Maximum Power Extraction by PMSG based Wind Energy Conversion System Using Particle Swarm Optimization Fractional Order PI Controller

Tenaye Niguse Wakjira

A Thesis Submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

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

Office of Graduate Studies

Adama Science and Technology University

September, 2024

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DECLARATION

I hereby declare that this Master Thesis entitled "**Maximum Power Extraction by PMSG based Wind Energy Conversion System using Particle Swarm Optimized Fractional Order PI Controller**" is my original work. That is, it has not been submitted for award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Tenaye Niguse Wakjira	________________	________________
Name of student	Signature	Date

RECOMMENDATION

I, the advisor of the thesis, hereby certify that I have read the revised version of the thesis entitled. "**Maximum Power Extraction by PMSG based Wind Energy Conversion System using Particle Swarm Optimized Fractional Order PI Controller**" prepared under my guidance by Tenaye Niguse wakjira. Submitted in partial fulfillment of the requirements for the degree of Master of Science in Control Engineering. Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Prof. Gang Gyoo Jin	________________	______________
Advisor	Signature	Data

APPROVAL SHEET

I, the advisor of the thesis entitled "**Maximum Power Extraction by PMSG based Wind Energy Conversion System using Particle Swarm Optimized Fractional Order PI Controller**" and developed by Tenaye Niguse wakjira, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Prof. Gang Gyoo Jin	______________	______________
Advisor	Signature	Data

We, the undesigned, member of the Board of Examiners of the thesis by Tenaye Niguse Wakjira have read and evaluated the thesis entitled "**Maximum Power Extraction by PMSG based Wind Energy Conversion System using Particle Swarm Optimized Fractional Order PI Controller**" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Control Engineering.

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Finally, approval and acceptance of the thesis are contingent upon the 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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LIST OF ACRONYMS

AC	Alternating Current
DC	Direct Current
DFIG	Double Fed Induction Generator
DTC	Direct Torque Control
FOPI	Fractional Order Proportional Integral
EMF	Electro Motive Force
PWM	Pulse Width Modulation
PMSG	Permanent Magnet Synchronous Generator
MPE	Maximum Power Extraction
MPPT	Maximum Power Point Tracking
PI	Proportional-Integral
IGBT	Insulated Gate Bipolar Transistor
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
PSO	Particle Swarm Optimization
SG	Synchronous Generator
SCIG	Squirrel-Cage Induction Generator
WESG	Wound Rotor Synchronous Generator
TSR	Tip Speed Ratio
VSWT	Variable Speed Wind Turbine
WECS	Wind Energy Conversion System

ABSTRACT

Wind energy is a renewable and environmentally friendly way to generate electricity. Because it is renewable it can reduce our reliance on fossil fuels and contribute to the fight against climate change. it is a reliable sustainable energy source for creating power due to its economic attractiveness with other conventional energy supplies. In wind energy conversion system maximizing power extraction is a crucial goal. To maximize the amount of energy captured from the wind, the system's operation must be optimized. The advantages of wind power for the environment and its economic feasibility are directly impacted by this efficiency. A major obstacle to efficiency and production for wind energy systems is obtaining the most electricity possible from the wind under a variety of wind conditions. A key consideration in wind turbine design is power extraction since under or over extraction leads to wasted energy potential decreased performance and increased expenses. The proposed designs focus on current regulation of PMSG. The objective is to enable the system to operate consistently at a specified current level, thereby optimizing energy capture across a variety of wind speeds. The PMSG adjustable speed wind turbine utilizes optimization to fine tune controller parameters, and Fractional Order Proportional Integral controllers for current control to achieve MPPT. The PSO procedure optimizes PMSG scheme regulator parameters to maximize wind power extraction. The MATLAB simulation study supports the evaluation of these control algorithms. Meanwhile, the FOPI controller demonstrated superior performance in comparison to conventional PI controllers, displaying enhanced dynamic response, improved disturbance rejection, and more accurate tracking of the desired power production. The power extraction graphs show that a fractional order PI controller has a much better transient response then a normal PI controller with wind speed of 12m/s. the settling time is lowered from 0.0034s to 0.000098s, overshoot from 0.693% to 0.126%, and rise time from 0.000069s to 0.000038s. when the wind speed lowers rudely to 8m/s the Fractional order PI controller again outperforms with settling time reducing from 0.004s to 0.001s, overshoot from 2.172% to 0.452%, and rise time from 0.000071s to 0.000028s.The expected outcome of the proposed approaches includes potential enhancements in system efficiency, reliability, and overall performance ultimately, these advancements aim to further promote the utilization of wind energy as a sustainable and impactful power source.

Keywords: *PMSG, FOPI controller, Parameter tuning, PSO, Maximum power extraction.*

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Wind energy can help address both the global energy issue and climate change. Interest in creating environmentally benign energy source to substitute fossil fuels, for instance wind, solar, hydropower, geothermal, hydrogen, and biomass, has surged due to growing worries about global warming, pollution in the environment, and energy security (Borowski, 2022). Recognizing the characteristics of wind energy utilization, from identifying appropriate sites and estimating the financial feasibility of wind farm projects involves designing wind turbines and understanding their influence on power delivery systems and clients. This is due to the fact that the energy accessible in the fluctuates with the wind speed cube (Ghaedi, 2021). Wind energy has been used for approximately three millennia, and the technology has advanced to a fairly sophisticated level. It incorporates technological fields like electrical, mechanical, structural, and aerodynamic engineering. Wind turbines are devices that employ wind energy to generate electricity, as opposed to windmills, which are utilized for tasks like grinding grain or moving water (Bourhis, 2022).

A wind turbine with many blades has a high initial torque but a low TSR. Single-blade wind turbines only have low initial torques but a high TSR. If the wind hits the operating range, these turbines may need to be started (Borowski, 2022) (Bourhis, 2022). Wind turbine designs have evolved ended the past 20 years advancing wind technology, which has resulted in a notable increase in wind power capacity. Wind energy conversation system (WECS) technology has advanced to include direct drive wind turbines and variable speed operation. Compared to fixed-speed processes, variable-speed provides numerous advantages (Hesari, 2018). The overflowing wind energy is extracted using wind energy technology, the process transforms it to mechanical and electrical energy. A generator is then utilized to produce the electrical energy. The wind turbines are essential components of WECS (Fotso, 2021).

Wind turbines are frequently coupled with permanent magnet synchronous generators using drive train technology (Lertnuwat, 2017). PMSG are extensively utilized in several different applications, including wind turbines, where they are essential to the process of transferring wind energy from mechanical to electrical power. Their high efficiency, variable speed operation, small design, and low maintenance requirements make them a desirable option for applications requiring dependable electrical power generation, including renewable energy systems.

This thesis focuses on the harmonious application of PSO and FOPI controller for the purpose of optimizing current control in VSWT utilizing PMSGs. By combining particle swarm optimization, an algorithm inspired by natural behavior, with fractional order proportional-integral, a fractional order control strategy, we aim to harness the synergies of these two approaches for addressing the intricate methodology holds significant promise in enhancing the efficiency and adaptability of PMSG-based wind turbines under various operational circumstances.

1.2 Statement of the Problem

A wind turbine system featuring PMSGs the optimization of power extraction under varying wind speeds is critical for achieving efficient energy generation. permanent magnet synchronous generators, stand out for their notable advantages, including enhanced efficiency, reliability, dynamic response, and environmental compatibility, establishing them as a top option for a range of energy conversion and power production applications. However, problems may arise, its operating inefficiencies prevent it from capturing the most energy from the wind. where in the system might not run at its peak power, resulting in decreased energy production and revenue loss.

To overcome this problem, this paper proposes the use of a FOPI controller to regulate current in PMSG-based wind turbines. The utilization of an FOPI controller aims to rise the degree of freedom, ensure stable and improve the overall performance of wind turbine activities to eliminate recognized concerns and contribute to the development of dependable and well-organized PMSG-based wind turbine systems.

1.3 Motivation

Wind energy a renewable and maintainable alternative to fossil fuels helps to mitigate climate change by lowering greenhouse gas emissions. It makes countries less susceptibility and to geopolitical instability and fluctuations in the price of fossil resources by decreasing reducing dependence on fossil fuels and improving energy security. Wind power generates minimal negative environmental effects improving air quality and ecosystem health. It generates employment opportunities in various industries boosts regional economies and supports businesses generating wind energy components. Wind energy has become more affordable significantly in the last decade improving its competitiveness with traditional energy sources. It diversifies the energy mix reducing disruptions and increasing grid stability. Wind energy conversion system have led to advancements in turbine design control system and grid integration. Current control is crucial for ensuring high-quality electrical power production in wind turbines. It reduces harmonics, enhances power quality, and maintains gird stability. By adjusting generator side currents, the control system optimizes wind turbine’s energy production and conversion efficiency. This ensures steady performance and grid compatibility. The system also regulates reactive power output enabling the PMSG to supply or absorb voltage enhancing grid stability and reliability. Current control also helps the wind turbine system withstand grid failures and disturbances ensuring system stability and reactive power support.

1.4 Objectives of the Thesis

1.4.1 General Objective

The primary objective of this thesis is to achieve maximum power extraction in a PMSG-based wind energy conversation system by utilizing a particle swarm optimized fractional order PI controller.

1.4.2 Specific Objectives

This thesis aims to accomplish the following precise goals:

- To study a PMSG mathematical model in a wind energy conversion system.
- To design a cascade technique that composes the primary FOPI speed regulator and the secondary PI current controllers.
- To tune the controller parameters using PSO.
- To simulate the scheme with MATLAB/Simulink in order to verify performance and assess the overall system effectiveness.

1.5 Scope of the Thesis

The scope of this thesis is to create a variable-speed regulator for PMSG based on optimization techniques. The study examines usage of the FOPI control in the PMSG scheme, focusing on their effectiveness in improving control performance, stability, and disturbance rejection in wind energy capture. The study using Simulink/MATLAB model severely tests the accuracy and reliability of the proposed method to optimize energy extraction, aiming to contribute valuable insights to the field of renewable energy control strategies.

1.6 Limitation of the Thesis

The fact that the component is unavailable in our nation and that their creation takes more time and money makes it challenging to execute the actual system. That's why this thesis will only be implemented in MATLAB/Simulink; it won't be executed in real life.

1.7 Significance of the Study

The paramount importance of maximizing power extraction efficiency from wind turbine for sustainable energy production cannot be overstated. This study holds significant relevance as it seeks to contribute to the enhancement of performance and efficiency in PMSG wind turbines, pivotal components of renewable energy systems. The optimization of power extraction achieved through this research not only advances the capabilities of PMSG wind turbine but also production. An important role in promoting the adoption of wind energy as a clean and sustainable power source. Such advancements align with global initiatives aimed at mitigating greenhouse gas releases and accelerating the adoption of renewable energy, underscoring the study's meaningful impact on the broader goals of sustainable energy development.

This study assesses the influence of PSO-based optimization and fractional order PI control on the functioning and stability of PMSG wind turbine. Through a comprehensive analysis encompassing power extraction efficiency, system dynamics, and responses to variable wind conditions and load fluctuations, the research provides insights in to the effectiveness of these strategies. The findings aim to shed light on the capacity of PSO-based optimization and FOPI control to uphold stable and reliable operation in PMSG wind turbines, thereby contributing to advancements in wind energy technology.

1.8 Outline of the Thesis

The thesis is organized into six chapters:

Chapter one: this chapter provides background information for the thesis and articulates the problem statement under investigation explains the motivation driving the research outlines the objectives guiding the study defines the scope within which the examine operates and underscores the implication of the study's contributions.

Chapter two: A long with advice on how to perform a literature review in these areas the talker gives a quick summary of the basic concepts underlying WECSs and PMSGs.

Chapter three: outlines the steps to complete the thesis development. This chapter gives a complete mathematical model of the wind energy conversion system, which includes the wind turbines, drive train, PMSG, rectifier, and inverter.

Chapter four: This section provides the PI controller and fractional order PI controller design.

Chapter five: Presents the proposed outcomes and conversations.

Chapter six: Discusses findings and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Chapter Overview

This chapter examines wind energy configurations, such as wind turbine with permanent magnet synchronous generator schemes. and advantages of this generator. The review concludes by examining previous related works.

2.2 Wind Energy Conversation System

WECS operates in a very simple manner. The turbine's blades rotate as a result of wind passing over them. The generator receives the rotational energy from the blades and transformer it into electrical energy via a shaft. after then residences and businesses receive the electricity through a network of transformers and power lines. The major components of the system comprise a wind turbine to harness wind energy and a PMSG to convert mechanical energy into electricity, a MPPT controller optimizes energy capture and a generator side controller regulates power output (Ameni Kchaou, 2018). Wind energy is transferred in two stages via a WECS. The mechanism for harvesting mechanical electricity is called the wind turbine rotor, and it revolves in response to wind speed.

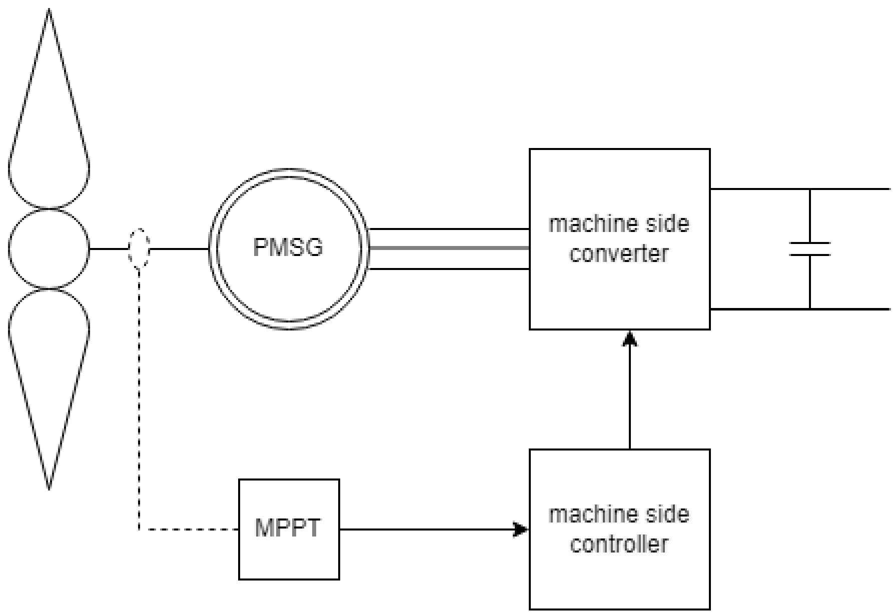

Figure 2.1: Block schematic of a WECS

2.2.1 Components of a Wind Turbine Generator Schemes

A wind turbine system's parts are made to cooperate with one another in order to efficiently harvest wind energy. Every part is essential to the system's overall functionality and performance. These components engineering and design have been meticulously refined to increase energy capture boost dependability and guarantee secure functioning. The proper integration and coordination of these components are essential to the system's effectiveness and efficiency. The wind turbine system comprises several essential components meticulously designed to harness wind kinetic energy efficiently:

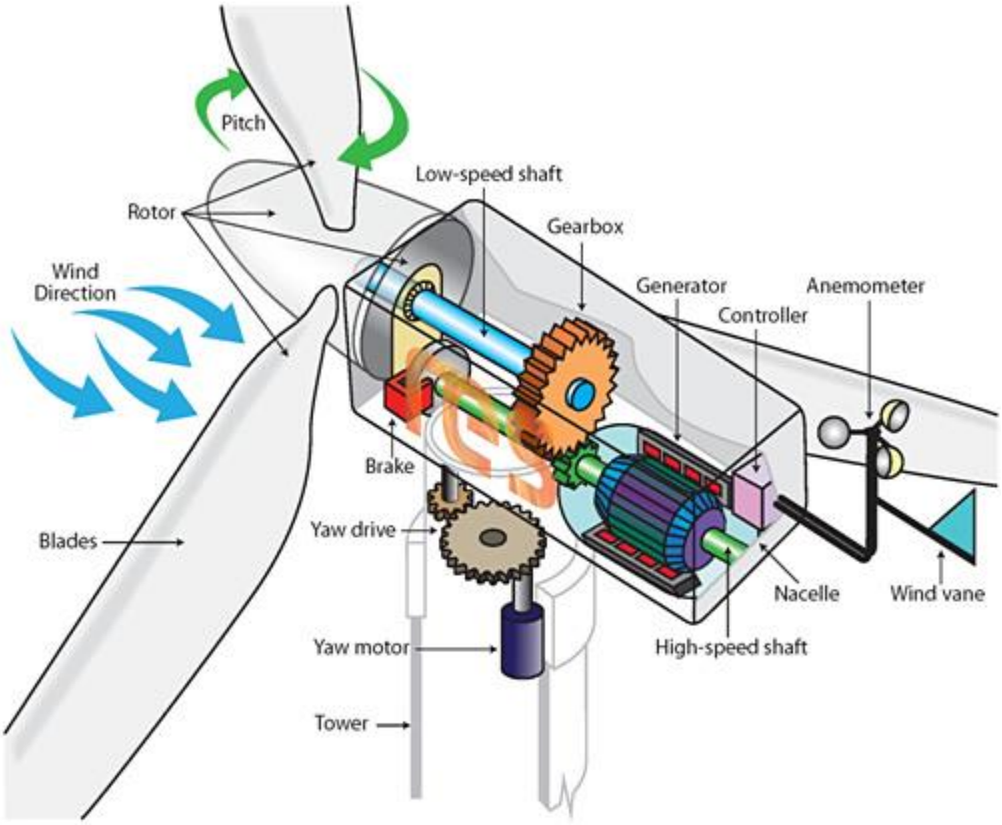

Figure 2.2: Component of wind turbine **(Rafaat, 2018)**.

(1) Rotor blades: these aerodynamically designed blades, affixed to the rotor hub, capture wind energy and are constructed from durable composite materials like fiberglass or polymers.

(2) Rotor hub: serving as a pivotal point hub transfers the rotational energy from the blades to the core shaft, which allows wind energy to be effectively converted in to mechanical power.

(3) Main shaft: this vital component connects the rotor hub to the generator, enabling seamless conversion of rotational energy into mechanical power.

(4) Gearbox: integral to the system, the gearbox optimizes rotor speed to match generator specification, ensuring efficient electricity generation.

(5) Generator: typically, a synchronous or doubly-fed induction generator, this component often found behind the gearbox, transfers mechanical energy into electrical energy.

(6) Yaw system: comprising yaw drive motors and a precision controller, this system dynamically aligns the turbine with the wind, maximizing energy harnessing efficiency.

(7) Tower: constructed primarily from steel or concrete, the two provides structure support, elevation, and height adjustment based on turbine size and wind conditions.

(8) Nacelle: positioned atop the tower, the nacelle shields critical components like the rotor hub, gearbox, and generator from environmental conditions, ensuring operation integrity.

(9) Control system: central to turbine operation, this system, consisting of sensors and controllers, optimizes efficiency and ensures safe, reliable operation, crucial for wind energy conversion.

(10) Foundation: a robust concrete structure, the foundation is essential for structural stability, transferring loads to the ground and enhancing the turbine's resilience against wind and gravity forces.

2.2.2 Operating Region of the Wind Turbine

Figure 2.3 displays the power curve of an adjustable speed variable pitch wind turbine, illustrating its capacity to generate power at various wind speeds. Optimizing power extraction is to make sure the wind turbine runs as efficiently as possible for the specific wind speed. For the turbine to produce the most power this means modifying the pitch angle or rotational speed. the power extraction optimization region is the area between the cut-in speed and the rated power.

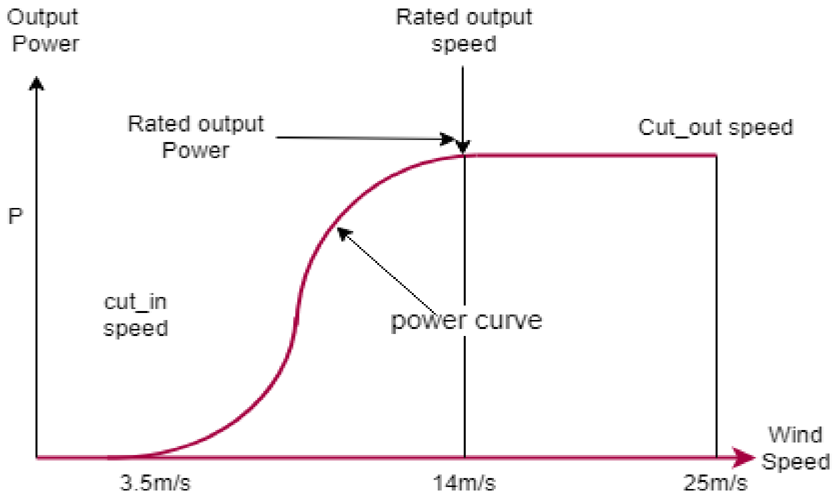

Figure 2.3: Power curve of the VSWT

(1) Cut in wind speed: wind speeds below this point on the power curve are insufficient to initiate turbine rotation and generator electricity. Consequently, the turbine does not produce any power output in this range.

(2) Low wind speed region: variable speed turbines excel in harnessing wind energy as they have the ability to optimize power extraction by dynamically adjusting the rotor speed increases in response to higher wind speed. This progressive increase in power output beyond the cut-in threshold demonstrates the superior performance of variable speed turbines.

(3) Rated power region: when the wind speed achieves its rated value, a turbine produces the most power possible. Variable speed turbines use finely regulated rotor speeds to maintain a steady power output. By dynamically adjusting the rotor speed variable speed turbine can effectively respond to changes in wind conditions and consistently operate at their optimal performance point maximizing power extraction and achieving the intended maximum power output.

(4) Cut-out wind speed (High wind speed region): for safety reasons wind turbine are designed with a cut-out setting beyond which the turbine automatically shuts down. When wind speed exceeds the cut-out threshold the turbine operates ceases operation resulting in a power output of zero. This safety feature is implemented to protect the turbine from excessive loads and potential damage that could occur during high wind speed circumstances, ensuring the turbine's durability and integrity.

2.3 Types of Wind Turbine

Wind turbines use a blade attached to a rotor hub to transform kinetic energy into mechanical energy. Wind turbines are classified into two types: horizontal axis wind turbines and vertical axis wind turbines. each has advantage and downsides. Since HAWT has a major advantage over VAWT, it is the most desired wind turbine alternative and has received greater money for research and development (Zou, 2020).

2.3.1 Horizontal Axis Wind Turbine

Horizontal axis wind turbine which has rotors similar to airplanes are the most commonly used design. The wind turbine consists of horizontally oriented blades that harvest energy from the wind. The aerodynamic lift causes the blades to spin when they face perpendicular to the wind velocity (Muhd Khudri Johari, 2018). Because HAWT is designed to collect energy by maximal rotation of the blades when exposed to a steady wind flow. it is more efficient than VAWT at doing so. Even through HAWT is best suited for using more wind energy, one major disadvantage is that, in order for it to work effectively, it must always be pointed in the way of the wind. When the way of the wind is unpredictable, to extract the greatest power generation an additional mechanism is required to ensure that the blades continue to face the wind's direction(Aisha Sa'ad, 2018).

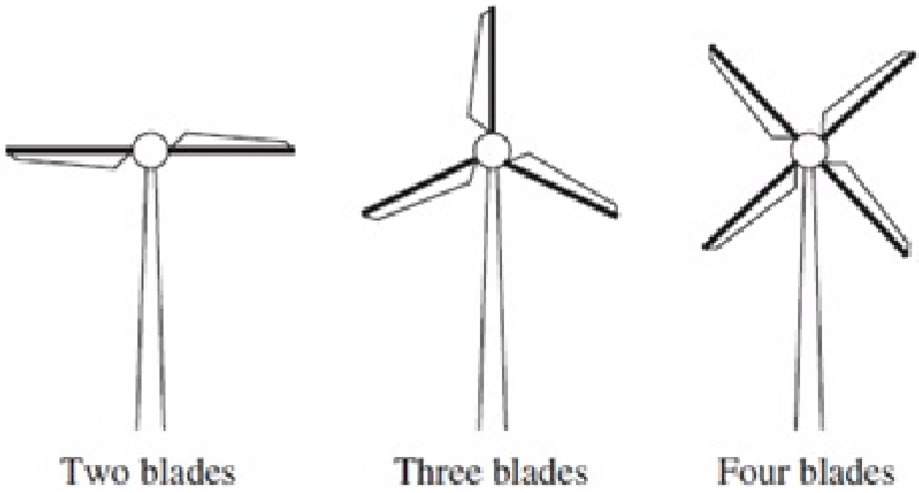

Figure 2.4: A horizontal axis wind turbine

2.3.2 Vertical Axis Wind Turbine

VAWT blades rotate perpendicular to the ground through their longitudinal poles. This kind of turbine runs by using a combination of the two turbines, drag, or lift. it is differing from HAWT in part because its massive machinery is on the ground and it can capture wind from all directions. Due to its ground-mounted design, the device makes building the wind tower easier and consequently lowers the turbine's cost (Chen, 2024). The drawback of vertical axis wind turbine is that because of its inadequate starting torques and issue with dynamic stability, it is useless in high-speed wind environments. It makes it susceptible to backpedaling since the blades rotate similarly to the wind and must first turn back in the way of the wind flow before being forced to turn about Vertical axis wind turbines can be separated into the darrieus and savonius rotors which are the two main varieties. The darrieus rotor operates on the ideal that its lift from revolving aerofoils causes it to rotate around a mid-axis; in contrast the savonius rotor alternates because of the effort produced by its blades. The darrieus rotor can be classified into three distinct types, as demonstrated in figure 2.5. These include the D type, H type, and helix type (Amlan Das, 2016).

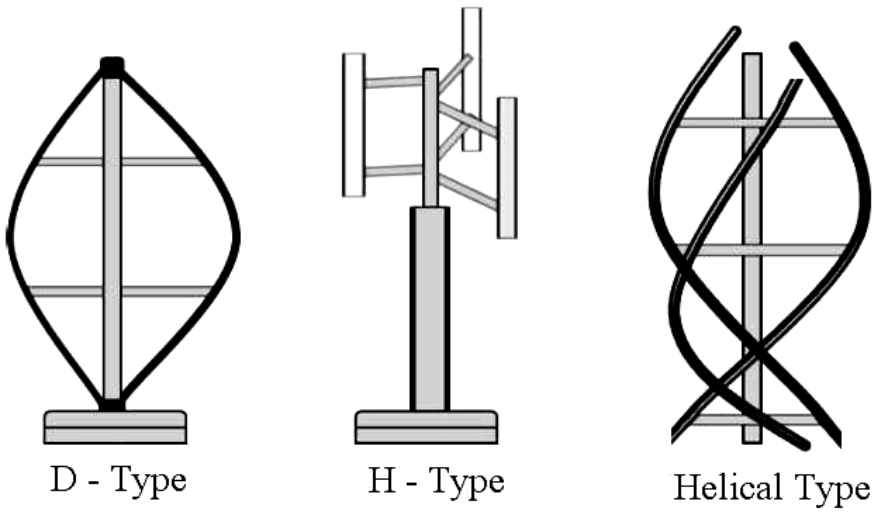

Figure 2.5: A vertical axis wind turbine

Table 2.1: Contrast between HAWT and VAWT

Types of wind turbines	Advantages	Disadvantages
HAWT	➢ Highly efficient ➢ Well-established technology ➢ Scalability	➢ Visual impact ➢ Bird and Bat collision ➢ Nosie
VAWT	➢ Omnidirectional ➢ Lower maintenance ➢ Urban application ➢ Quieter operation	➢ Lower efficiency ➢ Structure loads ➢ Less established technology

2.3.3 Overview of Wind Turbine Generators

During the initial phases of wind power production wind farms primarily used fixed speed wind turbines and induction generators. The turbines were linked directly to the electric grid eliminating the need for converters. However, drawbacks such as low efficiency, limited ability to withstand faults, and substantial power fluctuations were associated with these generators. Extensive literature exists on variable wind speed turbine systems employing PMSG. Variable speed wind turbine schemes use either double fed induction generator with partially rated power electronic borders or PMSG with fully rated interfaces (Aisha Sa'ad, 2018). These technologies form the cornerstone of modern wind power generation, offering enhanced efficiency and stability.

2.3.3.1 Squirrel Cage Induction Generator based WECS

During the 1980s, when most wind turbine technologies were directly linked that is, fixed speed SCIG are widely used in larger wind turbines that are directly connected to electricity grid. As a result, the generator's rotating speed is not totally consistent (Abo-Khalil, 2021). The fixed-speed wind system based on an induction generator using a squirrel cage is depicted in figure 2.6.

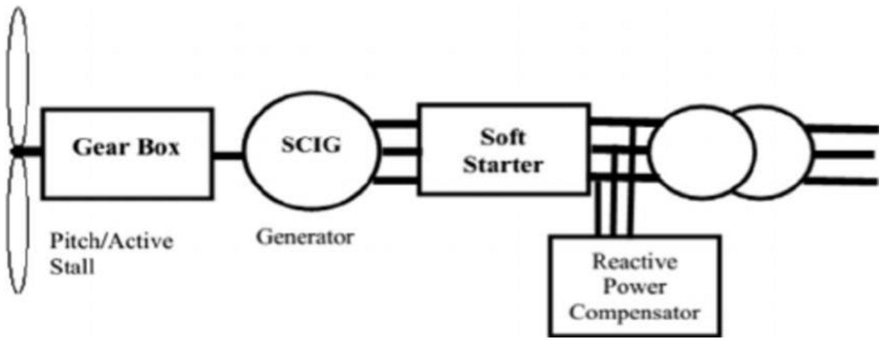

Figure 2.6: Induction generator for squirrel cages with fixed speed **(Sajid Hussain Qazi, 2016)**.

2.3.3.2 Doubly Fed Induction Generator based WECS

The DFIG-based WECS connects to the power supply through a partially rated converter coupled to the rotor circuit, whereas the stator is directly connected to the grid. To protect the converters, a crowbar circuit is attached to the rotor side converter is controlled in order to control generator speed and maximize wind energy capture. Furthermore, by decoupling active and reactive power the rotor side converter can regulate the reactive power fed into the grid. (Mohamed Hallouz, 2023).

2.3.3.3 Permanent Magnet Synchronous Generator based WECS

A completely rate power electronic converter connects the grid to the WECS which uses a permanent magnet synchronous generator. The fully rated power converter allows for better fault ride through capabilities and complete controllability of the system by completely decoupling the wind turbine from grid disturbances. The WECS in thesis study is run by a direct-drive PMSG. Thus, a thorough analysis of PMSG modeling and design will be conducted (Mohamed Abdelrahem, 2016). The full-scale power convertor enables an effortless grid connection at all speeds. This architecture's power electronic converters perform two functions operating as an energy barrier DC link for wind turbine power fluctuations and grid transients and managing active and reactive power.

PMSG systems have enhanced electrical efficiency because they lack field winding and excitation losses. The use of permanent magnet in PMSGs increases system reliability and reduces maintenance requirements PMSG system feature a simpler generator design compared to double fed induction generator which require slip rings and brushes. The full-scale power convertor in PMSG scheme enhances grid synchronization and regulator of active and reactive power leading to smoother grid integration. This converter allows the generator to operate at varying speeds enabling maximum power point tracking and increased energy capture. Achieving this variable speed operation is more challenging with partially rated power converted used in DFIG systems. Eliminating slip rings and brushes in PMSG system reduces maintenance needs and costs. Higher overall system efficiency translates into lower operating expenses over the wind turbine's lifetime. PMSG system are particularly well suited for offshore and remote wind farm application due to their increased reliability and minimal maintenance requirements. This is especially important in area with limited access and extreme climatic conditions.

Table 2.2: Contrasts between SCIG, DFIG and PMSG.

Generator types	**Advantages**	**Disadvantage**
Squirrel cage induction generator	➢ Simple solution for grid connection ➢ Easy to maintain ➢ Low cost ➢ Simple structure	➢ Lowest power factor ➢ Lowest efficiency ➢ It does not maintain an optimal tip speed ratio when speed varies
Doubly-fed induction generator	➢ Inexpensive small capacity PWM inverter ➢ The RSC enable for the regulation of reactive power provided to the grid.	➢ Regulator method s grid faults are quite complicated ➢ Need for gear ➢ Need slip rings

	➢ Complete regulator of reactive and active power	
Permanent magnet synchronous generator	➢ Low maintenance cost ➢ Easy of Controllability ➢ Improve the efficiency ➢ High energy density ➢ Self-excitation system	➢ Permanent magnets needed ➢ Full scale power converter ➢ Multipole generator

A wind energy system is comprised of two fundamental elements: a wind turbine and an electrical generator. The main goal of a wind turbine is to convert kinetic energy into mechanical generator. Meanwhile, the electric generator works as a prime mover, converting mechanical energy from the wind turbine into electric energy that is transferred to the electrical grid. bracket of the most common configurations is given in figure 2.6; wind turbine can be classified models. Fixed-speed turbines use a squirrel-cage induction generator, while variable-speed turbines can be direct or indirect driven. Low-speed synchronous generator is used by direct-drive turbines, although generous and permanent magnet synchronous generator with wound rotor is appropriate. (Abdelrahem, 2016). These turbines require a full-capacity power converter system.

Table 2.3: Contrasts between fixed speed and variable speed wind turbine.

WECS of wind turbines	**Advantages**	**Disadvantages**
Fixed speed	➢ Low upkeep ➢ Humble and robust construction ➢ Low cost	➢ Fewer efficiency ➢ Fewer power factors ➢ Advanced stress on turbine ➢ No regulator ended the active or reactive power

Variable speed	➢ Advanced efficiency ➢ Independent control of active and reactive power	➢ Limited fault managing capability ➢ Higher cost of power electronics

2.4 Wind Turbine PMSG System

A wind turbine PMSG system is a type of wind energy conversion system that uses a PMSG to convert wind energy into electrical energy. PMSG systems are becoming increasing popular in wind applications due to their great efficiency, dependability, and little maintenance requirements. The generator shaft transfer torque to the generator's rotor. The mechanical system accelerates or maintains a steady speed based on the differential among the mechanical torque on the wind turbine and the electrical torque on the generator (Ayadi, 2019). The d-axis reference current is adjusted to zero to reduce copper losses in the stator windings. The q-axis reference current varies with wind speed and is proportional to an MPPT control torque reference.

2.5 Related Works

The study describes a novel approach to designing a dissociated PI current controller for PMSG based turbines for wind power that combines feedback linearization and disturbance observer-based control. The proposed controller ensures improved transient performance during control saturation and recovery from model uncertainty. The proposed controller ensures better transient performances under control saturation and model uncertainty leads to minimal transitory performance recovery. But the proposed approach's uniqueness and effectiveness for PMSG-based wind turbines may have been better understood if comparisons with other current control system for these turbines were included explicitly (Rachid Errouissi, 2018).

The maximum power extraction in WECS, which is crucial for optimizing wind turbine performance and utilizing renewable energy the use of a generalized global SMC algorithm and feed forward NN for estimating uncertainties and controlling the wind turbine allows for robust MPPT control, ensuring stability and performance in practical scenarios. However, there could be a lack of robustness and effectiveness of existing MPE strategies in WECSs under variation in wind speed and parametric uncertainty (Izhar Ul Haq, 2020).

The investigate offers integral backstepping control a robust nonlinear control approach designed to our wind energy conversion technology utilizes PMSG to maximize power extraction. This technique overcomes the limitation of standard proportional integral controller particularly in system with changeable structures resulting in improved MPPT performance. The authors use comprehensive simulation to demonstrate the recital of the integral BSC in comparison to conventional PI controllers particularly under condition of variable wind speeds. The result demonstrates the integral backstepping controls better capacity to path the optimal rotor speed and extract maximum power. However, while the integral backstepping controller improves power extraction it introduces larger current and DC bus voltage ripples than the PI controller. Furthermore, the paper observes a rise in total harmonic alteration in stator currents with the integral backstepping control which may influence the quality of electricity sent to the system. This issue shows that further analysis and potential mitigating techniques are required to ensure grid compliance (Mohamed Makhad, 2020).

In this study an integral linear quadratic regulator with servomechanism for the machine side power converter in variable speed wind energy conversion systems based on permanent magnet synchronous generators is introduced. This novel method improves the efficiency of power extraction, which is a noteworthy development in the sector. Even in the presence of noise and unclear models, the suggested control method performs exceptionally well at reducing tracking errors. A thorough stability analysis validates the control technique's closed loop stability, guaranteeing consistent and dependable system performance across a speed data is enhanced by the employment of high order disturbance observers for aerodynamic torque estimation which is essential for the overall performance of the WECS. However, the precise assessment of aerodynamic torque and model parameters is critical to the control system's efficacy. Any differences in these estimates could result in less-than-ideal performance, exposing a possible weakness in the system (SARSEMBAYEV, 2024).

The sensorless high power output regulator system for small scale wind power conversion using a PMSG is simple low cost and responsive to wind speed variations, however. The traditional perturb and observe method for MPPT has limitations such as poor response low efficiency in quickly varying wind speed situations and difficulties setting the stage size to precisely follow the greatest power point. A straightforward sensorless peak power extraction control strategy a wind energy conversion scheme with variable speed using a PMSG. The established control method allows for the approximation of the PMSG generator's speed and the extraction of maximum power from wind energy by calculating the mechanical power generated from the wind power. however, does not provide a comprehensive comparison with existing control strategies or alternative approaches for maximum power extraction in VSWECSs, also does not address the impact of varying wind conditions or disturbances on the performance of the control strategy (Kushwaha, 2020).

Although different control solutions have been suggested to maximize PMSG power extraction in WECS, problems with parametric errors and wind speed unpredictability still exist. Even with these developments, explicit tuning consideration for these strategies have frequently been disregarded. In order to solve these problems and improve transient response and disturbance rejection this paper presents a unique method that combines a fractional order PI controller with PSO. The body of literature consistently highlights the superior control performance offered by FOPI controllers when comparative to traditional integral-order PI controllers. Leveraging fractional order calculus provides a level of flexibility that proves advantages in capturing the nuanced dynamics of wind turbine systems, facilitating the achievement of specific control objectives. Through the incorporation of fractional differentiation and integration orders, FOPI controllers exhibit a remarkable ability to the inherent nonlinearities, uncertainties, and time-varying characteristics intrinsic to wind turbine systems. This adaptability translates into an improvement in control accuracy and stability.

CHAPTER THREE

METHODOLOGY AND SYSTEM MODELING

3.1 Materials

The system model in this thesis is tested and analyzed through simulation using the MATLAB software package that is a general-purpose computing program with a large number of toolboxes. It has sophisticated mathematical package toolboxes with graphic user interface and numerical solution capabilities. Additionally, the documentation is written entirely in Microsoft Office, and formulas and equations are written in Math Type equation editor 7.0.

3.2 Methods

In order to attain the objective of the thesis, the next methods and strategies will be followed.

- Literature Review: In order to know what has been done previously and what needs to be improved for greater performance/efficiency in multi directions, thesis work requires previous work in relevant field. The thesis relies on previous academic work on the same issue, requiring thorough reading of their publication to gather essential information. There will be references to a variety of literatures from range of accessible sources, including books, journal, the internet, etc. As a result, reading books, articles, journal paper, modeling tools, and conducting online searches in relation to PMSG control system, and fractional order PID controllers, and their application.
- Data Collection: The information required to develop the wind energy conversion system is acquired from a number of sources, including as books, journals, papers, and websites. It is possible to create a fractional order PI controller by using the input and output data form a standard PI controller.
- Data Analysis: The collected data and reviewed literatures are analyzed to have proposed design and to get better performance efficiency.
- Conclusion and Recommendation: After assessing the designed system the thesis will be completed by offering suggested recommendations and further work.

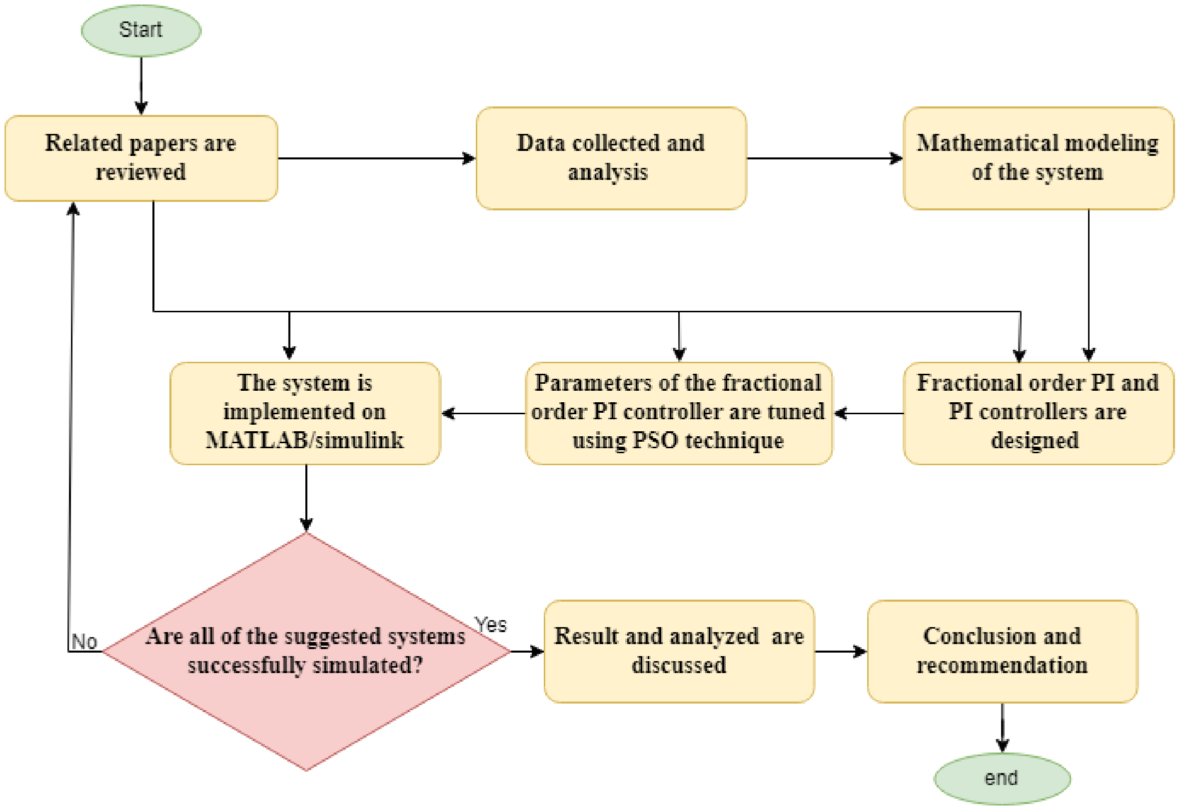

Figure 3.1: Block diagram for the suggested system technique

3.3 Wind Turbine Modeling

A wind turbine is used in a wind energy conversion system to harvest kinetic energy from the wind. The rotating blades of the turbine convert this energy into mechanical power, which turns the rotor of a generator attached to it producing electricity. The generator attached to the turbine then transforms the mechanical energy into usable electricity. The kinetic energy due to air for a moving object with mass and speed:

$$k_{\varepsilon} = \frac{1}{2} m v_w{}^2 \tag{3.1}$$

where m is the mass passing through a specific point per second and V_w is represents the wind speed. Wind power captures the energy carried by the wind, measured as the change in kinetic energy measured per unit time:

$$p_w = \frac{dk_{\varepsilon}}{dt} = \frac{1}{2} \dot{m} v_w{}^2 \tag{3.2}$$

It quantifies the quantity of mass flowing complete a cross-sectional area in one second involves measuring the mass of fluid that crosses an area perpendicular to its flow direction in given time frame as:

$$\dot{m} = \rho A v_w \tag{3.3}$$

where ρ represents the air density and A represents the cross-sectional area. Replacing Equation (3.3) into Equation (3.2) with the fact of $A= \pi r^2$ gives the following equation:

$$p_w = \frac{1}{2}\rho \pi r^2 {v_w}^3 \tag{3.4}$$

A variety of parameters determine a wind turbine's mechanical output, including air density, rotor radius, wind speed, angular velocity, power coefficient, tip speed ratio, and pitch angle. These variables are important factors in the equation that reflects the conversion of wind energy captured by the blades to mechanical power:

$$p_{mech} = C_P P_w = \frac{1}{2}\rho \pi r^2 {v_w}^3 C_P(\lambda, \beta) \tag{3.5}$$

where C_p represents the power coefficient, λ represents the tip speed ratio and β represents the pitch angle.

The power coefficient fluctuates with the turbine's tip speed ratio; it is not a stationary value as stated in the foremost question. The fundamental power coefficient formula utilized for simulation purposes can be distinct depending on the tip-speed ratio and prior literature study the following blade pitch angle:

$$C_P = c_1\left(\frac{c_2}{\lambda i} - c_3\beta - c_4\right)\mathrm{e}\frac{-c_5}{\lambda i} + c_6\lambda \tag{3.6}$$

where the values of c_1, c_2, c_3, c_4, c_5, and c_6 are $0.5170, 116, 0.4, 5, 21 \,\&\, 0.0068$, respectively. The manufacturer provides the coefficient values, which vary based on the kind of wind turbine (Abo-Khalil, 2021).

$$C_P = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{3.7}$$

$$\lambda_i = \frac{1}{\left[\dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.035}{\beta^3 + 1}\right]} \tag{3.8}$$

The blade space's pitch angle is denoted by β Pitch angle refers to the angle generated by the blade's orientation and wind speed. Wind turbines generator the most power from wind when the pitch angle is zero, meaning that the wind velocity fully affects the blade. The tip speed ration is the proportion of the rotor's rotating speed to the wind speed. the formula provides the tip speed ratio (Castillo, 2023). The TSR is a dimensionless quantity that represents the connection among the speed of the blade tip and the unaffected wind speed. The mechanical torque of the turbine is taken into:

$$T_{mech} = \frac{P_{mech}}{\dot{\omega_r}} = c_p \frac{P_w}{\dot{\omega_r}} \tag{3.9a}$$

$$\omega_r = \frac{\lambda v}{r} \tag{3.9b}$$

Substituting Equation (3.9b) into Equation (3.9a) gives

$$T_{mech} = \frac{1}{2}\rho\pi r^3 C_p(\lambda,\beta)\frac{v^2}{\lambda} \tag{3.10}$$

Figure 3.2 shows the Simulink classical that implements Equation (3.10).

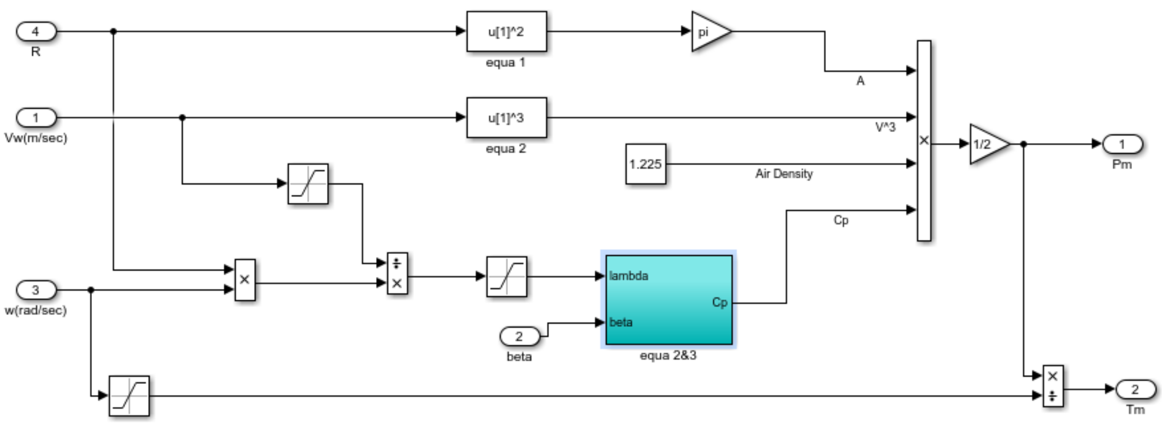

Figure 3.2: Simulink model of the wind turbine

3.4 Maximum Power Point Tracking

Wind energy conversation system use the MPPT technique for increasing wind turbine power production. Given the fluctuation wind speed and turbine characteristics MPPT's primary goal is to harness the greatest power from the wind. A wind turbine's power output within a WECS has a cubic relationship with wind speed. However, the efficiency of power conversion as represented by the turbine's power coefficient is conditional upon its rotational speed. To optimize power generation the turbine must operate at its optimal rotational velocity corresponding to the prevailing wind speed. In order to preserve the appropriate tip speed which is determined by combining turbine and wind speed the tip TSR based MPPT approach directly controls the shaft's speed. The TSR controller receives the real value in order to determine the peak point consistent to the variance in wind. To minimize the variance between the ideal worth and actual worth the TSR regulator adjusts the generator speed downwards (Ramji Tiwari, 2018).

$$v_w = \frac{\omega_r r}{\lambda_{opt}} \tag{3.11}$$

Where: ω_r is the reference rotating speed, λ_{opt} is the optimum TSR, the wind speed is denoted v_w ., R is the rotor radius.

This equation expresses the conversion of wind energy captured by the blade into mechanical power:

$$p_{mech} = \frac{1}{2}\rho\pi R^2 (\frac{\omega_r R}{\lambda_{opt}})^3 C_P \max(\lambda, \beta) \tag{3.12}$$

where λ_{opt} represents the tip speed ratio and $C_P \max$ represents the power coefficient are attained that can maximize the power that is extracted $p_{m\ op}$.

$$p_{m\ op} = \frac{1}{2}\rho\pi R^2 \left(\frac{\omega_r R}{\lambda_{opt}}\right)^3 C_P \max(\lambda, \beta) \tag{3.13}$$

$$p_{m\ op} = \frac{1}{2}\rho\pi R^5 \frac{\omega_r^{\ 3}}{\lambda_{opt}} C_P \max(\lambda, \beta) = \frac{1}{2}\rho\pi R^5 \frac{C_P \max(\lambda, \beta)}{\lambda_{opt}^{\ 3}} \omega_r^{\ 3} \tag{3.14}$$

$$k_{opt} = \frac{1}{2}\rho\pi R^5 \frac{C_P \max(\lambda, \beta)}{\lambda_{opt}} \tag{3.15}$$

$$p_{m\ op} = k_{opt}\omega_r^3 \tag{3.16}$$

Equation (3.9) shows the link between torque and mechanical power.

$$T_{m\ op} = \frac{p_{m\ op}}{\omega_r} = \frac{k_{opt}\omega_r^3}{\omega_r} \tag{3.17}$$

$$T_{m\ op} = k_{opt}\omega_r^2 \tag{3.18}$$

The generator characteristics in order to show understanding the link between mechanical and electric power. produced by a PMSG in relation to the rotor speed for various wind speeds. The generator’s characteristics dictate how variations in mechanical power input affect the generator’s electrical power output. The power coefficient of the wind turbine is an important component to consider. The power coefficient is a metric used to quantify how well a wind turbine captures wind energy. This expression implies the relationship between the power extracted by the rotor and the available wind power.

3.5 Drive Train Modeling

The wind turbine drive train includes mechanical components such blade pitching devices, hubs, rotor shafts, and gearbox. The drive train model given in this thesis takes into account the inertia of the generator and turbine. while capturing the details of a wind turbine's drive train system is crucial for accurate transient analysis, computational efficiency also matters (ULUTAŞ, 2019).

Different models balance detail and complexity: three-mass, two-mass and single-mass models offer faster simulations but may compromise precision, especially for complex scenarios. Six-mass model provides the most detailed representation, capturing various inertias and flexibilities within the system. However, it comes at the cost of increased computational time due to intricate calculations and smaller time steps required for stability. The choice boils down to finding the sweet spot between accuracy and efficiency for preliminary studies or when computational resources are limited, simpler models are valuable. However, for in-depth analysis requiring high fidelity, the six-mass model might be necessary despite the increased computational demands (Jiang, 2018). Reduced mass models are therefore thought to make computational easier while maintaining a fair level of accuracy for transient phenomena. The model's construction is seen in the figure below.

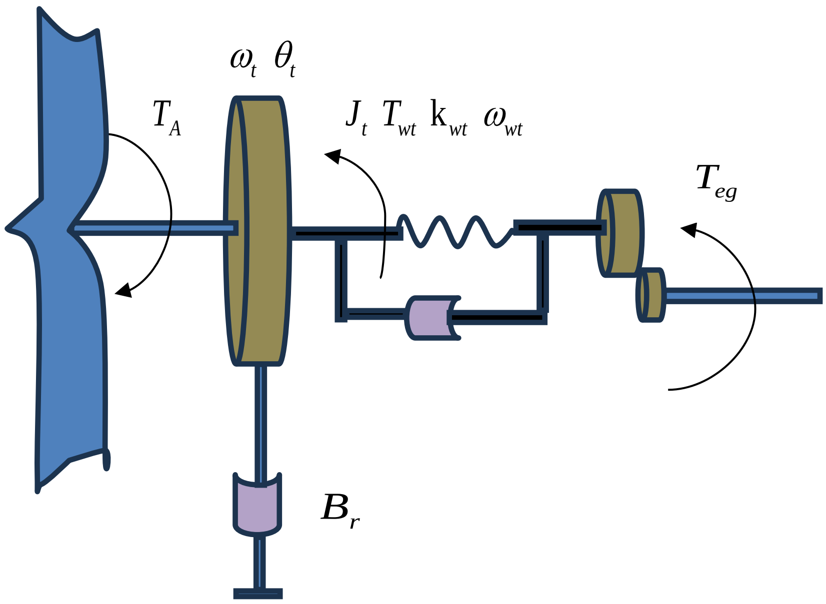

Figure 3.3: Single mass drivetrain

To understand how the PMSG rotor generates electricity, newton's second rule of spin must be used. Solving the problem yields the following calculation:

$$J_t \frac{d\omega_r}{dt} = T_A - T_{wt} - \beta_t \omega_r \tag{3.11}$$

$$\dot{\omega}_r = \frac{T_A - T_{wt} - \beta_t \omega_r}{J_t} \tag{3.12}$$

$$\frac{d\omega_r}{dt} = \dot{\omega}_r \tag{3.16}$$

where J_t represents the total inertia, ω_t represents the total speed, T_A represents the aerodynamic torque, T_{wt} represents the wind turbine output torque, β_t represents the total damping, $\theta_t = \int \omega_t dt$ is the total angle.

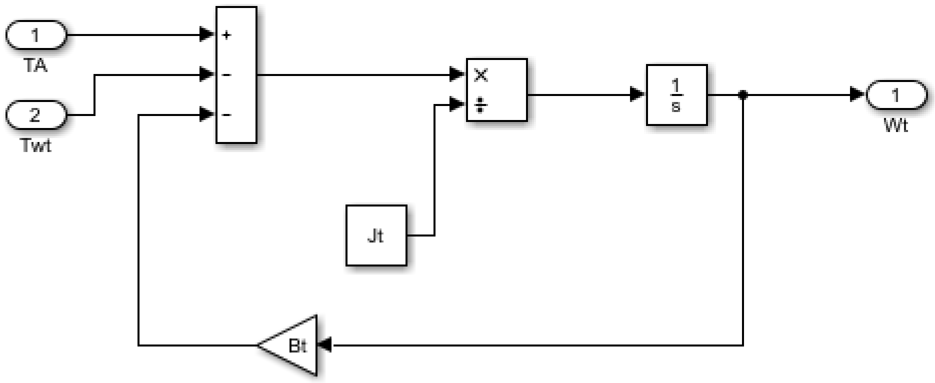

Figure 3.4: Single-mass drive train model

3.6 PMSG Modeling

Direct drive wind energy production systems use permanent magnet synchronous machines/generators are essential components that convert mechanical into electrical power. An examination of wind energy conversion system steady state and dynamic features, in addition to developing machine control method, require a comprehensive mathematical modeling of the permanent magnet synchronous magnet (Aisha Sa'ad, 2018). When developing a mathematical mode for a PMSG, several crucial presumptions and assumptions need to be established to simplify the analysis and create a manageable model some of the key presumptions include:

- Neglecting mechanical load dynamics to focus solely on the electrical aspects of the system.
- Neglecting the effects of core saturation in magnetic materials.
- Assuming lossless components, especially in electrical elements like wires and winding.

For wind turbine application, modeling the PMSG accurately is essential for optimizing energy capture and ensuring grid stability. The generator's electrical angular frequency f_a is exactly proportional to the mechanical rotor speed ω_r and number of generator poles p , as it is directly connected to the wind turbine rotor.

$$f_a = \frac{p}{2}\frac{\omega_r}{2\pi} \tag{3.17}$$

$$\omega_e = \frac{p}{2}\omega_r \tag{3.18}$$

A full-rating power converter and a PMSG make up the generating system. The magnet flux distribution surrounding a synchronous generator's air gap is taken to be sinusoidal in power system evaluation. The electromotive force is also sinusoidal, as is the flux distribution connected to the stator coil. (Ji, 2021).actually, the permanent magnet's induced voltage E_{pm} can be written as:

$$E_{pm} = \omega_e \lambda_r = 2\pi f_e \lambda_r \tag{3.19}$$

where ω_e represents the electrical angular frequency of the generator, E_{pm} represents the generator permanent magnet and λ_r represents the flux linkage of stator coil.

The dynamic conduct of a PMSM is modeled based on its three-phase stator voltage equation.

$$v_{abcs} = R_s i_{abcs} + \frac{d}{dt}\lambda_{abcs} \tag{3.20}$$

where R_s represents the per phase resistance of the stator winding v_{as}, v_{bs}, v_{cs} & i_{as}, i_{bs}, i_{cs} are the immediate flux interconnections caused by three-phase AC currents, as well as instantaneous flux linkages using the following expression (Gebremichael, 2020).

$$l_{abc} = \begin{bmatrix} l_{aa} & l_{ab} & l_{ac} \\ l_{ba} & l_{bb} & l_{bc} \\ l_{ca} & l_{cb} & l_{cc} \end{bmatrix} \quad \psi_{fg=} \begin{bmatrix} \psi_{gr}\cos(\theta r_g) \\ \psi_{gr}\cos(\theta r_g - \frac{2\pi}{3}) \\ \psi_{gr}\cos(\theta r_g + \frac{2\pi}{3}) \end{bmatrix} \tag{3.21}$$

$$\lambda_{abc} = l_{abc} i_{abc} + \lambda_r \tag{3.22}$$

where ψ_g is flux linkage of the rotor caused by permanent magnet, $l_{aa}, l_{bb} \,\&\, l_{cc}$ are the inductance of the stator winding, and $l_{ab}, l_{ac}, l_{bc}, l_{ba}, l_{cb} \,\&\, l_{cb}$ are the self-inductance is equivalent mutual inductance.

Park's transformation is a powerful mathematical tool for analyzing synchronous machine models, reducing complex three-phase AC calculation to simpler DC-like equation. The PMSM is typically analyzed using the usually used machine model in the dq, the device rotates in beat with rotor, with the d-axis perpendicular to and the q-axis parallel to the magnet axis. The phase quantities in three-phase system, such as PMSMs, are time-varying and the components include stator voltage, currents, and flux connections. AC quantities that are independent of time can be obtained by applying park's transformation, which projects phase quantities onto a rotating two axis reference frame. The following is an expression of the transformation in matrix form (Pietrzak, 2021). The abc-dqo transformation as a matrix:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{os} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta r) & \cos(\theta r - \frac{2\pi}{3}) & \cos(\theta r + \frac{2\pi}{3}) \\ -\sin(\theta r) & -\sin(\theta r - \frac{2\pi}{3}) & -\sin(\theta r + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{3.23}$$

The inverse park's transformation is:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta r) & -\sin(\theta r) & \frac{\sqrt{2}}{2} \\ \cos(\theta r - \frac{2\pi}{3}) & -\sin(\theta r - \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \\ \cos(\theta r + \frac{2\pi}{3}) & -\sin(\theta r + \frac{2\pi}{3}) & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{os} \end{bmatrix} \tag{3.24}$$

PMSG consider $L_d \,\&\, L_q$ inductance in the rotating frame

$$v_d = Ri_d + L_d \frac{di_d}{dt} - \lambda_q \omega_e \tag{3.25}$$

$$\frac{di_d}{dt} = \frac{1}{L_d}\left(v_d + L_q i_q \omega_e - Ri_d\right) \tag{3.26}$$

$$v_q = Ri_q + L_q \frac{di_q}{dt} + \lambda_d \omega_e \tag{3.27}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}\left(v_q - Ri_q - L_d i_d \omega_e - \lambda_r \omega_e\right) \tag{3.28}$$

where λ_d, λ_q are the dq-axis stator flux linkages given by

$$\lambda_d = -L_{Is} i_{ds} + L_{dm}(I_f - i_{ds}) = -(L_{Is} + L_{dm}) i_{ds} = -L_d i_d + \lambda_r \tag{3.29}$$

$$\lambda_q = -(L_{Is} + L_{qm}) i_{qs} = -L_q i_q \tag{3.30}$$

where λ_r represents the rotor flux and L_d, L_q are the stator's dq-axis self-inductance defined as follows:

$$\lambda_r = L_{dm} I_f \tag{3.31}$$

$$L_d = L_{ls} + L_{dm} \tag{3.32}$$

$$L_q = L_{ls} + L_{qm} \tag{3.33}$$

The instantaneous stator voltage in the dq-axis reference frame is represented by v_d and v_q, respectively, and the instantaneous stator current are i_d and i_q. Here, the d-axis and q-axis inductance are stated and ω_e represents the electrical angular speed of the rotor. Rotor mounted permanent magnets create a relationship between peak and maximum phase flux is represented by λ_r. Fundamental principles guide the development of equations that explain the relationship between voltage, current, resistance, inductance, angular velocity, and magnetic flux in electrical and rotational systems. Analyzing the PMSG in the dq-axis simplifies its complex behavior, allowing for convenient representation using equivalent circuits.

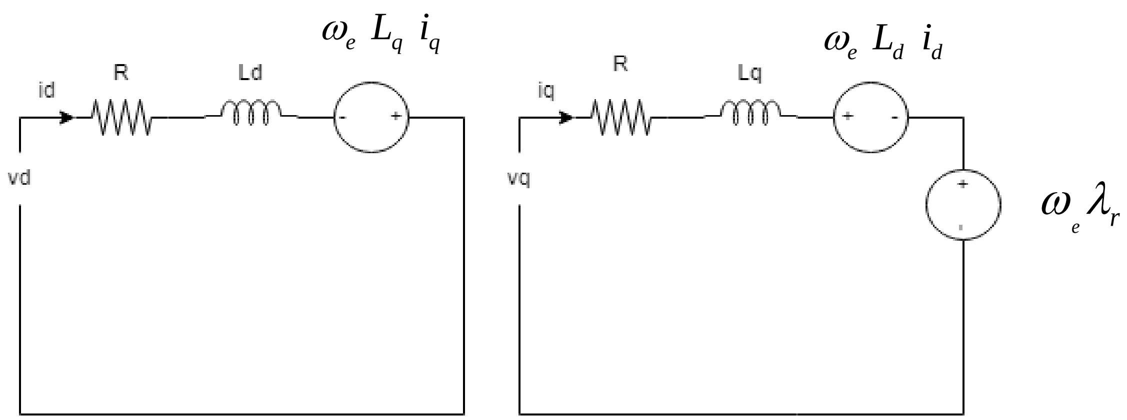

Figure 3.5: dq-axis equivalent circuits of a PMSG

In the abc reference frame, the electrical power input for any PMSM can be written as follows: alternatively, as follows in the dq-axis reference frame:

$$p_{abc} = v_a i_a + v_b i_b + v_c i_c \tag{3.34}$$

$$p_{dq} = \frac{3}{2}(v_d i_q + v_q i_d) \tag{3.35}$$

Active power in motoring mode refers to the machine's conversion of power into mechanical power. It can be expressed as

$$p_{em} = \frac{3}{2}(e_d i_d + e_q i_q) \tag{3.36}$$

$$e_d = -\omega_e L_q i_q = -\omega_e \lambda_q \tag{3.37}$$

$$e_q = \omega_e L_d i_d + \omega_e \lambda_r = \omega_e \lambda_d \tag{3.38}$$

where λ_d, λ_q are the dq-axis flux linkages, and e_d, e_q are the back EMFSs in dq-axis reference frame. Replacing Equations (3.37) and (3.38) into Equation (3.36) yields the active power as

$$p_{em} = \frac{3}{2}\omega_e(\lambda_d i_q - \lambda_q i_d) \tag{3.39}$$

A prime mover is required to power a generator when it is an electric machine. The generator's primary mover in wind turbine is a component of the wind energy system. When the machine reaches a steady state, its electromechanical torque wind turbines generate mechanical torque on their rotor shafts. Thus, the following can be inferred about the electromagnetic torque produced by a PMSM (Gencer, 2019):

$$T_e = \frac{p_{em}}{2 * \omega_e / p} = \frac{3}{2}(\frac{p}{2})(\lambda_d i_q - \lambda_q i_d) \tag{3.40}$$

$$T_e = \frac{3}{4}P\left[\left(L_d - L_q\right)i_q i_d + \lambda_r i_q\right] \tag{3.41}$$

where p represents the machine's number of poles, λ_r represents the magnetic flux, L_d represents the d-axis inductance, and L_q represents the inductance in quadrature.

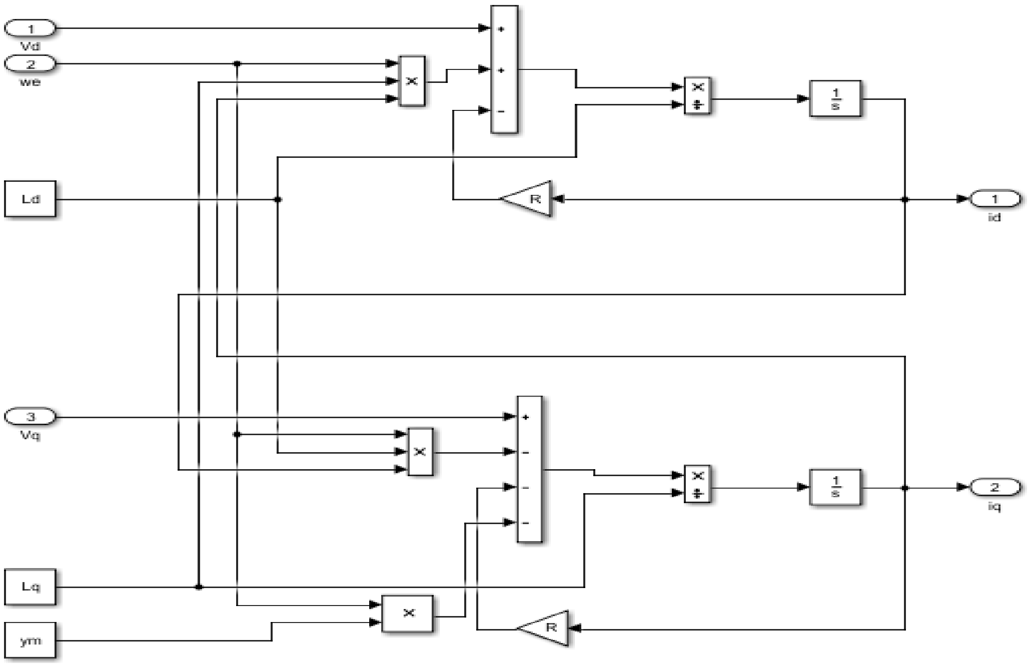

Figure 3.6: dq-axis equivalent circuit of a PMSG model.

3.7 Pitch Actuator Modeling

Pitch angle-controlled wind turbines required a pitch actuator as a critical component. The turbine's power production and efficiency can be modified in response to wind conditions by means of this control over the blade's longitudinal axis rotation. When wind speed exceeds the rated value, the pitch control mechanism decreases the angle of attack and spins the blades or pitches out of the wind. Electric or hydraulic devices are employed as pitch actuators (Ramji Tiwari R. B., 2017).

$$d\beta / dt = (\beta_r - \beta) / \tau_s \tag{3.42}$$

$$\tau_s \frac{d\beta}{dt} = \beta_r - \beta \tag{3.43}$$

$$\beta_r = \tau_s \frac{d\beta}{dt} + \beta \tag{3.44}$$

When Laplace transformation is used, we obtain

$$\tau_s(s)\beta(s) + \beta(s) = \beta_r(s) \tag{3.45}$$

$$(\tau_s s + 1)\beta(s) = \beta_r(s) \tag{3.46}$$

$$\beta(s) = \frac{1}{1+\tau_s s}\beta_r(s) \tag{3.47}$$

Where: β is calculating the pitch angle, β_r is reference pitch angle, and τ_s is the time constant

3.8 Power Converters

Power converters are electronics devices that change the form of electrical power. They are essential components in many electrical and electronic systems, including consumers electronic, power grids, motor drives, and renewable energy systems. These converters perform power conversion using various semiconductor devices, include diodes, thyristors, IGBTs, and MOSFETs. The selection of semiconductor devices and converter topologies is based on specific application requirements, such as power rating, input/output voltages efficiency and control capabilities.

3.8.1 AC to DC Rectifiers Modeling

A controlled rectifier such as one utilizing a thyristor or IGBT-based converter can regulate harvest voltage and current by adjusting the firing angles of the semiconductor devices. By changing the firing angles the yield voltage can be continuously controlled. Furthermore, regulated rectifiers can be built to do adjustment for power factor which improves the total power factor of the apparatus. the active front-end rectifier are crucial components in a PMSG based renewable energy system allowing for efficient operation in both driving and generating modes. They manage generators to the grid's flow of both active and reactive power. guaranteeing optimal energy and efficiency. In wind turbine applications they can operate in inverter mode for regenerative braking safeguarding optimal energy harvest under changing wind conditions. The permanent magnet synchronous generators instantaneous output voltage is expressed as follows:

$$\begin{aligned} v_{ay} &= v_m \cos(\omega_r t) \\ v_{by} &= v_m \cos(\omega_r t - 120^\circ) \\ v_{cy} &= v_m \cos(\omega_r t + 120^\circ) \end{aligned} \tag{3.48}$$

where v_m stands for the phase voltage's highest value and $\omega_r t$ is the rotor angular position of PMSG.

3.8.2 DC Link Model

In a WECS, the DC link serves as the link between the generator for the wind turbine and the machine side converter. The wind turbine generator harvests variable AC power which is transformed to DC by the DC link capacitor. This decoupling provides steady and regulated DC electricity to the grid regardless of wind conditions. The DC link capacitor regulates the DC voltage resulting in reliable and efficient power conversion. This feature enables autonomous control of the generator and grid which improves power delivery optimization.

$$E_{dc} = \int p_{dc} dt = \frac{1}{2} C_{V\,dc}^{\,2} \tag{3.49}$$

where c_{Vdc} represents the capacitance of the DC link capacitor while p_s and p_m denote the active power of the PMSG stator and machine side converter respectively. c_{Vdc}, p_g and p_f represent the active power flow into the DC link capacitor grid side converter and filter respectively. The power delivered from the PMSG to the grid can be defined as follows ignoring power losses in the converters can be machine or grid side, filter and transformer. a PMSG wind turbine connected into a grid ensures balanced power flow through converters and DC connection. Neglecting losses the net real power can be expressed by

$$p_s + p_{dc} + p_g \tag{3.50}$$

The DC link model can be described as follows:

$$c_{Vdc} \frac{dv_{dc}}{dt} = \frac{3}{2} \left(\frac{v_d}{v_{dc}} i_d + \frac{v_q}{v_{dc}} i_q \right) - i_{dc} \tag{3.51}$$

where c_{Vdc} and i_{dc} represent the DC bus voltage and current, i_d and i_q represent the d-axis current and q-axis current of the inverters, v_d and v_q represent the d-axis output voltage and q-axis output voltage of grid filters, respectively. The grid's q-axis output voltage is null resulting from phase locked loop gain.

CHAPTER FOUR

CONTROLLER DESIGN

This chapter covers the design of a cascade control approach that composes the frictional order PI controller, which serves as the primary controller and the PI controllers as secondary controllers. The PSO approach is used to get optimum parameters for the controller. The fractional order PI controller will be designed using the FOMCON toolbox.

4.1 Control Strategy

Cascade control is a widely used method in motor control systems due to its several advantages. It involves a hierarchical control structure where outer loop controls a higher-level variable (e.g., speed) while the inner loop controls a lower-level variable (e.g., current). Figure 4.1 shows Simulink model of the overall control system

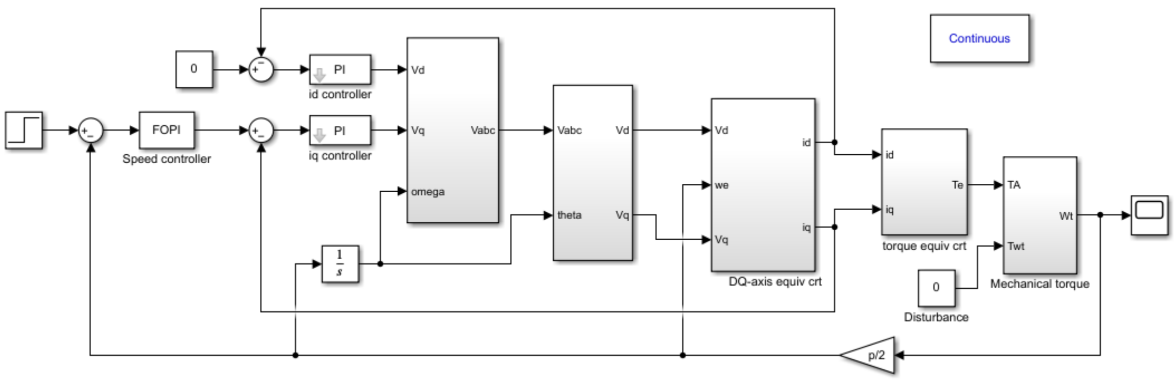

Figure 4.1: Simulink model of PMSG

4.2 PI Current Controller

The management and adjustment of the electrical current passing through a wind energy scheme is referred to as current control. Maintaining the intended power output and ensuring the stability and dependability of the scheme are the fundamental goals of current control. In a traditional wind energy conversation system, the wind turbine harnesses the kinetic energy of the wind and transforms it into mechanical energy which subsequently transforms into electrical energy. Alternating current (AC) is the most common electrical energy formed by wind turbines. Controlling the AC current is necessary in order to effectively integrate the WECS with the electric grid or to power nearby loads. For the inner current control, two PI controllers are used. The time domain formula of the PI controller is given by

$$u_l(t) = K_{pl} e_l(t) + K_{il} \int_0^t e_l(\tau) d\tau \tag{4.1}$$

where the index l denotes d or q, and K_{pj} and K_{ij} denote the proportional and integral gains, respectively. The error or the distinction between the reference signal and the measured current signal defined as

$$e_l(t) = i_{l\_ref}(t) - i_l(t),\ l = d \text{ or } q \tag{4.2}$$

In this study, i_{d_ref} is set to 0 and i_{q_ref} is produced by the primary controller, $e_l(t)$ that is, the output of the FOPI controller.

4.3 FOPI Speed Controller

The electrical system in wind turbine systems reacts faster than the mechanical parts. As a result, two separate control loops can be used to regulate the wind turbine and generator designs. In a wind turbine system, the functions of the two loops. An inner loop makes sure the generator runs smoothly and outputs the desired amount of power, while the outer loop modifies the rotor speed to maximum power capture. A fractional integral, and a linear accumulation of the inputs are used to express the output of FOPI controllers, which are a generalization of traditional PI controllers (Ioana Paducel, 2022). They are most frequently employed in the form PI_λ in scientific papers, where λ represents the fractional order of the integral.

Figure 4.2 depicts the FOPID configuration plane and the PID point on the horizontal and vertical axis using an integrator and derivative order. One obtains a traditional PID controller when both values equal 1. As a result, the interval (0;1), which provides a benefit for modifying a system's dynamic attributes, represents their values. The extra two degrees of freedom λ and μ allow for the monitoring of additional characteristics like robustness, system sensitivity, and complementary sensitivity (Adel Makhbouche, 2023).

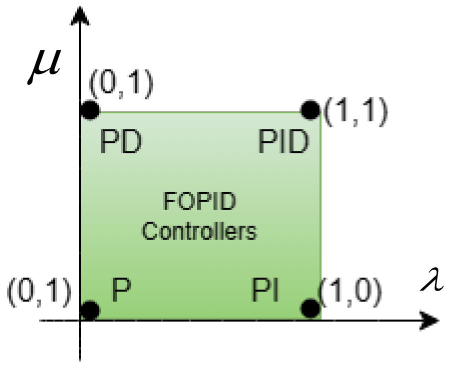

Figure 4.2: General form of the fractional order PID controller

4.3.1 Fractional calculus

Fractional calculus includes non-integer order operators in addition to integration and differentiation principles. The integral divergent operator D^{α} is defined as

$$D^{\sigma} = \begin{cases} \dfrac{d^{\sigma}}{dt}, & \sigma > 0 \\ 1, & \sigma = 0 \\ \int_0^t (d\tau)^{-\sigma}, & \sigma < 0 \end{cases} \tag{4.3}$$

The fractional order denoted by $\alpha \in R$.

Several definitions for the fractional operator D^{α}, including $Grünwald-Letnikov$, Caputo, and Riemann-Liouville. The R-L fractional integration and differentiation are defined below:

$$D^{-\sigma} f(t) = \frac{1}{\Gamma(\sigma)} \int_0^t (t-\tau)^{\sigma-1} f(\tau) d\tau \tag{4.4}$$

$$D^{\sigma} f(t) = \frac{1}{\Gamma(1-\sigma)} \frac{d}{dt} \int_0^t (t-\tau)^{-\sigma} f(\tau) d\tau \tag{4.5}$$

where Γ represents Euler's gamma function. Performing the Laplace transform of the R-L fractional integration and differentiation yields

$$L\left\{D^{-a} f(t)\right\} = s^{-a} F(s) \tag{4.6}$$

$$L\left\{D^{a} f(t)\right\} = s^{a} F(s) - D^{a-1} f(t)\Big|_{t=0} \tag{4.7}$$

4.3.2 FOPI speed controller as primary controller

A FOPI controller's mathematical equation is according to fractional calculus for producing the reference signal of the i_q current is given by

$$i_{q\_ref}(t) = k_p e(t) + k_i D^{-\lambda} e(t) \tag{4.8}$$

where *e(t)* represents the error as the variation among the setpoint and the result and i_{q_ref} represents the control input; K_p and K_i represent the proportional and integral gains of the speed controller, respectively; λ and μ represent the actual number orders satisfying $0 < \lambda, \mu < 2$. Observe that when $\lambda = \mu = 1$, the standard PID form is recovered. This expanded representation offers greater flexibility in controller design.

The equation's transfer function (4.8) is expressed by

$$\frac{I_{q\_ref}(s)}{E(s)} = K_p + \frac{K_I}{S^{\lambda}} \tag{4.9}$$

Figure 4.3 displays the construction of the FOPI controller

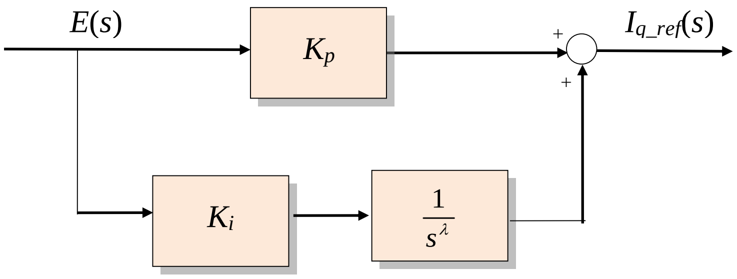

Figure 4.3: Structure of the FOPI controller.

4.4 Particle Swarm Optimization

PSO is a computational tool for identifying optimal solutions to problems. It is modeled after the coordinated movement of flocks of birds or schools of fish. in 1995, doctor kennedy and Eberhart proposed particle swarm optimization a heuristic global optimization method (Liu, 2017). Bird looks for food in groups or individually before finding a suitable location. bird have a keen sense of smell, allowing them to locate food sources with greater accuracy. The PSO technique is helped by a swarm of particles that change their positions between iterations, allowing for more efficient search results. The particles navigate the search space by updating their velocity and position based on these two variables. The general updating equations are:

$$v_i^{t+1} = \omega v_i^t + c_1 r_1 (pbest_i^t - x_i^t) + c_2 r_2 (gbest_i^t - x_i^t) \tag{4.10}$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{4.11}$$

where v_i^t and v_i^{t+1} are the previous and updated velocities of particle *i* at time *t* and *t*+1, respectively, x_i^t and x_i^{t+1} is the previous and updated positions of particle *i* at time *t* and *t*+1, respectively, ω is the inertia weight, controlling the prior velocity's influence is represented by c_1 and c_2 represent acceleration coefficients, and r_1 and r_2 represent random numbers between 0 and

Figure 4.4 depicts the iteration technique for any particle in each generation. A sociological examination of the velocity update formula shows that the first half takes into account the particles prior velocity. This indicates that the particle trusts its current state and moves inertially accordingly.

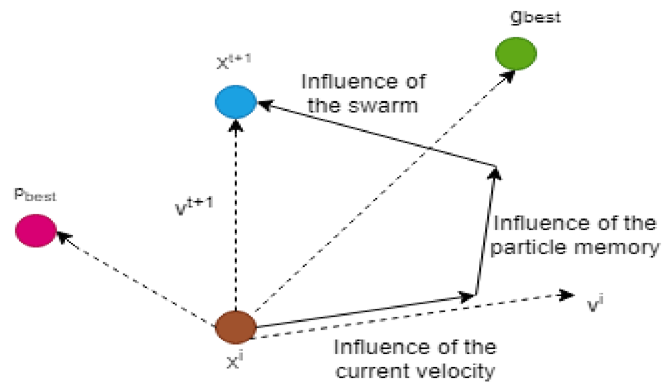

Figure 4.4: Iteration strategy for particles

Figure 4.5 displays a flowchart for the PSO Algorithm

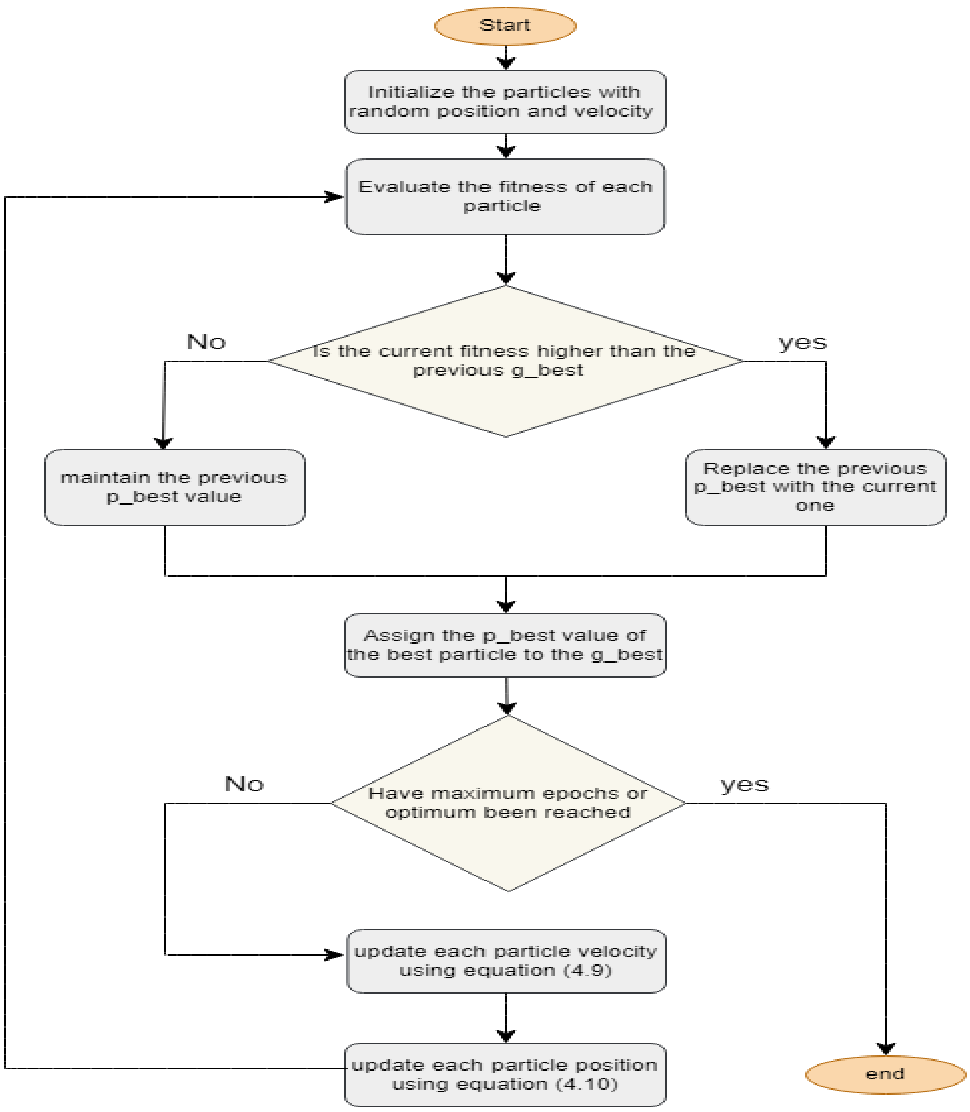

Figure 4.5: A flowchart for the PSO algorithm

4.5 Performance Indices

The previously designed FOPI controller has K_p, K_i, and λ parameters, and the two PI controllers have K_{pj} and K_{ij} (j= d or q) parameters each, for a total of 7. To optimize these parameters, a metric that can quantitatively evaluate the performance of the overall system is required. In essence, performance indices serve as the compass that guides optimization efforts. By providing a clear direction and measurable outcomes, they ensure that optimization initiatives are effective and aligned with overall goals. A variety of performance guides can be used to gauge the overall performance of the control scheme. By reducing the total inaccuracy up until the point at which the process has reached the intended setpoint, this demonstrated the effectiveness of the controlled response. Integral absolute error, integral square error, integral of time absolute error, integral of time square error are the four primary types of performance metrics (Sarir Noureddine, 2021). The imposed IAE function beat other performance indices, including ITAE, ITSE, and ISE, when it came to minimizing the principal function.

$$IAE = \int_0^\infty |e(t)| dt \tag{4.11}$$

$$ISE = \int_0^\infty e(t)^2 dt \tag{4.12}$$

$$ITAE = \int_0^\infty t|e(t)| dt \tag{4.13}$$

$$ITSE = \int_0^\infty te^2(t) dt \tag{4.14}$$

Smaller error is minimized by the usage of IAE compared to bigger faults. In addition, it does not give any weight to process errors, which results in a response that is typically slower that ISE but with fewer protracted fluctuation. ISE is used to minimize significant error as soon as possible, but it may also stand long-lasting tiny errors (Maroufi Oussama, 2018). Fast response yet little oscillation and amplitude are the results of this. The impact of ITAE and ITSE is to give far more weight to errors that arise over time than those that occur at the beginning of the response

CHAPTER FIVE

SIMULATION AND RESULT DISCUSSION

5.1 Chapter overview

In this episode, simulations are run under a variety of operating circumstances to evaluate the presentation of the developed FOPI regulator. This thorough testing sought to validate the advantages of the fractional order PI controller over the typical integer order regulator for wind energy producing systems. This study examines the step response of rotation at a wind speed controlled by both PI and FOPI controllers. The performance of these controllers is compared based on key metrics this includes rise time, settling time, overshoot, and IAE, allowing us to evaluate the potential advantages of the fractional order approach.

5.2 Controller parameter settlings

The particle swarm optimizer is dependent on numerous important parameters that determine its search behavior and convergence to the best solution. It is widely used to adjust the settings of many controllers, including PI and FOPI controllers to attain peak that minimize a stated objective function such as the integral of squared error or other relevant performance measures in order to enhance the control system's effectiveness. The table below shows the parameters used during optimization.

Table 5.1: Parameters of the PSO optimization algorithm

Parameter	PI controllers	FOPI controller
Number of particles	20	20
Maximum iteration	50	50
No. of parameters	4 $[K_{pd}\ K_{id}\ K_{pq}\ K_{iq}]$	3 $[K_p\ K_i\ \lambda]$
Lower bound	[0 0 0 0]	[0 0 0]
Upper bound	[50 150 50 150]	[150 50 2]

Figure 5.1 illustrates the convergence curve representing the particle swarm optimization method. The optimal function value rapidly drops reaching a low of 0.209633 by iteration 40.

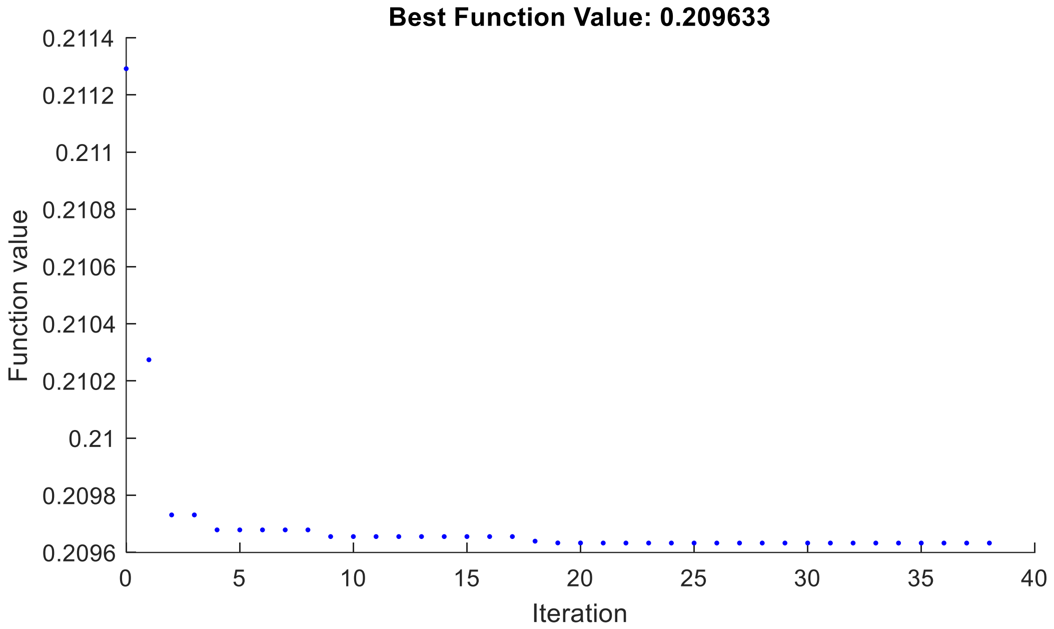

Figure 5.1: Fitness Vs iteration plot for PSO

The PSO method was employed to determine the ideal gains within specified ranges and to increase the value of k_p and k_i . Furthermore, the method was applied to raise the value of k_p k_i and λ picking the optimum gains within their respective higher and lower limits. The table below shows the ideal value for the controller's parameters.

Table 5.2: PSO tuned parameter settings for PI and FOPI.

Controller	k_{ps}	k_{is}	$k_{pd} = k_{pd}$	$k_{pd} = k_{pd}$	$k_{id} = k_{iq}$
FOPI-PI-PI	44.7098	37.0668	1.8014	68.5662	50.0000
PI-PI-PI	0.0264	35.2450	--	5.3640	1.9874

The chromosomes for PI controller parameters are [k_p, k_i], while those for fractional order PI controllers are [k_p, k_i , λ]. Table 5.1 lists the specific parameter values that would be utilized for the PSO operation and request described in that context.

5.3 Simulation Result for FOPI and PI.

This simulation tested the effectiveness of PI and FOPI controllers in managing the spinning speed of a wind powered PMSG. The transient and steady states were assessed using a step shift in wind speed responses of the rotational speed to each control approach.

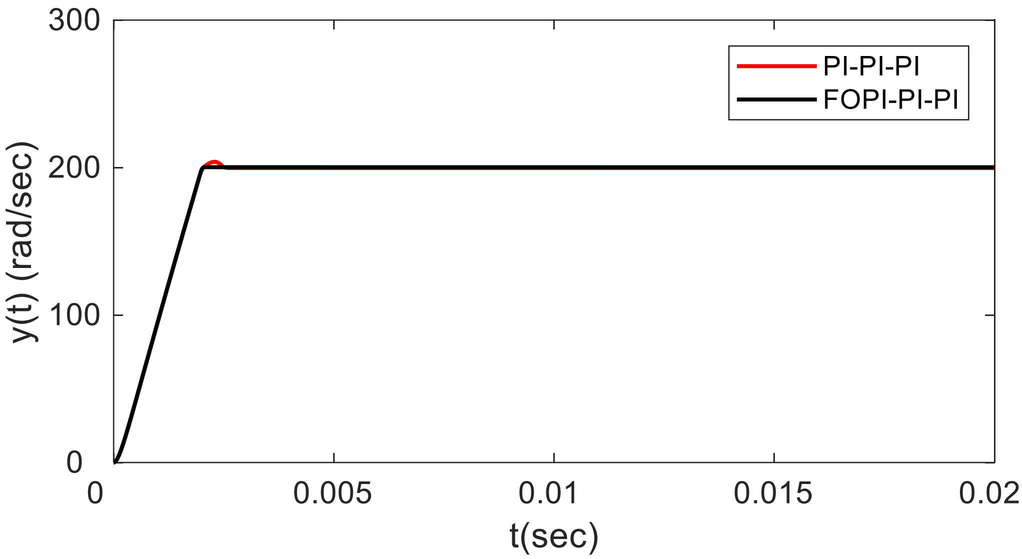

Figure 5.2: Rotational speed

When compared to the FOPI controller the PI controller response is likely to be slower to settling time and may have a bigger overshoot or undershoot. The FOPI controller with its fractional order derivative term may have a shorter rising time and less overshoot or undershoot resulting in faster stabilization at the target rotational speed. Both controllers are projected to attain a steady state rotating speed near the setpoint with the FOPI controller potentially having a lower steady state error.

The FOPI controller has a much lower overshoot (0.1496s) than the PI controller (1.9477s). this means that the FOPI controller achieves the desired speed with less oscillations. Settling time both controllers have extremely rapid settling time. This demonstrates a quick response to the speed adjustment. IAE the FOPI controller has a somewhat lower IAE (0.2156) than the PI controller (0.2200), indicating potentially superior overall performance.

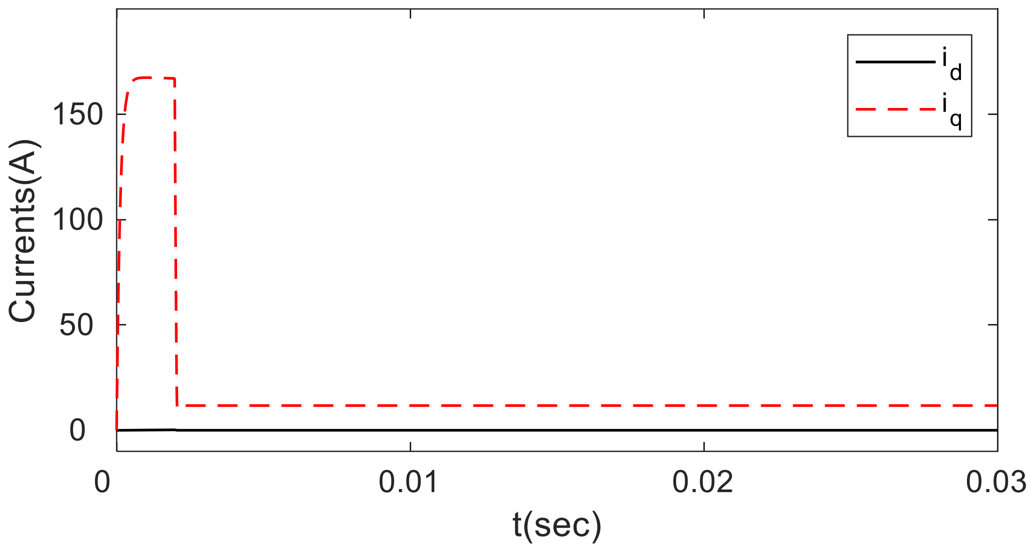

Figure 5.3: Step response of currents

A step response is the output of a system when the input quickly shifts from one steady state value to the next. In this situation, the system is your PI controller equipped d-axis current control loop and the input is a step change in the intended d-axis current value. Peak time refers to how long it takes for the system harvest to reach the initial peak following a step input. In your system the d-axis current reaches its peak value in 0.0020 seconds. The integral of IAE over time is used to evaluate performance a lower IAE indicates greater performance by reducing the difference among expected and actual direct axis currents. your IAE result of 0.000647 shows that you performed relatively well in terms of error minimization. The rise time of 0.000186 seconds reflects how quickly the system react to a step input with a shorter rise time typically indicating a faster response. The peak time of 0.000978 seconds is the time required for the quadrature axis current to spread its greatest value. The IAE of 0.0144 represents the overall difference among the actual quadrature axis current response and the planned step response with a lower IAE value indicating better performance.

The power coefficient (Cp) is a significant factor in wind turbine design and operation since it represents the efficiency with which wind energy is converted into electricity. A greater Cp signifies improved energy extraction. As demonstrated in figure 5.4 a wind turbine consistently maintained a power coefficient of 0.48 an optimal level independent of fluctuations in wind speed. This suggests successful control system performance in maximizing energy capture throughout variable meteorological circumstances.

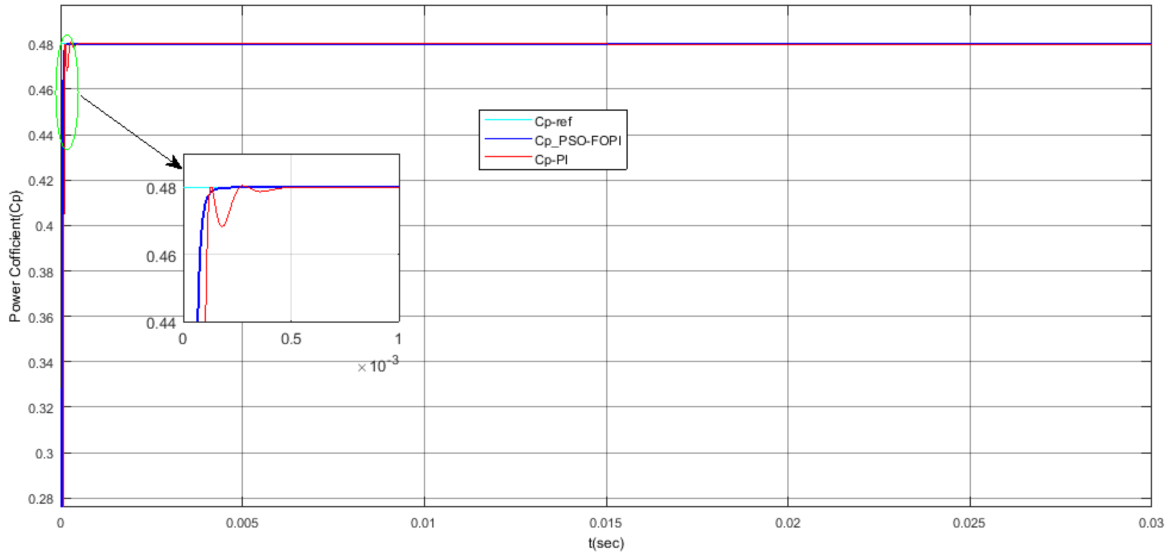

Figure 5.4: Step response of power coefficient (C_p)

Wind turbines must properly track variances in wind speed in comparison to rated speeds to achieve optimal power output. The maximum power production is known as the rated wind speed, whereas the cut-in wind speed is the speed at which the turbine starts to produce electricity. Turbines can maximize energy harvesting by modifying rotor speed to adapt to changing conditions of the wind within a specific range.

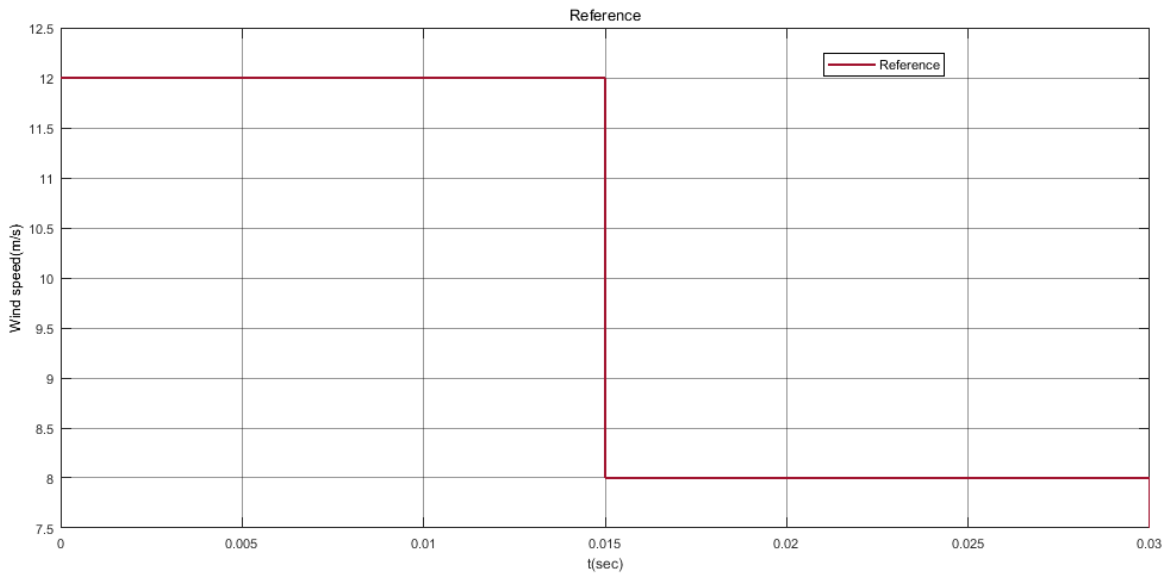

Figure 5.5: The wind speed graph

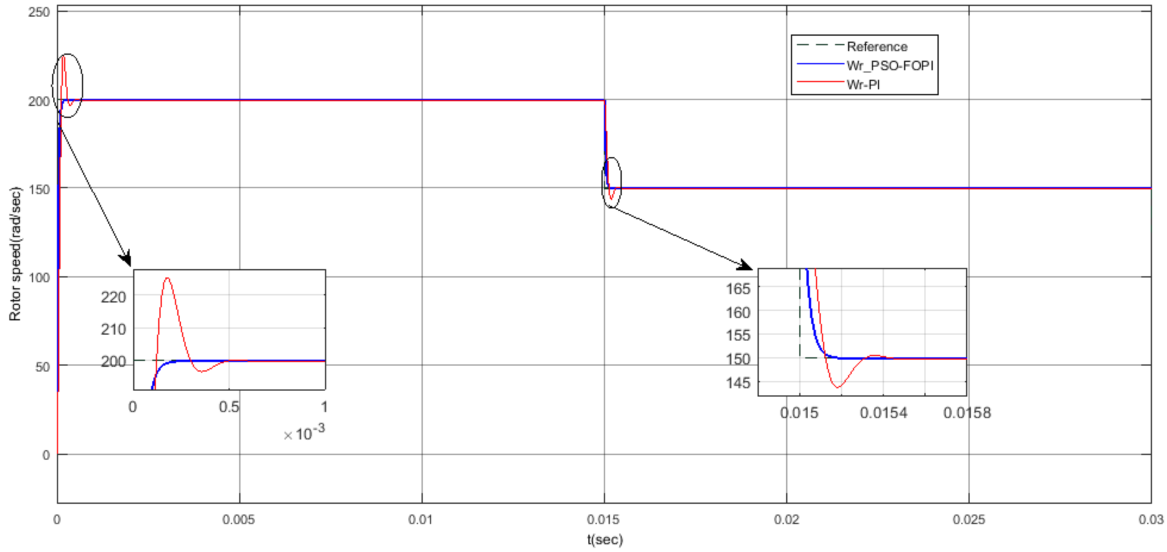

Figure 5.6: Step response to the speed of rotation

Figure 5.6 depicts the generator's dynamic reaction to varying wind conditions. As wind speed changes, the generator adjusts its rotating speed to maximize power generation. In terms of tracking the best rotational speed and extracting maximum power the FOPI controller outperforms the PI controller.

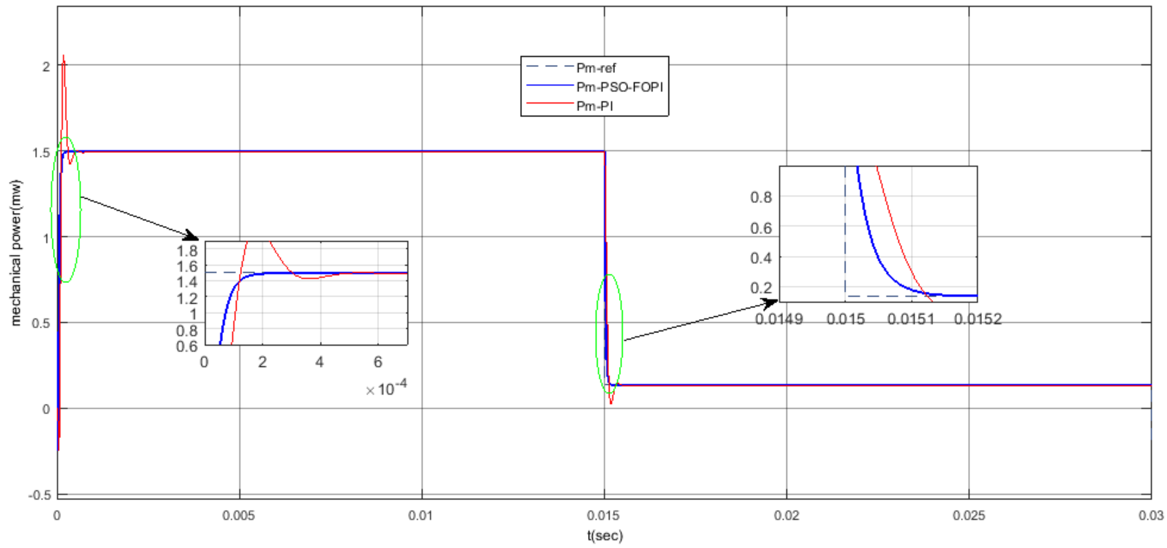

Figure 5.7: Step response of maximum power extraction.

Figure 5.7 shows the simulating a WECS is a useful way to evalute the performance of PMSG control strategies at various wind speeds. By assessing simulated power output control systems can be optimised to maximise energy extraction which is the fundamental purpose of PMSG control. At rated wind speed the generator's nominal power output is 1.5MW. as soon as the wind speed exceeded 12m/s, the PI controller generated 1.443MW where as the suggested PSO-FOPI controller produced 1.501MW suggesting an improvement over both the FOPI and traditional PI controllers. Under lower wind condition 8m/s the PI controller generated 0.7033MW less then the rated power whereas the FOPI controller produced 0.7419MW. In comparison the proposed controller surpassed the nominal power by 0.7467. the turbine's power generation nearly matched the ideal power curve with minimal integral absolute error, resulting in efficient power extraction under various wind conditions.

Table 5.3: Performance of mechanical power.

Mechanical power(watt)								
Wind speed	Settling time(t_s)		Overshoot(%)		Rise time(t_r)		IAE	
	FOPI	PI	FOPI	PI	FOPI	PI	FOPI	PI
12	98 μ s	0.34ms	0.126	0.693	38 μ s	69 μ s	0.039	0.058
8	0.1ms	0.4ms	0.452	2.172	28 μ s	71 μ s	0.032	0.047

A comparative investigation of FOPI and PI controllers revealed significant differences in mechanical power response. The FOPI controller functioned successfully at a wind speed of 12m/s, having a settling time of 0.000098s, overshoots of 0.126%, rise time of 0.000038s, and IAE of 0.0392. in contrast, the PI controller showed slower dynamics, including 0.00034s as the settling time, a greater 0.693% overshoot, a rising time of 0.000069s, and a larger IAE of 0.0579. At a wind speed of 8m/s, the FOPI controller performed well, with 0.0001s as the settling time, an overshoot of 0.452%, a rise time of 0.000028s, and an IAE of 0.032. the PI controller performed poorly, with a settling time of 0.0004s, overshoot of 2.172% overshoot, rising time of 0.000071s, and IAE of 0.0474. the FOPI controller exceeds the PI controller in speed, precision, and stability while regulating mechanical power under different wind situations.

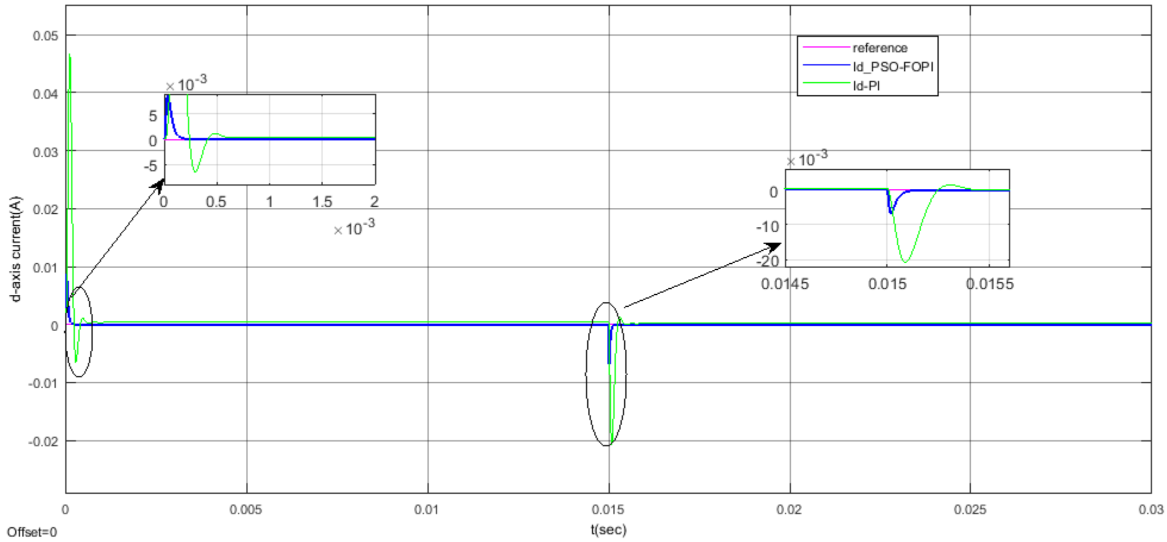

Figure 5.8: Step response of direct current

The d-axis current step response in a PMSG is crucial for analyzing the scheme. Because of its influence on the generator's magnetic flux fast fluctuations in d-axis current can have a major impact on overall performance and stability. PSO-FOPI controllers outperform typical PI controllers in terms of dynamic d-axis current regulation. This is demonstrated by faster rise time decreased overshoot and shorter settling times.

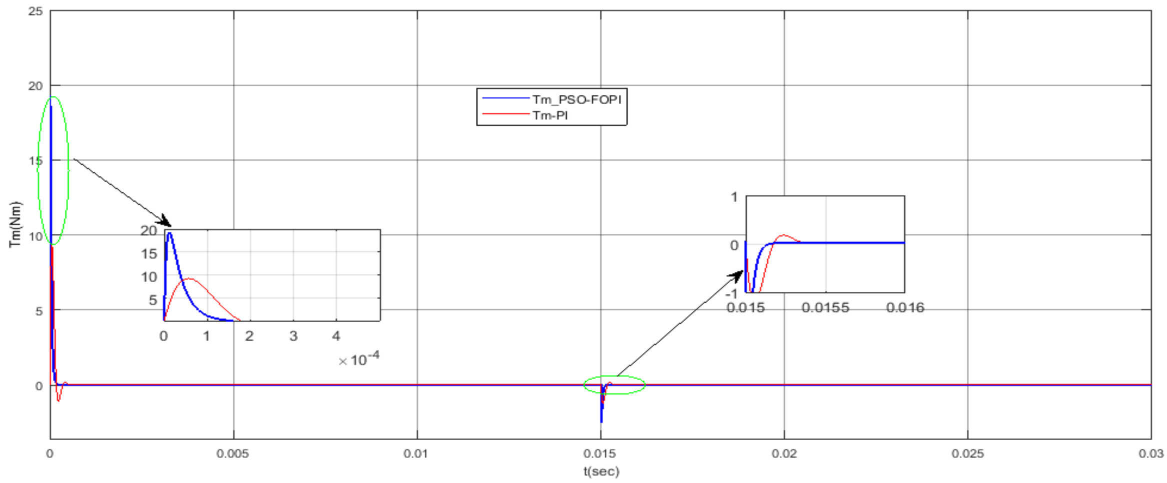

Figure 5.9: Step response of mechanical torque

The step response of mechanical torque in system such as a PMSG or other electromechanical system describes how torque reacts to a sudden change in control input or reference torque. This response is critical for determining system performance under dynamic conditions. Analyzing the step response of mechanical torque is critical for improving electromechanical system performance since it helps to optimize control techniques for increased efficiency and responsiveness. Understanding how torque responds to changes is critical to obtaining optimal system control.

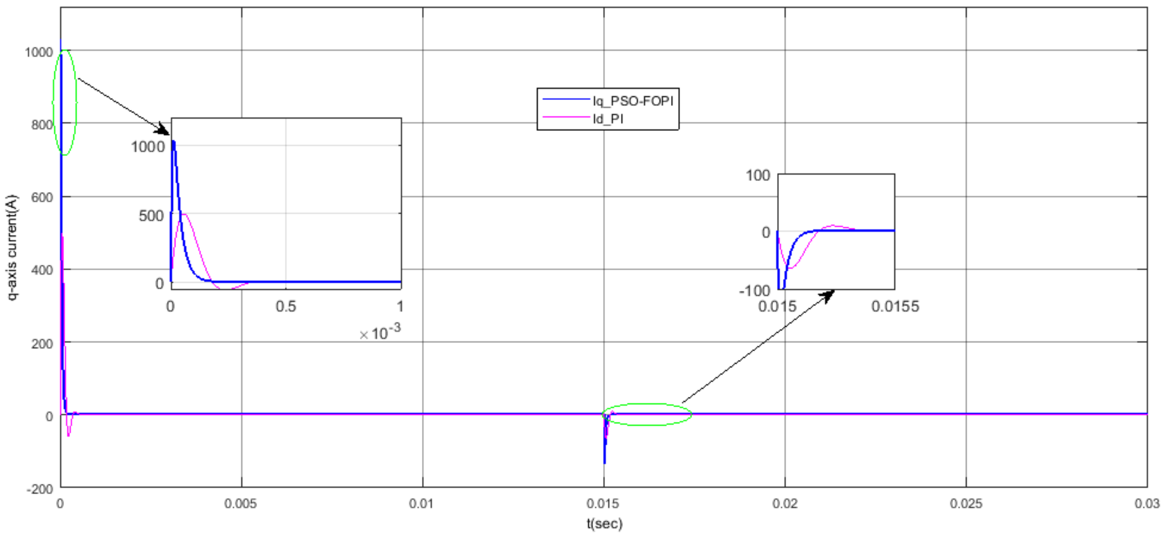

Figure 5.10: Step response of the quadrature current.

The quadrature current step response is critical to evaluate the dynamic effectiveness of a PMSG with various control schemes. q-axis current is usually regulated using both standard PI and PSO-FOPI controller. PI controller use proportional and integral terms to reduce current error while PSO-FOPI controllers use fractional calculus and optimization approaches to improve control. When contrasting with the PI controller, the PSO-based FOPI controller regularly outperforms it in terms of dynamic performance, with rising times, less overshoot and shorter settling times.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The proposed control system has substantial potential for increasing power extraction. It uses a fractional order PI controller that has been modified using particle swarm optimization for current management in a wind energy conversion system based on permanent magnet synchronous generators. The system successfully tackles the drawbacks of conventional control systems by utilizing the benefits of fractional order control and the optimization powers of PSO. The previous sections' analysis and simulation findings validate the suggested approach's superior performance in terms of transient response, rotor speed tracking accuracy and power output.

PMSG uses the integral absolute error statistic to assess system performance under existing regulations. The power extraction graphs show that a fractional order PI controller has a much better transient response then a normal PI controller with wind speed of 12m/s. the settling time is lowered from 0.0034s to 0.000098s, overshoot from 0.693% to 0.126%, and rise time from 0.000069s to 0.000038s. when the wind speed lowers rudely to 8m/s the Fractional order PI controller again outperforms with settling time reducing from 0.004s to 0.001s, overshoot from 2.172% to 0.452%, and rise time from 0.000071s to 0.000028s. both controller stabilize the wind power plant, however the fractional order PI controller has significantly better transient response characteristics. Current control systems respond rapidly to changes in wind speed or load conditions allowing them to adjust effectively and retain optimal performance. When compared to traditional PI controllers the FOPI controller improved by PSO greatly enhances power extraction. Under different wind conditions the system performs better by fine tuning the proportional and integral orders. Improved dynamic performance is demonstrated by the PSO-tuned FOPI controller which also minimizes overshoot and settling time faster. As a result, the energy conversion process runs more smoothly and efficiently.

This capacity is critical for ensuring that generators extract maximum power, particularly under variable situations. A fractional order PI controller on the other hand can improve system stability and performance while also increasing energy efficiency. By utilizing particle swarm optimization to modify the parameters of the FOPI controller the operation of the system can be further enhanced resulting in improving energy capture.

6.2 Recommendation

The following steps are recommended by this study for future researchers:

- Placing emphasis on the aspects being considered for integration in to the grid.
- Controlling the current becomes essential to prevent at high wind speed.
- Consider the hardware implementation for controlling the PMSG current.

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APPENDICES

Appendix A the specifications of wind turbines (JUN LIU, 2021)

Table A.1: specifications of wind turbines

Parameter	Symbol	Value	Units
Power Nominal	Pnom	1.5	Mw
Density of air	ρ	1.225	Kg/m^3
Rated wind speed	Vratd	12	m/sec
Cut-i wind speed	Vc-i	3	m/sec
Cut-o wind speed	Vc-o	25	m/sec
Maximum power coefficient	Cp-max	0.48	-
Optimal Tip Speed Ratio	λ_{opt}	8.1	-

Appendix B Setting for the permanent magnet synchronous generator

Table B.2: Electrical Machine Parameters

Parameter	Symbol	Value	Units
Rated power	Prated	1.5	MW
Pole	P	2	-
Rated speed	ω_m	17.3	Rpm
Stator resistance	Rs	0.289	℧
q-axis inductance, d-axis inductance	(Lqs, Lds)	0.395	mA
Flux	φ_m	0.125	Wb
Total damping coefficient	Bt	0.011	N*sec/rad

Appendix C: Concerning the MATLAB/Simulink Model

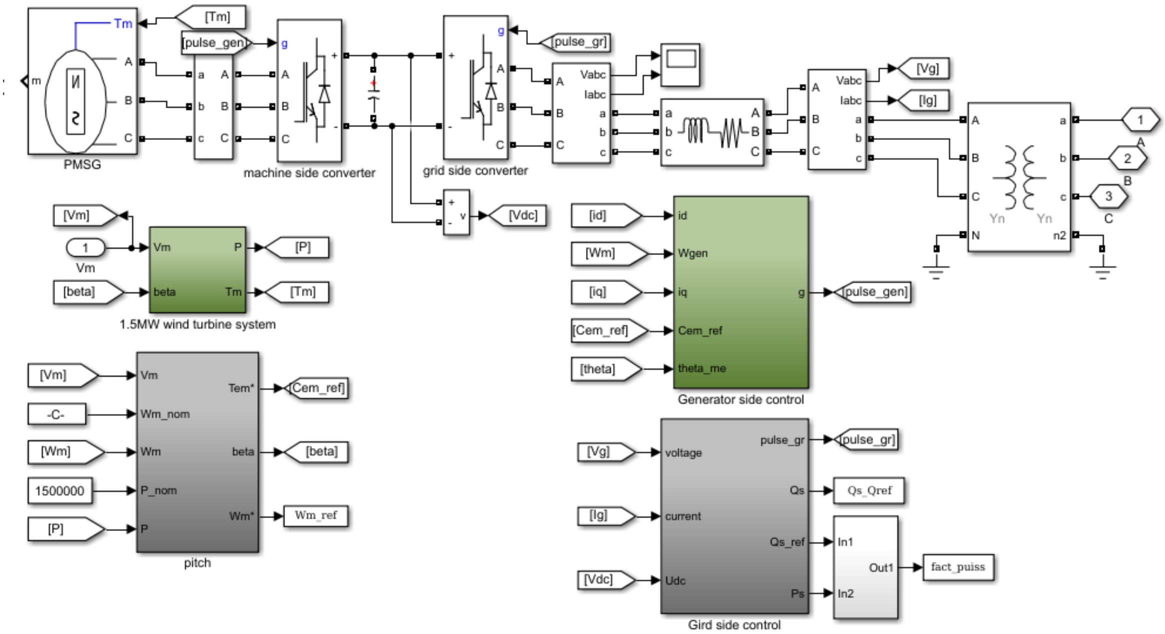

Figure C.1: Simulink model of the overall control system.

Appendix D MATLAB code of PSO-tuning parameters of fractional order PI

```
function Tune _tuning_ model_ PSO
Rng default % Initialize the random number generator
options = optim options('particleswarm');
options. Plocin= 'pswplotbestf';
options. MaxIterations= 50;
nvar= 5; % The quantity of variables
LB= [0 0 0 0 0]; % Lower bound for adjusting variables
UB= [50 150 2 150 50]; % Upper bound for adjusting variables
[x, fval] = particleswarm(@EvalObj, nvar,LB,UB,options)

% Generator of the Simulink model performance index
function obj= EvalObj(x)
simulink_model= 'Tuning_model';
load_system(simulink_model);
gains= get_param(simulink_model,'modelworkspace');
gains. assignin ('Kps', x(1));
gains.assignin('Kis', x(2));
gains.assignin('Lam', x(3));
```

```
gains.assignin('Kpd', x(4));
gains.assignin('Kid', x(5));

% Simulates the Simulink model to obtain the results
simOut= sim(simulink_model,'SaveOutput','on');

% Returns time t and error e
t= simOut.find('t');
e= simOut.find('e');

%Trapezoidal integration rule is used to compute a performance index.
n= length(e);
ae= abs(e); % IAE
obj= 0;
for i= 2:n
   stepsize= t(i)-t(i-1);
   obj= obj+0.5*stepsize*(ae(i-1)+ae(i)); % IAE
end
```