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Power Quality Improvement Performance of PV and Grid Connected System

Pradeep Kumar Singh
Assistant Professor, Electrical Engineering, Prabhat Engineering College, Kanpur Dehat
pradeepsingh200185@gmail.com

Akash Verma
Research Scholar, Prabhat Engineering College
akashv242492@gmail.com

Krishna Singh Parmar
Research Scholar, Prabhat Engineering College
gaurabthakur693@gmail.com

Nijam Akhtar
Research Scholar, Prabhat Engineering College
nijamakhtarnijam@gmail.com

ABSTARCT – This paper presents the design and simulation of a hybrid renewable energy system integrating solar photovoltaic (PV), battery storage, and fuel cell subsystems for improved power quality and reliable energy supply. The proposed system is developed in the MATLAB/Simulink environment, where the PV array generates DC power that is regulated using a DC/DC boost converter with Maximum Power Point Tracking (MPPT) to ensure maximum energy extraction. The battery subsystem, connected through a bidirectional DC–DC converter, enables efficient energy storage and management by supporting both charging and discharging operations based on system demand. Additionally, a fuel cell subsystem is incorporated as a backup power source to enhance system reliability during low renewable generation conditions. All energy sources are integrated through a common DC-link, which acts as a voltage stabilization unit. The DC-link output is then converted into AC using a voltage source inverter (VSI) and supplied to the load or grid through appropriate filtering components to reduce harmonics and improve power quality. Advanced control strategies are implemented to regulate DC-link voltage, manage energy flow, and ensure stable system operation under varying conditions. The simulation results demonstrate that the proposed system achieves stable voltage regulation, efficient energy management, reduced harmonic distortion, and improved dynamic response, making it suitable for modern grid-connected and standalone renewable energy applications.

Keywords- Grid, MPPT, Battery, fuel cell ANN-DVR, PV

1 INTRODUCTION

the increasing demand for clean and sustainable energy has led to the rapid integration of solar photovoltaic (PV) systems into modern power grids. While PV systems offer significant environmental and economic benefits, their integration into the grid introduces several power quality (PQ) challenges, such as voltage fluctuations, harmonic distortion, flicker, and reactive power imbalance. These issues arise due to the intermittent nature of solar energy and the extensive use of power electronic converters in grid-connected systems [1-2].

Power quality is a critical factor in ensuring the reliable and efficient operation of electrical systems. Poor power quality can lead to equipment malfunction, increased losses, reduced system efficiency, and instability in grid operation. Therefore, improving PQ in PV-grid connected systems has become a major area of research [3]. Advanced control techniques and converter topologies are required to maintain stable voltage, sinusoidal current, low Total Harmonic Distortion (THD), and proper power factor under varying operating conditions. In a grid-connected PV system, the generated DC power is converted into AC using inverters and injected into the grid. The performance of the inverter and its control strategy plays a key role in maintaining power quality. Techniques such as Maximum Power Point Tracking (MPPT) ensure optimal energy extraction, while grid synchronization methods and filtering techniques help in reducing harmonics and maintaining voltage stability. Additionally, control strategies such as Proportional–Integral (PI), Fractional Order PID (FOPID), and advanced adaptive controllers are widely used to regulate DC-link voltage and improve dynamic performance [4].

Furthermore, hybrid systems combining PV with other energy sources or grid support mechanisms enhance overall system reliability and PQ performance. The integration of energy storage systems and intelligent controllers helps in mitigating the effects of intermittency and maintaining continuous power supply [5]. Proper coordination between system components ensures smooth power flow, reduced disturbances, and improved grid stability. Renewable energy systems (RESs) are one of the most suitable and environmentally friendly solutions to provide electricity within urban and rural areas. On-grid and off-grid electrification based on the generation of power through the installation of renewable energy power systems in urban and rural households have been proven to be capable of delivering high quality and reliable electricity for heating, lighting, and demands alike. Using RESs have many advantages over conventional sources including the following [6]: Wind-solar hybrid systems can provide a steady community-level electricity service, such as residential electrification, also offering the possibility to rural areas to be upgraded through grid connection in the future. Furthermore, in case of installation and use in rural areas, due to their high levels of efficiency, reliability and long term performance, these systems can also be used as an effective backup solution to the public grid in case of natural disasters, emergencies, sudden blackouts or weak grids [7]. The main disadvantage of wind turbines and PV-systems is that naturally variable wind speed and variable solar irradiation cause voltage and power fluctuation problems at the load side. These problems can be solved by using appropriate power converters and proper controllers both for the PV and the wind turbine system. Another significant point is to store the energy generated by wind turbines and PV-systems for future use when no wind and/or no irradiation is available but the user demand exists. For this, an energy storage bank can be incorporated in such a way that the battery stores energy whenever there is excess supply and discharges when there is more demand than supply [8].

The power system is a complex consisting of power generation, delivery or transmission systems. It uses forms of power (such as coal and diesel) or exchanges it into power. The power arrangement comprises equipment related to classification, such as synchronous producer, motors, transformers, switches, conductors, etc [9]. Power plants, transformers, transmission lines, substations, allocation lines, and distribution transformers are the electricity system's six main apparatus. The power generated by the power plant is increased or stepped down through the transformer. Transmission lines transmit power to various transformer stations. The current is transferred to the distribution This work presents a new method of detection to protect distributed generator feed systems. The technique has been tested on allotment buses of 25 kV or below. The current interest in installing dispersed generators in low-voltage buses near customers has created new security engineers' disputes, which differ from traditional radial-based security methods. Therefore, it is necessary to reconsider typical protection configurations, such as closed sleepless monitoring, impedance relay security areas, and the discovery of unexpected islands in circulated generator systems. The island situation is defined as when part of the unusable energy production system is isolated from an effective supply system. It is generally measured undesirable because it can cause potential to injure to existing equipment, cause charge to public utilities, and reduce reliability and power quality. Current island detection methods usually passively and actively monitor over voltage / under voltage and overvoltage / under frequency ratios. However, each technique has ideal sensitive working conditions and insensitive working conditions, and its degree of deterioration in power quality is different, which is called the non-detection zone (NDZ). transformer through a substation, which reduces the current to a suitable value that suits the user [10].

II RELATED WORK

Table1: Literature Review on Power Quality Improvement in Renewable Energy Systems

Author(s) & Year	Objective	Methodology / Approach	Key Findings	Research Gap
G. S. Chawda et al.	Analyze PQ issues due to	Review of 220+ research articles,	Identified methods for detection and	Limited practical implementatio

(2020)[11]	renewable energy integration	feature extraction techniques	classification of PQ disturbances	n of detection techniques
E. Hernández-Mayoral et al. (2023)[12]	Study power quality issues in microgrids	Review of optimization and control strategies in MGs	Improved stability, power balance, and grid synchronization	Lack of unified control framework for hybrid microgrids
N. Kumar et al. (2023)[13]	Optimize smart grid power generation and scheduling	Genetic Algorithm (GA)-based optimization	Improved load scheduling and dynamic compensation of renewable fluctuations	High computational complexity and real-time challenges
N. Kanagaraj et al. (2023)[14]	Improve PQ using STATCOM in renewable systems	qZSI-based STATCOM with SOGI and Fuzzy Logic Control	Reduced harmonics and improved reactive power compensation	Complexity in controller tuning and implementation
Z. Reguieg et al. (2024)[15]	Reduce harmonics in grid-connected PV and wind systems	Series Active Power Filter (SAPF) implementation	Significant reduction in voltage harmonics and disturbances	Limited comparison with other filtering techniques
J. Jayaram et al. (2022)[16]	Develop hybrid AC–DC microgrid with renewable sources	PMSG wind, PV with MPPT, BESS, interlinking converter	Maintained THD < 5%, improved power exchange and reliability	Limited scalability for large grid applications

B. H. Alajrash et al. (2024)[17]	Evaluate FACTS devices in renewable-integrated systems	Comparative analysis of SVC, TCSC, UPFC, DPFC	Improved voltage stability, frequency control, and power flow	High cost and complexity of FACTS integration

III PROPOSED SYSTEM

The proposed method provides a fast response and effective sag compensation capabilities. In addition, in order to detect voltage sag, a Space Vector Modulation (SVM) is employed to estimate three-phase voltages. By using SVM, the voltage sag can be detected faster than other conventional methods. Therefore DVR can compensate voltage sag quickly and accurately. The obtained results that are simulated in Matlab/Simulink indicate that the proposed method can mitigate the balanced and unbalanced voltage sag types efficiently in the distribution networks. The figure 1 represents a MATLAB/Simulink model of a grid-connected photovoltaic (PV) system integrated with advanced power conditioning and control components. The system begins with a renewable energy source subsystem (PV-based DC source) whose output is regulated and fed into a DC-link. The DC-link acts as a central energy storage and stabilization unit, ensuring a constant DC voltage despite variations in generation. From the DC-link, power is supplied to a three-phase voltage source inverter (VSI), which converts DC power into AC power. The inverter is controlled through switching devices and gating signals to produce a balanced three-phase output. To improve power quality, the inverter output is passed through an LCL filter, which effectively reduces harmonics and ensures smooth sinusoidal voltage and current waveforms. The filtered output is then connected to the Point of Common Coupling (PCC), where it interfaces with the utility grid and local load. A Dynamic Voltage Restorer (DVR) is incorporated in the system to mitigate voltage disturbances such as sags and swells, thereby enhancing grid stability and protecting sensitive loads.

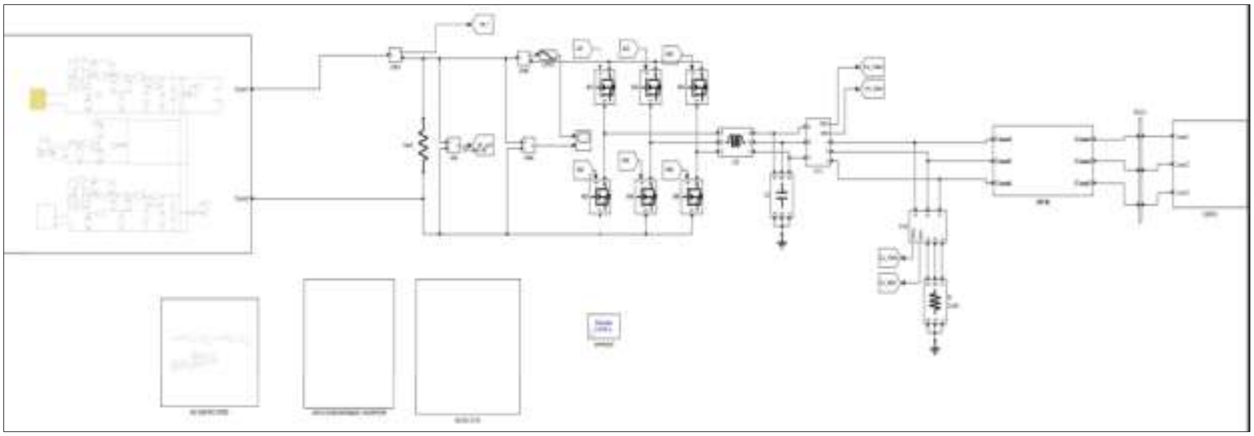

Figure 2 Proposed Simulink Model

This block models a solar cell as a parallel combination of a current source, two exponential diodes and a parallel resistor, Rp, that are connected in series with a resistance Rs. The output current I is given by:

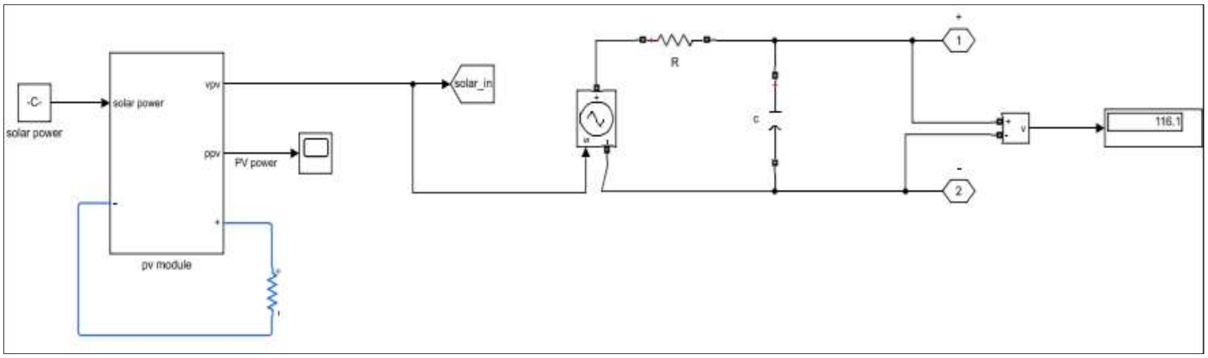

Figure 3 solar equivalent circuit

I = Iph - Is*(e^((V+I*Rs)/(N*Vt))-1) - Is2*(e^((V+I*Rs)/(N2*Vt))-1) - (V+I*Rs)/Rp

Where Is and Is2 are the diode saturation currents, Vt is the thermal voltage, N and N2 are the quality factors (diode emission coefficients) and Iph is the solar-generated current. Models of reduced complexity can be specified in the mask. The quality factor varies for amorphous cells, and typically has a value in the range of 1 to 2. The PS input Ir is the irradiance (light intensity) in W/m^2 falling on the cell. The solar-generated current Iph is given by Ir*(Iph0/Ir0) where Iph0 is the measured solar-generated current for irradiance Ir0.

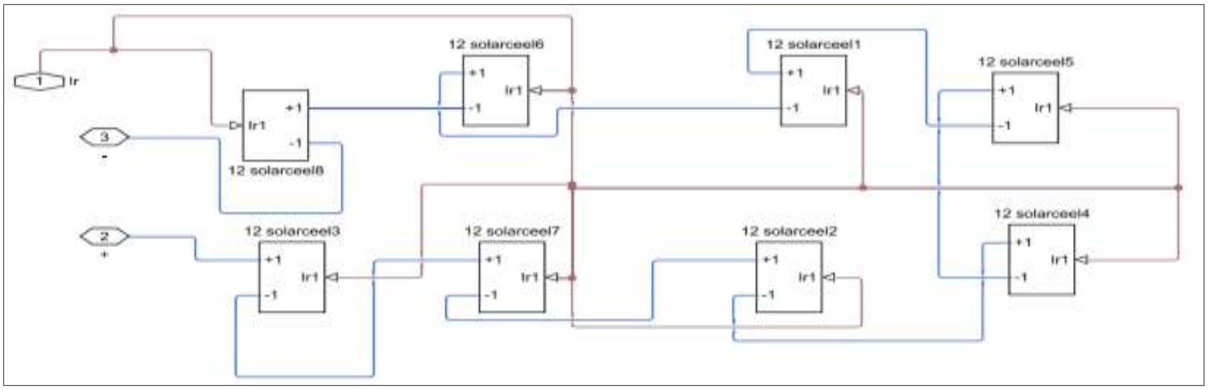

Figure 4 solar cell subsystem

Operationally the solar cell array is there to fulfill a defined electrical function. This can usually be reduced to a specified operating voltage and an expected peak daily or annual current output. Where the solar cell is used as a trigger to switch the product on in the dark. the electrical characteristic at low light level is also important. The voltage is proportional to the number of series-connected cells, while the current is related to the cell area. In monolithically interconnected thin-film arrays, these factors can bear a direct relationship to the dimensions of the solar cell array

Implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type.

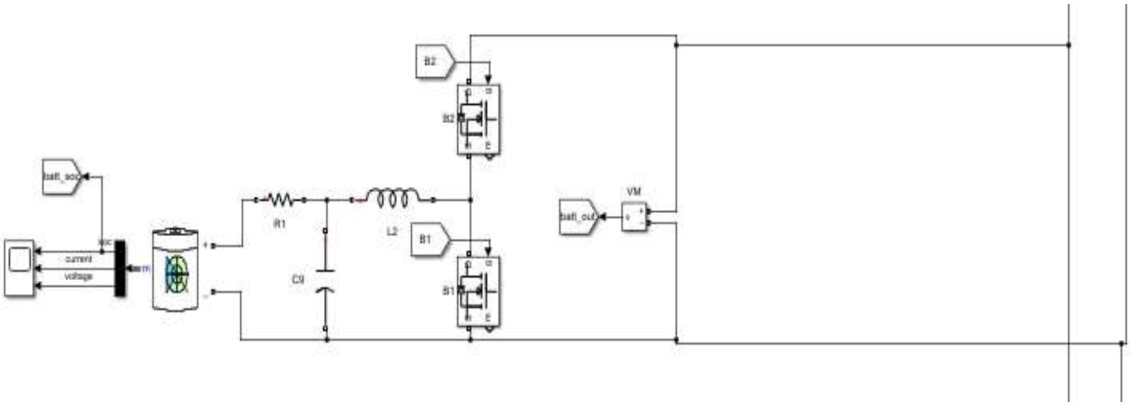

Figure 5 battery model

Figure 5 illustrates the battery energy storage subsystem integrated with a bidirectional DC–DC converter. The battery serves as an auxiliary energy source, supporting the system by storing excess energy and supplying power when required.The circuit includes filtering and energy storage components such as a resistor (R1), inductor (L2), and capacitor (C9), which help in smoothing voltage and current ripples. The presence of power electronic switches (B1 and B2) enables bidirectional operation, allowing the converter to function in both charging (buck mode) and discharging (boost mode). During charging mode, surplus energy from the DC-link is stored in the battery through controlled switching. In discharging mode, the stored energy is delivered back to the DC-link to maintain voltage stability and support the load. Measurement blocks are included to monitor battery voltage and current, ensuring proper control and protection

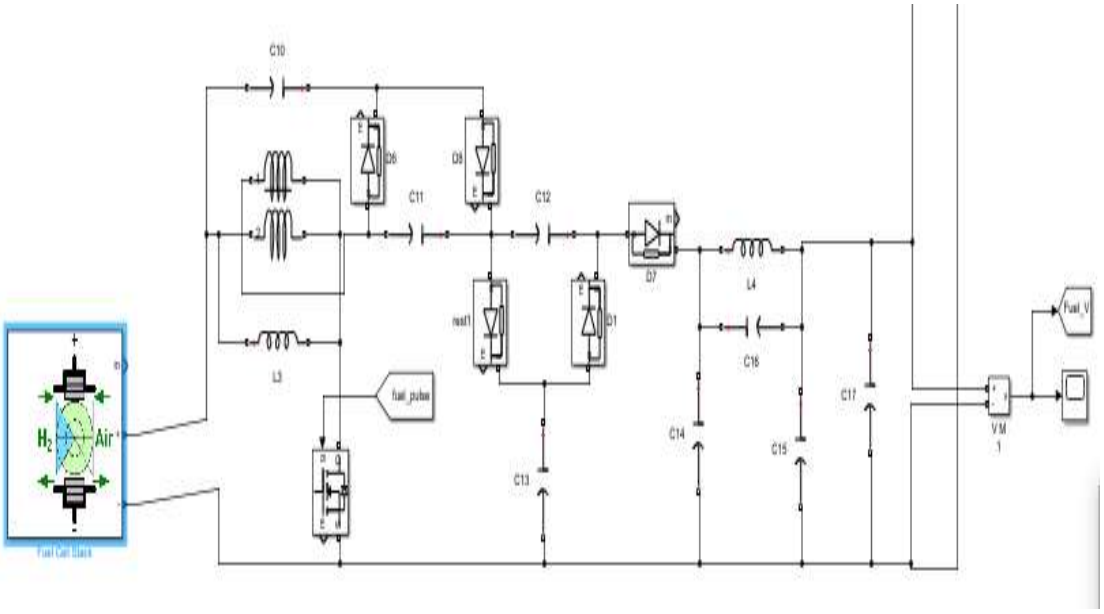

Figure 6 fuel cell subsystem

Figure 6 illustrates the Artificial Neural Network (ANN) controller used for system control and optimization. The ANN takes input signals (such as PV voltage/current or reference signals) and processes them through a trained neural network model. The controller generates an output signal that helps in improving system performance, tracking maximum power, and enhancing dynamic response. Compared to conventional controllers, the ANN provides adaptive and intelligent control, making the system more efficient under varying operating conditions.

ANN Controller

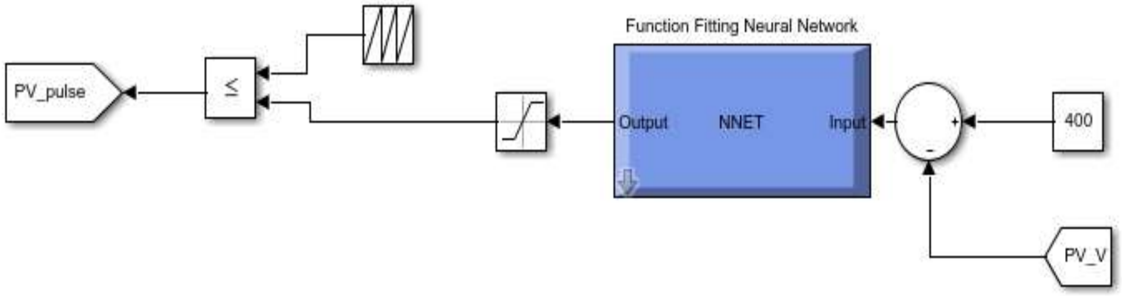

Figure 7: ANN Controller

Figure 7 illustrates the Artificial Neural Network (ANN) controller used for system control and optimization. The ANN takes input signals (such as PV voltage/current or reference signals) and processes them through a trained neural network model. The controller generates an output signal that helps in improving system performance, tracking maximum power, and enhancing dynamic response. Compared to conventional controllers, the ANN provides adaptive and intelligent control, making the system more efficient under varying operating conditions.

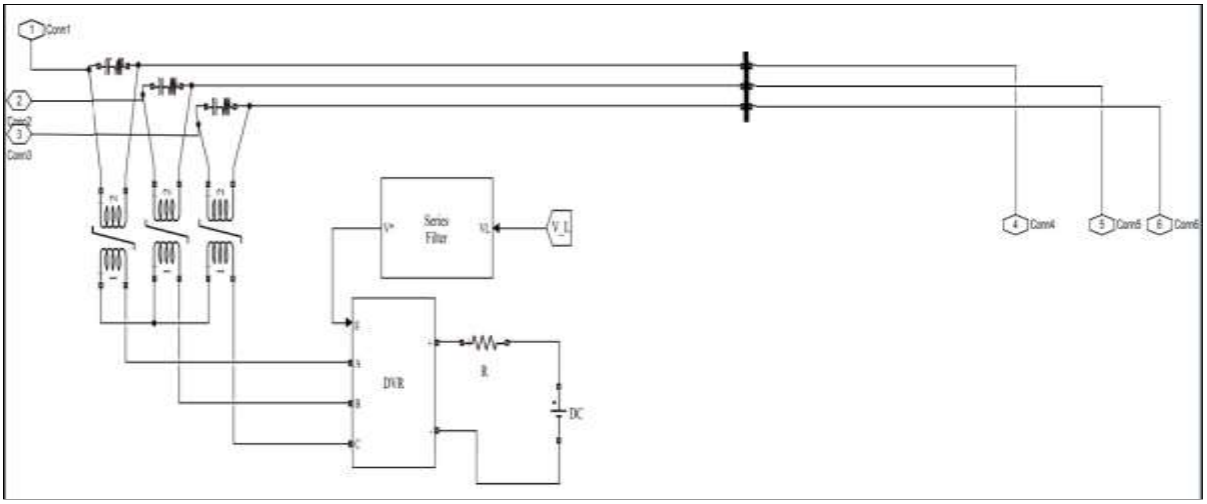

Figure 8 DVR Subsystem

figure 8 shows the Dynamic Voltage Restorer (DVR) subsystem, which is used to mitigate power quality issues in the grid. The DVR injects a compensating voltage into the system during disturbances such as voltage sags, swells, and harmonics. It consists of power electronic switches, transformers, filters, and control units that ensure fast response and accurate compensation. The DVR helps maintain a constant load voltage, thereby protecting sensitive equipment and improving overall system stability.

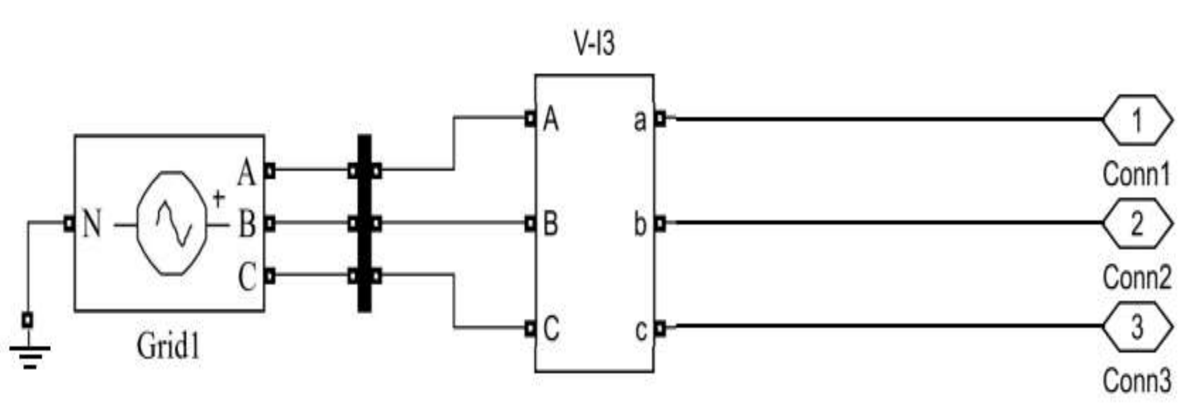

Figure 9 three-phase grid connection and measurement subsystem.

Figure 9 shows the grid (Grid1) provides a three-phase AC supply (A, B, C) along with a neutral connection. The output is passed through a voltage and current measurement block (V-I3), which measures the electrical parameters of each phase. The measured signals are then provided at output terminals (Conn1, Conn2, Conn3) for further processing or monitoring. This subsystem is essential for grid synchronization, system analysis, and control implementation, ensuring that voltage and current signals are accurately captured for maintaining stable operation.

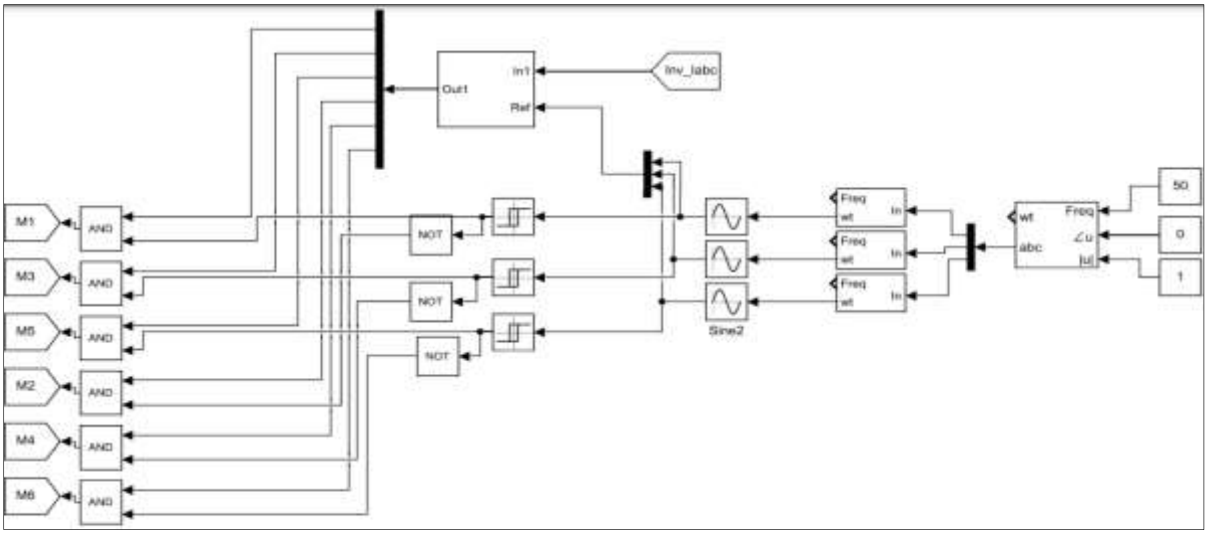

Figure 10 grid inverter synchronization subsystem

Figure 10 illustrates the inverter control subsystem with pulse generation logic. It consists of logic gates (AND, NOT), reference signals, and sine wave generators used to produce switching pulses for the inverter switches (M1–M6). The sine wave blocks generate reference signals based on system frequency, while the control logic processes these signals to generate appropriate gating pulses. These pulses ensure that the inverter produces a balanced three-phase AC output with proper frequency and amplitude. The subsystem plays a key role in controlling inverter operation, maintaining synchronization with the grid, and ensuring low harmonic distortion.

IV SIMULATION RESULT

The simulation of the proposed model has been performed on MATLAB software

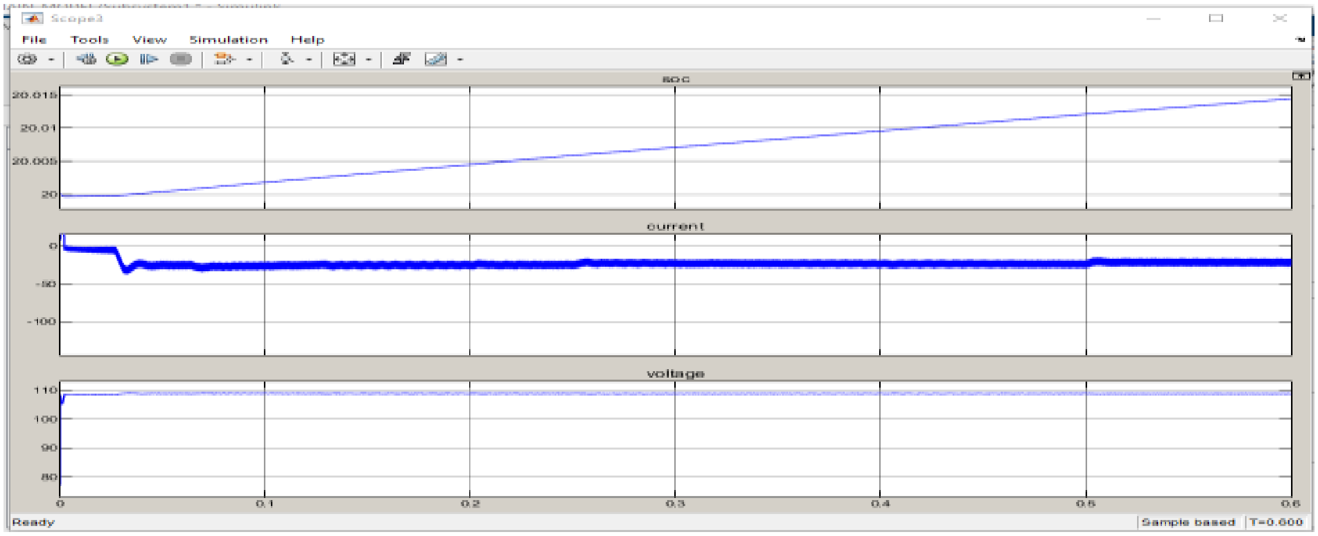

Figure 11 battery voltage and current

Figure 11shows the battery voltage and current characteristics during the simulation. The battery voltage increases gradually, indicating proper charging behavior, while the current stabilizes after initial transients. This confirms that the battery management system effectively controls charging and discharging, ensuring stable energy storage and supply.

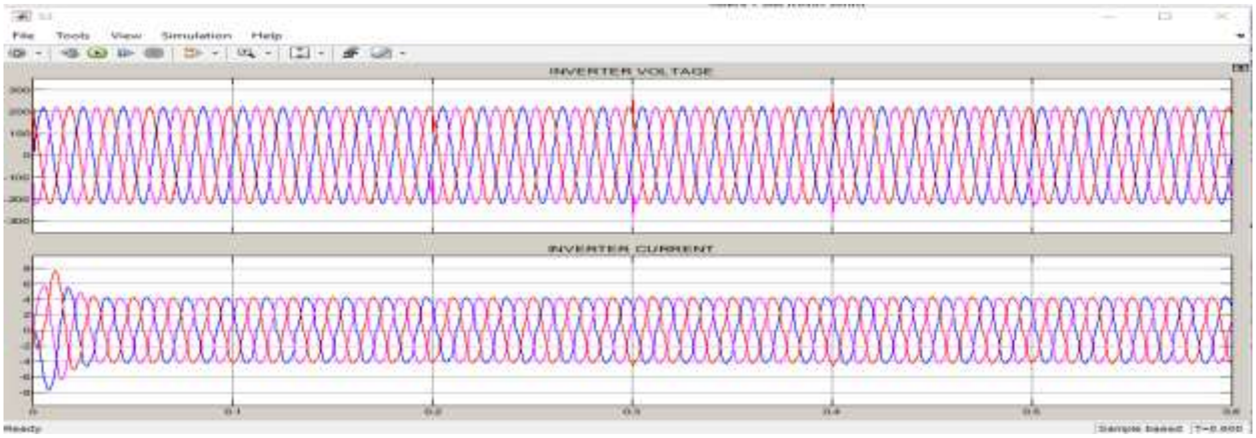

Figure 12 inverter current and voltage

Figure 12 illustrates the inverter output voltage and current waveforms. Both waveforms are sinusoidal and balanced, indicating that the inverter operates efficiently. The absence of distortion confirms low harmonic content and good power quality.

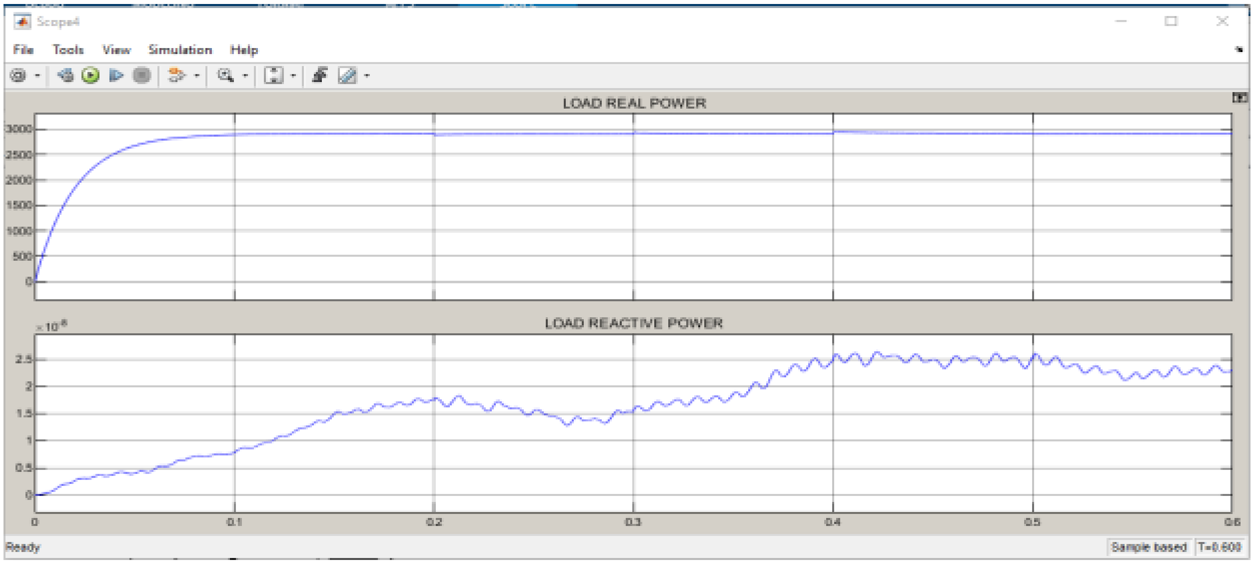

Figure 13: Load Real and Reactive Power

figure represents the active (real) and reactive power consumed by the load. The real power increases and stabilizes, while the reactive power shows controlled variation. This indicates stable load operation and effective power management within the system.

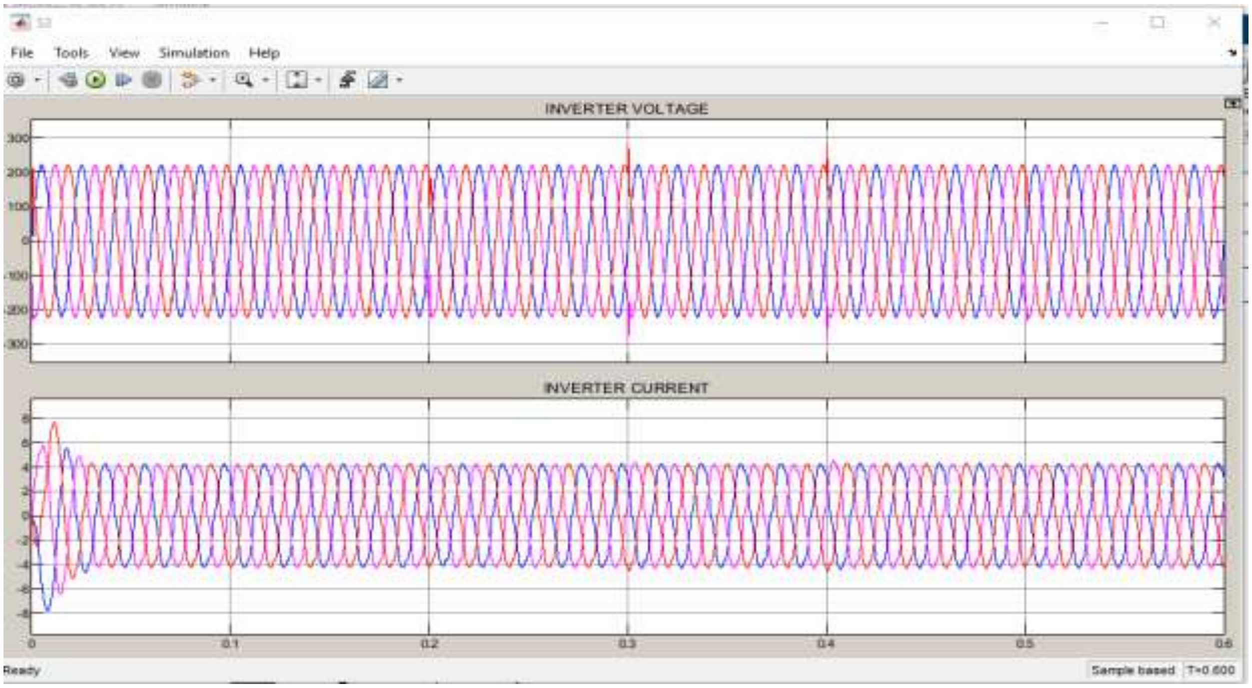

Figure 14: Inverter Voltage and Current

Figure 14 again shows the inverter voltage and current under steady-state conditions. The smooth sinusoidal waveforms confirm stable inverter performance and proper synchronization with the grid/load.

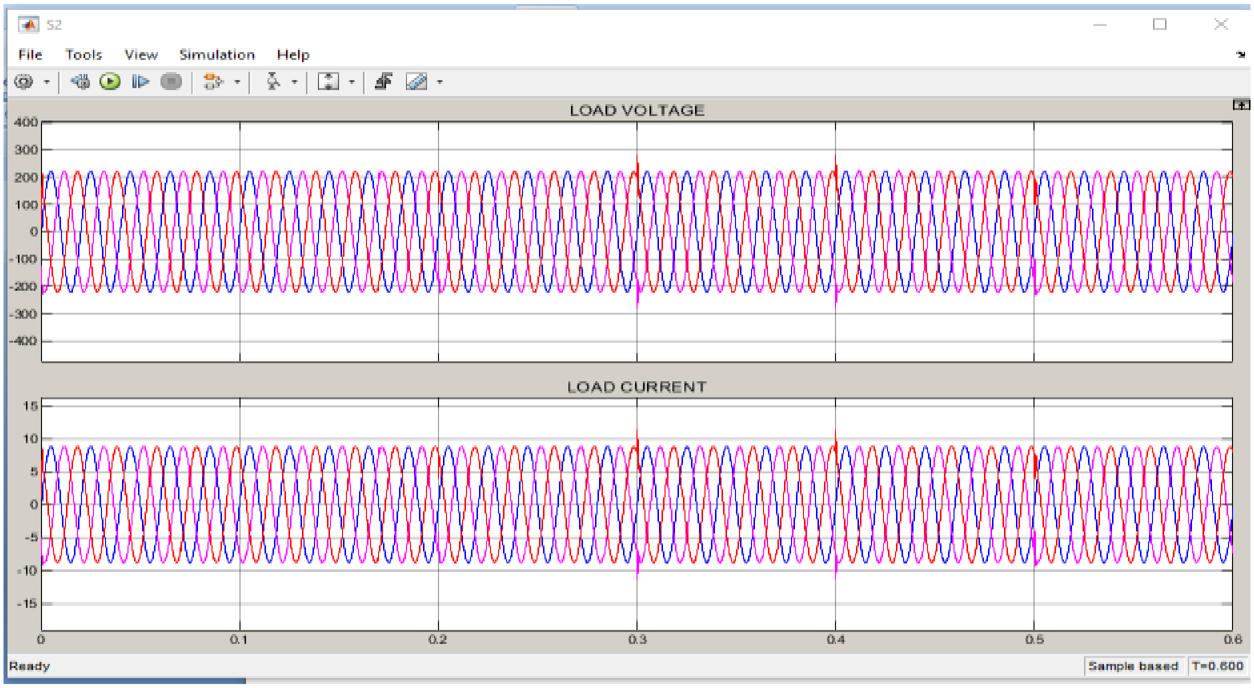

Figure 15 load voltage and load current

Figure 15 presents the load voltage and current waveforms. The voltage remains stable while the current follows a sinusoidal pattern, indicating proper load supply and balanced system operation.

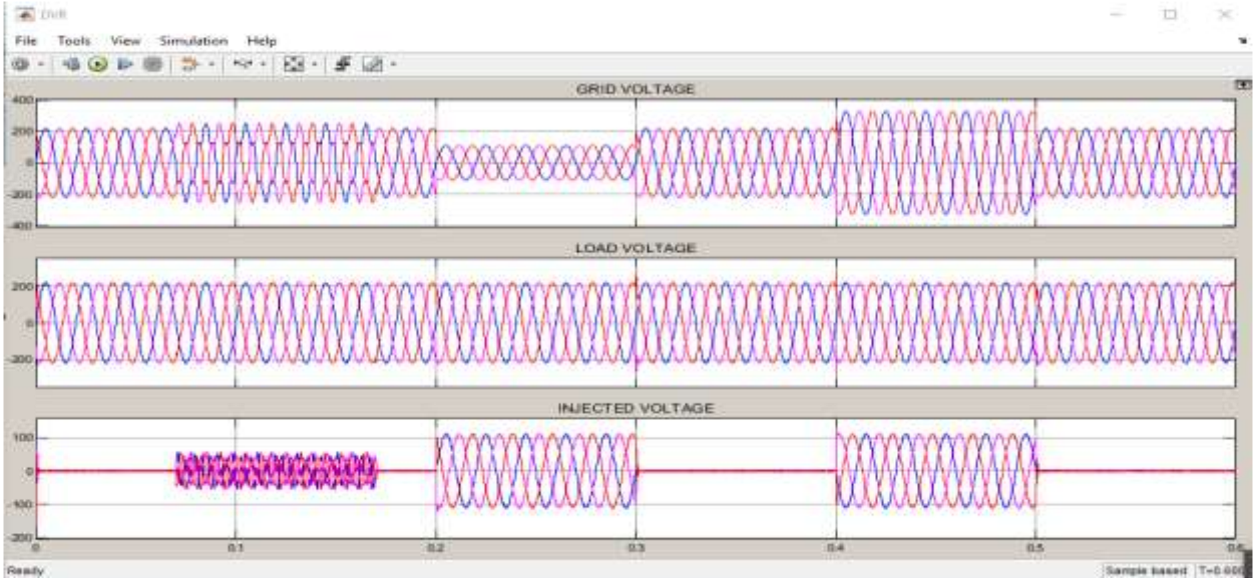

Fig. 16: Grid Disturbance and Compensation

Figure 17 shows the system response under grid disturbances such as voltage sag, swell, and harmonics. The injected voltage compensates for disturbances, demonstrating the effectiveness of the DVR (Dynamic Voltage Restorer) in maintaining stable load voltage.

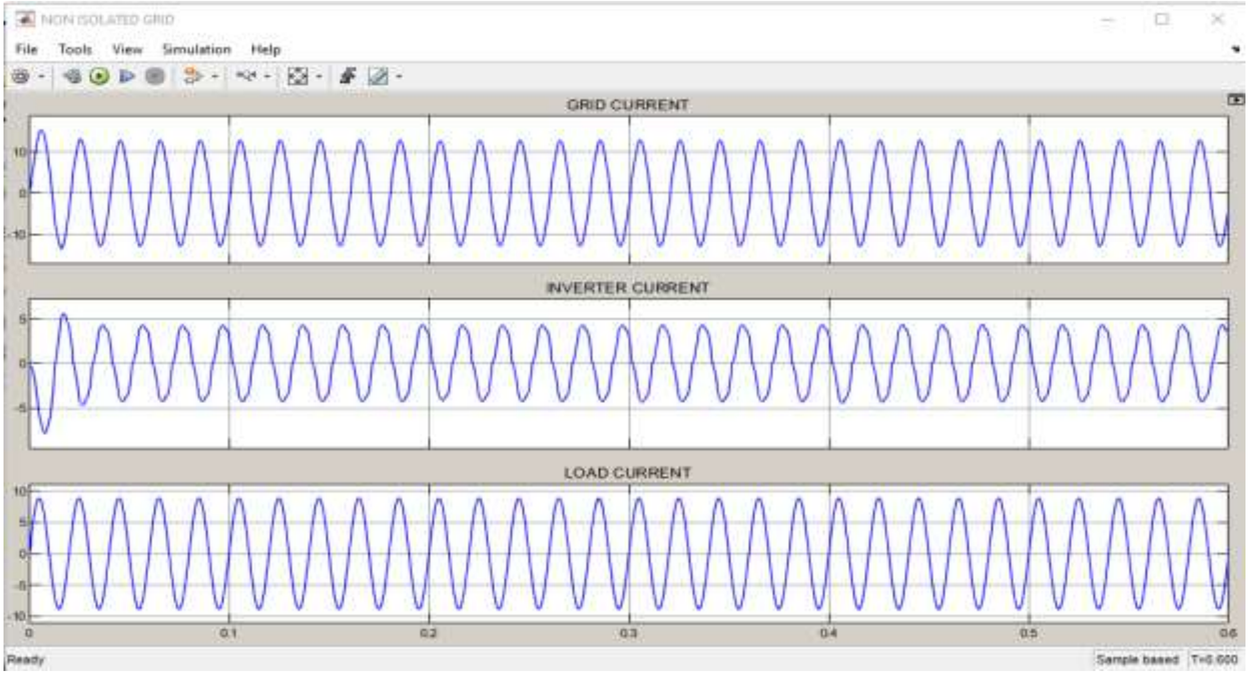

Figure 17 inverter current, grid current, load current

Fig 17 showing the inverter current, grid current, load current, the x axis showing simulation time, When the mains frequency changes from 50 Hz to 49 Hz and from 50 Hz to 51 Hz, as shown in Figure 4.16 .the PLL quickly detects the mains frequency change and accurately compensates for the mains frequency change in a short time. Less than 10 milliseconds, no effect on mains power.

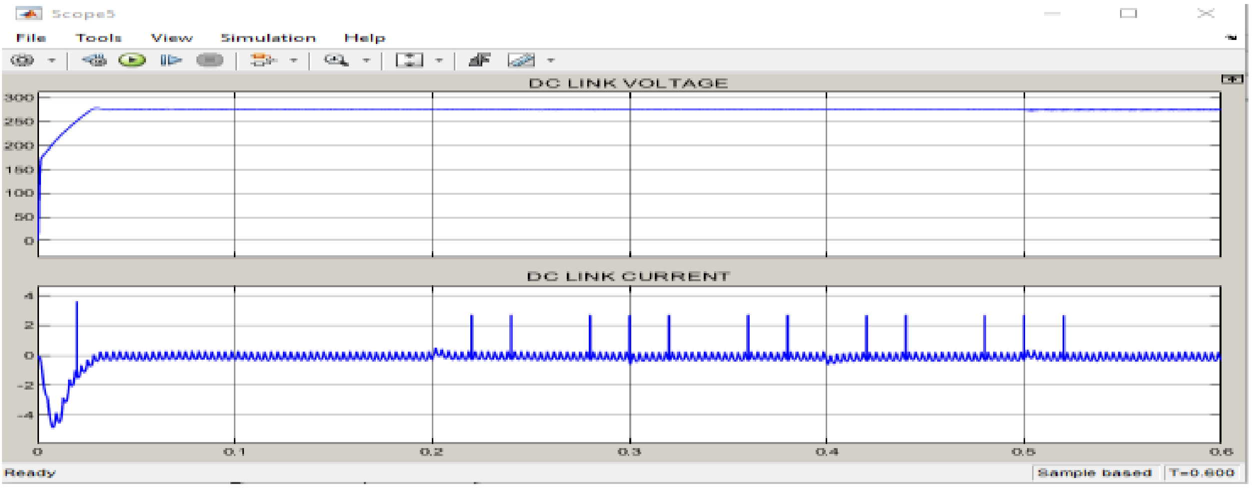

Figure 19 DC link output

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Figure 19 shows the DC-link voltage and current characteristics. The voltage quickly reaches a steady value, while the current stabilizes with minor fluctuations, indicating effective DC-link regulation and energy balancing.

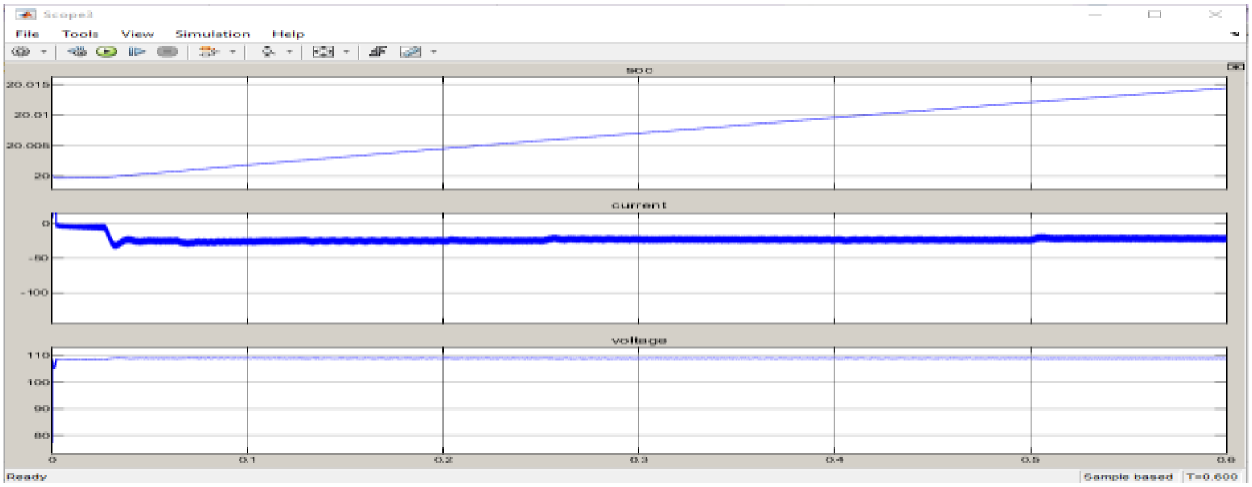

Figure. 20 battery current and voltage

figure 20 the battery charging behavior, showing smooth voltage rise and stable current. It confirms that the battery system operates efficiently and supports system stability during varying conditions.

Table:2 Simulation Parameters and Observed Values

Parameter	Value
Grid Voltage	230 V (RMS)
Grid Frequency	50 Hz
Inverter Voltage	230 V (RMS)
Inverter Current	5–8 A
DC-Link Voltage	300–350 V
DC-Link Current	5–10 A
Battery Voltage	48–52 V
Battery Current	±10 A
Load Voltage	230 V
Load Current	5–7 A
Real Power	1–2 kW
Reactive Power	0.2–0.5 kVAR
Switching Time (Battery)	0.02–0.05 s
Disturbance Duration	0 – 0.5 s
Compensation Time	< 10 ms

THD (Estimated)	< 5%
Motor Speed	0–1500 rpm

V CONCLUSION

This study presented the design and simulation of a grid-connected hybrid renewable energy system integrating solar PV, battery storage, fuel cell, ANN controller, and DVR to enhance power quality and system reliability. The entire system was developed and analyzed in the MATLAB/Simulink environment, demonstrating effective coordination between different subsystems for stable and efficient operation. The proposed system successfully addressed major power quality issues such as voltage sag, swell, harmonics, and fluctuations caused by the intermittent nature of renewable energy sources. The implementation of MPPT techniques ensured maximum energy extraction from the PV system, while the bidirectional DC–DC converter enabled efficient battery charging and discharging. The fuel cell subsystem provided additional backup support, improving overall system reliability. Furthermore, the integration of an ANN controller enhanced system adaptability and dynamic response, while the Dynamic Voltage Restorer (DVR) effectively compensated voltage disturbances, maintaining a stable load voltage under both balanced and unbalanced conditions. The inverter, along with synchronization and filtering techniques, ensured low harmonic distortion and high-quality sinusoidal output.

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