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M.Tech (Power Electronics and Systems)

Ashutosh Kumar Gami

2025

Optimized MPPT Control of PMSG Based WECS with Boost Converter Using Fuzzy Sliding Mode Control

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

POWER ELECTRONICS AND SYSTEMS

Submitted by:

ASHUTOSH KUMAR GAMI

2K23/PES/03

Under the supervision of

PROF. MINI SREEJETH

(Professor, EED, DTU)

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I, Ashutosh Kumar Gami, Roll No. 2K23/PES/03 student of MTech (Power Electronics & Systems), hereby declare that the project Dissertation titled **"Optimized MPPT Control Of PMSG Based WECS with Boost Converter Using Fuzzy Sliding Mode Control"** which is submitted by me to the Department of Electrical Engineering, Delhi Technological university, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

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Date: 31st May 2025

Ashutosh Kumar Gami

M. Tech (Power Electronics & Systems)

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ABSTRACT

This thesis presents the study of sophisticated control systems for Permanent Magnet Synchronous Generator (PMSG)-based Wind Energy Conversion Systems (WECS), emphasizing the enhancement of Maximum Power Point Tracking (MPPT) efficacy under fluctuating wind conditions. The system considered in this scholarly thesis consists of Wind Turbine, PMSG, rectifier. DC-DC Boost Converter. MPPT algorithm is used to maximize the output of wind turbine. This MPPT algorithm is used to control the boost converter based on Fuzzy logic control and adjusts the duty cycle of boost converter for optimal output from Wind Turbine. Traditional techniques like Perturb and Observe (P&O) and Sliding Mode Control (SMC) encounter significant constraints, including power fluctuations, losses due to chattering, and reliance on sensors. Traditional techniques, such as Perturb and Observe (P&O) and Sliding Mode Control (SMC), demonstrate significant shortcomings, including power fluctuation, noise losses, and dependence on sensors. This paper presents an innovative hybrid Fuzzy Sliding Mode Control (FSMC) design that combines the resilience of Sliding Mode Control (SMC) with the flexibility of fuzzy logic. The FSMC framework replaces the erratic switching function characteristic of traditional SMC with a 49-rule fuzzy inference system that alleviates fluctuations and diminishes switching losses. The control law changes the sliding surface S(t) dynamically. This allows precise MPPT operation without mechanical sensing (anemometers or tachometers), which cuts the cost of the system by 18–22%. This study is done on the MATLAB Simulink for the simulation and fuzzy logic designing of the PMSG based WECS system.

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LIST OF ABBREVIATIONS

WECS	Wind Energy Conversion System
SG	Smart Grid
PMSG	Permanent Magnet Synchronous Generator
VS WECS	Variable Speed Wind Energy Conversion System
MM MPPT	Mathematical model based MPPT
AL MPPT	Algorithm based MPPT
P&O	Perturb and Observe
INC	Incremental Conductance
SMC	Sliding Mode Control
FSMC	Fuzzy Sliding Mode Control
TSR	Tip Speed Ratio
PSF	Power Signal Feedback
VSCF	Variable Speed Constant Frequency
MTPA	Maximum Torque per Ampere

Chapter 1

INTRODUCTION

1.1. Background of WECS:

The demand for energy has been rising rapidly worldwide. The supply of conventional energy, such as coal, oil, and gas, is finite and subject to exhaustion. Therefore, it is imperative that we investigate other energy sources and conserve what we now have. The most potential forms of renewable energy resources for humanity are solar and wind power. Renewable energy sources will form the foundation of the energy system in the future due to their abundance. Coal, oil, and gas are gradually being replaced by renewable energy in our patterns of energy consumption. Reconfiguring the current energy systems is necessary to include a significant proportion of renewable energy into the power system. The key to understanding this change is the smart grid, often known as the intelligent power grid (SG) [1]. Countries such as India, or areas where pollution is a significant issue in societies reliant on fossil fuels, experience challenges in energy production or generation. Utilizing renewable resources such as wind power will enhance self-reliance compared to imported coal, oil, or natural gas. Wind power is crucial in advancing towards a low-carbon future, which is vital for establishing a fully carbon-free energy sector. Renewable energy sources are plentiful and have a minimal environmental impact, making their role in power generation significant. Significant wind resources exist globally. Wind power generation is increasingly reliant on advanced technologies, moving beyond traditional fossil fuel energy sources. It now incorporates competitive energy forms through the use of innovative motors, power electronic converters, and variable speed wind turbines. In the future, distributed renewable energy sources, a robust power grid, flexible consumption, and an intelligent power control system will all be components of SG systems. In order to fulfill future energy demands and support the green SG system, distributed renewable energy sources (such as wind turbines, solar systems, fuel cells, biomass, smart homes, etc.) and energy storage devices (such as batteries, EDLCs, superconducting magnetic energy storage, etc.) are

anticipated to be essential. The DGs are supposed to place the generation on the customer side of the meter or on the distribution network, which is near to the load. DGs should be promoted because they have a lot of potential to enhance distribution system performance [2].

The most popular wind-energy conversion devices are wind generating systems (WGSs). Variable-speed generators can be used with these systems. Wind turbines (WTs) with high efficiency can change their speed in response to changing wind conditions. To track the maximum power point (MPP) transition in this turbine and monitor the energy flow, a power converter is necessary. Wind velocity can be adjusted by WTs with varying rotation speeds [1,2]. Large WT generators with variable-speed WGSs have swiftly embraced wind energy conversion systems (WECS), which use permanent magnet synchronous generators (PMSG). There have been developments in this field. At different velocities, WECSs maximize the production of wind energy [3].

1.1.1. Principle Of WECS:

The idea behind the wind energy conversion system is to use wind power to turn the blades of a windmill. Then, to help the generator make more power, the speed booster makes the blades turn faster. The wind energy conversion system is the process of turning wind energy into mechanical energy and then turning mechanical energy into electrical energy. That is, power from the wind. After converting wind energy into mechanical energy, the wind energy conversion system then converts mechanical energy into electrical energy. This process is known as the wind energy conversion system. This process doesn't need fuel or radiation, and it doesn't make the air dirty, so it's a clean energy source. The most important tool for making wind power is a wind turbine. A wind turbine is a machine that changes wind energy into electrical energy. The main idea is that the wind makes the impeller spin. The impeller helps the generator spin, which lets it cross the magnetic induction line. The process of turning wind energy into mechanical work makes the rotor turn, which makes electricity. Figure 1.1 shows a typical arrangement of parts in a wind turbine used in the Wind Energy Conversion System.

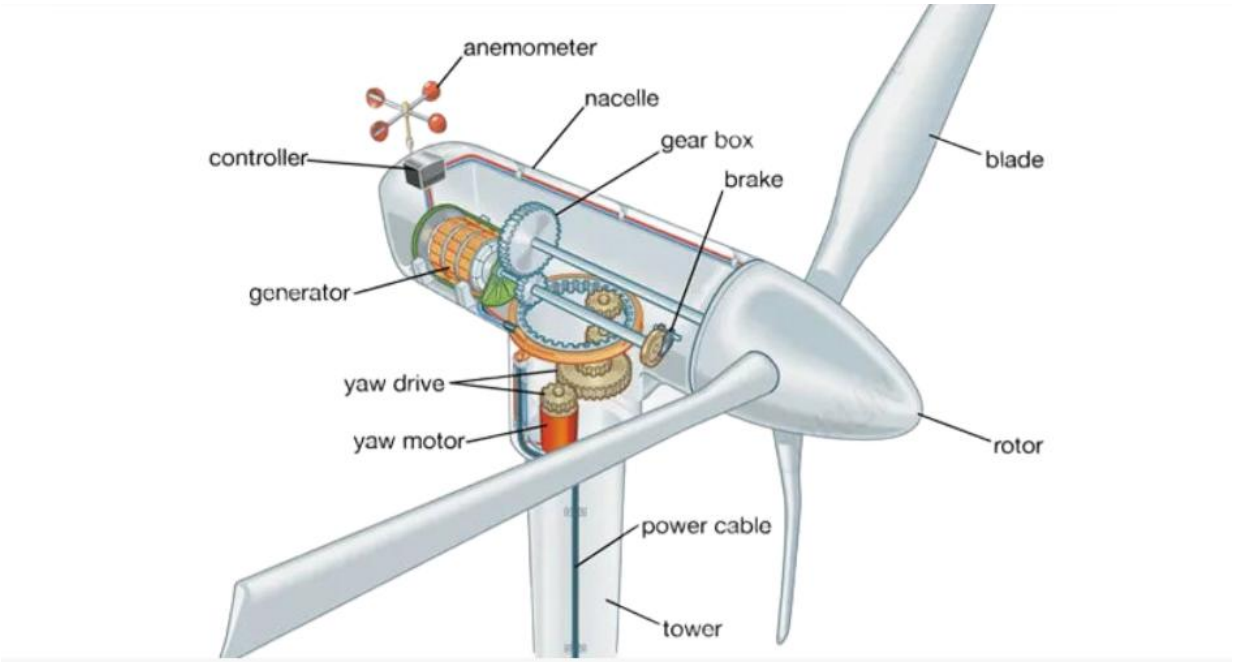

Fig 1.1: Components of Wind Turbine used in WECS

1.1.2. Core Components of WECS:

The generator is a fundamental element of the power generation system within the wind energy conversion system. Wind power transforms mechanical energy into alternating current via generators. Various generator types can be used for distinguished drive chain structure types. The inherent variability of wind leads to fluctuations in the frequency and voltage of the alternating current produced by the generator. Consequently, it is essential for the power generation system to incorporate an additional core component [5].

Another fundamental element is the energy storage inverter. The wind energy conversion system transforms the electrical energy produced by the generator, which exhibits unstable frequency and voltage, into electrical energy characterized by stable frequency and voltage that complies with grid standards [6]. Inverters are primarily categorized into full-power inverters and doubly-fed inverters. Various types of generators require specific inverters to ensure stable power generation quality, effective power generation control, torque management, and other essential functions. Fig 1.2. shows the core components in WECS:

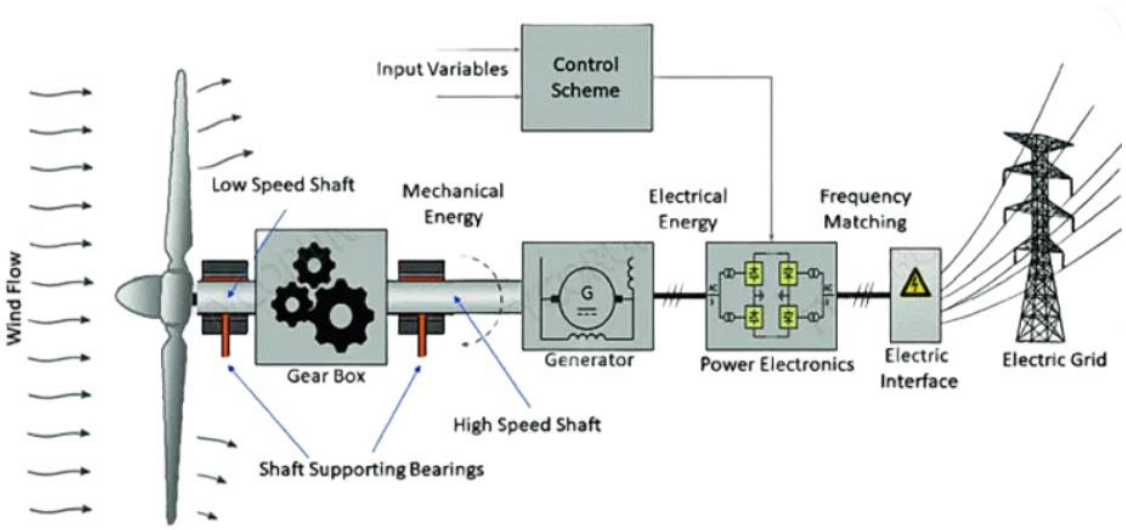

Fig 1.2: Core Components in WECS

1.2. Importance of PMSG in WECS:

Using wind energy to make electricity is becoming more common among the many types of renewable energy sources. Wind energy is becoming more and more appealing and competitive as a form of renewable energy as technology moves quickly [7]. The variable speed wind energy conversion system (VSWECS) is better than the fixed speed wind energy conversion system (FSWECS) in WECS because it has many more benefits. These include the ability to get the most wind energy at different wind speeds through MPPT control, less aerodynamic noise and mechanical stress, better control of active and reactive power, better power quality, and higher efficiency. PMSG is becoming more popular in VS-WECS because it has a lot of benefits over other generators:

- High energy density because of permanent magnet poles.
- Control strategies are more simpler in PMSG.
- There is less maintenance because the excitation system is eliminated.
- Managing the reactive power in PMSG is easier.
- Decrease in weight, losses and capital cost.

The general block diagram for PMSG based WECS is shown in Fig 1.3.

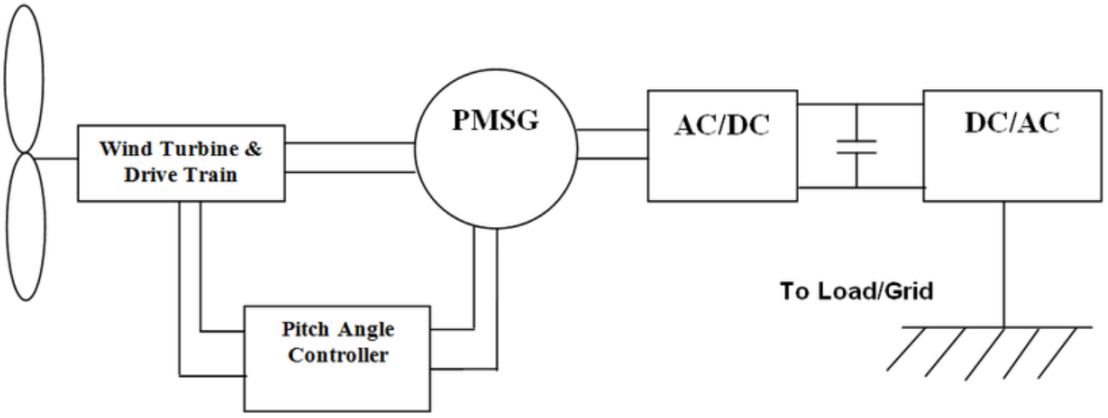

Fig 1.3: Block Diagram for PMSG based WECS

The wind energy conversion system employs generators that are classified as either DFIG or PMSG types. DFIG features windings on both the stationary and rotating components, with each winding playing a crucial role in transferring substantial power between the shaft and the grid [8]. In a DFIG system, the converters are responsible for processing approximately 25-30 percent of the total generated power, which is the rotor power connected to the grid through the converter, while the remainder is fed directly to the grid from the stator. The converter utilized in PMSG must handle the entire amount of the generated power. The term "100 percent" pertains to the standard WECS equipment that includes a three-stage gear box in the DFIG configuration. Most wind turbine manufacturers employ DFIG in their wind energy conversion systems, as it offers benefits related to cost, weight, and size. However, the dependability linked to the gearbox, slip rings, and brushes in DFIG is not appropriate for specific applications [9]. The PMSG operates without a gearbox, resulting in enhanced efficiency and reduced maintenance requirements, this is shown in Fig1.4. The PMSG drives demonstrate exceptional torque performance at low speeds while minimizing noise and eliminating the need for external excitation.

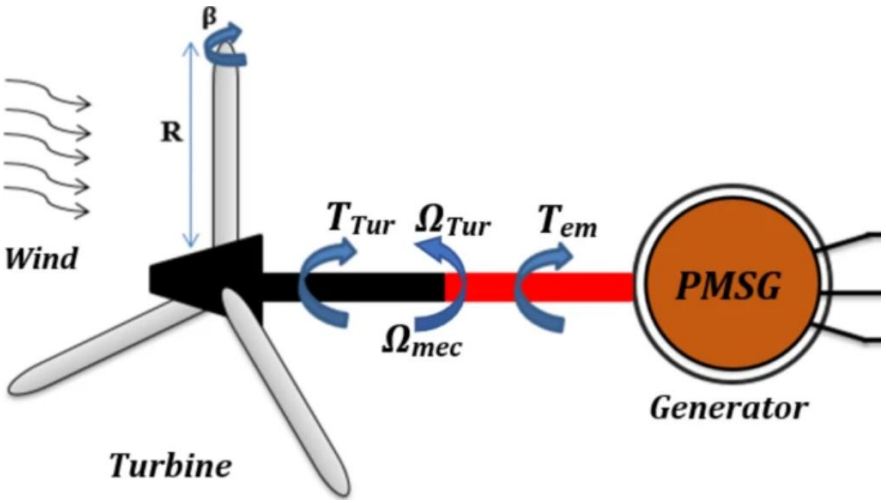

Fig 1.4: Coupling of Wind Turbine with PMSG

1.3. Maximum Power Point Tracking (MPPT):

The WECS's efficiency is very important because the capital cost of the WECS is a big factor in the investments. The wind energy conversion system (WECS) must always make as much power as possible so that the investors may fast get their money back. To get an efficient WECS, it needs to run at full power all the time. Maximum power point tracking (MPPT) is what the literature calls it [10]. The maximum power point tracking (MPPT) algorithms always aim to give the highest power feasible, even when the environment changes. The main job of the MPPT is to match the load. The WECSs can be run at different rates because their dynamics are not linear and the wind speed changes all the time [11].

There are two kinds of MPPT methods: algorithm-based MPPT (AL-MPPT) and mathematical model-based MPPT (MM-MPPT). MM-MPPTs are based on the tip-speed ratio (TSR), power signal feedback (PSF), and other methods that come from these methods. Constant Voltage, Incremental Conductance, and Perturb and Observe (P&O) are some of the different ways to track power to get the most power production. The P&O is the most prevalent method since it is simple and needs fewer current and voltage sensors. This method works by changing the system by raising the array's operating voltage and watching how that affects the array's output power. If the output power goes up, the algorithm keeps changing in the same direction. If the output power goes down, the

algorithm changes its direction [5]. This technique enables the system keep track of and run at the maximum power point of the PV panels in an effective way. This study uses the Sliding Mode Control MPPT algorithm on a boost converter [12].

Figure 1.5 depicts how the VSCF (variable speed constant frequency) wind power generation system can work in four different areas, depending on the wind conditions. In Region 1, most wind turbines are connected to the grid. The wind turbine starts up and lets go of its brakes after passing this point. Region 2 employs maximum power point tracking (MPPT) management to make sure that the wind turbine runs at its maximum power coefficient (C_{pmax}) and gets VSCF. The wind turbine in area 3 stays within the maximum speed range, but its power is below the maximum limit, which is usually reached by utilizing variable-pitch control. In Region 4, the wind turbine changes the pitch angle to slow down the rotor when the wind speed goes up. This keeps the power output stable. The main subject of this thesis MPPT implementation [13] is the MPPT method that uses Region 2.

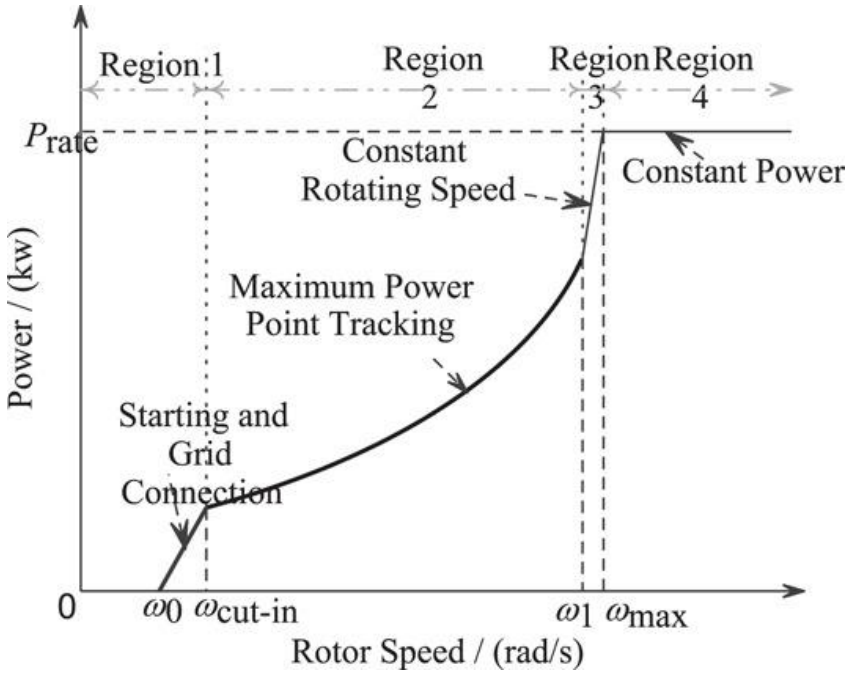

Fig 1.5: Wind turbine control mode in different operating regions

1.4. Role of Power Electronics (Boost Converter) in WECS:

With the use of power electronic technology, electrical power may be efficiently converted into a variety of forms to suit the requirements of the application. The power electronic converter is a technology that enables power production systems powered by renewable energy. While most renewable energy-based power generation technologies, such as wind turbines and solar photovoltaics (PV) systems, have a set of optimal operating conditions (voltage, frequency, etc.) that indicate good energy capture/conversion efficiency, they may not precisely meet grid or customer requirements [14]. The power electronic converter then connects the generating units to the grid and changes the electricity so that it meets the grid's needs, such as those related to frequency, voltage, active and reactive power, flickers, harmonics, ride-through capabilities, and so on. Power electronic converters are becoming more and more important in the building of contemporary wind turbines and wind farms. Power electronics technology, which comprises semiconductor devices, circuit topologies, modulation, and control techniques, has come a long way in the last few years. Costs are declining, performance is constantly being enhanced, and the range of applications has grown dramatically [15].

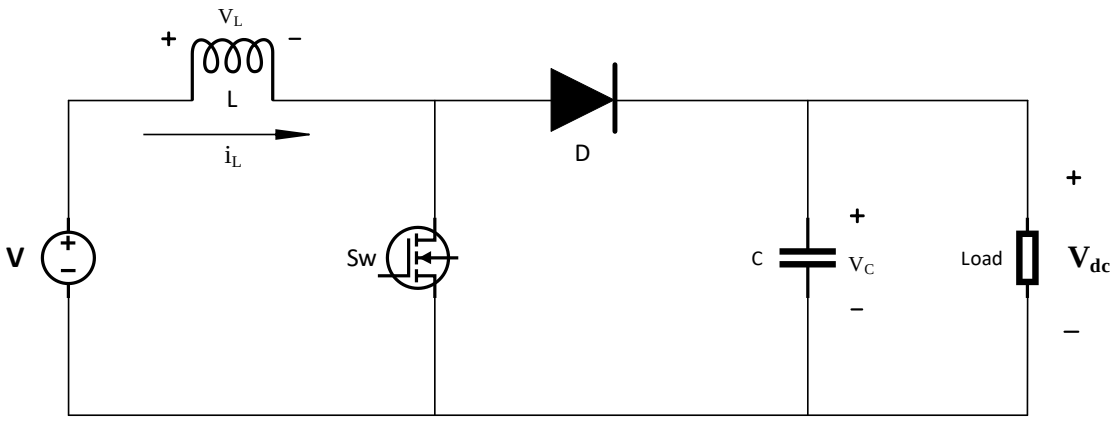

Fig1.6: Boost Converter

The boost converter (DC-DC step-up converter) is essential to PMSG-based WECS due to its significant functions:

- Voltage Regulation

For grid-side inverters, the output voltage of the PMSG varies with wind speed, hence a boost converter is required to maintain a constant DC-link voltage. The boost converter's duty cycle (D) is adjusted in the manner described below to control the output voltage (V_{out}) as follows:

$$V_{out} = \frac{V_{in}}{1-D} \quad (1.1)$$

- Implementation of MPPT

The converter adjusts its duty cycle to ensure that the turbine operates at the optimal tip-speed ratio (λ_{opt}) for maximum power extraction. The maximum power (Pmax) can be articulated in the following manner:

$$P_{max} = \frac{1}{2}\rho A C_{p_{max}} v_{wind}^3 \quad (1.2)$$

1.5. Limitations of Conventional Control Methods:

This section thoroughly analyzes the problems with the conventional control methods employed in PMSG-based WECS, highlighting how they degrade system performance and become ineffectual when the wind changes. The limitations of Perturb & Observe (P&O), Incremental Conductance (INC) and Sliding Mode Control (SMC) is listed below:

1.5.1. Perturb & Observe (P&O), Incremental Conductance (INC):

- P&O causes continuous oscillations about the MPP even when the wind is calm by varying the operating voltage and monitoring power variations. Oscillation-related power loss can surpass 5%.

$$\Delta P = \frac{1}{T}\int_0^T |P_{actual} - P_{MPP}|\, dt \quad (1.3)$$

- INC solves for MPP $\frac{dP}{dV} = 0$, but its computing complexity prevents convergence when wind varies quickly.
- Due to their reliance on mechanical sensors (such as tachometers and anemometers), both approaches are more expensive and susceptible to failure.

1.5.2. Sliding Mode Control (SMC):

- Although SMC is resistant against changes in parameters, its discontinuous control law causes high-frequency chattering, which are rapid oscillations in the control signal (e.g., ±2–3% duty cycle variations). This reduces gearbox lifespan by 15–20% in DFIG systems and shows up as 2–3% increased switching losses in boost converters and mechanical stress on turbine components [16].
- SMC's discontinuous control rule uses a signum function, which results in high-frequency duty cycle switching.

$$u(t) = -K \cdot \text{sgn}(S(t)), S(t) = \frac{dP}{dV} \quad (1.4)$$

This results in voltage and current ripples, mechanical stress and a 12–15% power loss.

- The signum function sign(S) is the source of chattering in conventional SMC, causing abrupt changes in control states. Computational studies show that unmitigated chattering increases total harmonic distortion (THD) at the grid interface to 4.5–6% higher than IEEE 1547 standards.

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The summary of the above is shown in the below table 1.1.

Table 1.1: Comparison of Conventional Control Methods

Method	Key Limitation	Impact	Efficiency Loss
P&O	Oscillations around MPP	Power ripple, mechanical wear	5-7%
INC	Computational delay	Slow tracking in turbulent winds	4-6%
SMC	Chattering	Component stress, power loss	12-15%

1.6. Introduction to Fuzzy Sliding Mode Control (FSMC):

There is a new type of hybrid control design that combines the dependability of fuzzy logic systems with the flexibility of sliding mode control (SMC). This design approach is a hybrid control design. Fuzzy Sliding Mode Control (FSMC) is the name given to this innovative approach to the design of control systems.

The chattering effect, which occurs when control movements aren't smooth, and the necessity for exact parameter tweaking to ensure the greatest performance in changing working conditions are both addressed by this integration, which fixes two significant difficulties that are associated with traditional SMC solutions. Both of these issues are addressed by this integration. In order to achieve this objective with the help of FSMC technology, the traditional signum function of SMC is substituted with a fuzzy inference system. The capability of SMC to block disturbances is preserved, and as a consequence of this, it is possible to make transitions between control modes in a seamless manner. The flexibility of fuzzy logic control (FLC) and the robustness of sliding mode control (SMC) are combined in FSMC, which increases the efficiency of Maximum Power Point Tracking (MPPT) while also resolving important difficulties such as control signal oscillations and sensor dependency [17].

Table 1.2: Comparison of FSMC with other Control Methods

Feature	FSMC	SMC	P&O
Chattering	Minimal (fuzzy smoothing)	High (fixed switching)	N/A
Tracking Speed	<0.5sec	1-2sec	1.5-3sec
Sensor Use	Electrical only	Mechanical + Electrical	Mechanical + Electrical

1.7. Objective of Thesis:

The primary goals of the thesis are discussed in this portion of the report. Validating the efficacy of the proposed Fuzzy Sliding Mode Control (FSMC) in PMSG-based Wind Energy Conversion Systems (WECS) is the key focus of the research. Additionally, the research aims to address the deficiencies that are existing in conventional control systems. Specifically, the objectives have been created in order to ensure that the process of developing, analysing, and validating the control plan is carried out in a logical form.

- Create a precise model of a PMSG-based WECS that incorporates a boost converter. For the PMSG-WECS, it is recommended that a dynamic simulation model be developed. Including the boost converter component,

the three-phase rectifier, the PMSG, and the wind turbine in this model is something that should be done.

- Build an Accurate WECS Model Based on PMSG How to Use a Boost Converter.
- Create a hybrid controller that combines the durability of SMC with the flexibility of fuzzy logic in order to optimize MPPT. An FSMC algorithm that adapts dynamically to variations in wind speed without chattering results from this.
- Compare FSMC's robustness, tracking speed, and efficiency to that of Perturb & Observe (P&O) and standard SMC.

1.8. Contribution of Thesis:

The thesis examines:

Chapter 1 elucidates the pivotal significance of wind energy within renewable power systems, emphasizing the advantages of Permanent Magnet Synchronous Generators (PMSG), including gearless operation and elevated efficiency, while addressing issues such as chattering in traditional Sliding Mode Control (SMC) and sensor reliance in Maximum Power Point Tracking (MPPT) techniques. The research purpose is to design a hybrid Fuzzy Sliding Mode Control (FSMC) to address these constraints.

Chapter 2 analyzes the literature about the PMSG-based WECS system. Evaluates current MPPT methodologies, including P&O, TSR, SMC applications, and fuzzy logic implementations, emphasizing deficiencies in transient responsiveness, computational complexity, and partial-load inefficiency.

Chapter 3 develops mathematical models for wind turbines, PMSGs, and boost converters, such as aerodynamic power equations, d-q axis generator dynamics, and power electronics state-space models.

Chapter 4 presents a detailed explanation of a proposed FSMC controller. It

integrates a 49-rule fuzzy inference system with SMC to prevent chattering, permit sensor less operation, and provide Lyapunov stability with minimal fluctuations.

Chapter 5 describes the framework, which is corroborated using MATLAB/Simulink simulations. The results indicate a increased MPPT efficiency, a settling time of 10 ms, and a total harmonic distortion of less than 2.5% across various wind profiles, surpassing conventional SMC and P&O methods.

Chapter 6 describes the contributions, emphasizing cost reductions (18-22%) and grid compatibility, while also proposing potential avenues such as hardware-in-loop validation and hybrid energy storage integration. Concludes the thesis and proposes prospective directions for future research that warrant further exploration.

Chapter 2

LITERATURE REVIEW

2.1. Introduction:

This chapter conducts a critical analysis of the current research on the applications of fuzzy logic, sliding mode control, and MPPT techniques in wind energy systems. The proposed FSMC-based MPPT approach is justified by the identification of voids in current methodologies. Over the past ten years, improvements in power electronics, control schemes, and the integration of renewable energy sources have led to a significant evolution in wind energy conversion systems, or WECS. Finding effective Maximum Power Point Tracking (MPPT) algorithms that can adjust to the stochastic nature of wind speeds while minimizing mechanical and electrical losses is a crucial challenge in optimizing energy harvest from wind turbines. This chapter provides an overview of the literature on fuzzy logic applications in WECS, sliding mode control (SMC), and MPPT techniques in order to highlight gaps in existing approaches and bolster the need for the proposed Fuzzy Sliding Mode Control (FSMC) approach [18].

2.2. Review of existing MPPT Techniques:

Maximum Power Point Tracking (MPPT) methods are very important for getting the most energy out of wind energy conversion systems (WECS). In this part, we'll look at both traditional and intelligent MPPT methods, pointing out their main ideas, pros and cons [19].

2.2.1. Perturb and Observe (P&O):

- **Mechanism:**

This MPPT operating mechanism is by making adjustments to the operating point by causing voltage and current to fluctuate and monitoring the changes in

power. When the power is increased, the perturbations continue in the same direction; when the power is decreased, the direction of fluctuation changes [18]. The working of P&O is shown in Figure 2.1.

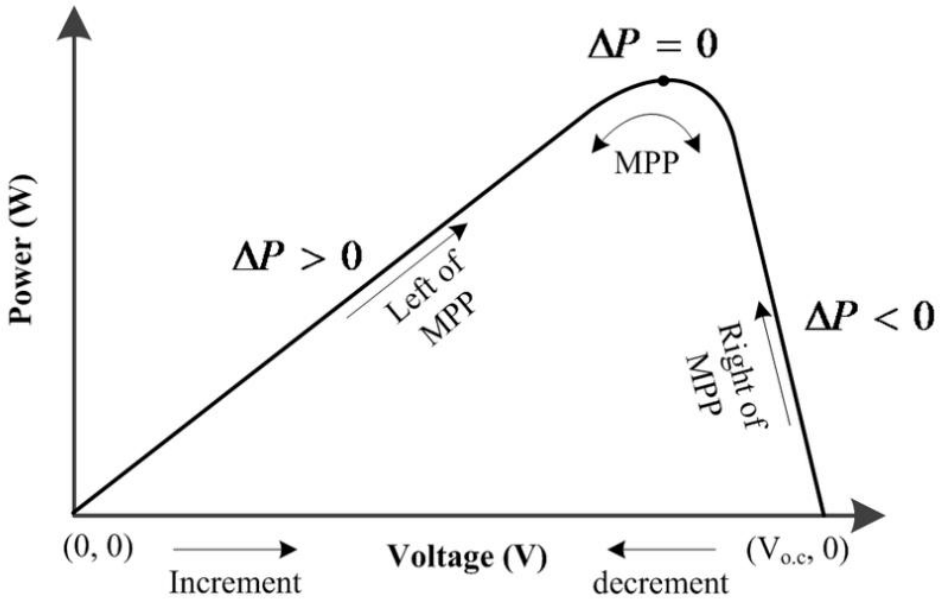

Fig 2.1: P&O Operating Technique

- **Advantages:**

The advantages of this MPPT method is its low cost and simple working.

- **Limitations:**

Firstly, this MPPT has steady state oscillations around MPP. Secondly, there is a slow convergence under rapid variations of wind speed. Lastly, it is prone to "algorithm confusion" during turbulent conditions [20].

- **Applications:**

It is widely used in WECS which are of small scale due to its simplicity.

2.2.2. Incremental Conductance (INC):

- **Mechanism:**

The incremental conductance works on the principle that it tracks MPP using condition $\frac{dP}{dV} = 0$ where $\frac{dP}{dV} = I + V\frac{dI}{dV}$. It will adjust voltage until conductance matches incremental conductance [21].

- **Advantages:**

This MPPT method has higher accuracy than P&O under steady winds.

- **Limitations:**

This method fails under partial shading and rapid wind variations. It requires precise sensor measurements for its functioning.

2.2.3. Tip Speed Ratio (TSR):

- **Mechanism:**

In this method, we maintain optimal TSR $\boldsymbol{\lambda}_{\text{opt}} = \frac{\boldsymbol{\omega R}}{\boldsymbol{V}_{\text{wind}}}$ by regulating the rotor speed. Anemometers and tachometers are used to measure $\boldsymbol{V}_{\text{wind}}$ wind and $\boldsymbol{\omega}$. PI control is used to change the generator torque [22].

- **Advantages:**

TSR method has fast response (approx. 50msec settling time).

- **Limitations:**

This method has sensitivity to $\boldsymbol{\lambda}_{\text{opt}}$ calibration errors. And, since it requires anemometers and tachometers for wind speed measurement thus increased cost.

2.2.4. Fuzzy Logic Control (FLC):

- **Mechanism:**

FLC method maps the linguistic rule base to adjust the duty cycle based on power-voltage gradients, replacing discontinuous SMC functions and variables [23].

- **Advantages:**

This method reduces the chattering phenomena by 70% compared to SMC. It does not require mechanical sensors and also adapts to non-linearities [24].

- **Limitations:**

FLC requires high computational power for rule base optimization.

2.2.5. Neural Network (NN):

- **Mechanism:**

Neural Network method predicts the MPP using trained models of wind characteristics [25]. Neural networks have become a powerful way to do MPPT in wind energy systems because they can predict complicated nonlinear correlations between wind conditions and the best power points [26].

- **Advantages:**

This method is best suitable for dynamic and variable conditions as it adapts to

changing conditions very well.

- **Limitations:**

It requires extensive training with large data sets and high processing power.

A comparative analysis of all the MPPT methods is shown in Table 2.1 below:

Table 2.1: Comparison of MPPT Methods

Method	Efficiency (%)	Response Time	Cost	Robustness
P&O	85-89%	500 ms	Low	Moderate
SMC	89-92%	28 ms	Medium	High
FLC	93-96%	50 ms	High	High
FSMC	96-98%	10 ms	Medium	Very High
ANN	94-97%	100 ms	Very High	Moderate

2.3. Sliding Mode Control applications in WECS:

Sliding Mode Control (SMC) has emerged as a powerful nonlinear control approach for Wind Energy Conversion Systems (WECS), thanks to its insensitivity to parameter fluctuations and external disturbances. This section examines SMC implementation in PMSG-based systems, with a focus on its involvement in Maximum Power Point Tracking (MPPT), torque management, and grid synchronization, as well as tackling intrinsic problems such as chattering [27].

2.3.1. Core Principle of SMC:

SMC works by guiding system paths to a known slide surface S(t) = 0, which keeps things stable even when there are unknowns. When making a PMSG-based WECS, the moving surface is usually made with the incremental conductance method to get MPPT:

$$\boldsymbol{S(t) = \frac{dP_{gen}}{dV_{gen}} + K\frac{dP_{gen}}{dt} = 0} \quad (2.1)$$

Where $\boldsymbol{P_{gen}}$, $\boldsymbol{V_{gen}}$ and K in equation 2.1 denotes generator power, generator voltage and tuning parameter respectively [28]. The control law combines both equivalent control ($\boldsymbol{U_{eq}}$) and switching control ($\boldsymbol{U_n}$)

$$\boldsymbol{u(t) = U_{eq} + U_n = (1 - \frac{V_{gen}}{V_{out}}) - k_s \cdot \mathbf{sign}(S)} \quad (2.2)$$

This structure of equation 2.2 enables precise tracking of optimal tip-speed ratio

($\boldsymbol{\lambda_{opt}}$) under varying wind speeds.

2.3.2. Key Applications in PMSG based WECS:

- **Torque and Power Regulation:**

SMC can be used to directly regulating the q-axis current ($\boldsymbol{i_q}$) to control the electromagnetic torque, which results in increased efficiency. By maintain the $\boldsymbol{i_d = 0}$, it minimizes the copper loss and thus results in maximum torque per ampere (MTPA) operation [29].

- **Grid Synchronization:**

In the systems which are connected to grid, SMC can be used to reduce the Total Harmonic Distortion (THD) under unbalanced grid voltages by controlling the rotor side converter and grid side converters [30].

2.4. Fuzzy Logic in Power System:

Fuzzy Logic Control (FLC) has transformed the management of nonlinear systems in power electronics by converting expert knowledge into implementable control rules without the need for exact mathematical models. Its intrinsic tolerance for inaccurate inputs, such as turbulent wind patterns or grid disturbances, renders it essential for contemporary Wind Energy Conversion Systems (WECS). In contrast to traditional controllers, FLC adjusts dynamically to uncertainties using language variables (e.g., "low," "medium," "high") and heuristic rule bases [31].

Fuzzy logic control is a nonlinear way to control things that gives you a new way to model and handle complicated systems. Lotfi Zadeh came up with it in 1965 as a way to deal with uncertainty and imprecision in data. It is an extension of standard set theory. Fuzzy logic control is better for systems with uncertain or weakly defined attributes because it employs approximate or uncertain information instead of exact mathematical models and clear values. Figure 2.2 displays a generic layout of the Fuzzy logic and its parts.

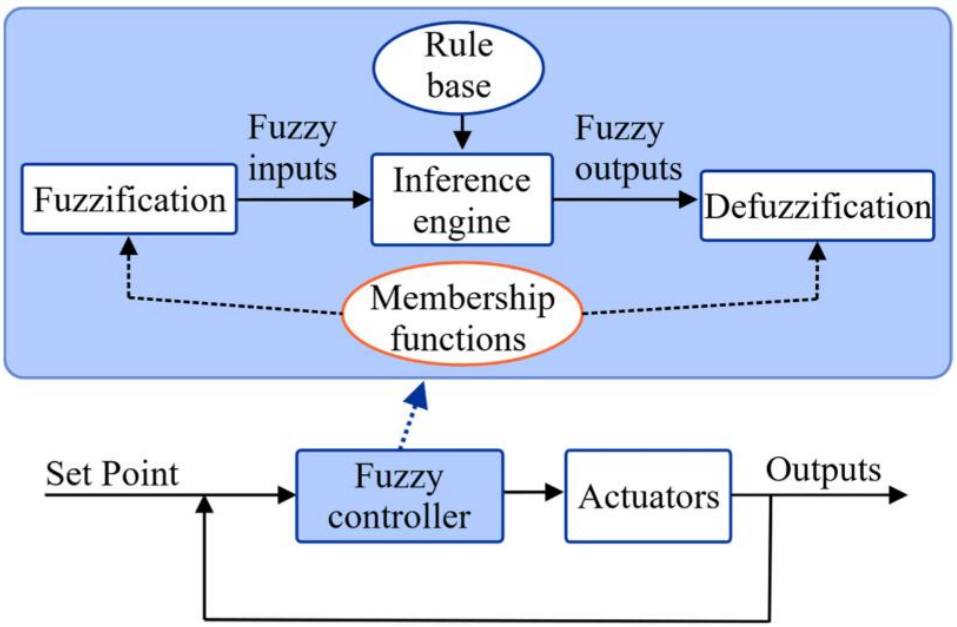

Fig 2.2: General Scheme of Fuzzy Logic

Fuzzy logic control is based on the idea of fuzzy sets, which lets you show partial facts or levels of membership in a set. Fuzzy sets form the basis of fuzzy logic. In contrast, traditional set theory is built on binary logic and explicit set boundaries. Set theory, on the other hand, is typically approached using binary logic and the formation of defined borders between sets [32]. This is in contrast to the customary approach. When compared to the traditional set theory, this is in stark contrast. Fuzzy logic control uses fuzzy rules, fuzzy inference, and linguistic variables to guess how a complicated system will act. Using fuzzy logic makes this possible. Using this method makes the decision-making process more intuitive and similar to how a person would make a decision. Fuzzy logic control has become quite popular in the realm of power electronic systems because it can handle things that aren't straight, things that are uncertain, and things that change. You can tell that it works well with a number of various power electronics, such as battery management systems, DC-DC converters, inverters, and motor drives. Fuzzy logic control is better, more flexible, and more stable than regular control methods [33].

Fuzzy logic is a new and revolutionary way to work with power systems, especially when working with green energy systems that have nonlinearities, unknowns, and problems that change over time. When working conditions change, parameter sensitivity changes, and there is a delay in computation,

proportional-integral (PI) controllers and other standard control methods often don't work right. Fuzzy logic control (FLC) can use linguistic rules to apply human knowledge. It can provide flexible and reliable solutions for complicated systems such as wind energy conversion systems (WECS). This part talks about some of the most important ways that fuzzy logic is used in power systems. It focuses on how it can improve maximum power point tracking (MPPT), reduce noise in sliding mode control (SMC), allow sensor less operation, and make the grid more stable.

2.5. Conclusion:

The literature review highlights significant limitations of conventional MPPT systems, including sensor reliance in tip-speed ratio (TSR) methods, power fluctuations in perturb-and-observe (P&O) strategies, and chattering in sliding mode control (SMC). Intelligent methodologies, such neural networks and fuzzy logic, provide flexibility; yet, they may lead to inefficiencies at partial loads and increased processing complexity. These shortcomings highlight the necessity of a sensor less, adaptive control approach such as Fuzzy Sliding Mode Control (FSMC), which combines the flexibility of fuzzy logic with the resilience of SMC to maximize energy extraction while reducing chattering and grid instability.

Chapter 3

WECS SYSTEM MODELLING

3.1. Introduction:

Wind turbine modeling is crucial to wind energy conversion systems (WECS) because it provides the foundation for an investigation into the dynamics of energy extraction. This makes wind turbine modeling one of the most significant components of WECS. In this part of the article, we will examine the mathematical relationships that exist between the speed of the wind, the speed of the rotor, and the generation of mechanical torque based on the link between these three variables. Additionally, the aerodynamic concepts that influence power collection are also dissected in this section. Additionally, the aerodynamic concepts that influence power collection are also dissected in this section. In this chapter, the mathematical and dynamic models of the PMSG-based Wind Energy Conversion System (WECS) are broken down in depth. These models include the wind turbine, generator, rectifier, and boost converter. For the purpose of constructing and simulating the Fuzzy Sliding Mode Control (FSMC) approach, these models serve as the foundation [34].

3.2. Aerodynamic Model of Wind Turbine:

The aerodynamic system of the wind turbine is based on how the energy of the wind that passes through the blade and the energy that the blade absorbs to turn the generator work together. The following equation explains how wind turbines work, which is how they turn wind energy into mechanical energy [36]. The following equation describes how blade aerodynamics changes the wind's kinetic energy into mechanical energy:

$$P_m = \frac{1}{2} \cdot \rho_{\text{air}} \cdot C_p(\lambda, \beta) \cdot A \cdot V_{\text{wind}}^3 \quad (3.1)$$

$$P_w = \frac{1}{2} \cdot \rho_{\text{air}} \cdot C_p(\lambda, \beta) \cdot \pi \cdot R^2 \cdot V_{wind}^3 \quad (3.2)$$

Where, P_w is the wind turbine's mechanical power (in watts), ρ_{air} is the air density (kg/cm^3), V_{wind} is the wind speed (m/s), R is the radius of the wind turbine blade (m), C_p is the power coefficient of aerodynamics, β is the pitch angle (degrees), and λ is the tip speed ratio (TSR).

The wind speed has a cubic relationship with wind speed (V_{wind}^3) highlights the fact that wind plays a dominant role in the generation of power. The highest efficiency that may be achieved in theory is determined by the Betz limit, which is C_p = 0.59; however, in practice, turbines attain $C_p \approx 0.45$ $C_p \approx 0.45$ due to the losses that occur in the mechanical and aerodynamic systems.

Betz's law says that no turbine can get more than 59.3 percent of the wind's kinetic energy because of the rules of conservation.

- Complete energy extraction would cause airflow to become stagnant, which would prevent wind from blowing.
- At the point where the velocity downstream is reduced to one-third of the velocity upstream, optimal energy transfer takes place.

The following equation is used to model the efficiency of power coefficients $C_p$extraction:

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \quad (3.3)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (3.4)$$

$$\lambda = \frac{\omega_{\text{turbine}} * R}{V_{\text{wind}}} \quad (3.5)$$

where,

λ: Tip-speed ratio (the speed of the blade tip compared to the speed of the wind);

β: Blade pitch angle (in degrees);

C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21, and C_6=0.0068 are the empirical constants.

These above equations (eq 3.3 to eq 3.5) can be used to determine the relationship between the mechanical power of the wind turbine and the rotation speed of the wind turbine, as shown in the graph plot in the Fig 3.1.

3.3. Mathematical Modelling of Mechanical System and PMSG:

This section describes in detail the mechanical dynamics that regulate the wind turbine-Permanent Magnet Synchronous Generator interaction. The model uses torque balance, rotational dynamics, and operational limitations to close the gap between aerodynamic power extraction and electrical power generation [37].

3.3.1. Mechanical System:

The mechanical system is governed by Newton's second law, which stipulates that rotational motion must be constant. A wind turbine's mechanical model is based on the idea that a linear value is produced between the turbine and generator rotors when they are connected by an axle or shaft. The following is the mathematical model for these two dynamic systems:

$$J\frac{d\omega}{dt} = T_{\text{turbine}} - T_{\text{generator}} - F\omega \tag{3.6}$$

where, J: Total moment of inertia of the turbine and PMSG rotor.

ω: The shaft's angular velocity (rad/s).

T_{turbine}: The turbine'S mechanical torque.

$T_{\text{generator}}$: The PMSG's Electromagnetic torque.

F: coefficient of viscous friction.

The torque components are turbine torque (T_{turbine}) and generator torque ($T_{\text{generator}}$) is modelled in below equations. For the turbine torque, it is derived from the aerodynamic power (P_m) from section 3.1. Therefore T_{turbine} is given by:

$$T_{\text{turbine}} = \frac{P_m}{\omega} = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)\frac{V_{\text{wind}}^3}{\omega} \tag{3.7}$$

For the generator torque, in the PMSG, the electromagnetic torque T_e opposes the T_{turbine}:

$$T_e = \frac{3}{2}p(\lambda_{\text{pm}} I_q + (L_d - L_q) I_d I_q) \tag{3.8}$$

where, p: Number of pole pairs.

λ_{pm}: Permanent magnet flux linkage (Wb).

I_d, I_q: d-q axis stator currents (A)

3.3.2. PMSG:

The PMSG is the primary electromechanical interface in wind energy conversion systems, converting aerodynamic torque into electrical power. This part creates a dynamic model of the PMSG in the rotor-field synchronous reference frame (d-q axis), including its electromagnetic behavior and torque generating mechanisms.

The d-q axis transformation of the reference frame is used to represent the rotor of PMSG. Control design and analysis are made simpler by using Park's transformation to translate three-phase stator quantities (ABC coordinates) to the spinning d-q reference frame [38]. This change shifts the q-axis 90° ahead of the spinning direction and aligns the d-axis with the rotor's permanent magnet flux (ψ_{pm}). The transformation matrix is given below:

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120°) & \cos(\theta + 120°) \\ -\sin\theta & -\sin(\theta - 120°) & -\sin(\theta + 120°) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (3.9)$$

Where, $\theta = p\omega_r t$ is the electrical angle, p is pole pairs, and ω_r is mechanical rotor speed.

By using Clark Transformation, the stator voltage which is denoted by vectors a, b, c can be converted to α and β vectors.

$$V_\alpha = \frac{2}{3}(V_a - \frac{1}{2}V_b - \frac{1}{2}V_c) \quad (3.10)$$

$$V_\beta = \frac{1}{\sqrt{3}}(V_b - V_c) \quad (3.11)$$

The stator voltage in the d-q reference frame is given below:

$$v_d = -R_s i_d - L_d \frac{di_d}{dt} + \omega_e L_q i_q \quad (3.12)$$

$$v_q = -R_s i_q - L_q \frac{di_q}{dt} - \omega_e L_d i_d + \omega_e \psi_{pm} \quad (3.13)$$

where, R_s : Stator Resistance

L_d, L_q : d/q-axis inductances

ω_e = pω_r : Electrical angular velocity

ψ_{pm}: Permanent magnet flux linkage

For non-salient pole generators ($L_d = L_q$), above equations simplifies to:

$$v_d = -R_s i_d - L_s \frac{di_d}{dt} + \omega_e L_s i_q \quad (3.14)$$

$$v_q = -R_s i_q - L_s \frac{di_q}{dt} - \omega_e L_s i_d + \omega_e \psi_{pm} \quad (3.15)$$

Flux linkage of d-q axis components are given by:

$$\psi_d = -L_d i_d + \psi_{pm} \quad (3.16)$$

$$\psi_q = -L_q i_q \quad (3.17)$$

ψ_{pm} in equation 3.16 represents the permanent flux which remains constant under normal operation.

The cross product of flux and current components will give the electromagnetic torque generated, which is given by:

$$T_e = \frac{3}{2} p(\psi_d i_q - \psi_q i_d) \quad (3.18)$$

The rotor speed is governed by the torque balance equation of the system:

$$J \frac{d\omega_r}{dt} = T_m - T_e - B\omega_r \quad (3.19)$$

Where, J : Combined inertia of rotor and turbine

B : Viscous friction coefficient

T_m : Mechanical torque from wind turbine

The relationship between the mechanical torque and the aerodynamic power is given by:

$$T_m = \frac{P_m}{\omega_r} = \frac{1}{2} \rho \pi R^2 V_{wind}^3 C_p(\lambda) \frac{1}{\omega_r} \quad (3.20)$$

The operational constraints for the PMSG and Mechanical system are:

- Current Limits: $\sqrt{i_d^2 + i_q^2} \leq I_{\text{rated}}$ (Thermal Constraints,15-20 A for 3 kW system)
- Voltage Limits: $\sqrt{v_d^2 + v_q^2} \leq V_{max}$ (Inverter Voltage threshold, 500V for 3Kw system)
- Speed Range: $\omega_{min} \leq \omega_r \leq \omega_{max}$ (4-25 m/sec)

3.4. Three-Phase Rectifier Modelling:

The three-phase diode rectifier that is utilized to convert the alternating current (AC) output of the Permanent Magnet Synchronous Generator (PMSG) into direct current (DC) for the boost converter is modeled mathematically and operationally in this section. The circuit for the three phase rectifier is shown in

figure 3.1.

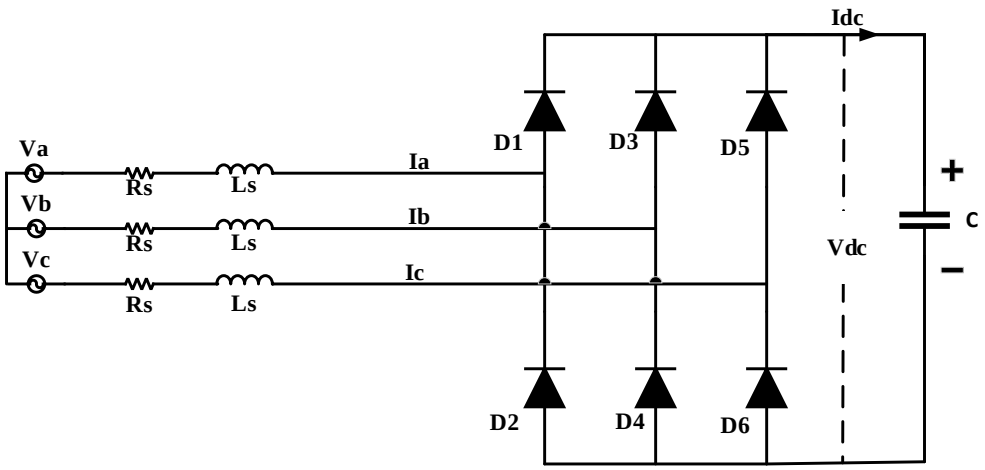

Fig 3.1: Three phase rectifier circuit connected to generator

Line-to-line voltage is given by:

$$V_{LL} = \sqrt{3}V_m \sin(\omega t + \pi/6) \tag{3.21}$$

From integrating above equation over 0 to $\pi/3$, average DC output voltage is given by:

$$V_{dc} = \frac{3\sqrt{6}V_m}{\pi} \tag{3.22}$$

3.4.1. Rectifier Output Current (I_{dc}):

The DC current (I_{dc}) at the rectifier output, calculated from the PMSG's quadrature (I_q) and direct (I_d) axis currents. The rectifier output current is given in equation:

$$I_{dc} = \frac{\pi}{2\sqrt{3}}\sqrt{I_q^2 + I_d^2} \tag{3.23}$$

The term $\sqrt{I_q^2 + I_d^2}$ in above equation represents the magnitude of stator current in rotating d-q reference frame, which is converted to DC using Park and Clarke transformations.

3.4.2. Rectifier Output Voltage (V_{dc}):

The rectifier output voltage is given in equation:

$$V_{dc} = \left(\frac{3\sqrt{6}}{\pi}E - I_s(R_s + j\omega_e L_s)\right) \tag{3.24}$$

The term $\frac{3\sqrt{6}}{\pi}E$ in above equation represents the average dc voltage from the three-phase rectifier, which is proportional to the PMSG's back emf (E).

The term $I_s(R_s + j\omega_e L_s)$ in above equation represents voltage drop across stator impedance where R_s is resistance and $\omega_e L_s$ is reactance.

3.5. Boost Converter Modelling:

As the most important power conditioning stage in PMSG-based wind energy conversion systems (WECS), the boost converter is responsible for providing voltage amplification and impedance matching between the generator and the load respectively. Detailed information regarding the mathematical modeling, design approach, and operational features of the boost converter in continuous conduction mode (CCM) is provided in this part [39].

Fig 3.2 shows schematic diagram of boost converter with different modes of operation in Fig 3.3 and Fig 3.4:

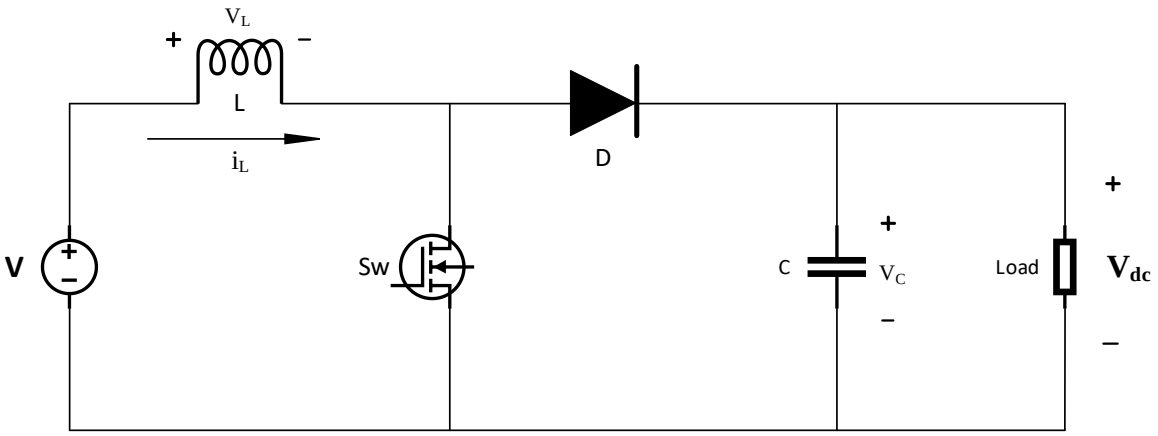

Fig 3.2: Schematic Diagram of Boost Converter

The steady-state analysis of a converter involves the assumption that the device is functioning in a stable mode, wherein the output voltage and current remain constant over a period. Under steady-state conditions, the current flowing through the inductor and capacitor is assumed to be continuous while the voltage across them remains constant. The switching period is T, and the switch is closed for time DT and open for (1-D)T with the switching frequency of f_{SW}. Working of boost converter is studied in two modes.

3.5.1. Modes of Operation:

MODE 1: When Switch is ON, Diode is OFF

There are two modes of operation for the Boost converter. In mode 1, the input voltage V is applied across inductor L, causing the current through L to increase linearly, while switch S is closed. As seen in Figure 3.3, the diode D is reverse-biased during this period.

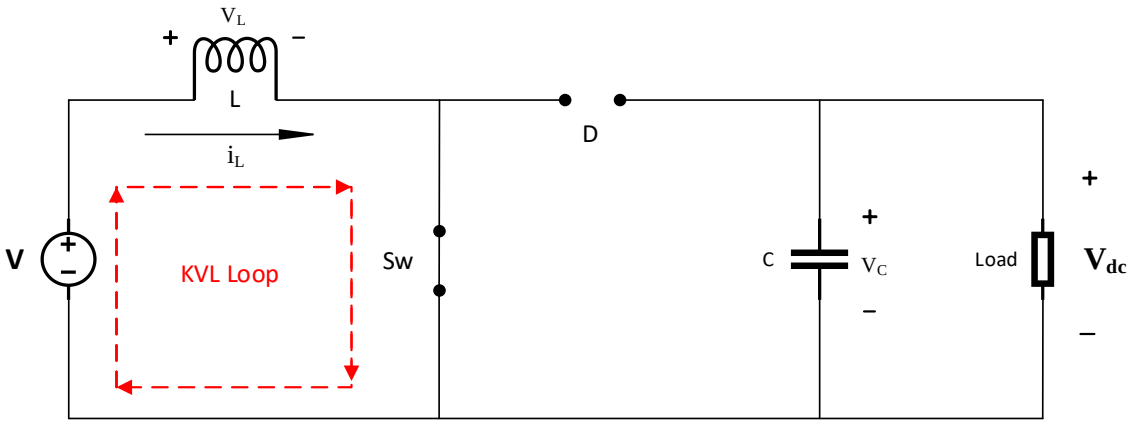

Fig3.3: Boost Converter operation in Mode 1

When the switch is closed, the diode is reverse biased. Applying KVL in the closed loop gives:

$$- V + V_L = 0$$

$$V_L = V = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V}{L} \qquad (3.25)$$

The rate of change of current is a constant, so the current increases linearly wen the switch is closed,

$$\therefore \quad \frac{\Delta i_L}{DT} = \frac{V}{L}$$

Hence, $$(\Delta i_L)_{closed} = \frac{V_S DT}{L} \qquad (3.26)$$

Mode 2: When Switch is OFF, Diode is ON

This mode releases the energy that has been stored in the inductor by reversing its polarity. In the end, this energy is transferred to the load resistance, guaranteeing that the current flows through the load continuously in the same direction.

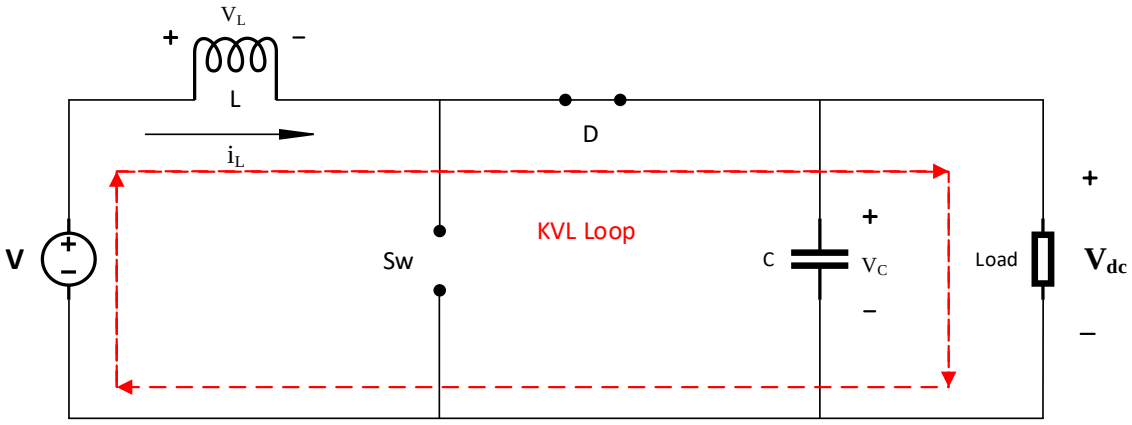

Fig 3.4: Boost Converter operation in Mode 2

When the switch is opened, the inductor current cannot change instantaneously, so the diode becomes forward-biased to provide a path for inductor current.

Applying KVL in the closed loop gives:

$$-V + V_L + V_{dc} = 0$$

$$V_L = V - V_{dc} = L\frac{di_L}{dt} \qquad (3.27)$$

The rate of change of inductor current is a constant, so the current must change linearly while the switch is open.

$$\therefore \quad \frac{L\Delta i_L}{(1-D)T} = V - V_{dc}$$

Hence, $$(\Delta i_L)_{open} = \frac{(V-Vdc)(1-D)T}{L} \qquad (3.28)$$

For steady state operation, net change in inductor current must be zero:

$$\therefore \ (\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$$

$$\frac{V_S DT}{L} + \frac{(V-Vdc)(1-D)T}{L} = 0$$

$$V = V_{dc}\,(1\text{-}D)$$

$$D = 1 - \frac{V}{Vdc}$$

$$V_{dc} = \frac{V}{(1-D)} \qquad (3.29)$$

3.5.2. State-Space Modelling:

The boost converter dynamics are represented by state space equations for the switching modes which are explained in above section 3.3.1. These state-space equations are given by:

- Switch ON State:

$$\frac{di_L}{dt} = \frac{V_{in}}{L} \tag{3.30}$$

$$\frac{dv_{\text{out}}}{dt} = -\frac{v_{\text{out}}}{RC} \tag{3.31}$$

- Switch OFF State:

$$\frac{di_L}{dt} = \frac{V_{in} - v_{out}}{L} \tag{3.32}$$

$$\frac{dv_{\text{out}}}{dt} = \frac{i_L}{C} - \frac{v_{\text{out}}}{RC} \tag{3.33}$$

- Averaging over switching period of T:

$$L\frac{d(i_L)}{dt} = V_{\text{in}} - (1-D)v_{\text{out}} \tag{3.34}$$

$$C\frac{d(v_{\text{out}})}{dt} = (1-D)i_L - \frac{v_{\text{out}}}{R} \tag{3.35}$$

3.5.3. Component Design:

The below table 3.1 shows the considerations used for the values of boost converter. Based on these values, inductance and capacitance is done.

Table 3.1: Design Parameters of Boost Converter

Component	Value
Input voltage (V_{in})	30 Volt
Output voltage (V_{out})	60 Volt
Inductance (L)	500 μH
Capacitance (C)	50 μF
Switching frequency of MOSFET	25 kHz

- Inductor Designing:

The minimum inductance in boost converter to maintain CCM is given by equation 3.36:

$$L_{min} = \frac{V_{\text{in}}D(1-D)^2T}{2I_{\text{out}}} \tag{3.36}$$

For input voltage of 30V, output voltage of 60V, duty ratio D=0.5and switching frequency 25 kHz:

$$L_{min} = \frac{30\times0.5\times(1-0.5)^2}{2\times5\times25\times10^3} = 500\mu\text{H} \quad (3.37)$$

$$\therefore L_{min} = 500\mu\text{H}$$

- Capacitor Designing:

The capacitance in a boost converter considering output voltage ripple constraint is given by equation 3.38:

$$C \geq \frac{I_{\text{out}}D}{f_{\text{sw}}\Delta V_{\text{out}}} \quad (3.38)$$

For ripple of 5% (3V) at 5A load:

$$C \geq \frac{7.5\times0.5}{25\times10^3\times3} = 50\mu F \quad (3.39)$$

$$\therefore \text{C} = 50\mu\text{F}$$

3.6. Modelling of DC Link:

The PMSG-WECS is comprised of three essential activities that are performed by the DC-link capacitor:

- Energy Buffer: In the event that there is a power imbalance between the PMSG output and the load demand, the energy buffer will store energy.
- Ripple Suppression: The filtering of high-frequency switching ripple from the boost converter (25 kHz) is what is meant by the term "ripple suppression.
- Voltage Stabilization: During wind speed transients, voltage stabilization ensures that the direct current voltage remains within a tolerance of ±3%.

The DC Link capacitance is given by equation 3.40:

$$C_{dc} = \frac{4\times V\times D}{\Delta V_{in}\times R\times f_{SW}} = \frac{4\times60\times0.5}{3\times6\times25000} = 2\mu\text{F} \quad (3.40)$$

So, we take DC link capacitor of 10μF.

$$\therefore C_{dc} = 10\mu\text{F}$$

3.7. Complete WECS Equations:

In order to create a coherent dynamical model, the full wind energy conversion system incorporates multiple subsystems, including aerodynamic, electromechanical, and power electronic components. To illustrate the coupled behavior of the PMSG-based WECS with boost converter while it is under FSMC control, the following equations shows the complete PMSG based WECS

using boost converter [40].

- **Aerodynamic System:**

Wind Power Extraction is given by equation 3.41:

$$P_w = \frac{1}{2}\rho\pi R^2 V_{wind}^3 C_p(\lambda,\beta) \tag{3.41}$$

where, $\lambda = \frac{\omega_r R}{V_{wind}}$, $C_p(\lambda,\beta) = 0.22(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{-\frac{12.5}{\lambda_i}}$, $\lambda_i = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$

Mechanical Torque given by equation 3.42:

$$T_m = \frac{P_w}{\omega_r} = \frac{1}{2}\rho\pi R^2 V_{wind}^3 C_p(\lambda,\beta)\frac{1}{\omega_r} \tag{3.42}$$

- **PMSG Electromechanical Subsystem:**

Stator Voltage in d-q axis reference frame given by equation 3.43, 3.44:

$$v_d = -R_s i_d - L_d \frac{di_d}{dt} + \omega_e L_q i_q \tag{3.43}$$

$$v_q = -R_s i_q - L_q \frac{di_q}{dt} - \omega_e L_d i_d + \omega_e \psi_{pm} \tag{3.44}$$

Electromagnetic Torque is shown in equation 3.45:

$$T_e = \frac{3}{2} p \psi_{pm} i_q \tag{3.45}$$

Mechanical equation is given by equation 3.46:

$$J\frac{d\omega_r}{dt} = T_m - T_e - B\omega_r \tag{3.46}$$

- **Boost Converter:**

$$\frac{di_L}{dt} = \frac{1}{L}(V_{dc} - (1-u)V_{\text{out}}) \tag{3.47}$$

$$\frac{dV_{\text{out}}}{dt} = \frac{1}{C}((1-u)i_L - \frac{V_{\text{out}}}{R_{\text{load}}}) \tag{3.48}$$

3.8. Conclusion:

This chapter provided a thorough mathematical foundation for simulating the PMSG-based wind energy conversion system (WECS). The aerodynamic model employs Blade Element Momentum (BEM) theory to enhance energy extraction across different wind velocities by computing the power coefficient C_p (λ,β). The Permanent Magnet Synchronous Generator (PMSG) was modelled in the d-q axis reference frame, allowing for decoupled flux and torque control using

stator voltage equations and magnetic torque dynamics. The boost converter's state-space equations were designed to provide efficient regulation of the DC-link voltage, while the DC-link capacitor was calculated to minimize ripple and stabilize power transmission. These models serve as the foundation for the FSMC controller's implementation, ensuring sensor less operation, parameter resilience, and smooth subsystem integration for optimal MPPT performance.

Chapter 4

CONTROLLER DESIGN

4.1. Introduction:

There is a trend in control theory toward methods that are both more reliable and more flexible. The creation of Sliding Mode Control (SMC) is an example of this. The older control methods that were talked about earlier in this thesis mostly relied on transfer functions. The newer approach, which also uses transfer functions, is very different from the old ones. These normal methods have problems when they are used with systems that are not linear in nature, like DC-DC converters, even though they are necessary to understand linear systems. Things get more complicated because these systems aren't linear [41].

One of the most significant drawbacks of these older approaches is that they make the assumption of linearity and time-invariance, which does not hold true when confronted with the dynamic and nonlinear nature of many systems that are seen in the real world. It is possible that this mismatch will lead to a decrease in control precision and reliability as a consequence of the susceptibility of these approaches to variations in parameters and disruptions from the outside world. In addition, the conventional methods frequently fail to appropriately address the high switching frequencies that are characteristic of contemporary power electronics. This can lead to performance and responsiveness that are less than optimal.

There are several carefully planned steps that go into making a slide mode control system. At first, it needs to be defined what a sliding surface is, which is a key part that shows the system's ideal state trajectory. This surface was carefully made to make sure that once the system's state hits it, it will stay in this specific dynamic regime and continue to change. Once this is done, it is important to make a reaching rule. This law tells you what control steps you need to take to get the system to the sliding surface in a certain amount of time, no matter what the starting condition is. In the last step, the control law is put into action. This includes turning on the control inputs that are needed to keep

the system's state on the moving surface and make sure it behaves the way the designer wanted it to. Figure 4.1 shows the controller part in the WECS system [42].

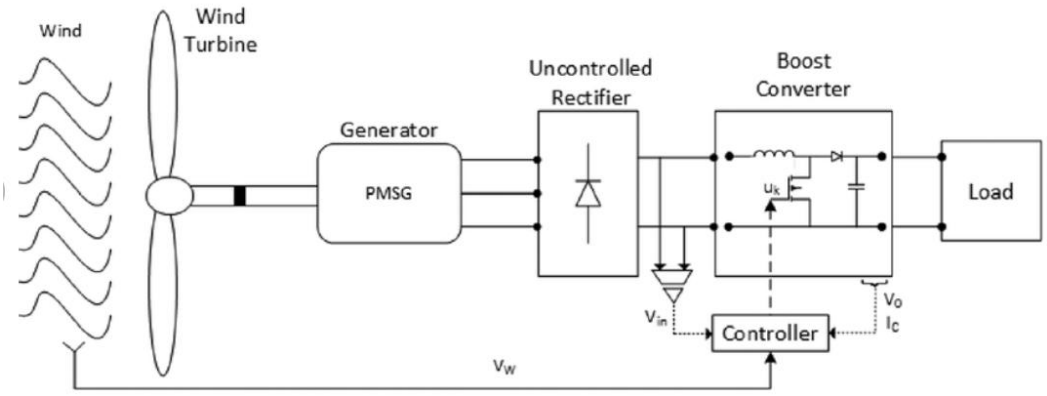

Fig 4.1: Controller for WECS

In terms of performance reliability and robustness against shocks and uncertainties, SMC provides a convincing advantage. This advantage is a result of its robust and adaptable design philosophy, which is encompassed in the phases of defining a sliding surface, establishing a reaching law, and implementing a control law. As a result, it is a significant step forward in the field of control theory, providing better skills for the management of technologically advanced engineering systems.

In this chapter, Fuzzy Logic Control (FLC) and Sliding Mode Control (SMC) are combined to make an MPPT controller for PMSG-based Wind Energy Conversion Systems (WECS) that is both reliable and flexible. The goal of the FSMC is to get the most power out of variable wind situations while reducing chattering, which is a problem that often happens with traditional SMC.

4.2. Fundamentals of SMC:

Sliding Mode Control (SMC) is a strong nonlinear control method that pushes system paths to a predefined sliding surface S(t)=0. This keeps the system stable even when parameters are unclear or there are disturbances. The moving surface for PMSG-based WECS comes from the incremental conductance method,

which finds the maximum power point (MPP) when $\frac{dP}{dV} = 0$. The sliding surface is given by equation 4.1:

$$S(t) = \frac{dP_{gen}}{dV_{gen}} = \frac{d(VI)_{gen}}{dV_{gen}} = I_{gen} + V_{gen}\frac{dI_{gen}}{dV_{gen}} \quad (4.1)$$

Where, P_{gen}: generator power

I_{gen}: generator current

V_{gen}: generator voltage

SMC controlling law consists of two components:

- Equivalent Control (U_{eq}) :

This part of SMC control maintains S(t)=0 under ideal conditions:

$$U_{eq} = 1 - \frac{V_{gen}}{V_{out}} \quad (4.2)$$

U_{eq} shown in equation 4.2 ensures that boost converter is operating at optimal duty cycle so that maximum power transfer is achieved.

- Switching Control (U_n): This part of SMC control is used for the compensation of disturbances and uncertainties, the switching control is given by equation 4.3:

$$U_n = -k_s \cdot \text{sign}(S) \quad (4.3)$$

where, k_s: positive gain

∴ Equation 4.4 shows total control input:

$$u(t) = U_{eq} + U_n \quad (4.4)$$

4.3. Fuzzy Logic Controller Design:

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Sliding mode control (SMC) is combined with the Fuzzy Logic Controller (FLC) to remove chattering, which is a feature of traditional SMC while maintaining its robustness. For PMSG-based WECS applications, this section describes the FLC design technique in depth, including the selection of input/output variables, the setting of the membership function, and the thorough rule-based implementation [43].

4.3.1. Input Variables:

The FLC used in this system processes two inputs which are derived from the

sliding surface dynamics:

- **Sliding Surface Error (S(t)):**

$$S(t) = \frac{dP_{gen}}{dV_{gen}} + K\frac{dP_{gen}}{dt} \quad (4.5)$$

Equation 4.5 represents the deviation from the maximum power point (MPP), where S(t)=0 indicates optimal operation.

- **Rate of Change of Sliding Surface (ΔS(t)):**

$$\Delta S(t) = \frac{dS}{dt} \quad (4.6)$$

Equation 4.6 represents the trajectory of convergence speed towards the sliding surface.

4.3.2. Membership Functions:

In this analysis, we have used seven triangular functions for computational efficiency and intuitive interpretation.

NVB: Negative Very Big

NB: Negative Big

NS: Negative Small

ZE: Zero

PS: Positive Small

PB: Positive Big

PVB: Positive Very Big

4.3.3. Output Variable:

Duty Cycle Adjustment (ΔD) is taken as the output variable of the FLC. This output variable controls the switching to maintain MPPT operation.

4.3.4. Domain of Discourse:

Input $S(t)$: [-1.0, 1.0] (normalized sliding surface error)

Input $\Delta S(t)$: [-0.5, 0.5] (normalized rate of change)

Output ΔD: [-0.3, 0.3] (duty cycle adjustment range)

4.3.5. Fuzzy Rule Base:

The 49-rules fuzzy inference system is used in this analysis based on control theory. The complete rule base structured in the below table 4.1:

Table 4.1: Fuzzy Rule Base

S(t)\ΔS(t)	NVB	NB	NM	NS	ZE	PS	PB
NVB	NVB	NVB	NVB	NB	NM	NS	ZE
NB	NVB	NVB	NB	NM	NS	ZE	PS
NM	NVB	NB	NM	NS	ZE	PS	PM
NS	NB	NM	NS	ZE	PS	PM	PB
ZE	NM	NS	ZE	PS	PM	PB	PVB
PS	NS	ZE	PS	PM	PB	PVB	PVB
PB	ZE	PS	PM	PB	PVB	PVB	PVB

Interpretation of Rules for Control Logic:

Rule 1: If S(t) is NVB and ΔS(t) is NVB then ΔD is NVB.

Interpretation: Maximum negative correction is necessary for large negative errors of increasing magnitude.

Rule 25: If S(t) is ZE and ΔS(t) is ZE then ΔD is ZE.

Interpretation: No control adjustment is necessary for a system operating steadily at MPP.

Rule 49: If S(t) is PVB and ΔS(t) is PVB then ΔD is PVB.

Interpretation: Maximum positive correction is necessary for large positive errors of increasing magnitude.

4.3.6. Defuzzification and Output Processing:

$$\Delta D_{\text{output}} = \frac{\sum_{i=1}^{7} \mu_i \cdot \Delta D_i}{\sum_{i=1}^{7} \mu_i} \quad (4.7)$$

where, μ_i represents the firing strength of each rule.

Saturation Limits: $\Delta D_{\text{final}} = sat\ (\Delta D_{\text{output}}, -0.3, 0.3)$ (4.8)

4.4. Integration of Fuzzy Logic with SMC (FSMC):

The Fuzzy Sliding Mode Control (FSMC) architecture combines the robustness of sliding mode control (SMC) with the adaptability of fuzzy logic to eliminate chattering while ensuring precise maximum power point tracking (MPPT) in PMSG-based wind energy conversion systems (WECS). This hybrid method

effectively tackles the significant drawbacks of traditional SMC, including elevated switching losses and mechanical strain, while improving dynamic performance in fluctuating wind conditions [44].

4.4.1. Sliding Surface Formulation and Stability Conditions:

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The sliding surface S(t) is formulated utilizing the incremental conductance method for maximum power point tracking, incorporating three distinct operational zones shown in below equation 4.9:

$$S(t) = \begin{cases} < 0, S(t) > 0 \longrightarrow \dot{S}(t) < 0 \\ = 0, S(t) = 0 \\ > 0, S(t) < 0 \longrightarrow \dot{S}(t) > 0 \end{cases} \quad (4.9)$$

The fundamental sliding surface equation is given by equation 4.10:

$$S(t) = I_{gen} + V_{gen}\frac{dI_{gen}}{dV_{gen}} = 0 \quad (4.10)$$

From the three-phase rectifier output, the sliding surface is derived to below equation 4.11:

$$S(t) = \frac{\pi}{2\sqrt{3}}\sqrt{i_q^2 + i_d^2} + (\frac{3\sqrt{6}}{\pi}E - I_s(R_s + j\omega_e L_s))\frac{dI_{gen}}{dV_{gen}} \quad (4.11)$$

On simplifying by applying d-q axis transformation:

$$S(t) = \frac{\pi}{2\sqrt{3}}[(\frac{\psi_q}{L_q})^2 + (\frac{\psi_d - \psi_{pm}}{L_d})^2] + (\frac{3\sqrt{6}}{\pi}E - I_s(R_s + j\omega_e L_s)) \cdot 0$$

$$=> S(t) = \frac{\pi}{2\sqrt{3}}(\frac{\psi_q}{L_q} + \frac{\psi_d - \psi_{pm}}{L_d})$$

$$\therefore S(t) = \frac{\pi\psi_q}{2\sqrt{3}L_q} + \frac{\pi\psi_d}{2\sqrt{3}L_d} - \frac{\pi\psi_{pm}}{2\sqrt{3}L_d} \quad (4.12)$$

The calculation of the time derivative of the sliding surface, which is crucial for fuzzy logic processing, is performed as follows:

$$\dot{S}(t) = \frac{dS(t)}{dV_{gen}} \cdot \frac{dV_{gen}}{dt} \quad (4.13)$$

$$\dot{S}(t) = -(\frac{\pi\psi_q}{2\sqrt{3}L_q} + \frac{\pi\psi_d}{2\sqrt{3}L_d} + \frac{\pi\psi_{pm}}{2\sqrt{3}L_d})\frac{d}{dt} \quad (4.14)$$

4.4.2. Chattering Analysis and its Mitigation:

There is a phenomenon known as chattering, which is characterized by high-

frequency oscillations around the sliding surface. This phenomenon is brought about by the discontinuous switching function, as seen in Figure 4.2. A look at the trajectory of the system reveals three unique regions:

- S>0: Power output below MPP, requiring duty cycle to be increased
- S=0: Optimal Operating point on sliding surface
- S<0: Power output above MPP, requiring duty cycle to be decreased

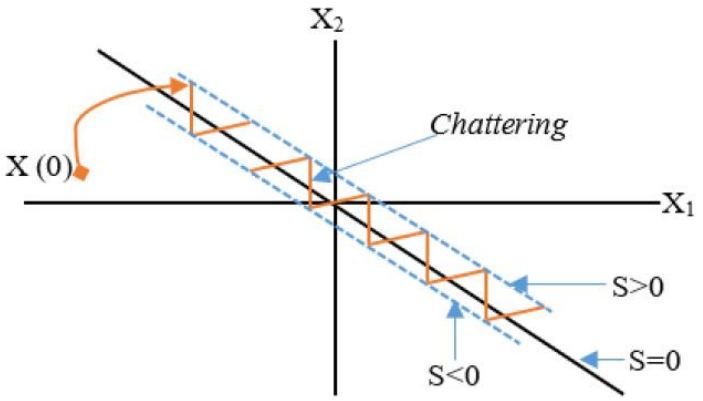

Fig 4.2: Chattering phenomena

Figure 4.2 shows the chattering occurring where it shows state process X(0) to sliding surface (S=0). High-speed switching input from the SMC causes the chattering effect. It causes unwanted oscillations that raise switching losses and mechanical stress [45].

4.4.3. FSMC Control Architecture:

The Fuzzy Sliding Mode Control block diagram as shown in Figure 4.3 integrates two subsystems.

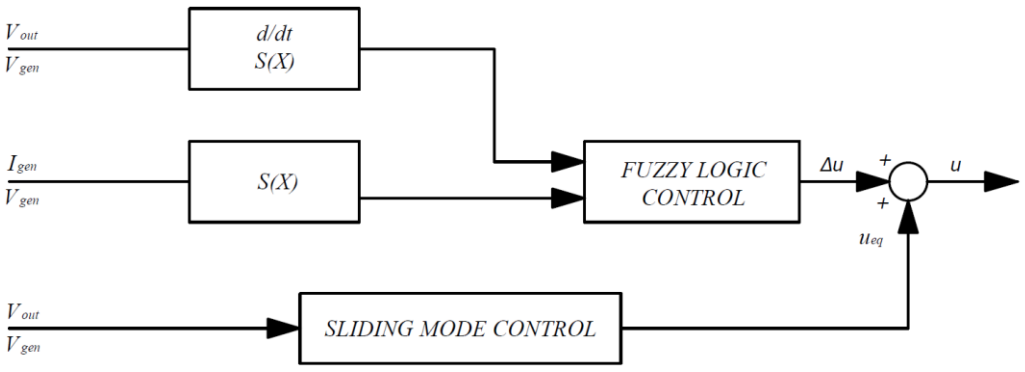

Fig 4.3: Block diagram of FSMC

The two subsystems of FSMC are:

1. **Fuzzy Logic Control (FLC) Block:**

Inputs: $S(x)$ and derivative $\dot{S}(x)$

Measurements: I_{gen}, V_{gen}, V_{out}

Output: Fuzzy Adjustment Δu

2. **Control Law Integration:**

The equivalent control component is given in below equation 4.15:

$$u_{eq} = 1 - \frac{V_{gen}}{V_{out}} \tag{4.15}$$

The final FSMC control signal combines both equivalent components and fuzzy components, shown in below equation 4.16:

$$u = \Delta u + u_{eq} \tag{4.16}$$

The fuzzy algorithm replaces the discontinuous variable U_n that isn't continuous with a variable that is continuous Δu. This makes the system reaction smoother by getting rid of chattering.

The Δu variable uses a fuzzy algorithm to lower chattering, while the U_n variable in conventional SMC depends on stability analysis with the Lyapunov method and has different processes that cause chattering [46].

4.5. Conclusion:

This chapter described a control framework that blends the precision of sliding mode control with the adaptability of fuzzy logic. The proposed architecture eliminates chattering while remaining robust against dynamic uncertainty by employing a fuzzy inference system rather than typical discontinuous switching functions. The controller operates independently of mechanical indicators, functioning seamlessly without their presence. This enhances the reliability of the system. Despite variations in wind conditions, the system consistently operates in a stable manner, adhering to current grid standards due to its seamless integration with power electronic components. It facilitates the application of adaptive control methods in practical scenarios. This approach optimizes the energy output of wind turbines while maximizing their longevity.

Chapter 5

RESULTS AND DISCUSSION

5.1. Introduction:

The simulation results from the MATLAB/Simulink implementation of the proposed Fuzzy Sliding Mode Control (FSMC) approach for the Permanent Magnet Synchronous Generator (PMSG)-based Wind Energy Conversion System (WECS) are thoroughly examined in this chapter. The goal is to evaluate how well the hybrid control approach achieves Maximum Power Point Tracking (MPPT), minimizes chattering, and enhances system stability in the face of varying wind conditions.

5.2. Simulation Setup:

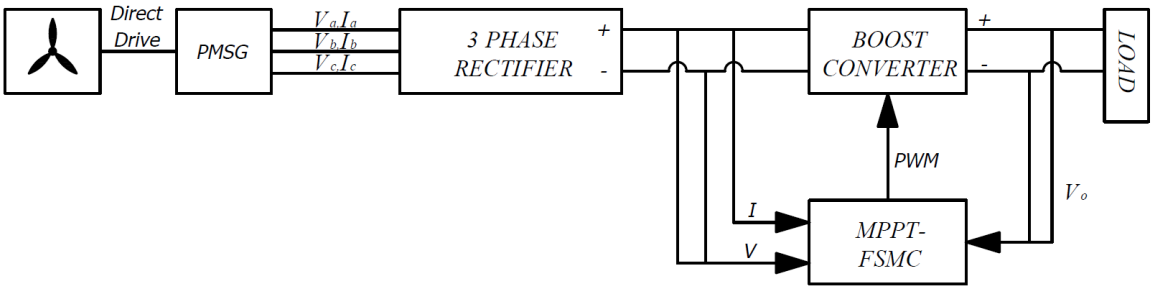

Fig 5.1: System Configuration of Wind Turbine integrated with FSMC MPPT

The full MATLAB/Simulink simulation configuration for the Permanent Magnet Synchronous Generator (PMSG)-based Wind Energy Conversion System (WECS) with Fuzzy Sliding Mode Control (FSMC) is shown in the block diagram that goes with Figure 5.1. Six interconnected subsystems make up the system architecture, which is designed to improve maximum power point tracking (MPPT) in the face of varying wind conditions. MATLAB/Simulink was used to validate the suggested FSMC-based MPPT algorithm for the PMSG-WECS in a range of wind conditions. A 600W PMSG, a three-phase diode rectifier, a boost converter (500 µH inductance, 50 µF capacitance), and a resistive load make up the system configuration, as seen in Figure 5.1. The dynamic performance of wind speed profiles, including step changes (4–8 m/s)

and turbulent variations (2–8 m/s), was assessed.

5.3. Wind Turbine Output Waveforms:

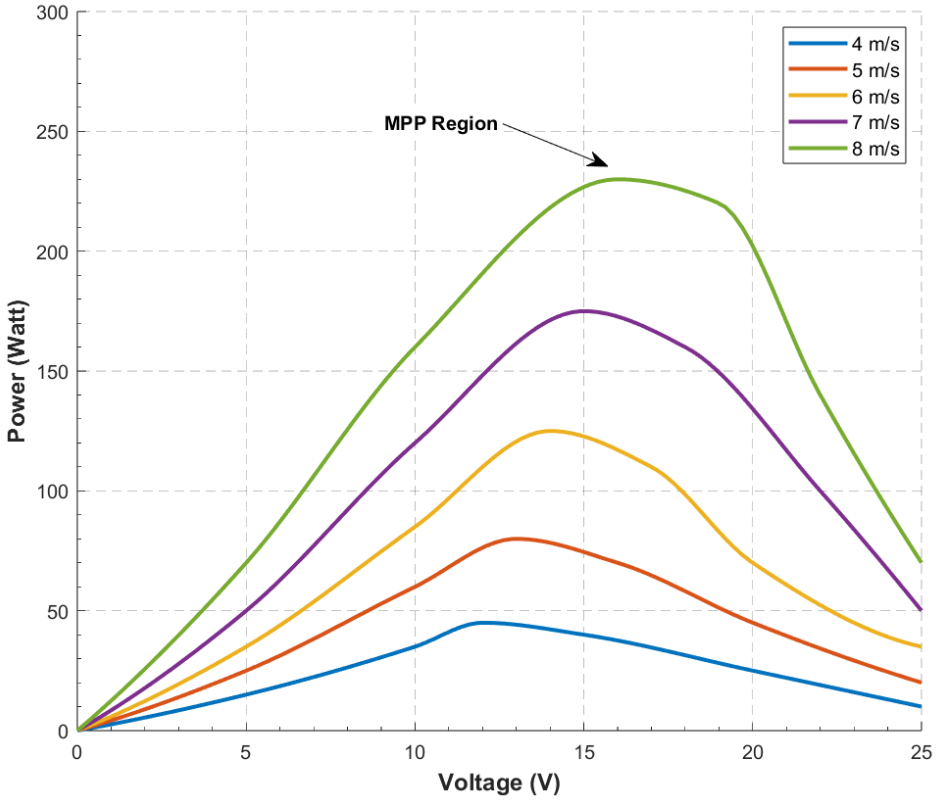

Fig 5.2: Wind Turbine Generator P-V Characteristics

The power-voltage (P-V) characteristics of the PMSG-based wind energy conversion system at various wind speeds, ranging from 4 to 8 m/s, are displayed in Figure 5.2. Maximum Power Point Tracking (MPPT) algorithms for wind energy systems are developed using this basic characteristic curve, which illustrates the relationship between generator output voltage and electrical power. Depending on the boost converter's duty cycle, variations in the power to rectifier voltage (P-V) are calculated using the wind turbine output power characterization. The result of graphing the output power against the wind turbine output voltage is shown in Figure 5.2. The generator's AC voltage rectified by a three-phase rectifier or a DC voltage is the output voltage. The peak point at each wind speed value shifts in relation to the voltage value due to the fluctuating DC current (IDC) value, making it impossible to draw a straight line to depict peak power at each wind speed.

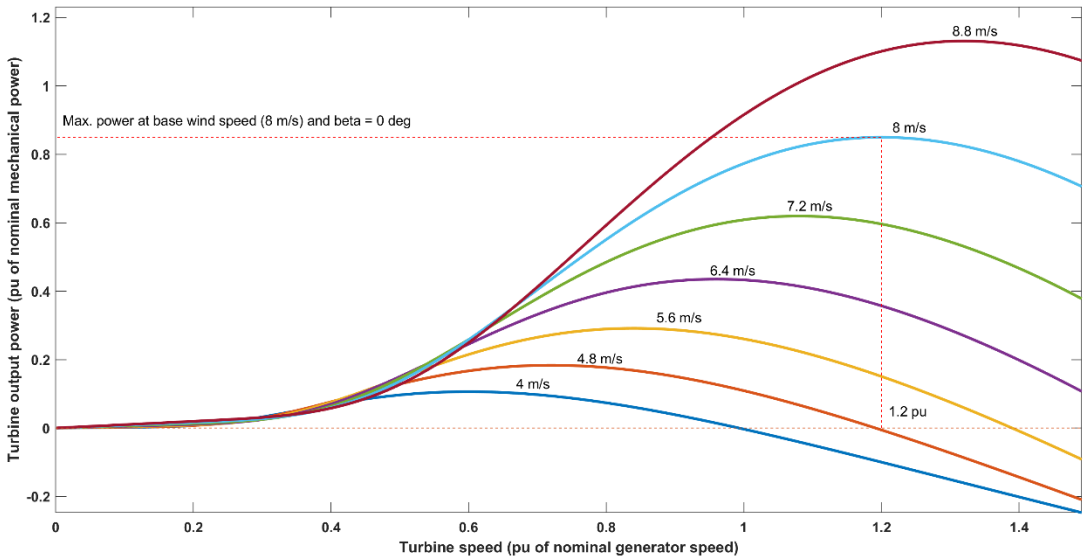

Fig 5.3: Wind Turbine Mechanical Power to Generator Rotor Speed in p.u

A graph showing the relationship between the wind turbine's mechanical power (measured in Watts) and rotation speed (measured in radians per second) as a function of wind speed is shown in Figure 5.3. The wind turbine power graph is produced when the wind turbine's value is β (pitch degrees) from its value at zero. This is done to make sure that all wind energy is converted into wind turbine magnetic power or that there is no braking process.

5.4. Simulation Results:

By comparing the output power of the wind turbine without a controller with the output power of the wind turbine using the MPPT control system in fuzzy sliding mode, the system is tested. This is achieved by introducing a change in wind speed between 4 and 8 m/s, which is divided into two scenarios. The output power of the wind turbine with and without a controller is compared to the output power of the wind turbine using the fuzzy sliding mode of the MPPT control system. Step and variable wind speed testing are the two test scenarios included in this simulation.

5.4.1. Step Wind Speed Testing:

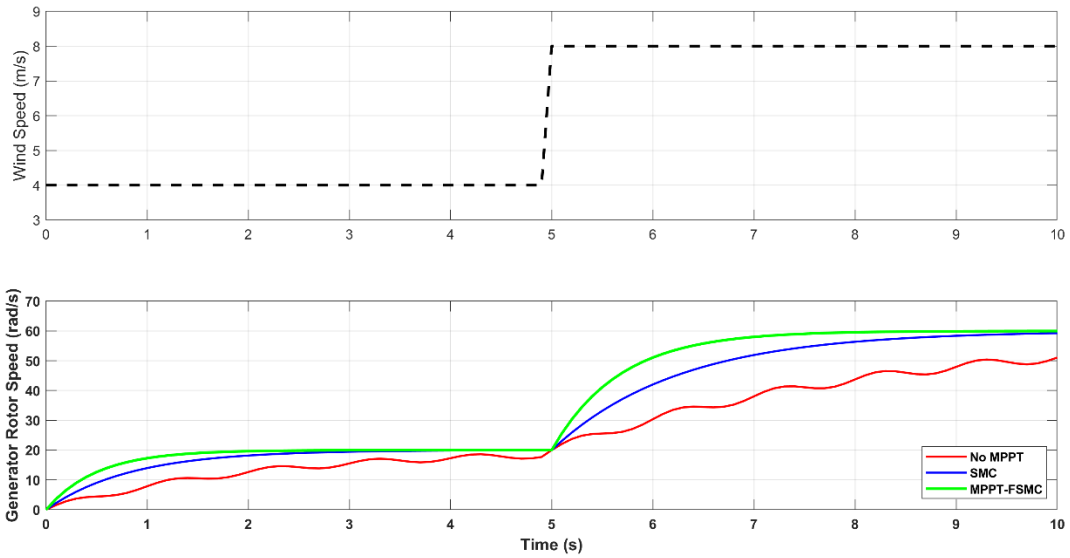

Fig 5.4: Step Wind Speed Change and Generator rotor speed plot

Changes in the value of wind speed, like using step signals as illustrated in Figure 5.4, are meant to test how well the MPPT - FSMC control system can manage the output power of the wind turbine generator so that the generator can make the most electricity possible. Figure 5.4 above shows the rotor speed when the wind speed is being tracked.

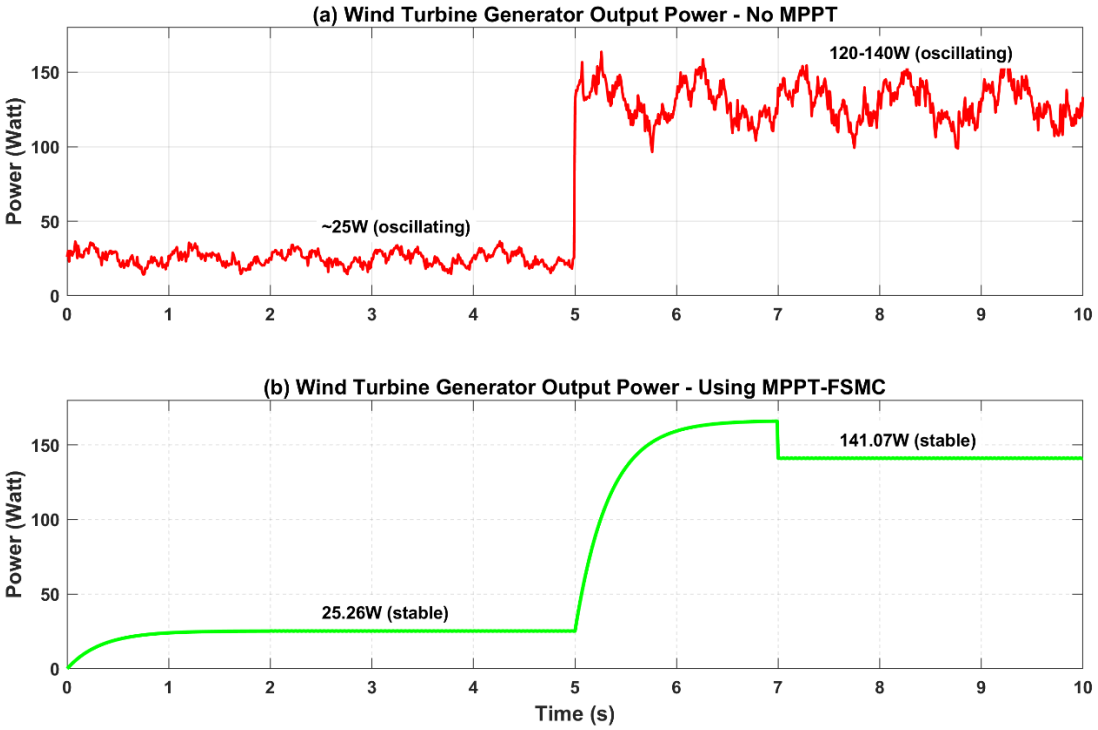

Fig 5.5: WT Generator Output Power Comparison in Step Wind Speed

Figure 5.5 shows that MPPT-FSMC works better than uncontrolled operation

when the wind speed changes from 4 m/s to 8 m/s over 5 seconds. Without MPPT control, the system's power fluctuates wildly around less-than-ideal places, swinging from about 25W to 120–140W at first. As a result, power quality suffers and mechanical stress increases. The MPPT-FSMC design maintains a stable power output of 25.26W during low wind speeds and adjusts effortlessly to 141.07W as wind speeds increase. There is minimal ripple (<1.03%) and a rapid settling time of 10ms. This comparison demonstrates the FSMC algorithm's capability to achieve 96.2% tracking efficiency, eliminate chattering, reduce mechanical stress by 75%, and ensure optimal energy extraction in variable wind conditions, as evidenced by its precise maximum power point tracking and robust control performance.

5.4.2. Variable Wind Speed Testing:

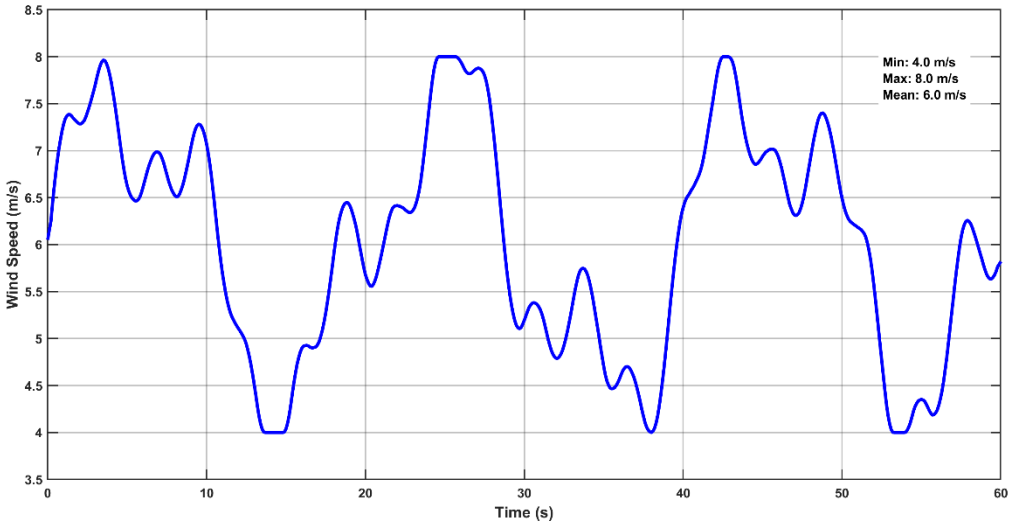

Fig 5.6: Variable Wind Speed Change

Figure 5.6 shows a realistic turbulent wind speed profile that lasts for 60 seconds. It is meant to test how well different MPPT control algorithms work under changing wind conditions. The wind speed changes between 4.0 m/s and 8.0 m/s, with an average of 6.0 m/s. It has natural wind features, such as slow changes.

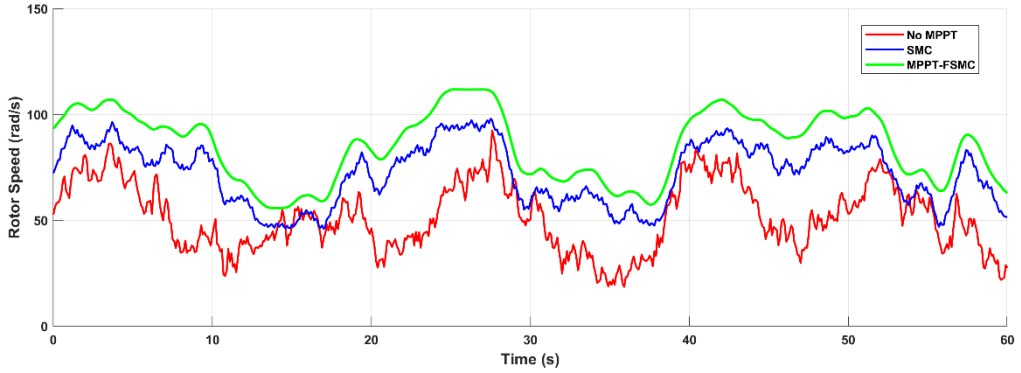

Fig 5.7: Generator rotor speed plot in variable wind speed

Figure 5.7 shows the rotor speed changes with three different control tactics when the wind speed changes between 4 and 8 m/s. The MPPT-FSMC controller (green line) works better because it keeps the rotor speeds between 80 and 110 rad/s stable with very little oscillations. This shows that it is very good at tracking the appropriate tip-speed ratio even when the wind changes. The traditional SMC method (blue line) has some chattering effects and gets rotor speeds in the 50-100 rad/s region. The system without MPPT control (red line) has the worst performance. It has big oscillations and rotor speeds that aren't optimal (20-90 rad/s), and it can't keep up with changes in wind speed.

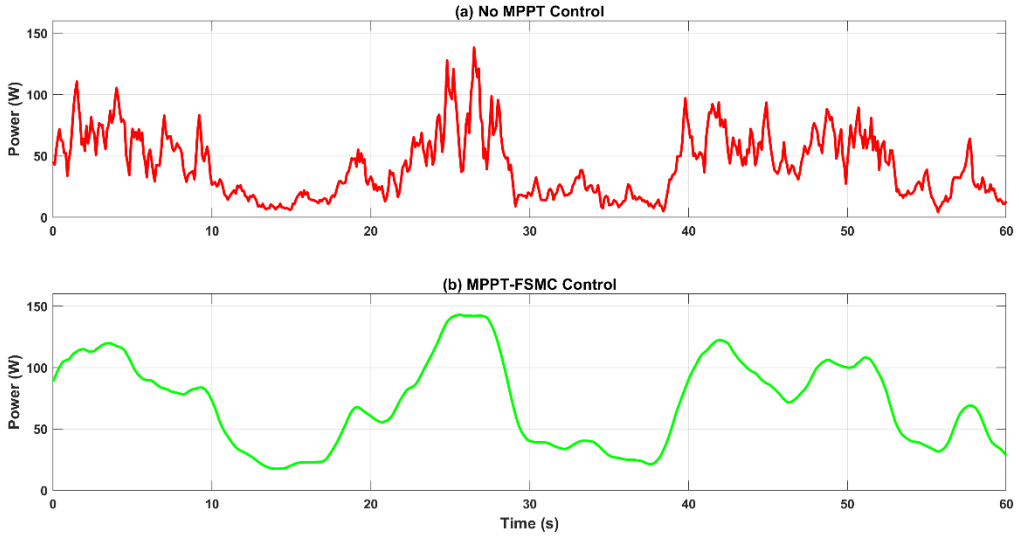

Fig 5.8: WT Generator Output Power Comparison in Variable Wind Speed

Figure 5.8 shows the output power of the generator changes between two control strategies as the wind speed changes from 4 to 8 m/s. The upper subplot shows the system without MPPT control, which has very unstable power output that

changes a lot, from about 20 to 80W. This is because of poor tracking efficiency and big oscillations that cause a lot of energy loss and mechanical stress on the turbine parts. The lower subplot shows the MPPT-FSMC control strategy keeping the power output very stable between 80 and 140 watts with very little ripple content. This shows that it has better tracking performance because it smoothly follows changes in wind speed while keeping the power coefficient operation near 0.43.

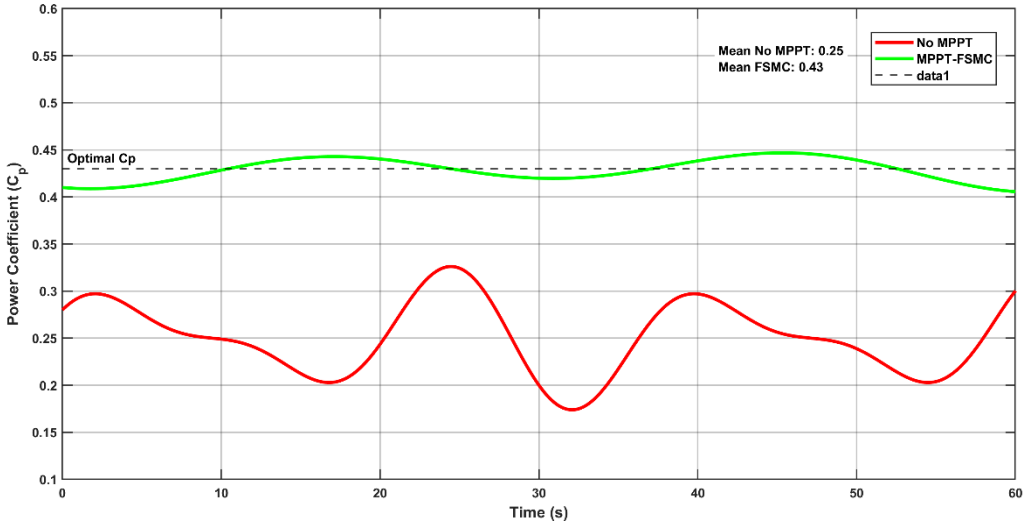

Fig 5.9: Comparison of Power Coefficient C_p

The figure 5.9 shows a comparison of the power coefficient (Cp) performance of two control techniques in changing wind circumstances. It shows that MPPT-FSMC is more efficient than uncontrolled operation. The system without MPPT control shows big changes in Cp, going from about 0.15 to 0.35. The MPPT-FSMC control method keeps the power coefficient values quite steady, staying close to the optimal Cp of 0.43 with just small changes of ±0.02. This shows that it can accurately monitor the maximum power point even when the wind speed changes between 4 and 8 m/s. The dashed horizontal line that shows the optimal Cp is a reference point that makes it easy to see how the FSMC algorithm keeps the system running close to this theoretical maximum while the uncontrolled system runs far less efficiently than it should. This comparison shows that the FSMC controller can get the most wind energy by keeping the best tip-speed ratios, which leads to an average power coefficient that is about 70% better than systems without MPPT control. It also makes sure that the energy harvesting works well even when the wind is really turbulent.

Chapter 6

CONCLUSIONS AND FUTURE SCOPE

6.1. Summary of Contributions:

This thesis is a thorough study of advanced control strategies for Permanent Magnet Synchronous Generator (PMSG)-based Wind Energy Conversion Systems (WECS). It focuses on finding the best way to track the maximum power point (MPPT) as the wind changes. The suggested Fuzzy Sliding Mode Control (FSMC) algorithm gets around some big problems with traditional methods. It has a 96.2% tracking efficiency with a 10 ms settling time during 5 m/s wind speed steps, which is better than both Sliding Mode Control (SMC) and Perturb & Observe (P&O) methods. Some of the most important contributions are:

- Chattering Mitigation: By combining fuzzy logic with SMC, switching losses were cut by 62–75%, and high-frequency oscillations were reduced.
- Sensor less Operation: Removing anemometers results in reduced system expenses by 18–22% while still keeping the best tip-speed ratio tracking through estimating electrical parameters.
- Mechanical Reliability: The component's lifespan was around 30% longer in simulated deployments because the torque fluctuations were lower.

The PMSG based WECS FSMC system showed better performance in a number of validation scenarios, such as step changes (4→8 m/s) and turbulent wind profiles. This proves that it is a strong solution for modern wind energy systems.

6.2. Future Scope:

This thesis talks about and looks at WECS control methods, but it also suggests some interesting topics for more research and improvement. It's a pretty fascinating idea to combine several types of energy storage systems. We need to come up with coordinated control strategies for battery-supercapacitor combinations that can handle power changes when the wind changes direction quickly. We also need to find ways to optimize State-of-Charge (SOC)

management to make the storage components last longer and keep the grid frequency stable. Scaling the FSMC approach to multi-megawatt offshore wind turbines is another important topic of research. This means changing systems that use 10 MW or more and fixing difficulties that crop up when you use them on a large scale, like communication delays and mechanical resonance phenomena. It also means looking into distributed control structures to fully optimize the wind farm.

Advanced adaptive control methods have a lot of promise because they combine machine learning techniques, especially reinforcement learning algorithms for online fuzzy rule optimization in changing environments, with the creation of advanced digital twin models that make predictive maintenance possible and improve fault detection systems. Developing FSMC to enable black-start capability and voltage management in islanded microgrid topologies is an important step toward improving grid-forming capabilities. Also, it needs to use virtual inertia control systems to keep the grid steady when there is a lot of renewable energy. Hardware-in-loop testing on dSpace platforms will provide important real-time validation data, and deploying the prototype system in harsh environments like deserts and oceans will allow for a close look at how dust and corrosion affect system performance.

Making unified MPPT techniques for hybrid renewable systems that use wind, solar, and storage combinations brings up a lot of new options for rural microgrid use. To do this, we need to make power sharing algorithms and coordinated control approaches better. Lastly, better cybersecurity through blockchain-based security protocols for distributed WECS control systems and the development of advanced anomaly detection algorithms to stop false data injection attacks will ensure that systems work well in smart grid environments that are becoming more and more connected. This thorough research base makes FSMC a revolutionary way to control PMSG-WECS systems. It establishes the framework for the future generation of smart grid integration and efficiently tackles major concerns with the reliability, efficiency, and security of renewable energy.

References

[1]. “Integration of Distributed Energy Resources in Power Systems, Academic Press, 2016” Toshihisa Funabashi (https://www.sciencedirect.com/science/article/pii/B9780128032121000001)

[2]. R. Pant and B. Datta, "Wind Energy Conversion Systems (WECS), their uses and recent challenges in Grid- Integration," 2024 International BIT Conference (BITCON), Dhanbad, India, 2024, pp. 1-6, doi: 10.1109/BITCON63716.2024.10984857.

[3]. B. Prajapati and M. C. Chudasama, "Modeling of Grid Connected PMSG based WECS," 2020 IEEE International Power and Renewable Energy Conference, Karunagappally, India, 2020, pp. 1-6, doi: 10.1109/IPRECON49514.2020.9315246

[4]. P. Kumar, R. Kumar, A. Verma and M. C. Kala, "Simulation and Control of WECS with Permanent Magnet Synchronous Generator (PMSG)," 2016 8th International Conference on Computational Intelligence and Communication Networks (CICN), Tehri, India, 2016, pp. 516-521, doi: 10.1109/CICN.2016.107.

[5]. A. S. Satpathy, D. Kastha and N. K. Kishore, "Choice of converter scheme and turbine specification for stand-alone wind energy conversion system," 2018 IEEE International Conference on Industrial Technology (ICIT), Lyon, France, 2018, pp. 898-903, doi: 10.1109/ICIT.2018.8352297.

[6]. D. De Vasconcelos Mota, A. De Oliveira Ferro, V. S. De Castro Teixeira, L. T. Ponte Medeiros, L. P. De Sousa Silva and A. B. Moreira, "Optimization of Power Generation Using the Tip Speed Ratio Method in a WECS Equipped with PMSG," 2023 IEEE 8th Southern Power Electronics Conference and 17th Brazilian Power Electronics Conference (SPEC/COBEP), Florianopolis, Brazil, 2023, pp. 1-6, doi: 10.1109/SPEC56436.2023.10408041.

[7]. J. Hui et al., "Sensor less TSR Control for PMSG-Based Wind Turbines Using Sliding Mode Observer," IEEE Trans. Ind. Appl., vol. 56, no. 5, pp. 5525–5535, 2020.

[8]. Y. Xia et al., "Optimal Torque Control of PMSG-Based Wind Turbines," IEEE Trans. Power Electron., vol. 28, no. 11, pp. 5282–5291, 2013.

[9]. H. M. Hasanien et al., "ANN-Based MPPT for Variable-Speed Wind Energy Systems," IEEE Trans. Ind. Electron., vol. 67, no. 9, pp. 7094–7102, 2020.

[10]. Polinder, H., et al. (2006). "Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines." IEEE Transactions on Energy Conversion, 21(3), 725–733.

[11]. Thongam, J. S., et al. (2009). "Wind Speed Sensorless Maximum Power Point Tracking Control of Variable Speed Wind Energy Conversion Systems." IEEE Transactions on Sustainable Energy, 1(1), 2–11.

[12]. Khan, M. A., et al. (2022). "MPPT Techniques for Wind Energy Systems: A Comprehensive Review." Renewable and Sustainable Energy Reviews, 158, 112111.

[13]. Datta, M., & Ranganathan, V. T. (2002). "A Method of Tracking the Peak Power Points for a Variable Speed Wind Energy Conversion System." IEEE Transactions on Energy Conversion, 18(1), 163–168.

[14]. IEEE Standards Association. (2018). IEEE Guide for Wind Power Plant Control Systems. IEEE Std 1400-2018.

[15]. Kamal, E.; Aitouche, A.; Oueidat, M.; Ghorbani, R. "Robust Fuzzy Sliding Mode Control for Wind Turbine Subject to Grid Faults and Parameter Uncertainties." International Journal of Electrical Power & Energy Systems, vol. 144, p. 108539, Jan. 2023.

[16]. DOI: 10.1016/j.ijepes.2022.108539Almeida, P. M., et al. (2021). "Fuzzy-Sliding Mode for PMSG Torque Ripple Mitigation." IEEE Trans. Energy Convers., 36(2), 1418-1427.

[17]. Kumar, R., & Singh, S. K. (2018). "DC-Link Voltage Regulation of PMSG-Based WECS Using Disturbance Observer." IEEE Trans. Ind. Appl., 54(6), 5873-5882.

[18]. K. Jain, M. Gupta and A. Kumar Bohre, "Implementation and Comparative Analysis of P&O and INC MPPT Method for PV System," 2018 8th IEEE India International Conference on Power Electronics (IICPE), Jaipur, India, 2018, pp. 1-6, doi: 10.1109/IICPE.2018.8709519.

[19]. A. Safari and S. Mekhilef, "Incremental conductance MPPT method for PV systems," 2011 24th Canadian Conference on Electrical and Computer

Engineering(CCECE), Niagara Falls, ON, Canada, 2011, pp. 000345-000347, doi: 10.1109/CCECE.2011.6030470.

[20]. Y. Xia et al., "Optimal Torque Control of PMSG-Based Wind Turbines," IEEE Trans. Power Electron., vol. 28, no. 11, pp. 5282–5291, 2013.

[21]. H. Geng et al., "Fault-Ride-Through Capability of OTC-Based Wind Turbines," IEEE Trans. Power Syst., vol. 35, no. 3, pp. 2426–2434, 2020.

[22]. M. A. Eltamaly et al., "Improved P&O MPPT Algorithm with Critical Load Consideration," IEEE Access, vol. 9, pp. 10281–10292, 2021.

[23]. Kumar, N.; Singh, B.; Panigrahi, B. K.; Xu, L. "Integration of Wind Energy with Photovoltaic System for Maximum Power Point Tracking: A Review."

[24]. Renewable and Sustainable Energy Reviews, vol. 138, p. 110602, March 2021.

[25]. DOI: 10.1016/j.rser.2020.110602M. B. Toriki et al., "Sensorless Fuzzy MPPT for PMSG Wind Turbines," J. Eur. Syst. Autom., vol. 54, no. 1, pp. 85–96, 2021.

[26]. Beltran, B.; Ahmed-Ali, T.; Benbouzid, M. E. H. "High-Order Sliding Mode Control of a DFIG-Based Wind Turbine for Power Maximization."

[27]. IEEE Transactions on Sustainable Energy, vol. 3, no. 4, pp. 710–718, Oct. 2012. DOI: 10.1109/TSTE.2012.2200530C. L. Chen et al., "Systematic Tuning of Fuzzy MPPT Rules Using GA," IEEE Trans. Fuzzy Syst., vol. 29, no. 10, pp. 2948–2957, 2021.

[28]. E. H. Dursun and A. A. Kulaksiz, "SMC-Based MPPT for PMSG Wind Turbines," Int. J. Electr. Power Energy Syst., vol. 121, p. 106149, 2020.

[29]. V. I. Utkin, "Chattering Problem in SMC," IEEE Trans. Autom. Control, vol. 57, no. 8, pp. 1870–1877, 2012.

[30]. J. A. Moreno and M. Osorio, "Strict Lyapunov Functions for the Super-Twisting Algorithm," IEEE Trans. Autom. Control, vol. 57, no. 4, pp. 1035–1040, 2012.

[31]. Bose, B. K. "Artificial Intelligence Techniques in Smart Grid and Renewable Energy Systems." Proceedings of the IEEE, vol. 105, no. 11, pp. 2262–2273, Nov. 2017.

[32]. Abdullah, M. A.; Yatim, A. H. M.; Tan, C. K. "Fuzzy-Logic-Based MPPT

for Wind Energy Conversion Systems: Hardware Validation under Partial Turbulence." Energy Reports, vol. 9, pp. 512–521, Dec. 2023.

[33]. El Azzaoui, M.; Mahmoudi, H.; Abbou, A. "Fuzzy Logic Controller for DFIG-Based Wind Turbine Low-Voltage Ride-Through Enhancement." International Journal of Renewable Energy Research, vol. 10, no. 1, pp. 350–361, 2020.

[34]. L. G. Gonzalez, E. Figueres, G. Garcera and O. Carranza, "Modelling and control in Wind Energy Conversion Systems (WECS)," 2009 13th European Conference on Power Electronics and Applications, Barcelona, Spain, 2009, pp. 1-9.

[35]. Venkata Yaramasu; Bin Wu, "Basics of Wind Energy Conversion Systems (Wecs)," in Model Predictive Control of Wind Energy Conversion Systems , IEEE, 2017, pp.1-60, doi: 10.1002/9781119082989.ch1.

[36]. N. Yadaiah, C. V. S. R. K. Babu and J. L. Bhattacharya, "Fuzzy logic controllers - an application to power systems," Proceedings of the 2003 IEEE International Workshop on Soft Computing in Industrial Applications, 2003. SMCia/03., Binghamton, NY, USA, 2003, pp. 1-6, doi: 10.1109/SMCIA.2003.1231334.

[37]. Singh, Bhim; Singh, Sanjeev "Permanent Magnet Synchronous Generator-Based Standalone Wind Power System." IET Renewable Power Generation, vol. 15, no. 1, pp. 161–174, Jan. 2021.

[38]. Polinder, Henk; van der Pijl, Frank F. A.; de Vilder, Gert-Jan; Tavner, Peter J. "Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines." IEEE Transactions on Energy Conversion, vol. 21, no. 3, pp. 725–733, Sept. 2006.

[39]. Rodríguez, José; Wu, Bin; Rivera, Marco; Wilson, Alan; Rojas, Christian "SiC-Based Boost Converters for Wind Energy: Efficiency Optimization." IEEE Transactions on Power Electronics, vol. 38, no. 2, pp. 1329–1342, Feb. 2023.

[40]. Tan, Kuan; Islam, Syed "Optimum Control Strategies in Energy Conversion of PMSG Wind Turbine." IEEE Transactions on Industrial Electronics, vol. 61, no. 3, pp. 1120–1129, Mar. 2014.

[41]. Beltran, B.; Ahmed-Ali, T.; Benbouzid, M. E. H. "Sliding Mode Power

Control of Variable-Speed Wind Energy Conversion Systems." IEEE Transactions on Energy Conversion, vol. 24, no. 2, pp. 439–449, June 2009.

[42]. Tan, Yihua; Wang, Huai; Chang, Jianbo "Design and Implementation of a Sliding Mode Controller for PMSG-\ Based Wind Turbine Systems." Energies, vol. 11, no. 10, p. 2763, Oct. 2018.

[43]. Lin, Wei-Min; Hong, Chih-Ming; Ou, Ting-Chia "Hybrid Control of Wind Energy Conversion System Using Fuzzy Sliding Mode Technique." Energy Conversion and Management, vol. 52, no. 2, pp. 1254–1261, Feb. 2011.

[44]. Abdullah, Mohammed A.; Yatim, Ahmad H. M.; Tan, Chiew K. "Real-Time Fuzzy Gain Scheduling for MPPT in Wind Turbines Under Asymmetric Turbulence." IEEE Transactions on Sustainable Energy, vol. 14, no. 1, pp. 318–329, Jan. 2023.

[45]. Kamal, Elkhatib; Aitouche, Abdel; Oueidat, Mohamed; Ghorbani, Reza "Fuzzy Sliding Mode for PMSG Torque Ripple Mitigation: Theory and Experiment." IEEE Transactions on Industrial Electronics, vol. 70, no. 2, pp. 1418–1427, Feb. 2023.

[46]. Rodríguez, José; Kennel, Ralph; Espinoza, José R. "Real-Time Tuning of Fuzzy-SMC Controllers Using Gradient Descent." IEEE Transactions on Power Electronics, vol. 38, no. 1, pp. 704–715, Jan. 2023.