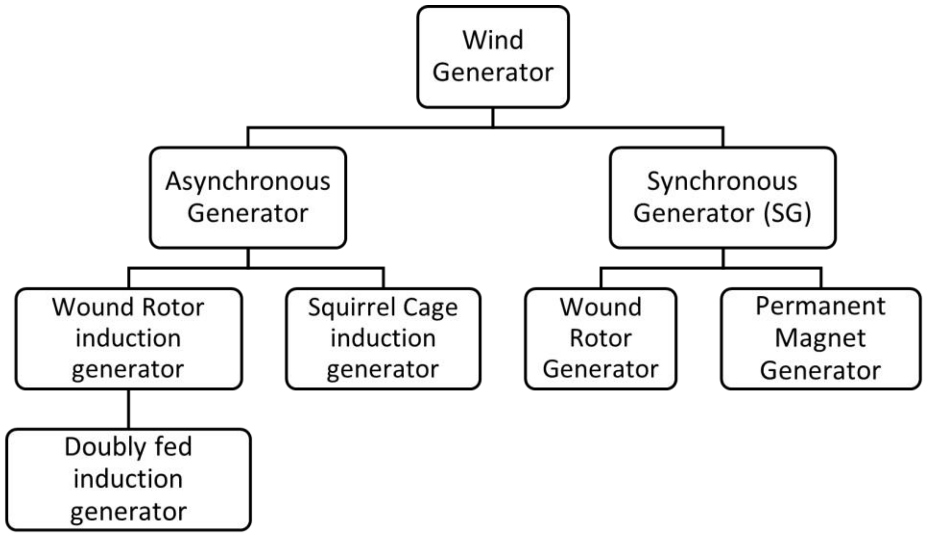


Figure 1.1 Generator classifications

An example of a WTs system in figure (1.2), Different parts of the entire system are highlighted and the important components of the turbine systems such as generator, blade, tower, gearbox, pitch, brake, nacelle, etc. (Chavero-Navarrete et al., 2019)

Currently wind turbine system is controlled using different control mechanisms and different controlled parameters of wind components. In this thesis controlling of the pitch angle is conducted where the control methods have crucial aspects of wind turbine operation, The WT's pitch angle adjusted to maximize power output while also stabilizing the turbine system. The primary purpose of pitch angle control (PAC) is adjusting power output. In high winds, increasing the pitch angle slows the turbine's rotation, preventing excessive power generation. In low winds, reducing the pitch angle allows the WT to extract more energy from the wind.

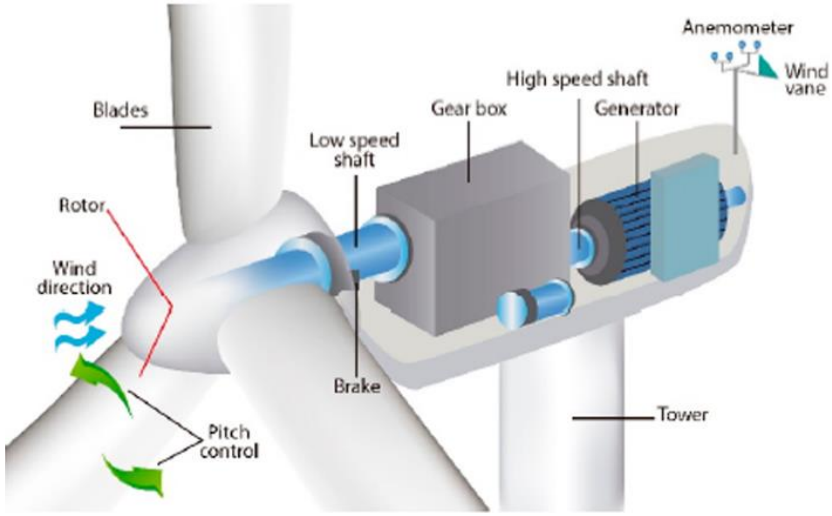


Figure 1.2 Schematic diagram of wind turbine (Chavero-Navarrete et al., 2019)

Also adjusting pitch angle will helps to manage the mechanical loads on the turbine, hence increasing the pitch angle can reduce forces on blades and decreasing angle of pitch can minimize the mechanical stress. Furthermore, pitch angle control has main effect to the stability of the system, by means of if a sudden fault or changes occurred to the turbine system or in to the grid adjusting the pitch angle can handle consistent power output can also increase the entire performance of the WT system.

WECS are highly nonlinear systems with significant disturbances and uncertainties. To meet their demanding control requirements, advanced approaches like backstepping, fractional order proportional-derivative, and predictive controls are necessary. Sliding mode controllers are a popular method in advanced control that advances the previously discussed control techniques. When compared to other complex control systems, SMC is a popular nonlinear robust control technique that's easy to design and implement. It's a prominent choice for controlling complex WECS. It is a well-liked as nonlinear robust technique with a relatively simple creation and execution process as compared to other complex control systems. A primary disadvantage is the chattering phenomenon, which involves high-frequency oscillations around the sliding surface. Most studies are focused on to develop strategies on the reduction of chattering effect using high order sliding mode control system. The best-known controller used by high order algorithms are “super-twisting method (ST)”, which is gaining popularity because of its ease of execution and effectiveness.”(Chen et al., n.d.)

Therefore, controlling pitch angle of PMSG based wind turbine requires careful control methods due to its complex dynamics, uncertainties, system stabilization. Conventional controllers like PID, PI and PD couldn’t able to overcome these problems. Supper-Twisting Sliding mode controller with optimization algorithms will adjust the reference pitch angle by taking the error and change of errors between the desired and the actual values of the power generated as an input. The detail analysis will be given within discussion in the coming chapters.

1.2 Statement of the Problem

Wind energy is a promising technology for sustainable global development due to its safety and environmental benefits. However, maintaining power stability and safe operation of wind turbines presents challenges due to wind energy’s nonlinear nature.

A blade rotation of wind turbine's causes a constant variation in wind speed in both upstream and downstream directions. Wind energy cannot be extracted sufficiently due to the variation characteristics of wind speed. Low wind speeds result in low power generation from wind turbines, requiring power optimization methods like MPPT. Wind speeds exceeding the rated speed can damage the wind turbine, cause unstable output, and lead to blade damage. To address these issues, pitch angle control system techniques should be implemented to vary actuator pitch angle in response to variations in wind speed. Given to its superior energy density, efficiency, and reliability, PMSG is chosen as the model for this system over double-feed induction generators (DFIG). Conventional control mechanisms such as PID could not perform better in nonlinear system, therefore to resolve these problems it needs to use non-linear controller. In this thesis Sliding mode controller integrated with Super Twisting algorithm is developed, which designs controller for the pitch angle to keep the system on safe mode and to stabilize the output power. To minimize the errors and provide optimal control performances, STSMC parameters tuned using PSO optimization techniques. Using this method controller could involve in reducing or eliminating the steady-state error to achieve more accurate output power, also it involves in achieving better robust stability and precise control of system stability.

The proposed controller and optimizations in this study aims controlling the pitch angle of WT, which maintain and stabilize power output, thereby preventing damage to the turbine caused by wind speed variations. Therefore, this study is presented to solve the above problem for wind turbine system.

1.3 Objectives

1.3.1 General Objectives

The general objective of this thesis is to design optimal Super-Twisting Sliding Mode Controller (STSMC) for pitch angle control of WT based PMSG employing in MATLAB/Simulink.

1.3.2 Specific Objectives

- Develop mathematical models of aerodynamic part of wind turbine with PMSG and variable speed.
- Design a STSMC for pitch angle of WT.
- Tune the STSMC parameters using PSO.
- Implement the overall system in MATLAB/Simulink environment and run (or simulate) the system.
- Test and verify the controller's such as (PID, SMC and STSMC) results of the study with MATLAB/Simulink.

1.4 Scope

This study's primary goal is mathematical modeling of WT, wind drive train and PMSG and develop a Sliding Mode Controller for pitch angle, which manipulate the mechanical power. The Supper Twisting algorithm used to reduce the chattering of the SMC. PSO Optimization techniques has been applied to meet specific parameter requirements and to enhance the output by reducing the system errors. To evaluate performance of the STSMC-based pitch angle control system by maintaining the rotor speed under a wide range of wind conditions, simulations are carried out with MATLAB/Simulink software. The simulation uses detailed models of wind turbine’s aerodynamics, mechanical dynamics of drive train, and electrical systems which provides a realistic assessment of STSMC’s capability.

1.5 Limitation

In order to show how this system's numerous components, interact, this thesis will only focus on mathematical system design and simulation using MATLAB/SIMULINK. This is because the system's real deployment is difficult due to the higher time and expense needed.

1.6 Significance

Wind turbine system operates in dynamic and uncertain environments because of wind speed variation, directions and other disturbances and the blade pitch angle plays essential role on obtaining the maximum available wind energy which can optimizes the power generation efficiency. PMSG based wind turbine systems display intricate nonlinear dynamics because of things like aerodynamic effects, mechanical couplings, and electromagnetic properties. SMC's robustness to external disruptions and parameter fluctuations is the reasons for its popularity in many applications, also it can respond more quickly and dynamically. However, sliding mode controller has a drawback on the chattering effect, to minimize this effect the super twisting algorithm will apply to the SMC. To obtain the optimal control performances optimization algorithms will be applied to the parameters of controller. Studying the optimal based Super Twisting Sliding mode controller (STSMC) can inherent with the ability to handle the uncertainties and robustness, is well-suited for pitch angle control in such tough conditions.

1.7 Motivation

The increasing need for energy has driven the development of pure energy through the use of renewable and alternative energy sources. The economic and practical potential of renewable energy has been thoroughly investigated for all types of renewable energy, including wind, geothermal, solar, biofuels, and hydroelectric power. Because of its performance and efficiency, the wind turbine sector has garnered more attention than other energy sources.

Wind turbines can become unstable during rapid increases in wind speed, which can lead to costly damage. This research focuses on overcoming the challenges related to pitch angle control, such as uncertainties in parameters, fluctuations in wind speed, and external disturbances, in order to strengthen system performance and reliability.

By employing STSMC approach, it develops a more responsive and adaptive pitch angle control system that can maximize power extraction, mitigate mechanical stresses and fatigue, even under highly variable and uncertain wind conditions. This research seeks to address the limits of conventional control and expand wind turbines operational envelope, ultimately contributing to the widespread adoption and cost-effectiveness wind power as a sustainable energy source.

1.8 Thesis Organization

This research work is structured as follow:

Chapter one: Background, problem statement, objectives, scope of the thesis, limitation, significance, and motivation are explained.

Chapter two: background of wind energy, PMSG and related work to this thesis are discussed.

Chapter three: materials and methods, system modeling and controller design, and particle swarm optimization PSO algorithm are presented.

Chapter four: result and discussion based on the proposed controller and comparison of the performances with other control performances.

Chapter five: Summarize the result, draws conclusions, and makes suggestions for additional research.

CHAPTER TWO

2. BASIC THEORIES AND RELATED WORK

2.1 Basic Theories

Wind energy conversion control system is a very attractive area for many researchers. Basically, wind turbine operates under four different operation regions. To perform the variety of tasks the proper combination of pitch actuators, generators and controller of the WT is mandatory techniques. Control of Pitch angle is a vital part of wind turbine operation since it directly effects power generation efficiency and stability. Several control systems have been proposed and implemented to regulate the pitch angle blades of wind turbines. Common technique includes PID control, backstepping control, fuzzy logic control (FLC), SMC, and model predictive control.

2.1.1 History of Wind turbines

The history of wind turbines (WT) spans several centuries, with the concept of harnessing wind energy for several purposes evolving over time, here there are some overviews of the history of wind turbines. The concept of a WT was originated around 200BC in Persia. Wind power has been used by ancient civilizations in various forms, such as sailboats and windmills, for tasks like pumping water, extracting oil, and grinding cereals. In 1887, the Scottish engineer James Blyth created a wind turbine to generate power in his lawn. Following to Blyth's establishing work, several invertors and engineers further developed the wind turbine technology. Charles F. Brush, an American inventor had built a large wind turbine in Cleveland, Ohio, in 1888. It had a diameter of 56 feet and powered his mansion's lighting system. Brush's designed incorporated a few key innovations such as, self-regulating mechanisms to control the turbine speed. (Gipe & Möllerström, 2022)

Wind turbine technology made significant advancements in the mid-20th century, including utilization in lightweight materials, an effective rotor design, and many control systems. The 1970s oil crisis and growing environmental concerns brought renewable energy, especially wind power, back into the spotlight. It drives the expansion of wind turbine installations and additional developments in grid integration, aerodynamics, and power conversion systems. (Winslow, 2017)

Nowadays, the modern wind turbines are typically large and multi-megawatt machines which can be found in wind farms. They have advances feature designs including horizontal-axis turbines with three blades, variable-speed generators, and intelligent control systems to maximize energy capture and ensures safe operations. Ongoing research and development activities aim to improve wind turbine technology by increasing efficiency, integrating wind power into existing energy systems, and minimizing costs.(Winslow, 2017)

2.1.2 Wind turbines

Wind turbine generates electricity by using wind energy, the main components of wind turbines are: generators, Towers, blades, rotor, yaw drives and motor. The wind turbine can be classified due to its structural view and based on the orientation of central axis such as: "Vertical axis wind turbines (VAWTs) and Horizontal axis wind turbines (HAWTs)".(Winslow, 2017)

- **Vertical axis wind turbines (VAWT)**

VAWTs considered as the oldest wind turbine, and it has two or three blades. It may have used reinforced wire (guy wires) to keep the structure standing. The gearbox and generator are typically positioned at the ground base of the tower support.(RAJENDRAN & JENA, 2015) . The VAWT operates only on the bottom where the wind speeds are minimum. This does not produce efficient electricity production. Furthermore, in case of high speed the output power cannot be easily controlled. (Md Maruf Billah & Motamed Ektesabi Nasser Hosseinzadeh, 2012a)

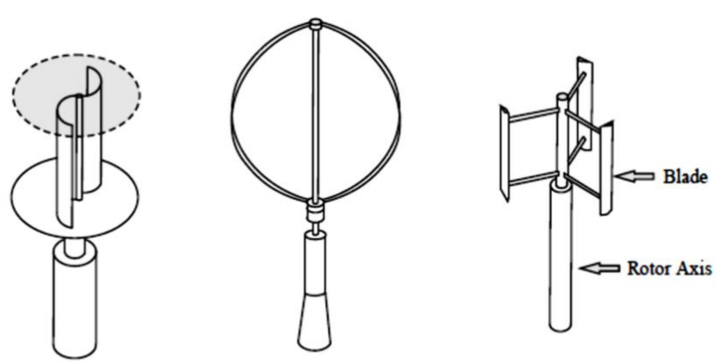


Figure 2.1 VSWTs Schematic Diagram(Adel Merabet et al., 2011)

Figure (2.1) shows that some schematic pictures of VAWTs with various types of rotors named as Savonius-Rotor, Darrieus-Rotor and H-type Rotor respectively.

The VAWTs has some advantages such as: it has easy maintenance; sufficient wind approaching from any direction will rotate the blade. It doesn't require mechanism of yaw control; used in lower urban area, rooftop, lower elevation etc. There are also some disadvantages since it has features complicated geometric shapes, installation, and very high angle change difficulties, which will reduce the output of the turbine. The average generated energy of VAWTs is small compared to HAWTs.(Winslow, 2017)

- **Horizontal axis wind turbines (HAWT)**

The **HAWT** power generation is mostly used wind turbines in current days. These turbines are almost mainly found on large wind farms, especially in Ethiopia. The rotating axis of HAWT is position horizontally along with ground. The rotation blades are on the horizontal axis where the wind direction and the blades rotate it same direction. It has two types: upwind machine and downwind machine type. It depends on the direction of wind approaching to the turbine, where if the wind comes in front side of the wind it is known as upwind. Whereas if the wind comes from the back side of the wind and the wind first reaches into the tower and then gets the blade, then it is called downwind type machine. (Md Maruf Billah & Motamed Ektesabi Nasser Hosseinzadeh, 2012a)

HAWT has high output power, high efficiency, more reliable, has high speed rotation, higher rate capacity, has better stability than the vertical axis wind turbine. However, it also has some drawbacks such as: Because of its great size, the system is difficult to install and for transportation. There are a few components of HAWTs, those are: Rotor system, Hub, Power train subsystem, Blades, Tower, and Foundation. Figure (2.2) shows that schematic diagram of the HAWT with components.

- **Rotor Blade:** Rotor blades are massive aerodynamic blades that draw energy from the wind. Typically, they are constructed of lightweight materials such as fiberglass or carbon fiber reinforced composite. It collects kinetic energy (KE) from the wind, and converts it into rotation.
- **Rotor Hub:** is the core component of a HAWT that joins turbine shaft and the rotor blades. It is a long, cylindrical component that connects the rotor hub with the gearbox. The

gearbox enhances the rotational speed of the main shaft and aids in the adjustment of the generator's rotational speed to maximize energy production.

- **Generators:** the generator also the main components of the HAWTs which converts the mechanical energy from the rotating shaft in to electrical energy. Usually it uses three-phase generator either asynchronous or synchronous generator.
- **Nacelle:** is a housing structure which shelter the gearbox, generator and other components. It is on top of the WT tower.; it rotates to face wind for a maximum energy capture.
- **Tower:** The tower is one of the components of the HAWTs which provides a structural support which assists the rotor hub and the nacelle and elevates the turbine to higher altitudes where the wind speeds are generally stronger and more consistent. Tower designs can vary in many ways, but they are usually tubular steel or concrete structures.
- **Yaw System:** is also components of HAWTs that permits rotor and nacelle to rotate horizontally to face the wind direction and controlled by a yaw driver and uses various sensors which detects the wind direction.
- **Foundation:** is the main frame that supports the entire WT and designed to provide stability and bases to endure the forces exerted by the wind and ensures the turbine remains straight-up. Figure shown below shows that the schematic diagram of the HAWT and its components.

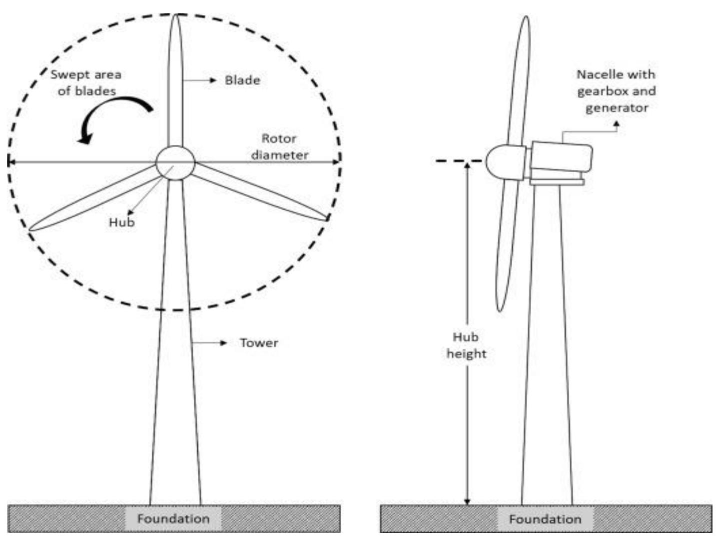


Figure 2.2 HAWTs schematic diagram (Elbeji et al., 2014)

Wind turbine system can also classify as fixed speed and variable speed depending on their operation mechanisms.

- **Fixed speed wind turbine (FSWT)**

FSWT maintains a constant rotational speed throughout its operation, and turbine's rotor is designed to keep this speed consistent, even if wind speed changes. If the wind speed is below the turbine's rated speed, the turbine will not rotate. For higher wind speeds, the turbine's rotational speed will be reduced to match the fixed speed.

- **Variable speed wind turbine (VSWT)**

A dynamic speed of WT system operates on VSWT adjusts the turbine blade rotation consistent with variability of wind speed. The area in which the region of the speed become high and low is where the variable speed turbine operated. VSWT offer several advantages over FSWT, including higher energy production, better conversion efficiency, less stress of component, and minimal power fluctuations. VSWT adjusts output power and torque parameters dependent on wind speed circumstances. "Torque control is used in low wind speeds, while pitch angle control is used for wind speeds exceeding the rated speed, thus blade pitch angle control method regulates output power.". (Md Maruf Billah & Motamed Ektesabi Nasser Hosseinzadeh, 2012) Here in this thesis the pitch angle control system is employed within the VSWT, to regulate rotation and power.

2.1.3 VSWT Operation Area

Based on the parameter specifications provided in this thesis work, WT operates as depicted in figure (2.3) and is split in to four zones.

Region I (Parking mode): first region (parking mode) is the region having a speed less than cut-in (3m/s). For economic purposes, it is not recommended for a WT to operate in the cut in WS. **Region II (3m/s-11m/s):** from the region of cut-in speed wind to rated speed. Power output increases as wind speed increases until it reaches rated value. This area's controllers are made to harness as much wind energy as feasible. This area's controllers are made to harness as much wind energy as feasible. This area's controllers are made to harness as much wind energy as feasible.

Region III: (Constant power region) (11m/s-25m/s): is a region between rated and cut-out WS. Pitch angle adjustment is crucial for maintaining constant generator torque and power output. To keep within the rated range, the turbine rotor must be turned away from strong winds. This is achieved by adjusting blade pitch angles while maintaining constant generator torque.

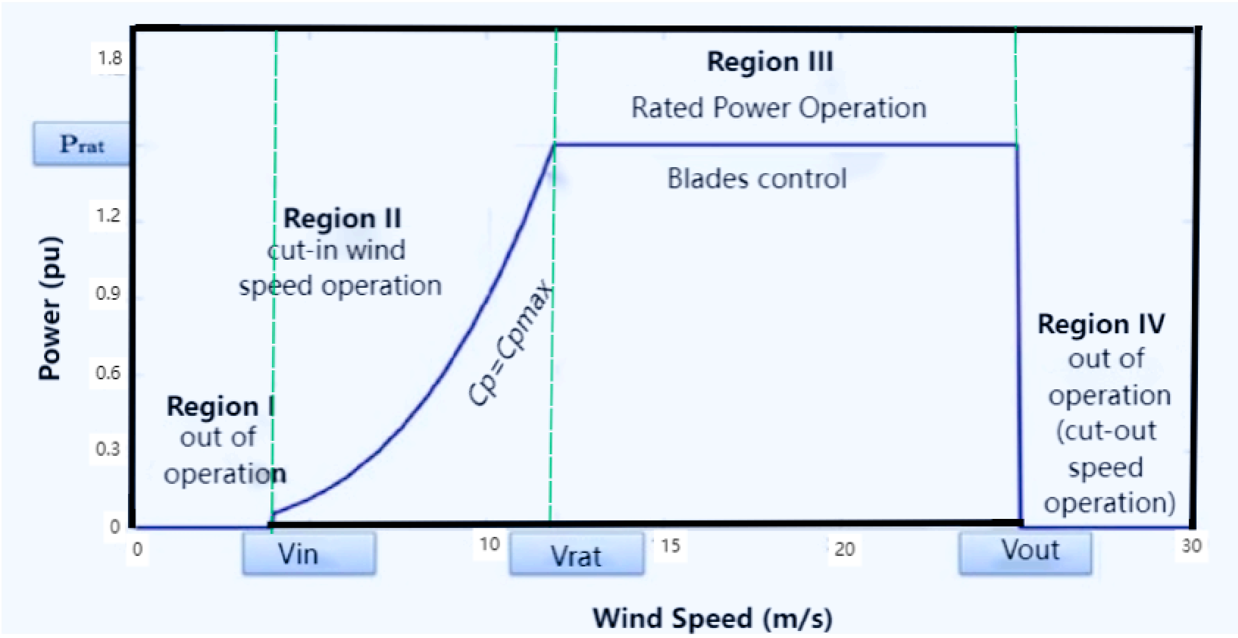


Figure 2.3 characteristics of output power and wind speed(Contreras et al., n.d.)

Region IV (>25 m/s) lies above the cut-out region, where WT is intended to shut down to prevent damage.

2.1.4 WECS Control Methods

WT systems are mostly built to achieve maximum power output at wind speeds around 12 m/s. In high WS, controller mechanism should be applied to the system unless it can cause damaging into the turbines. Most of wind turbine system are designed with power control mechanism which protects the turbine from destruction. There are three control mechanisms of WT to maintain the power performance and protect safety for the wind turbines those are: pitch control, stall control and active control.

❖ **Pitch Angle Control (PAC):** These methods involve adjusting the blade pitch angles to accommodate several WS and modifying the control system according to design requirements. PAC offer the benefits of maintaining output closer to rated power, lowering the load in high wind areas, and regulating rotational mechanical speed. When wind conditions return to normal, the blades are facing the wind again. Without a PAC, the WT may shut down if it reaches a predetermined speed. To protect the WT from damage, the blade pitch angle should be modified in response to wind speed. This blade PAC system is both effective and dominant. In this thesis, PAC method has been used to limit extracted wind power by the rotational mechanical speed of the generation, which allows it to operate at its rated speed.

- **Passive Stall control:** this control method uses the rotor blades at fixed at a constant angle to the hub. The blades are fixed in place and cannot be rotated around their axis. They are designed to automatically stop at higher wind speeds due to their aerodynamic shape, and their power input is kept close to its maximum rated value. Despite the fixed blade angle, the rotor blades are designed to generate turbulence on the back of the blades at high wind speeds, causing them to slow down, as a result the torque produced limits to its rated value. Regardless of the wind, the wind turbines' output frequency must remain constant.
- **Active control:** in this control approach combines PAC and passive stall control. The blades are adjusted in a similar way to a pitch-controlled turbine when the wind speed is low or moderate. In contrast to pitch-controlled turbines, the blades of passive stall turbines are spun a few degrees in the opposite direction, so power output does not decrease at greater speeds.

Generally, an expansion of the conventional PID, SMC will be used in this study, SMC can offer better performance and resilience in a variety of control applications, it has drawn attention recently. Wind turbine system naturally contain nonlinearities, disturbances, and uncertainties, these can be managed effectively by using SMC. Hence SMC has drawbacks on the chattering phenomena in the control signal around the sliding surface, it can cause high frequency oscillation. To minimize this effect super twisting algorithm will be conduct. STSMC is an improved version of SMC with faster transient response. improved robustness, and reduced chattering. Using PSO optimization techniques to control pitch angle in a PMSG wind turbine with STSMC can result in improved energy capture, improved tracking performance, robustness to wind variations, and adaptability to changing wind conditions, maximizing the turbine's energy production and performance. This study concentrated on the STSMC controller design for the system to stabilize the turbine system and track the maximum power extraction. Several previous works are reviewed and discussed in the next topic, with a gap obtained.

2.2 Related Work of Studies

In the work of (Maknunah et al., 2019) the “control system design of adaptive wind turbine pitch angle using PSO using the PID controller” has been proposed. To monitor pitch angle adjustment, a PID controller is used, and the best value conducted with PSO algorithm. The performance of a

PID controller was compared to PID controllers tuned using PSO and FLC. While the PID tuned with PSO produced a faster response, the gap of the study is it had a higher overshoot, causing the system's response to exceed the set-point value, which ultimately reduced the overall system performance.

(Pachauri et al., 2016) pitch angle controlling of WT using PI and FLC has proposed for the improvement of pitch angle WT and TSR. According to the paper conducts comparison between the FLC and PI controller, the results show that FLC outperforms a PI controller for controlling the tip speed ratio (TSR) of a WT. However, it has limitation has high overshoot, better performance can be achieved using other controllers.

In study of (Belounis & Labar, 2017) “fuzzy sliding mode controller (FLC) of DFIG for wind energy conversion system” has been proposed. This study model designed of a DFIG wind turbine and a hybrid fuzzy sliding mode (FSMC) based on vector control strategy (VCS). The paper indicates that the FSMC system demonstrated strong performance in reference tracking and was relatively insensitive to perturbations. The chattering effect has been minimized improved performance of the FSMC. The gab can be reduced system output will be maximizes using pitch angle control method using higher order algorithms with sliding mode controller

(Xin et al., n.d.) has proposed chattering Free SMC Pitch Control of PMSG WT, to improve dynamic performance in areas where power output is constant, the study proposes a free sliding mode variable structure pitch controller for wind turbines based on system dynamic model analysis. It achieved to reduce chattering a new support vector machine (SVM)-based reaching law is introduced. Despite these efforts, some chattering effects still persist. This gap can be minimized using another controller which can adapt with non-linearity.

In the work of (Iqbal et al., 2020) it proposes “a particle swarm optimization (PSO) for the pitch control system” of a WT. This study is based on conventional PID controllers for the pitch angle due to the nonlinear and uncertainty of WT systems. To address this, they develop a modified PSO algorithm that combines PSO with the fmin search optimization method to calculate the optimal parameters. The proposed technique is implemented and validated on a 5 MW WT model, the result shows improved power, speed, and torque regulation than conventional approaches. The performance will be maximized and minimized the settling time if another controller is applied.

In the study of (Adel Merabet et al., 2011) refers that a multivariable control strategy for VWSTs which focuses on the torque control design and PAC. The study demonstrates that zero speed-speed tracking error can be achieved by using a torque controller for wind speeds below and above the rated speed. The incorporation turbine torque and the pitch control estimation to provide robustness. PI controller is used with gain of Kp=100 and Ki=0 and the proposed control system results effective in the simulation. Hence in this research uses conventional control methods it couldn’t results satisfactory so we can increase using another controller and control methods.

In general, the literature examined in this part reviews and discussed the various controller methods and controls parameters to improve efficiency and the output power of WT. Many controller methods are used to improve wind turbine performance and efficiency. This thesis aims to design a controller that performs optimally by considering load characteristics, uncertainties, external disturbances, and the nonlinear nature of the WT. While many studies focus solely on maximizing power output from wind energy, this thesis aims to improve the robustness of the pitch angle control (PAC) system to wind speed variations and turbulent conditions.; by applying STSMC the transient response and the steady state responses will be analyzed; the mechanical or the rotor speed is used as reference to be controlled and maintain the system by controlling the errors with its actual rotor speed; control operations to modifies pitch angle for maximum power output via establishing an optimization problem that considers wind speed, wind direction, and other environmental parameters. This can lead to enhanced energy production and better overall turbine performance.

CHAPTER THREE

3. SYSTEM MODELING AND CONTROLLER DESIGN

3.1 Introduction

The methods, the system modeling of whole system will be discussed such as wind turbine, drive train and generator, the controllers design for the proposed dynamic model are explained in details. In this thesis PMSG has been used, Since the wind is variable in nature, there should be proper modeling of generator and WT. In this study the proposed controller carried out for pitch actuator, thereby adjusting pitch angle and maintains mechanical speed to achieve the objectives explained in previous. To have better performance parameters the optimization techniques are applied and the controller's parameters are tuned based on the fitness functions.

3.2 Methods

In this research the methods that has been used is shown below in figure, first the related work, research papers, and literatures is conducted regards to this thesis title. Then reviewing and analyzing different related study, dynamic models of the system intended from several perspectives. The required data sheet for overall system such as, wind turbine, generator data, and other specifications is gathered from the manufacturing company and from the different studies which had similar specifications to the Adama wind farm. The dynamic modeling of the WT, generator (PMSG), and pitch actuator is developed based on the data in different literatures. Based on developed model the controller design has been conducted for the PAC from the rotor of WT in which the mechanical speed is taken as fed for WT. Then based on mathematical models the proposed controller SMC, with Super Twisting algorithm (STSMC) and Proportional Integrative Derivative (PID) has been designed. The controller parameters were tuned using PSO optimization algorithms. The simulation is implemented using MATLAB/Simulink. Proposed work flow methods shown in Figure 3.1 below:

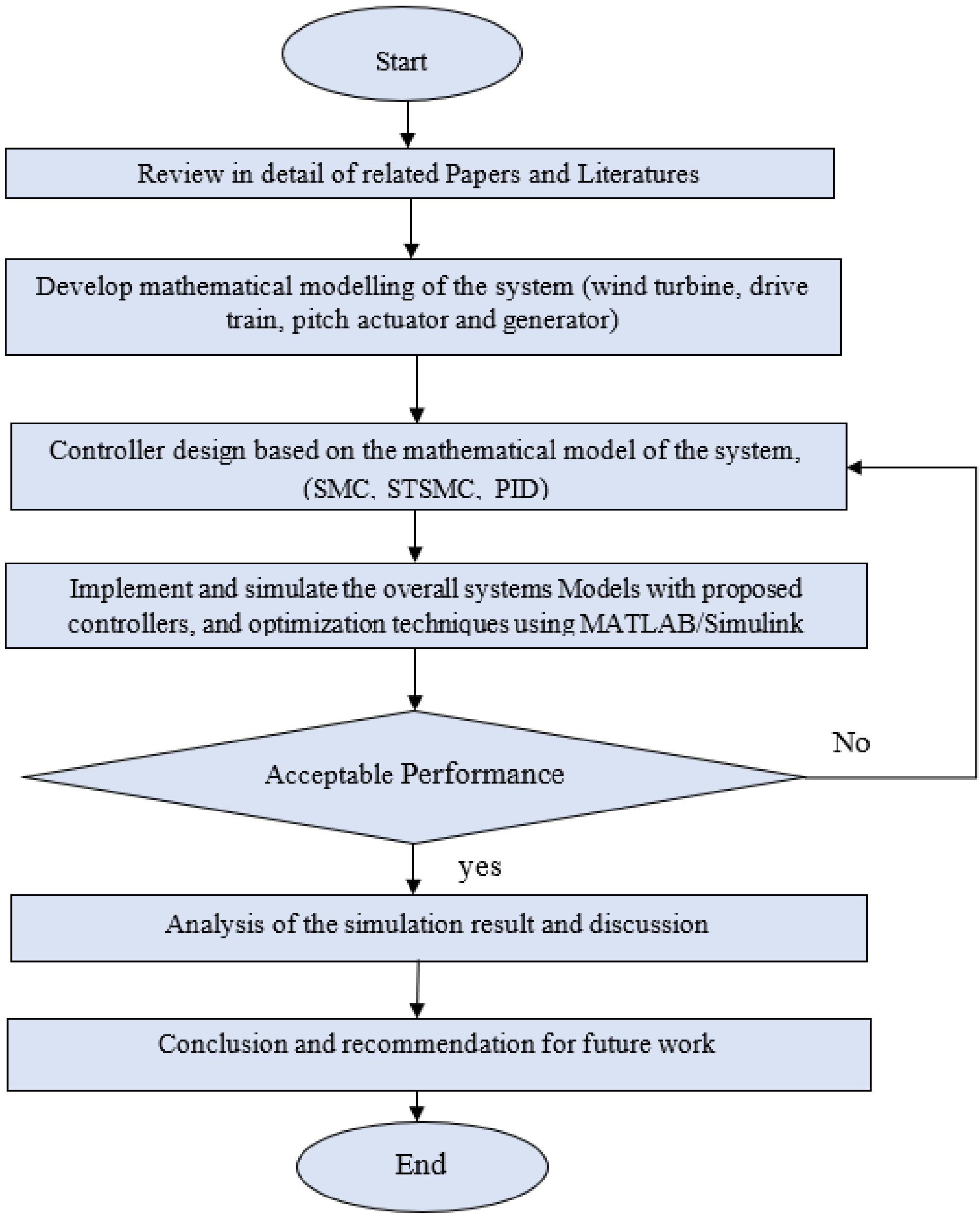


Figure 3.1 proposed methods

3.3 Mathematical Modeling of WECS

There are four primary components of WECS those are, the Aerodynamics or wind turbine blades, the actuator system, generator dynamics and the drive train. Hence the WECE model is determined mathematically by modeling the components. Since wind energy conversion systems differ greatly from conventional generators, integrating with power system will require addressing dynamic studies. Therefore, for many systems such as stability analysis, control system, dynamics system designing the dynamic model is required. As a result, the model of WECS will be determined mathematically by modeling each component shown in Figure 3.2.

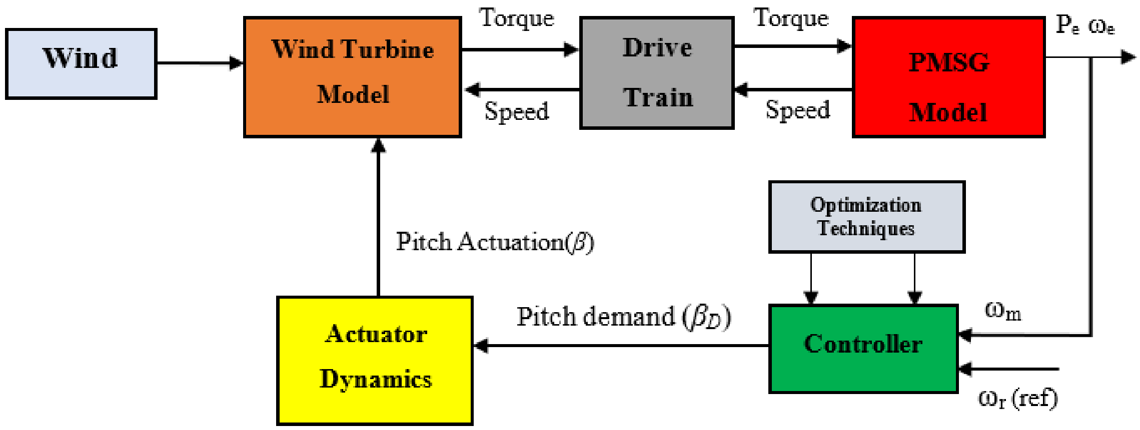


Figure 3.2 WECS block diagram

3.3.1 Wind Turbine Aerodynamics

Aerodynamics is the study of how air moves and the forces it exerts on objects moving through or stationary in the air. It is also the science of designing objects, like airfoils, to achieve desired responses from the air. Therefore, every component of the aircraft is converted for utilized force.(*Wind-Turbine Aerodynamics - Wikipedia*, n.d.)

Wind machines are devices that move in a straight path due to the force of the wind. The direction of the movement determines the type of force acting on it, which can be lift or drag. These forces are perpendicular to each other's which helps the wind turbine blade to rotate.(Wilson, 1980) The lift forces are the primary force which drives the rotation of the wind turbines blades. WTs use the pressure difference between the top and bottom of their blades to create lift, which makes them spin. However, there's also drag, which slows them down. Drag is caused by the pressure difference between the front and back of the blades and the friction between the blades and the air. Drag forces have a cantilever beam effect on the blade which causes the maximum stress at the joint between the blade and the hub, where it is connected to the main shaft of the turbine. (*Wind Turbine Blade Forces - Windmills Tech*, n.d.)

3.3.2 Wind Turbine Modeling

In this section the mathematical models of WT such as the mechanical power and the parameters which characterizes the wind turbines have been discussed in the following sections:

- **Mechanical Power of Wind Turbine**

Wind is the movement of air, which has mass and velocity. This movement creates kinetic energy, which rotates the rotor blades and the turbine shaft. This kinetic energy is then converted into mechanical energy. Flux developed by the synchronous generator will be cut by the rotation of the turbine shaft and then the mechanical energy will be transformed to the electrical energy.(Maknunah et al., 2019)

According to classical physics, kinetic energy (K.E) is the energy of an object in motion. It is equal to the work done (W) to move the object a distance (s) under a force (F). The equation for kinetic energy is:

$$K.E = W = F \times s \tag{3.1}$$

Based on Newton's second law of motion,

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

and inserting into the above equation.

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

Using solid motion of kinematics,

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

Assuming the initial velocity u=0 m/s, then

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

Substituting Equation (3.5) into Equation (3.3):

$$K.E = W = \frac{1}{2} mV^2 \tag{3.6}$$

The mechanical power is obtained as:

$$P = \frac{d(K.E)}{dt} = \frac{d}{dt}(\frac{1}{2} mV^2) = \frac{1}{2} \frac{dm}{dt} V^2 \tag{3.7}$$

Where, $\frac{dm}{dt}$: mass flow rate and it is given as:

$$\frac{dm}{dt} = \rho AV \tag{3.8}$$

Substituting Equation (3.8) into Equation (3.7) gives:

$$P = \frac{1}{2}\rho AV^3 = \frac{1}{2}\rho\pi r^2 V^3 \tag{3.9}$$

Where: ρ is air density, it expressed as:

$$\rho = \rho_o - 1.194 \times 10^{-4} H$$

$\rho_o = 1.225 kg/m^3$, is the density of the air at sea level at T = 298K.

A is a swept area by rotor blade measured in m^2. $A = \pi r^2$, r is the radius of the rotor.

and V is wind speed or velocity.

Equation (3.9) states that wind power is the total available energy per unit time. It is directly proportional to the cube of wind speed and the square of the rotor radius. This means that wind power increases significantly with higher wind speeds and larger rotor sizes. While small variations in wind speed and rotor radius can increase extracted wind power, it's important to note that not all the wind's kinetic energy is captured due to wind passing through the turbine blades. This results in energy loss. Therefore, a correction factor should be included in real-time applications to account for this inefficiency. “The theoretical optimum wind power utilization was first calculated by Betz in 1926, where he included a factor called power coefficient *Cp*, by extracting a fraction of power it will compensate this issue”.

- **Wind turbine model**

The wind speed passing through the rotor blade is assumed to be uniform V, with the value of upstream wind speed V_1 and downstream wind speed V_2 which is $V_2 < V_1$. from Equation (3.2) we have:

$$F = ma = m\frac{dV}{dt} = \frac{m}{dt}dV = \frac{m}{dt}(V_1 - V_2) \tag{3.10}$$

The mass flow rate is considered as constant $\frac{m}{dt} = \rho AV$

The difference between wind power of the upstream and downstream is the mechanical power P_m extracted by the rotor blades expressed as:

$$P_m = \frac{1}{2}\rho\pi r^2 V(V_a{}^2 - V_b{}^2) \tag{3.11}$$

These speed produces blade tip speed ratio (TSR), V is the average speeds of the turbine rotor blades, can be expressed as

$$V = \frac{1}{2}(V_a + V_b) \tag{3.12}$$

Where, V_a is the rotor blade inlet's upstream wind speed (wind speed = V)

V_b is the rotor blade exit's downstream wind speed

Substituting Equation (3.12) in to Equation (3.11), gives:

$$P_m = \frac{1}{2}\rho\pi r^2 (\frac{V_a + V_b}{2})(V_a{}^2 - V_b{}^2) \tag{3.13}$$

$$P_m = \frac{1}{2}\rho\pi r^2 ((\frac{V_a{}^3}{2} - \frac{V_a V_b{}^2}{2}) + (\frac{V_a{}^2 V_b}{2} - \frac{V_b{}^3}{2})) \tag{3.14}$$

Divide both halves by the upper wind $(V_a)^3$ and gives as:

$$\frac{P_m}{V_a{}^3} = \frac{1}{2}\rho\pi r^2 (\frac{1}{2} - \frac{\left(\frac{V_b}{V_a}\right)^2}{2} + \frac{\left(\frac{V_b}{V_a}\right)}{2} - \frac{\left(\frac{V_b}{V_a}\right)^3}{2}) \tag{3.15}$$

$$P_m = \frac{1}{2}\rho\pi r^2 V_a{}^3 \left[\frac{1 - \left(\frac{V_b}{V_a}\right)^2 + \left(\frac{V_b}{V_a}\right) - \left(\frac{V_b}{V_a}\right)^3}{2}\right] \tag{3.16}$$

From this equation power coefficient C_p can be determined as:

$$C_p = \frac{1 - \left(\frac{V_b}{V_a}\right)^2 + \left(\frac{V_b}{V_a}\right) - \left(\frac{V_b}{V_a}\right)^3}{2} \tag{3.17}$$

The TSR or (λ) can be defined as the ratio of blade tip speed and the wind speed, and expressed as:

$$\lambda = \frac{V_b}{V_a} \tag{3.18}$$

Substituting Equation (3.18) into Equation (3.17) using by the TSR and after simplifying the power coefficient gives:

$$C_p = \frac{1-\lambda^2+\lambda-\lambda^3}{2} = \frac{\left(1-\lambda^2\right)\left(1+\lambda\right)}{2} \tag{3.19}$$

The power coefficient C_p varies with the WT speed ratio λ, differentiating the C_p to lambda λ and equating zero will provides us the maximum power coefficient.

$$\frac{d(C_p)}{d\lambda} = \frac{d(\frac{1-\lambda^2+\lambda-\lambda^3}{2})}{d\lambda} = 0 \tag{3.20}$$

Solving the equation will gives, $\lambda_1 = -1$ or $\lambda_2 = \frac{1}{3}$ and substituting in place of λ in equation (3.19) gives:

$$\text{When } \lambda_1 = -1,\ C_p = \frac{\left(1-(-1)^2\right)\left(1+(-1)\right)}{2} = 0$$

$$\lambda_2 = \frac{1}{3},\ C_p = \frac{\left(1-(\frac{1}{3})^2\right)\left(1+(\frac{1}{3})\right)}{2} = \frac{16}{27} = 0.5926$$

The maximum or optimum value of power coefficient C_p can be found when $\lambda_2 = \frac{1}{3}$ which is approximately, $C_p = 0.593$.

According to Betz law, neglecting the mechanical loss and any other loss in a wind energy conversion system, the maximum mechanical power is used as:

$$P_{m\ \max} = \frac{1}{2}\rho\pi r^2 V^3 C_p = \frac{0.593}{2}\rho\pi r^2 V^3 \tag{3.21}$$

"If all losses are neglected the maximum wind power extracted is 59.3% of the actual total power of wind for a particular speed and the taking over a particular radius area", called the Betz limit, even though in real world the best designed wind turbine is below Betz's limit, mostly with Betz value ranging from 0.35 to 0.45.

"The aerodynamic power P captured by the wind turbine is expressed by the following relation":(Quanminnzhu, n.d.)

$$P_m = \frac{1}{2}\rho\pi r^2 C_p(\lambda,\beta) V^3 \tag{3.22}$$

Where: P_m is the mechanical power, C_p is power coefficient, V is wind speed, r is radius

The TSR λ can be expressed as the relationship between the wind speed V and rotor speed ω_m, it denotes as:

$$\lambda = \frac{V_t}{V} = \frac{r\omega_m}{V} \tag{3.23}$$

Where, ω_m is the rotor angular velocity, r is the rotor radius, V_t is the tip speed of the blade, V is the wind speed, and C_p is the power coefficient. The power factor coefficient C_p in WT expressed in equation 3.24 as function of TSR λ and the pitch angle β .(Rashid et al., 2018)

$$C_p(\lambda,\beta) = C_1(C_2\frac{1}{\lambda_i} - C_3\beta - C_4)e^{-C_5\frac{1}{\lambda_i}} + C_6\lambda \tag{3.24}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \quad 3.25)$$

Where C_1, C_2…C_6 are coefficients, in this thesis the value for the coefficients is [C_1, C_2, C_3, C_4, C_5, C_6] = [0.5654, 116, 0.4, 5, 21, 0.0068], λ_i is initial tip speed ratio (TSR), β is the pitch angle. TSR λ is expressed in equation (3.23).

After transforming wind energy into mechanical torque, a WT can be used to generate electricity. The mechanical power extracted from wind power can be determined by calculating the torque produced by the turbine. The power coefficient can also be expressed as the ratio of mechanical power to aerodynamic wind power, thus $C_p = \frac{P_m}{P}; C_p < 1$ (Rashid et al., 2018)

“The wind turbine's tip speed is determined by the rotor speed, radius, and wind speed, while the power coefficient is determined by the pitch angle and tip speed ratio”.(Vijayan & Professor, 2016)

- **Maximum power extraction**

The maximum power extracted from the wind occurs when the power coefficient (C_p) is maximized. This optimum value of Cp corresponds to a specific tip speed ratio. The tip speed ratio (TSR) remains constant at all maximum power points. Consequently, to extract maximum power from variable wind speed, the wind turbine must always operate at its optimal TSR λ_{opt} in speeds below the rated speed. This can be monitored by adjusting the wind turbine's rotating speed to match the optimal rotational speed. Assuming a constant wind speed, the value power coefficient depends on the wind turbine's rotor speed. Therefore, controlling the rotor speed indirectly controls the P_m of the WT. Furthermore, decreasing or minimizing the pitch angle β will increase the power input to the turbine generator. whereas increasing the angle or pitch angle β will reduce or minimize the power input. So, for extracted optimum power blade pitch angle should be zero degree. When β =0, The WT blade is completely impacted by wind velocity, and the WT collects the most power from the wind.

At pitch angle $\beta = 0$, the maximum power extracted can be captured. It can be expressed as follows:

$$P_m = PC_p(\lambda, \beta) \tag{3.26}$$

Where P_m is mechanical power and P is the wind power, the maximum power can be determined by the optimal tip speed ratio λ_{opt} and optimal power coefficient $C_{p(opt)}$. Thus:

$$P_{m(\max)} = \frac{1}{2}\rho\pi r^2 V^3 C_{p(opt)} = \frac{1}{2}\rho\pi r^2 \left(\frac{r\omega_m}{\lambda_{opt}}\right)^3 C_{p(opt)} \tag{3.27}$$

Equation (3.23) defines the TSR, and using that equation, one can represent wind speed in terms of the TSR. The maximum power is obtained if the coefficient power as a function of tip speed is equal to its optimum tip speed ratio as a function will gives the maximum or optimum coefficient power $C_{p(opt)}$.

$$\begin{aligned} &C_p(\lambda, \beta) = C_p(\lambda_{opt}, \beta) = C_{p(opt)} \\ &P_{m(\max)} = \frac{1}{2}\frac{\rho\pi r^5 C_{p\ opt}}{\lambda_{opt}{}^3}\omega_{m(opt)}{}^3 = H_{opt} * \omega_{m(opt)}{}^3 \end{aligned} \tag{3.28}$$

Where $H_{opt} = \frac{1}{2}\frac{\rho\pi r^5 C_{p\ opt}}{\lambda_{opt}{}^3}$,

$\omega_{m(opt)}$: is the optimal rotational speed

$P_{m(\max)}$: optimum mechanical power

λ_{opt}: optimal TSR where the power coefficient becomes maximum.

- **Aerodynamics torque of WT**

A WT system converts kinetic energy into mechanical energy. The rotor blades' aerodynamic shape produces torque. The blade diameter increases from the center to the edges. The angle of incidence on a blade is large at low shaft speeds, resulting in minimal torque production due to the small amount of drag force created. As the shaft speed increases, so does the wind velocity impacting the rotor blade, decreasing the angle of incidence. This reduction in angle of incidence maximizes torque production. However, when the shaft speed increases further, the angle of incidence approach to zero as the wind velocity becomes relatively low compared to the shaft speed. Because torque output is related to the angle of incidence, at high wind speeds, the torque produced approaches zero. (Md Maruf Billah & Motamed Ektesabi Nasser Hosseinzadeh, 2012)

Since the mechanical power is a product of the rotor torque and the rotor speed, thus the mechanical torque is:

$$T_m = \frac{P_m}{\omega_m} = \frac{1}{2}\frac{\rho\pi r^2 V^3 C_p(\lambda,\beta)}{\omega_m} \tag{3.29}$$

Where T_m : mechanical torque, ω_m is rotor speed, P_m : mechanical power.

The optimal torque can be obtained from the optimal mechanical power and optimal rotational speed thus:

$$\begin{aligned} T_{m(opt)} = \frac{P_{m(\max)}}{\omega_{m(opt)}} &= \frac{\frac{1}{2}\frac{\rho\pi r^5 C_{p(opt)}}{\lambda_{opt}{}^3}\omega_{m(opt)}{}^3}{\omega_{m(opt)}} \\ &= \frac{1}{2}\frac{\rho\pi r^5 C_{p(opt)}}{\lambda_{opt}{}^3}\omega_{m(opt)}{}^2 \end{aligned} \tag{3.30}$$

This maximum torque can be simplified as:

$$T_{m(opt)} = H_{opt}\omega_{m(opt)}{}^2 \tag{3.31}$$

3.3.3 Drive Train Model

The drive train is the critical mechanical part component of wind turbine, in which it facilitates the efficient conversion of wind energy in to electrical power. Drive train technology is constantly evolving with the goal of increasing wind turbine performance, lowering maintenance costs, and increasing efficiency. The drive train refers to has responsible for transferring the rotational motion of the turbine blades to generate the electrical power. It consists of several components which used to convert the kinetic energy of the wind in to the electrical energy. The main components of the drive trains in wind turbine includes: Rotor, Gearbox, Generator, shaft and coupling bearing. In this thesis no gearbox is used due to several reasons according to permanent magnet synchronous generators (PMSG). The gearbox is not considered in this evaluation because the system comprises a WT equipped with a multi-pole PMSG, which offers high efficiency, reduced maintenance, enhanced reliability, increased durability, and decreased stress and noise. The drivetrain can be regarded as “one-lumped mass model” for the saving time and acceptable efficiency. (Vijayan & Professor, 2016).

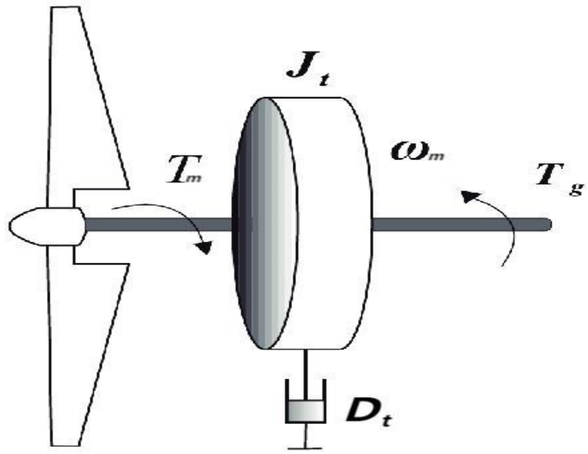


Figure 3.3 One mass model of WT (Vidal et al., 2012)

Figure 3.3 shown above shows the scheme of the “one mass model” of the wind turbine equation which represents the dynamics of the rotor speed ω_m with the rotor inertia J_r driven by the aerodynamic torque T_m. The mathematical model of the one mass wind turbine rotor speed is expressed by first order differential equation:

$$J_t \dot{\omega}_m = \sum T \tag{3.34}$$

$$J_t \frac{d\omega_m}{dt} = T_m - T_g - T_d \tag{3.35}$$

$$T_d = D_t * \omega_m \tag{3.36}$$

Substituting Equation (3.36) into Equation (3.35):

$$\frac{d\omega_m}{dt} = \frac{1}{J_t}\left(T_m - T_g - D_t * \omega_m\right) \tag{3.37}$$

Where T_m : the mechanical torque shaft (Nm),

T_g : the generated torque (Nm),

T_d : damping torque,

D_t : is damping coefficient,

ω_m : is rotational speed, and

J_t : is the total moment of the inertia and it is expressed as:

$J_t = J_g + \frac{J_w}{n_g^2}$ where J_g and J_w is the generator and the rotor rotational inertias [kgm^2] respectively, and n_g is the gear ratio which is equal to 1, hence in this thesis gear box isn't used.

3.3.4 Permanent Magnet Synchronous Generator (PMSG) Model

PMSG is a kind of electrical generator where the magnetic field is produced using permanent magnets fixed on the rotor. It converts mechanical energy to electrical energy by using the electromagnetic induction theory to drive its operation. Hydroelectric power plants, wind turbines, and some automobile systems are just a few of the many applications that frequently use PMSGs. (Rashid et al., 2018)

In WECS there are two generators widely used those are permanent magnet synchronous generator (PMSG) and Double Feed Induction Generator (DFIG). In this thesis PMSG is chosen due to its several advantages over DFIG, such as PMSG have higher efficiency, lower maintenance cost, has capacity to operate without gearbox, has simple control system, higher power quality, and lower noise and vibration.

PMSGs are crucial in direct-drive wind power generation systems for converting mechanical energy into electrical energy. Accurate mathematical modeling of PMSGs is essential for designing machine control algorithms and analyzing the steady-state and dynamic characteristics of the WECS. In modeling of PMSG, considering some important assumptions might be necessary such as: The magnetic saturation effects are neglected; The damping effect in the rotor and magnets are negligible; The eddy current and hysteresis losses are neglected; The back electromotive force induced in the stator winding are sinusoidal; The stator windings are sinusoidal distributed along the air gap. (Keisoku Jidō Seigyo Gakkai (Japan) et al., 2009)

3.3.4.1 Dynamic Model of PMSG

This thesis focuses on PMSG as a system that converts mechanical wind energy into electrical energy. A dynamic model of PMSG is developed using d-q synchronous reference frame, where the q-axis is 90 degrees ahead of the d-axis in terms of rotational direction. The synchronization between abc-three phase frame and the d-q rotating reference frame is maintained by utilizing a phase locked loop (PLL).(Keisoku Jidō Seigyo Gakkai (Japan) et al., 2009)

Figure 3.4 shown below shows that the cross-sectional view of the PMSG with 3-phase and 2-phase, where the θ is the mechanical angle in which the angle between the rotor q-axis and the stator axis.

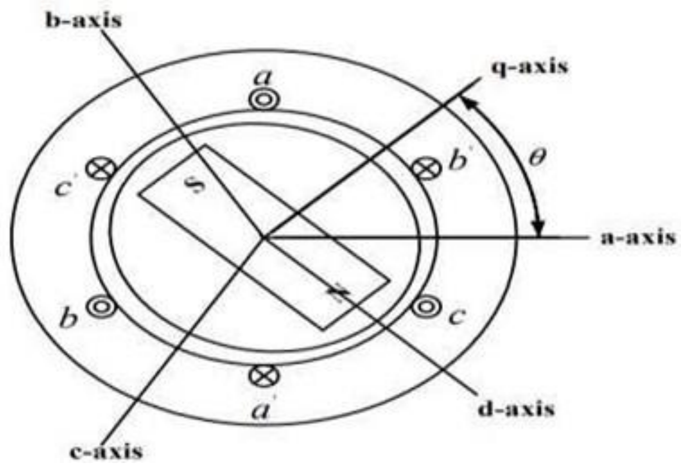


Figure 3.4 Permanent magnet synchronous machine(Qinghua & Eng, 2005)

The generator equation will develop "based on the reference of d-q axis coordinate system, in which it rotates synchronously with the magnetic flux thus the generator control system can be easily constructed using the generator dynamic model."(Keisoku Jidō Seigyo Gakkai et al., 2009) The electrical dynamic equation of PMSG in terms of phase variable is given by:

$$V_a = R_s i_a + \frac{d}{dt}\lambda_a \tag{3.38}$$

$$V_b = R_s i_b + \frac{d}{dt}\lambda_b \tag{3.39}$$

$$V_c = R_s i_c + \frac{d}{dt}\lambda_c \tag{3.40}$$

Where: (V_a, V_b, V_c): phase voltage

(i_a, i_b, i_c): phase current

R_s is stator resistance and

$(\lambda_a, \lambda_b, \lambda_c)$ is phase flux linkage provided by the permanent magnet and three phase currents. The equation is given as:(Qinghua & Eng, 2005)

$$\lambda_a = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + \lambda_{ma} \tag{3.41}$$

$$\lambda_b = L_{ab} i_a + L_{bb} i_b + L_{bc} i_c + \lambda_{mb} \tag{3.42}$$

$$\lambda_c = L_{ac} i_a + L_{bc} i_b + L_{cc} i_c + \lambda_{mc} \tag{3.43}$$

Where ($\lambda_{ma}, \lambda_{mb}, \lambda_{mc}$) is phase flux linkage provided by permanent magnet, (L_{aa}, L_{bb}, L_{cc}) refers to self-inductance and (L_{ab}, L_{bc}, L_{ac}) are mutual inductance. In the above equations, the inductance is a function of the angle θ, hence the mutual inductances are maximized when the rotor q-axis is between the two phase and the stator self-inductance is maximum when the rotor q-axis is coincided with phase axis. The effect of saliency on stator self-inductance and mutual inductance is illustrated by 2θ. (Qinghua & Eng, 2005) However, the flux linkage at the stator winding due to the permanent magnets are:

$$\lambda_{ma} = \lambda_m \cos\theta \tag{3.44}$$

$$\lambda_{mb} = \lambda_m \cos(\theta - \frac{2\pi}{3}) \tag{3.45}$$

$$\lambda_{mc} = \lambda_m \cos(\theta + \frac{2\pi}{3}) \tag{3.46}$$

3.3.4.2 Transformation Axes

In the realm of mathematical computing, transformations used to simplify complex systems by converting them into a simpler form and to obtain the system result in simulation, practical manner and to gain more control over parameter processing, three-axes to two-axes conversions are performed. One of the basic transformations of three phase into two phase is a Park transformation and Clark transformation.

- **Clark Transformation**:

In this transformation the balanced three phase vectors such as voltage, current and flux is converted into balanced two – phase quadrature variables, those are alpha and beta perpendicular axes.

❖ Park's transformation:

Park transformation is a phase transformation of the three physical phases into the two orthogonal balanced phase and also this transformation used to change vectors in balanced two-phase perpendicular axes in to orthogonal moving reference frame. The two orthogonal axes can be defined as, thus, one is along the axis in which the current in the rotor windings generates flux, called the direct axis (d-axis) and the other one is in axis which is perpendicular to d-axis, called quadrature axis (q-axis). This transformation called the d-q transformation.

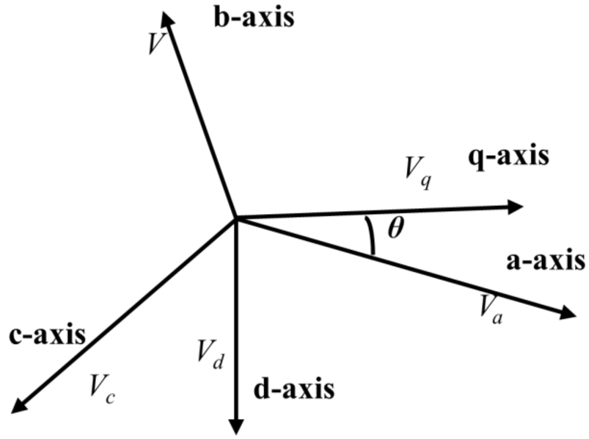


Figure 3.5 Synchronous transformation of d-q reference frame

Figure 3.5 shows the d-q conversion of electrically rotating reference frame using vector diagram. This determines the rotational angle between the synchronously revolving and stationary reference frames, as well as the angular rotation at synchronous speed.

Park's transformation converts the three-phase frame into d-q frame. This transformation changes time-varying AC quantities into time-invariant DC variables. Any variable (voltage, current, or flux linkage) represented by Z can be transformed from the three-phase frame to the d-q frame using Park's transformation.

$$\begin{bmatrix} Z_{qs} \\ Z_{ds} \\ Z_{0s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} Z_a \\ Z_b \\ Z_c \end{bmatrix} \tag{3.47}$$

Where Z is the transformed variable such as voltage or current, with this transformation the voltage equation in d-q axis.

3.3.4.3 PMSG Equivalent Circuit

Equivalent circuit representation is used to analyze the electrical networks. Figure 3.6 shows the simple known representation of PMSG, where from the grid side view of the PMSG is considered as the voltage source, V_d and V_q ; and currents i_d and i_q flows in the impedance of d-q reference frame.

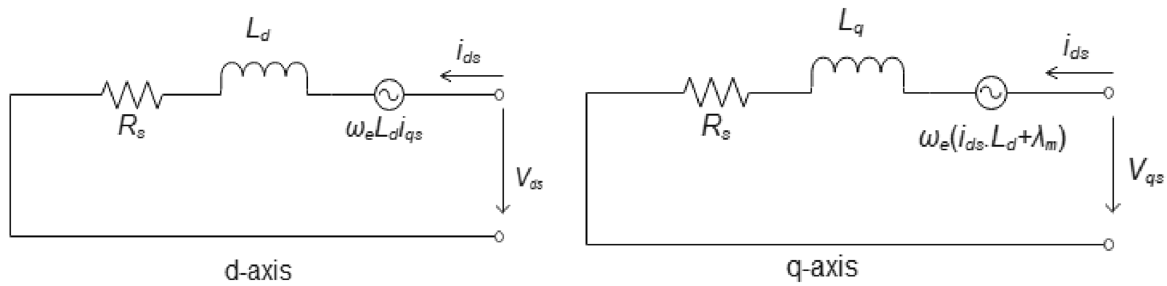


Figure 3.6 PMSG's equivalent circuit in d-q reference frame

Applying Kirchhoff's voltage law in the equivalent circuit of PMSG yields:

$$V_{ds} = R_s i_{ds} + L_d \frac{d}{dt} i_{ds} - \omega_e i_{qs} L_q \tag{3.48}$$

$$V_{qs} = R_s i_{qs} + L_q \frac{d}{dt} i_{qs} + \omega_e i_{ds} L_d + \omega_e \lambda_m \tag{3.49}$$

then the above equation can be simplified as:

$$\frac{d}{dt} i_{ds} = \frac{1}{L_d}(V_{ds} - R_s i_{ds} + \omega_e i_{qs} L_q) \tag{3.50}$$

$$\frac{d}{dt} i_{qs} = \frac{1}{L_q}(V_{qs} - R_s i_{qs} - \omega_e i_{ds} L_d - \omega_e \lambda_m) \tag{3.51}$$

Where: V_{ds} and V_{qs}, i_{qs} and i_{ds} are the instantaneous stator voltage and current in d-q axis reference frame respectively, L_q and L_d are q- axis and d-axis inductances respectively, ω_e is an electrical angular speed of the rotor and it is equal to $\omega e = P\omega m$, λ_m is the maximum phase flux linkage.

- **Power Equation**

The electrical power generation system denoted by multiplying the two-axis system by one and half (1.5). It is assumed that the voltages and currents in the two-axis system are known, the electrical power in dq reference frame is derived from the three-phase voltage and current, we can get the power as shown by the following formula:

$$P_e = \begin{bmatrix} V_a & V_b & V_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{3}{2} \begin{bmatrix} V_{qs} & V_{ds} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \tag{3.52}$$

$$P_e = \frac{3}{2}(V_{qs} i_{qs} + V_{ds} i_{ds}) \tag{3.53}$$

- **Torque Equation**

The electromagnetic torque T_e is the power divided by the mechanical speed which can be expressed as:

$$T_e = \frac{3}{2}\frac{P}{2}((L_d - L_q) i_{ds} i_{qs} + \lambda_m i_{qs}) \tag{3.54}$$

The given equation shows that the torque is constituted of two separate mechanisms. The first term corresponds to the reluctance torque because of the difference in d-axis and q-axis inductance, while the magnet excitation torque or synchronous torque occurring between i_q and the permanent magnet. (Qinghua & Eng, 2005) Hence ($L_{ds} = L_{qs}$) then electrical torque becomes as follows;

$$T_e = \frac{3}{4} P \lambda_m i_{qs} \tag{3.55}$$

The electrical power can also be expressed as:

$$P_e = T_e \omega_e \tag{3.56}$$

It can also be expressed by taking the efficiency of the generator we can get the output power from the input mechanical power as follows:

$$\eta = \frac{P_e}{P_m} \tag{3.57}$$

Where P: number of stator poles, η: Efficiency, P_e: electrical output power, P_m : mechanical input power.

3.3.5 Pitch Actuator (PA)

A pitch actuator (PA) is a mechanism that adjusts the angle of wind turbine blades, where the angle of pitch at the blades are tilted relative to the wind direction. Pitch control is a primary method for regulating the rotational speed of WT axes.(Hosseini & Shahgholian, 2017) Pitch-controlled WT have blades that are changeable along their longitudinal. When wind speed exceeds the rated value, the pitch controller reduces the angle of attack by turning the blades out of the wind. This minimizes the pressure difference between the front and back of the blade, resulting in a lower lifting force on the blade.(Hamoodi et al., 2020)

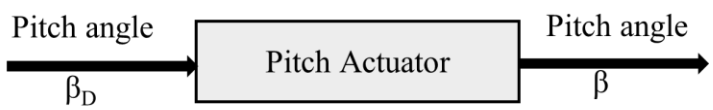


Figure 3.7 Pitch actuator system

The pitch actuator can be Electric actuator (servo motor) or hydraulic. In electric or servo motor control method each of the WT blade can be individually adjusted by a servo motor. Most wind turbines use this electric pitch angle control system methods. Since DC servo motors have faster dynamic response times and more accuracy than hydraulic control systems, in this thesis pitch actuator is used. The actuator model lays out the dynamic behavior between the pitch demand β_D from the pitch controller and pitch angle measurement of pitch angle β. (Hosseini & Shahgholian, 2017)

An expression for a servo motor's change in pitch angle is:

$$\frac{d}{dt}\beta = \frac{\beta_D - \beta}{\tau_c} \tag{3.58}$$

$$\beta_D = \tau_c \frac{d}{dt}\beta + \beta \tag{3.59}$$

Where: β_D is reference pitch demand angle

β: pitch angle measurement

τ_c: time constant

By applying the Laplace transform in Equation (3.59), the first-order-linear system can be found as:

$$L\left\{\beta_D = \tau_c \frac{d}{dt}\beta + \beta\right\} \tag{3.60}$$

$$\beta_D(s) = \tau_c s\beta(s) + \beta(s) \tag{3.61}$$

$$\beta_D(s) = \beta(s)(\tau_c s + 1) \tag{3.62}$$

$$\frac{\beta(s)}{\beta_D(s)} = \frac{1}{(\tau_c s + 1)} \tag{3.63}$$

Equation (3.63) shows that the transfer function of the PA, the direct relation of between the demand pitch angle β_D and pitch angle β can be found by reducing the inner closed loop of the actuator. (Hamoodi et al., 2020) Several researches used different values of time constant depending on their model, in this study small amount of time constant has been used (τ_c=0.01) which increases the control system effort.

$$\frac{\beta(s)}{\beta_D(s)} = \frac{1}{(|0.01s + 1|)} \tag{3.64}$$

3.4 Controller Design

WT systems are highly nonlinear and unstable, so their controllers must be designed to maintain system performance and consistency. Wind turbines can achieve maximum power production and rotor speed at both wind speeds above and below the rated speed of 11 m/s using the PAC. By setting the β to zero, control mechanism optimizes the power coefficient (C_p) and TSR λ. The goal of maximizing the turbine's aerodynamic output while operating at maximum power coefficient is to capture as much wind power as possible. The equation below can be used to compute the maximum power gained using the MPPT technique. So:

$$T_{ref} = \frac{P_{m(\max)}}{\omega_m} \tag{3.65}$$

TSR is a technique for boosting output power by adjusting the rotational speed to achieve the appropriate TSR.

$$\omega_{ref} = \frac{\lambda_{opt} * V}{r} = \frac{6.141*11}{37.3} = 1.811\, rad/\sec \tag{3.66}$$

Where: ω_{ref} : rotational speed reference, λ_{opt} : Optimum tip speed ratio, *V*: is wind speed and *r*: is rotor radius.

The pitch angle remains constant while the power coefficient and captured power reach their maximum values at the optimal TSR and specific speeds. Therefore, for wind speeds below the rated speed, the TSR should be maintained at its optimal level to capture optimum energy. Another method for tracking is optimal torque control technique.

$$\lambda = \frac{\omega_m r}{V} \Rightarrow V = \frac{\omega_m r}{\lambda} \tag{3.67}$$

From Equation (3.28) we have defined the optimal or maximum power output $P_{m(opt)}$ as:

$$P_{m(\max)} = H_{opt} * \omega_{m(opt)}{}^3 \tag{3.68}$$

The maximum power point tracking can be defined as:

$$P_{MPPT} = H_{opt} * (\omega_m)^3$$

And the optimal torque can be obtained from the optimal mechanical power and optimal rotational speed thus from Equation (3.30):

$$T_{m(opt)} = H_{opt} \omega_{m(opt)}{}^2 \tag{3.69}$$

Where, $H_{opt} = \frac{1}{2} \frac{\rho \pi r^5 C_{p(opt)}}{\lambda_{opt}{}^3}$, $P_{m(max)}$: maximum mechanical, $T_{m(opt)}$ is optimal mechanical torque

The extracted power output is determined by measuring the mechanical torque and optimizing it. However, the control mechanism in this thesis operates under conditions of higher-than-usual wind speeds. When wind speed exceeds the rated wind speed, the pitch angle control (PAC) mechanism is used to regulate rotor speed, power output, and protect the WT. This thesis explores various PAC approaches to regulate the wind turbine's rotational speed and reduce mechanical stress. Output of WT is restricted by various aerodynamic control techniques if exceeds rated speed. This thesis aims to reduce the cumulative tensions on the turbine's components by controlling pitch angle of the rotor blade.

3.4.1 Proportional-Integral-Derivative (PID) controller

In engineering and automation systems, the PID controller is a mostly used feedback control technique. The goal is to continuously alter an output variable by measuring the discrepancy between the process variable and the intended setpoint. “The PID controller incorporates three major components: proportional, integral, and derivative actions.”(Hamoodi et al., 2020)

Proportional (P): produces an output which is directly proportional to the error of current. It is calculated by multiplying the error by a proportional constant gain (K_P). It reduces the steady-state error and provides an immediate response to changes in the error.

Integral (I): collects error over time and it produces an output which is related directly to the integral of the error. It is determined by multiplying the error integral by integral gain constant (K_I) and its action helps to reduce the steady-state error which is caused by a changing error.

Derivative (D): it predicts the tendency of error based on its rate changes for the future. Which is determined by the error and the derivative gain constant (K_D). It provides damping and reduces overshoot and oscillations.

The PID controller output is the sum of the P, I and D. The control signal output can be expressed as:

$$u(t) = K_P e(t) + K_I \int e(t) d(t) + K_D \frac{d}{dt} e(t) \qquad (3.70)$$

and in Laplace domain form:

$$U(s) = \left(K_P + \frac{K_I}{s} + K_D s \right) E(s) \qquad (3.71)$$

The values of PID gains have to be appropriately tuned for each specific control application to achieve the desired system response. In order to achieve the desired system response, the value of PID gains have to be appropriately tuned for each control applications.

- **Design of PID Pitch Angle Controller**

The PAC mechanism is designed to keep the output power from exceeding the nominal value over the wind speed limit. In other word, when wind speed exceeds the nominal value, the mechanism adjusts the pitch angle to limit power production. Conversely if it is below the nominal value, the pitch angle controls the power capture can adjust accordingly the transfer function of the system can be expressed as:

$$G(s) = C(s) G_a(s) \qquad (3.72)$$

Where; *C(s)* is the transfer function PID controller and $G_a(s)$ is the transfer function of wind turbine actuator and it is denoted as:

$$C(s) = K_P + \frac{K_I}{s} + K_D s \ \ and \ \ G_a(s) = \frac{1}{0.01s+1} \tag{3.73}$$

$$x \to \omega_m$$

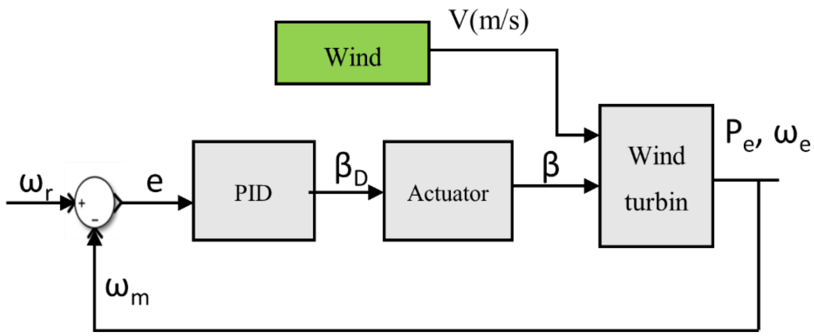


Figure 3.8 Pitch angle control system with the PID controller

3.4.2 Design of Sliding Mode Controller (SMC)

SMC is a powerful and widely-used control technique that provides robust and high-performance control for a system and it is designed to drive the plant's state trajectory for a predefined sliding surface and maintain the trajectory on this surface. A variable structure command (VSC) that can change structure and commute between two values in accordance with highly particular switching logic *S(y)* is the first order sliding mode control.(Semmah et al., 2019) Figure 3.9 shown below shows that the variable structure command (VSC) is done in two steps: the convergence towards the surface and the sliding along it.

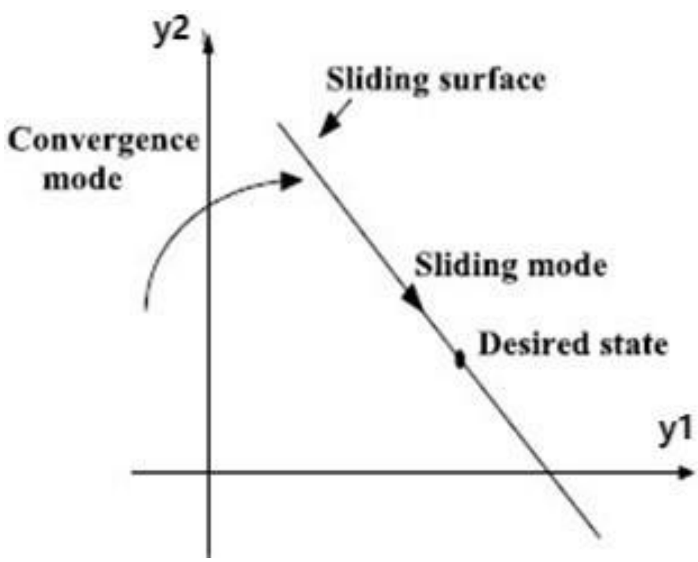


Figure 3.9 sliding surface convergence(Semmah et al., 2019)

The key aspects of a sliding mode controller are: system modeling, sliding surface design, control law design and stability analysis. There are three steps involved in the synthesis of the SMC:

- Selection of the sliding surfaces.
- Condition of stability existences.
- Establish the control laws.

- **Selection of the sliding surface**

Consider an nth-order system as:

$$\begin{cases} y^n = f(y,t) + g(y,t)u(y,t) \\ y \in \Re^n, u \in \Re \end{cases} \tag{3.74}$$

Where: $f(x,t), g(x,t)$ are the nonlinear functions. We take the form of a general equation proposed by Slotine and Li expressed as: (Slotine & Li, 2005)

$$S(y) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(y) \tag{3.75}$$

$$e = y - y_d \tag{3.76}$$

$e(y)$: error size to adjust object, λ: positive coefficient, *y*: state variable of the ordered quantity, y_d : desired size, *n*: system order.

Here based on Equations 3.75 we can select or choose the sliding surface of our system; since our dynamic system order is first order, so sliding surface should be:

$$S(y) = (\frac{d}{dt} + c)^0 e(y) \\ S(y) = e(y) \tag{3.77}$$

The state variable *y* in this thesis has been taken as the rotational mechanical speed ω_m thus:

$$y = \omega_m \\ e(\omega_m) = \omega_{ref} - \omega_m \tag{3.78}$$

Where $e(\omega_m)$ is the error that tracks for the rotor speed.

- **The control laws**

After properly selection of the sliding surface, we will proceed to the control laws. The control law SMC consists of mainly two components those are equivalent and switching control. Equivalent control (u_{eq}) maintains the system trajectory on the surfaces of sliding and the equivalent control can be obtained from the system dynamics and the sliding surface definition, which indicates the desired pitch angle tracking performance. The switching control (u_d) is a control component that is designed to drive the systems trajectory towards the sliding surface while compensating for system uncertainties and disturbances. The switching control normally takes the shape of a signum function.

By the methods that chosen is that of the equivalent control in which it can be determined by applying the corresponding instruction, which maintains the controlled variable at S=0 on the sliding surface using a continuous function. The result is obtained from the surface's invariance conditions yields: $S = 0 \, and \, \dot{S} = 0$.(Bellarbi et al., 2018) However, this order does not cause the system's paths to converge on the sliding surface. Thus, "the command u is the sum of the corresponding command and a discontinuous component, which provides a convergence and sliding regime."(Semmah et al., 2019) the command u can be expressed as:

$$u = u_{eq} + u_d \tag{3.79}$$

$$u_d = -\mu \operatorname{sgn}(S) \tag{3.80}$$

Where: u_d is command of discontinuous, μ is a positive constant number

Therefore, we can design the control law by calculating the equivalent control signal using the following methods by applying in variance conditions:

3.4.2.1 SMC Design for Pitch Angle

The SMC design for pitch angle control in this thesis uses a constant reaching law method. This standard SMC design approach ensures the constant reaching of the sliding surface. The sliding surface is a linear combination of the pitch angle error and its derivative, as previously described in equation (3.77).

$$S(y) = e(y) \tag{3.81}$$

the sliding surface using a continuous function is obtained from the surface's invariance conditions yields: the first order derivatives of sliding surface $\dot{S} = 0$, then using the control law methods:

The general expression of constant reaching law is defined as in time function:

$$\dot{S}(t) = \dot{e} = -\mu \,\mathrm{sgn}(S(t)), \mu > 0 \tag{3.81}$$

Where μ is the constant reaching rate towards into the sliding surface and the signum function $\mathrm{sgn}(S)$ is:

$$\mathrm{sgn}(S) = \begin{cases} +1, & S > 0 \\ 0, & S = 0 \\ -1, & S < 0 \end{cases}$$

The first order system of the sliding surface's general formula is:

$$\dot{S}(t) = \dot{e} = u + d(t) \tag{3.82}$$

Where *d(t)* is external disturbance if exists:

Since the command u is the sum of the equivalent command and the discontinuous command, the discontinuous command is expressed in the signum function and the equivalent command u_{eq} can be design as:

Then next the control command stated as:

$$\dot{S} = \dot{e} = u_{eq} + d(t) \tag{3.83}$$

$$u_{eq} = \dot{e} - d(t) \tag{3.84}$$

and the error e as expressed in equation (3.78) as a control input of mechanical rotational speed and the first order derivatives of error e is given as:

$$\begin{aligned} e &= \omega_{ref} - \omega_m \\ \dot{e} &= \dot{\omega}_{ref} - \dot{\omega}_m \end{aligned} \tag{3.85}$$

Substituting in the above equation in to equation (3.84) gives:

$$\begin{aligned} u_{eq} &= \dot{\omega}_{ref} - \dot{\omega}_m - d(t) \\ u_{eq} &= -\dot{\omega}_m - d(t) \end{aligned} \tag{3.86}$$

The dynamics model of the mechanical or rotational speed in first order as expressed in equation (3.37)

$$\dot{\omega}_m = \frac{1}{J_t}\left(T_m - T_g - D_t * \omega_m\right)$$

Then substituting in to equation (3.87) the equivalent command will be:

$$u_{eq} = -\left(\frac{1}{J_t} \left(T_m - T_g - D_t * \omega_m \right) + d(t) \right) \quad (3.87)$$

Therefore, the total command u will be:

$$u = u_{eq} + u_d$$
$$u = -\left(\frac{1}{J_t} \left(T_m - T_g - D_t * \omega_m \right) + d(t) \right) - \mu \operatorname{sgn}(S) \quad (3.88)$$
$$u = -\left(\frac{1}{J_t} \left(T_m - T_g - D_t * \omega_m \right) \right) - \mu \operatorname{sgn}(S) - d(t)$$

Hence *u* is the overall command for controlling design of pitch angle controller by maintaining the mechanical speed of the system using the constant reaching law. The method that is used in this thesis for SMC of pitch angle is schematically shown below in Figure 3.10.

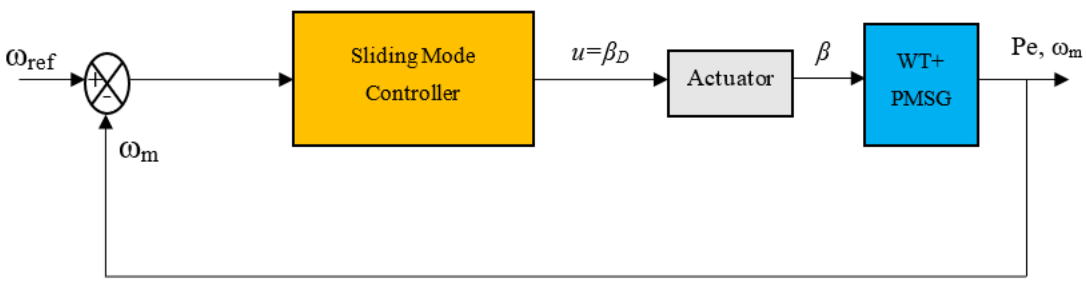


Figure 3.10 sliding mode controller design for pitch angle

Therefore, the sliding model controller might have some drawbacks as mentioned earlier like chattering problem might be the main reason. A perfect sliding regime necessitates a command capable of switching at infinite frequencies. During the sliding regime, the discontinuous control signals can cause chattering, which is characterized by significant oscillations in the system trajectories around the sliding surface, as illustrated in the Figure 3.11. (Semmah et al., 2019)

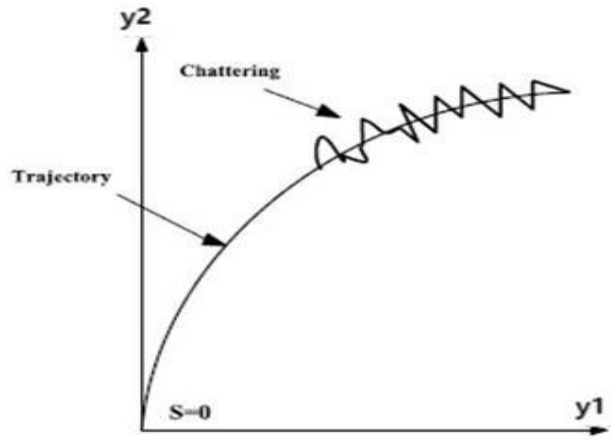


Figure 3.11 chattering effect (Semmah et al., 2019)

Many strategies for reducing or eliminating this issue have been proposed, including the fuzzy sliding mode, high-order sliding mode, backstepping etc. In this thesis the super-twisting algorithm with SMC (STSMC) approach is used.

3.4.3 Super-Twisting Sliding Mode Control

Super-twisting algorithms (STA): This algorithm is an advanced sliding mode control technique that is particularly useful dynamic system with one relative degree, in this sliding surface design, the control input appears linearly in the first-time derivative of the sliding surface. The STA law is used to push the system trajectory to the sliding surface and keep it there, as it has several advantages, including reduced chattering, resilience, and finite time convergence. STA does not employ information, which is beneficial, and the STA command v is divided into two parts: continuous and discontinuous. Thus:

$$\begin{aligned} v(t) &= v_1(t) + v_2 \\ \dot{v}(t) &= \dot{v}_1(t) + \dot{v}_2 \end{aligned} \tag{3.89}$$

$$\begin{aligned} \dot{v}_1 &= \begin{cases} -k_1 |S_0|^{\rho} \operatorname{sgn}(S) & if\ |v| > S_0 \\ -k_1 |S|^{\rho} \operatorname{sgn}(S) & otherwise \end{cases} \\ \dot{v}_2 &= -k_2 \operatorname{sgn}(S) \end{aligned} \tag{3.90}$$

Where, S is the sliding surface; k_1, k_2 are positive parameters, $0 > \rho > 0.5$

So, the super twisting command can be simplified as:

$$\begin{cases} v = -k_1 |S|^{\rho} \operatorname{sgn}(S) + v_2 \\ \dot{v}_2 = \int -k_2 \operatorname{sgn}(S) \end{cases} \tag{3.91}$$

The STSMC technique is implemented as an observation algorithm for calculating derivative of a signal measure based on the model and sliding surface used.

3.4.2.1 Design of STSMC for Pitch Angel

By addressing crucial factors such as disturbance rejection, parameter uncertainties, finite-time convergence, and chattering reduction, the STSMC design can provide a robust and effective solution for pitch angle control (PAC) in WT. The general block diagram of STSMC for controlling pitch angle for variable wind speed that has been used in this thesis is shown in Figure 3.12:

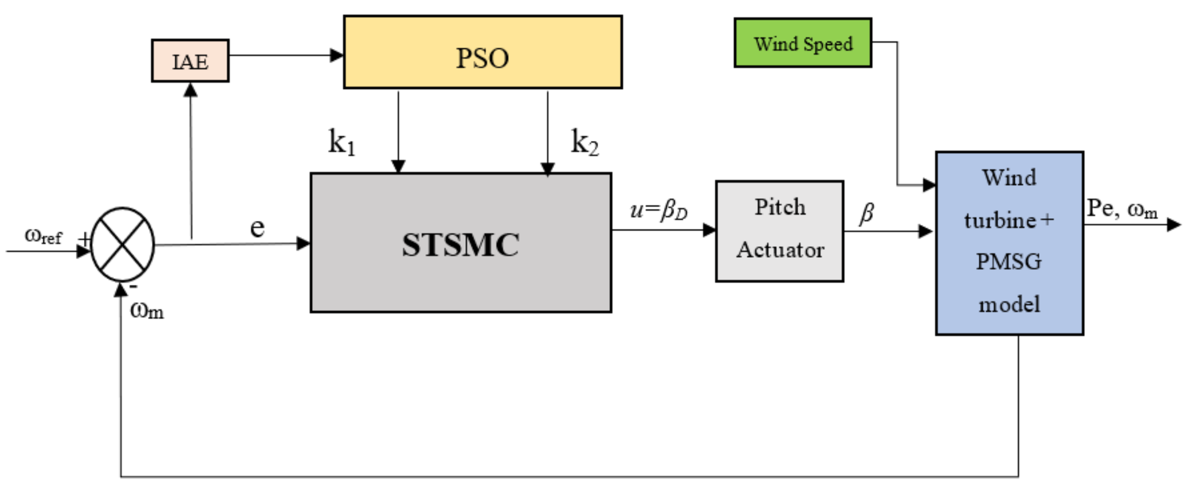


Figure 3.12 STSMC design for pitch angle

By applying general algorithms of super twisting, the sliding surface can by expressed as:

$$\begin{aligned} \dot{S}(t) &= -k_1 |S|^{\frac{1}{2}} \operatorname{sgn}(S) + v_2 \\ \dot{v}_2 &= -k_2 \operatorname{sgn}(S) \end{aligned} \tag{3.92}$$

Therefore, the overall design of STSMC is:

$$\dot{S}(t) = -k_1 |S|^{\frac{1}{2}} \operatorname{sgn}(S) - \int k_2 \operatorname{sgn}(S)\, dt \tag{3.93}$$

Where: k_1 and k_2 are the coefficient parameters, The amplitude of the control action that moves system determined by k_1 while k_2 maintain the system trajectory once it has been reached. The ideal values for k_1 and k_2 are determined by balancing the desired convergence rate, chattering reduction, and disturbance robustness.

The overall control signal for pitch angle control system using this ST algorithms will be determined as the reference for pitch angle actuator dynamics. So, the total control input is:

$$u = -k_1 |S|^{\frac{1}{2}} \operatorname{sgn}(S) - k_2 \int \operatorname{sgn}(S)\, dt \quad (3.94)$$

3.4.3.1 Existence Condition of Stability

- **Stability Analysis Existence of SMC**

The stability of the closed-loop system can be assessed using Lyapunov's stability theorem to ensures system trajectories converge and remain on the sliding surface. By choosing design parameters to satisfy a certain condition, the S will converge towards zero in a finite time, which ensures the convergence of the pitch angle β into the desired β_D. The Lyapunov stability theory is expressed as:

$$V(S) = \frac{1}{2} S^2 \quad (3.95)$$

And the time derivatives of $V(s)$ must be negative in order to ensure stability and condition of attractiveness for sliding surface $S(y,t)$ to tend to 0. Such that:

$$\dot{V} = \dot{S}.S < 0 \quad (3.96)$$

The asymptotic convergence with respect to the S is substituted with a more exclusive requirement called ξ attractively, and it proofed as:

$$\left.\begin{aligned} &\dot{V}(t) = S * \dot{S} = S * \dot{e} = S * (u + d(t)) \\ &\dot{V}(t) = S * [-\mu \operatorname{sgn}(S) + d(t)] \\ &\dot{V}(t) \le -[\mu - d(t)]|S| \\ &S.\dot{S} \le -\xi |S| \\ &\dot{S}.S \le -\xi |S|,\ \xi > 0,\ \xi > |d(t)| \end{aligned}\right\} \quad (3.97)$$

- **Stability Analysis Existence of STSMC**

The stability condition for the STSMC in PAC of a WT. The stability condition for the STSMC-based pitch angle control can be derived using Lyapunov stability analysis, similar to the Sliding Mode Control (SMC) case.

$$\begin{aligned}\dot{V} &= S\dot{S} \\ &= S\left(-k_1|S|^{\frac{1}{2}}\operatorname{sgn}(S) - k_2\int \operatorname{sgn}(S)\right) \\ &= S\left(-k_1|S|^{\frac{1}{2}}|S| - k_2|S|\right) = S*\left(-k_1|S|^{\frac{3}{2}} - k_2|S|\right) \\ \dot{V}(t) &\le -C_1|S|^{\frac{3}{2}} - C_2|S|\end{aligned} \tag{3.98}$$

Where C_1 and C_2 are positive constant

Substituting the equation and rearranging the terms, the stability condition becomes: $k_1 > 0, k_2 > 0$. These stability conditions ensure that S converges to zero in finite time, which in turn guarantees the convergence of the pitch angle β to desired reference β_D.

3.4.4 MPPT PI Controller Design

Hence in the d-q reference frame the coupling between the d and q axis mentioned as $\omega_e i_{qs} L_q$ and $\omega_e i_{ds} L_d$ might have problems. So, we can use a controller based on the field orientation system and to drive the system to the MPPT. Hence in dq reference frame id=0. Then according to equation (3.55) the electromagnetic torque Te is directly proportional to the q-axis current iq since maximum flux linkage is constant. Hence the two inputs V_{ds} and V_{qs} are defined to run and compensate the coupling terms.(Elbeji et al., 2014)

From the equation 3.50 and 5.51 we can rearrange it as:

$$\begin{aligned}U_d &= V_{ds} + \omega_e L_q i_{qs} \\ U_q &= V_{ds} - \omega_e L_d i_{ds} - \lambda_m \omega_e\end{aligned} \tag{3.99}$$

Where the term U_d and U_q is:

$$U_{ds} = R_s i_{ds} + L_d \frac{di_{ds}}{dt} \tag{3.100}$$

$$U_{qs} = R_s i_{qs} + L_q \frac{di_{qs}}{dt} \tag{3.101}$$

From the above equations we can get as the two separate similar first order models in dq reference frame. Solving the above equations gives:

$$\frac{i_{ds}}{U_d} = \frac{1}{(L_d s + R_s)}$$
$$\frac{i_{qs}}{U_q} = \frac{1}{(L_d s + R_s)} \qquad (3.102)$$

Thus, we will use two similar PI regulators, one for the q-axis and one for the d-axis component. q-axis maintains rotor speed by controlling the input voltages Vds and Vqs, which helps adjust the generator speed until the rated wind speed is reached. Above the rated wind speed, the PAC operates to limit power capture to its rated value. Using PSO optimization the parameters of PI controller will reduce the deviation and tracks the rated rotor speed.

3.4.5 Optimization Techniques

❖ **Particle Swarm Optimization (PSO)**

PSO is a stochastic optimization Techniques based on the social behavior of birds and fish, invented by Kennedy and Eberhart in 1995, it simulates particle movement in a specific dimension space with a finite number of iterations. The goal is to improve particle positions with each iteration, whether for minimization or maximization problems.(Maknunah et al., 2019). The PSO method is developed using the MATLAB in the form of an m-file and is getting data from the Simulink model of the WT pitch control system. The goal function in this problem is to minimize the Integral Absolute Error (IAE), which is the difference between the set point and the system response. Optimized STSMC parameters are k_1 and k_2. For a D-dimensional target search with N particles, each particle coordinate position vector can be computed as:

$$X_i = (X_{i1}, X_{i2}, X_{i3}, \ldots X_{id}) = [k_{1i}, k_{2i}] \qquad (3.103)$$

The velocity vector indicated as:

$$V_i = (V_{i1}, V_{i2}, v_{i3}, \ldots V_{id}) = [V_{i1,} V_{i2}] \qquad (3.104)$$

The optimal position of Swarm with individual and global position is:

$$p_{best\,i} = (k_{1i}^{p_{best}}, k_{2i}^{p_{best}})$$
$$g_{best\,i} = (k_{1i}^{g_{best}}, k_{2i}^{g_{best}}) \quad (3.105)$$

The above equations are individual positions and their neighbors' global best position, respectively. With this data, the PSO algorithm adjusts the updated velocity of each individual represented in equation (3.104) and Particles can update their position as shown in equation (3.103) below thus:

$$V_i^{n+1} = wV_i^n + c_1 rand_1 (p_{best\,i}^n - X_i^n) + c_2 rand_2 (g_{best\,i}^n - X_i^n) \quad (3.106)$$

$$X_i^{n+1} = X_i^n + V_i^{n+1} \quad (3.107)$$

Where: V_i^n is the individual velocity at iteration n, X_i^n is individual position *i* and at iteration n, c_1, c_2 is acceleration constant coefficient, $rand_1$, $rand_2$ is a random number within range [0 1], $p_{best\,i}, g_{best\,i}$ are best individual and best global position at iteration n.

$$w_n = w_{\max} - \frac{(w_{\max} - w_{\min})n}{n_{\max}} \quad (3.108)$$

w is the inertia weight, which is used to vary the particle's velocity and range of search; w_n represents the n^{th} iteration, w_{max} refers to the initial weight, *w* denotes the final weight, and n indicates current iteration and n_{max} indicates the maximum number of iterations. The objective function and PSO can be related as:

$$J(X) = w_n(ITAE)$$
$$X = [k_1, k_2] \quad (3.109)$$

Figure (3.13) illustrates the optimization algorithms of PSO, It is used to optimize constraints for the STSMC.

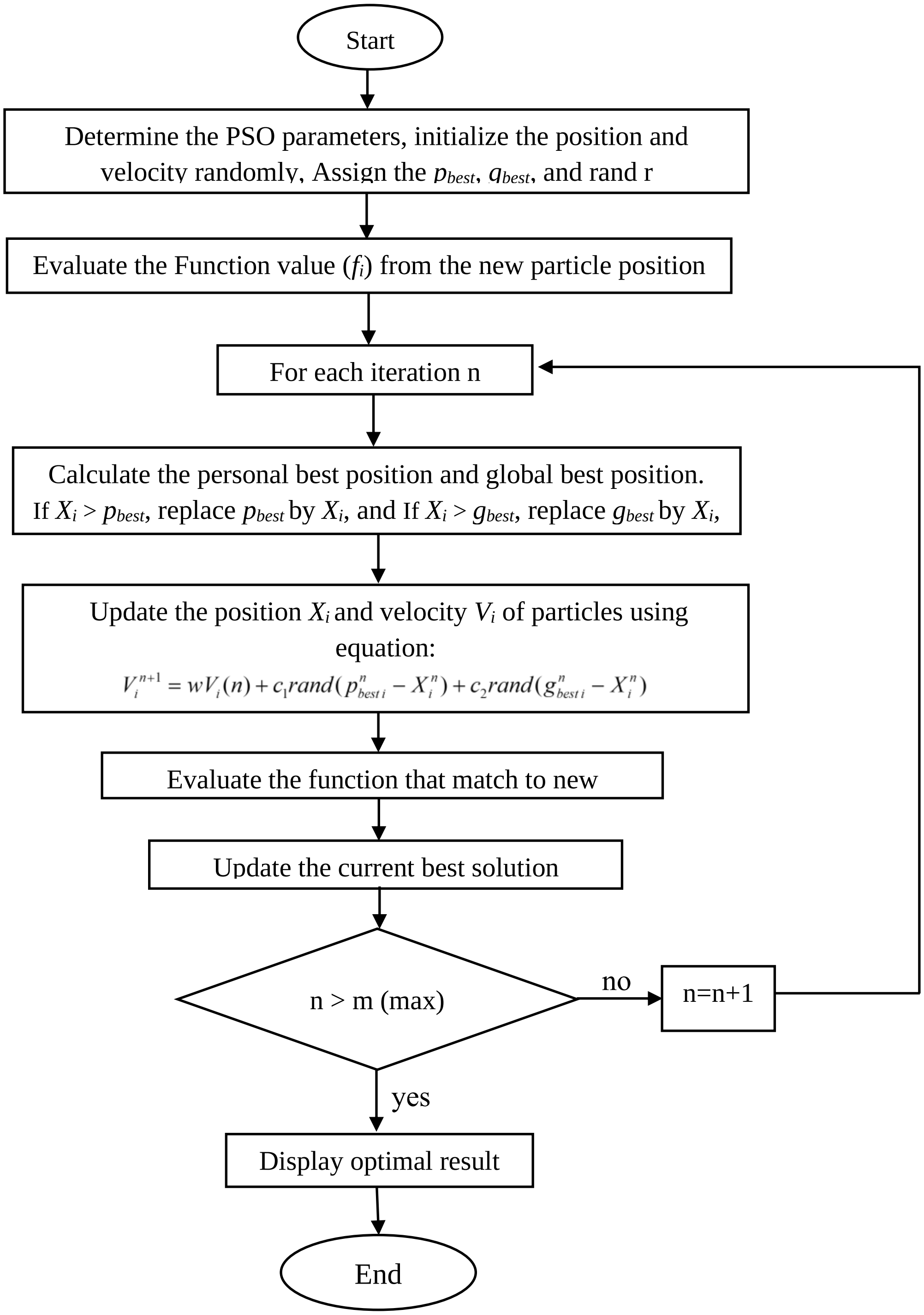


Figure 3.13 PSO algorithm flowchart

The parameters of PSO algorithm are listed in Table (3-1). It indicates parameter tuning ranges of STSMC controllers gains for WT pitch actuator the system. The tuned parameters of these controllers are in Tables (3-2). The tuned PID controller is also mentioned in table (3-2). Three PI controllers are used to regulate rotor speed. The first PI controller uses Kp and Ki to directly control rotor speed. The other two PI controllers regulate the input voltages Vds and Vqs, indirectly affecting rotor speed.

Table 3-1 PSO algorithm parameters

Optimization Technique Algorithms	Optimization Parameters			
Particle Swarm Optimization (PSO)	Swarm size (No of Particles)			30
	Maximum iteration			100
	Personal best P_{best} coefficient c_1			2
	Personal best g_{best} coefficient c_2			2
Boundary of the controller gains of STSMC				
Boundary	STSMC Parameters			
	k_{1c}		k_{2c}	
LB	0		0	
UB	500		500	
Boundary Parameters gain of PID				
	Kp		Ki	Kd
LB	0		0	0
UB	500		500	500
Boundary of PI controller Parameters				
	Kp	Ki	kp	ki
LB	0	0	0	0
UB	500	500	500	500

Table 3-2 PSO algorithm with PID, PI, STSMC response

Boundary of the controller gains of STSMC				
Boundary	STSMC Parameters			
	k_{1c}		k_{2c}	
LB	0		0	
UB	500		500	
Boundary of tuned the controller gains				
LB	0		0	
UB	70.7765		4.9798	
Tuned PID controller Parameters of pitch angle				
	Kp		Ki	Kd
LB	0		0	0
UB	1.337		267.355	0.000485
Tuned PI controller Parameters				
	Kp	Ki	kp	ki
LB	0	0	0	0
UB	99.9995	0.0426	55.2185	39.6811

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 Introduction

In the previous chapter, the controllers such as PID, SMC and STSMC are designed as well as optimization algorithms are used to get better performance parameters in STSMC. In this chapter the response of the system with designed controllers are discussed briefly. The entire system simulated using the MATLAB/Simulink. The designed model of the WT, drive train and PMSG based on VSWT has installed on the Simulink to evaluate the system result. The simulation performed 1.5 MW WT based PMSG, where the designed parameters are listed in Appendix A and B. The simulation result analysis for the regulation of the pitch angle and maintaining aerodynamic power by adjusting rotor blade in the desired position will be discussed. The performance of the designed PID, SMC, and STSMC of pitch angle controller for variable wind speed will be evaluated and discussed in the next subsections. The constant wind speed operation of the WT is discussed with the three designed controllers, and their performance analysis will be described at the end of this chapter. The overall system model is shown in figure (4.1).

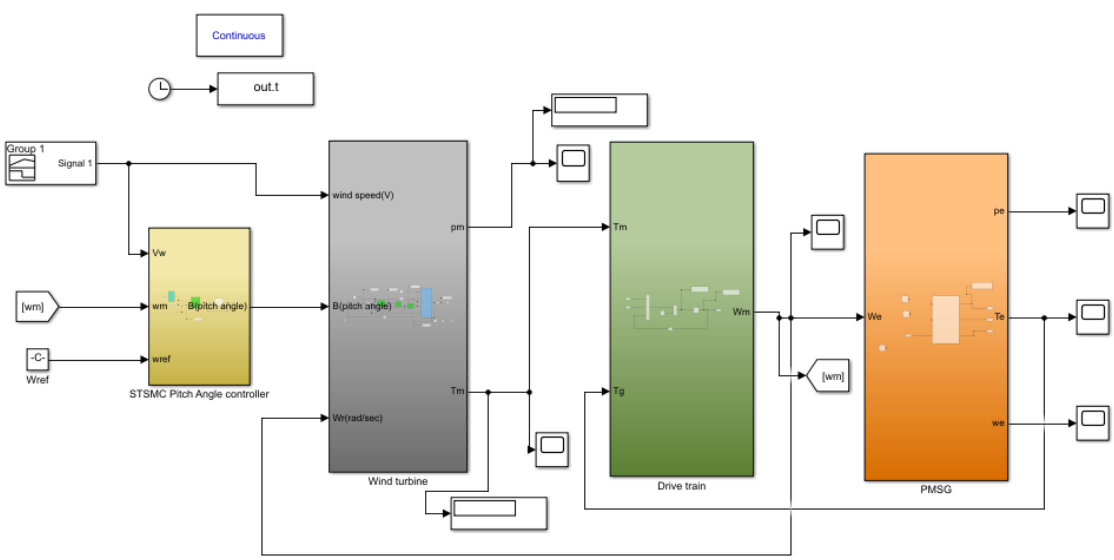


Figure 4.1 Overall WECS in MATLAB/simulink

The overall proposed system of WECS is depicted as in the Figure 4.1 shown above with four main subsystems such as the WT model, the drive train, the generator PMSG and the controllers. The WT system has modeled with several interconnected Simulink blocks, includes power function calculation block, tip speed ratio block, power coefficient, torque calculation block. The drive train model block represents dynamics of the WT drivetrain, it takes input mechanical developed torque and the generated electrical torque and the mechanical speed as an output. The wind turbine system can run at peak efficiency by adjusting rotor speed using the STSMC controller, maximizing power output. The STSMC Controller block implements the sliding-mode and Super twisting algorithms, which generate the desired pitch angle instruction by using actual and reference rotor speeds as inputs. The required pitch angle is transmitted to the pitch angle actuation block that simulates the pitch angle actuation system of WT. The entire system aims to maintain the rotor speed and power at their desired reference values by adjusting pitch angle, thereby improving the wind turbine's power generation while ensuring safe and efficient operation.

4.2 Simulation Analysis of the system

Wind turbine MATLAB/Simulink is designed in Figure 4.1 using Equations (3.22), (3.24), (3.25), (3.26) and (3.29) from dynamic modeling of WT. The mechanical speed in equation (3.37) from the drive train dynamic model, using variable wind speed. The PMSG model block is designed using Equation (3.50), (3.51), (3.52), (3.55), (3.56) for defining the electrical power, developed electrical torque and electrical speed in the Simulink model. The system response without a pitch control system is will be simulated in Figure 4.3 shown below. The WT mechanical power mostly depends on blade length, wind speeds, pitch angle, and the rotor speed, as well as mechanical or rotor speed also depend on the wind speed and pitch angle. In this thesis, a combination of real wind speed data and some adjustment has been taken for simulation purpose as shown in Figure 4.3 in a which varies between around (8 m/s and 17 m/s) within 25 seconds.

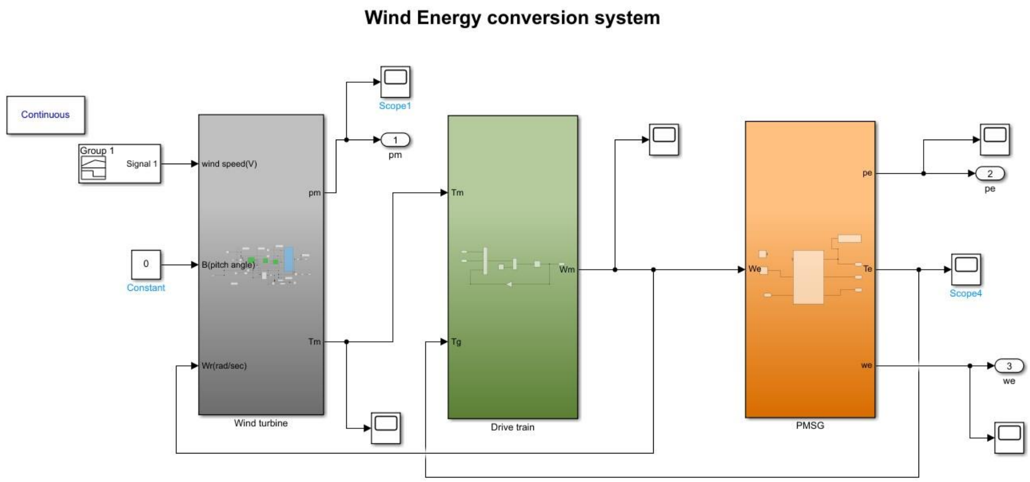
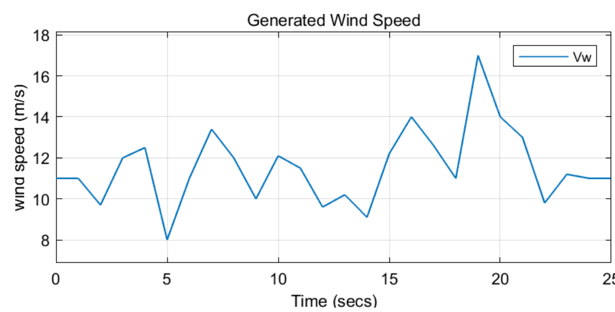
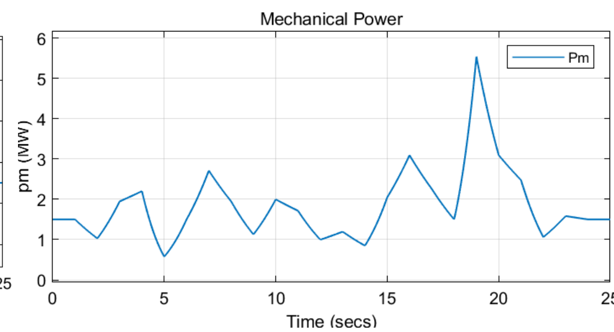


Figure 4.2 Pitch Angle Controller Without a Controller

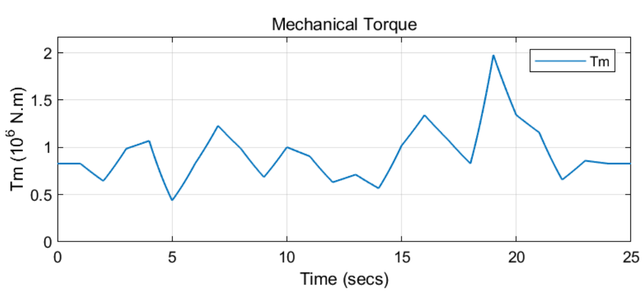
The following simulation results show the behavior (characteristics) of WT model without controller constructed.



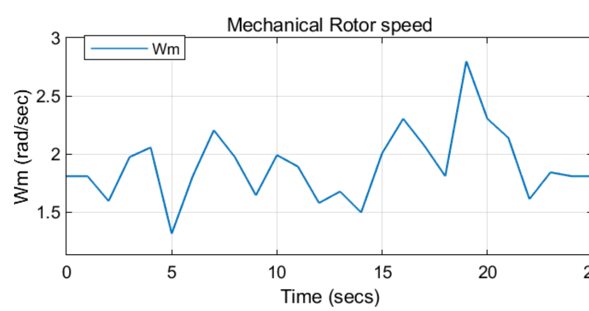
a. wind Speed



b. uncontrolled mechanical torque



c. uncontrolled mechanical torque



d. uncontrolled mechanical speed

Figure 4.3 Simulink Uncontrolled System Response

Figure 4.3 shows that the responses of the wind speed which has a different speed range in which it is from 8m/s upto 17.1m/s. Using various wind data ensures the effective response of the controller, such that fluctuation wind speed makes the controller to control the pitch angles which protects the system turbine from damages. In Figure 4.3 (b) it shows that the uncontrolled mechanical power at variable wind speed which results an extremely high power more than 5MW for 1.5MW wind turbine. This power is beyond the rated power which might be led the turbine to damage. In Figure 4.3 (c) it shows that the uncontrolled mechanical torque. Figure 4.3(d) shows that the uncontrolled mechanical or rotor speed, since rotor speed has a direct relationship with the input VSWT adjusting the pitch angle, we can maintain the rotor speed, the rated rotor speed with the rated TSR (6.141) and wind speed (11m/s) is 1.811 rad/s, but the uncontrolled WT as shown in Figure 4.3(d) at wind speed 17 m/s it becomes 2.8 rad/s. This value is more than the designed rated value, it will cause several problems such as turbine damages, over voltage, fluctuation in the power, frequency devotion, generator fault. Therefore, by controlling the rotor speed, we can maintain the rated speed and extract maximum mechanical power when the WT is operating at the rated power coefficient.

4.3 Response of the System Using the Controllers

The pitch controller was designed in MATLAB/Simulink shown in Figure (4.4), based on the mathematical model and control design. In this study, the control variable is the rotor speed. The error between the reference rotor speed and the actual drive train speed is fed into the controllers.

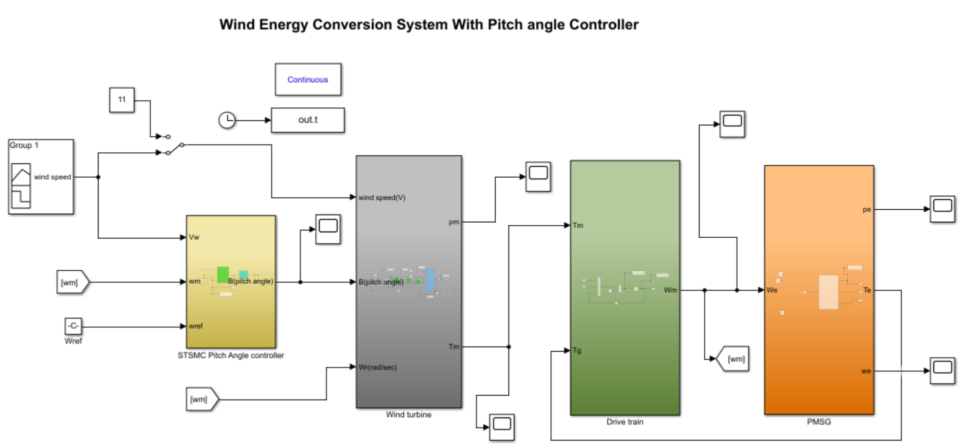


Figure 4.4 WECS with pitch angle controller Simulink model

The proposed controller is STSMC which maintains the rotor speed, by minimizing the errors using optimization techniques the gain of the controller is found. Which is then fed to the pitch actuator models, as a result it will maintain the pitch angle appropriately based on the rotor speed error. The wind speed is considered as the disturbance; The pitch angle controller is simulated as shown in figure (4.5) with STSMC with considering disturbance.

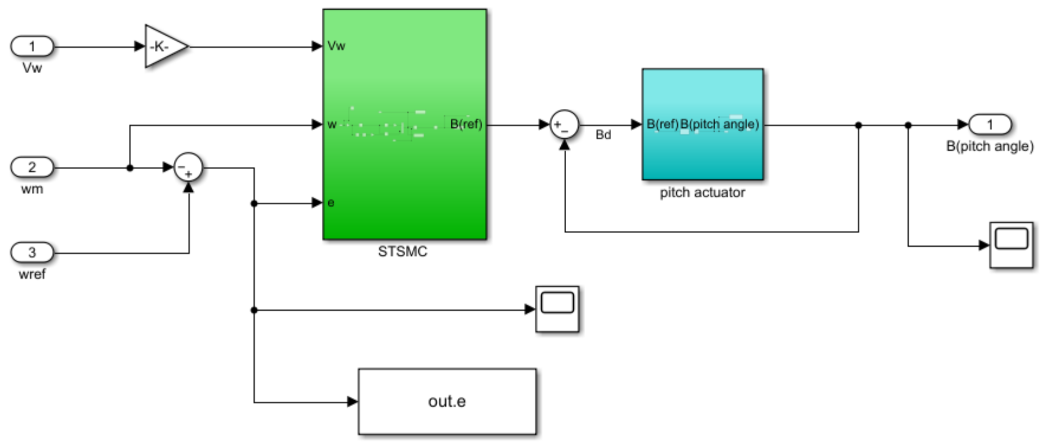


Figure 4.5 Pitch angle controller with actuator Simulink model

4.3.1 The Simulation Result of the System Using STSMC, SMC, and PID

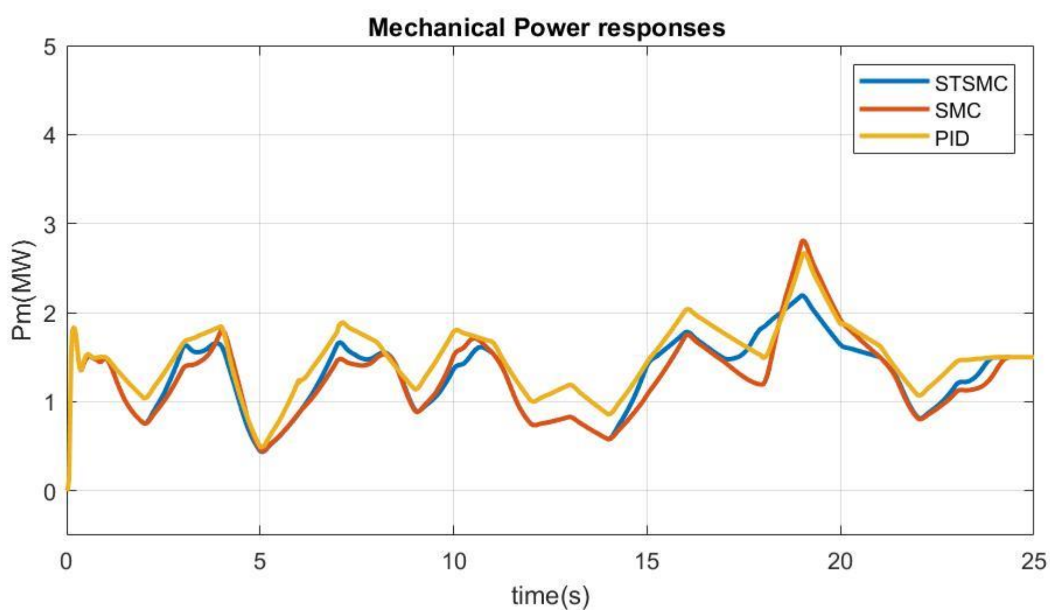


Figure 4.6 Mechanical Power Using STSMC, SMC, and PID

In Figure 4.6 shows the mechanical power responses of STSMC, SMC, and PID, the controller of pitch angle maintains mechanical power near to its rated value which is 1.5 MW as the wind is above the 11 m/s. The PAC controls the system by controls the rotor speed as much as possible to track to the rated speed. Supper twisting approach is used to tune the sliding surface with two constants k_1 and k_2 using PSO optimization techniques. we can observe that the chattering effect is reduced in case of the STSMC, wherever the SMC controller reach the target output value due to the variation of error the outputs fluctuation is increase, so the proposed controller reaches the target value with minimizing the fluctuation. The response of SMC is almost same as the proposed STSMC controller, in fact its response delayed compared to STSMSC. As we can see from the Figure the response will vary with wind speed where the rated power is 1.5 MW, and the response shows near to this value, compared to the STSMC it has less response eventually.

Since the mechanical torque can be calculated at the rated value is the ratio between the rated mechanical power and the rated rotor speed, the simulated the controlled mechanical toque is shown in Figure 4.7 is the response of STSMC, SMC and PID.

$$T_m = \frac{P_m}{\omega_m} = \frac{1.5\times10^6 W}{1.811 rad/s} = 0.828\times10^6 N.m$$

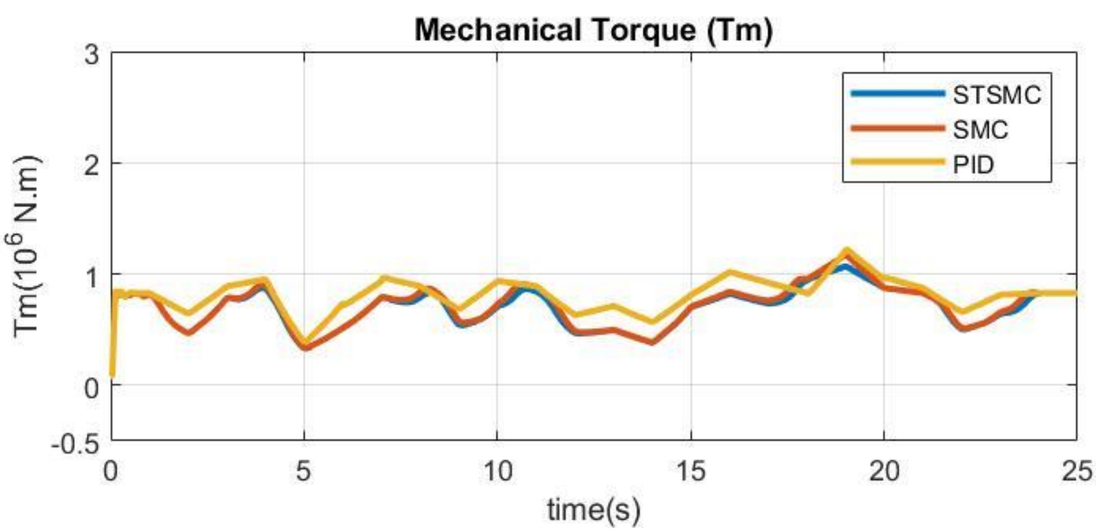


Figure 4.7 Mechanical Torque using STSMC, SMC, and PID

The rotor speed depends on the dynamic models of the drive train which is coupled WT with the PMSG, which feedbacks to the turbine and to the controller input it helps to maintain the extracted power as the wind speed is above rated value. The controller's responses for the rotor speed are illustrated in Figure 4.8. The STSMC response maintains the rotor speed with minimizing the fluctuation error caused by the wind speed, which maintains to track the rated speed as much as possible and it results better compared to the other controllers since the rated speed is 1.811 rad/s.

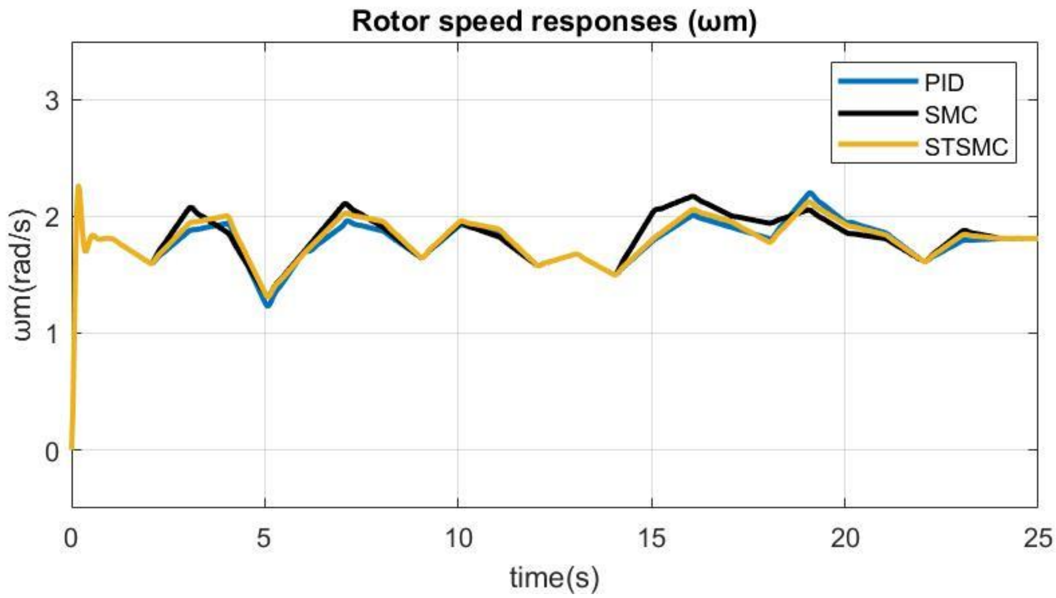


Figure 4.8 Rotor speed with STSMC, SMC, and PID

The simulation result of electrical power depends on the electrical speed and generated electrical torque. Electrical speed is the product mechanical rotor speed and poles. In this study based on the generator parameters the number of poles is 44 as mentioned in appendix A. as shown in Figure 4.9 the rated electrical power responses are:

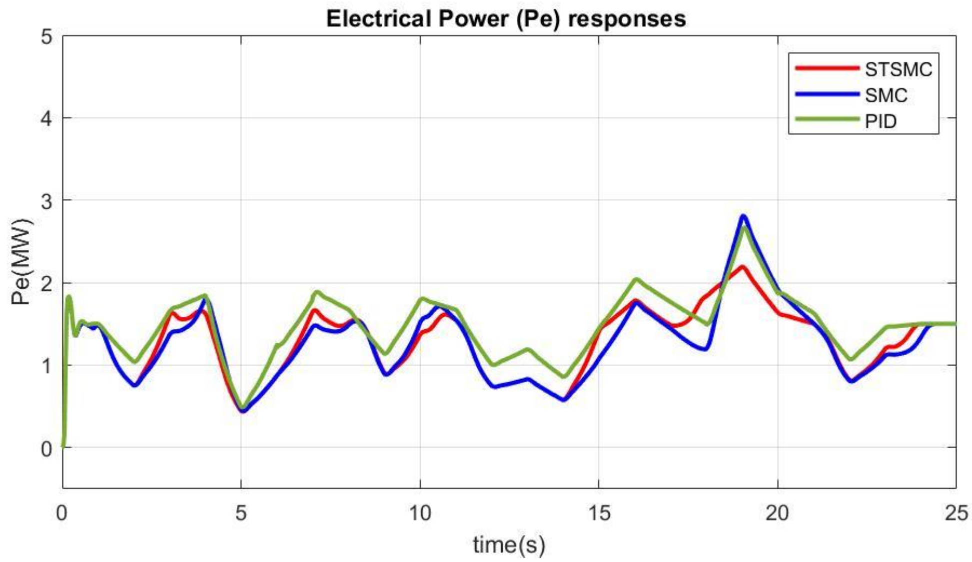


Figure 4.9 Electrical Power with STSMC, SMC, PID

The proposed controller produces error with the reference speed and rotor actual speed. STSMC response in simulation is illustrated in Figure 4.10 which generates the better tracking errors performance based on the minimum distortion frequency than other controllers.

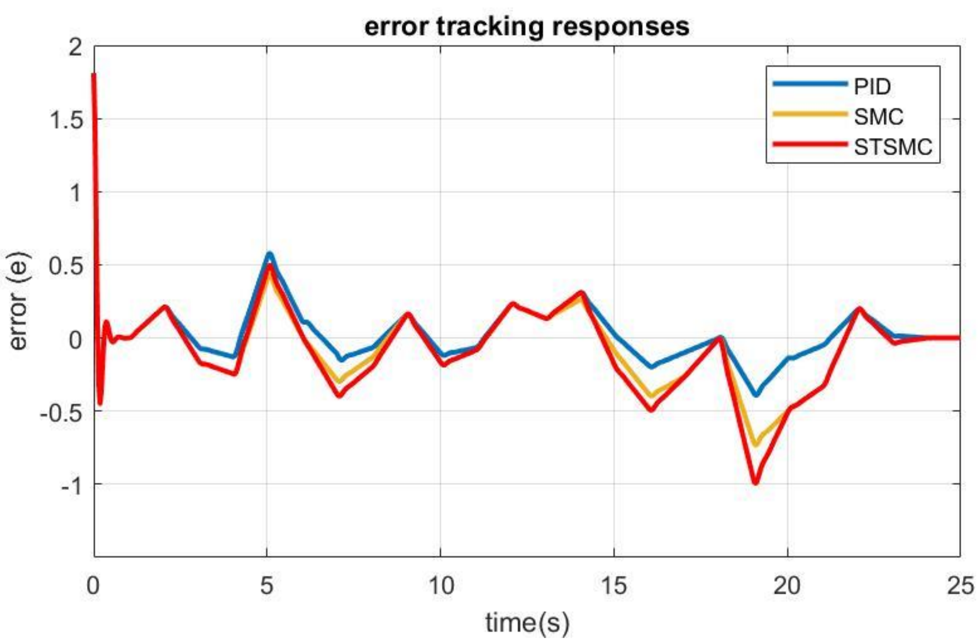


Figure 4.10 STSMC, SMC and PID tracking error responses

The pitch angle response obtained from in figure 4.11 STSMC generates the pitch demand angle which fed into the actuator input, based on the wind speed and the rotor speed. The power output reaches the target value quicker in STSMC than the two controllers. The range of the angle is from 0 to 90 degrees. Where in this sample simulation data of wind speed the maximum speed taken is 17.2 m/s, the PAC is adjusted the β around 1.48, which minimize the output power. Using STSMC provides satisfactory results than the conventional methods SMC and PID controllers. When the wind speed is below the rated, the β will be 0, which makes the maximum power extraction, also as the wind speed is above rated the PAC mechanisms adjusts the angle β to protect WT.

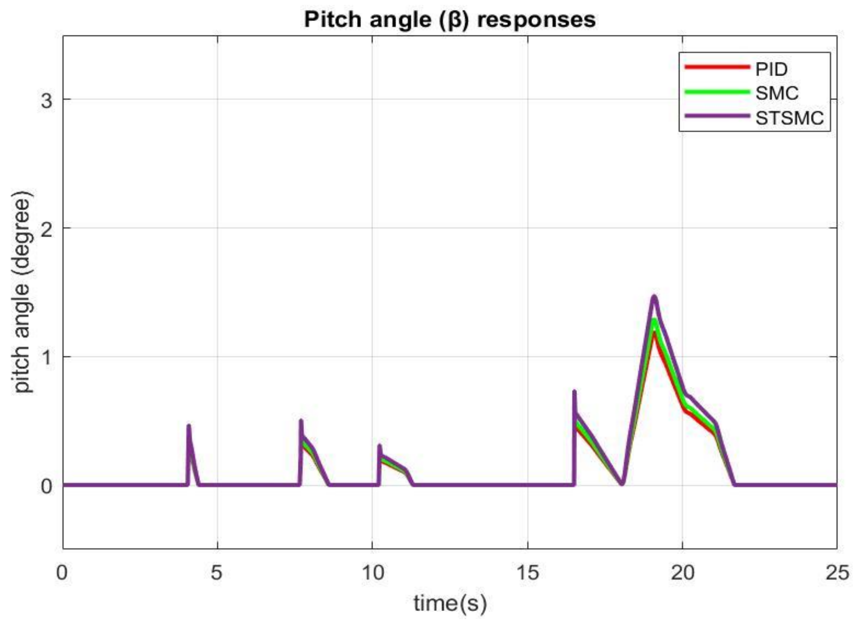


Figure 4.11 Pitch angle responses using STSMC, SMC, and PID

4.3.2 Responses Under Constant Speed Operation

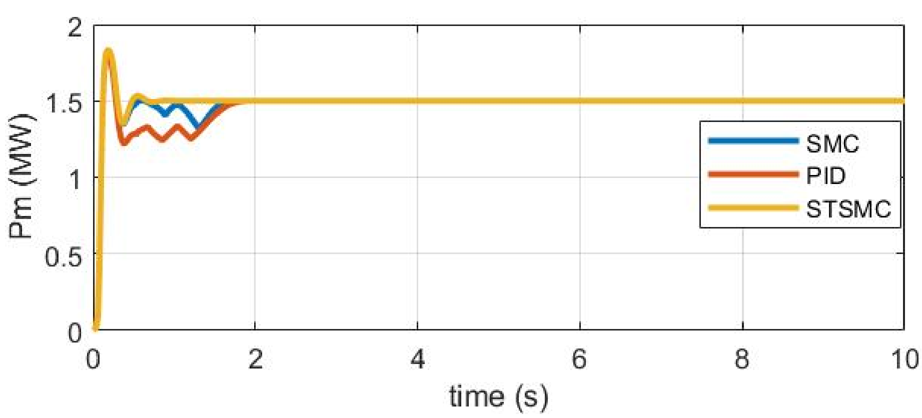


Figure 4.12 Mechanical power with STSMC, SMC, PID under constant speed

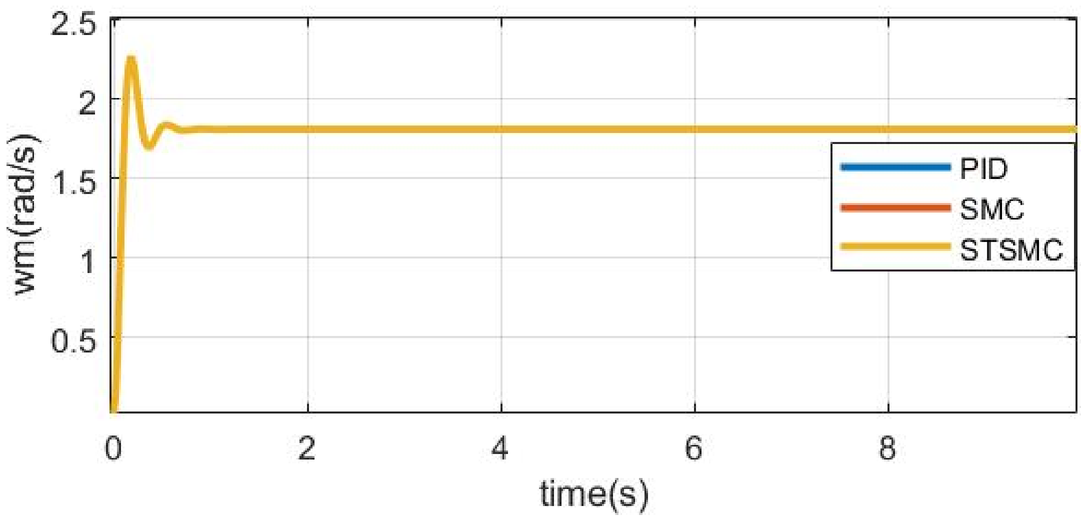


Figure 4.13 Mechanical speed with STSMC, SMC, PID under constant speed

Based on the rated wind speed 11(m/s) the mechanical power and rotor speed is simulation shown in figure (4.18, 4.19, 4.20), the proposed controller STSMC performs better than SMC and PID controllers. According to the simulation result using STSMC results it produced 19.880% overshoot, and the SMC with 21.341%, and PID produced 22.840%. Table 4-1 indicates the response of controller under constant speed.

Table 4-1 Performance responses under constant speed

Controllers	**System Performance**			
	Overshoot (%)	**Undershoot (%)**	**Settling time (sec)**	**Rise time (ms)**
STSMC	19.880	1.942	0.3814	44.671
SMC	21.341	1.982	0.884	44.991
PID	22.840	1.998	1.0211	44.998

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This research has developed a variable speed wind turbine (VSWT) coupled with the PMSG pitch angle controller based on the rotor speed references to maintain the output power of the WT. The system has been demonstrated to be non-linear, with the power production mostly determined by the mechanical torque and the rotor's speed shaft. To achieve best response in MATLAB/SIMULINK, many control algorithms (standard PID, SMC, and STSMC) are utilized to regulate the pitch angle, restrict the extracted power, and manage output of rotating speed.

From the result obtained from the previous chapter, the STSMC controller responses exceeds both the conventional controllers such as PID and SMC controllers. In SMC case the power output will response near to the target value but quickly it will change due to the change of errors, between actual rotor speed and the rated speed there will remain some fluctuations. Therefore, applying supper twisting algorithm make this system to reaches at the rated speed early and minimizes the fluctuations. At 17.1 m/s wind speed using STSMC controller we get 1.811 rad/s and the output power of 1.5MW, which shows that the response of the system under proposed controller shows better performance than the two controller.

Generally, the proposed methods effectively reduce the error between the actual speed and the rotor speed caused by wind speed fluctuations. This improves the impact of wind power output on the operation of variable wind speed systems. This study provides simple, robust, and economical control techniques to limit the impact of wind fluctuations on the power system response, thereby regulating the rotor speed.

5.2 Recommendations

Nowadays, generating electricity from renewable energy sources especially wind, solar and hydropower plant have gotten more attention in the world to decrease environmental pollution and to balance demand and generation of electricity. This research focuses only on regulation of power output and the rotor speed by controlling the pitch angle using STSMC controller using the optimization techniques PSO, this research does not consider the grid connected plant and wind turbine power generation systems. So, I recommend that future research focus the applying the proposed control strategy to design the grid connected system. Furthermore, the proposed controller design generates modest harmonic signals in order to completely overcome these harmonic signals, I recommend that using a hybrid intelligent controller with a nonlinear controller mechanism, such as an adaptive neuro fuzzy inference system and an adaptive super twisting sliding mode controller can able to overcome these problems.

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APPENDICES

Appendix A: List of parameters used

Table A1 Data set of 1.5MW wind turbine

Parameters	Amount	Scale
Wind turbine nominal power	1.5	MW
Wind turbines	34	Quantity
Number of blades	3	Quantity
Rotor radius	37.3	m
Tower height	65	m
Cut-in wind speed	3	m/s
Cut-out wind speed	22	m/s
Optimal TSR (λopt)	6.141	-
Rated wind speed	11	m/s
Maximum Power coefficient (C_{popt})	0.45	
Swept area	4649	m^2

Table A2 PMSG Parameters and Data

Generator Type PMSG, 1.5 MW, 620 V, 12.7 Hz, multi - pole (non-salient pole)		
Parameters	Amount	Scale
Rated Mechanical Power	1.5	MW
Apparent Power Rated	1.6	MVA
Inertia	35000	J(kg.m2)
Rated Power Factor	0. 97	-
Viscous damping	1.5	
Rated torque	9549	Nm
Stator Winding Resistance	0.006	Ω
Rated rotor speed	17.3	Rpm
Speed Range	9-17.3	Rpm
Number of Pole Pairs	44	Quantity
Shaft stiffness	0.3	Pu
Rated current	680	A
Rated Rotor Flux Linkage	1.48	Wb
q axis and d-axis Synchronous Inductances	0.395	mH
Static friction	0.01	

Appendix B: Diagram of Simulink

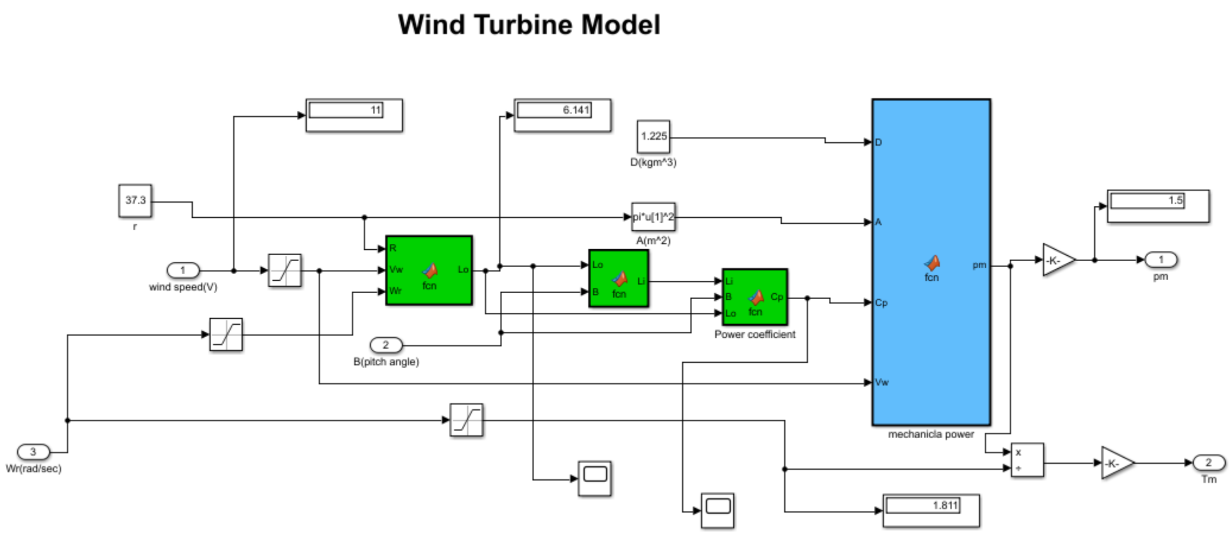

Figure B1 Wind turbine

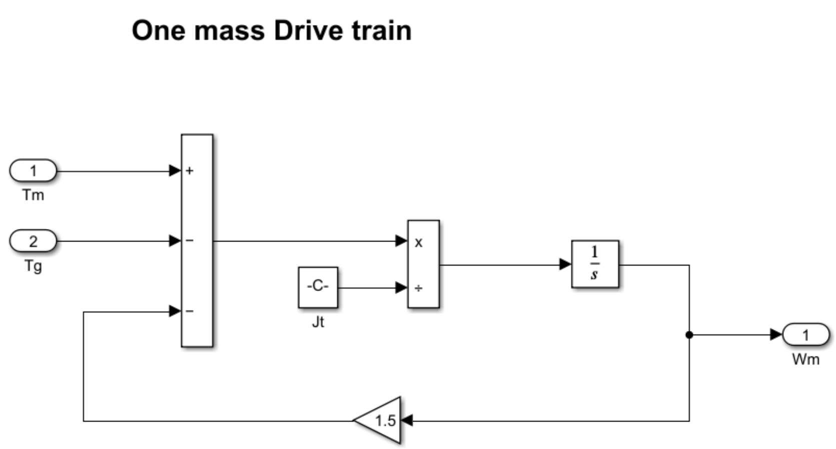

Figure B2 one mass Drive train

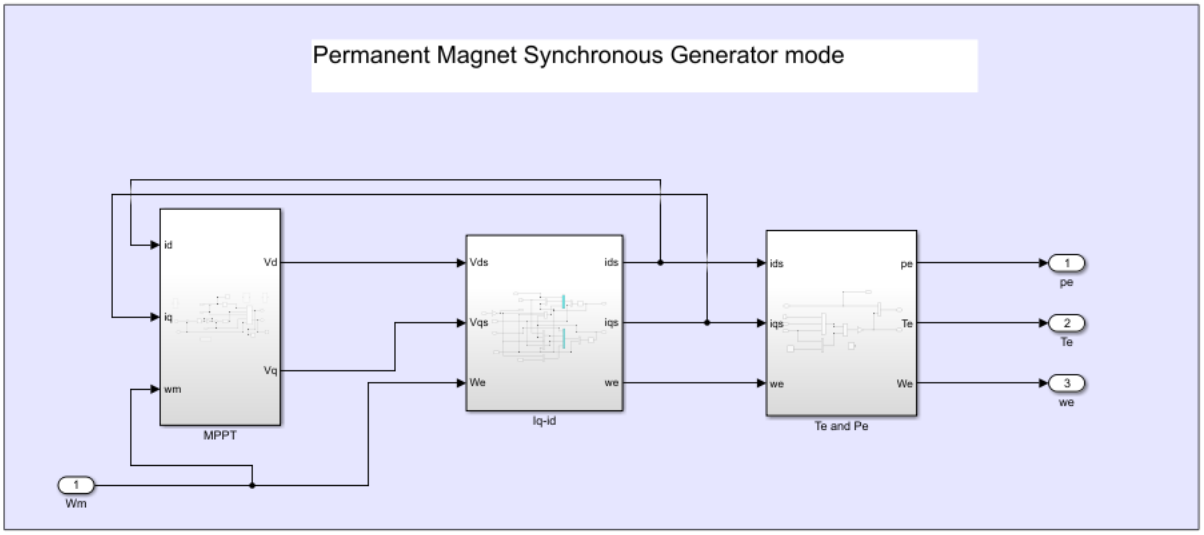

Figure B3 PMSG Subsystem

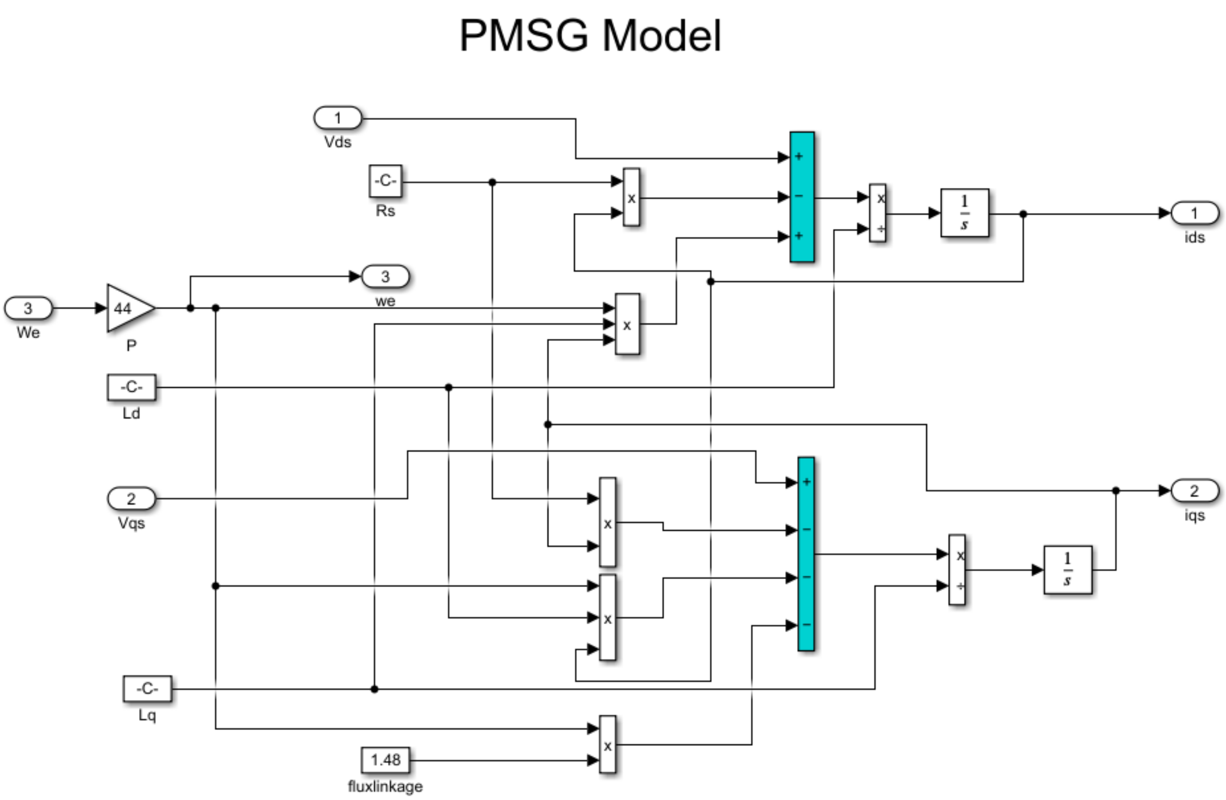

Figure B4 PMSG d-q Model

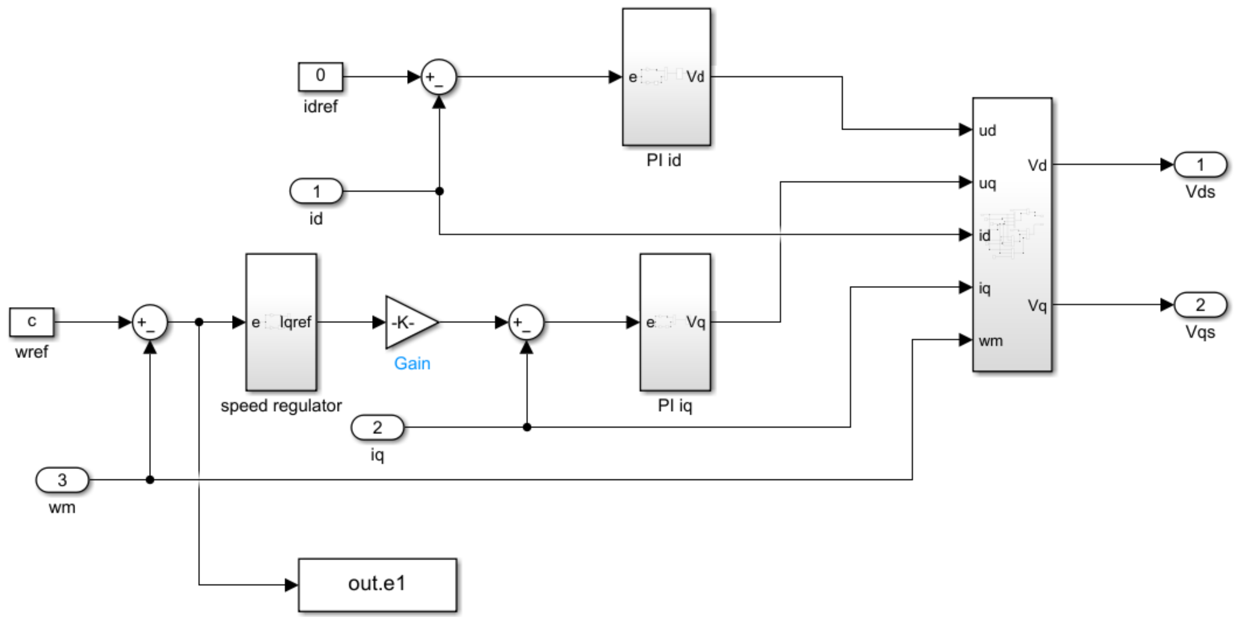

Figure B5 MPPT Rotor Speed Regulation

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