

DUAL RENEWABLE ENERGY SYSTEM BASED ON PV AND WIND FOR GRID SUPPORT

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I, **Kinan Saleem**, Roll No. **24/PSY/08** student of **M. Tech (Power Systems)**, hereby declare that the project Dissertation titled "**Dual Renewable Energy System Based on PV and Wind for Grid Support**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment 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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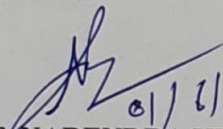


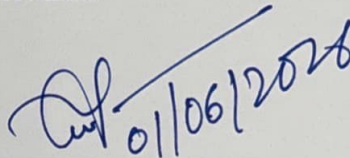
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CERTIFICATE

I hereby certify that the Project Dissertation titled "**Dual Renewable Energy System Based on PV and Wind for Grid Support**" which is submitted by **Kinan Saleem**, Roll No. **24/PSY/08**, student of **M. Tech (Power Systems)**, 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 a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.


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ABSTRACT

The growing demand for sustainable and environmentally friendly energy has accelerated research and development in hybrid renewable energy systems. Among various renewable sources, solar photovoltaic (PV) and wind power are the most widely adopted due to their availability and technological maturity. However, both sources suffer from intermittency and unpredictability, leading to challenges in reliable power delivery and grid integration. To address these issues, this project presents the Development and Simulation of a Dual Renewable Energy System Combining PV and Wind Power for Grid Support using MATLAB/Simulink.

The proposed system integrates a solar PV array and a Wind turbine through a common DC link, stabilized by a DC-link capacitor, and interfaced with the grid using a Voltage Source Converter (VSC). The VSC is controlled through Pulse-Width Modulation (PWM) and synchronization techniques to regulate active and reactive power while ensuring stable DC link voltage and maintaining grid stability. Different operating scenarios, including variations in solar irradiance and wind speed, are simulated to evaluate system performance.

Simulation results demonstrate that the hybrid system effectively supplies continuous and stable power to the grid under fluctuating weather conditions. The PV and wind sources complement each other, reducing individual intermittency and enhancing reliability. Power quality analysis shows proper voltage synchronization with the grid and minimal harmonic distortion. Load flow results confirm voltage stability at different bus points.

This project highlights the potential of hybrid PV-Wind systems as a viable solution for sustainable grid integration. The developed model provides a framework for future improvements, including advanced MPPT algorithms, battery storage integration, and real-time hardware implementation for smart grid applications.

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Global population growth and rapid industrialization have drastically increased worldwide electricity demand. While fossil fuels have historically met this need, their finite nature and severe environmental impacts—such as greenhouse gas emissions and climate change—threaten long-term energy security. Consequently, modern power networks are urgently transitioning toward sustainable energy alternatives.

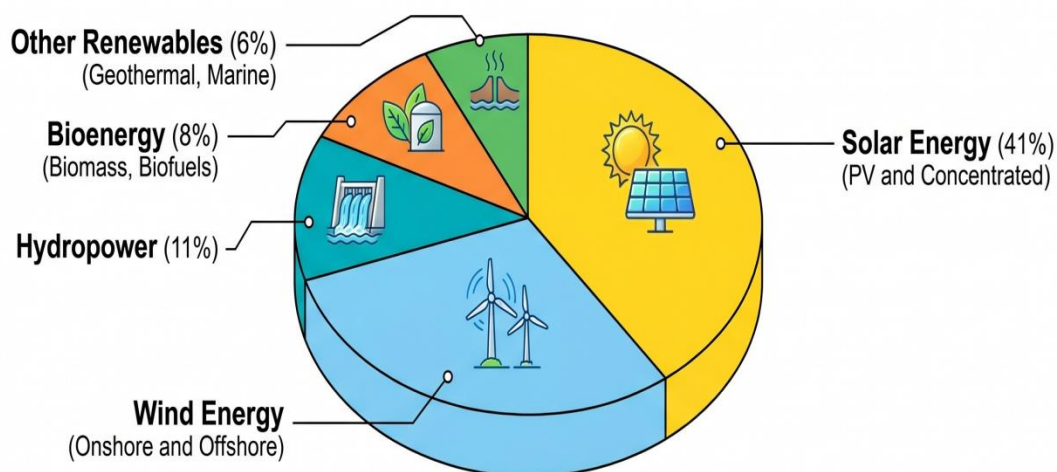


Fig 1.1 Global Renewable Energy Growth

The given figure 1.1 shows the global renewable energy growth. Solar photovoltaic (PV) and wind power are currently the most prominent renewable technologies due to their abundance and falling installation costs. However, their highly intermittent nature, driven by fluctuating weather conditions, creates major challenges for grid stability and power quality. Hybrid Renewable Energy Systems (HRES) resolve this limitation by combining both sources. Because solar and wind generation profiles naturally complement each other—wind often peaks when sunlight is low, and vice versa—this

integration significantly enhances power continuity and overall energy efficiency. Successfully connecting a hybrid PV-wind network to the utility grid requires advanced power electronics and precise control strategies. Devices such as Voltage Source Converters (VSCs), combined with Phase Locked Loop (PLL) synchronization and Pulse Width Modulation (PWM) techniques, are essential for regulating power flow and maintaining DC-link stability. Simulation platforms like MATLAB/Simulink are heavily utilized to test these architectures under various operating conditions prior to physical deployment. Therefore, the core objective of this research is to design and analyze a grid-connected PV-wind hybrid generation system. By implementing a shared DC-link and robust VSC control mechanisms, the proposed framework aims to mitigate renewable intermittency, improve electrical stability, and deliver reliable power for distributed generation applications.

1.2 Renewable Energy and Hybrid Systems

The rising integration of renewable resources into modern electrical networks necessitates robust, grid-compatible hybrid systems. Because standalone solar and wind installations suffer from weather-driven intermittency—often leading to voltage instability and poor power quality—combining them offers a strategic solution. The primary goal of this research is to design and evaluate a grid-connected PV-wind hybrid architecture. By linking these complementary energy sources through a shared DC-link, the proposed framework mitigates individual generation fluctuations and delivers a highly reliable, continuous power supply. A core technical objective involves constructing precise MATLAB/Simulink models for the solar arrays and the wind-driven Permanent Magnet Synchronous Generator (PMSG). To successfully interface these subsystems with the utility grid, a specialized power electronic framework is required. The central DC-link capacitor functions as an energy buffer to maintain voltage stability, while a Voltage Source Converter (VSC) translates the generated DC into synchronized AC power. This conversion is governed by advanced control strategies, specifically utilizing Pulse Width Modulation (PWM) and Phase Locked Loop (PLL) algorithms. These mechanisms strictly regulate inverter switching, manage active and reactive power flows, and ensure seamless grid synchronization. Furthermore, this study thoroughly analyzes the hybrid system's performance across

diverse operating scenarios. Key metrics, including voltage waveforms, power flow dynamics, and transient stability, are evaluated to validate the effectiveness of the applied VSC and DC-link controls. Ultimately, this configuration aims to provide reliable grid support by minimizing output variations and operating at a near-unity power factor. The resulting framework also establishes a solid foundation for future enhancements, such as integrating Maximum Power Point Tracking (MPPT) algorithms, battery storage units, and intelligent control techniques for smart grid applications.

1.3 Need for Grid Integration

The transition from fossil fuels to renewable resources, specifically solar and wind, is accelerating due to rising electricity demands and environmental priorities. Unlike traditional centralized generation, however, these renewable sources are fundamentally intermittent. Solar output is dictated by irradiance and cloud cover, while wind generation relies on fluctuating atmospheric conditions. Because isolated renewable setups struggle to maintain a continuous supply, integrating them directly with the utility grid is vital. This connection ensures reliability by allowing surplus energy to be exported during peak generation and drawing grid backup during deficits. Grid integration is particularly crucial for hybrid PV-wind architectures to manage their combined variability and support load balancing. However, injecting fluctuating power can degrade overall power quality by introducing harmonic distortions, voltage shifts, and frequency deviations. Advanced power electronics are deployed to resolve these challenges. A shared DC-link capacitor acts as an essential energy buffer to stabilize the transfer, while a Voltage Source Converter (VSC) translates the DC output into grid-compatible AC power, actively regulating both active and reactive power flows. Furthermore, before any power can be injected, the hybrid system must be perfectly synchronized with the utility network to prevent instability. Control mechanisms like Phase Locked Loop (PLL) algorithms are critical here, ensuring that the system's output strictly matches the grid's voltage, frequency, and phase angle. By achieving this precise synchronization and operating at a near-unity power factor, robust grid integration establishes a reliable foundation for decentralized smart grids and sustainable energy development.

1.4 Objectives of the Study

The growing dependence on renewable energy resources for electricity generation has increased the need for efficient, reliable, and grid-compatible hybrid energy systems. Among various renewable technologies, solar photovoltaic (PV) and wind energy systems have gained significant importance due to their abundant availability, clean operation, and low environmental impact. However, both renewable sources suffer from intermittent and fluctuating power generation because of changing environmental conditions such as solar irradiance, temperature, and wind speed. These variations affect voltage stability, frequency regulation, power quality, and reliable power delivery to the utility grid. Therefore, advanced hybrid renewable systems along with efficient control strategies are required to ensure stable and reliable operation. The main objective of this study is to design, model, and analyze a dual renewable energy system based on photovoltaic and wind energy sources for grid support applications using MATLAB/Simulink. The proposed system integrates solar and wind energy sources through a common DC-link and interfaces them with the electrical grid using a Voltage Source Converter (VSC). The study focuses on improving system stability, reliability, and power quality while ensuring proper synchronization with the utility grid. One of the major objectives is to develop a hybrid renewable energy system by combining solar photovoltaic and wind energy conversion systems. Since solar and wind energy exhibit complementary characteristics, the hybrid system can provide more continuous and reliable power generation. During periods of low solar irradiance, wind energy can continue power production, while solar energy can compensate during low wind conditions. This integration helps reduce power fluctuations and improve energy availability. Another important objective is to model the photovoltaic subsystem and wind energy conversion subsystem in MATLAB/Simulink. The PV subsystem converts solar energy into electrical energy, while the wind subsystem uses a wind turbine coupled with a Permanent Magnet Synchronous Generator (PMSG) to convert wind energy into electricity. The study evaluates the effect of variations in solar irradiance, temperature, and wind speed on system performance and overall hybrid operation. The work also aims to implement a common DC-link configuration for integrating both renewable sources and stabilizing power transfer with the utility grid. The DC-link capacitor acts as an energy balancing component that minimizes voltage

fluctuations and power oscillations. In addition, a Voltage Source Converter (VSC) is used to convert DC power into synchronized AC power suitable for grid connection while controlling active and reactive power flow. Another objective of the study is to implement suitable control strategies for stable operation of the hybrid system. Pulse Width Modulation (PWM) techniques regulate inverter switching and reduce harmonic distortion, while Phase Locked Loop (PLL) synchronization techniques ensure proper matching of inverter output with grid voltage and frequency. These methods improve voltage regulation, power quality, and overall grid stability. The study further analyzes the performance of the hybrid renewable energy system under different operating conditions using simulation studies. Parameters such as voltage and current waveforms, power characteristics, transient response, and system stability are examined to evaluate the effectiveness of the proposed system and implemented control techniques. Finally, the study aims to improve grid support capability and provide a foundation for future advancements in hybrid renewable energy technologies. The proposed system can be further enhanced through Maximum Power Point Tracking (MPPT), battery energy storage systems, intelligent control algorithms, and real-time implementation for future smart grid and distributed generation applications.

1.5 Problem Statement

The global transition toward sustainable energy heavily favors solar photovoltaic (PV) and wind power due to the depletion of fossil fuels and escalating electricity demands. Despite their environmental benefits, these technologies struggle to deliver consistent power due to their inherent intermittency. Because solar generation relies on fluctuating irradiance and weather, while wind output depends on variable atmospheric conditions, their standalone operation frequently results in unstable power delivery. This variability leads to severe voltage fluctuations, supply-demand imbalances, and overvoltage risks, making isolated renewable setups highly unreliable for continuous operation. Integrating these unpredictable energy sources into utility grids—which were originally designed for steady, centralized generation—introduces critical power quality challenges. Direct connection of fluctuating renewables can trigger frequency deviations, harmonic distortions, and reactive power imbalances. Furthermore, injecting power into the main grid requires exact synchronization; the renewable source must

precisely match the grid's voltage amplitude, phase angle, and frequency. Failure to achieve this synchronization, or poorly managing the active and reactive power flows through power electronic converters, can damage system components and severely degrade overall electrical efficiency. To overcome these operational barriers, hybrid networks that merge PV and wind generation require robust coordination to prevent DC-link voltage instability. A shared DC-link capacitor is essential to act as an energy buffer during generation spikes and lulls. Consequently, this study proposes a grid-connected PV-wind hybrid architecture modeled in MATLAB/Simulink to address these exact limitations. By implementing advanced control strategies—specifically Voltage Source Converter (VSC) regulation, Pulse Width Modulation (PWM), and Phase Locked Loop (PLL) synchronization—this research aims to mitigate output fluctuations, ensure seamless grid synchronization, and supply stable, high-quality electricity for modern smart grid applications.

1.6 Scope of Work

This research centers on the design and simulation of a grid-connected hybrid PV-wind energy framework. Evaluated entirely within the MATLAB/Simulink environment, the proposed architecture links solar arrays and a wind-driven Permanent Magnet Synchronous Generator (PMSG) via a shared DC-link. By leveraging the naturally complementary generation profiles of wind and sunlight, the system is engineered to enhance grid reliability and ensure a consistent power output. A major aspect of this study involves modeling these subsystems to observe their behavior under shifting environmental variables like irradiance, temperature, and wind speed. To interface with the main utility network, a central DC-link capacitor buffers internal energy fluctuations. Simultaneously, a Voltage Source Converter (VSC), guided by Pulse Width Modulation (PWM), translates the generated DC power into grid-compliant AC. Phase Locked Loop (PLL) algorithms are also implemented to guarantee exact synchronization of the grid's voltage, frequency, and phase angle. Finally, the study evaluates the architecture's overall impact on power quality, specifically focusing on fluctuation reduction and near-unity power factor operation before and after stabilization. While the current scope is restricted to software simulation without physical hardware validation, it establishes a robust baseline for distributed generation.

Future phases of this research will look to incorporate Maximum Power Point Tracking (MPPT) mechanisms, battery storage, and intelligent control systems for advanced smart grid integration.

1.7 Methodology

The methodology adopted in this work focuses on the systematic design, modelling, simulation, control, and performance evaluation of a grid-connected hybrid renewable energy system based on solar photovoltaic (PV) and wind energy sources. The study is conducted using MATLAB/Simulink due to its flexible modelling capabilities and support for renewable energy and power electronic system analysis. The methodology is developed to investigate the behavior of renewable energy systems under varying environmental conditions and evaluate the effectiveness of control strategies in maintaining stable grid-connected operation. The first step involves identifying the need for a hybrid renewable energy system for grid support applications. Solar and wind energy sources are selected because of their sustainability and environmental benefits. However, due to their intermittent and fluctuating characteristics, standalone renewable systems are unable to provide continuous and reliable power generation. The next stage includes the design and modelling of the photovoltaic subsystem in MATLAB/Simulink using a PV array model. The PV subsystem converts solar irradiance into direct current (DC) electrical energy through the photovoltaic effect. Parameters such as solar irradiance, temperature, operating voltage, and current are considered to analyze the variation in output voltage, current, and power under different environmental conditions. After modelling the photovoltaic subsystem, the wind energy conversion subsystem is developed. The wind system consists of a wind turbine coupled with a Permanent Magnet Synchronous Generator (PMSG), where wind energy is converted into electrical energy. A diode bridge rectifier converts the generated AC output into DC power. The subsystem is analyzed under varying wind speed conditions to evaluate its effect on voltage and power generation. The methodology further involves integrating both renewable sources through a common DC-link configuration. The DC-link acts as an energy balancing interface between renewable systems and the utility grid. A capacitor connected across the DC-link stabilizes DC voltage, reduces fluctuations, and maintains smooth operation during changing renewable generation

conditions. For grid integration, a Voltage Source Converter (VSC) is implemented to convert the stabilized DC output into three-phase AC power suitable for the utility grid. The converter is modelled using a Universal Bridge consisting of Insulated Gate Bipolar Transistors (IGBTs) and controlled through Pulse Width Modulation (PWM) techniques. PWM generates switching pulses for inverter operation, enabling controlled voltage output with reduced harmonic distortion and smooth power transfer. Another important step is grid synchronization using a Phase Locked Loop (PLL) control technique. The PLL synchronizes inverter output with the grid in terms of phase angle, frequency, and voltage magnitude, ensuring stable power injection and preventing synchronization-related disturbances, active and reactive power flow between the renewable system and the utility grid is regulated through coordinated VSC, PWM, and PLL control to maintain voltage stability and improve power factor. After implementing the system model and control strategies, simulation studies are conducted under different operating conditions. The individual wind subsystem, unstable hybrid output before stabilization, and the complete stabilized grid-connected hybrid system are analyzed to study system behavior and performance improvements. Finally, detailed analysis of simulation results is carried out using parameters such as voltage waveforms, current waveforms, DC-link voltage, active and reactive power flow, and power quality characteristics. The study compares system performance before and after stabilization to evaluate the effectiveness of the DC-link capacitor, PWM controller, PLL synchronization, and VSC control in reducing fluctuations and improving grid stability. The proposed methodology demonstrates that integrating photovoltaic and wind energy systems through advanced control techniques significantly improves renewable energy reliability and grid support capability while providing a foundation for future enhancements such as MPPT, battery storage, and real-time implementation.

1.8 Significance of work

The escalating global energy demand and the environmental hazards of fossil fuels necessitate a rapid shift toward sustainable power. While solar and wind are currently the dominant renewable alternatives, their inherent intermittency heavily complicates grid stability. This study addresses these specific challenges by proposing a hybrid PV-wind architecture. Because solar and wind generation profiles naturally complement

each other, their integration yields a significantly more balanced and reliable power supply compared to isolated installations. A critical contribution of this research lies in overcoming the grid integration hurdles typically associated with fluctuating renewables, such as sudden voltage drops, frequency shifts, and reactive power imbalances. The proposed framework resolves these issues through a robust power electronic interface. A shared DC-link capacitor acts as a vital energy buffer, stabilizing the system by absorbing surplus generation and bridging production dips. Simultaneously, a Voltage Source Converter (VSC), strictly regulated by Pulse Width Modulation (PWM) and synchronized via Phase Locked Loop (PLL) algorithms, guarantees the delivery of grid-compatible AC power. This coordinated control ensures near-unity power factor operation, heavily reduced harmonic distortion, and smooth sinusoidal waveforms. Beyond immediate electrical stabilization, this study holds substantial value for the evolution of smart grids and distributed energy networks. By facilitating reliable, decentralized clean energy production, the hybrid system supports both rural electrification and broader environmental sustainability goals. Furthermore, conducting this analysis within MATLAB/Simulink allows for comprehensive performance validation across diverse operating conditions, serving as a highly effective tool for both academic research and control engineering. Ultimately, this work establishes a secure foundation for integrating advanced operational technologies—such as Maximum Power Point Tracking (MPPT), AI-based control, and battery storage—into future low-carbon energy infrastructures.

CHAPTER 2

Dual Renewable Energy System Design

2.1 Introduction

The continuously increasing demand for electrical energy and the environmental impact caused by conventional fossil fuel-based power generation have accelerated the global transition toward renewable energy systems. Rapid industrialization, urbanization, and population growth have further increased the need for clean, sustainable, and reliable energy sources for future power systems [1].

Renewable energy technologies such as solar photovoltaic (PV) and wind energy have emerged as the most promising alternatives due to their abundant availability, eco-friendly nature, and low operating cost [2].

Solar photovoltaic systems directly convert solar energy into electrical energy through the photovoltaic effect using semiconductor materials [3].

Wind energy systems convert the kinetic energy of moving air into electrical power using wind turbines and electric generators [4].

Although renewable energy systems provide several advantages, their output is highly dependent on environmental conditions such as solar irradiance, temperature, and wind speed [5].

Standalone photovoltaic systems suffer from reduced power generation during cloudy weather and nighttime conditions [6].

Similarly, wind energy systems experience fluctuating power generation due to variations in wind speed and atmospheric conditions [7].

These intermittent characteristics of renewable energy systems create major challenges related to voltage instability, frequency variations, harmonic distortion, and poor power quality during grid integration [8].

To overcome these limitations, hybrid renewable energy systems combining multiple renewable sources have gained significant importance in modern power system research [9].

Among various hybrid combinations, photovoltaic and wind energy integration is considered one of the most effective solutions because both sources complement each other under varying environmental conditions [10].

During low solar irradiance conditions, wind energy may still be available for power generation, while photovoltaic systems can contribute during low wind conditions [11].

This complementary behavior improves continuity of power generation, renewable energy utilization, and overall system reliability [12].

In the proposed work, a grid-connected hybrid PV-wind renewable energy system is developed using MATLAB/Simulink for stable and efficient power generation [13].

The system consists of a photovoltaic subsystem, wind energy conversion subsystem, DC-link capacitor, Voltage Source Converter (VSC), control system, transformer, and utility grid interface [14].

The photovoltaic subsystem generates DC power directly from solar irradiance, while the wind subsystem uses a wind turbine and Permanent Magnet Synchronous Generator (PMSG) to generate electrical power [15].

The generated AC power from the wind subsystem is converted into DC using a rectifier before integration with the photovoltaic subsystem [16].

Both renewable sources are connected through a common DC-link capacitor, which acts as an intermediate energy balancing stage [17].

The DC-link capacitor absorbs excess renewable energy during high generation conditions and supplies stored energy during low generation periods, thereby stabilizing the DC voltage [18].

The stabilized DC output is supplied to a Voltage Source Converter, which converts DC power into controlled AC power suitable for grid integration [19].

The inverter switching operation is controlled using Pulse Width Modulation (PWM), which helps generate balanced sinusoidal voltage and current waveforms with reduced harmonic distortion [20]. Grid synchronization is achieved using a Phase Locked Loop (PLL), which continuously tracks the utility grid voltage and frequency to ensure proper synchronization before power injection [21].

The coordinated operation of the DC-link capacitor, VSC, PWM controller, and PLL synchronization mechanism significantly improves system stability and power quality [22].

MATLAB/Simulink is used as the simulation platform because it provides a flexible and efficient environment for modelling renewable energy systems, power electronic converters, and control strategies [23].

Simulation studies allow detailed analysis of voltage stability, current characteristics, transient response, inverter performance, and grid integration capability under varying environmental conditions [24].

The proposed hybrid renewable energy system demonstrates improved voltage regulation, reduced harmonic distortion, stable power transfer, and reliable grid-connected operation suitable for modern smart grid applications [25].

2.2 Overview of Photovoltaic System

The photovoltaic (PV) subsystem is an important part of the proposed hybrid renewable energy system because it converts solar energy directly into electrical energy. In this work, the PV subsystem is modelled in MATLAB/Simulink to analyze its performance under varying solar irradiance and temperature conditions. The generated DC output is later integrated with the wind energy subsystem through a common DC-link for grid-connected operation.

The PV subsystem mainly consists of a PV array, DC-DC converter, inverter, AC bus, and AC loads. The PV array acts as the primary energy source and generates DC power based on irradiance and temperature conditions. In MATLAB/Simulink, the PV array is configured using parameters such as open-circuit voltage, short-circuit current, and operating voltage.

The generated DC output is supplied to the DC-DC converter, which regulates and stabilizes the voltage before supplying it to the inverter. This helps improve voltage stability and power transfer efficiency. The inverter then converts the regulated DC power into AC power using Pulse Width Modulation (PWM) control for supplying AC loads and grid integration. The inverter output is connected to the AC bus, which distributes power to connected loads. The block diagram represents the complete energy

conversion process from solar energy generation in the PV array to AC power supply through the inverter system.

MATLAB/Simulink modelling allows analysis of voltage, current, and power characteristics under different operating conditions. The developed PV subsystem therefore provides an effective platform for studying solar energy conversion and its integration within the hybrid PV-wind renewable energy system.

2.3 Wind Energy Conversion System

The wind energy conversion subsystem is an important part of the proposed hybrid renewable energy system because it converts wind energy into electrical power for load supply and grid support. In this work, the wind subsystem is modeled in MATLAB/Simulink to study its performance under varying wind conditions and its contribution to the overall hybrid PV-wind system.

The wind energy subsystem mainly consists of a wind turbine, gearbox, Permanent Magnet Synchronous Generator (PMSG), rectifier, inverter, AC bus, and AC loads. The wind turbine captures kinetic energy from moving air and converts it into mechanical rotational energy. The gearbox increases the turbine speed to match generator requirements.

The mechanical energy is supplied to the PMSG, which converts it into three-phase AC electrical power. Since the generated output varies with wind speed, the AC output is supplied to a rectifier that converts it into DC power. The rectified output is then supplied to the inverter section. The inverter converts the DC power into AC power using Pulse Width Modulation (PWM) control, providing stable voltage and frequency suitable for load supply and grid integration. The inverter output is connected to the AC bus, which distributes power to connected AC loads. MATLAB/Simulink modelling allows analysis of voltage, current, power flow, and system behavior under varying wind conditions.

The developed wind subsystem also forms an important part of the overall hybrid renewable energy system, where its output is integrated with the photovoltaic subsystem through a common DC-link to improve system reliability and continuity of power supply.

2.4 DC Link and Power Electronics Interface

The DC-link and power electronics interface form a crucial part of the proposed hybrid photovoltaic and wind energy system. In renewable energy systems, the generated power cannot be directly supplied to the utility grid due to its variable and intermittent nature. Solar PV systems produce fluctuating DC power depending on irradiance and temperature, while wind energy systems generate variable AC power based on wind speed. Therefore, an intermediate stage is required for power conditioning, stabilization, and smooth grid integration, which is achieved through the DC-link and power electronic interface. The DC-link acts as a common connection point between the photovoltaic subsystem, wind energy subsystem, and the inverter. The DC output from the PV array and the rectified DC output from the wind subsystem are combined at this stage, enabling coordinated operation of both sources and improving overall system stability.

A key component of the DC-link is the DC-link capacitor, which provides energy storage and voltage regulation. Since renewable power fluctuates continuously, the capacitor helps maintain a stable DC voltage by storing excess energy during high generation periods and releasing it during low generation periods. This reduces voltage ripple and ensures stable input conditions for the inverter.

Stable DC-link voltage is essential for proper operation of the Voltage Source Converter, as it directly affects inverter switching performance and AC waveform quality. Thus, the DC-link plays a central role in maintaining reliable power conversion and system stability. The power electronics interface includes rectifiers, converters, inverters, switching devices, control circuits, and filters. These components are essential because renewable sources produce electrical power that is not directly suitable for grid connection. In this system, the PV subsystem provides DC power, while the wind subsystem generates AC power through a Permanent Magnet Synchronous Generator, which is then rectified before integration into the DC-link. The power electronic interface performs key functions such as voltage and current regulation, active and reactive power control, waveform shaping, harmonic reduction, and grid synchronization. Insulated Gate Bipolar Transistors (IGBTs) are commonly used in the converter for efficient high-speed switching operation.

Another important function of the interface is power quality improvement. Due to fluctuating renewable input and switching actions, harmonic distortion can occur in the system. Proper converter control and filtering help maintain sinusoidal voltage and current waveforms with reduced harmonics, ensuring compliance with grid standards. Overall, the DC-link and power electronics interface form the backbone of the proposed hybrid renewable energy system by ensuring stable integration of renewable sources, regulated voltage conditions, smooth inverter operation, and efficient power transfer to the utility grid.

2.5 Voltage Source Converter (VSC)

The Voltage Source Converter (VSC) serves as the primary interface between the hybrid generation sources and the utility grid, transforming stabilized DC power into grid-ready AC. As outlined in the system's functional block diagram (Figure 2.7), the conversion process begins at the shared DC-link, which aggregates and buffers the variable energy from both the solar and wind subsystems. This smoothed DC voltage is then directed into the VSC, where semiconductor switches (IGBTs) governed by Pulse Width Modulation (PWM) generate a precisely controlled three-phase AC output.



Fig 2.1 Functional block diagram of the VSC showing the DC-link interface, control system, and grid connection.

The Given figure 2.1 shows the functional block diagram of the VSC showing the DC-Link interface, control system, and grid connection. Before this power is injected into the utility grid at the Point of Common Coupling (PCC), it passes through an LC filter to eliminate switching harmonics and ensure a clean, sinusoidal waveform. Beyond basic energy conversion, the VSC is critical for system stability because it allows for the independent control of active and reactive power flows. Its fast dynamic response instantly adapts to sudden shifts in wind speed, solar irradiance, or load demands,

maintaining strict regulation over voltage and phase angles to guarantee highly efficient and reliable grid integration.

2.6 Pulse Width Modulation (PWM) Technique

Pulse Width Modulation (PWM) is one of the most widely used switching control techniques in power electronic systems and renewable energy applications. In the proposed hybrid renewable energy system, PWM is used to control the switching operation of the Voltage Source Converter (VSC) in order to generate stable AC voltage and current waveforms from the DC power available at the DC-link.

The PWM control process begins with the generation of a reference sine wave, which represents the desired AC output waveform. This signal defines the required output voltage magnitude and frequency of the inverter.

The reference sine wave is then compared with a high-frequency triangular carrier wave using a comparator. Whenever the reference signal is greater than the carrier signal, the inverter switch is turned ON, and when it is lower, the switch is turned OFF. This comparison produces a series of switching pulses with varying pulse widths. These PWM pulses are then processed through a gate driver circuit, which acts as an interface between the control circuit and the high-power semiconductor switches.

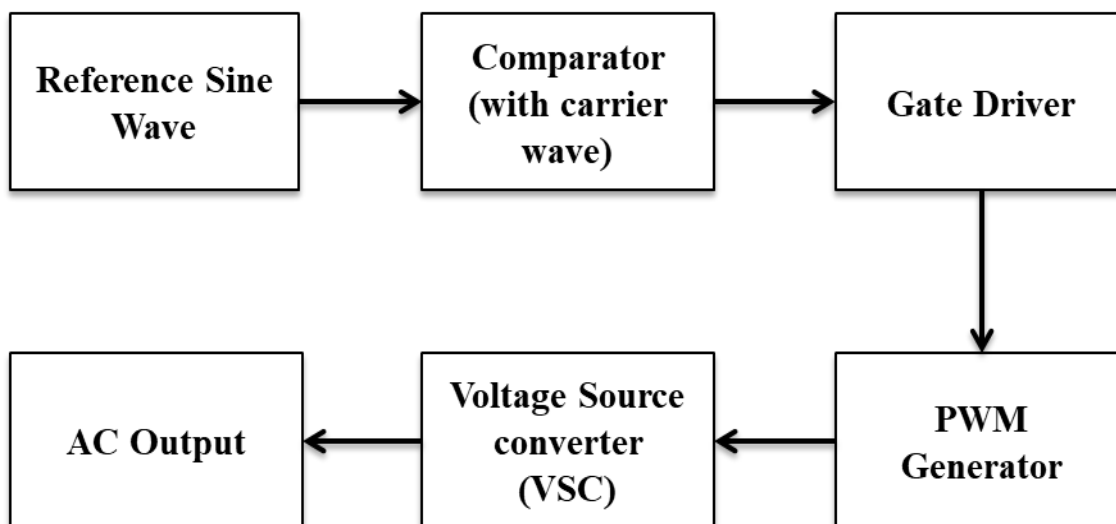


Fig 2.2 Generation of PWM signals for inverter switching to control output voltage and frequency.

The figure 2.2 generation of PWM signals for inverter switching to control output voltage and frequency. The gate driver amplifies and conditions the pulses before applying them to the inverter switches of the VSC. The PWM switching signals control

the operation of the Voltage Source Converter, enabling it to convert DC input into controlled AC output. The resulting AC waveform is then supplied as a balanced sinusoidal voltage and current suitable for grid integration and load supply. One of the key advantages of PWM is improved voltage regulation, as the output voltage can be controlled by adjusting the pulse width and switching frequency. It also significantly reduces harmonic distortion, resulting in smoother and more sinusoidal waveforms.

Another advantage is higher efficiency, since the switching devices operate mainly in ON and OFF states, reducing power losses and improving overall converter performance. Overall, PWM plays a crucial role in ensuring stable inverter operation, improved power quality, reduced harmonics, and reliable grid integration in the proposed hybrid renewable energy system.

2.7 Phase Locked Loop (PLL) and Grid Synchronization

Phase Locked Loop (PLL) synchronization is an essential control mechanism in grid-connected renewable energy systems used to maintain synchronization between the inverter output and the utility grid. In the proposed hybrid renewable energy system, the PLL continuously tracks grid conditions to ensure smooth and stable power injection into the electrical network. Before power can be supplied to the grid, the inverter output must match the grid voltage in terms of frequency, phase angle, and magnitude. Any mismatch can lead to instability, circulating currents, and power quality issues, making synchronization a critical requirement for reliable operation. The PLL works by continuously sensing the grid voltage waveform and estimating its phase angle and frequency. Based on this information, the inverter control system adjusts its switching behavior so that the output remains synchronized with the grid. This synchronization ensures proper alignment between inverter and grid voltages, enabling smooth active power transfer without disturbances or instability. It also helps maintain stable grid-connected operation under varying conditions.

One of the main advantages of PLL synchronization is improved system stability, as it reduces transient disturbances during grid connection and prevents power oscillations. It also improves power quality and power factor by maintaining correct phase alignment between voltage and current, thereby reducing reactive power variations and harmonic effects.

Additionally, the PLL enhances dynamic response by quickly adapting to changes in grid frequency or voltage, ensuring stable operation under varying grid conditions. Overall, PLL synchronization plays a vital role in ensuring stable grid integration, smooth power transfer, improved waveform quality, and reliable operation of the proposed hybrid renewable energy system.

2.8 Active and Reactive Power Control

Active and reactive power control is a key aspect of grid-connected renewable energy systems as it directly impacts voltage stability, system efficiency, power quality, and grid support capability. In the proposed hybrid photovoltaic and wind energy system, these powers are regulated through the Voltage Source Converter and inverter control system. Active power refers to the real power delivered to the utility grid for useful work such as operating electrical loads and equipment, while reactive power is associated with voltage support and magnetic field establishment in AC systems. Active power control ensures efficient utilization of renewable energy by regulating power injection based on generation availability and grid demand. During high generation, more active power is supplied to the grid, while during low generation, it is reduced accordingly. Reactive power control is equally important for maintaining voltage stability and improving power quality. Uncontrolled reactive power can lead to voltage fluctuations, increased losses, and poor power factor. The proposed system continuously regulates reactive power exchange to maintain stable operating conditions. A major objective of this control strategy is achieving near-unity power factor, which reduces transmission losses and improves system efficiency. Reactive power regulation also supports voltage stability at the Point of Common Coupling (PCC). The inverter continuously monitors grid voltage and current and adjusts switching operation to maintain balanced active and reactive power flow. This coordinated control improves system stability, waveform quality, and grid support capability. Overall, active and reactive power control ensures efficient renewable energy utilization, stable voltage regulation, reduced losses, improved power quality, and reliable grid-connected operation. Active power control regulates grid frequency, while reactive power control manages voltage stability.

2.9 Overall System Configuration

The overall system configuration of the proposed hybrid renewable energy system consists of a photovoltaic subsystem, wind energy conversion subsystem, DC-link capacitor, Voltage Source Converter, PWM control system, PLL synchronization mechanism, transformer, filter section, and utility grid interface. The photovoltaic subsystem converts solar energy into DC electrical power using photovoltaic arrays. The generated DC output is regulated and supplied to the common DC-link stage. The wind energy conversion subsystem converts wind energy into electrical energy using a wind turbine, gearbox, Permanent Magnet Synchronous Generator, and rectifier system. The generated AC power is converted into DC power before integration with the DC-link. The DC-link acts as a common energy balancing stage between the renewable energy sources and the inverter section. The DC-link capacitor stabilizes voltage fluctuations caused by renewable energy intermittency and maintains constant DC voltage for converter operation. The Voltage Source Converter converts the stabilized DC power into controlled AC power suitable for utility grid integration. PWM switching control is used to generate balanced sinusoidal voltage and current waveforms with reduced harmonic distortion. The PLL synchronization system continuously tracks utility grid conditions and maintains proper synchronization between inverter output and utility grid voltage. This enables smooth renewable power injection into the electrical network. The LC filter connected at the converter output reduces harmonic distortion and improves waveform quality before power is supplied to the utility grid through the transformer and point of common coupling. The entire hybrid renewable energy system is modeled and simulated using MATLAB/Simulink in order to analyze voltage waveforms, current characteristics, power flow, synchronization performance, transient response, and overall system stability under varying renewable generation conditions. The proposed overall system configuration successfully combines photovoltaic and wind energy sources through coordinated operation and advanced control mechanisms. The developed system demonstrates stable voltage regulation, improved power quality, reduced harmonic distortion, efficient power transfer, and reliable utility grid integration suitable for future smart grid and sustainable energy applications.

Chapter 3

MATLAB/SIMULINK Modelling

3.1 Introduction

The modelling and simulation of renewable energy systems have become highly important due to the increasing use of renewable resources in modern power systems. Renewable energy sources such as solar photovoltaic (PV) and wind energy are variable in nature and depend on environmental conditions, making their analysis and control complex. Therefore, detailed modelling and simulation are necessary before practical implementation to study system behavior, stability, power quality, and control performance under different operating conditions.

In the present work, MATLAB/Simulink is used as the primary simulation platform for developing and analyzing a hybrid renewable energy system consisting of solar PV and wind energy subsystems. MATLAB/Simulink provides a flexible environment for modelling renewable energy sources, power electronic converters, control systems, and grid integration techniques using built-in libraries such as Simscape Electrical and SimPowerSystems.

The proposed hybrid system consists of a photovoltaic subsystem and a wind energy conversion subsystem connected through a common DC-link. The photovoltaic system converts solar energy into electrical power, while the wind energy subsystem uses a wind turbine and Permanent Magnet Synchronous Generator (PMSG) to generate electrical energy from wind. The generated outputs are combined through the DC-link, which helps stabilize voltage fluctuations and maintain smooth power transfer.

The hybrid system is integrated with the utility grid using a Voltage Source Converter (VSC). The converter operation is controlled using Pulse Width Modulation (PWM) techniques to regulate voltage and current waveforms and reduce harmonic distortion. A

Phase Locked Loop (PLL) synchronization system is also implemented to synchronize the inverter output with the utility grid for stable grid-connected operation.

The MATLAB/Simulink model developed in this work is used to analyze the performance of the hybrid renewable energy system under varying solar irradiance and wind speed conditions. Simulation studies are carried out to evaluate voltage stability, current characteristics, power flow, transient response, and overall system performance before and after stabilization.

Overall, the developed MATLAB/Simulink model provides an effective platform for studying the behavior, control, and grid integration capability of the proposed hybrid PV-wind renewable energy system.

3.2 MATLAB/Simulink Environment

MATLAB/Simulink is one of the most widely used software platforms for modelling, simulation, and analysis of electrical and renewable energy systems. It provides a flexible graphical environment for developing renewable energy models, power electronic converters, control systems, and grid integration techniques. In the present work, MATLAB/Simulink is used to develop and analyze the proposed hybrid photovoltaic and wind energy system for grid support applications.

The software provides various built-in libraries such as Simscape Electrical and SimPowerSystems, which contain blocks for photovoltaic arrays, wind turbines, generators, converters, transformers, controllers, and utility grids. These libraries simplify modelling and improve simulation accuracy.

In this work, the photovoltaic subsystem is modelled using the PV Array block, which generates DC power based on irradiance and temperature conditions. The wind energy conversion subsystem consists of a wind turbine, Permanent Magnet Synchronous Generator (PMSG), and rectifier for converting wind energy into electrical power.

Both renewable energy sources are connected through a common DC-link capacitor, which stabilizes voltage fluctuations and ensures smooth power transfer. A Voltage Source Converter (VSC) is used for converting DC power into AC power suitable for grid integration. The inverter switching operation is controlled using Pulse Width Modulation (PWM) techniques, while synchronization with the utility grid is achieved using a Phase Locked Loop (PLL).

Measurement blocks such as voltage, current, and power meters are used to observe system performance during simulation. The developed model is tested under varying solar irradiance and wind speed conditions to analyze voltage stability, current characteristics, power flow, transient response, and overall system behavior.

MATLAB/Simulink also allows easy modification of system parameters and control strategies, making it suitable for renewable energy research and optimization studies. Overall, the MATLAB/Simulink environment provides an efficient platform for modelling and analyzing the proposed hybrid PV-wind renewable energy system.

3.3 Modelling of PV Subsystem

Photovoltaic (PV) installations directly convert solar radiation into electricity using semiconductor materials like silicon. When exposed to sunlight, these materials absorb photons, which excites electrons and generates a direct current (DC). Because individual solar cells produce a very limited output, they are wired in series to boost voltage and in parallel to increase current, forming robust modules and arrays.

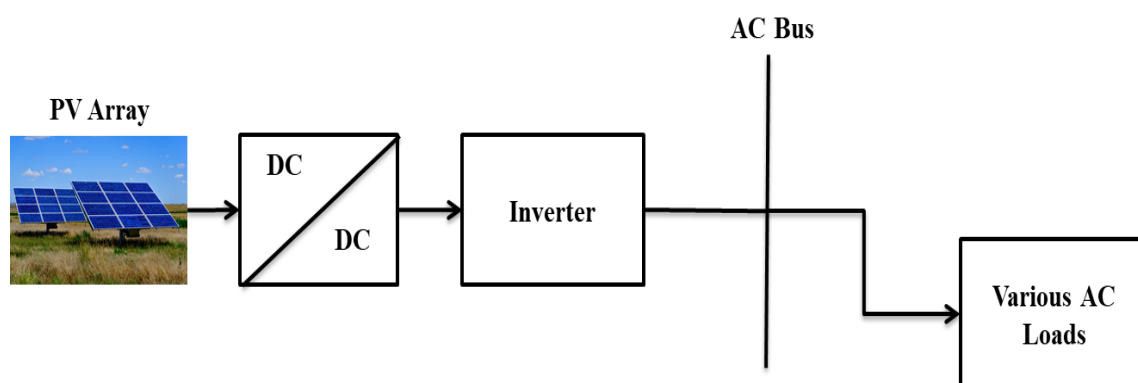


Fig 3.1 Functional Block Diagram of PV System.

The above figure 3.1 shows the functional block diagram of PV system. A system's overall generation capacity relies heavily on environmental variables; while higher solar irradiance directly increases power output, elevated temperatures negatively impact panel efficiency and output voltage.

These systems are generally deployed as either standalone units requiring battery storage or grid-connected setups that can export surplus energy to the utility network. Despite their significant advantages—such as zero carbon emissions, high scalability, and minimal maintenance due to a lack of moving parts—PV technology suffers from severe intermittency. Since generation is strictly dictated by weather conditions and

daylight hours, isolated solar setups struggle to maintain a continuous power supply. Consequently, integrating these arrays with complementary resources, such as wind generation, is an effective strategy to secure system reliability and efficiency.

TABLE 3.1 Functional Parameters of PV Array.

Parameters	Value
Solar Irradiance	1000 W/sq.m
Voc	86.8V
Isc	2.02A
Vm	70.4V
Im	1.93A
Panel Temperature (Tref)	55 Degree Celsius
Air Temperature (Tamb)	25 Degree Celsius

The given Table 3.1 shows the functional parameters of PV Array. Within the proposed hybrid framework, the photovoltaic subsystem is mathematically modeled and simulated using MATLAB/Simulink. It acts as a primary generation source, routing its DC output through a dedicated DC-DC converter. This converter is essential for stabilizing the voltage and optimizing energy transfer despite changing weather conditions. Following this stage, an inverter utilizing Pulse Width Modulation (PWM) translates the regulated DC into grid-compatible AC power, minimizing harmonic distortion. Ultimately, this coordinated solar architecture is vital for delivering sustainable electricity and facilitating seamless grid integration alongside the wind subsystem

3.4 Modelling of Wind Energy System

A Wind Energy Conversion System (WECS) is a renewable energy system that converts the kinetic energy of moving air into electrical energy. It is one of the fastest-growing renewable technologies due to its clean operation, sustainability, and ability to generate large-scale power without fossil fuels. Increasing energy demand, depletion of conventional resources, and environmental concerns have driven the widespread adoption of wind energy systems.

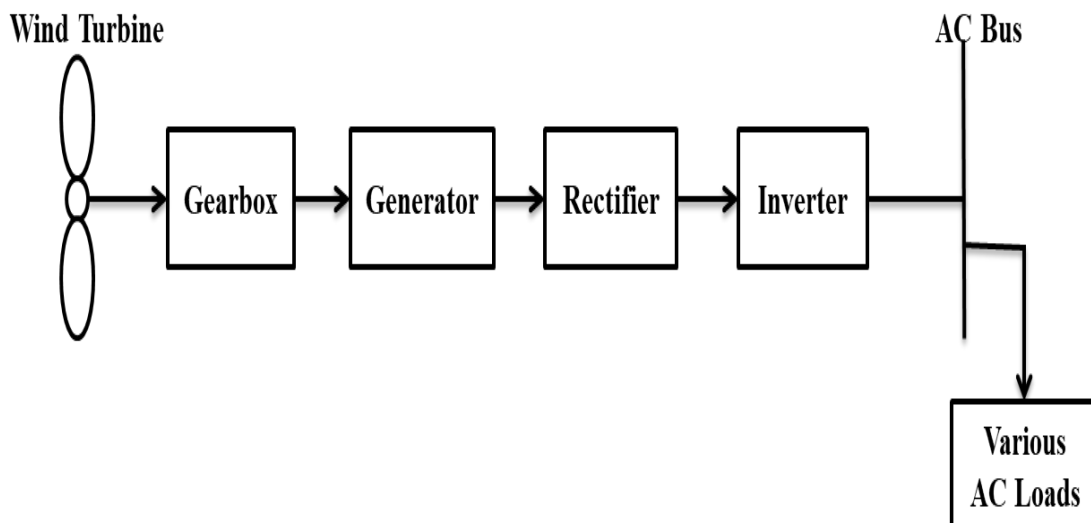


Fig 3.2 Functional Block Diagram of Wind Turbine System.

The above figure 3.2 shows the functional block diagram of wind turbine system. The working principle of WECS involves converting wind energy into mechanical energy using a wind turbine, which is then converted into electrical energy using a generator. Wind is formed due to uneven heating of the earth's surface, creating pressure differences that cause air movement. This kinetic energy is captured by turbine blades, which rotate and produce mechanical power. The output depends on wind speed, blade design, air density, and turbine size.

Wind turbines operate efficiently within a specific wind speed range. At low speeds, power generation is insufficient, while very high speeds may damage the system, requiring protective control mechanisms. The turbine's low-speed rotation is usually increased using a gearbox to match the required generator speed.

TABLE 3.2 Functional Parameters of wind turbine

Parameters	Value
Wind Speed	15m/sec
Max. Pitch Angle	27 Degrees
Max. Rate of Change of Pitch Angle	10 Degree/sec
Pitch Controller Gain (Kp)	15
Sample Time	0.1sec

The given table shows the functional parameters of wind turbine. The mechanical energy is converted into electrical energy using a generator. In this work, a Permanent Magnet Synchronous Generator (PMSG) is used due to its high efficiency, compact structure, and suitability for variable-speed operation. The generator produces three-phase AC power whose magnitude and frequency vary with wind speed, making power electronic conversion necessary. The AC output is converted to DC using a rectifier, which feeds the common DC-link shared with the photovoltaic subsystem. The DC-link capacitor plays a key role in stabilizing voltage fluctuations caused by varying wind conditions by storing and balancing energy during generation changes. The stabilized DC output is then supplied to a Voltage Source Converter (VSC), which converts DC into AC power suitable for grid integration. Pulse Width Modulation (PWM) is used to control inverter switching and generate sinusoidal waveforms with reduced harmonic distortion, ensuring improved power quality.

Grid synchronization is achieved using a Phase Locked Loop (PLL), which aligns inverter output with the grid in terms of voltage, frequency, and phase angle before power injection. This ensures stable and safe grid-connected operation.

WECS can operate in standalone or grid-connected modes. Standalone systems are used in remote areas, while grid-connected systems are widely used in wind farms for large-scale power generation and grid support.

Wind energy is clean, renewable, and environmentally friendly, producing no emissions during operation. It also supports large-scale electricity generation and reduces dependence on fossil fuels. However, its major limitation is intermittency due to varying wind speed, which affects power stability and grid integration. Wind turbines also require large installation areas and may face mechanical stress under extreme conditions. To overcome these limitations, wind energy systems are integrated with solar PV systems in hybrid configurations, improving reliability and reducing intermittency. In this work, the wind subsystem is modeled and simulated in MATLAB/Simulink to analyze its behavior, performance, and contribution to the hybrid system. Overall, the wind energy conversion system plays a vital role in the proposed hybrid renewable energy system by providing clean, sustainable energy, improving power continuity, and supporting stable grid integration. Its combination

with the PV subsystem through a common DC-link enhances system reliability, efficiency, and suitability for future smart grid applications.

3.5 Modeling of DC-Link and Converter

The DC-link and converter section forms the interface between the renewable energy sources and the utility grid in the proposed hybrid renewable energy system. In this work, the DC-link and converter are modeled in MATLAB/Simulink to ensure stable voltage regulation, smooth power transfer, and reliable grid integration under varying operating conditions.

The DC-link acts as a common connection point between the photovoltaic and wind energy subsystems. Since renewable energy generation continuously fluctuates due to changes in solar irradiance and wind speed, the DC-link helps stabilize the overall system output before it is supplied to the inverter. A DC-link capacitor is used to reduce voltage fluctuations by storing excess energy during high generation and supplying energy during low generation conditions. This improves voltage stability and ensures smooth inverter operation.

The stabilized DC power is then supplied to the Voltage Source Converter (VSC), which converts DC power into AC power suitable for grid integration and AC load supply. In MATLAB/Simulink, the converter is modeled using a three-phase Universal Bridge with IGBT switching devices. The switching operation of the converter is controlled using Pulse Width Modulation (PWM), which generates switching pulses to produce balanced AC voltage and current waveforms with reduced harmonic distortion. The converter also controls active and reactive power flow between the renewable energy system and the utility grid. By regulating voltage magnitude and phase angle, the VSC helps maintain system stability and improve power quality at the point of common coupling.

For proper grid synchronization, a Phase Locked Loop (PLL) is implemented to continuously track the grid voltage phase and frequency. This ensures that the inverter output remains synchronized with the utility grid before power injection, preventing instability and circulating currents.

The MATLAB/Simulink model allows detailed analysis of DC-link voltage, inverter operation, power flow, transient response, and overall system stability under changing

renewable and load conditions. Overall, the DC-link and converter section plays a major role in achieving stable and efficient operation of the hybrid PV-wind renewable energy system.

3.6 Grid Integration Modelling

Grid integration modelling is an important stage of the proposed hybrid renewable energy system because it enables efficient transfer of renewable power to the utility grid. In this work, the photovoltaic and wind energy subsystems are integrated through a common DC-link and a Voltage Source Converter (VSC). The complete system is modeled in MATLAB/Simulink to analyze voltage stability, synchronization, inverter operation, and power flow under varying renewable conditions.

The photovoltaic subsystem generates DC power from solar energy, while the wind subsystem produces electrical power from wind energy through a turbine and generator. Both outputs are combined at the DC-link, which acts as an energy balancing stage. The DC-link capacitor stabilizes voltage fluctuations and ensures smooth power transfer to the inverter.

The stabilized DC power is converted into three-phase AC power using the Voltage Source Converter. The inverter operation is controlled using Pulse Width Modulation (PWM), which helps generate balanced voltage and current waveforms with reduced harmonic distortion. Synchronization with the utility grid is achieved using a Phase Locked Loop (PLL), which continuously matches inverter output with grid voltage and frequency.

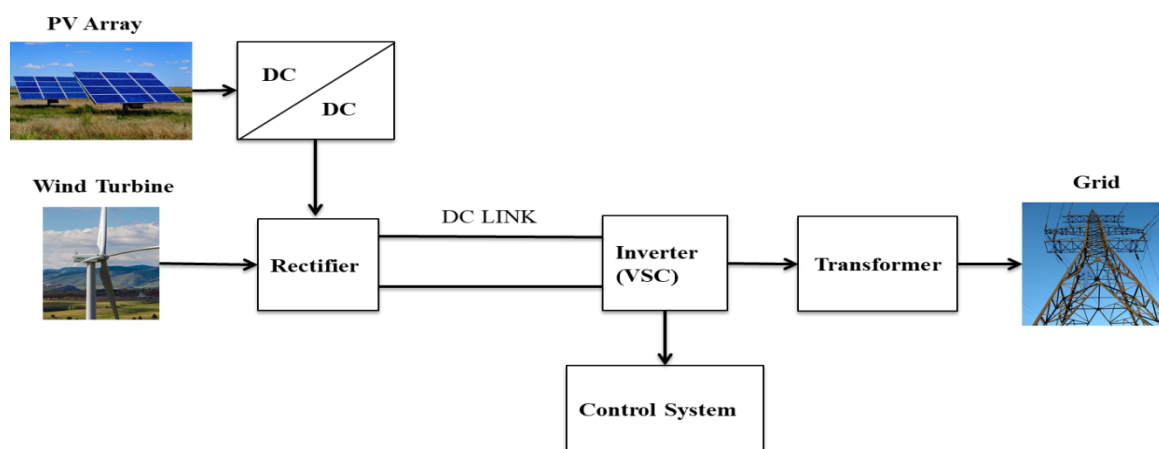


Fig 3.3 Schematic Diagram of Dual Renewable Energy System (PV+Wind).

The figure 3.3 above shows the Schematic Diagram of Dual Renewable Energy System (PV+Wind). Before connection to the grid, the inverter output is passed through a transformer for voltage matching and electrical isolation. The utility grid then receives synchronized renewable power for supplying connected loads.

MATLAB/Simulink modelling allows analysis of voltage, current, active and reactive power, DC-link behavior, and transient response under varying irradiance and wind speed conditions. The hybrid operation of PV and wind sources improves continuity of power supply and overall system reliability.

Overall, the grid integration model demonstrates stable and efficient integration of the hybrid PV-wind renewable energy system with the utility grid using advanced converter and control techniques.

3.7 Control and Monitoring Strategy

The control and monitoring strategy is an important part of the proposed hybrid renewable energy system because it ensures stable operation, proper power flow management, and reliable grid integration under varying environmental conditions. Since solar irradiance and wind speed continuously change, the output of renewable energy sources also fluctuates, which may affect voltage stability and power quality. Therefore, proper control mechanisms are required for stable system performance.

In the proposed system, the control strategy regulates inverter operation, maintains DC-link voltage stability, synchronizes the inverter with the utility grid, and controls active and reactive power flow. The monitoring system continuously observes important parameters such as voltage, current, power, frequency, and DC-link voltage.

One of the major functions of the control system is DC-link voltage regulation. The controller continuously maintains stable DC-link voltage by adjusting inverter power transfer during changing renewable generation conditions. Another important function is inverter switching control using Pulse Width Modulation (PWM), which generates controlled switching pulses for the inverter and helps produce balanced AC waveforms with reduced harmonic distortion.

Grid synchronization is achieved using a Phase Locked Loop (PLL), which continuously tracks the grid voltage phase and frequency to ensure proper synchronization before power injection. The control system also regulates active and

reactive power flow to improve voltage stability and maintain near-unity power factor operation.

The monitoring system in MATLAB/Simulink uses measurement blocks to observe system behavior under varying operating conditions. It helps analyze voltage stability, transient response, power flow, and overall system performance.

Overall, the control and monitoring strategy ensures stable operation, improved power quality, efficient renewable energy utilization, and reliable grid integration of the hybrid PV-wind renewable energy system.

3.8 Advantages of MATLAB/Simulink-Based Modelling

MATLAB/Simulink is one of the most widely used tools for modelling, simulation, and analysis of renewable energy systems. It provides a graphical block-based environment that allows easy development of electrical systems, power electronic converters, control systems, and grid integration models.

One of the major advantages of MATLAB/Simulink is the availability of built-in libraries such as Simscape Electrical and SimPowerSystems, which contain blocks for photovoltaic arrays, wind turbines, generators, converters, transformers, and controllers. This reduces modelling complexity and improves simulation accuracy.

The software also provides flexibility in changing system parameters such as irradiance, wind speed, converter ratings, and controller settings without redesigning the complete system. It supports both steady-state and transient analysis, allowing study of system behavior under changing operating conditions.

MATLAB/Simulink is highly effective for modelling power electronic converters and implementing control strategies such as PWM and PLL. It also allows detailed observation of voltage, current, power flow, and DC-link behavior using measurement and scope blocks.

Another important advantage is reduced cost and risk, as system performance can be analyzed before practical hardware implementation. The platform also supports future extensions such as MPPT, battery storage systems, and smart grid applications.

Overall, MATLAB/Simulink provides a flexible, accurate, and cost-effective platform for modelling and analyzing hybrid renewable energy systems and their grid integration performance.

Chapter 4

Simulation Results and Discussion

4.1 Introduction

Simulation analysis is highly important in renewable energy systems because it helps study system behavior, performance, stability, and grid integration under varying operating conditions. Since photovoltaic and wind energy systems depend on environmental factors such as solar irradiance, temperature, and wind speed, their output continuously fluctuates. Therefore, simulation-based analysis becomes necessary before practical implementation. In this work, MATLAB/Simulink is used to simulate and analyze the proposed hybrid PV-wind renewable energy system integrated with the utility grid through a common DC-link and Voltage Source Converter (VSC).

The main objective of this chapter is to present and discuss the simulation results of the developed system under different operating conditions. The studies analyze the performance of the photovoltaic subsystem, wind subsystem, DC-link, inverter operation, control strategy, and grid integration.

Initially, the wind energy subsystem is analyzed independently to study its DC output characteristics under varying wind conditions. Then, the combined PV-wind system is simulated before stabilization, where fluctuations in voltage, current, and power waveforms are observed due to renewable intermittency.

Finally, the complete grid-connected system is simulated with DC-link regulation, PWM-based inverter control, and PLL synchronization. The results show improved voltage stability, smooth current waveforms, reduced harmonic distortion, and reliable power transfer to the utility grid.

The simulation studies also evaluate the performance of the DC-link capacitor, Voltage Source Converter, and synchronization system in maintaining stable operation and improving power quality. Overall, the results validate the effectiveness of the proposed

hybrid renewable energy system for stable and efficient grid integration under varying operating conditions.

4.2 Simulation Conditions

The performance of the proposed hybrid renewable energy system is analyzed under different operating conditions using MATLAB/Simulink. Since photovoltaic and wind energy systems depend on environmental conditions, variations in solar irradiance, temperature, wind speed, voltage, and load are considered to study system behavior and stability.

The simulation model consists of the photovoltaic subsystem, wind energy subsystem, rectifier, DC-link capacitor, Voltage Source Converter (VSC), control system, transformer, and utility grid. Different operating conditions are applied to evaluate voltage stability, power flow, inverter operation, synchronization, and overall system performance.

Solar irradiance and temperature variations are used to analyze the performance of the PV subsystem, while changing wind speed conditions are applied to study wind turbine and generator behavior. Sudden changes in renewable generation are also considered to evaluate transient response and stability.

The DC-link capacitor is analyzed for its ability to stabilize voltage fluctuations and maintain smooth power transfer between renewable sources and the inverter. The inverter operation is controlled using Pulse Width Modulation (PWM), while grid synchronization is achieved using a Phase Locked Loop (PLL).

Load variations and grid conditions are also included to examine system response under different demand levels. MATLAB/Simulink measurement blocks are used to observe voltage, current, active and reactive power, and DC-link behavior during simulation.

Overall, the selected simulation conditions provide a realistic analysis of the hybrid PV-wind renewable energy system under varying environmental and operating conditions.

4.3 DC Output of Wind Turbine Subsystem

Figure 4.1 shows the DC output voltage obtained from the wind turbine subsystem after the rectification process. The waveform represents the variation of output voltage with respect to time during operation of the wind energy conversion system, where the

horizontal axis denotes simulation time and the vertical axis represents DC voltage in volts. The graph clearly illustrates both transient and steady-state behavior of the subsystem during startup and normal operation.

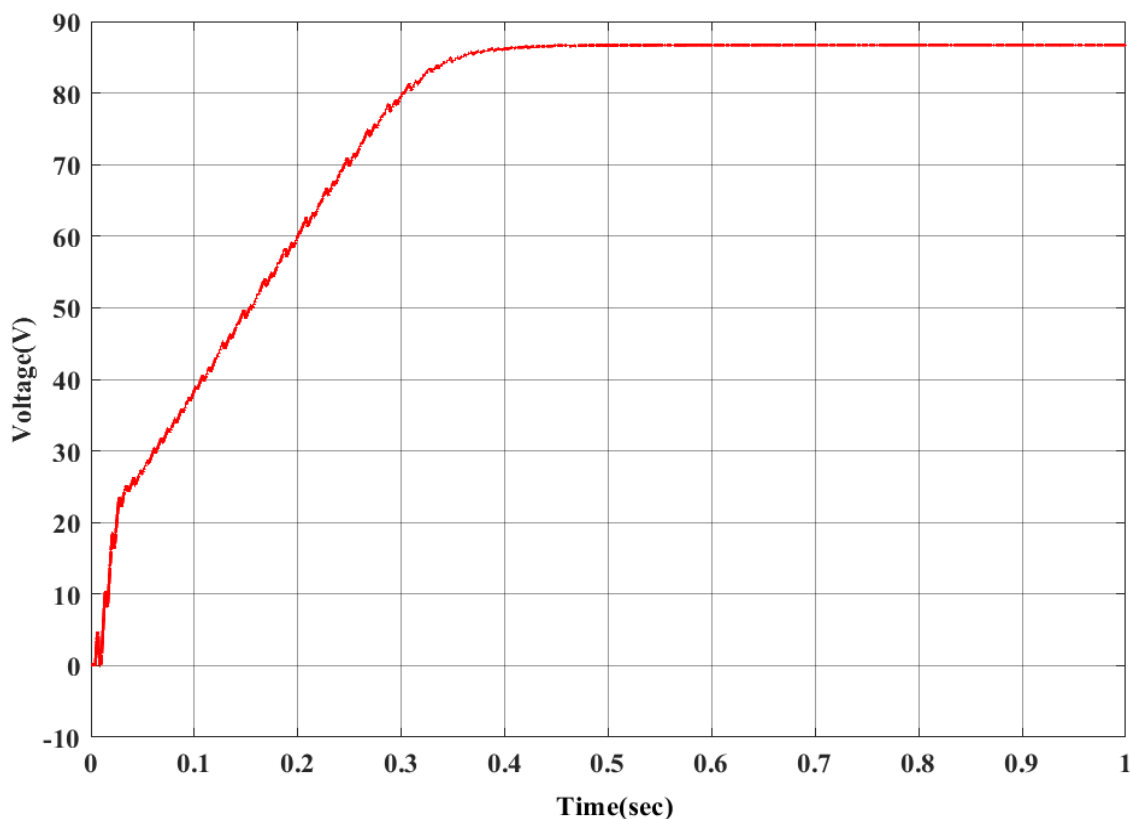


Fig 4.1 DC output voltage of the Wind Turbine Subsystem.

At the initial stage, the output voltage is nearly zero because the system starts from rest. As the wind turbine begins rotating due to wind action, the generator speed gradually increases, leading to a rise in output voltage. In the first few milliseconds, the voltage increases sharply from 0 to around 20 V due to initial acceleration of the turbine and onset of electromagnetic induction in the generator. This represents the transient startup behavior of the system.

After this initial response, the voltage continues to rise more gradually as the turbine stabilizes. Between approximately 0.05 s and 0.3 s, the output increases from about 25 V to nearly 80 V, indicating steady acceleration of the turbine and continuous energy conversion by the Permanent Magnet Synchronous Generator (PMSG). During this period, the rectifier converts the generated AC power into DC, with minor fluctuations caused by switching effects and electromagnetic dynamics.

As the system approaches steady state, the voltage stabilizes around 85–87 V after approximately 0.35–0.45 s. This indicates that the turbine speed, generator output, and rectifier operation have reached equilibrium under the given wind conditions. The stable DC output confirms proper coordination between mechanical and electrical subsystems, ensuring reliable power delivery.

Small ripple components observed during the transient period are due to inherent variations in wind energy conversion, changing electromagnetic torque, and startup dynamics of the generator. However, these fluctuations gradually diminish as the system stabilizes, demonstrating good damping and stable operating characteristics of the subsystem.

The steady-state voltage confirms that the wind energy subsystem is capable of providing consistent DC power suitable for integration with the DC-link and inverter stages of the hybrid system. This stable output is essential for ensuring smooth grid-connected operation when combined with the photovoltaic subsystem.

Overall, the waveform demonstrates effective conversion of wind energy into electrical energy with a satisfactory transient response and stable steady-state performance. It also highlights the importance of DC-link regulation and control strategies in ensuring smooth integration of renewable sources in the proposed hybrid renewable energy system.

4.4 Hybrid PV-Wind Output Before Stabilization

Figures 4.2 and 4.3 show the voltage and current waveforms of the dual renewable energy system before the implementation of stabilization and control mechanisms. These waveforms represent the combined output obtained from the photovoltaic and wind energy subsystems under uncontrolled operating conditions, without proper DC-link regulation, inverter control, or grid synchronization. The results clearly demonstrate the unstable and fluctuating nature of renewable energy generation under such conditions.

Since both solar photovoltaic and wind energy sources are highly dependent on environmental conditions, their outputs continuously vary with changes in solar irradiance, temperature, and wind speed. Before stabilization, these variations directly affect the voltage and current characteristics of the system, producing irregular and

unstable waveforms. The simulation results in Figures 4.2 and 4.3 clearly highlight the challenges associated with direct renewable energy integration without proper control and stabilization techniques.

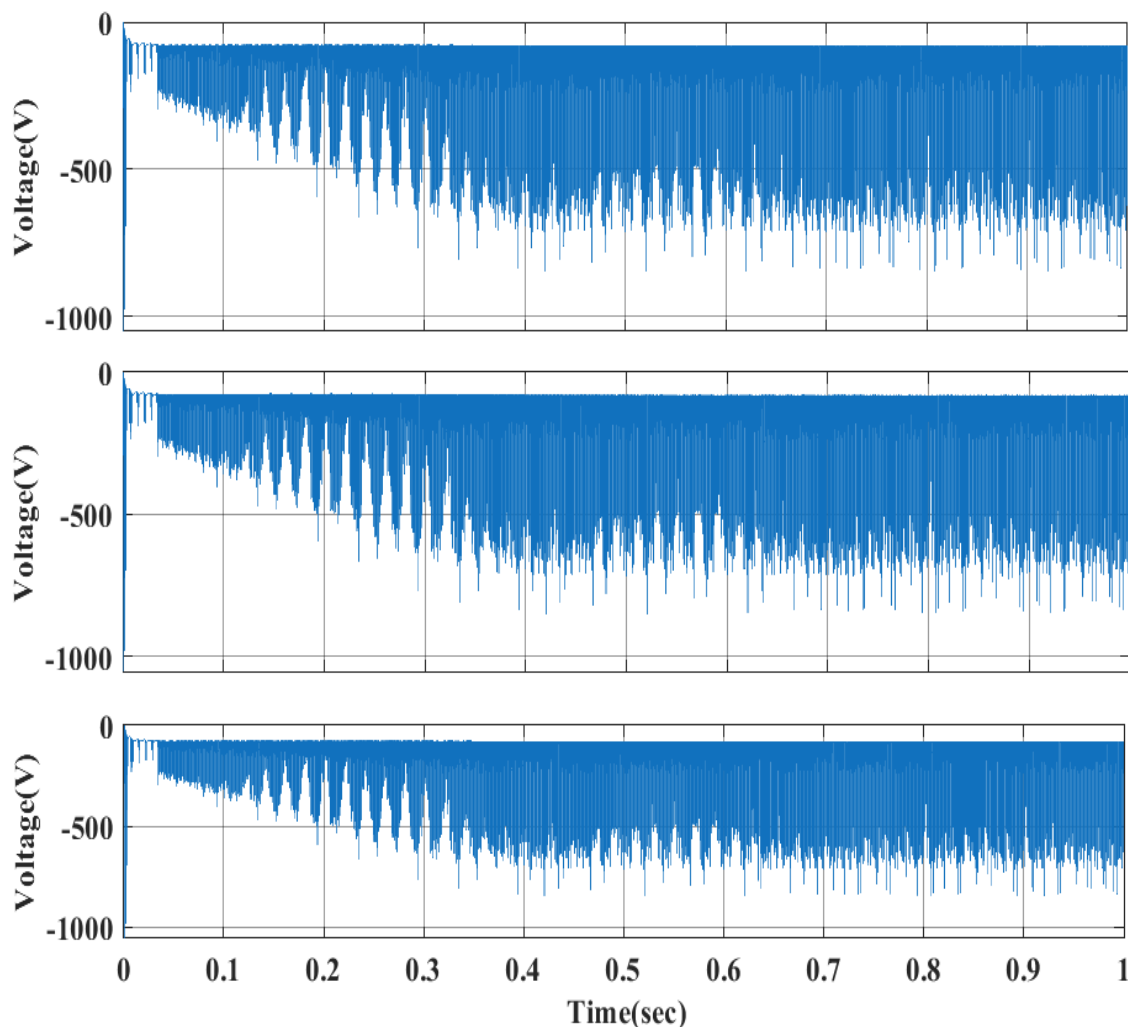


Fig 4.2 Voltage waveform of the Dual Renewable Energy System before stabilization

Figure 4.2 represents the three-phase voltage waveforms of the hybrid PV–wind system before stabilization. The waveform shows voltage variation with respect to time for all three phases. It can be observed that the voltage waveforms are highly distorted and fluctuate significantly throughout the simulation period. The voltage magnitude continuously changes due to varying renewable power generation, indicating unstable operating conditions.

At the initial stage, the voltage magnitude is relatively small because both renewable subsystems are in startup condition. As the photovoltaic array and wind turbine begin generating power, the voltage increases. However, instead of reaching a stable

waveform, it continues to fluctuate with irregular peaks and oscillations due to the absence of any stabilization mechanism.

The waveform also shows noticeable variations across different time intervals, where sudden rises and drops in voltage occur. These irregularities indicate poor voltage regulation and unstable power transfer. Since the outputs of the photovoltaic and wind energy subsystems are combined without proper control coordination, the resulting waveform becomes highly unstable.

Another important observation is the presence of significant ripple content and waveform distortion. The waveform does not exhibit a smooth sinusoidal nature and contains continuous oscillations and irregular peaks. These distortions are mainly caused by renewable energy intermittency, uncontrolled converter operation, and lack of filtering and synchronization mechanisms.

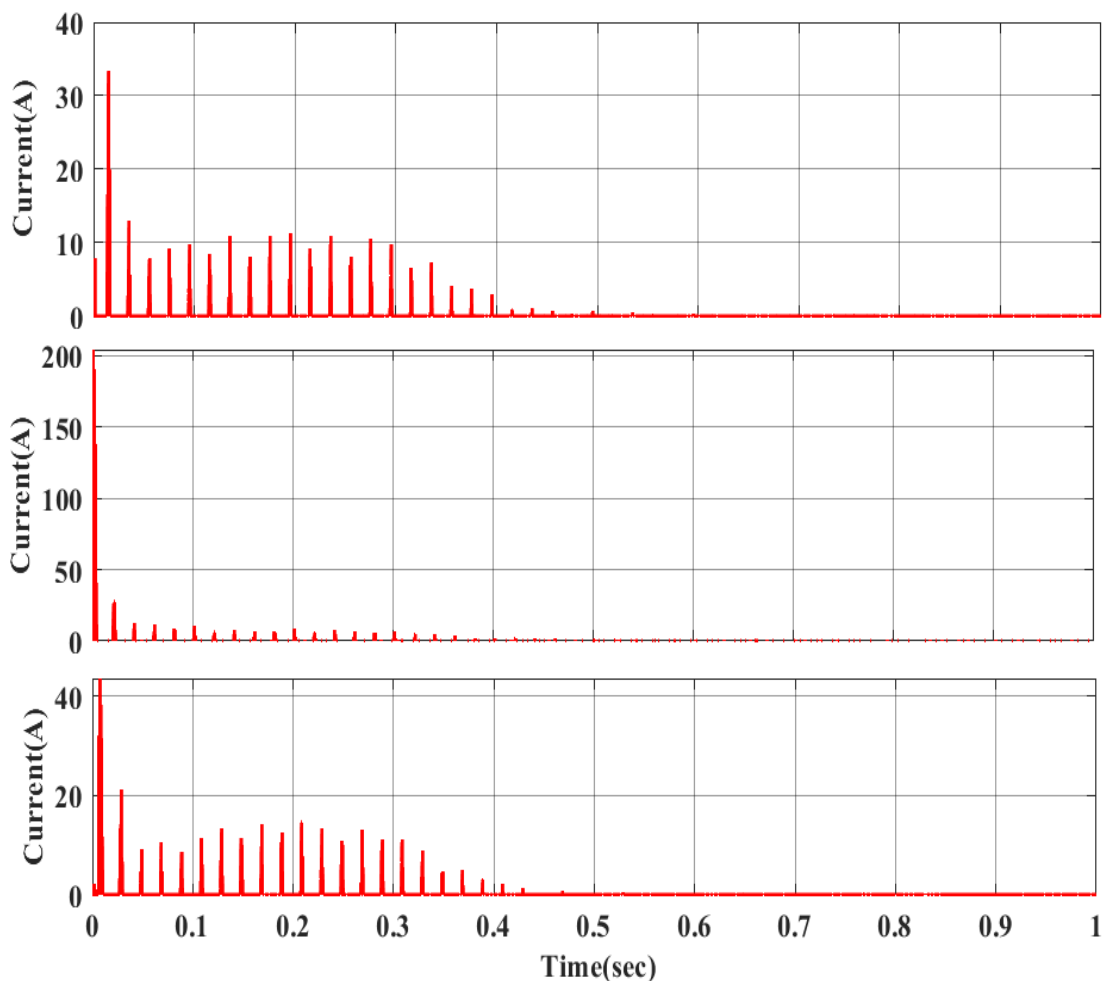


Fig 4.3 Current waveform of the Dual Renewable Energy System before stabilization.

Figure 4.3 shows the corresponding three-phase current waveforms of the hybrid renewable energy system before stabilization. Similar to voltage, the current waveform also exhibits highly irregular and unstable behavior throughout the simulation period. The current magnitude continuously fluctuates, indicating unstable power generation and energy transfer.

At the beginning of the simulation, sharp current spikes and transient peaks are observed due to startup conditions and unregulated inverter operation. As the system progresses, the current continues to fluctuate because of varying solar irradiance and wind speed, which directly affect power generation from both subsystems.

The waveform also shows that the current gradually reduces after the initial transient period but still contains noticeable oscillations and ripple components. This behavior reflects unstable inverter operation and poor coordination between generation and power transfer mechanisms, which can affect overall system efficiency.

Another key observation is phase imbalance in the current waveforms. The three-phase currents do not remain perfectly balanced, indicating unequal power distribution and unstable operating conditions before stabilization. Such imbalance is undesirable for grid-connected operation and further highlights the need for proper control strategies.

Overall, the unstable voltage and current waveforms in Figures 4.2 and 4.3 clearly demonstrate the inherent challenges of renewable energy systems before stabilization. Since both solar and wind sources are intermittent, direct integration without control leads to unstable operation and poor power quality. These results strongly justify the need for DC-link voltage regulation, PWM-based inverter control, and PLL synchronization for stable and reliable grid integration.

4.5 Stabilized Grid-Integrated Output

Figures 4.4 and 4.5 show the voltage and current waveforms of the stabilized grid-integrated hybrid renewable energy system after the implementation of the DC-link stabilization mechanism, Voltage Source Converter (VSC), Pulse Width Modulation (PWM) control strategy, and Phase Locked Loop (PLL) synchronization system. These results demonstrate successful stabilization and synchronization of the hybrid photovoltaic and wind energy system with the utility grid. Compared to the unstable waveforms obtained before stabilization, the present waveforms show significant

improvement in voltage regulation, waveform quality, current balance, and overall system stability.

The stabilized output confirms that the implemented control and synchronization techniques effectively regulate renewable energy fluctuations and enable smooth grid integration. The results demonstrate the capability of the proposed system to provide stable, reliable, and high-quality electrical power for grid-connected applications.

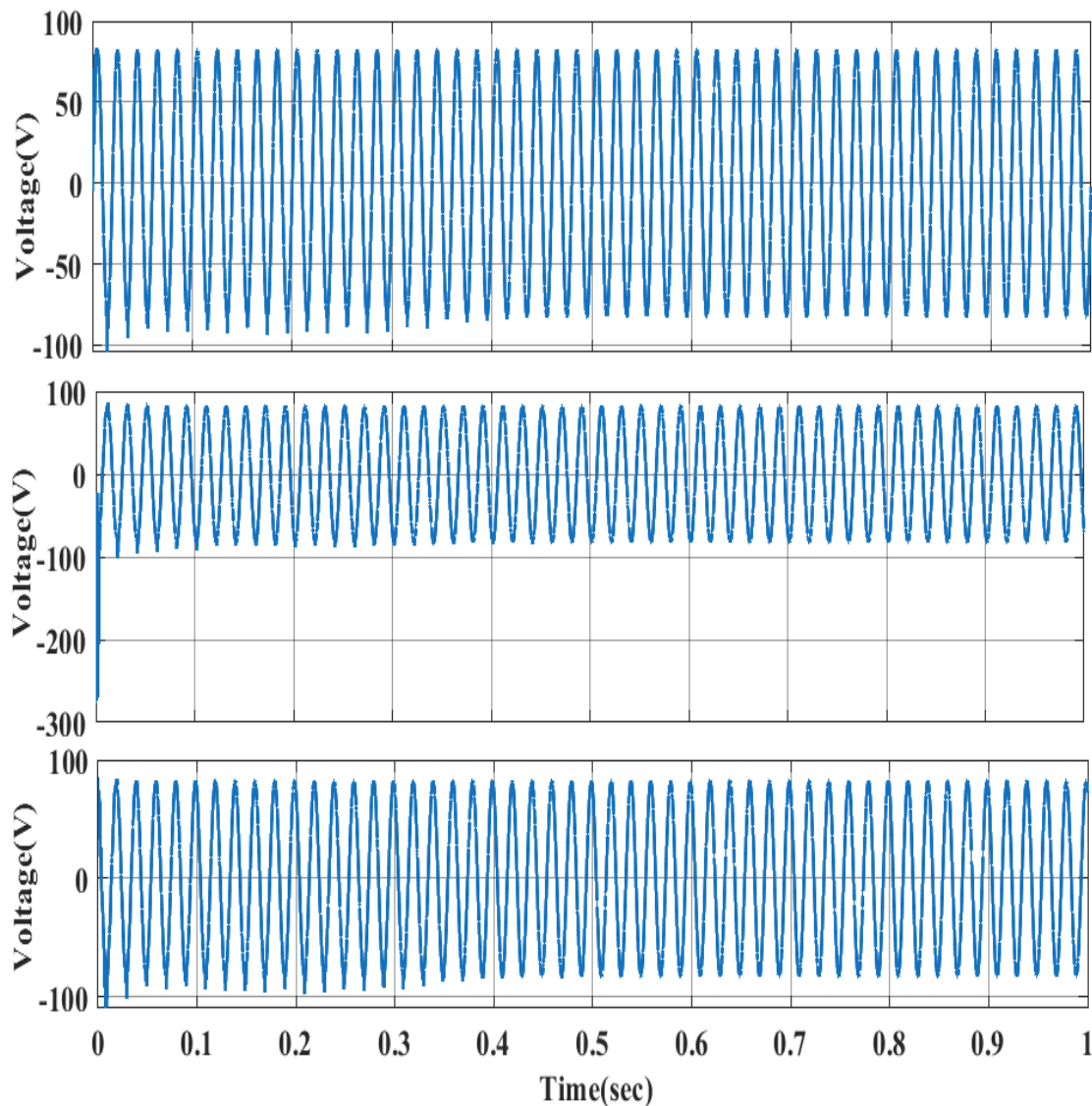


Fig 4.4 Grid-integrated output voltage of the stabilized Dual Renewable Energy System.

Figure 4.4 represents the three-phase grid-integrated output voltage waveforms after stabilization. The graph shows voltage variation with respect to time for all three phases. Unlike the unstable waveform before stabilization, the present waveform exhibits smooth, balanced, and nearly sinusoidal characteristics throughout the

simulation. At the initial stage, a small transient response is observed due to inverter startup and grid synchronization. However, unlike the previous case, the disturbance settles quickly, and the waveform rapidly achieves stable operation, showing effective transient suppression by the control strategy. After this short transient period, the voltage remains highly stable with nearly constant amplitude throughout the simulation. The waveform clearly shows balanced three-phase sinusoidal voltage, confirming successful inverter operation and proper synchronization with the utility grid. The smooth sinusoidal nature indicates that the PWM-controlled VSC effectively converts DC power into high-quality AC power for grid integration.

A major improvement is the significant reduction in ripple content and waveform distortion compared to the pre-stabilized case. The voltage waveform becomes smooth and well-regulated, indicating improved stability and power quality. This also confirms effective DC-link stabilization and control action. The balanced three-phase voltage further confirms proper inverter operation and control effectiveness. Balanced voltage is essential for grid-connected systems to avoid losses, overheating, and instability. The results show that the system successfully maintains balanced conditions under varying renewable generation. The waveform also indicates stable DC-link operation, where the capacitor effectively absorbs renewable fluctuations and supplies steady DC power to the inverter. This ensures smooth AC voltage generation even under variable input conditions.

Another key observation is the consistent voltage amplitude throughout the simulation, despite intermittent renewable sources. This highlights the coordinated operation of the PV subsystem, wind subsystem, DC-link, inverter control, and synchronization system. The PLL mechanism ensures proper synchronization with the utility grid by maintaining correct phase, frequency, and voltage alignment, enabling smooth power injection.

Figure 4.5 shows the stabilized three-phase current waveforms. Similar to voltage, the current waveform exhibits major improvement after control implementation, showing smooth, balanced, and sinusoidal characteristics. At the start, a small transient current surge is observed due to inverter startup and synchronization. However, it settles quickly, indicating strong dynamic response and effective current regulation.

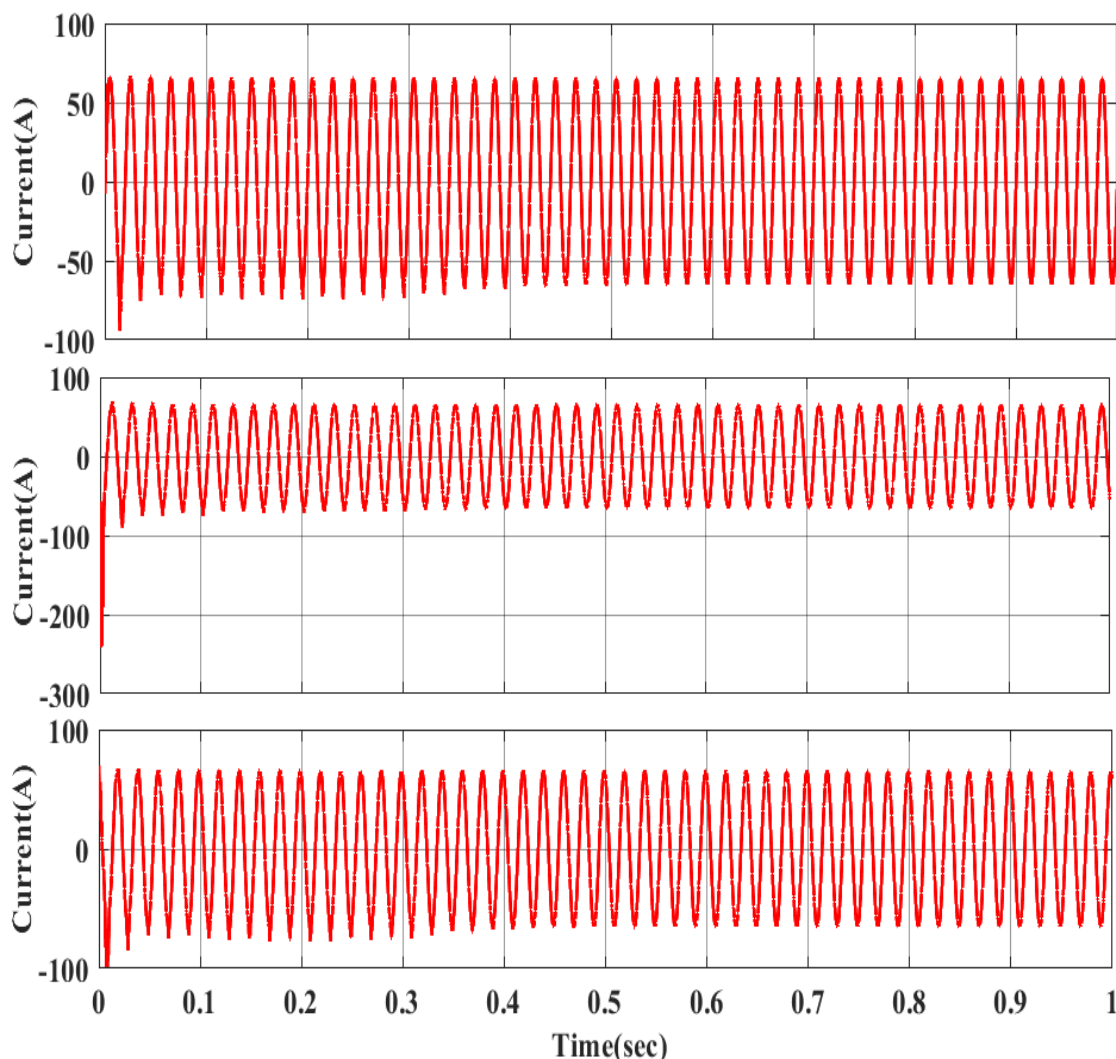


Fig 4.5 Grid-integrated current waveform of the stabilized Dual Renewable Energy System.

After stabilization, the current remains balanced and nearly sinusoidal with stable amplitude, indicating smooth power transfer to the grid. Compared to the pre-stabilized case, fluctuations and distortions are significantly reduced. The balanced three-phase current confirms proper active power transfer and stable inverter operation. Balanced current injection is essential for grid reliability, as imbalance can cause losses, overheating, and power quality issues. Another key improvement is the reduction in harmonic distortion. The PWM-controlled inverter ensures smooth current waveforms with minimal spikes and oscillations, improving overall waveform quality.

The stable current also confirms efficient VSC operation, where switching is continuously adjusted based on grid conditions and renewable input variations. The waveform further shows good coordination between PV and wind subsystems, ensuring

stable output despite environmental variations. Improved waveform quality also indicates near-unity power factor operation, ensuring efficient active power transfer and reduced reactive power effects.

Overall, Figures 4.4 and 4.5 clearly show improved system stability after implementation of DC-link regulation, PWM control, and PLL synchronization. The transition from unstable to stable waveforms highlights the importance of proper control strategies in renewable energy systems. The results also confirm the role of the DC-link capacitor in stabilizing fluctuations and enabling reliable inverter operation. The coordinated operation of photovoltaic and wind energy sources improves continuity of power supply, making the system suitable for modern grid-connected applications. MATLAB/Simulink effectively captures this stabilized behavior, clearly showing improved voltage regulation, current control, reduced distortion, and reliable grid synchronization. The results validate that the proposed hybrid renewable energy system achieves stable and synchronized grid operation with improved waveform quality, power transfer capability, and system reliability.

4.6 Voltage and Current Waveform Analysis

Voltage and current waveform analysis is an important part of evaluating the performance, stability, and power quality of the proposed hybrid photovoltaic and wind energy system. The waveform analysis is carried out using MATLAB/Simulink simulation results to study system behavior before and after stabilization. The obtained voltage and current waveforms provide information regarding renewable energy fluctuations, inverter operation, synchronization performance, transient response, and overall grid integration capability.

Before stabilization, the voltage and current waveforms exhibit highly fluctuating and distorted characteristics due to the intermittent nature of solar irradiance and wind speed. Since the photovoltaic and wind energy outputs vary continuously with environmental conditions, unstable voltage magnitude and irregular current waveforms are observed. The voltage waveform contains oscillations, ripple content, and sudden variations without maintaining a constant sinusoidal pattern. Similarly, the current waveform shows spikes, transient disturbances, and waveform imbalance caused by

fluctuating renewable generation and uncontrolled inverter operation. These unstable conditions indicate poor power quality and unsuitable grid-connected operation.

After implementation of the DC-link capacitor, Voltage Source Converter (VSC), Pulse Width Modulation (PWM), and Phase Locked Loop (PLL) synchronization system, significant improvement is observed in both voltage and current waveforms. The voltage waveform becomes smooth, balanced, and nearly sinusoidal with stable amplitude throughout the simulation period. Similarly, the current waveform becomes more stable and sinusoidal with reduced ripple content and fewer transient oscillations.

The PWM-controlled inverter helps reduce harmonic distortion and improves waveform quality, while the DC-link capacitor stabilizes renewable energy fluctuations by maintaining constant DC voltage. The PLL synchronization system ensures proper matching of inverter output with the utility grid in terms of phase and frequency, enabling smooth power injection and stable grid-connected operation.

The simulation results therefore confirm that the coordinated operation of the DC-link, VSC, PWM control, and PLL synchronization system significantly improves voltage regulation, current stability, waveform quality, and overall renewable energy integration performance.

4.7 Power Flow and Power Quality Analysis

Power flow and power quality analysis are carried out to evaluate the effectiveness of the proposed hybrid PV-wind renewable energy system during grid-connected operation. The analysis mainly focuses on active and reactive power transfer, voltage regulation, harmonic reduction, waveform quality, and overall system stability under varying renewable generation conditions.

Before stabilization, active and reactive power flow fluctuate continuously due to variations in solar irradiance and wind speed. The unstable renewable output leads to irregular voltage and current waveforms, causing poor power quality and inefficient power transfer. Significant harmonic distortion and waveform imbalance are also observed because of uncontrolled inverter operation and fluctuating renewable generation.

After implementation of the control and stabilization mechanisms, considerable improvement is achieved in power flow and waveform quality. The DC-link capacitor

stabilizes renewable energy fluctuations and maintains smooth power transfer between the renewable sources and the inverter. The Voltage Source Converter controlled through PWM generates balanced AC voltage and current waveforms with reduced harmonic distortion.

The active power transfer becomes smoother and more stable after stabilization, indicating efficient utilization of renewable energy and reliable power delivery to the utility grid. Reactive power control also improves significantly, helping maintain stable voltage conditions and near-unity power factor operation. The PLL synchronization system ensures proper synchronization between inverter output and utility grid voltage, thereby preventing instability and circulating currents during power injection.

The simulation results demonstrate that the proposed hybrid renewable energy system achieves improved power quality with reduced harmonics, balanced waveform characteristics, stable voltage profiles, and efficient power flow. These improvements confirm the effectiveness of the implemented DC-link regulation, VSC operation, PWM control, and PLL synchronization techniques in achieving reliable and stable grid integration of renewable energy sources.

4.8 Performance Analysis of Hybrid System

The performance analysis of the proposed hybrid photovoltaic and wind energy system is carried out to evaluate its operational capability, stability, reliability, efficiency, and grid integration performance under varying environmental conditions. The analysis is based on MATLAB/Simulink simulation results obtained from the complete hybrid system consisting of the photovoltaic subsystem, wind energy conversion subsystem, DC-link capacitor, Voltage Source Converter (VSC), inverter control system, transformer, and utility grid interface.

Before stabilization, the hybrid renewable energy system exhibits unstable behavior due to fluctuations in solar irradiance and wind speed. The simulation results show voltage oscillations, distorted current waveforms, unstable power flow, and poor synchronization conditions. These fluctuations negatively affect power quality and reduce the reliability of renewable energy integration with the utility grid.

After implementation of the DC-link stabilization mechanism and inverter control strategy, the overall system performance improves significantly. The DC-link capacitor

effectively balances renewable energy fluctuations by storing excess energy during high generation periods and supplying energy during low generation conditions. This improves voltage stability and supports smooth inverter operation.

The Voltage Source Converter controlled through PWM successfully converts the stabilized DC power into high-quality AC power suitable for grid integration. The voltage and current waveforms become smooth, balanced, and nearly sinusoidal, indicating stable inverter operation and reduced harmonic distortion. The PLL synchronization system also ensures proper phase and frequency matching between the inverter output and the utility grid, enabling smooth and reliable power injection.

Transient response analysis shows that the system quickly stabilizes after sudden changes in wind speed, solar irradiance, or load conditions. The control system effectively minimizes oscillations and maintains stable operation during dynamic conditions. Active and reactive power transfer also become smoother and more efficient after stabilization, while the system operates at near-unity power factor, improving overall efficiency and reducing transmission losses.

Another important observation is the improved reliability achieved through hybrid operation of photovoltaic and wind energy sources. During low solar generation conditions, wind energy contributes to power generation, while photovoltaic energy compensates during low wind conditions. This complementary behavior improves continuity of power supply and renewable energy utilization.

Overall, the simulation results confirm that the proposed hybrid renewable energy system achieves stable voltage regulation, balanced current injection, improved power quality, reduced harmonics, efficient power transfer, and reliable grid synchronization. The coordinated operation of the DC-link capacitor, VSC, PWM control, and PLL synchronization significantly enhances system performance and makes the proposed system suitable for modern smart grid and sustainable energy applications.

4.9 Discussion of Results

The simulation results obtained from the MATLAB/Simulink model of the proposed hybrid photovoltaic and wind energy system demonstrate the effectiveness of the implemented control and stabilization techniques in achieving stable and reliable grid-connected operation. The results show that renewable energy fluctuations caused by

variations in solar irradiance and wind speed can significantly affect voltage, current, and power quality if proper control mechanisms are not applied.

Initially, the wind energy subsystem produces fluctuating DC output during startup due to changing mechanical and electrical conditions. However, the voltage gradually stabilizes, confirming proper operation of the turbine, generator, and rectifier. Before stabilization, the combined PV-wind output exhibits unstable voltage and current waveforms with oscillations, distortion, and transient peaks, indicating poor power quality and unsuitable grid integration conditions.

After implementation of the DC-link capacitor, Voltage Source Converter (VSC), Pulse Width Modulation (PWM), and Phase Locked Loop (PLL) synchronization system, significant improvement is observed. The voltage and current waveforms become smooth, balanced, and nearly sinusoidal with reduced fluctuations and harmonic distortion. The DC-link capacitor effectively stabilizes renewable power variations, while the PWM-controlled inverter ensures stable AC output and improved waveform quality.

The PLL synchronization system successfully matches inverter output with grid voltage and frequency, enabling smooth power injection into the utility grid. Active and reactive power control also improve system stability, voltage regulation, and overall efficiency. The hybrid combination of photovoltaic and wind energy sources further enhances reliability because both sources complement each other under varying environmental conditions.

Overall, the simulation results confirm stable voltage regulation, improved power quality, reduced harmonics, efficient power transfer, and reliable grid synchronization. The proposed hybrid renewable energy system therefore demonstrates good suitability for modern smart grid and sustainable energy applications.

Chapter 5

CONCLUSION AND FUTURE SCOPE

5.1 Summary of Work

The present research work focused on the modelling, simulation, and grid integration of a hybrid renewable energy system based on photovoltaic and wind energy sources using MATLAB/Simulink. The main objective was to develop a stable and efficient renewable energy system capable of supplying reliable power to the utility grid under varying environmental conditions.

Initially, detailed studies were carried out on photovoltaic systems, wind energy conversion systems, DC-link stabilization, Voltage Source Converters (VSC), PWM control, and PLL-based grid synchronization techniques. The photovoltaic subsystem and wind energy subsystem were individually developed and analyzed in MATLAB/Simulink. The PV system converts solar energy into DC power, while the wind subsystem converts wind energy into electrical power using a wind turbine, PMSG, and rectifier.

Both renewable sources were integrated through a common DC-link capacitor, which stabilizes voltage fluctuations and ensures smooth power transfer. A PWM-controlled Voltage Source Converter was used to convert DC power into AC power suitable for grid integration, while PLL synchronization ensured proper matching of inverter output with the utility grid.

Simulation results showed that before stabilization, the system exhibited fluctuating voltage and current waveforms due to renewable energy intermittency. After implementation of the DC-link, VSC, PWM, and PLL control mechanisms, significant improvement was observed in voltage stability, current regulation, power quality, and synchronization performance. The waveforms became smooth and nearly sinusoidal with reduced harmonic distortion and stable power transfer.

The results also confirmed improved active and reactive power control, near-unity power factor operation, and reliable grid-connected performance. The hybrid combination of photovoltaic and wind energy sources enhanced system reliability by providing more continuous power generation under changing environmental conditions. Overall, the research successfully demonstrated the effectiveness of the proposed hybrid PV-wind renewable energy system for stable, efficient, and reliable grid integration suitable for modern smart grid and sustainable energy applications.

.5.2 Key Findings

The research work on the hybrid photovoltaic and wind energy system produced several important findings related to renewable energy integration, voltage stabilization, power quality improvement, and grid synchronization. The MATLAB/Simulink simulation results demonstrated that combining solar and wind energy sources with proper control techniques provides stable and reliable renewable power generation suitable for grid-connected applications.

One of the major findings is that standalone renewable energy systems are highly unstable due to variations in solar irradiance and wind speed. Before stabilization, the system showed fluctuating voltage and current waveforms, oscillations, harmonic distortion, and unstable power transfer, making direct grid integration unsuitable.

The study also found that the hybrid PV-wind configuration improves reliability and continuity of power generation because both renewable sources complement each other under varying environmental conditions. The DC-link capacitor played an important role in stabilizing voltage fluctuations and maintaining smooth power transfer between renewable sources and the inverter.

Another key finding is the effectiveness of the PWM-controlled Voltage Source Converter (VSC), which converted fluctuating DC power into stable three-phase AC output with reduced harmonic distortion. After stabilization, the voltage and current waveforms became smooth, balanced, and nearly sinusoidal, confirming improved inverter operation and power quality.

The Phase Locked Loop (PLL) synchronization system successfully maintained proper phase and frequency matching with the utility grid, enabling stable and reliable power

injection. The system also achieved improved active and reactive power control with near-unity power factor operation.

Overall, the results confirmed stable voltage regulation, reduced harmonics, improved power quality, efficient power transfer, and reliable grid synchronization, demonstrating the suitability of the proposed hybrid renewable energy system for smart grid and sustainable energy applications.

5.3 Advantages of Proposed System

The proposed hybrid photovoltaic and wind energy system offers several advantages over standalone renewable energy systems and conventional power generation methods. The integration of solar and wind energy sources along with advanced control techniques improves system reliability, stability, power quality, and renewable energy utilization.

One of the major advantages is improved continuity of power generation. Since solar and wind sources complement each other under varying environmental conditions, the system provides more reliable and continuous power compared to standalone renewable systems.

Another important advantage is enhanced voltage stability. The DC-link capacitor reduces voltage fluctuations by balancing renewable power variations, ensuring stable inverter operation and smooth power transfer.

The system also improves power quality through the PWM-controlled Voltage Source Converter, which generates balanced sinusoidal voltage and current waveforms with reduced harmonic distortion. This makes the system suitable for grid-connected operation.

Efficient grid integration is achieved using PLL synchronization, which maintains proper phase and frequency matching between inverter output and utility grid voltage. The system also supports improved active and reactive power control with near-unity power factor operation, reducing losses and improving efficiency.

Another advantage is reduced dependence on fossil fuels and lower environmental pollution due to the use of clean renewable energy sources. The hybrid configuration further improves renewable energy utilization efficiency and system reliability.

The proposed system also provides flexibility for future expansion, including integration of battery storage systems, intelligent controllers, and smart grid technologies. Overall, the system offers stable operation, improved power quality, reliable grid integration, and sustainable renewable energy generation suitable for modern power systems.

5.4 Limitations of Work

Although the proposed hybrid photovoltaic and wind energy system showed stable and reliable performance through MATLAB/Simulink simulation studies, certain limitations are associated with the present work. The study is mainly based on simulation analysis, and practical hardware implementation or experimental validation was not carried out. Therefore, real-time factors such as switching delays, thermal effects, hardware losses, and practical component limitations may not be fully represented.

Another limitation is the simplified modelling of environmental conditions. Solar irradiance and wind speed variations were applied under predefined conditions, whereas practical renewable energy systems experience highly random and unpredictable variations.

The present work also does not include Maximum Power Point Tracking (MPPT) techniques, which could further improve renewable energy utilization and system efficiency. In addition, battery energy storage systems were not considered, limiting long-term energy storage capability during low renewable generation periods.

The study mainly focuses on grid-connected operation and does not analyze standalone or islanded modes. Fault analysis, protection mechanisms, and detailed harmonic analysis such as THD calculation were also not included.

The proposed control strategy is based on conventional PWM and PLL techniques, while advanced intelligent control methods such as fuzzy logic and AI-based control were not considered. Economic analysis and cost evaluation of the system were also beyond the scope of this work.

Despite these limitations, the research successfully demonstrates the modelling, stabilization, control, and grid integration capability of the proposed hybrid PV-wind renewable energy system through detailed simulation analysis.

5.5 Future Scope

The present research work provides a strong foundation for future development of hybrid renewable energy systems. Several advanced techniques and technologies can be incorporated to further improve system performance, efficiency, and practical applicability.

One important future scope is the implementation of Maximum Power Point Tracking (MPPT) techniques for both photovoltaic and wind energy systems to maximize power extraction under varying environmental conditions. Integration of battery energy storage systems can also improve continuity of power supply and enhance energy management during low renewable generation periods.

Future work may include practical hardware implementation and experimental validation of the proposed system to verify simulation results under real operating conditions. Advanced intelligent control methods such as fuzzy logic, neural networks, and AI-based optimization can also be used to improve system stability, synchronization, and power quality.

Further improvements may include harmonic reduction techniques, detailed fault analysis, and protection schemes for safe and reliable operation. The proposed system can also be extended for smart grid and microgrid applications by integrating distributed generation, intelligent energy management, and communication systems.

Electric vehicle charging integration, IoT-based monitoring, and real-time simulation techniques can also be explored in future studies. In addition, economic analysis and optimization of renewable energy systems can be carried out for large-scale practical implementation.

Overall, the proposed hybrid photovoltaic and wind energy system has significant future potential for sustainable energy generation, smart grid development, and modern renewable power system applications.

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