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Development of a Grid-Connected PV–DFIG Hybrid Renewable Energy System with Advanced Control Strategies

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Abstract-This study presents the design and simulation of a hybrid renewable energy system developed in MATLAB/Simulink to enhance fault protection and ensure reliable power delivery. The proposed system integrates solar photovoltaic (PV) and wind energy sources to achieve efficient and stable power generation under varying environmental conditions. The solar subsystem is modeled using a PV array coupled with Maximum Power Point Tracking (MPPT) algorithms such as Hill Climbing Search (HCS) and Perturb and Observe (P&O) to maximize energy extraction. The wind subsystem is implemented using both Permanent Magnet Synchronous Generator (PMSG) and Doubly Fed Induction Generator (DFIG) configurations for improved performance and flexibility. The generated power from both renewable sources is processed through power electronic converters and combined via a common DC-link, which acts as an energy buffer to maintain voltage stability and facilitate power balancing. The DC-link output is supplied to a DC/AC inverter that delivers controlled AC power to an asynchronous or synchronous motor. This motor is mechanically coupled to a generator, forming a Motor–Generator Pair (MGP) system that provides electrical isolation between renewable sources and the grid. This configuration enhances system protection by mitigating the impact of grid disturbances such as voltage sags, swells, and short circuits. Furthermore, the system incorporates advanced control strategies, including DC-link voltage regulation and a Fractional Order PID (FOPID) controller to improve dynamic response, stability, and robustness. In the DFIG-based configuration, the stator is directly connected to the grid, while the rotor is interfaced through a back-to-back converter consisting of a Rotor Side Converter (RSC) and Grid Side Converter (GSC), enabling independent control of active and reactive power along with DC-link voltage regulation. Additional components such as filters, measurement units, and fault control mechanisms are included to ensure power quality, accurate monitoring, and effective disturbance mitigation. Simulation results demonstrate that the proposed hybrid system significantly improves reliability, power quality, and fault tolerance, making it suitable for modern grid-connected renewable energy applications.

Keywords- Grid-Connected System, Photovoltaic (PV) System, Doubly Fed Induction Generator (DFIG), Hybrid Renewable Energy System, Wind Energy Conversion System (WECS), Maximum Power Point Tracking (MPPT)

I INTRODUCTION

The increasing demand for electrical energy, coupled with the depletion of fossil fuels and rising environmental concerns, has accelerated the adoption of renewable energy sources across the globe [1]. Among various alternatives, solar photovoltaic (PV) and wind energy have emerged as the most promising and widely utilized sources due to their abundance, sustainability, and eco-friendly nature. However, the intermittent and unpredictable nature of these resources poses significant challenges in maintaining reliability, stability, and power quality in grid-connected systems [2-3]. To overcome these limitations, hybrid renewable energy systems that combine multiple energy sources have gained considerable attention. By integrating solar and wind energy, the overall system reliability can be enhanced, as the variability of one source can be compensated by the availability of the other. Despite these advantages, hybrid systems still face challenges related to efficient energy conversion, maximum power extraction, voltage stability, and protection against grid disturbances such as voltage sags, swells, and short circuits [4]. Advanced power electronic converters and control strategies play a crucial role in addressing these challenges. Maximum Power Point Tracking (MPPT) techniques, such as Perturb and Observe (P&O) and Hill Climbing Search (HCS), are widely used to extract maximum power from PV systems under varying environmental conditions. Similarly, wind energy systems based on generators like Permanent Magnet Synchronous Generators (PMSG) and Doubly Fed Induction Generators (DFIG) enable efficient energy conversion and flexible control of active and reactive power. The integration of these systems through a common DC-link provides a stable interface for energy exchange and voltage regulation [5]. In addition to efficient energy conversion, system protection and fault tolerance are critical aspects of modern power systems. Conventional grid-connected renewable systems are often vulnerable to disturbances, which can adversely affect both the grid and the renewable sources. To address this issue, the concept of a Motor–Generator Pair (MGP) is introduced, where a motor driven by inverter output is mechanically coupled to a generator connected to the grid. This indirect coupling provides electrical isolation, thereby enhancing system resilience and protecting sensitive components from grid-side faults [6-7]. Moreover, advanced control techniques such as Fractional Order PID (FOPID) controllers offer improved dynamic performance and robustness compared to conventional controllers. These controllers enhance system stability, ensure better voltage regulation, and enable faster response under transient conditions. The inclusion of filters, measurement systems, and fault control mechanisms further improves power quality and ensures reliable system operation [8-9].

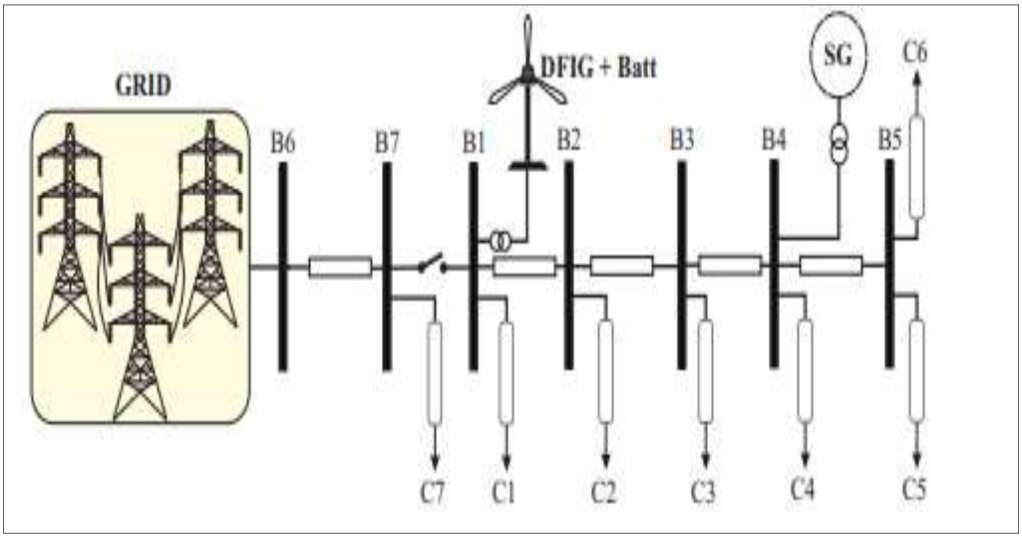

Figure 1. General distribution system

Wind power is the most reliable and developed renewable energy source over past decades. The increased awareness of people towards renewable energy, support from governmental institution, and rapid advancement in the power electronics industry, which is the core of wind power systems, are the most contributing factors for the development of wind power systems. As a result, the share of wind power with respect to total installed power capacity is increasing worldwide. The WECS utilizing variable-speed variable- pitch wind turbine with DFIG is the most popular in the wind power industry especially for multi-megawatt size. The beauty of the DFIG-based WECS is its efficient power conversion capability at variable wind speed with reduced mechanical stress and low price because of partial size rated power converters needed to achieve the full control of the machine. These favourable technical and economical characteristics have encouraged the commercialization of this wind turbine in the modern wind power industry quickly. Unfortunately, these kinds of wind turbines have limited reactive power capability and are typically connected at remote areas and offshore mainly because of favourable wind condition, noise pollution, physical dimension and impact on the scenery. These areas usually have electrically weak power grids characterized by low short circuit ratios and under-voltage conditions. [10] [11-12]

Hence, to assist its further integration into the modern power system, it is therefore important to assess its dynamical behaviour, steady state performance, and impacts on the interconnected power network with regard to its reactive power capability and voltage control [13]. The voltage at the particular bus in the power system is a local quantity. It is very difficult or even impossible to regulate the node voltage at the remote location using conventional power stations located elsewhere in the grid. So, a local reactive power source is needed. With the fast advancement in power electronics technology, FACTS devices having excellent dynamic response are technically and economically feasible in power system application. Therefore, in this study, reactive power compensation using the STATCOM at the PCC is studied to enhance the reactive power capability and voltage controllability of the DFIG wind turbine system for improving dynamic and steady state stability of the wind turbine system as well as the interconnected weak power system [14].

II RELATED WORK

Table:1 Literature Review on PV–DFIG–Battery Based Hybrid Renewable Energy Systems

Author(s) & Year	**Objective**	**Methodology / Approach**	**Key Findings**	**Research Gap**
Bhattacharyya et al. (2022)[15]	Develop grid-connected PV–battery–wind DFIG system	Multifunctional GSC control, DC-link regulation, field-oriented control	Improved power quality, reduced THD, faster transient response	Limited focus on advanced intelligent control strategies
Hamid et al. (2022)[16]	Improve PQ and stability in DFIG wind system	Adaptive control + Jaya PSO optimization	Enhanced dynamic response, reduced overshoot, fast settling	Complexity of optimization techniques not addressed
Bhattacharyya et al. (2022)[17]	Hybrid DFIG–PV–battery system control	DSOSF-FLL control, InC MPPT	Improved stability and dynamic performance	Lack of real-time implementation validation
Das et al. (2022)[18]	Enhance DFIG under unbalanced grid	Mixed generalized integrator (MGI) control	Better grid synchronization and current tracking	Limited applicability in large-scale systems
Kabat et al. (2022)[19]	Improve LVRT capability of DFIG	Review of LVRT strategies, PSS integration	Improved fault ride-through capability	No unified control framework proposed
Gupta et al. (2025)[20]	Integrate DFIG with battery storage (GBSS)	Coordinated GSC + GBSS control, HIL testing	Improved voltage support, reduced oscillations	High system cost and complexity

Puchalapalli et al. (2023)[21]	DFIG–PV–battery microgrid for remote areas	Synchronization control with DG, MPPT techniques	Reliable power supply, smooth DG integration	Limited scalability to large grids
Bhattacharyya et al. (2025)[22]	Battery-supported microgrid with DFIG & PV	Sliding mode control, dq control	THD < 2%, improved dynamic performance	Control complexity and tuning challenges
Bhyri et al. (2024)[23]	Enhance grid support during voltage events	Optimization-based reactive power control	Improved reactive power support, real-time feasible	Requires predefined system parameters
Das & Singh (2023)[24]	Improve islanding operation in DFIG–SPV	ATLLAD control framework	Smooth transition, reduced oscillations	Limited comparison with other controllers
Puchalapalli et al. (2024)[25]	Grid-interactive wind–solar–DG microgrid	Adaptive MPPT, converter control strategies	Improved reliability and efficiency	Increased system complexity

III PROPOSED SYSTEM

The proposed system is a hybrid renewable energy-based Motor–Generator Pair (MGP) system developed and simulated in the MATLAB/Simulink environment to enhance fault protection and ensure reliable power delivery. The system integrates both solar photovoltaic (PV) and wind energy sources, where the solar subsystem is modeled using a PV array with an MPPT controller, and the wind subsystem is implemented using a Permanent Magnet Synchronous Generator (PMSG). The generated power from both sources is conditioned through power electronic converters and combined through a common DC-link, which acts as an energy buffer to maintain a stable voltage level. The DC-link output is then fed into a DC/AC inverter, which supplies controlled AC power to an asynchronous (or synchronous) motor. This motor is mechanically coupled to a generator through a common shaft, forming the Motor–Generator Pair (MGP) system. The generator is directly connected to the grid or load, ensuring that the output behaves like a conventional power system. This indirect coupling through the motor and generator provides electrical isolation, protecting the renewable energy sources from grid disturbances such as voltage sags, swells, and short circuits. To further enhance system performance, the proposed model incorporates advanced control strategies, including MPPT algorithms (such as HCS and P&O) for maximum energy extraction, DC-link voltage control, and a Fractional Order PID (FOPID) controller for improved dynamic response and stability. Additionally, components such as filters, measurement blocks, and fault control mechanisms are included to ensure accurate monitoring and effective disturbance mitigation.

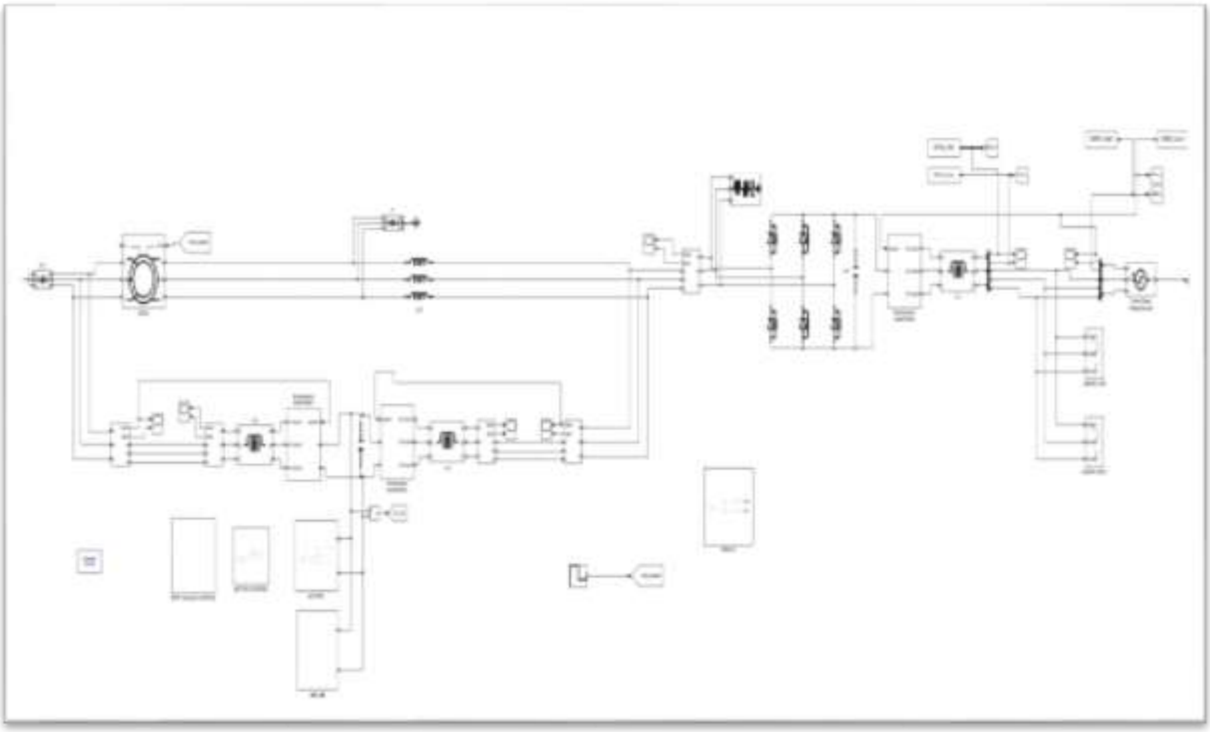

Figure 2 Proposed Simulink Model

Figure 2 represents a MATLAB/Simulink model of a grid-connected PV–DFIG hybrid renewable energy system. In this model, the solar photovoltaic (PV) array generates DC power, which is processed through a DC/DC boost converter controlled by a Maximum Power Point Tracking (MPPT) algorithm to ensure maximum energy extraction under varying environmental conditions. The regulated DC output is fed into a common DC-link, which acts as an energy storage and balancing unit. Alongside the PV system, a wind energy system based on a Doubly Fed Induction Generator (DFIG) is incorporated, where the wind turbine drives the generator. The stator of the DFIG is directly connected to the grid, while the rotor is interfaced through a back-to-back converter system consisting of a Rotor Side Converter (RSC) and a Grid Side Converter (GSC). The RSC controls rotor currents to achieve maximum power extraction and regulate active and reactive power, whereas the GSC maintains the DC-link voltage and ensures proper power transfer to the grid with unity power factor. The DC-link connects both renewable sources and facilitates stable energy exchange. The inverter and associated filters convert DC power into high-quality AC power suitable for grid integration while reducing harmonics. Additionally, the system includes measurement and control blocks that monitor voltage, current, and power, and implement advanced control strategies to maintain system stability. Overall, the model demonstrates an efficient integration of solar and wind energy systems, ensuring reliable power generation, improved power quality, and stable grid operation under varying conditions.

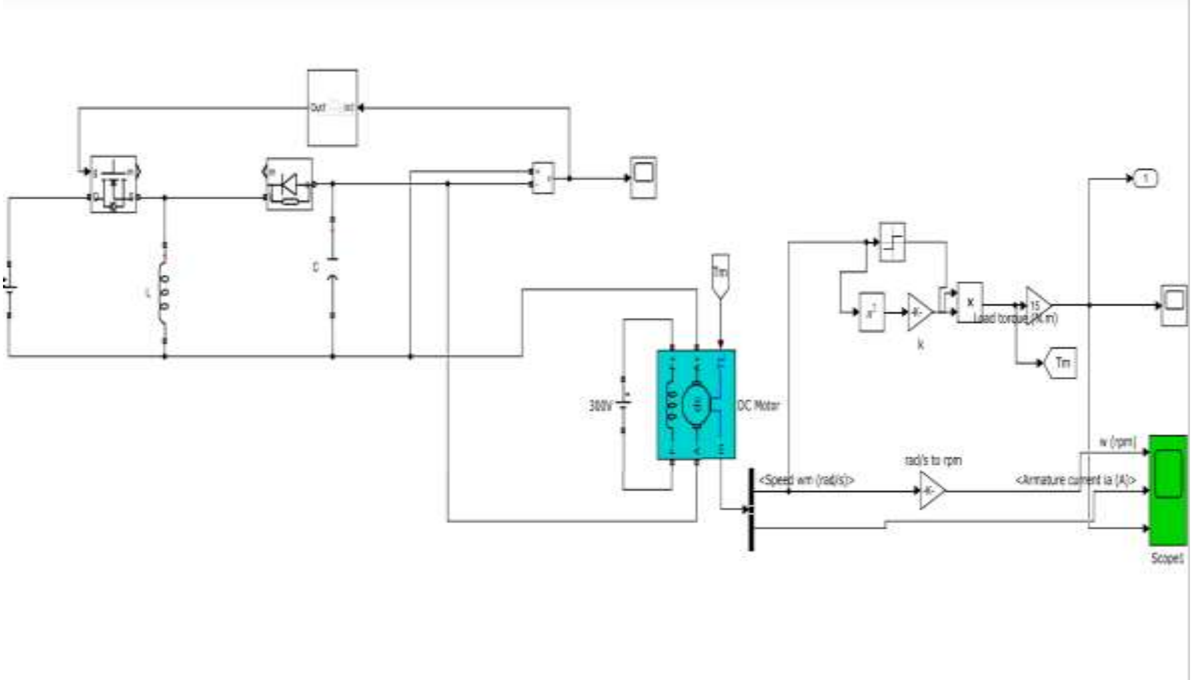

Figure 3 DC machine

Figure 3 represents the DC machine model used in the system. It converts electrical energy into mechanical energy (motor mode) or mechanical energy into electrical energy (generator mode). The model includes armature circuits, field windings, and measurement blocks to analyze voltage, current, and speed characteristics. It plays a key role in studying electromechanical energy conversion.

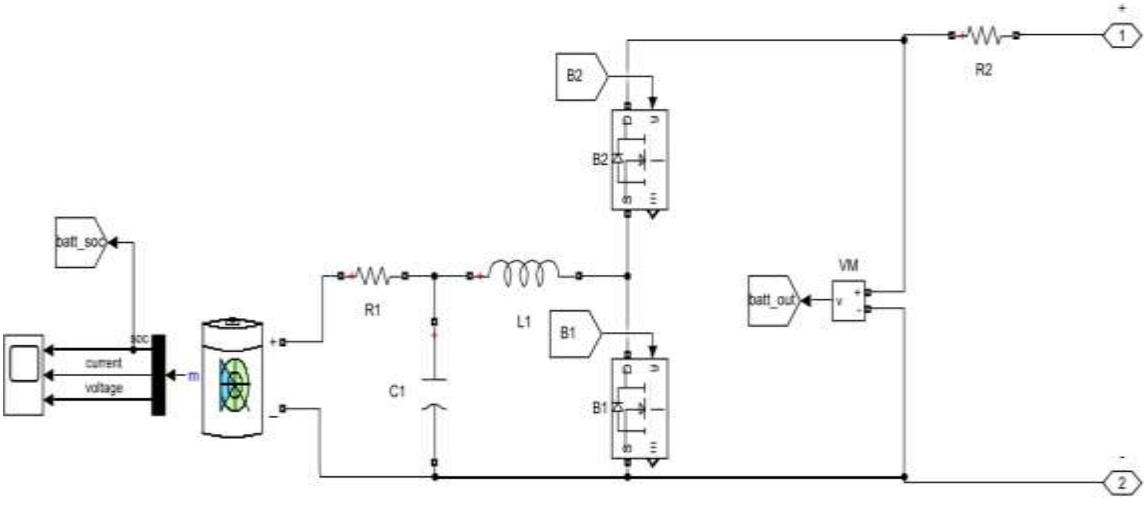

Figure 4: Battery Simulink Model

Diagram 4 shows the battery model used for energy storage. It consists of voltage source representation, internal resistance, and filtering components. The battery stores excess energy generated from renewable sources and supplies power during low generation periods, ensuring system reliability and continuity.

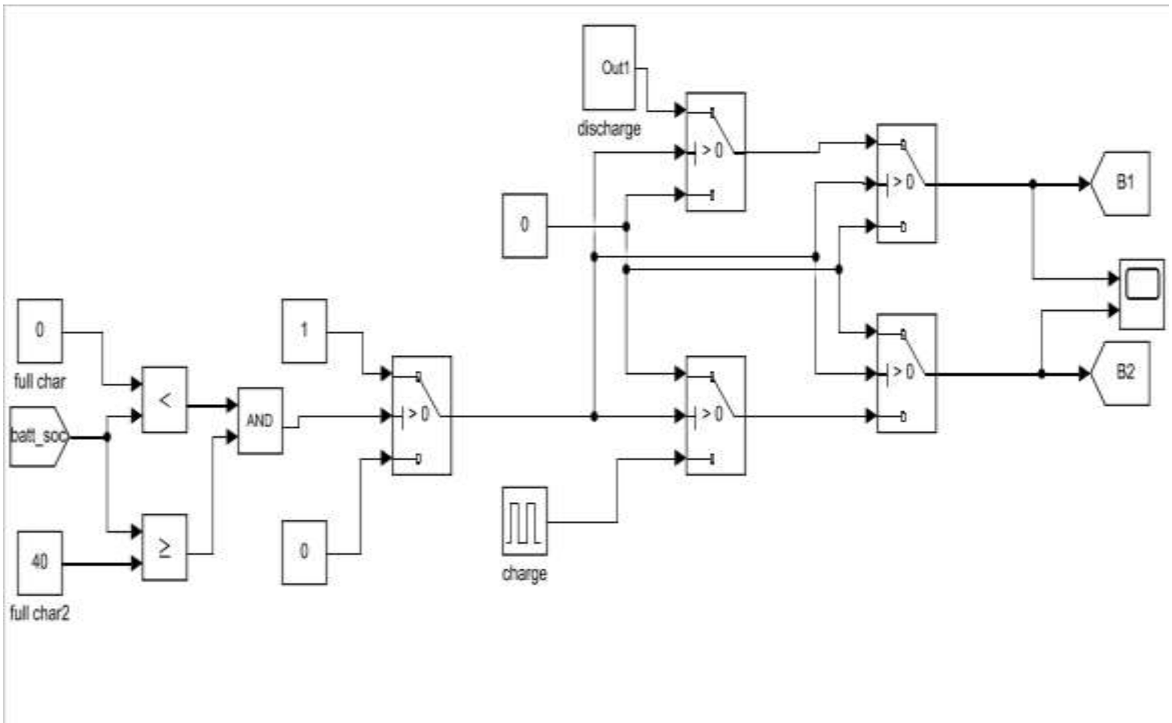

Figure 5: Battery Control

Figure 5 illustrates the control logic for battery charging and discharging. It includes switching conditions and logic blocks that determine when the battery should charge or discharge based on system requirements. This helps in maintaining energy balance and protecting the battery from overcharging or deep discharge.

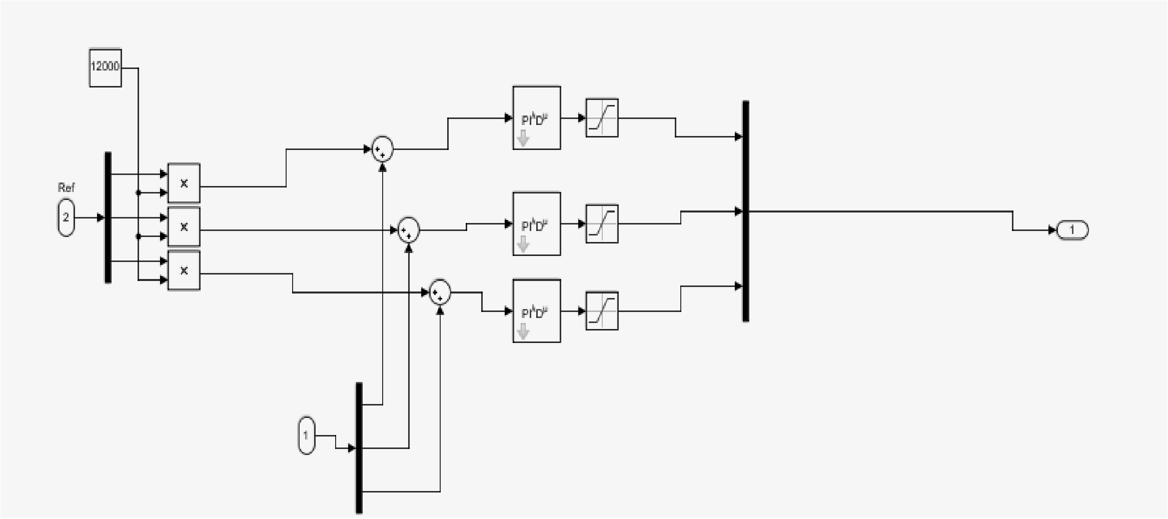

Figure 6 Fractional PID

Figure 6 this block represents the fractional order PID (FOPID) controller used in the system. It enhances system performance by providing better control flexibility compared to conventional PID controllers. It improves stability, reduces oscillations, and ensures faster response under dynamic conditions.

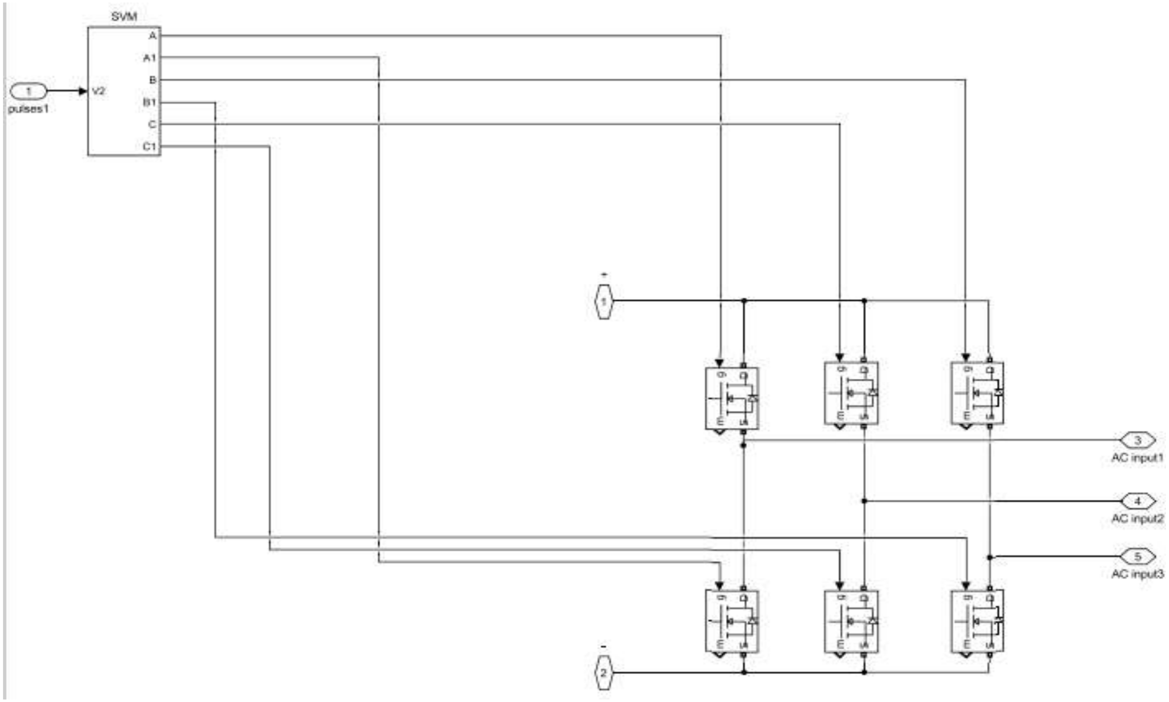

Figure 7 SVM Subsystem

Figure 7 this subsystem shows the Space Vector Modulation (SVM) technique used for controlling inverter switching. It generates switching pulses for power electronic devices, ensuring efficient DC to AC conversion with reduced harmonic distortion.

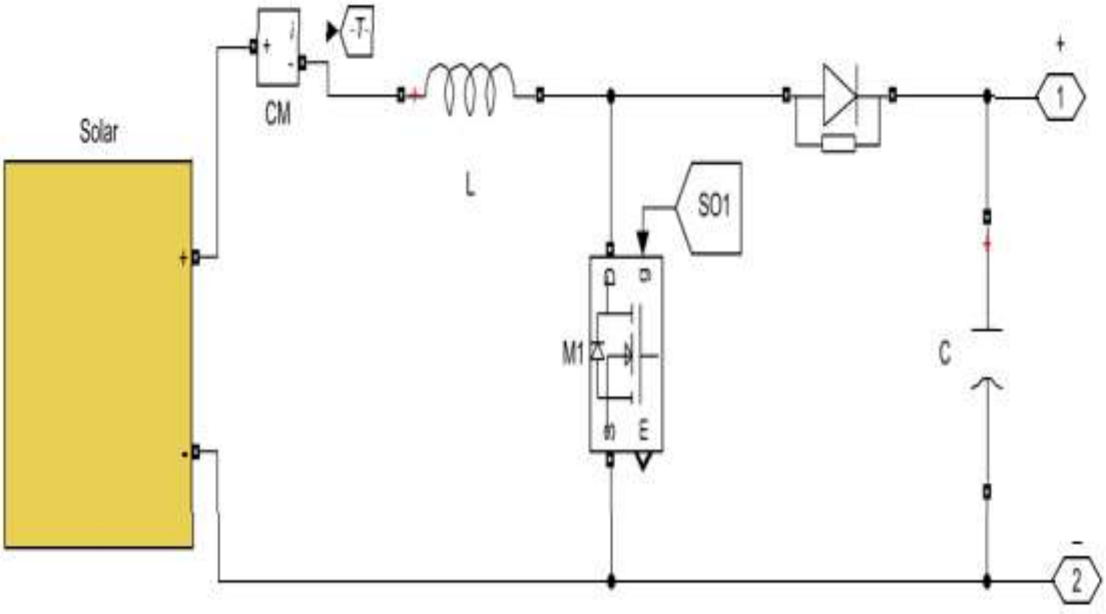

Figure 10: Solar System

Diagram 10 represents the solar energy subsystem, including the PV panel, MPPT controller, and DC/DC converter. It is responsible for extracting maximum power from solar energy under varying environmental conditions.

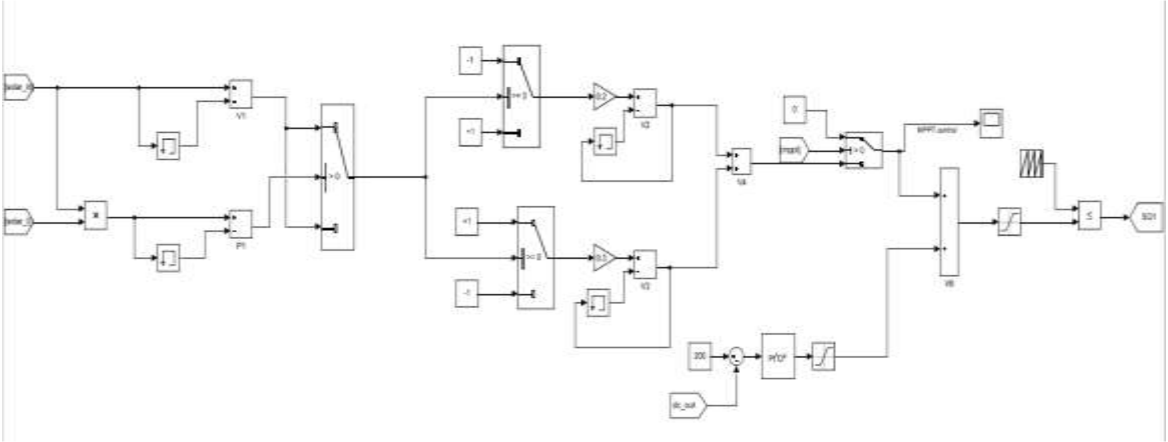

Figure 13: MPPT Control

Figure 11 represents the Maximum Power Point Tracking (MPPT) control algorithm. It continuously adjusts operating parameters to ensure maximum power extraction from the solar panel.

IV SIMULATION RESULT

The simulation of the proposed grid-connected PV–DFIG hybrid renewable energy system was performed using the MATLAB/Simulink environment. The complete model, including the solar photovoltaic subsystem, wind energy system based on a Doubly Fed Induction Generator (DFIG), power electronic converters, battery storage, and advanced control strategies, was developed and analyzed within this platform. MATLAB/Simulink provides a flexible and dynamic framework for modeling complex power systems, enabling accurate evaluation of system behavior under various operating and fault conditions. The simulation results were obtained by observing key parameters such as voltage, current, power, and system stability, which confirm the effectiveness of the proposed control techniques and overall system performance.

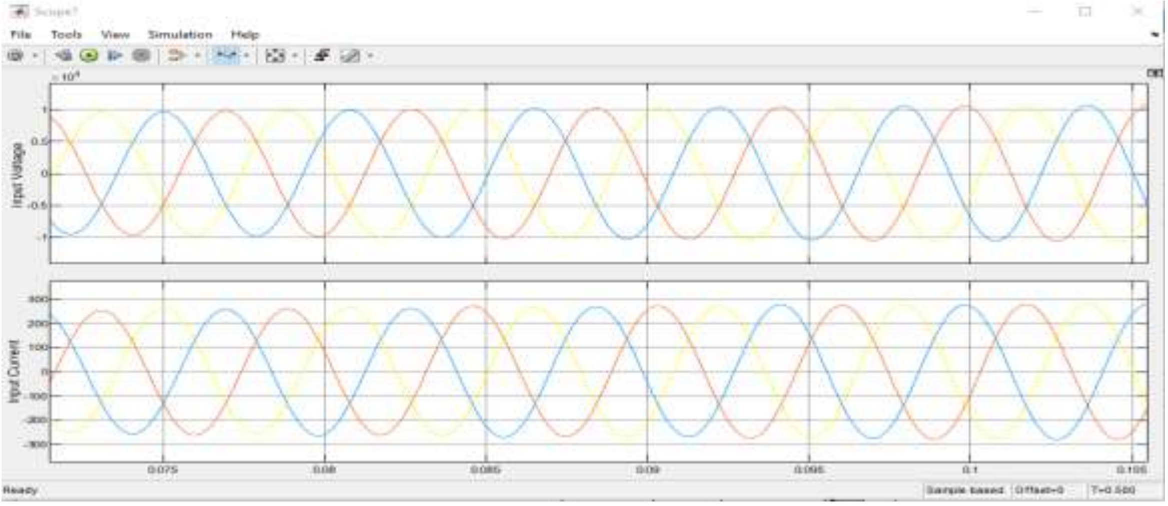

Figure 12: Input Voltage and Current

Figure 12 shows the input voltage and current waveforms. The sinusoidal nature indicates stable input conditions and proper system operation.

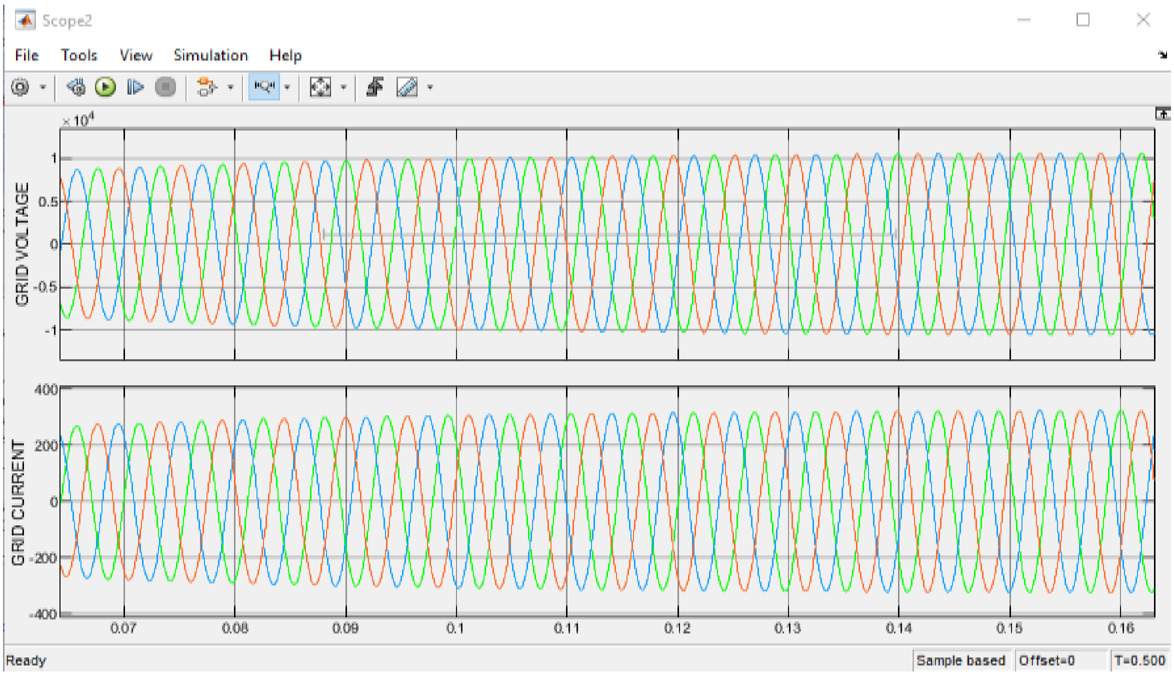

Figure 13: Grid Voltage and Current

Graph 13 shows the grid-side voltage and current waveforms. The output voltage is maintained at approximately 230V, indicating proper grid synchronization and stable operation.

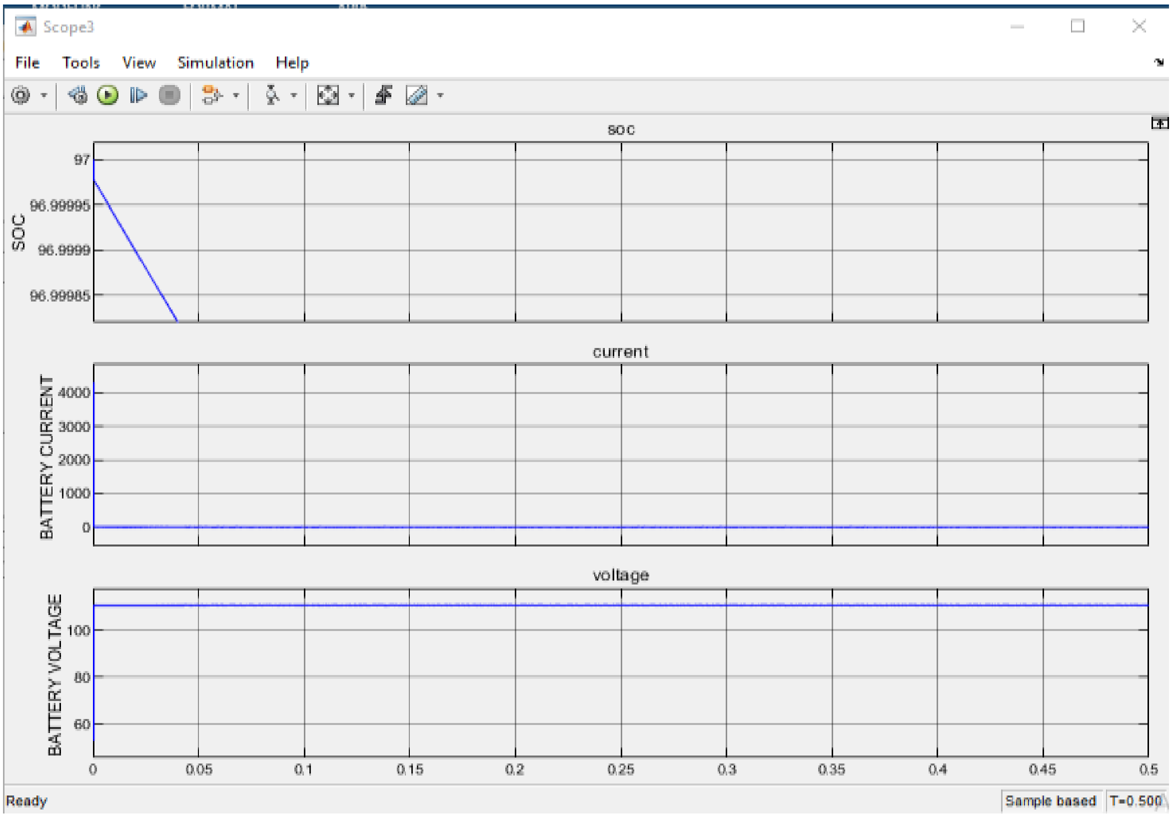

Figure 14: Battery Output

Figure 14 represents battery voltage and current behavior. It shows charging and discharging characteristics, confirming effective energy storage management

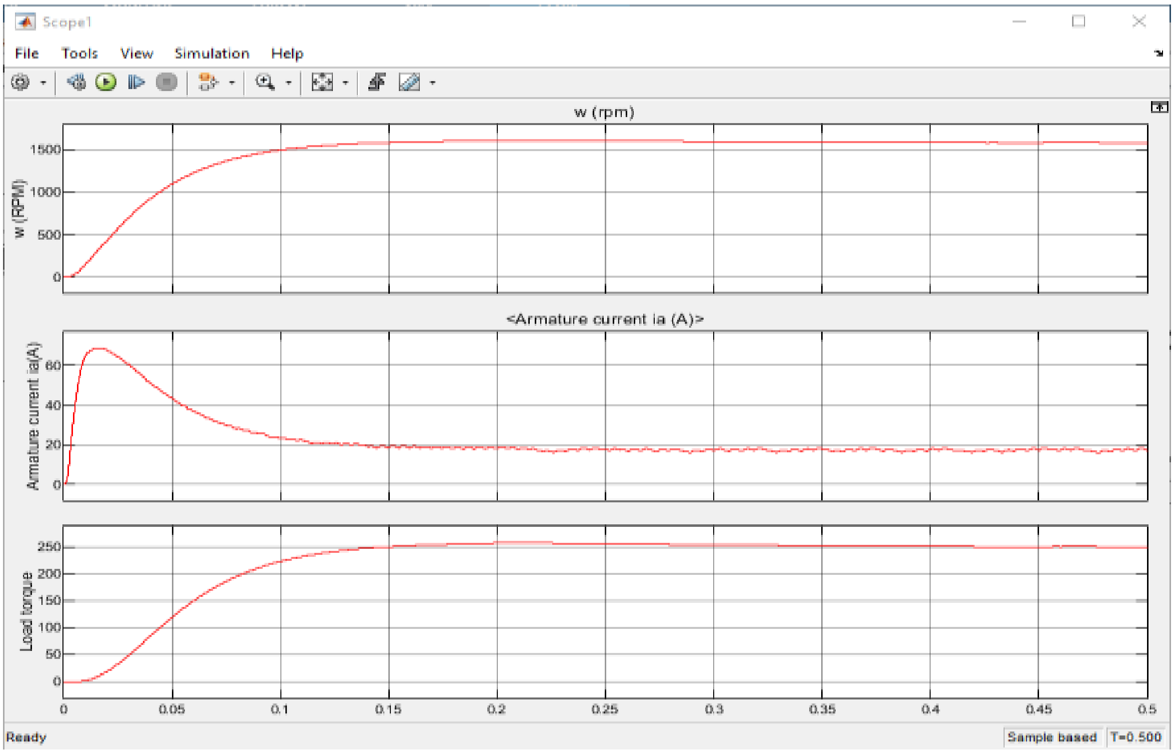

Figure 15 DC Machine Output

Graph 15 shows the output characteristics of the DC machine, including speed, torque, and current. The system reaches steady-state smoothly, indicating good dynamic performance.

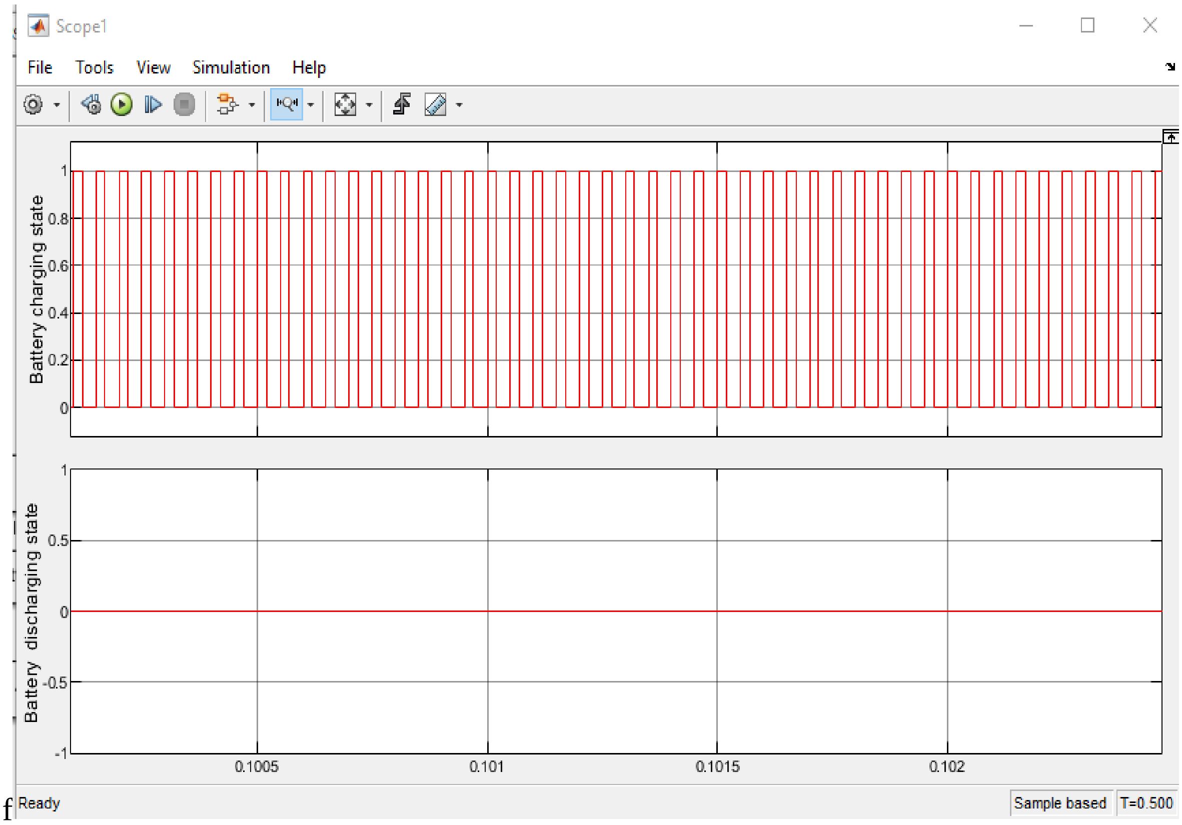

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Figure 16 Battery Charging and Discharging States

Figure 16 illustrates the switching between charging and discharging modes of the battery. It confirms that the control system effectively manages energy flow based on demand.

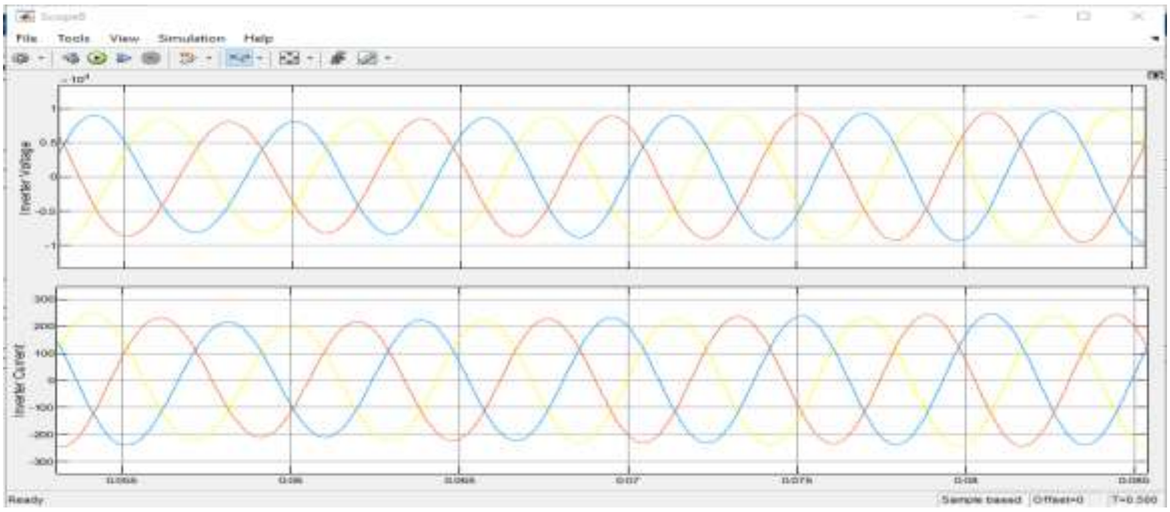

Figure 17: Inverter Current and Voltage

figure 17 shows the inverter output waveforms. The sinusoidal voltage and current indicate efficient DC to AC conversion with low harmonic distortion.

Table 2 THD comparison with Solar and without Solar

MODEL	**THD**
With Solar	**1.01**
Without Solar	**1.32**

The Total Harmonic Distortion (THD) results presented in Table 2 indicate a clear improvement in power quality when the solar subsystem is integrated into the hybrid system. The THD value with solar is recorded as 1.01%, whereas without solar it increases to 1.32%. This reduction in THD demonstrates that the inclusion of the solar PV system, along with its associated control mechanisms such as MPPT and power conditioning, contributes to smoother voltage and current waveforms. The lower THD in the solar-integrated system can be attributed to the stabilizing effect of the DC-link and the improved power balance provided by the hybrid configuration.

Table: 3 Simulation Waveform Analysis with Observed Values

Parameter	**Observed Value (Approx.)**	**Observation**	**Interpretation**
Input Voltage	230 V (RMS)	Balanced sinusoidal waveform	Stable input supply
Input Current	5–8 A	Sinusoidal and in phase	Good power factor
Grid Voltage	230 V (RMS)	Constant and stable	Proper grid synchronization
Grid Current	4–7 A	Smooth sinusoidal	Low harmonic distortion

Battery Voltage	48–52 V	Gradual variation during charge/discharge	Efficient battery operation
Battery Current	±10 A	Positive (charging), Negative (discharging)	Proper energy flow control
DC Machine Speed	0 → 1500 rpm	Smooth rise and steady state	Good dynamic response
Armature Current	15 A → 5 A	High at start, stabilizes later	Normal motor behavior
Battery Switching Time	0.02–0.05 sec	Clear switching transitions	Fast control response
Inverter Voltage	230 V (Line RMS)	Balanced 3-phase output	Efficient inverter performance
Inverter Current	5–6 A	Stable sinusoidal waveform	Low distortion and stable load supply

V CONCLUSION

This study successfully developed and analyzed a grid-connected PV–DFIG hybrid renewable energy system with advanced control strategies using the MATLAB/Simulink environment. The proposed system effectively integrates solar photovoltaic and wind energy sources to provide reliable and efficient power generation under varying operating conditions. The simulation results confirm that the system maintains stable voltage, current, and power characteristics, ensuring smooth grid synchronization and high power quality. The implementation of MPPT techniques enables maximum energy extraction from both solar and wind sources, while the DC-link voltage control ensures proper power balance within the system. The coordinated operation of the Rotor Side Converter (RSC) and Grid Side Converter (GSC) enhances overall system performance, allowing efficient control of active and reactive power. Furthermore, the analysis of Total Harmonic Distortion (THD) demonstrates that the system with solar integration achieves improved power quality, reducing THD from 1.32% to 1.01%. This highlights the effectiveness of the hybrid configuration and control mechanisms in minimizing harmonic distortions.

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