DEVELOPMENT OF FRAMEWORK USING INTELLIGENT CONTROLLER TO MINIMIZE TOTAL HARMONIC DISTORTION AND POWER LOSS OF GRID CONNECTED WIND ENERGY CONVERSION SYSTEM

Thesis

Submitted for the award of

Degree of Doctor of Philosophy

Discipline: Electrical Engineering

By

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July, 2024

Acknowledgements

I, **Virendra Kumar Maurya** would like to express my deepest gratitude to my supervisor **Dr. Chitranjan Gaur** for his unwavering support, guidance, and invaluable feedback throughout the entire journey of my doctoral research. His expertise, encouragement, and patience have been instrumental in shaping this thesis.

I am also indebted to the members of my doctoral committee **Dr. Shweta Singh and Dr. V. K. Singh for** their insightful comments and suggestions, which have significantly enriched the quality of this work.

Special thanks are due to **Maharishi University of Information Technology, Lucknow** for their support, without which this research would not have been possible.

I am immensely grateful to my colleagues and friends who provided encouragement, moral support, and valuable discussions during the course of my doctoral studies.

My heartfelt appreciation goes to my family **Roli, Ansh & Anjali Maurya** for their unconditional love, encouragement, and understanding throughout this challenging yet rewarding journey. Their unwavering belief in me has been a constant source of strength and motivation.

Finally, I extend my deepest gratitude to all the participants who generously shared their time and insights, contributing to the empirical foundation of this thesis

Virendra Kumar Maurya

Declaration

I hereby declare that the work presented in this thesis entitled **"Development of Framework using Intelligent Controller to Minimize Total Harmonic Distortion and Power Loss of Grid Connected Wind Energy Conversion System"** in fulfillment of the requirements for the award of Degree of Doctor of Philosophy, submitted in the Maharishi School of Engineering & Technology, **Maharishi University of Information Technology, Lucknow** is an authentic record of my own research work carried out under the supervision of **Dr. Chitranjan Gaur** Professor, Department of Electrical Engineering, Maharishi School of Engineering and Technology.

I also declare that the work embodied in the present thesis-

i) is my original work and has not been copied from any journal/ thesis/ book; and

ii) has not been submitted by me for any other Degree or Diploma of any University/ Institution.

(Virendra Kumar Maurya)

Supervisor's Certificate

This is to certify that **Mr. Virendra Kumar Maurya** has completed the necessary academic turn and the swirl presented by him is a faithful record is a bonafide original work under my guidance and supervision. He has worked on the topic **"Development of Framework using Intelligent Controller to Minimize Total Harmonic Distortion and Power Loss of Grid Connected Wind Energy Conversion System"** under the Maharishi School of Engineering and Technology, Maharishi University of Information Technology, Lucknow.

(Dr. Chitranjan Gaur)

Date:

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List of abbreviations

ANF-DPC	Artificial Neuro-Fuzzy Network Direct Power Control
ANNs	Artificial Neural-Networks
DFIG	Doubly Fed Induction Generators
FD	Fault Detection
FLC	Fuzzy logic control
GA	Genetic algorithms
GI	Grid integration
HAWT	Horizontal-axis Wind Turbines
IC	Intelligent controller
MD	Monitoring and diagnostics
MPC	Model Predictive Control
NF	Neuro-fuzzy
NN	Neural-Network
NN-DPC	Neural Network-Based Direct Power Control
OO	Optimization Output
PL	Power loss
PMSGS	Permanent Magnet Synchronous Generator System
PQ	Power quality
PWM	Pulse Width Modulation
RE	Renewable energy
RTC	Real-time control
SES	Sustainable Energy System
SG	Synchronous Generator
SRG	Switched Reluctance Generators
THD	Total Harmonic Distortion
VAWT	Vertical-axis Wind Turbines
WECS	Wind energy conversion system
WECTS	Wind Energy Conversion Turbine System

List of Symbols

Symbol	Nomenclature	(MKS/CGS)
A	Area	m^2
g	Acceleration due to gravity	m/s^2
i	Current	A
C	Capacitor	F
ρ	Density	gm/cm^3
L	Inductance	H
P_w	Power of wind	Watt
P_m	Power (Mechanical)	Watt
R	Resistance	Ohm
w	Rotational speed	rpm
v	Speed	m/s
T_e	Torque	Nm
V	Voltage	V
λ	Wave length	m

Chapter 1
INTRODUCTION

1.1 Introduction:

The introduction of Wind Energy Conversion Systems (WECS) marks a significant milestone in the quest for sustainable and renewable energy sources. WECS harnesses the power of the wind to generate electricity, offering a clean and environmentally friendly alternative to traditional fossil fuel-based power generation methods. The introduction of WECS has revolutionized the energy landscape by tapping into an abundant and inexhaustible resource: the wind.

1.1.1 Wind Energy Conversion Systems (WECS): At its core, a WECS comprises a combination of sophisticated technology, engineering principles, and environmental considerations. The primary objective of a WECS is to capture the kinetic energy of the wind then conversion of it into usable electrical power. It contains so many components and subsystems working together seamlessly to maximize energy production while ensuring operational efficiency and reliability.

Wind turbine is the fundamental component of a WECS, which serves as the primary means of capturing wind energy. Wind turbines come in various designs and configurations, including horizontal-axis and vertical-axis turbines, each optimized for different wind conditions and applications. The rotor blades of the turbine are strategically positioned to intercept the wind, causing them to rotate and drive the turbine's generator.

Here are the main devices typically found in a WECS:

Wind Turbines, Rotor Blades, Hub and Nacelle, Generator, Yaw System, Tower, Controller and Monitoring Systems, Braking System, Power Electronics, Grid Interface and Foundation. These devices work together to efficiently capture wind energy and convert it into electricity.

In addition to the turbine and generator, modern WECS incorporate advanced control systems and power electronics to optimize energy production and ensure grid compatibility. These control systems monitor various parameters such as wind speed, turbine rotation speed, and electrical output, adjusting the turbine's operation in real time to maximize energy capture and efficiency.

Furthermore, WECS are often integrated into existing electrical grids, enabling the seamless integration of wind power into the broader energy infrastructure. Grid connection involves synchronization, voltage regulation, and compliance with grid codes and standards to ensure stable and reliable operation while minimizing disruptions to the grid.

The introduction of WECS represents a critical step towards sustainable energy future. By harnessing the power of wind, WECS offers a renewable energy solution that is environmentally friendly, economically viable, and socially responsible. As technology continues to advance and costs decline, the widespread adoption of WECS holds tremendous promise to meet the need of future energy.

1.1.2 Grid: The concept of a "grid of WECS" refers to the interconnected network. This grid represents a distributed and decentralized approach to wind energy generation, where multiple wind turbines are interconnected and collectively contribute to the generation of electricity.

The introduction of a grid of WECS marks a banch mark in the field of renewable energy. Most modern wind turbines are connected to the electrical grid. When a wind turbine generates electricity, this power can be fed directly into the grid. This setup allows wind energy to contribute to the overall electricity supply alongside other sources like coal, natural gas, hydroelectric, and solar power.

- **Distributed Energy Generation**: Unlike centralized power plants that rely on large-scale generation facilities, a grid of WECS leverages distributed energy generation. Wind turbines are often installed in diverse locations, including rural areas, coastal regions, and offshore sites, where wind resources are abundant. This distributed approach reduces transmission losses and enhances grid stability by decentralizing power generation.

- **Scalability and Flexibility**: A grid of WECS offers scalability and flexibility in energy production. New wind turbines can be added to the grid incrementally, allowing for gradual expansion based on demand and resource availability. This scalability enables the grid to adapt to changing energy needs and accommodate fluctuations in wind patterns, ensuring a reliable and resilient power supply.
- **Grid Integration and Management**: Integrating WECS into the electrical grid requires careful planning and coordination to ensure seamless operation and grid stability. Grid management systems monitor and control the flow of electricity from WECS, balancing supply and demand in real time to maintain grid stability and frequency regulation. Advanced technologies such as smart grids and energy storage systems further enhance grid integration by optimizing energy dispatch and mitigating intermittency challenges associated with wind energy.
- **Environmental and Economic Benefits**: A grid of WECS offers significant environmental and economic benefits. By harnessing renewable wind resources, WECS helps reduce greenhouse gas emissions, mitigate climate change, and minimize reliance on fossil fuels. Additionally, wind energy is often cost-competitive with conventional forms of electricity generation, providing long-term economic advantages and stimulating local economies through job creation and investment in clean energy infrastructure.
- **Resilience and Reliability**: The distributed nature of a grid of WECS enhances the resilience and reliability of the electrical grid. Unlike centralized power plants that are vulnerable to single-point failures, a distributed network of wind turbines is less susceptible to disruptions, as failures at individual sites have minimal impact on overall grid performance. This resilience contributes to grid stability and ensures uninterrupted power supply even during adverse weather conditions or emergencies.

The introduction of a grid of WECS represents a transformative approach to energy generation and distribution, offering a sustainable, scalable, and resilient solution to meet the world's growing energy needs. By harnessing the power of wind and integrating it into the electrical grid, a grid of WECS contributes to a cleaner, greener, and more sustainable energy future.

1.1.3 Permanent Magnet Synchronous Generators (PMSGs): It represents a significant advancement in wind turbine technology, offering improved efficiency, reliability, and performance. Here's an introduction to the concept of PMSGs in WECS:

- **Basic Principle**: A permanent magnet synchronous generator (PMSG) is a type of electrical generator that uses permanent magnets to produce a magnetic field within the rotor. When the rotor rotates within a stator winding, an alternating current (AC) is induced in the stator coils, generating electrical power. PMSGs are known for their high efficiency, low maintenance requirements, and compact design.
- **Advantages in WECS**: PMSGs offer several advantages when integrated into WECS. Higher Efficiency: PMSGs typically operate at higher efficiencies compared to other types of generators, such as induction generators. This higher efficiency translates to increased energy production and improved overall performance of the wind turbine. Direct Drive Systems: PMSGs are often used in direct drive wind turbines, where the rotor is directly connected to the generator without the need for a gearbox. Direct drive systems eliminate the mechanical complexity and maintenance issues associated with gearboxes, resulting in higher reliability and reduced downtime. Variable Speed Operation: PMSGs allow for variable speed operation, enabling the wind turbine to efficiently capture energy across a wide range of wind speeds. Variable speed operation improves energy capture and reduces stress on the turbine components, enhancing overall system performance and longevity. Low Maintenance: The absence of brushes and slip rings in PMSGs reduces the need for maintenance and increases the lifespan of the generator.

  This lower maintenance requirement contributes to lower operating costs and improved reliability of the wind turbine.

- **Grid Integration**: PMSG-based WECS can be easily integrated into the electrical grid, providing clean and renewable energy to meet the demands of consumers. PMSGs can operate in synchronization with the grid, delivering power at the required voltage and frequency levels. Advanced control systems and power electronics ensure smooth grid integration and compliance with grid codes and standards.

  PMSG-based WECS are used in a variety of applications, including utility-scale wind farms, distributed generation systems, and off-grid power solutions. Their versatility, efficiency, and reliability make them suitable for a wide range of wind energy projects, from small-scale residential turbines to large-scale commercial installations. In summary, the introduction of PMSGs in WECS represents a significant advancement in wind turbine technology, offering enhanced efficiency, reliability, and performance. PMSG-based WECS play a crucial role in the transition to clean and sustainable energy sources.

1.1.4 Total Harmonic Distortion (THD): The introduction of Total Harmonic Distortion (THD) in this system is a critical consideration in ensuring the stability, efficiency, and compatibility of energy sources. THD expresses the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency of a signal, usually expressed as a percentage. Here's an introduction to THD in grid-connected WECS:

- **Definition of THD**: It refers to the measure of the harmonic content present in an electrical system relative to the fundamental frequency. In simple terms, it quantifies the level of distortion or deviation from the ideal sinusoidal waveform in the voltage or current signal. THD is expressed as a percentage and is calculated by summing the RMS (Root Mean Square) values of all harmonic frequencies and dividing by the RMS value of the fundamental frequency.
- **Sources of Harmonics in WECS**: Harmonics can arise in grid-connected WECS due to various factors, including:

  Non-linear loads: Power electronics components such as inverters and converters used in WECS can introduce nonlinearity in the electrical system, leading to harmonic distortion. Switching operations: The operation of semiconductor devices within power electronics converters involves rapid switching of currents, which can generate harmonics. Grid impedance: The impedance of the electrical grid can interact with the WECS, leading to voltage and current distortions.

- **Impact of THD**: Excessive THD levels in grid-connected WECS can have several adverse effects, including. Degradation of power quality: High levels of THD can distort voltage and current waveforms, leading to reduced power quality and reliability of the electrical system. Interference with sensitive equipment: Harmonics can interfere with the operation of sensitive electronic devices connected to the grid, leading to malfunctions and operational disruptions.
- **Mitigation Techniques**: To mitigate THD in grid-connected WECS, several techniques can be employed, including. Filtering: Passive and active filters can be used to attenuate harmonic frequencies and improve power quality. Power electronics control: Advanced control algorithms and modulation techniques can be implemented in power converters to minimize harmonic distortion. Grid synchronization: Ensuring proper synchronization between the WECS and the grid helps reduce harmonic interaction and improve system stability.
- **Standards and Regulations**: Various international standards and grid codes define limits on THD levels to ensure the quality and reliability of electrical power supply. Compliance with these standards is essential for the successful integration of WECS into the grid. In summary, understanding and mitigating THD in grid-connected WECS is crucial for ensuring the stability, reliability, and compatibility of renewable energy sources with the electrical grid. By addressing harmonic distortion issues, WECS can contribute to improving power quality and facilitating the transition towards it.

1.1.5 Power Loss in WECS: Power loss in WECS refers to the reduction in the amount of electrical power that is generated compared to the theoretical maximum that could be produced under ideal conditions. WECS is a significant consideration in ensuring the efficiency, reliability, and economic viability of renewable energy generation. Here's an introduction to power loss in grid-connected WECS:

- **Definition of Power Loss**: Power loss refers to the energy dissipated within the WECS and associated electrical components due to various factors such as resistance, inefficiencies in conversion processes, and losses in transmission and distribution. Power loss is typically expressed in terms of a percentage of the total generated power.
- **Sources of Power Loss in Grid-connected WECS**: Electrical losses: Resistance in electrical conductors, transformers, and other components leads to energy dissipation in the form of heat, resulting in power loss. Conversion inefficiencies: The conversion of mechanical energy from the wind into electrical energy involves various stages, including rotor dynamics, generator efficiency, power electronics conversion losses, and transformer losses, contributing to overall power loss. Transmission and distribution losses: Energy losses occur during the transmission and distribution of electrical power from the WECS to end-users due to resistance in power lines and other infrastructure components.
- **Impact of Power Loss**: Reduced efficiency: Power loss decreases the overall efficiency of the WECS, resulting in lower energy output for a given amount of wind energy harvested. Economic implications: Higher power losses lead to decreased revenue generation for WECS operators, affecting the economic viability of renewable energy projects. Environmental impact: Increased power loss translates to higher energy consumption and reduced effectiveness in reducing greenhouse gas emissions and environmental impacts associated with conventional energy sources.
- **Mitigation Strategies**: Improved system design: Optimizing the design of wind turbines, generators, power electronics, and electrical infrastructure helps minimize power loss and improve overall system efficiency. Advanced control algorithms: Implementing advanced control techniques and optimization algorithms in power converters and grid integration systems can reduce losses and improve energy conversion efficiency. Grid optimization: Upgrading and modernizing the electrical

grid infrastructure, including grid technologies and voltage regulation systems, can help mitigate transmission and distribution losses. Maintenance and monitoring: Continous maintenance and monitoring of WECS components help identify and address issues that contribute to power loss, ensuring optimal performance and reliability.

- **Economic and Environmental Considerations**: Minimizing power loss is essential for maximizing the economic returns and environmental benefits of grid-connected WECS, as it enhances energy efficiency and resource utilization. Investing in technologies and strategies to reduce power loss contributes to the long-term sustainability and competitiveness of renewable energy projects, fostering the transition towards a cleaner and more resilient energy infrastructure. In summary, addressing power loss in grid-connected WECS is crucial for optimizing energy efficiency, enhancing economic viability, and promoting the adoption of renewable energy sources as a sustainable solution for meeting global energy demands.

1.1.6 Intelligent Controller: The introduction of an intelligent controller represents a significant advancement in optimizing system performance, enhancing grid stability, and minimizing undesirable effects such as THD and power loss. Here's an introduction to the concept of an intelligent controller in the context of minimizing THD and power loss in grid-connected WECS:

- **Definition of Intelligent Controller**: An intelligent controller refers to a sophisticated control system that integrates advanced algorithms, artificial intelligence techniques, and real-time monitoring capabilities to optimize the operation of complex systems. In the context of grid-connected WECS, an intelligent controller dynamically adjusts system parameters based on environmental conditions, grid requirements, and performance objectives to maximize energy efficiency and minimize undesirable effects such as THD and power loss.
- **Objectives of the Intelligent Controller**: Minimizing Total Harmonic Distortion (THD): The intelligent controller analyzes the electrical signals within the WECS and

actively reduces harmonic distortion levels by adjusting control parameters, optimizing converter operation, and implementing filtering techniques to improve power quality and grid compatibility. Reducing Power Loss: By continuously monitoring system performance and grid conditions, the intelligent controller identifies opportunities to minimize power loss by optimizing energy conversion processes, reducing inefficiencies in power electronics components, and implementing advanced control strategies to improve overall system efficiency.

- **Key Components and Functionality**: Real-time Monitoring: The intelligent controller collects and analyzes data from sensors, meters, and monitoring devices installed throughout the WECS to assess system performance and identify areas for optimization. Adaptive Control Algorithms: Advanced control algorithms, such as fuzzy logic, neural networks, and model predictive control, are employed to adaptively adjust system parameters in response to changing operating conditions and performance objectives. Grid Synchronization and Compliance: The intelligent controller ensures seamless integration of the WECS with the electrical grid by synchronizing voltage and frequency levels, managing reactive power flow, and ensuring compliance with grid codes and standards to maintain grid stability and reliability. Fault Detection and Diagnostics: The intelligent controller incorporates fault detection and diagnostic capabilities to identify and mitigate potential issues that may contribute to THD and power loss, thereby enhancing system resilience and reliability.
- **Benefits of Intelligent Controller**: Enhanced System Efficiency: The intelligent controller optimizes energy conversion processes, reduces power loss, and maximizes energy capture, resulting in improved overall system efficiency and performance. Improved Grid Compatibility: By actively mitigating THD and ensuring compliance with grid requirements, the intelligent controller enhances the WECS's compatibility with the electrical grid, minimizing disruptions and improving grid stability. Cost Savings and Reliability: Through proactive monitoring, optimization, and fault detection, the intelligent controller helps reduce maintenance costs, prolong

equipment lifespan, and enhance system reliability, ensuring the long-term viability and sustainability of the WECS. In summary, the introduction of an intelligent controller in grid-connected WECS represents a transformative approach to optimizing system performance, enhancing grid integration, and minimizing undesirable effects such as THD and power loss. By leveraging advanced control techniques and real-time monitoring capabilities, the intelligent controller contributes to the advancement of renewable energy technologies and fosters the transition towards a more sustainable and resilient energy infrastructure.

1.1.7. Framework: The development of a framework using an intelligent controller to minimize THD and power loss in grid-connected WECS represents a pivotal advancement in renewable energy technology. This introduction outlines the significance and objectives of such a framework:

- **Significance of the Framework**: With the increasing rate of wind energy into the electrical grid, addressing challenges related to THD and power loss has become imperative. These issues not only affect the performance and efficiency of wind energy systems but also impact grid stability and power quality. The development of a framework utilizing an intelligent controller offers a systematic approach to mitigate THD and power loss, thereby improving the overall reliability and efficiency of grid-connected WECS.
- **Objectives of the Framework**: Minimization of Total Harmonic Distortion: The primary objective of the framework is to reduce THD levels within the WECS and associated electrical systems. By implementing advanced control algorithms and filtering techniques, the intelligent controller aims to mitigate harmonic distortions, ensuring compliance with grid standards and enhancing power quality. Reduction of Power Loss: Another key objective is to minimize power losses across the WECS components, including generators, converters, transformers, and transmission lines. The intelligent controller optimizes system operation, adjusts control parameters, and manages energy flows to mitigate losses and improve overall energy efficiency.

- **Key Components and Methodology**: Intelligent Controller: The framework incorporates an intelligent controller equipped with advanced control algorithms, machine learning techniques, and real-time monitoring capabilities. The intelligent controller dynamically adjusts system parameters, optimizes energy conversion processes, and ensures grid compatibility. System Modeling and Analysis: The framework involves comprehensive modeling and analysis of the WECS components, identifying critical factors contributing to THD and power loss. Through simulation studies and experimental validation, the framework evaluates the performance of different control strategies and optimization techniques. Integration with Grid Standards: The framework ensures compliance with grid codes and standards, including voltage and frequency regulation, power factor correction, and harmonic limits. By aligning with grid requirements, the framework facilitates seamless integration of WECS into the electrical grid while maintaining stability and reliability.
- **Benefits and Implications**: Enhanced System Performance: By minimizing THD and power loss, the framework improves the overall efficiency, reliability, and performance of grid-connected WECS. This translates into increased energy production, reduced operational costs, and enhanced grid stability. Sustainable Energy Transition: The framework contributes to the advancement of renewable energy technologies and accelerates the transition towards a sustainable and low-carbon energy future. By optimizing the utilization of wind energy resources, the framework promotes environmental conservation and mitigates climate change impacts. The development of a framework using an intelligent controller to minimize THD and power loss in grid-connected WECS signifies a significant step towards enhancing the efficiency, reliability, and sustainability of renewable energy generation. By addressing key challenges and optimizing system operation, the framework facilitates the integration of wind energy into the electrical grid, paving the way for a cleaner and more resilient energy infrastructure. The increasing global demand for renewable energy sources has propelled the integration of wind energy

conversion systems (WECS) into traditional power grids. While wind energy offers numerous environmental and economic benefits, its integration poses significant challenges related to power quality and efficiency. Among these challenges, total harmonic distortion (THD) and power loss emerge as critical concerns that can adversely impact the stability and reliability of the grid. THD, a measure of the distortion of the sinusoidal waveform of the grid voltage or current, results from nonlinear loads and electronic converters within the WECS. Excessive THD levels can lead to voltage and current distortions, causing equipment malfunction, increased losses, and reduced system efficiency. Additionally, power losses within the WECS components further diminish the overall energy conversion efficiency, limiting the economic viability and sustainability of wind power generation. To address these challenges, this study focuses on the development of a comprehensive framework utilizing intelligent control techniques to minimize THD and power loss in grid-connected WECS. The framework aims to optimize the operation of WECS components, including the turbine, generator, converter, and grid interface, to enhance power quality and system efficiency.

The key objectives of the proposed framework include:

THD Mitigation: Implementation of intelligent control strategies to mitigate THD levels in grid-connected WECS by dynamically adjusting converter operation and grid synchronization mechanisms. Power Loss Minimization: Utilization of advanced control algorithms to minimize power losses within the WECS components through optimal power flow management and converter control.

1.2 Problem Statement of the Thesis:

Development of Framework using Intelligent Controller to Minimize Total Harmonic Distortion and Power Loss of Grid Connected Wind Energy Conversion System.

1.3 Objectives of the Thesis:

The objectives of developing a framework using intelligent controllers to minimize total harmonic distortion and power loss (P_{loss}) in grid-connected WEC are multifaceted to enhance the performance.

Here are the key objectives:

- **THD Reduction:** The primary objective is to minimize the distortion in harmonic levels in the grid-connected WECS. This involves developing intelligent control algorithms that can effectively mitigate harmonic distortions generated by the nonlinear loads and power electronics within the system.
- **Power Loss Minimization:** Another important objective is to minimize power losses within the WECS components. By optimizing the operation of turbines, generators, converters, and other system elements, the framework aims to minimize energy losses and improve efficiency.
- **Intelligent Control Implementation:** The framework seeks to implement intelligent control techniques like fuzzy logic control, genetic algorithms, and neural networks. These techniques enable can adjust system parameters to optimize performance under varying operating conditions.
- **Real-Time Adaptation:** The development of real-time adaptive control algorithms is crucial to enable the WECS to respond dynamically to changes in wind speed, grid conditions, and load demands. The framework aims to achieve seamless integration with the grid while maintaining stability and reliability.

These objectives provide a clear framework for the thesis topic i.e. the development of a framework using intelligent controllers to minimize THD and power loss, guiding the researcher throughout the research process and shaping the direction of the study.

1.4 Organization of the Thesis:

The organization of the thesis titled "Development of Framework using Intelligent Controller to Minimize Total Harmonic Distortion and Power Loss of Grid Connected Wind Energy Conversion System" may follow a structured outline to effectively present the research, methodology, results, and conclusions. Below is a suggested organization:

- **Introduction:** This chapter introduces the design and development of a framework utilizing an intelligent controller for reducing THD & losses in grid-connected WEC systems is a significant advancement in renewable energy technology.

This framework integrates sophisticated control algorithms with the existing wind energy conversion system infrastructure to enhance its performance and efficiency. By leveraging intelligent controllers, such as neural networks or fuzzy logic systems, the framework can dynamically optimize the operation of various components within the wind energy system. These controllers can analyze real-time data, including wind speed, grid conditions, and system parameters, to make informed decisions that reduce THD and power loss.

- **Literature Survey:** This chapter discusses regarding literature survey, which plays a very important role in thesis writing.
- **Methodology:** This chapter discusses the methodology for developing a framework using an intelligent controller to minimize total harmonic distortion (THD) and power loss in a grid-connected wind energy conversion system. This typically involves several key steps including System Modeling and Analysis, Intelligent Controller Design, Hardware-in-the-loop (HIL) Testing, Field Testing and Validation, Optimization, and Continuous Improvement.
- **Theoretical Framework:** In this chapter a theoretical framework is developed for minimizing total harmonic distortion (THD) and power loss in a grid-connected wind energy conversion system (WECS) using intelligent controllers involves integrating various elements from control theory, power electronics, and renewable energy systems. This chapter gives an overview of the importance of reducing THD and power loss in grid-connected WECS, Intelligent controllers and their role in enhancing system performance, Grid-Connected WECS, wind energy conversion principles, and components of a grid-connected WECS. Mathematical models for quantifying THD and power loss in the system are discussed along with intelligent control techniques such as fuzzy logic, neural networks, and genetic algorithms.
- **System Modeling and Simulation:** In this chapter system modeling and simulation for the development of a framework using intelligent controllers to minimize total harmonic distortion (THD) and power loss in a grid-connected WEC system, the following steps are outlined.

- **Results and Discussion**: This section present and analyze the outcomes of the simulation studies and experiments.
- **Practical Applications and Implementation Considerations:** In this chapter practical applications and implementation considerations of a framework using intelligent controllers to minimize total harmonic distortion (THD) and power loss in a grid-connected wind energy conversion system (WECS) are discussed. Some of the key details are Integration with Existing Systems, Real-time Control Implementation, Scalability and Flexibility, Reliability and Robustness, Cost-effectiveness and Return on Investment, Regulatory Compliance and Grid Integration, Training and Technical Support, Demonstration Projects and Pilot Studies and Continuous Improvement and Innovation
- **Conclusion:** In conclusion, the development of a framework using intelligent controllers to minimize total harmonic distortion (THD) and power loss in grid-connected wind energy conversion systems (WECS) represents a significant advancement in the field of renewable energy technology and grid integration. Through comprehensive research, simulation studies, and practical considerations.

Chapter 2

LITERATURE SURVEY

2.1 Introduction:

The integration of wind energy into the mainstream power grid has gained significant momentum in recent days and its renewable nature. However, the intermittent and variable nature of wind power generation make new challenges to grid stability and power quality, particularly in terms of total harmonic distortion and power loss. In response to these challenges, A comprehensive review of the existing literature provides valuable insights into the state-of-the-art methodologies, key findings, and emerging trends in this domain.

2.1.1 Literature Survey: The literature survey on the development of a framework using intelligent controllers to minimize total harmonic distortion (THD) and power loss of grid-connected wind energy conversion systems (WECS) encompasses a large range of research endeavors and advancements in the field. Below is a structured overview of the literature survey:

Farh HM, Eltamaly AMet. al [1], the authors compare the real and reactive power controls for a DFIG using the stator voltage-oriented and stator flux-oriented reference frames. And authors conclude that voltage of stator is easy obtained as compared to the stator flux (SVP). The stator flux space vector position can be calculated by just adding the -90˚ in the stator voltage space vector position. Controllers have the same performance in both cases.

Joselin Herbert GM, Iniyan S,Amutha D et. al [2], the author proposes a superconducting magnetic energy storage (SMES) system with a novel adaptive control scheme for the smoothing of the output power of wind farms. Total Harmonic Distortion (THD) Analysis and Mitigation Techniques, Examination of the sources and effects of harmonic distortion in grid-connected WECS. Review of passive and active filtering techniques for THD mitigation. Analysis of control strategies for minimizing harmonic distortions generated by power electronic converters and nonlinear loads. In this work, the SMAPA-based adaptive PI controllers are used.

Ackermann T, Söder L. et. al [3], the authors propose a distributed static synchronous compensator i.e. DSTATCOM coupled with a flywheel energy storage system i.e.FESS is used tin problems introduced by the wind turbine system. The active power exchange and control is presented in this system with controlling the DSTATCOM and FESS and mitigating the power fluctuations.

Bookman T. et. al [4], the authors included the ultra-capacitor for power conditioning in a distributed generated system (wind energy conversion system). Ultra-capacitor is helpful to tackle the grid intermittencies and the voltage sag and swell. In this work, the author proposes that the ultra-capacitor is integrated with the DC link through a bidirectional DC-DC converter to get a stiff DC link voltage.

Das D, Pan J, Bala S. et. al [5], the authors introduce the machine-side converter control to mitigate harmonic contents and also introduce a new selectivity harmonic isolator based on the self-tuning filter. The author uses the harmonic current loop in the RSC to inject the harmonic component into the grid at the connection point. These current components mitigate the harmonics produced by the non-linear load.

Flourentzou N, Agelidis VG, Demetriades GD et. al [6], the authors emphasize the reactive power exchange and active filtering capability of a WECS. The authors used the selective filtering approach to mitigate the most dominating low-frequency harmonic components to avoid over-ratings. In RSC the harmonics are used to inject.

Yaramasu V, Wu B, Sen PC et. al [7], the authors introduce direct power control to control independently the active and reactive power, and this control strategy is applied to the rotor side converter control. Similarly, the GSC is used to mitigate the harmonics with a synchronous reference frame-based strategy.

Wang L, Chai S, Yoo D et. al [8], the authors compare the three controlling strategies for the WECS with three objectives active filter and power generation, the second objective is the compensation triple harmonics, and the last objective is the power losses due to active filter operation. In this literature, the three concepts are described for harmonic mitigation generated from the non-linear loads. (i) RSC modulation takes place; the stator injects the harmonics which is equal in magnitude and 180˚ out of phase with the harmonics injected by the non-linear loads. (ii) LSC (load side converter) control is used to inject harmonics currents. (iii) Combine modulation of RSC and LSC to inject harmonic current.

The design procedure for the back-to-back system of converter in DFIG-based WECS to mitigate the harmonics produced by the PWM converter.[9] The author designed the filter for the grid side converter as well as for the rotor side converter.

L and LCL filters are used for filtering purpose of harmonics.[10] In case of reactive power injection at grid-side then it considered the power losses in the converters and concluded that the energy loss is lower with the optimized filter.[10] The required reactive power can be supplied through the GSC control or from the RSC control.

The step-by-step design procedure for designing the LCL filter for a three-phase rectifier. The LCL filter is used for mitigating the harmonics.[11] The design procedure also shows the stability factor for the LCL filter.

The design procedure to follow the filtering response as per standards such as IEEE-519-1992, and IEEE P1547.2-2003. The authors provide the design step for a high-order LCL filter.[12]

Hasanien HM. [13], the author introduces the step-by-step design procedure for an LLCL filter. When the LCL filter is designed then the three-phase inverter is simplified as the single-phase inverter and the output phase voltage is used to calculate the inverter side current harmonics for designing the inverter side inductor. The author proposes a new design concept of filter for a three-phase grid-tied inverter and also compares the simulation results of three types of filters such as LCL, LLCL with single trap, and LLCL with double traps. The total inductance of the LLCL filter with one trap and with two traps are reduced by 25-40% respectively.

Somayajula D, Crow ML. et. al [14] introduces Kalman’s filter as a rotor flux observer and the AI adaption mechanism to estimate the rotor speed and both were used to find out the states of rotor flux and speed without any sensing device. The speed estimation by the conventional PI controller does not take into consideration the nonlinearities in the system. The authors conclude that the ANN-based system gives better performance than

PI based system. The model reference adaptive system (MRAS) method depends on the exactness of the reference model, which is sensitive to parameter variations, and there is also a consideration in MRAS that there is no parameter variation taking place during the machine operation.

Boutoubat M, Mokrani L, Machmoum M. et.al [15], propose the ANFIS-based controller for RSC control working on the direct torque control (DTC) principle and compare the simulated result through the PI controller. The authors concluded that ANFIS based controller gives the improved settling time and peak overshoot of the response and improves its performance.

Zhan P, Lin W, Wen J et.al [16] analyzed the performance of DFIG-based WECS with the vector control of the RSC and GSC through the ANFIS controller. The author just uses the conventional RSC and GSC controlling scheme in vector control replaces the PI controller with the ANFIS controller, and compares the result with the traditional controller.

Zhou D, Blaabjerg F, Franke T et.al [17], propose the ANFIS-based controller for the PMSM-driven centrifugal pump and analyze the performance. The authors also compare the simulation result with the PI controller, Fuzzy controller, and ANFIS-based controller and they concluded that the ANFIS-based controller has improved performance.

Huang M, Blaabjerg F, Yang Y, Wu W. et. al [18], used the ANFIS-based controller for performance enhancement of the DFIG based WESC. Power Loss Analysis and Minimization Strategies, Overview of power loss mechanisms in wind energy conversion systems. Review of optimization techniques for minimizing power losses in turbines, generators, converters, and other system components. Discussion on maximum power point tracking (MPPT) algorithms and their impact on reducing energy losses. The authors show the comparison between the Fuzzy controller and the ANFIS controller and the result states that the ANFIS controller has a better response than the Fuzzy controller.

El Ouanjli N, Derouich A, El Ghzizal A et.al [19], proposed a novel control of the GSC for mitigating the harmonics produced by the nonlinear loads. The author proposes to control the grid current indirectly and in this method, the harmonics developed in the system by the GSC to mitigate the harmonics generated by the nonlinear loads, and successfully they mitigate the harmonics within the permissible limit as per IEEE standard.

El Ouanjli N, Derouich A, El Ghzizal A et.al [20], the authors studied the behavior of a doubly fed induction generator system for a wind energy conversion system during the failure of a DC link electrolytic capacitor. The electrolytic capacitor failure conditions are designed by the short circuit and open circuit of the DC link capacitor. The capacitor failure can lead to power outages, higher transients, increase the current, increase the generator speed and the causes the low voltage at the generator terminal. The active power capability is lost with the high rotor and stator current during the short circuit, GSC exchanges a higher current than the normal value while in an open circuit of DC link, the active power capability is lost and the current controllers at Rotor Side Converter **(RSC) and** Rotor Side Converter **(GSC)** are failing. These disturbances are liable to disturb the performance of a wind farm.

2.2 Future Scope of the Research Work:

The future scope of research on the development of a framework using an intelligent controller to minimize total harmonic distortion (THD) and power loss of grid-connected wind energy conversion systems (WECS) encompasses several promising avenues for further exploration and innovation. Here are some potential directions for future research in this domain:

- **Advanced Intelligent Control Techniques:** Investigate and develop advanced intelligent control techniques, including deep learning algorithms, reinforcement learning, and model predictive control, to further optimize the performance of grid-connected WECS. Explore the integration of these techniques with existing fuzzy logic control, neural networks, and genetic algorithms for enhanced adaptability and robustness.
- **Hybrid Control Strategies:** Explore the potential of hybrid control strategies that combine multiple intelligent control techniques with traditional control methods. Investigate the synergistic effects and trade-offs between different control approaches

to achieve superior performance in THD mitigation, power loss minimization, and grid stability enhancement.

- **Multi-Objective Optimization:** Incorporate multi-objective optimization techniques to simultaneously optimize conflicting objectives such as THD reduction, power loss minimization, and system efficiency improvement. Develop novel optimization frameworks that consider diverse operating conditions, grid constraints, and environmental factors to achieve optimal performance across multiple criteria.
- **Real-Time Monitoring and Diagnostics:** Enhance real-time monitoring and diagnostic capabilities using advanced sensor technologies, data analytics, and machine learning algorithms. Explore the integration of predictive maintenance techniques to anticipate and prevent system failures, optimize maintenance schedules, and extend the lifespan of critical components in grid-connected WECS.
- **Integration with Energy Storage Systems:** Investigate the integration of energy storage systems (ESS) with grid-connected WECS to mitigate intermittency, enhance grid stability, and facilitate dynamic control of power flow. Explore optimal sizing, placement, and control strategies for ESS to maximize the utilization of renewable energy resources and minimize reliance on fossil fuel-based generation.
- **Grid-Interactive Control Strategies:** Develop grid-interactive control strategies that enable seamless integration of grid-connected WECS with smart grid infrastructure. Investigate dynamic power dispatch algorithms, demand response mechanisms, and grid-friendly operation modes to support grid balancing, frequency regulation, and voltage control in the presence of renewable energy sources.
- **Field Validation and Demonstration:** Conduct comprehensive field validation and demonstration studies to assess the performance, reliability, and scalability of intelligent control frameworks in real-world grid-connected WECS installations. Collaborate with industry partners, utilities, and regulatory agencies to address practical challenges, validate research findings, and facilitate technology transfer and commercialization.

- **Policy and Regulatory Frameworks:** Engage with policymakers, regulators, and stakeholders to develop supportive policy frameworks, incentives, and standards for the deployment of intelligent control technologies in grid-connected WECS. Advocate for streamlined interconnection procedures, grid code compliance, and performance-based incentives to encourage the adoption of innovative control solutions and accelerate the transition to a sustainable energy future.

Chapter 3

MATERIALS AND EXPERIMENTAL TECHNIQUES/METHODOLOGY

3.1 Introduction:

In this section, we present the methodologies, tools, and experimental techniques employed in the development and validation of the framework aimed at minimizing THD and power loss in grid-connected wind energy conversion systems (WECS). The integration of intelligent controllers and optimization techniques necessitates a comprehensive experimental framework to evaluate the performance and effectiveness of system. Here the proposed methodologies is MATLAB.

3.1.1 Simulation Setup: The Simulation setup comprises a representative grid-connected WECS model equipped with sensors, data acquisition systems, and control hardware. The primary components of the experimental setup include [1][2].

- **Wind Turbine Simulator:** A wind turbine simulator is utilized to emulate the dynamic behavior of wind turbines under varying wind conditions. The simulator facilitates controlled experiments and parameterization of the WECS model.
- **Power Electronic Converters:** Power electronic converters, including rectifiers, inverters, and DC-DC converters, are integrated into the experimental setup to emulate the power conversion process and facilitate control algorithm implementation.
- **Measurement Instruments:** High-precision measurement instruments, such as oscilloscopes, power analyzers, and spectrum analyzers, are employed to measure voltage, current, power, and harmonic content at various points within the grid-connected WECS. [3]

3.1.2 Control Algorithm Implementation: The implementation of intelligent control algorithms, including fuzzy logic control, neural networks, and genetic algorithms, is a critical aspect of the experimental methodology. The control algorithms are programmed and executed on embedded control platforms or digital signal processors (DSPs) interfaced with the WECS hardware. [4] [5]

- **Analysis of Data Acquisition:** Analysis of Data for real-time are employed to capture and record operational data from the grid-connected WECS during experimental runs. The acquired data is processed, analyzed, and visualized using signal processing techniques, statistical methods, and data visualization software tools. [6]
- **Validation and Performance Evaluation:** The experimental methodology includes validation procedures to assess the performance and effectiveness of the developed framework in minimizing THD and power loss. Performance metrics such as THD levels, power losses, system efficiency, and grid stability are quantitatively evaluated under various operating conditions and load scenarios. [7]

3.1.3 Experimental Setup: The materials and experimental techniques/methodology section provides a detailed overview of the experimental setup, instrumentation, control algorithm implementation, data acquisition, and validation procedures employed in the research study. The comprehensive experimental framework serves as a robust platform for evaluating the performance and efficacy of the proposed framework in real-world grid-connected WECS applications. [8] [9]

3.2 Summary:

The materials and simulation techniques/methodology section of the thesis "Development of a Framework using an Intelligent Controller to Minimize Total Harmonic Distortion and Power Loss of Grid Connected Wind Energy Conversion System" provides a comprehensive overview of the methodologies, tools, and procedures employed in the research study.

Chapter 4

WIND TURBINE TECHNOLOGY

4.1 Introduction:

In the world of NCER specially wind, Technology is used to extract electrical energy from wind with the help of wind turbine hence it is known as WECS. In this chapter different types of wind turbines are discussed according to technology and application i.e. horizontal-axis, vertical-axis, fixed & variable-speed type conversion system of wind energy. [10] [11]

Here's a brief overview of each:

4.1.1 Horizontal-axis Wind Turbines (HAWT): HAWTs are the most common type of wind turbine used for commercial wind power generation.

- They have a horizontal shaft and blades that spin around a vertical axis.
- The rotor faces the wind, and the blades are designed to capture wind energy efficiently.
- HAWTs can vary in size from small to large according to utility.
- They typically require a yaw mechanism to turn the turbine to face the wind direction.
- HAWTs are often mounted on tall towers to capture stronger and more consistent wind speeds found at higher altitudes. [12]

4.1.2 Vertical-axis Wind Turbines (VAWT): It is a turbine having vertical axis. [13] [14]

- They can have various designs, including Darrieus, Savonius, and helical designs.
- It can capture wind from all direction, which simplifies their design.
- They are generally closer to the ground, so easy for installation and maintenance.
- VAWTs are less common in large-scale commercial applications compared to HAWTs but are often used in smaller-scale applications and experimental projects.
- One advantage of VAWTs is that they can be mounted closer to the ground and are less affected by turbulent winds near the surface.

4.2 Wind Energy Conversion Systems (WECS):

A Wind Energy Conversion System (WECS) is a technology that harnesses the kinetic energy of the wind and converts it into electrical energy. [15] An importtent components of a typical WECS are given in Fig 4.1 along with SSC and GSC. The Technical components of a Wind Turbine systems are shown in Fig 4.2.

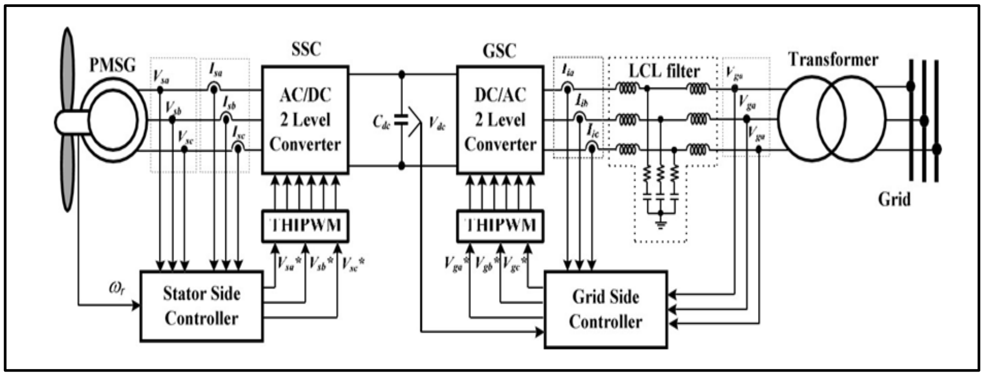

Fig.4.1. Conversion System of Wind Energy

- **Wind Turbine:** The main work of turbine is to capture the energy from the wind. It consists of rotor blades connected to a hub, and as the wind blows, it causes the blades to rotate as shown in Fig 4.2.
- **Rotor Blades:** The rotor blades are aerodynamically designed structures attached to the turbine hub. Their shape and orientation are critical for efficient energy capture. [16]

Here formula is given for the calculation of wind power, which depends on the following factors i.e. ρ, A & v_w.

$$P_w = \frac{1}{2}.\rho.A.v_w^3 \tag{4.1}$$

ρ : Air density (1.225 kg/m^{3at} 15^{0}C)

A : Area sweeped by blads of turbine (m^2)

v_w : Wind speed (m/s)

In case of coefficient of blade, it is convered as follows.

$$P_m = \frac{1}{2}.\rho.A.v_{w.}^3C_p \quad (4.2)$$

C_p : Coefficient of the blade ($0.22 < C_p > 0.58$). [17] [18]

Table: 4.1 Data for 3MW Turbine

Type	Rotor Size	Power Coefficient	Wind Speed	Air Density ρ
3-blade turbine	Rotor diameter of 82 m	Power coefficient of $C_p = 0.36$	wind speed of 14 m/s	Air density ρ=1.22 kg/m^3

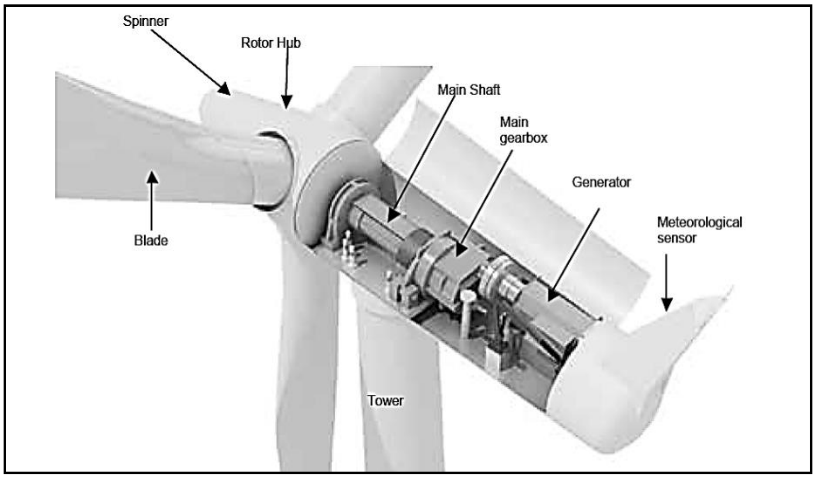

Fig. 4.2. Components of Wind Turbine System

- **Hub:** The hub serves as the central attachment point where the rotor blades of the wind turbine are mounted. Typically, modern wind turbines have either three or more blades that radiate outward from the hub. [19]
- **Generator:** The generator is a fundamental component responsible for converting mechanical energy from the rotation of the wind turbine's blades into electrical energy.[20]
- **Gearbox:** Gear box ratio is represented by r_{gb} and its formula is given as follows.

$$r_{gb} = \frac{n_M}{n_m} = \frac{(1-s)\,.60\,.f_s}{P\,.n_M} \quad (4.3)$$

s : slip

P : number of poles

f_s : rated stator frequency

n_M : rated speed in rpm of turbine

n_m : rated speed in rpm of generator

Value of slip is 1% for an induction generator used in turbine. [21] [22]

Table: 4.2Gear Box Specifications for 3MW Turbine

Type	Rotor Speed rpm	Poles	Frequency	Speed Gearbox
3-blade turbine	6-20 rpm	4- or 6-poles	50 Hz	1000 or 1500 rpm

Blades of wind turbine are draven by the kinetic energy of the wind. [23]

$$P_{wind} = 0.5\rho_{air}\pi R^2 V_{wind}^3 \qquad (4.4)$$

Where $P_{wind} = Wind\ Power$; $\rho_{air} = air\ density$ approximately 1.225 Kg/m^3;$R = Wind\ Turbine\ Blade$; and $V_{wind} = Speed\ of\ Wind.$

For the Power available in the wind:

$$C_p = \frac{P_m(windturbinepower)}{P_{wind}} \qquad (4.5)$$

$$P_m = P_{wind} * C_p \qquad (4.6)$$

λ : blade tip raito

β : pitch angle

$$\lambda = \frac{\omega_{turb} * R}{V_{wind}} \qquad (4.7)$$

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\left(\frac{C_5}{\lambda_i}\right)} + C_6 \qquad (4.8)$$

$$1/\lambda_i = \left(\frac{1}{\lambda + 0.08\beta}\right) - \frac{0.035}{\beta^3 + 1} \qquad (4.9)$$

Table: 4.3 Coefficients for 3MW Turbine

Coefficient: C_1	**Coefficient: C_2**	**Coefficient: C_3**
0.5177	116.0000	0.4100
Coefficient: C_4	**Coefficient: C_5**	**Coefficient: C_6**
5.0000	21.0000	0.0068

Now, the mechanical power of the wind turbine is converted into torquewith by turbine speed. [24]

$$T_m = P_m / \omega_{turb} \tag{4.10}$$

- **C_p and λ curve :** Fig. 4.3 shows the curve in between the Power coefficient vs. tip speed ratio curve. Fig. 4.4 shows the curves at different speed levels.

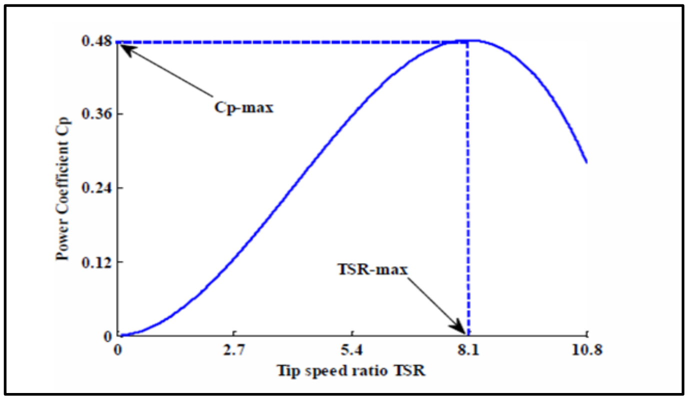

Fig. 4.3. C_p and λ curve

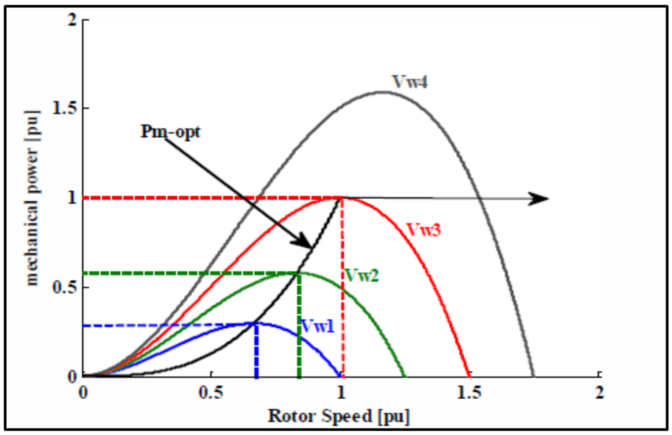

Fig. 4.4. Four different Speed Ratio Curves

➢ **Characteristic curve:** A very special curve of a wind turbine is shown in Fig 4.5, in which dependent variable (mechanical power) of the wind turbine is drawn by the independent variable (wind speed). This curve is further divided in four regions according to the operation & performance of the turbine. Characteristic is drawn at maximum power point tracking (MPPT). It is also known as manufacturers dependent curve. [25] [26]

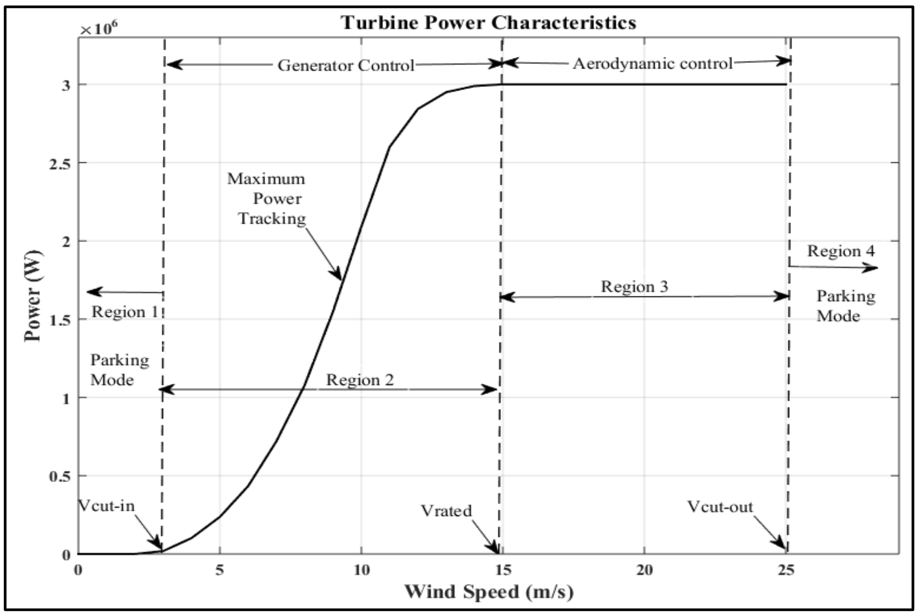

Fig. 4.5. Characteristics curve of 3MW wind turbine

➢ **Tabular discussion of Characteristic Curve:** The tabular discussion of the Characteristic curve in different four points is given below:

Table: 4.4 Three Regions of Characteristics

Power characteristic (3MW)		
1	Power speed (0-5 m/s) characteristic **Region-1**	**Cut-In Wind Speed:** The wind speed at which the turbine starts generating power. Below this speed, the turbine may not be producing significant power.
2	Turbine power Speed (5-15 m/s)characteristic	**Rated Wind Speed:** The wind speed at which the turbine reaches its rated optimal efficiency.

	Region-2	
3	Turbine power Speed (15-25 m/s) characteristic **Region-3**	**Cut-Out Wind Speed:** It is the maximum wind speed at which a turbine is designed to operate safely. After that, the turbine goes into a shutdown or braking mode.
4	Turbine power Speed (Above 25 m/s) characteristic **Region-4**	**High Wind Speed:** The wind speed at which the turbine reaches parking mode. The power output is zero but the Wind turbine remains safe. It is more necessary to make it safe rather than the production of electricity at so high a speed of wind.

- **Yaw System:** By this system turbine will rotate around its vertical axis to face the wind. This ensures optimal energy capture as the wind direction changes. [27]
- **Tower:** It is supporting system. Taller towers also reduce the impact of turbulence.
- **Nacelle:** The nacelle houses critical components like the generator, gearbox, and control systems. It is often located at the top of the tower.
- **Control Systems:** Intelligent control systems monitor and regulate the operation of the wind turbine. They adjust parameters such as blade pitch, rotor speed, and yaw angle for optimal performance. [28]
- **Power Electronics:** Power electronics, including inverters and converters, are used to convert the electrical output from the generator to a form suitable for grid connection. Power electronics components are used at grid and machine side of the system.
- **Grid Connection:** The electrical energy generated by the wind turbine is connected to the electrical grid for distribution and consumption. This is the bank of energy. All the connection are made over here for collection and distribution.

4.3 Type of Wind Energy Conversion Systems (WECS): Wind energy conversion systems (WECS) can be categorized based on the types of generators used to convert one type of energy from the wind into other type of energy as electrical energy. The main generator types include:

- **WECS of Synchronous Generators:** Commonly used in large-scale, grid-connected wind turbines. Operate at a fixed speed and synchronized with the grid frequency. Synchronizing is one of the important factor in case of frequency. Require power electronics for grid connection. [29]
- **WECS of Asynchronous or Induction Generators:** Suitable for variable-speed wind turbines. Do not require synchronization with the grid frequency. Typically used in both onshore and offshore wind turbines.
- **WECS of Permanent Magnet Synchronous Generators (PMSG):** Utilize permanent magnets to generate a magnetic field. Commonly used in direct-drive wind turbines. Efficient and compact design. [30]
- **WECS of Doubly Fed Induction Generators (DFIG):** Combine features of both asynchronous and synchronous generators. Allow variable rotor speed, enhancing efficiency. Use power electronics to control rotor currents.
- **WECS of Switched Reluctance Generators (SRG):** Employ a rotor with salient poles and a stator with windings. Relatively simple construction. Suitable for small to medium-sized wind turbines. [31]
- **WECS of Hybrid Excitation Generators:** Combine features of synchronous and asynchronous generators. Use both permanent magnets and electromagnetic excitation. Aim to improve overall efficiency. [32]

Chapter 5

PERMANENT MAGNET SYNCHRONOUS GENERATOR

5.1 Introduction:

A permanent magnet synchronous generator is a type of electrical generator that converts energyfrom one to other system. It operates based on the principles of electromagnetism and utilizes permanent magnets rather than electromagnets to produce a magnetic field. Here's an introduction to the key components and principles of a PMSG: [33] [34]

- **Permanent Magnets**: Unlike traditional generators which use electromagnets to create a magnetic field, PMSGs utilize permanent magnets made of materials like neodymium-iron-boron (NdFeB) or samarium-cobalt (SmCo). These permanent magnets are fixed on the rotor of the generator.
- **Stator**: It is the stationary part of the generator. It consist of a core made of laminated steel sheets and copper wire windings. When the rotor spins, it induces a varying magnetic field in the stator windings, which in turn generates an alternating current (AC) output. [35]
- **Rotor**: The rotor is the rotating part of the generator. It contains the permanent magnets. As the rotor spins, it creates a rotating magnetic field, which induces an alternating voltage in the stator windings.
- **Power Electronics and Control System**: PMSGs often require power electronics and a control system to regulate the output voltage and frequency. This system may include inverters, rectifiers, and controllers to manage the power flow and ensure stable operation under varying load conditions. [36]
- **Advantages**: High efficiency: PMSGs typically have higher efficiency compared to traditional generators. Reduced maintenance: Since they do not require a separate excitation system (as in the case of induction generators), PMSGs tend to have lower maintenance requirements. Compact and lightweight: The absence of a separate excitation system and the use of permanent magnets contribute to a more compact and lightweight design. [37]

- **Applications**: PMSGs find applications in various renewable energy systems such as wind turbines, hydroelectric generators, and tidal energy converters. They are particularly suitable for variable-speed wind turbines where they can efficiently capture energy from varying wind speeds. [38]

5.2 Selecting Permanent Magnet Synchronous Generator (PMSG) for the framework: Using a Permanent Magnet Synchronous Generator (PMSG) in the development of an intelligent controller for a grid-connected wind energy conversion system offers several advantages when the goals are to minimize Total Harmonic Distortion (THD) and power losses:

- **Efficiency and High Power Density:** PMSGs are known for high efficiency due to the absence of rotor losses associated with copper winding in traditional generators. This characteristic contributes to maximizing power output and minimizing losses.
- **Direct Drive Configuration:** PMSGs are often employed in direct-drive configurations, eliminating the need for a gearbox. This reduction in mechanical components reduces maintenance requirements, minimizes mechanical losses, and increases reliability. [39]
- **Variable Speed Operation:** PMSGs can efficiently operate at variable speeds, enabling the wind turbine to capture maximum energy across a range of wind conditions. Variable speed operation is crucial for optimizing power production and reducing power losses. [40]
- **Reduced Size and Weight:** The use of permanent magnets in the rotor allows for a more compact and lightweight generator design. This is especially beneficial for offshore installations where size and weight considerations are crucial.
- **Fast Response to Load Changes:** PMSGs exhibit a fast response to changes in load conditions, allowing for quick adjustments to varying wind speeds. This responsiveness enables efficient energy capture and contributes to minimizing power losses. [41]
- **High Power Quality:** PMSGs inherently provide high power quality, producing cleaner electrical waveforms. This characteristic is vital for minimizing Total

Harmonic Distortion and ensuring compatibility with grid codes and standards.

- **Low Maintenance Requirements:** PMSGs have fewer mechanical components, such as brushes, reducing maintenance requirements. This simplicity contributes to increased reliability and decreased downtime.
- **Enhanced Control Options:** The control of PMSGs is generally more straightforward compared to other generator types. This simplicity facilitates the implementation of advanced control strategies, allowing for effective THD minimization and power loss optimization. [42]
- **Grid Compatibility:** PMSGs can be easily integrated into grid systems, providing stable and reliable power output. This ensures compliance with grid codes and standards, contributing to reduced power losses during grid interaction.
- **Regenerative Braking Capability:** PMSGs shown in Fig. 5.1 as a section view can be utilized for regenerative braking, allowing the wind turbine to capture excess energy during high wind conditions. This capability helps in maximizing energy production and minimizing power losses. As per the properties of PMSG, its diagram is shown in Fig. 5.1, This configuration also reduces rotational stress of the machine, hence used at high rotor speed. [43] [44]
-

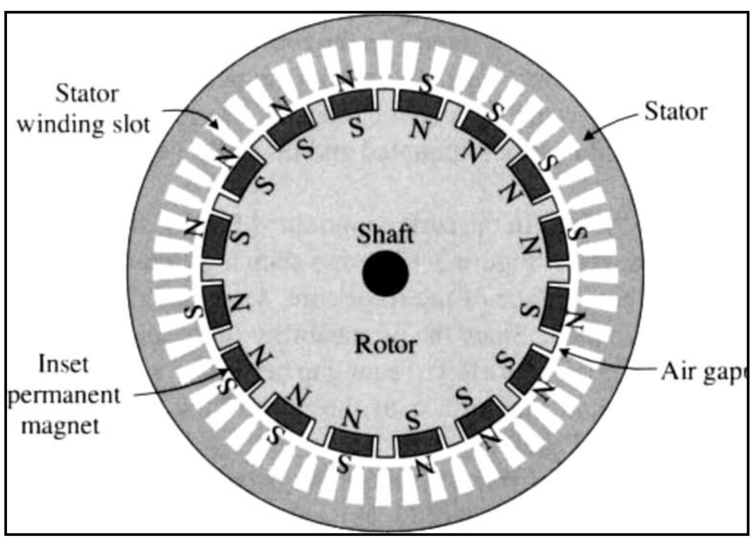

Fig. 5.1. Stator and Rotor (Pole configured)PMSG

- **Stator Winding:** The stator winding of a Permanent Magnet Synchronous Generator (PMSG) shown in Fig. 5.2 is a crucial component responsible for generating electrical power. It's typically composed of coils of wire arranged in a specific configuration to produce a rotating magnetic field when energized by an alternating current (AC). Here's an overview of the stator winding in a PMSG. The stator winding of a PMSG is usually configured as a three-phase system [45]. This means there are three sets of windings spaced 120^0 apart from each other around the stator core. Each phase generates an alternating current waveform, and together they create a rotating magnetic field when supplied with three-phase AC power. The stator winding is wound around a laminated core made of thin insulated steel sheets[46]. The laminations help reduce eddy current losses and improve the efficiency of the generator. The conductors used in the stator winding are typically made of copper due to their excellent electrical conductivity and high mechanical strength. Copper offers low resistance, which minimizes energy losses and heat generation within the winding. The conductors in the stator winding are insulated to prevent short circuits and ensure the integrity of the winding insulation over the generator's lifetime. Within each phase of the stator winding, the coils are arranged in a specific pattern to achieve the desired magnetic field distribution and maximize power generation efficiency[47].

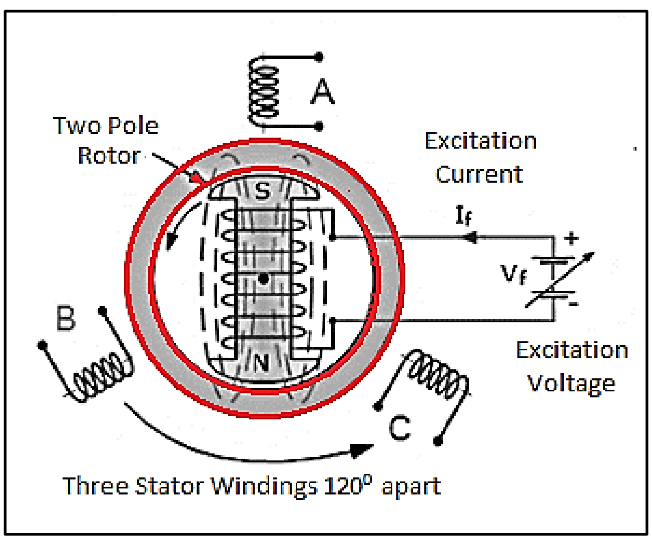

Fig. 5.2. PMSG with Stator Winding

The ends of the stator winding coils are connected to the generator's output terminals through a series of conductors and junction boxes. The generated AC voltage is extracted from these terminals and can be used directly or converted to the required voltage and frequency for various applications [48].

- **Output in terms of Waveforms:** The waveform of a PMSG output shown in Fig. 5.3 is typically sinusoidal, reflecting the nature of the alternating current (AC) generated by the stator windings as they interact with the rotating magnetic field produced by the permanent magnets on the rotor. Here's a breakdown of the waveform characteristics: [49]

Table: 5.1 Outputs of PMSG

Sinusoidal Nature	Three-Phase AC	Voltage Regulation	Harmonic Content
The output waveform of a PMSG is sinusoidal, meaning it follows the shape of a sine wave.	PMSGs are commonly configured as three-phase generators, meaning they produce three separate sinusoidal waveforms that are 120^0 with each other.	PMSGs typically require voltage regulation to ensure that the output voltage remains stable within acceptable limits under varying load conditions.	While the ideal output waveform of a PMSG is sinusoidal, there may be some harmonic distortion present due to non-idealities in the generator and connected loads.

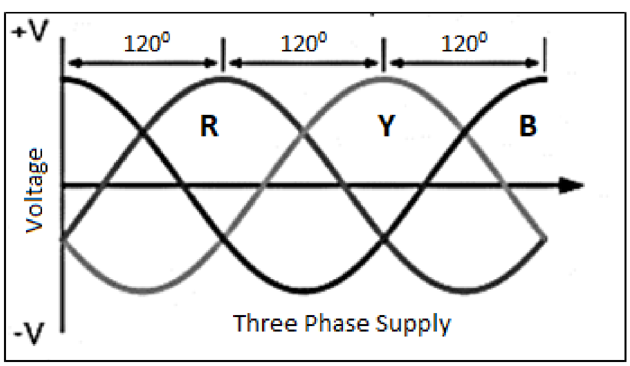

Fig. 5.3. Stator coil outputs of PMS

5.3 Mathematical Modeling of PMSG:

Mathematical modeling of a PMSG part. It involves describing its electrical, mechanical, and magnetic characteristics. Here's a basic outline of the mathematical modeling of a PMSG: [50]

(a) Electrical Model

(b) Mechanical Model

(c) Magnetic Model

(d) Integration of Sub-Models

(e) Control System Model:

(f) dq-axis, d- and, q-axis

To simplify the SG model, the following mathematical equations are here. d-axis model of SG in the rotor field Synchronous reference frame is shown in Fig. 5.4 and the q-axis model of SG in the rotor field Synchronous reference frame is shown in Fig. 5.5. The voltage equations are given by

$$V_{ds} = -R_s * i_{ds} - \omega_r * \lambda_{qs} + p * \lambda_{ds} \quad (5.1)$$

$$V_{qs} = -R_s * i_{qs} - \omega_r * \lambda_{ds} + p * \lambda_{qs} \quad (5.2)$$

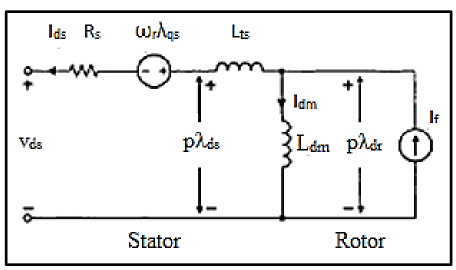

Fig. 5.4. *d-axis* model of SG

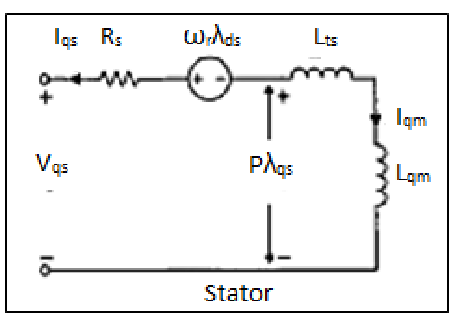

Fig. 5.5. q-axis model of SG

Where lambda-ds and lambda-qs are d and q axis stator flux linkages, given by [51]

$$\lambda_{ds} = -L_{is} * i_{ds} + L_{dm}(I_f - i_{ds}) \quad (5.3)$$

$$= -(L_{is} + L_{dm})i_{ds} + L_{dm} * I_f - L_d * i_{ds} + \lambda_r$$

$$\lambda_{qs} = -(L_{is} + L_{qm})i_{qs} \quad (5.4)$$

$$= +L_q * i_{qs}$$

Where lambda-r is the rotor flux and L_d and L_q are the stator dq-axis self-inductance, defined by

$$\lambda_r = -L_{ds} * i_f \quad (5.5)$$

$$L_d = L_{is} + L_{dm} \quad (5.6)$$

$$L_q = L_{is} + L_{qm} \quad (5.7)$$

Substituting above equation and considering $d\lambda_r/dt = 0$ for constant field current. we have

$$v_{ds} = -R_s * i_{ds} - \omega_r * L_q * i_{qs} - L_d * p * i_{ds} \quad (5.8)$$

$$v_{qs} = -R_s * i_{qs} - \omega_r * L_d * i_{ds} + \omega_r * \lambda_r - L_d * p * i_{qs} \quad (5.9)$$

equations of torque,

$$T_e = \frac{3}{2} p\left(i_{ps} * \lambda_{rs} - i_{ds}\lambda_{qs}\right) \quad (5.10)$$

$$T_e = \frac{3}{2} p\,(\lambda_r * i_{qs} - (L_d - L_q)i_{ds} * i_{qs} \quad (5.11)$$

The rotor speed $\boldsymbol{\omega_r}$ *is* governed by the motion equation as under:-

$$\omega_r = \frac{P}{js} * (T_e - T_m) \quad (5.12)$$

Equations for dynamic simulation model of synchronous generator are rearranged as under [52] [53]

$$\omega_r = \frac{P * (T_e - T_m)}{js} \quad (5.13)$$

$$\omega_r = \frac{P}{js} * (T_e - T_m) \quad (5.14)$$

T_e, T_m = Torques

$$i_{ds} == \frac{1}{s}\left(-v_{ds} - R_s * i_{ds} + \omega_r * L_q * i_{qs}\right) / L_d \quad (5.15)$$

$$i_{qs} == \frac{1}{s}\left(-V_{qs} - R_s * i_{qs} + \omega_r * L_d * i_{ds}\right) /L_q \qquad (5.16)$$

With the help of these equations, the block diagram can be drawn for simulation the result of SG/ PMSG is derived [53]. The derived model and block diagram are shown in Fig. 5.6, Fig. 5.7, and Fig 5.8.

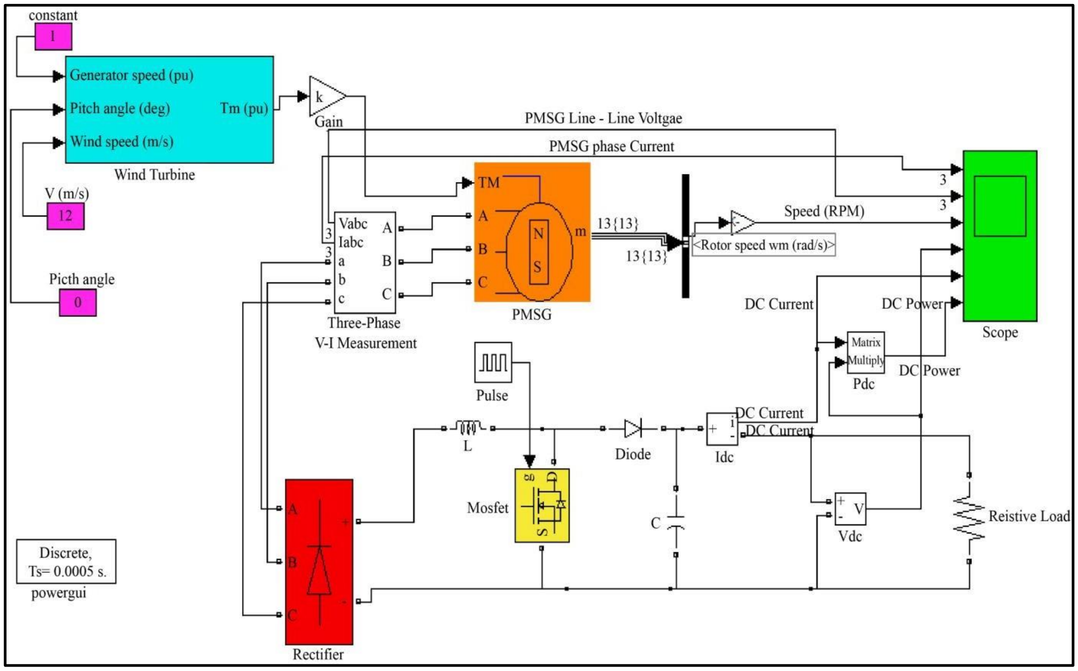

Fig. 5.6. MATLAB Model of Wind-Driven PMSG System

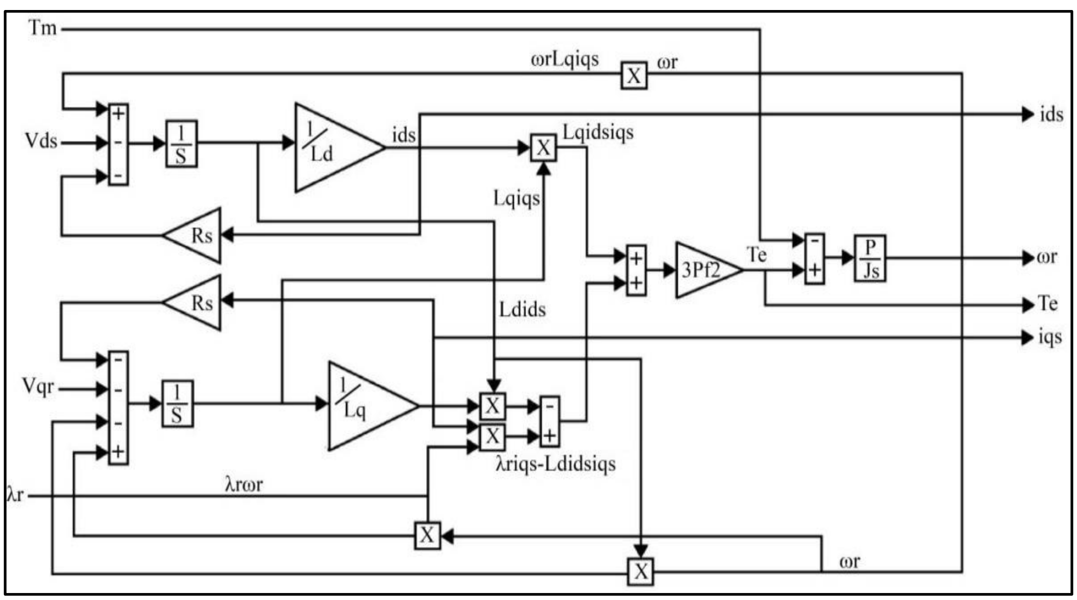

Fig. 5.7. Block Diagram of Synchronous Generators Simulated with MATLAB

Table: 5.2 Typical Rating of PMSG for 3MW

S.N.	Type	Ratingp.u.
1.	Mechanical Power (rated)	2.48 MW
2.	Apparent Power (rated)	$Power\ (MW) = \sqrt{3} \times Voltage\ (kV) \times Current\ (kA) \times Cos\ \Phi$ 3.42 MVA
3.	V_{LL}	400 V (rms value)
4.	V_{ph}	232.4 V (rms value)
5.	I_{stator}	38.7 A (rms value)
6.	f_{stator}	53.33 Hz
7.	$Cos\ \Phi$	0.8162
8.	n_{rotor}	1000 rpm
9.	P	Eight
10.	T_m	58.4585 kNm
11.	Φ Rotor Flux Linkage	4.971 Wb (rms)
12.	Stator Winding Resistance R_s	24.4 kΩ
13.	d-axis Synchronous Inductance L_d	9.84 mH
14.	q-axis Synchronous Inductance L_q	9.84 mH
15.	Base Flux Linkage λ_s	6.87 Wb (rms)
16.	Base Inductance L_s	13.8mH
17.	Base Capacitance C_s	637.7 μF

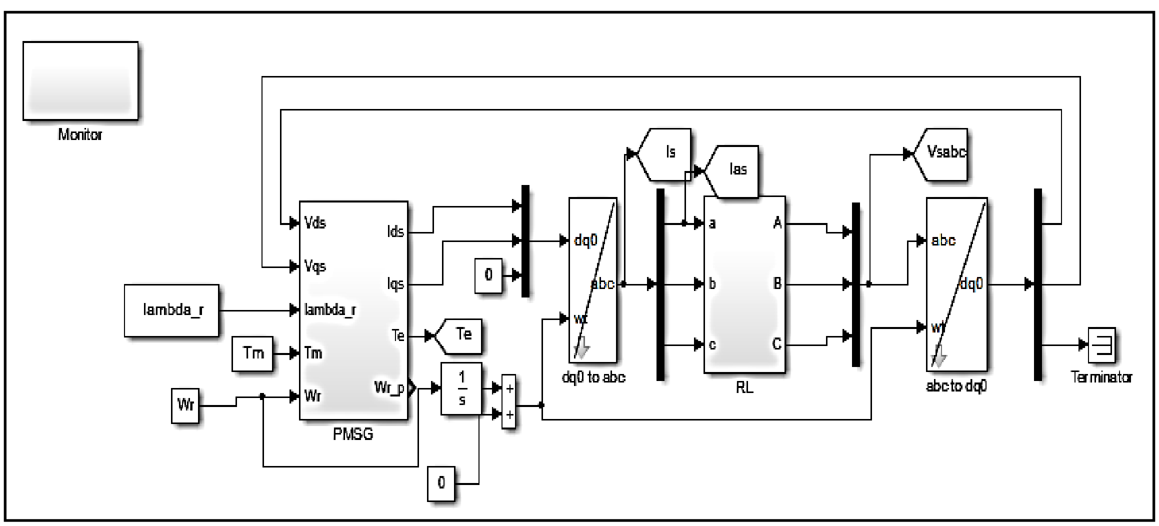

Fig. 5.8. Simulink Model of PMSG with Resistive Load

5.4 Several factors and parameters can influence the THD in a Grid-Connected WECS:

Several factors and parameters can influence the THD in a grid-connected wind energy conversion system are listed below: [54]

Table: 5.3 Factors & Parameters influencing THD

S.N.	Factors	Parameters
1.	Converter Design	Converter Design and Control Algorithms
2.	Control Strategies	Harmonic Filters
3.	Grid Requirements	Wind Turbine Type
4.	Transformer Characteristics	Generator Type
5.	Wind Turbine Type	Converter and Inverter Efficiency
6.	Wind Variability	Grid Codes
7.	Harmonic Filters	Grid Standards
8.	Maintenance and Aging	Transformer Characteristics

5.5 Several factors and parameters can influence the Power Loss Grid-Connected system: Several factors and parameters can influence the Power Loss in a grid-connected wind energy system are listed below: [55]

Table: 5.4 Factors & Parameters Influencing Power Loss

S.N.	Factors	Parameters
1.	Wind Variability	Wind Turbine Efficiency
2.	Turbine Efficiency	Converter and Inverter Efficiency
3.	Converter and Inverter Efficiency	Transmission and Transformer Losses
4.	Transmission & Transformer Losses	Generator Type
5.	Electrical Network Impedance	Operational Control Strategies
6.	Operational and Control Strategies	Mechanical Component Efficiency
7.	Maintenance and Aging	Blade Pitch Control
8.	Environmental Conditions	Wind Variability
9.	Grid Integration	Yaw System Efficiency, Maintenance & Aging
10.	System Configuration	Environmental Condition & Grid Integration Quality

Chapter 6

INTELLIGENT CONTROLLER TO MINIMIZE TOTAL HARMONIC DISTORTION AND POWER LOSS OF GRID-CONNECTED WECS

6.1 Introduction:

The primary objective of the intelligent controller is to mitigate two key issues in grid-connected wind energy conversion systems:

Total Harmonic Distortion (THD): THD refers to the distortion of the sinusoidal waveform of the grid voltage or current caused by the non-linear characteristics of power electronic converters and other system components. High THD levels can lead to interference with other electrical equipment connected to the grid and violate grid codes.

Power Loss: Power loss within the system components, including converters and transmission lines, reduces overall system efficiency and increases operational costs.

- **Harmonic Mitigation:** The intelligent controller employs advanced algorithms and control strategies to actively mitigate harmonics generated by power converters. This may involve implementing selective harmonic elimination techniques, adaptive filtering, or predictive control methods to reduce harmonic content and maintain grid compatibility. [56] [57]
- **Optimized Operation:** The controller continuously monitors system parameters such as wind speed, grid conditions, and load demands to optimize the operation of the wind energy conversion system. By dynamically adjusting control parameters, the controller maximizes energy capture from the wind while minimizing power losses and maintaining grid stability.
- **Fault Detection and Diagnostics:** Integrated fault detection algorithms enable the controller to identify and diagnose system faults in real time. By promptly detecting issues such as component failures or grid disturbances, the controller can initiate appropriate mitigation actions to prevent system downtime and ensure reliable operation. [58]
- **Adaptive Control:** The intelligent controller utilizes adaptive control techniques to

adaptively adjust its operating parameters in response to changing environmental conditions, system dynamics, and grid requirements. This adaptability enhances system robustness and ensures optimal conditions. [59]

- **Implementation:** The intelligent controller is typically implemented using advanced digital signal processors (DSPs), microcontrollers, or programmable logic controllers (PLCs) capable of high-speed computation and real-time control. It interfaces with the power converters, sensors, grid interface, and other system components to orchestrate coordinated control actions and optimize system performance. Communication protocols such as Modbus, DNP3, or IEC 61850 may be utilized for SCADA use.[60]
- **Benefits:** Improved Power Quality: By minimizing THD and adhering to grid standards, the intelligent controller enhances power quality and reduces the risk of grid disturbances and equipment damage.
- **Enhanced Efficiency:** Through optimized control strategies and power management techniques, the controller reduces power losses within the wind energy conversion system, thereby improving overall system efficiency and economic viability. [61]
- **Grid Compliance:** The controller ensures compliance with regulatory requirements and grid codes, facilitating seamless integration. In summary, an intelligent controller designed to minimize THD and power loss in a grid-connected system is a critical component that optimizes system performance, enhances power quality, and ensures grid compatibility. By leveraging advanced control algorithms and adaptive strategies, the controller enables efficient and reliable operation of renewable energy systems in dynamic grid environments. [62] [63]

6.2 Development of Framework: Implementing an intelligent controller to minimize Total Harmonic Distortion (THD) & Power loss in a grid-connected wind energy conversion system involves advanced control strategies and monitoring. The proposed system is shown here in Fig. 6.1.[64]

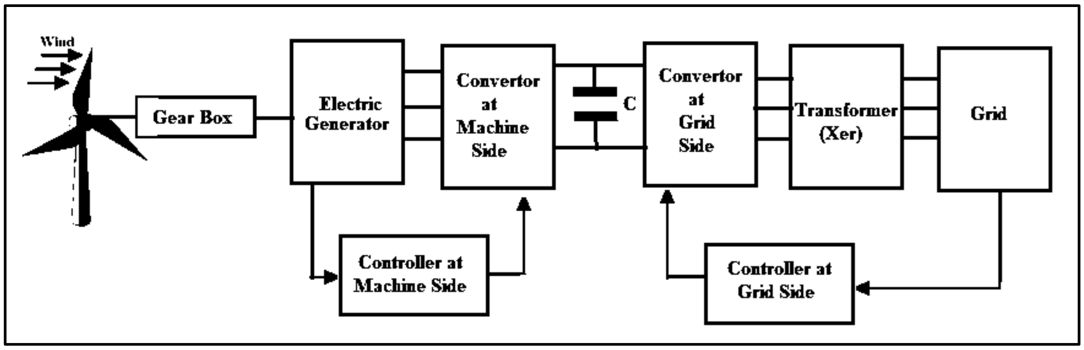

Fig. 6.1 Proposed WECS with controllers

6.2.1 Intelligent controller to minimize THD in a grid-connected WECS:

- **Predictive Control Algorithms:** Utilize predictive control algorithms that anticipate variations in wind speed and turbine load. This helps optimize the operation of power converters in real time to reduce harmonic distortions.
- **Active Filtering:** Implement active filtering techniques using power electronics to actively compensate for harmonics in the generated power. This involves injecting counteracting harm. [65]
- **Model Predictive Control (MPC):** MPC considers the dynamic behavior of the wind turbine and adjusts control inputs to minimize THD. It uses a predictive model to optimize system performance while adhering to grid codes and standards.
- **Advanced Pulse Width Modulation (PWM):** Use advanced PWM techniques in the power converters to control the switching of semiconductor devices. Optimizing the PWM strategy helps minimize harmonic content in the generated waveform.
- **Harmonic Resonance Mitigation:** Employ control strategies to mitigate harmonic resonance issues that may arise between turbine & grid. This can involve adjusting the system parameters to avoid resonant frequencies. [66]
- **Filtering Strategies:** Implement harmonic filters in the wind energy conversion system to attenuate specific harmonic components. Tuning these filters according to the system's operating conditions can effectively reduce THD.
- **Adaptive Control:** Incorporate adaptive control algorithms that continuously monitor and adjust parameters based on the changing operating conditions of the wind turbine. This adaptability helps maintain low harmonic distortion levels.

- **Fault Detection and Diagnostics:** Integrate intelligent fault detection and diagnostic systems that can identify issues leading to increased harmonic distortion. Rapid response to faults ensures timely correction and minimizes THD.
- **Grid Synchronization:** Ensure accurate synchronization with the grid by employing advanced synchronization methods. Proper synchronization helps in maintaining the desired power quality and minimizing harmonics. [67]
- **Real-time Monitoring and Communication:** Implement a real-time monitoring system that continuously assesses harmonic distortion levels. Enable communication for turbine & grid to facilitate dynamic adjustments for optimal performance.

Integrating these intelligent control strategies requires a combination of advanced algorithms, sensing technologies, and communication systems. Collaborative research and development efforts between wind energy experts and control systems engineers are essential to designing effective intelligent controllers for minimizing THD in grid-connected wind energy conversion systems. [68]

6.2.2 Intelligent Controller: The principle behind an intelligent controller designed to minimize power loss in a grid-connected WECS lies in its ability to optimize energy conversion, grid interaction, and system operation in real-time.

- **Maximum Power Point Tracking (MPPT):** Implement advanced MPPT algorithms that continuously adjust the rotor speed or pitch angle to extract maximum power from the wind under varying conditions, reducing energy losses.
- **Advanced Control Strategies:** Use sophisticated control algorithms that optimize the operation of the wind turbine based on real-time data, considering factors like wind speed, turbine load, and grid conditions to minimize power losses.
- **Variable Speed Operation:** Wind turbine can operate at variable speeds, adjusting to changing wind conditions. Variable-speed turbines often exhibit higher efficiency, reducing overall power losses. [69]
- **Smart Blade Pitch Control:** Incorporate intelligent blade pitch control systems that adjust the pitch angle of the turbine blades to optimize energy capture and prevent stall conditions, improving overall efficiency and minimizing losses.

- **Wake Steering Algorithms:** Employ wake steering algorithms that optimize the alignment of multiple turbines in a wind farm to reduce wake effects, enhancing overall efficiency and minimizing power losses.
- **Fault Detection and Diagnostics:** Integrate intelligent systems for fault detection and diagnostics that can identify issues such as mechanical faults or electrical failures promptly. Early detection allows for timely maintenance, minimizing downtime and associated losses. [70]
- **Grid-Friendly Operation:** Design the controller to ensure grid-friendly operation by adhering to grid codes and standards. This helps avoid unnecessary power losses due to grid-related issues.
- **Energy Storage Integration:** Implement intelligent energy storage systems to store excess energy during favorable wind conditions and release it during low-wind periods. This can help smooth out fluctuations and reduce overall power losses.
- **Advanced Power Electronics:** Utilize state-of-the-art power electronics with high efficiency in the conversion process. This includes inverters and converters that minimize losses during the conversion of electrical power. [71]
- **Real-time Monitoring and Analytics:** Employ real-time monitoring and analytics systems that continuously assess the performance of the wind turbine and provide insights for optimizing operation, reducing losses over time. Integrating these intelligent control strategies requires a multidisciplinary approach, involving expertise in control systems, wind energy, and data analytics.

Continuous research and development efforts are crucial to refining and advancing these technologies for more efficient grid-connected WECS. [72] [73]

6.3 Development of Framework of an Intelligent Controller on the Machine Side:

A machine-side controller system in a Wind Generator Control System (WGCS) plays an important role in regulating the operation of wind turbines and ensuring optimal performance and safety. A typical machine-side controller system works in a WGCS as shown by Fig. 6.2: [74]

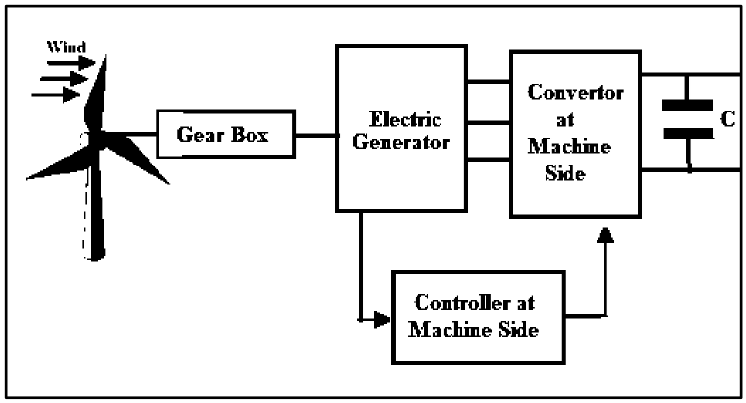

Fig. 6.2. Function of the Controller on the Machine Side

- **Sensor Data Acquisition:** The machine-side controller continuously gathers data from various sensors installed on the wind turbine. These sensors monitor parameters such as wind speed, rotor speed, temperature, vibration, pitch angle, and electrical output. [75]
- **Data Processing and Monitoring:** The controller processes the sensor data to assess the current operating conditions of the wind turbine. It monitors critical parameters in real time operation.
- **Control Algorithms*:*** Based on the collected data and predefined control algorithms, the machine-side controller determines the optimal settings for the wind turbine operation. Control algorithms may include pitch control algorithms to adjust the angle of the turbine blades, yaw control algorithms to orient the turbine towards the wind direction, and speed control algorithms to regulate the rotor speed. [76]
- **Fault Detection and Diagnostics:** The machine-side controller includes fault detection algorithms to identify any malfunctions or abnormalities in the turbine components. In case of a fault or anomaly, the controller initiates appropriate responses such as shutting down the turbine or activating backup systems. [77]

- **Communication Interface:** The controller interfaces with other components of the wind turbine system, including the pitch control system, yaw control system, generator control system, and supervisory control and data acquisition (SCADA) system.It exchanges data and instructions with these components to coordinate the overall operation of the wind turbine and communicate the operational status to the central control center.[78]Safety Features and Remote Monitoring and Control are also.

P_{ref} : active power

Q_s : reactive power

$1/(R+L_s s)$: Transfer function

eference is determined by the MPPT method of the wind turbine characteristic as shown in Fig. 3. By using the pole placement method, the gain of the PI controller can be tuned as shown in Fig. 6.3. [79]

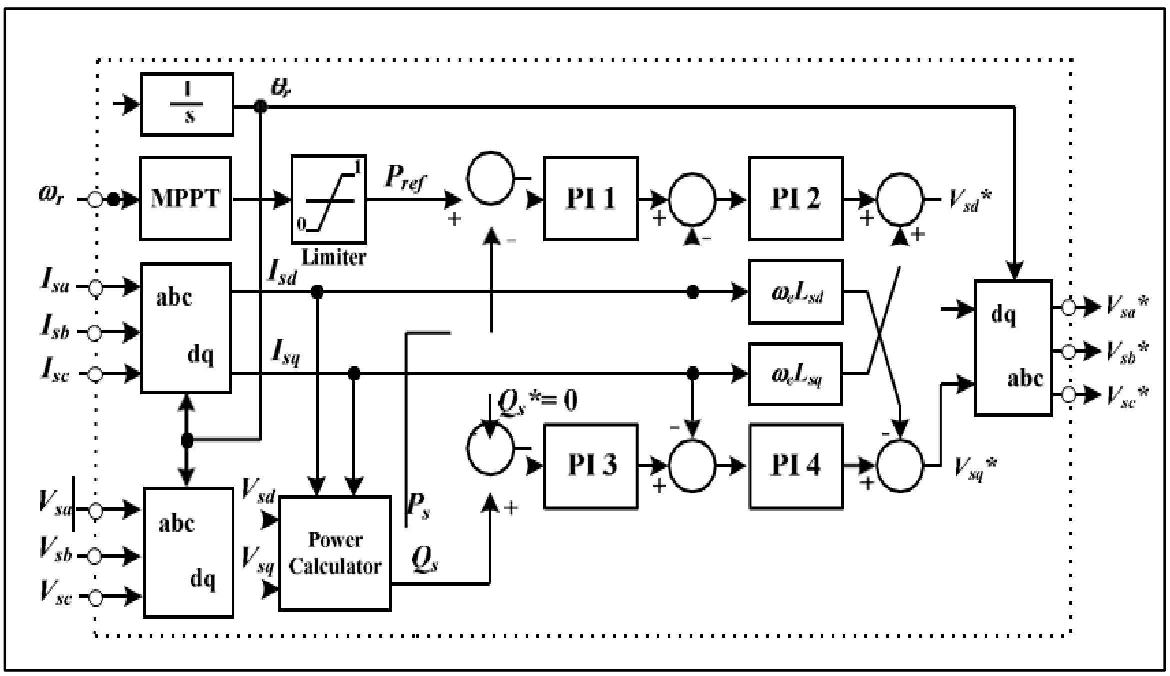

Fig. 6.3. Stator Side Controller System

6.4 Development of Framework of an intelligent controller on the Grid side:

Developing a framework for an intelligent controller at the grid side involves designing a system capable of efficiently managing it. The outline of the key components and steps involved in developing such a framework is given in Fig. 6.4.

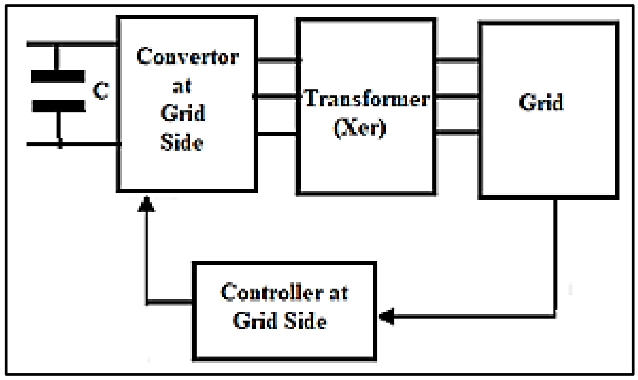

Fig. 6.4. Function of the controller at the Grid side

- **System Architecture Design:** Define the overall architecture of the intelligent controller system. Identify the components, interfaces, and communication protocols involved. Determine the integration points with other grid infrastructure and control systems. [80]
- **Data Acquisition and Monitoring:** Implement mechanisms for collecting real-time data from various sources within the grid, such as sensors, meters, and monitoring devices. Collect data related to grid voltage, frequency, power flow, line currents, and other relevant parameters. Utilize advanced measurement technologies like synchro-phasors for precise monitoring. [81]
- **Data Processing and Analytics:** Develop algorithms and analytical models to process and analyze the collected data. Apply techniques such as machine learning, statistical analysis, and optimization algorithms to derive insights and make informed decisions. Implement predictive analytics to anticipate grid conditions and identify potential issues before they occur. [82]
- **Control Strategies and Optimization:** Design control strategies to regulate grid parameters and optimize its operation. Implement voltage and frequency regulation algorithms to maintain stability within acceptable limits. Develop load balancing and demand response mechanisms to manage electricity consumption efficiently. Optimize power flow and routing to minimize losses and improve grid efficiency.

- **Decision Making and Adaptation:** Implement decision-making logic based on the analysis of real-time and historical data. Incorporate adaptive control algorithms capable of adjusting parameters dynamically in response to changing grid conditions. Ensure resilience and robustness to handle uncertainties, fluctuations, and unexpected events. [83]
- **Integration and Communication:** Integrate the intelligent controller framework with existing grid infrastructure, control systems, and communication networks. Establish secure and reliable communication channels for data exchange and command execution. Support interoperability standards to facilitate integration with third-party systems and devices. Verify its performance, stability, and effectiveness under various scenarios and operations shown in Fig. 6.5.[85] [84]

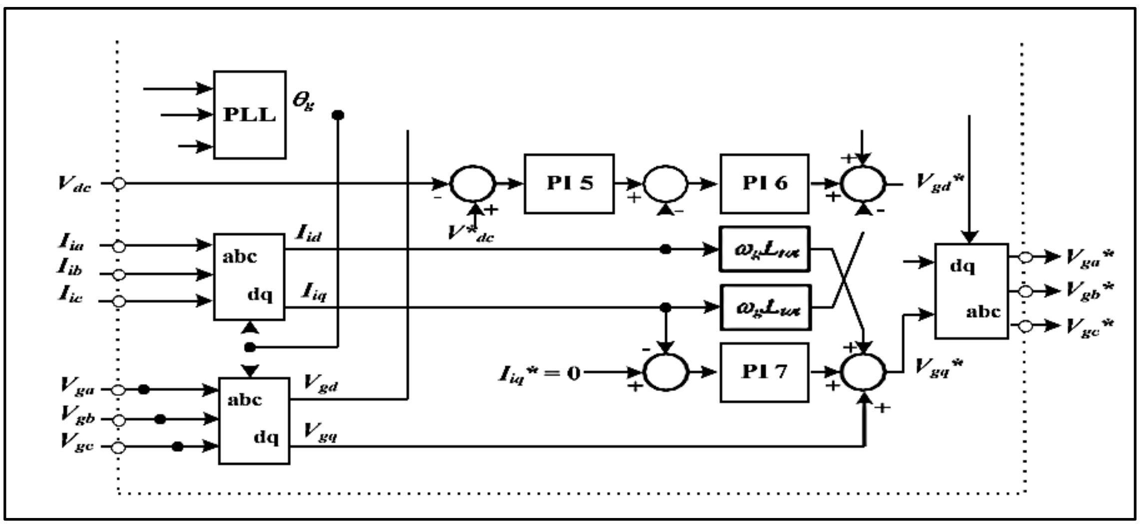

Fig. 6.5.Simulink Model of PMSG

Fig. 6.5 shows transformation to d-q Reference Frame, The d-q transformation simplifies the control of the WECS by decoupling the stator currents into two orthogonal components: the direct axis (d-axis) and the quadrature axis (q-axis).

- **Minimizing Harmonics:** By transforming the three-phase currents (or voltages) into the d-q frame, it becomes easier to control and minimize the generation of harmonics. This is because control actions can be directly applied to the d-q components, targeting specific performance metrics like THD reduction.

- **Field Oriented Control (FOC):** FOC is a popular control strategy where the d-q transformation is used to regulate the currents in the d-q frame. This enables precise control of torque and flux, reducing harmonics and improving efficiency.
- **Direct Torque Control (DTC):** DTC also utilizes the d-q transformation to control torque and flux directly, thereby reducing THD and improving dynamic performance. [86] [87]

6.5 Development of LCL Filter for Framework:

A single-phase LCL filter is used to reduce the harmonics in the circuit. The LCL filter circuit is shown in Fig. 6.6.

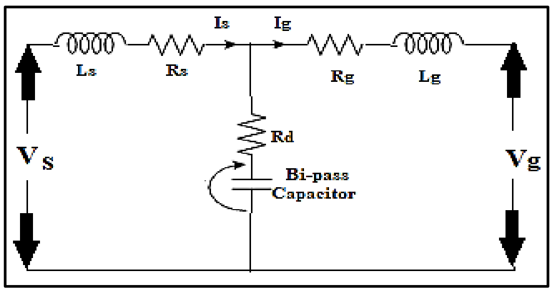

Fig. 6.6. 1-Phase LCL Filter Equivalent Circuit

On the Machine side:

L_i = Inductance

R_i= Resistance

V_i = Voltage

I_i= Current

$$L_i * \frac{dIi}{dt} = v_i - v_{cf} - (R_i + R_d)I_i + R_d * I_g \quad (6.1)$$

The differential equations for LCL filter are as follows:

At Grid side:

L_g= Inductance

R_g= Resistance

V_g= Voltage

I_g= Current

C_f = Filter capacitor

R_d= Damping Resistance

On the other side of LCL filter equations are as follows: [88]

$$L_g * \frac{dIg}{dt} = v_{cf} - v_g - (R_g + R_d)I_g + R_d * I_i \quad (6.2)$$

$$C_f * \frac{dV_{cf}}{dt} = I_i - I_g \quad (6.3)$$

From the above differential equations in the d-q (rotating reference frame):

$$L_i * \frac{dI_{id}}{dt} = v_{id} - v_{cfd} - (R_i + R_d)I_{id} + R_d * I_{gd} \quad (6.4)$$

$$L_i * \frac{dI_{iq}}{dt} = v_{iq} - v_{cfq} - (R_i + R_d)I_{iq} + R_d * I_{gq} \quad (6.5)$$

$$L_g * \frac{dI_{gd}}{dt} = v_{cfd} - v_{gd} - (R_g + R_d)I_{gd} + R_d * I_{id} \quad (6.6)$$

$$L_g * \frac{dI_{gq}}{dt} = v_{cfq} - v_{gq} - (R_g + R_d)I_{gq} + R_d * I_{iq} \quad (6.7)$$

$$C_f * \frac{dV_{cfd}}{dt} = I_{id} - I_{gd} + \omega * C_f * v_{cfq} \quad (6.8)$$

$$C_f * \frac{dV_{cfq}}{dt} = I_{iq} - I_{gq} + \omega * C_f * v_{cfd} \quad (6.9)$$

Block diagram dynamic in nature of LCL filter at grid is shown in Fig. 6.7.

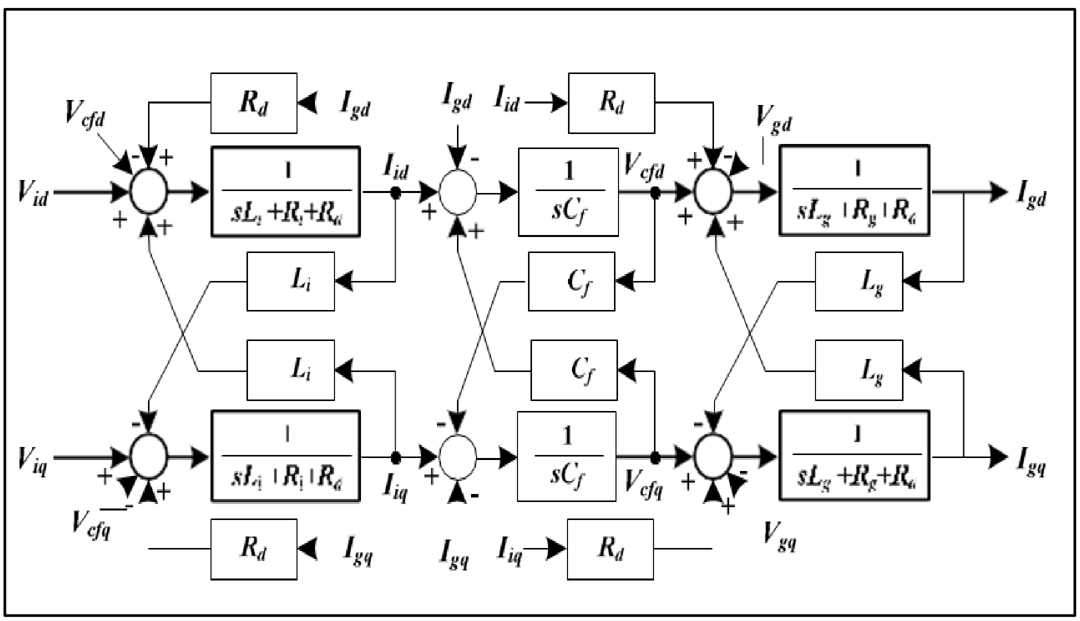

Fig. 6.7. Dynamic block Diagram of LCLFilter at grid

6.6 LCL Filter Parameters:

In a wind energy conversion system (WECS), an LCL filter is often used to connect the inverter to the grid. The primary goals of using an LCL filter are to reduce Total

Harmonic Distortion (THD) and minimize power losses. Here are the key parameters and considerations for designing an LCL filter:

Table: 6.1 ParametersPMSG System per unit along with LCL Filter

Component	Parameter	Value
Resonant Frequency	The resonant frequency of the LCL filter determines its filtering characteristics. It should be chosen such that it can effectively attenuate the switching harmonics generated by the inverter.	50 Hz or 60 Hz
Inductance (LLL) of the Filter	The inductance LLL helps to maintain a resonant frequency that effectively filters out higher harmonics.	8.02-9.04 mH
Capacitance (CCC) of the Filter	The capacitance CCC determines the resonant frequency and the damping of the filter.	0.7 to 1.0
Resistance (RRR) of the Filter	The resistance RRR is mainly due to the losses in the filter components (inductor and capacitor).	20.2-24.4 kΩ

Damping Ratio:

The damping ratio determines the amount of damping in the LCL filter to prevent oscillations and instability. It is typically set between 0.7 and 1.0 for stable operation.

Design Considerations:

- **Voltage Rating:** Ensure that the filter components can handle the voltage stress during operation.
- **Current Rating:** Components should be sized to handle the maximum current without excessive losses or heating.
- **Heat Dissipation:** Consider cooling requirements for the filter components, especially if operating in high-power applications.

When designing an LCL filter for a WECS, simulations and calculations are typically performed to optimize these parameters for minimum THD and power loss while ensuring stability and reliability. It's often a balance between filter size, cost, and performance requirements dictated by grid standards and system specifications. [89] The resonance frequency of the LCL filter is around 1.4 kHz. The setup of the proposed system is shown in Fig. 6.8.

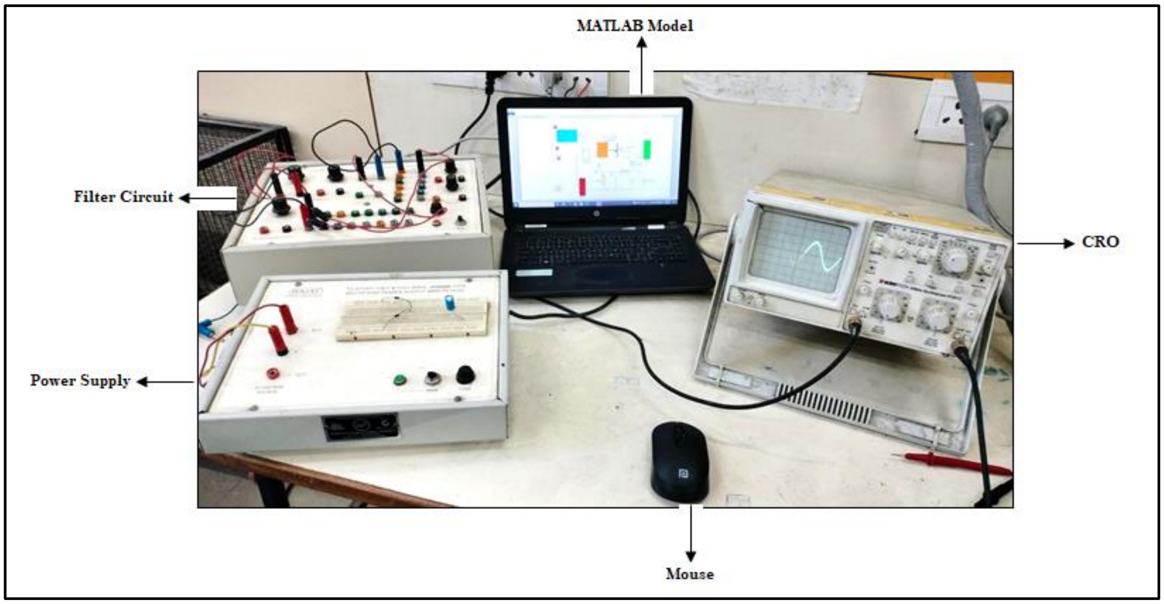

Fig. 6.8. Experimental setup of proposed system

Chapter 7

RESULT & WAVEFORMS OF AN INTELLIGENT CONTROLLER TO MINIMIZE TOTAL HARMONIC DISTORTION AND POWER LOSS OF GRID-CONNECTED WECS

7.1 Waveforms:

An intelligent controller is used to minimize total harmonic distortion and power loss of grid-connected WECS. In figure 7.1 rotor speed is maintained up to 500 rpm w.r.t. time with the help of gear box.

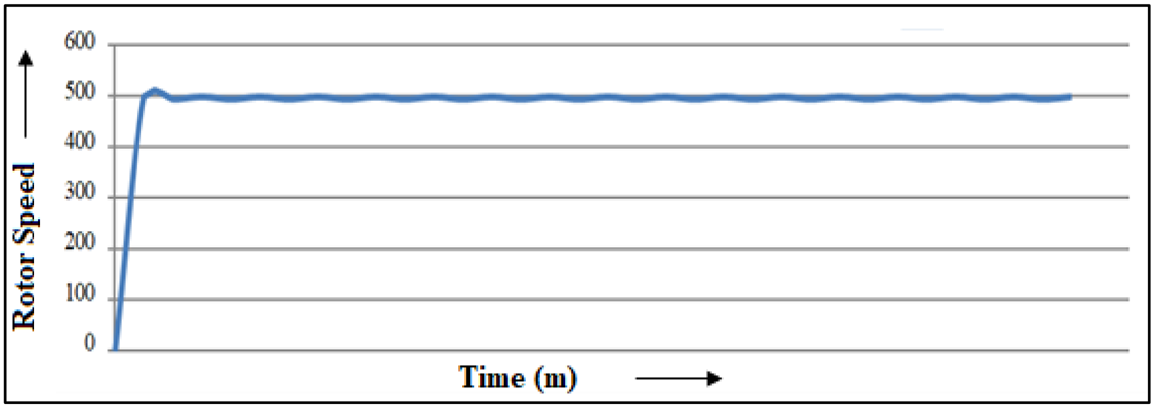

Fig. 7.1. Rotor Speed Waveform

Obtained output voltage (440V) of PMSG w.r.t. time is shown in Fig. 7.2, which is obtained at a fixed wind speed of 14 m/s.

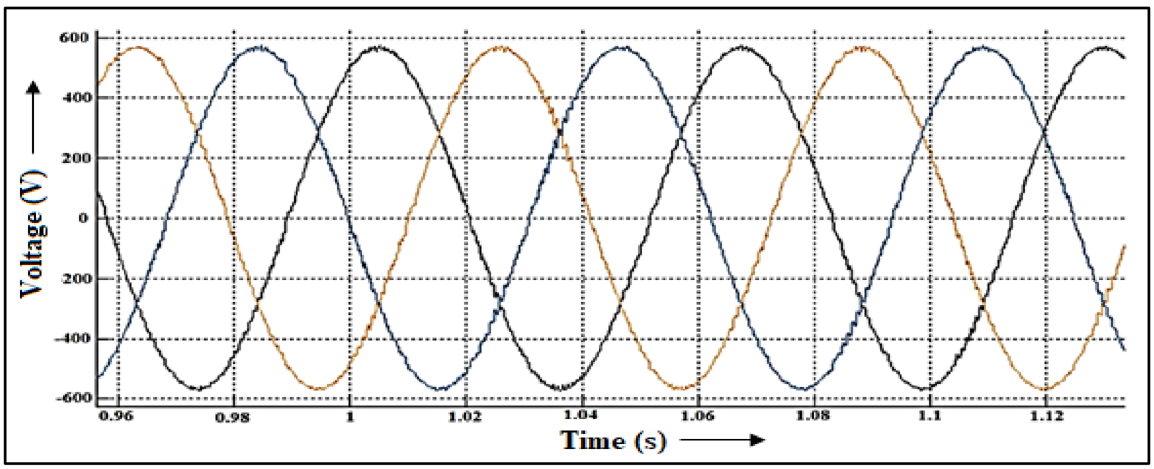

Fig. 7.2. PMSG Voltage

Obtained output current (15A) of PMSG w.r.t. time is shown in Fig. 7.3, which is obtained at a fixed wind speed of 14 m/s.

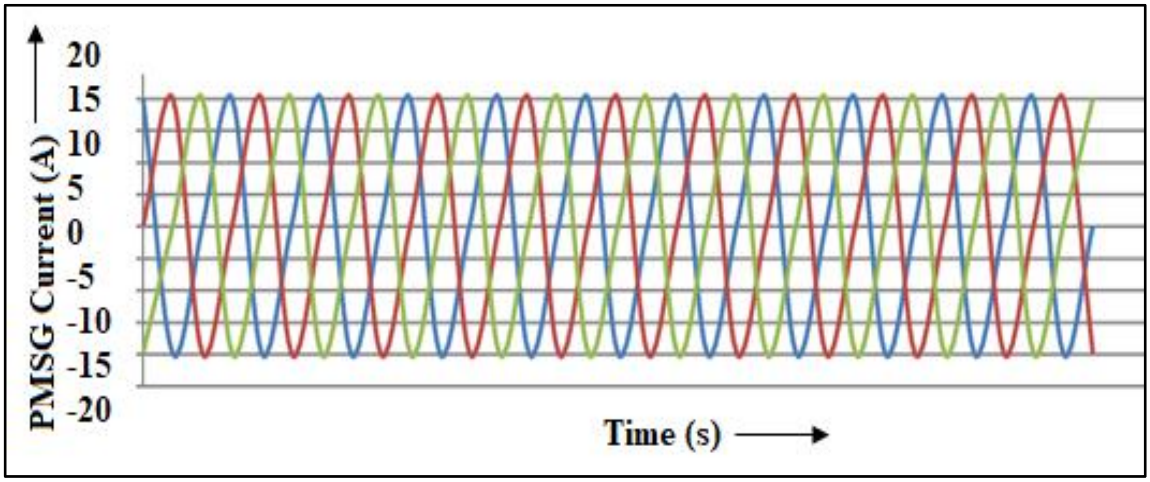

Fig. 7.3. PMSG Current

In Fig 7.4 shows the Load power of PMSG w.r.t. time which is approximately uniform. Power reaches to its peak value in a very short interval of time.

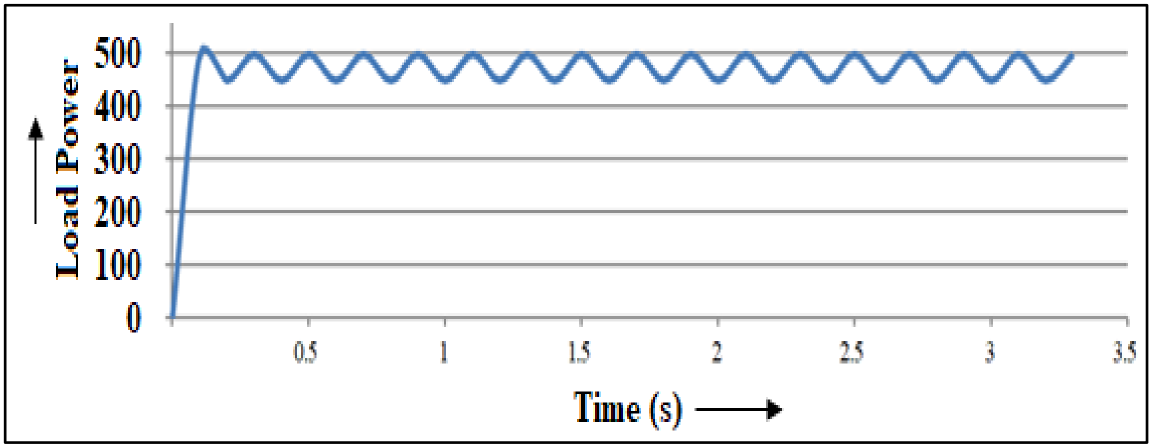

Fig. 7.4. Load Power

In Fig 7.5 shows the current I_s which is stator current and it is a resultant of two axis currents I_{ds} I_{qs} I_{ds} is the direct axis current and I_{qs} is the quadrature axis current.

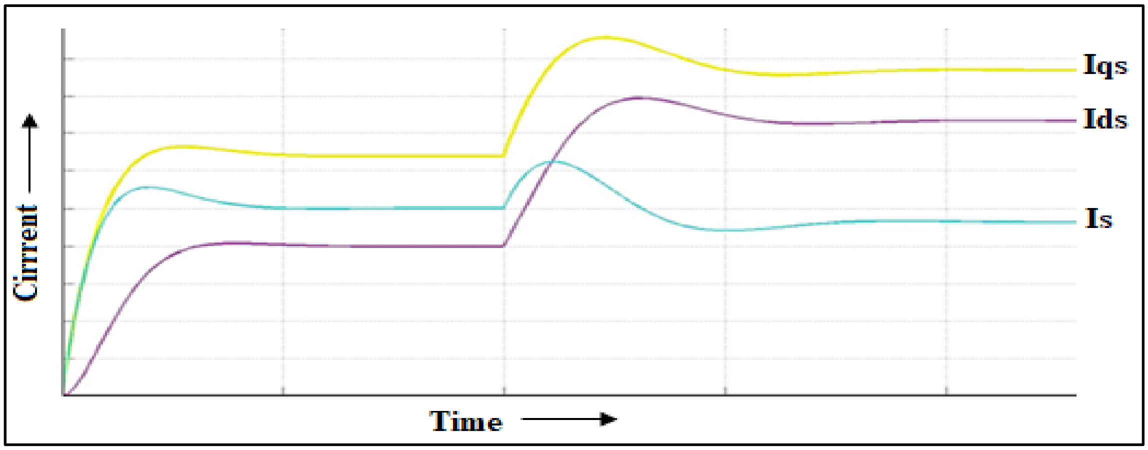

Fig. 7.5. $\boldsymbol{I_{ds}, I_{qs}}$ **and** $\boldsymbol{I_s}$

In Fig 7.6 shows abc -axis stator currents I_{as} I_{bs} and I_{cs} where ia typically refers to the current in phase A, ib refers to the current in phase B, and ic refers to the current in phase C. These currents are often represented in a coordinate system where the "a" phase is along the x-axis, "b" phase is 120^0 ahead of the "a" phase, and "c" phase is 120 degrees ahead of the "b" phase.

So, I_{as} I_{bs} and I_{cs} would denote the currents in the "a," "b," and "c" phases, respectively, of the stator in an electric machine.

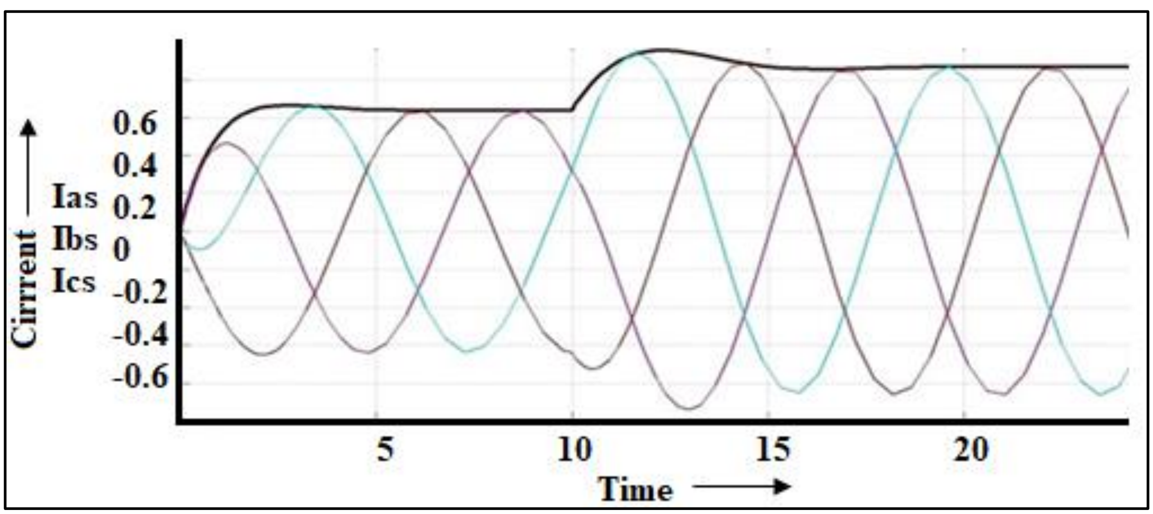

Fig. 7.6. $\boldsymbol{I_{as}, I_{bs}}$ **and** $\boldsymbol{I_{cs}}$

In Fig 7.7 shows abc -axis stator voltages V_{as}, V_{bs}, and V_{cs} Similarly to the currents, the subscripts "as," "bs," and "cs" denote the voltages in the "a," "b," and "c" phases, respectively. V_{as} refers to the $(V_{ph})_A$ and the stator neutral. V_{bs} refers to the $(V_{ph})_B$ and the stator neutral. V_{bs} refers to the $(V_{ph})_C$ and the stator neutral. These voltages are often measured relative to a neutral point in a three-phase system and can be represented in a coordinate system similar to the currents, with phase "a" along the x-axis, phase "b" 120^0 ahead, and phase "c" 240^0 ahead.

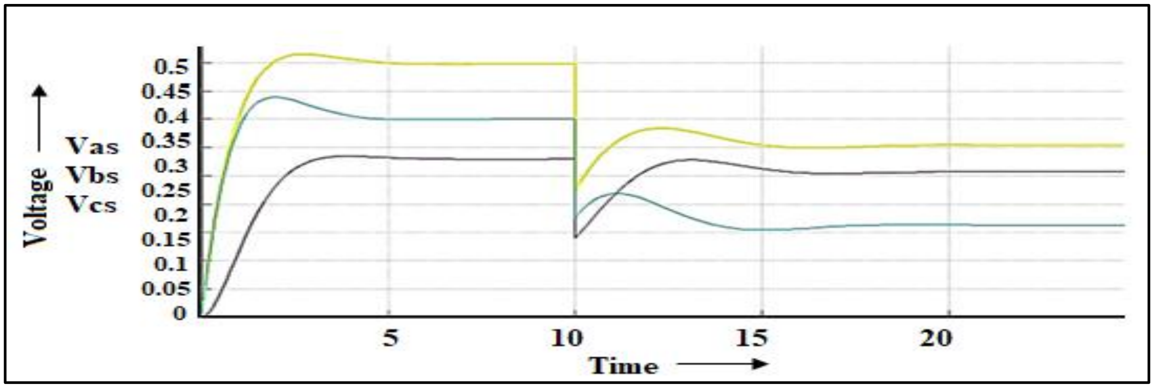

Fig. 7.7. V_s, V_{as}, V_{bs} and V_{cs}

In Fig 7.8 T_e and T_s refers to electromagnetic torque and mechanical power, which have high initial value in starting and then maintain a constant value after a time constant.

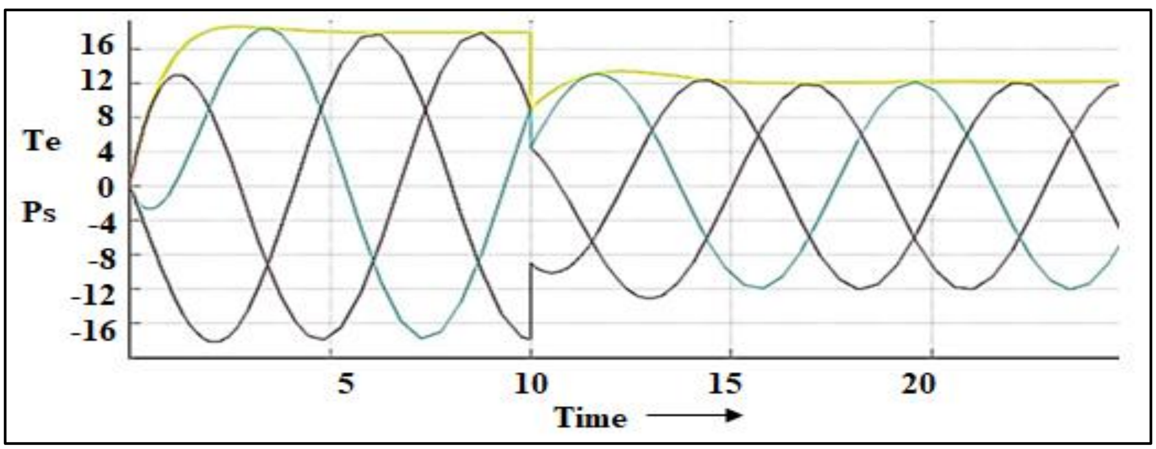

Fig. 7.8. T_e And P_s

Table7.1. Previous Result of PMSGS

(Output parameters at different wind speed range)

(6-14 m/s)

S. No.	Wind Speed (MPS)	Rotor speed (RPM)	Output voltage VOLT)	Output current (A)	Developed Power(VA)	Useful Power (W)	Power Loss (W)
1	6	273.9	16.1	8.7	140.07	109.87	30.2
2	7	301.4	17.8	9.7	172.66	141.46	31.2
3	8	334.2	22.5	9.6	216	183.8	32.2
4	9	411	22.8	10.6	241.68	207.48	34.2
5	10	426	26.5	14.6	386.9	356.7	30.2
6	11	484.1	29.9	14.9	445.51	425.31	**20.2**
7	12	552.2	31.3	10.7	334.91	309.81	25.1
8	13	575.4	33.8	9.7	327.86	293.46	34.4
9	14	619.5	36.3	9.2	333.96	302.76	31.2

Table7.2. Current Result of PMSGS

(Output parameters at different wind speed ranges) (6-14m/s)

S. No.	Wind Speed (MPS)	Rotor speed (RPM)	Output voltage VOLT)	Output current (A)	Developed Power(VA)	Useful Power (W)	Power Loss (W)
1	6	271.8	16.2	8.7	140.94	109.84	31.1
2	7	302.2	17.5	9.7	169.75	139.55	30.2
3	8	333.4	22.3	9.6	214.08	182.76	31.32
4	9	412.8	22.1	10.6	234.26	201.06	33.2
5	10	425.6	26.6	14.6	388.36	356.16	32.2
6	11	481.1	29.9	14.9	445.51	425.91	**19.6**
7	12	552.2	31.2	10.7	333.84	302.74	31.1
8	13	575.7	33.8	9.7	327.86	302.46	25.4
9	14	616.8	36.1	9.2	332.12	300.92	31.2

7.2 Implementing Neural Network-Based Direct Power Control (NN-DPC)

- **Data Collection and Preprocessing**: Gather historical data related to wind speed, turbine power output, grid conditions, and any other relevant variables. Preprocess takes places with inputs to the neural network.
- **Neural Network Architecture Design**: Choose the appropriate neural network architecture for the control task. Decide the number of layers. Consider using recurrent neural networks (RNNs) or convolutional neural networks (CNNs) for time-series data if needed.
- **Training the Neural Network**: Split the preprocessed data into training, validation, and test sets. Train the neural network using the training data, using techniques like backpropagation and gradient descent. Validate the network's performance using the validation set and adjust hyper parameters as necessary to prevent overfitting.
- **Integration with Wind Energy Conversion System (WECS)**: Develop interfaces to acquire real-time data from sensors and control actuators in the WECS. Integrate the trained neural network model into the control system of the WECS to regulate the power output based on grid conditions and other factors.

7.3 Neuro-Fuzzy Direct Power Control (NF-DPC):

- **Fuzzy Logic System Design**: Identify the input variables (e.g., wind speed, grid voltage, and turbine speed) and output variables (e.g., power reference). Design fuzzy sets and membership functions for each input and output variable. Develop fuzzy rules based on expert knowledge and experience. A Multi-Layer perceptron model is shown in Fig. 7.9.
- **Training the Neuro-Fuzzy System**: Use historical data to tune the parameters of the fuzzy logic system. Employ techniques like adaptive neuro-fuzzy inference systems (ANFIS) to automatically adjust membership functions and fuzzy rules based on training data.
- **Integration with WECS**: Implement interfaces to collect real-time data from sensors and actuators in the WECS. Integrate the trained neuro-fuzzy system into the control architecture of the WECS to adjust power output according to grid requirements.
- **Testing and Evaluation**: Test the NF-DPC system under different operating conditions and grid disturbances. Assess its performance in terms of response time,

accuracy, and robustness. Fine-tune the neuro-fuzzy system based on the testing results.

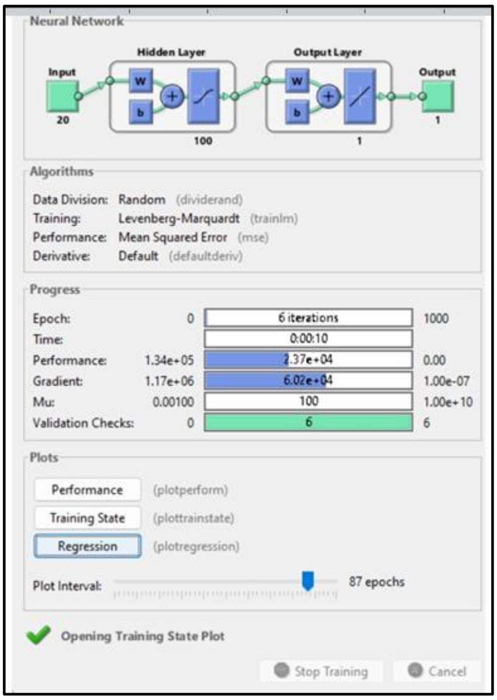

Fig. 7 .9 Structure of Multilayer Perceptron.

7.4 Artificial Neural Network Direct Power Control (ANN-DPC):

It is an epoch approach, which represents a complete iteration over the entire training dataset. This means that during one epoch, every sample will update the model parameters.

➢ **Artificial Neural Network (ANN) Architecture Design:** Choose appropriate neural network architecture suitable for the control task. Feed-forward neural networks or recurrent neural networks might be suitable. Design the input layer to include features such as wind speed, turbine speed, grid voltage, etc. Define the output layer to represent the control action, such as the power reference to be applied to the wind turbine.

➢ **Training the Artificial Neural Network:** Split the preprocessed data into training, validation, and test sets. Train the ANN using supervised learning algorithms such as backpropagation or more advanced techniques like gradient descent optimization algorithms. Validate the ANN's performance using the validation set and adjust hyperparameters to avoid overfitting.

- **Integration with Wind Energy Conversion System (WECS):** Develop interfaces to acquire real-time data from sensors and actuators in the WECS. Integrate the trained ANN model into the control system of the WECS to regulate the power output based on grid conditions and other factors. Ensure that the control system can handle communication delays and real-time constraints. The performance curve is shown in Fig. 7.10.

Conclusion: It is the curve in between mean squared error to epochs. With the help of this curve following may be concluded:

Forecasting Voltage, Current and Power

Forecasting efficiency of the machine

Forecasting regarding errors

Ambient operation of turbine

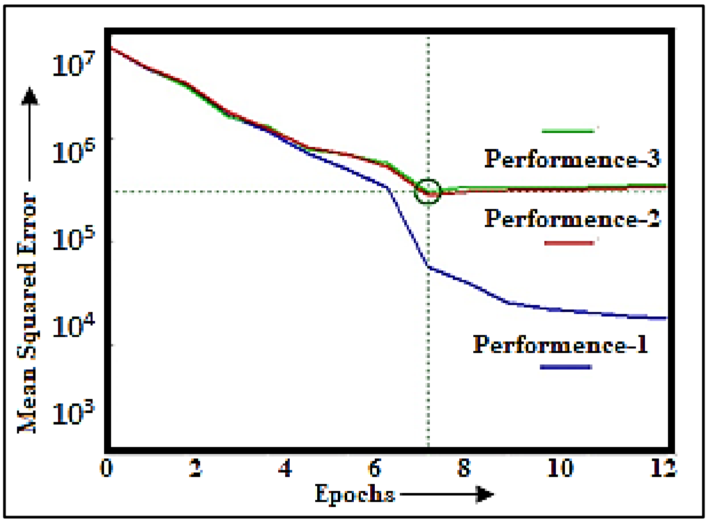

Fig. 7.10. Performance Curve

7.5 Artificial Neuro-Fuzzy Network Direct Power Control (ANF-DPC) for a Grid-Connected Wind Energy Conversion System:

Implementing an Artificial Neuro-Fuzzy Network Direct Power Control (ANF-DPC) for a grid-connected wind energy conversion system involves integrating neuro-fuzzy logic with direct power control strategies to regulate power flow in between them. Here's a structured approach to implementing ANF-DPC:

- **Data Collection and Preprocessing:** Gather historical data related to wind speed, turbine power output, grid conditions, and other relevant variables. Preprocess the data to handle missing values, remove noise, and normalize the inputs for the neuro-fuzzy network.

- **Designing the Neuro-Fuzzy Network**: Design the input layer to incorporate features such as wind speed, turbine speed, grid voltage, etc. Define membership functions for each input variable in the fuzzy logic system. Determine the fuzzy rules based on expert knowledge and experience. Implement the fuzzy inference system to map inputs to outputs using fuzzy logic.
- **Training the Neuro-Fuzzy Network:** Utilize historical data to tune the parameters of the fuzzy logic system. Employ techniques like adaptive neuro-fuzzy inference systems (ANFIS) to automatically adjust membership functions and fuzzy rules based on training data. Fig. 7.11 gives the structure of the ANFIS system and Fig. 7.12 gives the regression plot for the NN system.
- **Integration with Wind Energy Conversion System (WECS):** Develop interfaces to acquire real-time data from sensors and actuators in the WECS.Integrate the trained neuro-fuzzy system into the control architecture of the WECS to adjust power output according to grid requirements.

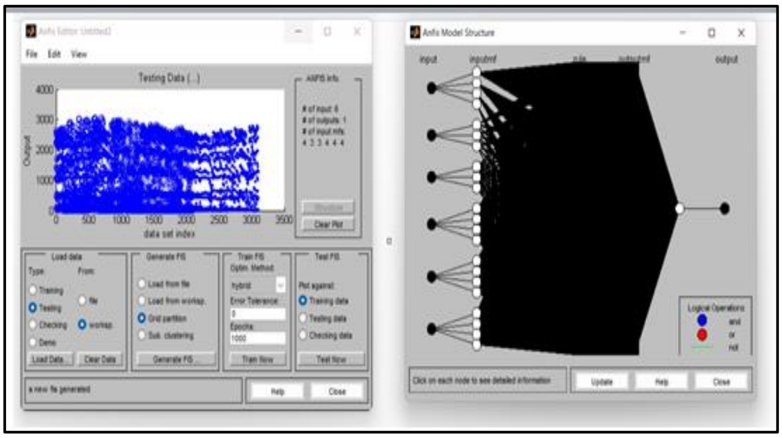

Fig. 7.11 Structure of ANFIS System

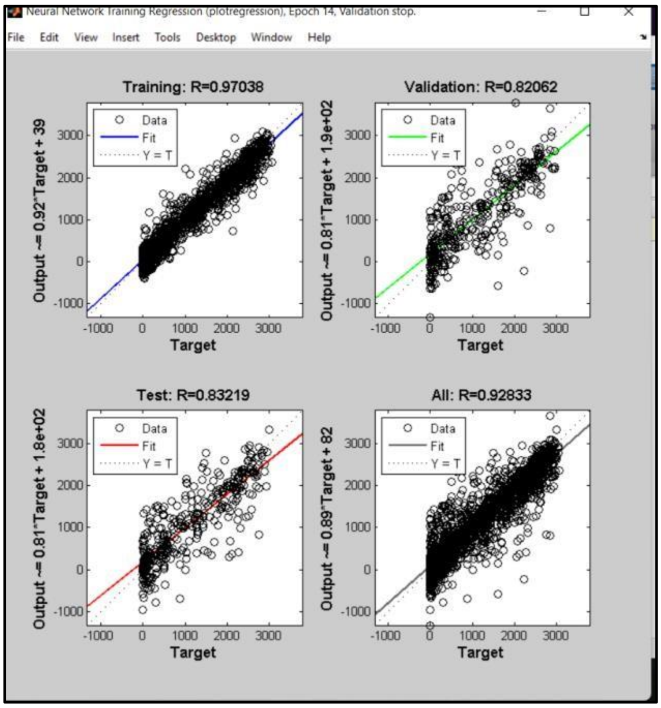

Fig. 7 .12 Regression Plot for the NN System.

- **Testing and Evaluation:** Test the ANF-DPC system under different operating conditions and grid disturbances. Assess its performance in terms of response time, accuracy, and robustness. Fine-tune the neuro-fuzzy system based on the testing results.
- **Deployment and Monitoring:** Deploy the ANF-DPC system in a real-world environment. Implement monitoring and fault detection mechanisms to ensure system reliability and safety. Continuously monitor the system's performance and make adjustments as needed.
- **Actual and Reactive Power:** The primary aim of the DPC control is to maintain the generated true power. Which is given by the following formula $P = VI\ cos\varphi$. It is the power delivered by the wind turbine, Reactive power is $P = VI\ sin\varphi$. The reactive power is compensated by the capacitor bank and the rest is delivered to the grid.

Table7.3.THD Reduction Table

S.N.	Type	mode-1 (Sub-Synchronous)	mode-2 (Super synchronous)	mode-3 (Synchronous)
1.	DPC	8.87	6.72	6.69
2.	NN-DPC	2.91	2.49	2.19
3.	NF-DPC	**2.72**	**2.31**	**2.08**
Total Harmonic Distortion				
Percentage of THD		1.	No filter	36%
		2.	Active filter	8%
		3.	Hybrid filter	**2%**

Table7.4. Comparison of Computational Cost

S.N.	Type	DPC	NN-DPC	NF-DPC
1.	Time of ANN straining	-	5min45s	-
2.	Time of NF network	-	25s	8s
3.	Time of Simulation	12	18s	22s
4.	Total time	**12**	**8min4s**	**24s**

Operation of WECS in three different modes (three modes) to optimize the generated power, an MPPT algorithm has been employed and evaluated by the system through simulation using MATLAB with improved control strategies. The effectiveness and robustness of the proposed controls, NN-andNF-DPC, have been demonstrated and compared to conventional DPC. Results have shown that the proposed controls, especially NF-DPC, are capable of reference tracking and power ripple mitigation in all operating conditions or demands.

Chapter 8

CONCLUSIONS AND FUTURE SCOPE

8.1 Conclusion: To minimize harmonics, a simulation-based module utilizing SIMULINK is proposed for the wind energy conversion system. The WECS's power circuit is housed within the PMSG, while the control circuit is contained within MATLAB/SIMULINK. The integration between PMSG and SIMULINK is used to model the WECS, enabling the integrated system to be easily modified for future use. Reduced power loss is shown in table no. 7.2 & 7.3 and the harmonic result is shown in Table no 7.4. The interconnection of PMSG and SIMULINK also improves the simulation process in terms of speed and efficiency. The WT is connected back to back with grid.

Major Findings:

8.1.1 Power Loss: Power loss in a wind turbine system occurs due to various factors such as electrical losses in cables, transformers, converters, and mechanical losses in the generator and drivetrain. Excessive power loss reduces the efficiency of the system, leading to decreased energy output and increased operational costs.

Power loss can be minimized through:

- Optimal design and selection of electrical components with low resistance and high efficiency.
- Proper maintenance to reduce mechanical losses and ensure optimal performance of the generator and drivetrain.
- Efficient control strategies to minimize losses in power electronic converters and other electrical components.
- Monitoring and analyzing power loss in the wind turbine system provide insights into its overall performance and can help identify areas for improvement.

Table 8.1. Power Loss

S. No.	Wind Speed (MPS)	Rotor speed (RPM)	Output voltage VOLT)	Output current (A)	Developed Power(VA)	Useful Power (W)	Power Loss (W)
1	11	484.1	29.9	14.9	445.51	425.31	**20.2**
2	11	481.1	29.9	14.9	445.51	425.91	**19.6**

8.1.2 Total Harmonic Distortion (THD):

THD refers to the harmonic distortion present in the electrical waveform compared to the frequency. In the context of a wind turbine system, high THD levels such as:

- Increased losses in the electrical components due to additional heating caused by harmonic currents.
- Degradation of the performance of power electronic converters.
- Interference with other electrical equipment connected to the grid.
- Lower THD levels are desirable as they indicate a cleaner electrical waveform and better overall system performance.
- Monitoring and controlling THD levels in the wind turbine system is crucial to ensure reliability, efficiency, and compliance with grid standards.

Table 8.2. THD Table

Total harmonic distortion			
Percentage of THD	1.	No filter	36%
	2.	Active filter	8%
	3.	Hybrid filter	**2%**

- **8.2 Future Scope of the work:** Further exploration and development of advanced control techniques can contribute to reducing harmonic distortion and power loss. Techniques such as Model Predictive Control (MPC), Adaptive Control, and Advanced Optimization Algorithms can be investigated and applied to improve it. Utilizing intelligent optimization algorithms. Machine Learning-based algorithms, can help optimize the parameters of the intelligent controller for minimizing harmonic distortion and power loss. These algorithms can efficiently explore the solution space and find optimal controller settings to improve system performance. One of the key areas for researchers is to investigate hybrid control approaches by combining multiple control strategies:

  fuzzy logic control

  neural network control

  Traditional control techniques that can leverage the strengths of different approaches to achieve better control accuracy and system efficiency.

- The performance can furthermore be improved by developing robust fault detection and diagnosis algorithms specific to WECS that can help identify and mitigate issues related to harmonic distortion and power loss promptly. Early detection of faults can enable timely corrective actions and prevent system degradation. Advancements in power electronics and converter design canals so contribute to reducing harmonic distortion and power loss in wind energy conversion systems. Developing more efficient converter topologies, improving component selection, and optimizing the converter control strategies can be so many search areas that can enhance overall system performance.

- **Predictive Control Strategies:** Investigate and implement predictive control techniques that anticipate changes in wind speed and turbine load, allowing for proactive adjustments to reduce THD and optimize energy capture.
- **Harmonic Filtering Techniques:** Explore innovative harmonic filtering methods and devices to effectively mitigate harmonics in the generated power, enhancing power quality and minimizing THD.
- **Hybrid Intelligent Systems:** Investigate the integration of artificial intelligence (AI) in dual mode of control system for adaptive and self-learning capabilities, enabling the controller to continuously improve performance.
- **Fault Tolerance and Diagnostics:** Develop intelligent fault detection and diagnostic systems that can identify issues leading to increased THD or power losses. Implement automated responses to faults for efficient system recovery.
- **Wind Farm Layout Optimization:** Research optimal wind farm layout designs and turbine placement strategies to reduce wake effects and turbulence, thereby minimizing power losses and improving overall efficiency.
- **Coordinated Control in Wind Farms:** Investigate coordinated control strategies among turbines in a wind farm to optimize power production and reduce harmonic distortions collectively.
- **Grid-Interactive Control:** Develop control strategies that enhance the interaction between the wind energy system and the electrical grid, ensuring compliance with grid codes and minimizing disturbances that can lead to power losses.
- **Real-time Monitoring and Communication:** Explore advanced real-time monitoring systems that provide detailed insights into system performance, allowing

for timely adjustments to minimize THD and power losses.

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Thesis

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IMPROVEMENT OF POWER QUALITY BY REDUCING HARMONIC DISTORTION IN MICROGRIDS BY USING ANN AND SHUNT ACTIVE POWER FILTER TECHNIQUES Mr. Mayur D Patil*1, Dr. Pooja V. Paratwar*2, Prof. Tushar V. Deokar*3, Prof. Rupali R Bairagi*4 *1,2Asst.Professor, Dept. Of Electrical Engineering, DGOIFOE, SPPU Pune, Maharashtra, India. *3,4Asst.Professor, Dept. Of Electrical Engineering, S.B. PATIL College Of Engineering, Vangali, Maharashtra, India. DOI: https://www.doi.org/10.56726/IRJMETS39815.
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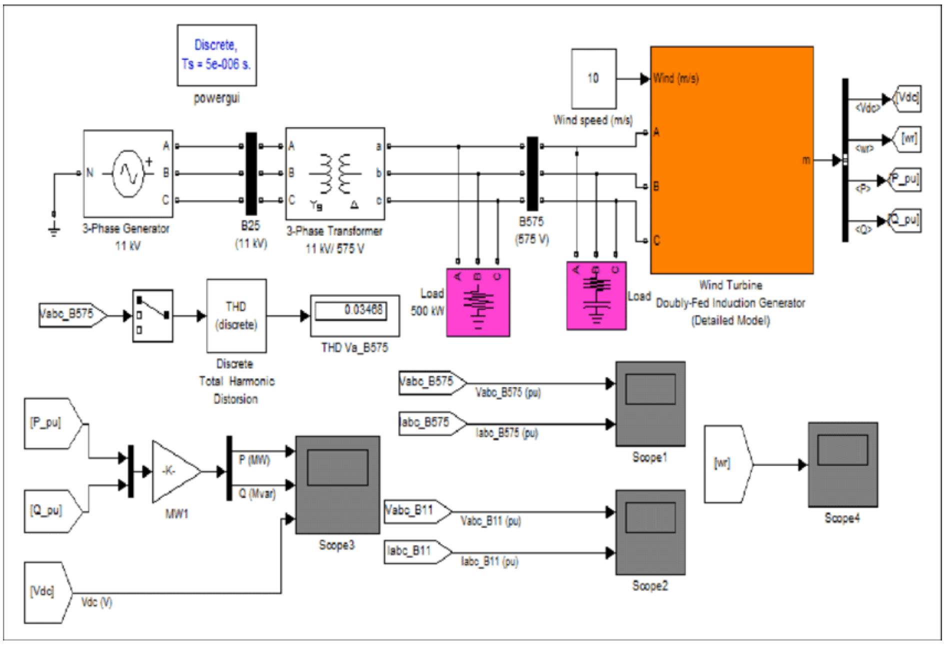
Patents:

NA

Appendix:



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Wind (m/s)
A
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Wind Turbine
Doubly-Fed Induction Generator
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B25
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3-Phase Transformer
11 kV/ 575 V
B575
(575 V)
Load
500 kW
Load
Vabc_B575
THD
(discrete)
Discrete
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Distorsion
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Vabc_B575 (pu)
Iabc_B575
Iabc_B575 (pu)
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MW1
P (MW)
Q (Mvar)
Scope3
Vdc (V)
Vabc_B11
Vabc_B11 (pu)
Iabc_B11
Iabc_B11 (pu)
Scope2
Scope4