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Efficient Energy Management in a PV–Battery Hybrid System Using a Single-Stage Bidirectional Converter

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Abstract

The increasing penetration of renewable energy sources necessitates efficient and reliable power conversion systems for seamless grid integration. This paper proposes a single-stage bidirectional power conversion system for interfacing a solar photovoltaic (PV) and battery energy storage system with the AC grid. The system employs a voltage source inverter (VSI) with an LCL filter to enable bidirectional power flow while maintaining high power quality and system stability.A centralized control strategy is developed to regulate the DC link voltage, manage battery energy, and ensure synchronization with the grid. The control scheme effectively coordinates power exchange between the DC and AC sides under different operating modes, including battery-to-grid and grid-to-battery operation. The model is implemented and simulated using MATLAB/Simulink to validate system performance.Simulation results demonstrate that the DC link voltage is well regulated with minimal ripple, while the grid and load currents remain sinusoidal with low harmonic distortion. The system achieves near unity power factor and ensures stable battery operation with controlled state of charge. The proposed configuration offers a compact, efficient, and cost-effective solution for hybrid renewable energy systems and smart grid applications.

Keyword- MPPT, Solar Panel, Fuzzy Logic, Grid,DC-DC Converter

I. INTRODUCTION

The growing global demand for sustainable energy solutions has placed renewable energy technologies at the center of research and development efforts aimed at reducing greenhouse gas emissions and mitigating climate change [1]. Among the various applications of renewable energy, the integration of electricity systems with water management infrastructure has gained significant importance, especially in remote and rural areas where energy access remains a challenge [2]. Hybrid groundwater pumping systems powered by renewable sources represent a promising solution to ensure a reliable water supply and reduce dependence on fossil fuels [3]. However, one of the main challenges facing these systems is the intermittency of renewable resources, particularly solar and wind energy, which can lead to mismatches between energy availability and pumping demand [4]. In this context, the integration of battery energy storage systems (BESSs) becomes essential, enabling the efficient management of energy flows, supply stabilization, and greater operational flexibility to ensure continuous water pumping even during periods of low generation [5]. The concept of combining groundwater pumping with battery storage within a renewable energy framework is particularly relevant in regions where water scarcity and energy insecurity coincide [6]. These systems can offer a dual solution: ensuring access to groundwater for agricultural, industrial, and domestic uses, while simultaneously contributing to the decarbonization of the energy mix [7]. By using solar photovoltaic panels, wind turbines, or other renewable technologies as the primary energy source, the system reduces its environmental impact and long-term operating costs [8]. The incorporation of BESSs ensures that excess energy generated during peak renewable energy production can be stored and subsequently used during periods of low availability, such as at night or on cloudy days [9]. This hybridization not only improves the reliability of water supply systems but also increases their resilience to external impacts such as climate variability, extreme weather events, or power grid disruptions [10]. Furthermore, the modularity and scalability of hybrid systems make them adaptable to a wide range of contexts, from small rural communities to larger urban infrastructures [11]. The increasing penetration of dispersed energy resources (DERs) in distribution systems has improved microgrids' implementation. The concept of the microgrid [1,2] includes the operation and control scheme, voltage and power regulation and energy management. At the beginning, AC microgrids were evolved, as the conventional power systems were dominated by the AC form. However, power generations from various DERs, such as photovoltaic systems, are DC power, so are modern electrical loads and energy storage systems. Those DC technologies are integrated with the existing AC systems through converters, which would expend more component costs and increase power losses. Moreover, it would add more power quality problems. According to those issues, DC microgrids, which are considered feasible to be implemented for commercial facilities [3], are proposed as a better alternative for DERs. DC microgrids also offer more technical and economic benefits compared to AC microgrids [4]. Since the utilization of AC power is still required, the integration of AC and DC microgrids is proposed, and this emerges the concept of hybrid AC/DC microgrids [5,6].

Control of microgrids becomes a critical issue for ensuring reliable operation of the microgrid. A variety of research has been conducted particularly on the subject of the control system and power management in order to improve the system stability [7]. Each AC and DC microgrid has different hierarchical controls, but those could be generalize into three levels in reference to the hierarchical control standard of international society of automation (ISA)-95: (1) the primary control is based on the droop method, including an output-impedance virtual loop; (2) the secondary control allows the restoration of the deviations produced by the primary control; and (3) the tertiary control manages the power flow between the microgrid (MG) and the external electrical distribution system [8].

In hybrid AC/DC microgrids, AC and DC buses are connected through interlink AC/DC bidirectional converters (ICs). The IC should be able to control and manage power properly in both operating mode, grid-connected mode and stand-alone mode [9,10]. Operating the microgrid in stand-alone mode would lead to more challenges, particularly when the imbalance of generation and consumption happen because of flexible load and DERs. Various droop control methods have been proposed to maintain the system stability by sharing power between AC and DC subgrids, as in [11]. Incorporating an energy storage system into the IC will improve its control performance; meanwhile, DC link capacitors support the voltage regulation, as in [12].

The contribution of this paper is proposing a coordination control strategy of IC to maintain secure operation of the microgrid system in terms of frequency and voltage regulation. It is assumed that a battery energy storage system (BESS) is installed in the DC microgrid for voltage support of the corresponding bus by charging or discharging, controlled by a DC/DC bidirectional converter. When the microgrid gets into the stand-alone mode, the BESS can provide an amount of power for the weak portion of the microgrid through the IC. However, active power support cannot be sustained because of the limitation of the state of charge (SOC) level of BESS. The IC controller needs to include the method to deal with the physical limits of the SOC of the BESS. In this circumstance, the weak portion of the microgrid might experience the severe degradation of system security. The last countermeasure that can be adopted is load shedding for secure operation, and the IC controller also needs to take into account the load shedding scheme. The proposed coordination control strategy between the IC and BESS converters can facilitate a smooth transition of the power transfer between AC and DC subgrids in stand-alone mode for secure operation, using the available resources and the last resort action of load shedding within the feasible operational region of BESS.

II RELATED WORK

Table 1 Literature Review on Hybrid AC/DC Microgrid Systems

Author(s) & Year	Objective	Methodology / Technique	Key Findings / Results	Limitations / Remarks
Ding et al. (2025)	To improve droop control in islanded hybrid AC/DC microgrids	Adaptive bidirectional droop control using weighted coefficients based on AC frequency & DC voltage	Enhanced regulation by prioritizing larger deviations; reduced unnecessary converter operations	Complexity in tuning adaptive weights
Tang et al. (2025)	To enhance AC & DC	Virtual synchronous generator (VSG)-based	Improved DC voltage stability,	Limited real-time

	inertia in DC microgrids	inertia enhancement strategy	smoother power control, reduced frequency fluctuation	implementation challenges
Meena et al. (2024)	To develop energy management strategy (EMS) for hybrid microgrid	ANN-based two-step EMS controlling operation modes and ESS charging/discharging	Stable microgrid operation; effective converter coordination	Requires training data and computational resources
Kim et al. (2023)	To improve power supply reliability in microgrid clusters	Novel hybrid AC/DC microgrid structure using thyristor switches	Reduced outage time, improved efficiency and power quality	Cost considerations and implementation complexity
Ren et al. (2024)	To design control for bus-sectionalized hybrid microgrids	Hierarchical control paradigm for multi-mode operation	Seamless mode switching, uninterrupted power supply	Complexity in system design and scalability
Pratticò et al. (2025)	To develop LVDC back-to-back converter for hybrid systems	Dual inverter-based converter with sensorless current estimation	Improved system stability, energy quality, and reduced sensor dependency	Requires accurate mathematical modeling

III PROPOSED SYSTEM

The proposed system represents a grid-connected hybrid renewable energy system with bidirectional power flow control, modeled in MATLAB/Simulink. It primarily integrates a DC energy source (such as a photovoltaic system or battery) with the AC grid through a controlled power electronic interface.

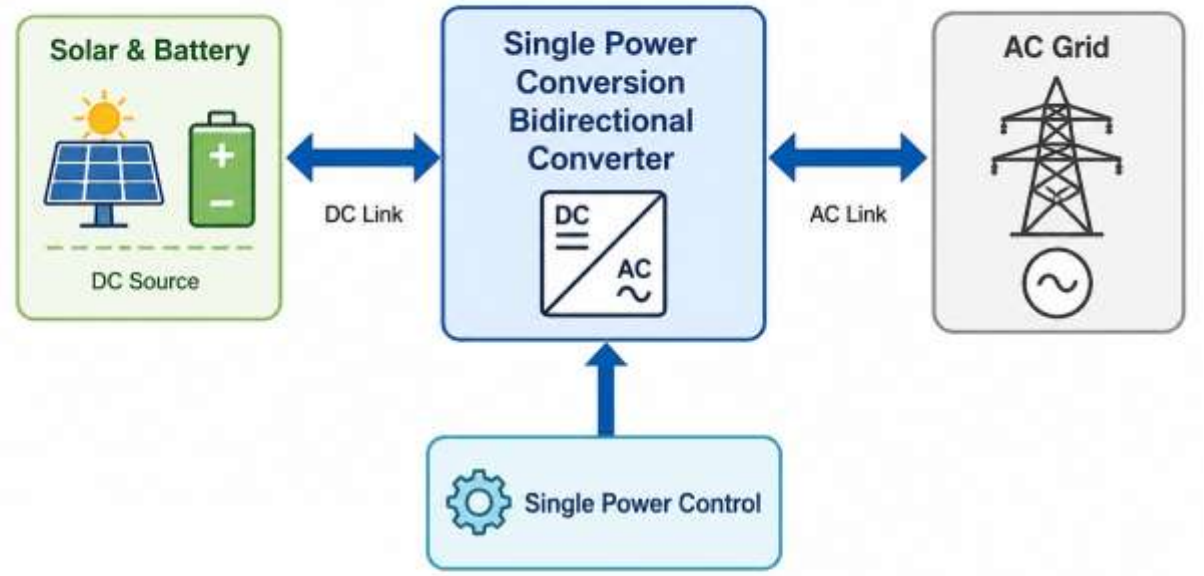

Fig.1 Proposed Block Diagram

The system begins with a DC subsystem, which acts as the energy source and feeds power into a DC link capacitor, ensuring voltage stabilization and reducing ripples. This DC voltage is then processed through a bidirectional inverter bridge (IGBT-based converter) that converts DC power into AC power when supplying the grid, and vice versa during charging mode. The switching of the inverter is governed by a PWM (Pulse Width Modulation) control technique, which ensures proper waveform shaping and minimizes harmonic distortion.The inverter output is connected to an LC filter (inductor L and capacitor C) that smooths the switching waveform into a near-sinusoidal AC signal suitable for grid interfacing. On the AC side, the system is synchronized with the utility grid using a grid synchronization unit, which ensures matching of voltage magnitude, frequency, and phase angle before power injection. This prevents disturbances and enables seamless power transfer. Measurement blocks are used throughout the system to monitor voltage, current, and power parameters, feeding real-time data back to the controller for dynamic adjustments.A key feature of the proposed system is its bidirectional operation capability, controlled by a mode selector (1: battery to grid, 0: grid to battery). In the “battery-to-grid” mode, excess energy stored in the battery or generated by renewable sources is delivered to the grid, supporting load demand and improving system efficiency. In the “grid-to-battery” mode, the system operates as a rectifier, drawing power from the grid to charge the battery, ensuring energy availability during low generation periods. The MPPT (Maximum Power Point Tracking) control block optimizes the extraction of power from the renewable source, ensuring maximum efficiency under varying environmental conditions. As shows in fig. 1

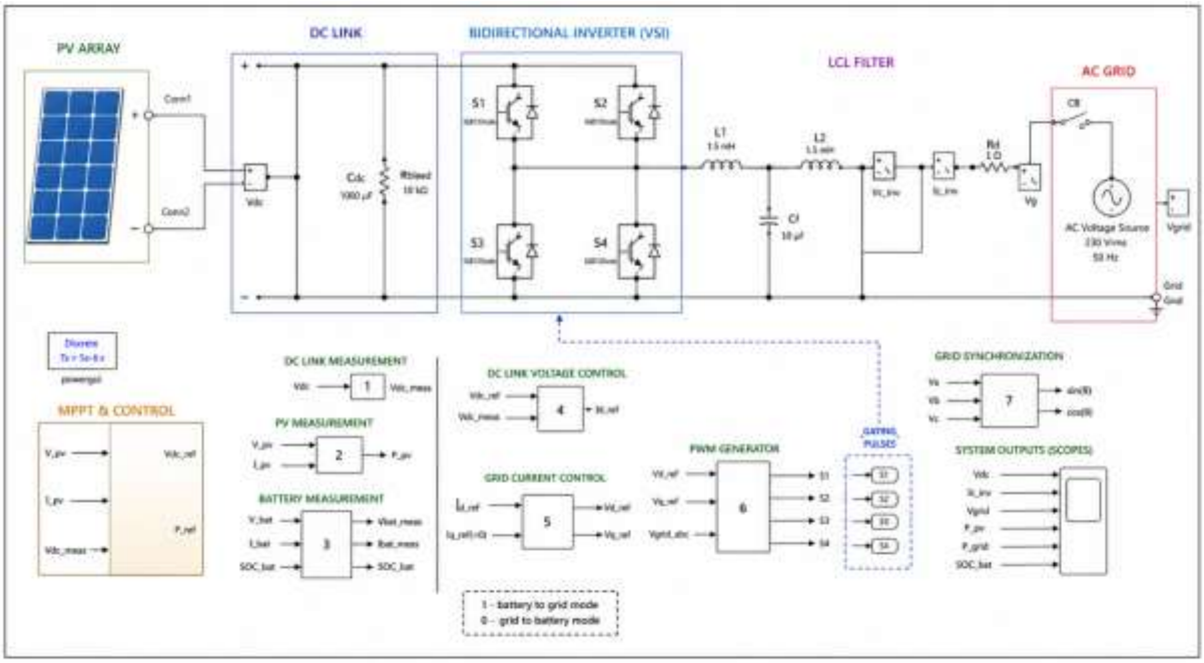

Fig. 2 Proposed Simulink Model

PV Array (Solar Source)

The PV array is the primary energy source in the system. It converts solar irradiance into DC electrical power using photovoltaic cells. The output of the PV array depends on environmental conditions such as sunlight intensity and temperature. This generated DC power is fed into the DC link for further processing.

Battery Energy Storage System (BESS)

The battery stores excess energy generated by the PV system and supplies power when required. It enables bidirectional energy flow, meaning it can charge when surplus power is available and discharge when demand is high or generation is low. This improves system reliability and ensures continuous power availability.

DC Link (Capacitor)

The DC link acts as an intermediate energy buffer between the DC sources (PV and battery) and the inverter. It consists of a capacitor that smooths voltage fluctuations and maintains a constant DC voltage. A stable DC link voltage is essential for proper operation of the inverter and overall system stability.

Bidirectional Inverter (Voltage Source Inverter – VSI)

The bidirectional inverter converts DC power into AC power and vice versa. During normal operation, it converts DC power from the PV/battery into AC power for the grid or load. In reverse mode, it can convert AC power from the grid to charge the battery. It operates using switching devices controlled by PWM techniques.

LCL Filter

The LCL filter is connected between the inverter and the grid. Its main function is to reduce high-frequency harmonics generated by the inverter switching. By filtering these harmonics, it ensures that the output voltage and current are smooth and sinusoidal, thereby improving power quality and reducing Total Harmonic Distortion (THD).

AC Grid

The AC grid acts as both a source and a sink of electrical power. It can receive excess power generated by the PV system or supply power when generation is insufficient. The system must synchronize with grid voltage and frequency to ensure safe and efficient operation.

MPPT (Maximum Power Point Tracking) Controller

The MPPT controller ensures that the PV system operates at its maximum power point under varying environmental conditions. It continuously adjusts the operating voltage or current of the PV array to extract maximum available power, thereby improving system efficiency.

DC Link Voltage Control

This control block maintains the DC link voltage at a constant reference value. It generates reference signals for the inverter to regulate power flow. Proper DC link voltage control ensures stable system operation and prevents voltage fluctuations.

Grid Current Control

This module controls the current injected into or drawn from the grid. It ensures that the current is sinusoidal and synchronized with the grid voltage. This helps achieve near unity power factor and reduces harmonics.

PWM Generator

The PWM (Pulse Width Modulation) generator produces switching pulses for the inverter switches. These pulses control the switching of IGBTs/MOSFETs, enabling conversion of DC to AC with desired voltage and frequency.

Grid Synchronization (PLL – Phase Locked Loop)

The synchronization unit ensures that the inverter output matches the grid in terms of frequency, phase, and voltage. It uses a PLL to track grid parameters, which is essential for safe grid-connected operation.

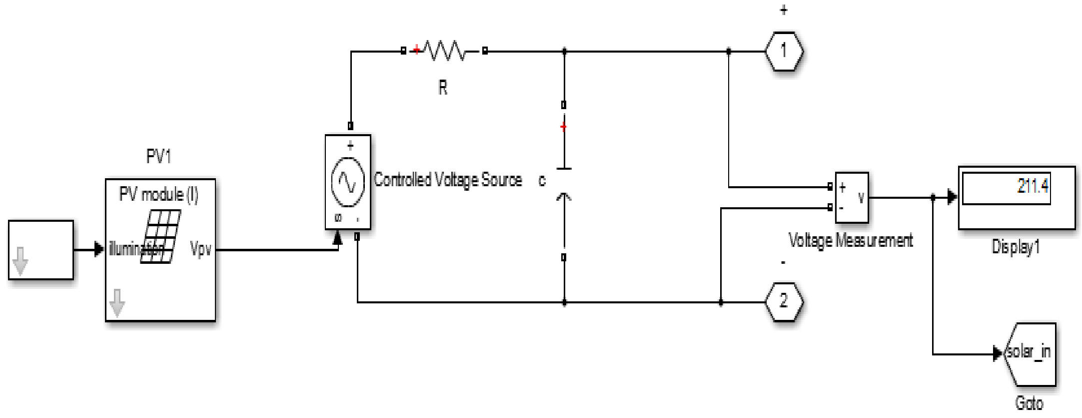

Fig. 3 Solar Panel

The photovoltaic (PV) module acts as the primary source of energy in the system by converting solar irradiation into DC electrical power. The generated output is conditioned using a controlled voltage source to simulate or regulate the PV behavior under varying conditions. A series resistor represents internal losses and helps limit current flow, while a capacitor is used to smooth the output and reduce voltage ripple. A voltage measurement block continuously monitors the PV output, ensuring that the generated voltage remains within the desired range. This conditioned and measured DC output is then forwarded to the next stage of the system for further processing. As shows in fig. 3

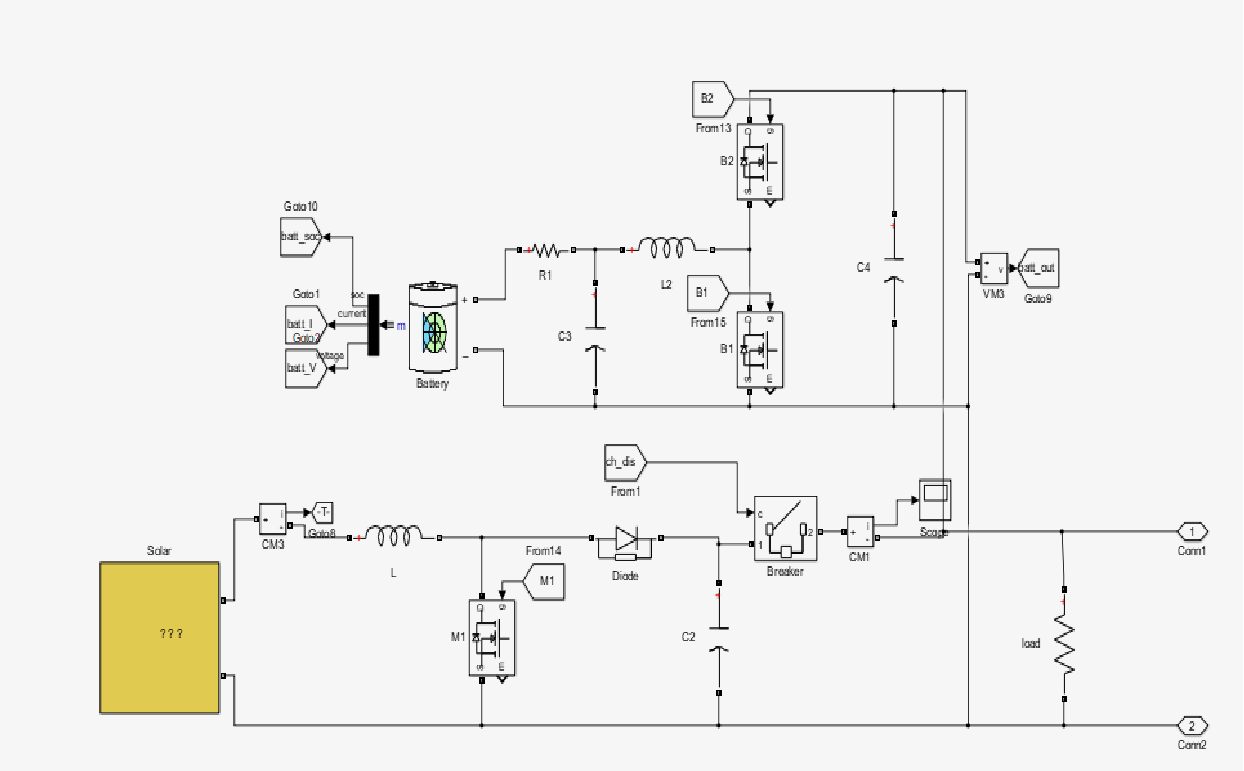

Fig. 4 Solar Panel

The power converter module is the core of the system, responsible for managing energy flow between the solar source, battery, and load. The battery serves as an energy storage unit, capable of both charging and discharging depending on system requirements. Switching devices such as IGBTs or MOSFETs control the direction and magnitude of power flow. Passive components including inductors, resistors, and capacitors are used to filter signals, reduce ripple, and maintain system stability. A diode ensures proper current direction, while a breaker provides protection and control during abnormal conditions. This module ensures efficient energy conversion and distribution, enabling continuous and reliable power supply. As shows in fig. 4

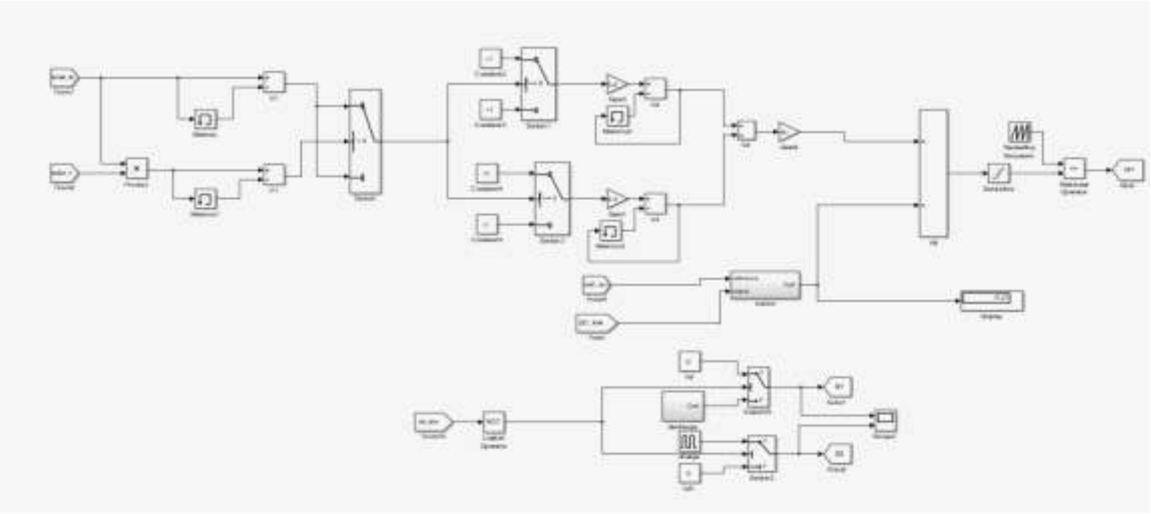

Fig.5 Grid Synchronization

The control system governs the overall operation of the model by implementing intelligent control strategies. It incorporates a Maximum Power Point Tracking (MPPT) algorithm to extract maximum available power from the PV module under varying environmental conditions. The system compares measured values with reference signals to generate error signals, which are processed through control logic to determine appropriate actions. A Pulse Width Modulation (PWM) generator produces switching signals for the power converter, ensuring precise control of the inverter switches. Additionally, mode selection logic enables bidirectional operation, allowing the system to switch between battery charging and discharging modes. This control mechanism ensures optimal performance, stability, and efficient energy management throughout the system. As shows in fig. 5

IV SIMULATION RESULT

The proposed grid-connected hybrid renewable energy system has been successfully modeled and simulated using MATLAB/Simulink. The simulation results validate the effective operation of the single-stage bidirectional voltage source inverter (VSI) in integrating the PV array and battery system with the AC grid. The DC link voltage is maintained at a stable level with minimal ripple, ensuring reliable converter performance.

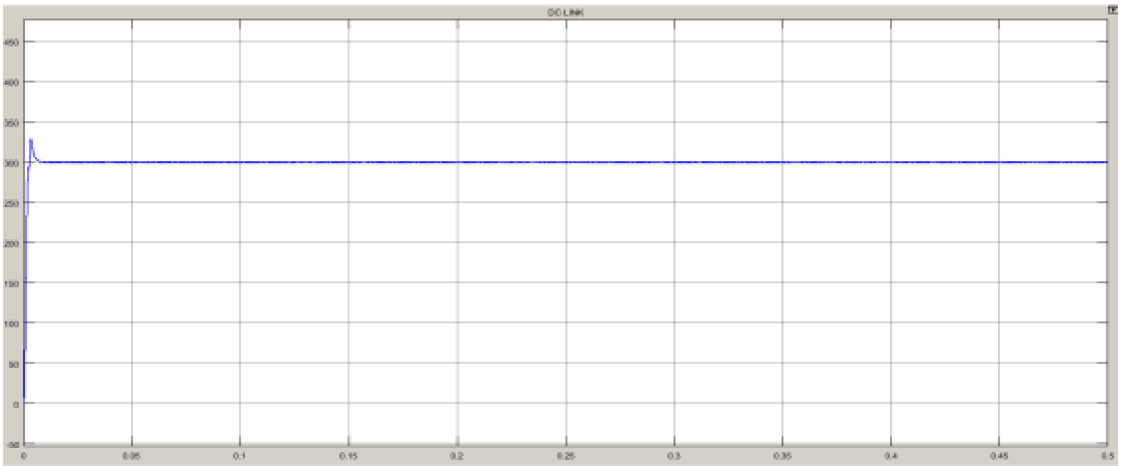

Fig.6 Dc Link

The DC link voltage initially shows a small transient rise and then quickly stabilizes at a constant value (around 300 V). The ripple is very small, indicating good filtering and stable DC bus regulation, which is essential for proper converter operation. As shows in fig. 6

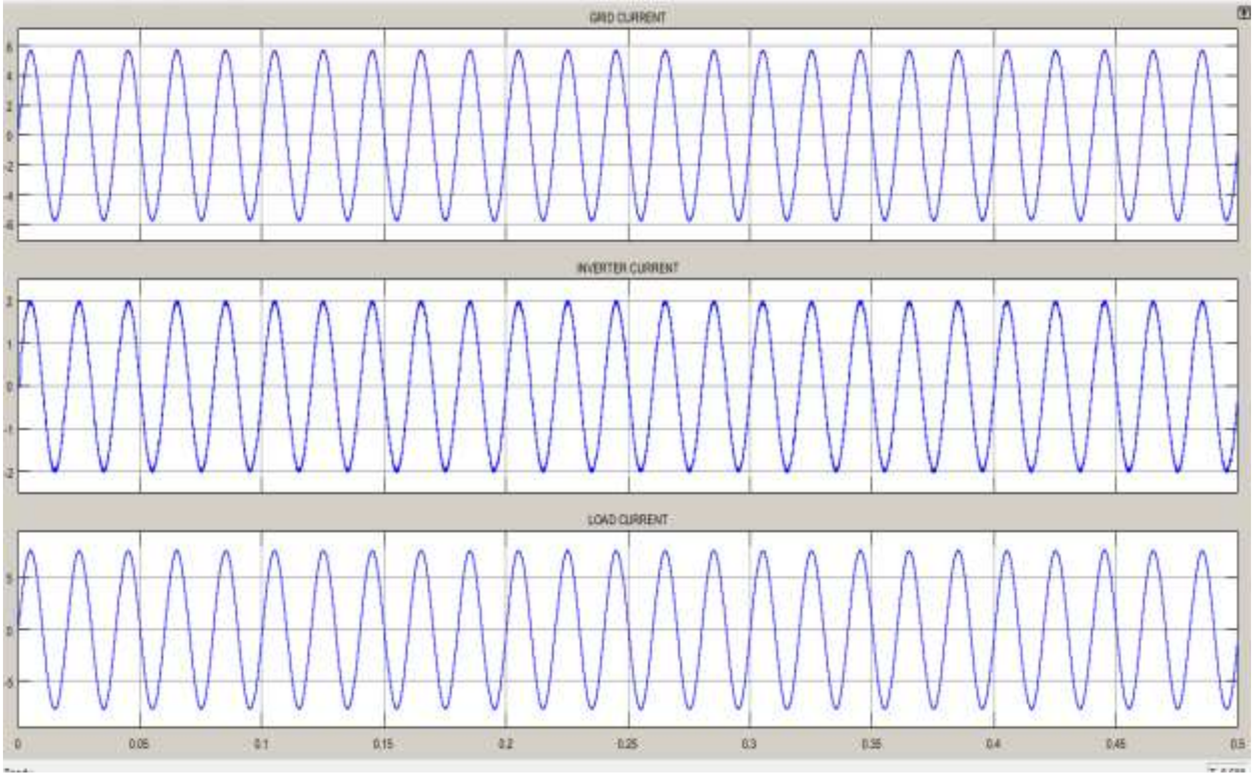

Fig.7 Grid, Inverter and Load Current

Figure 7 shows three current waveforms: grid current, inverter current, and load current. All three waveforms are pure sinusoidal, indicating proper operation of the inverter and synchronization with the grid. The amplitudes are consistent, and there is no visible distortion, which confirms low harmonic content and good power quality. The inverter successfully transfers power between the DC source and AC load/grid.

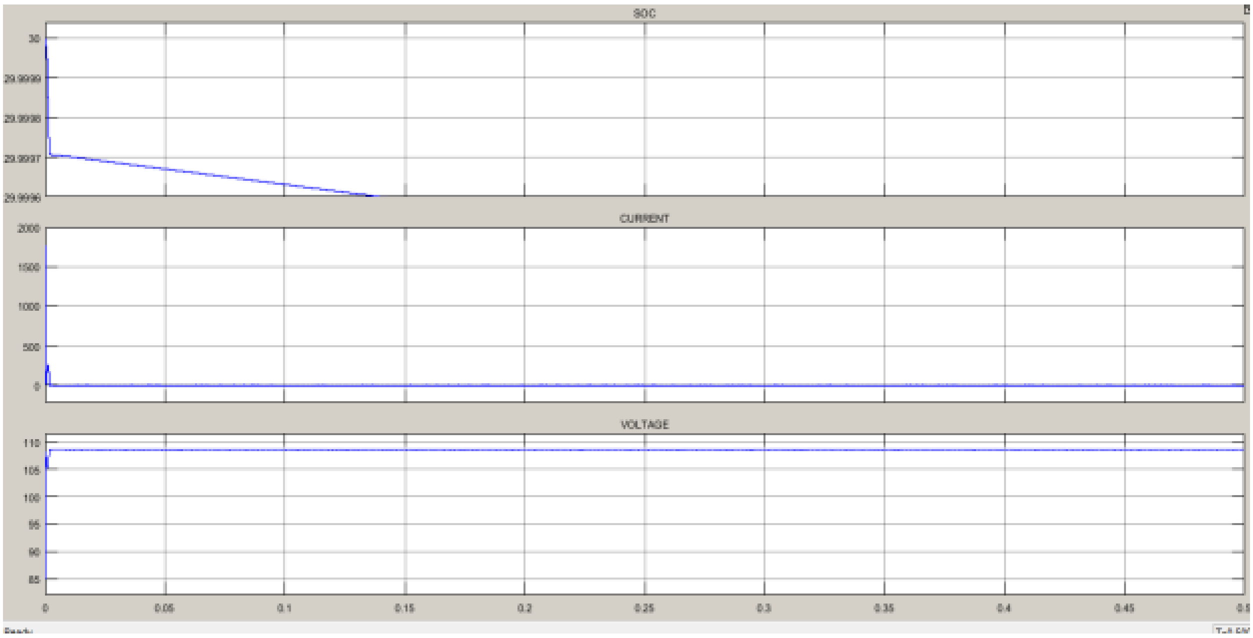

Fig.8 Battery Soc, Voltage and Current

Figure 8 represents battery behavior. The state of charge (SOC) slightly decreases over time, indicating controlled discharge. The battery voltage remains almost constant, showing stable DC operation. The current shows a small initial spike and then settles near zero, meaning the battery is operating in a balanced condition without heavy charging or discharging.

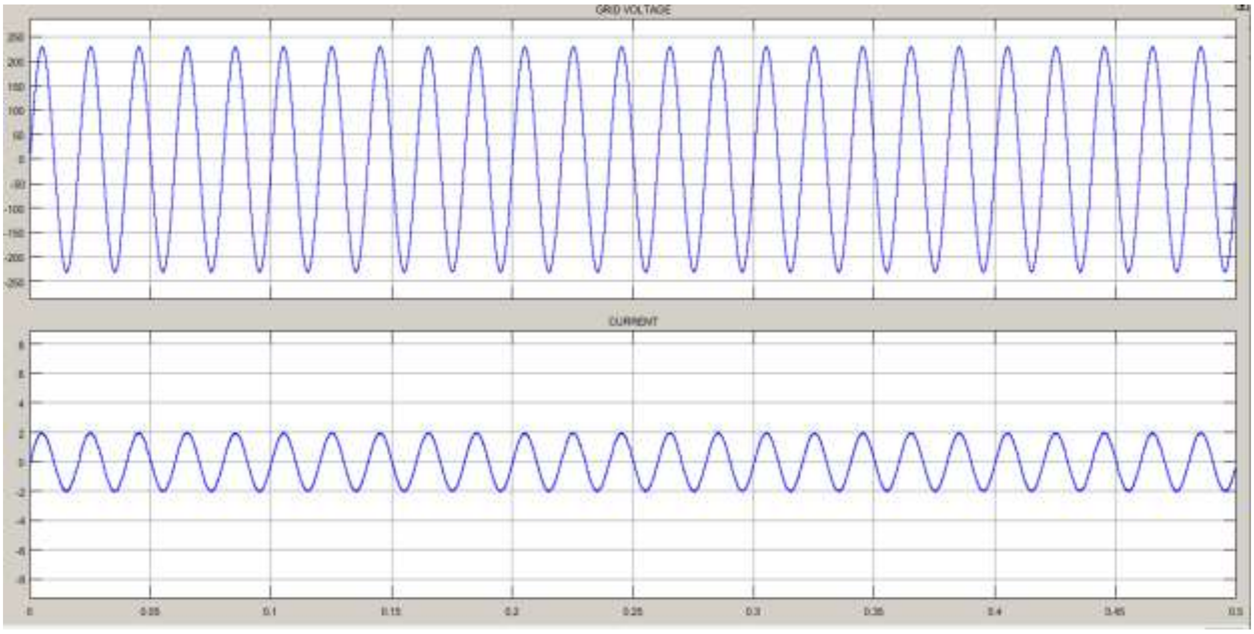

Fig.9 Grid Voltages and Current

Fig.9 shows the grid voltage is a clean sinusoidal waveform, and the grid current follows the same pattern. Are well aligned, indicating proper synchronization and near unity power factor operation. This ensures efficient energy transfer and minimal losses in the system.

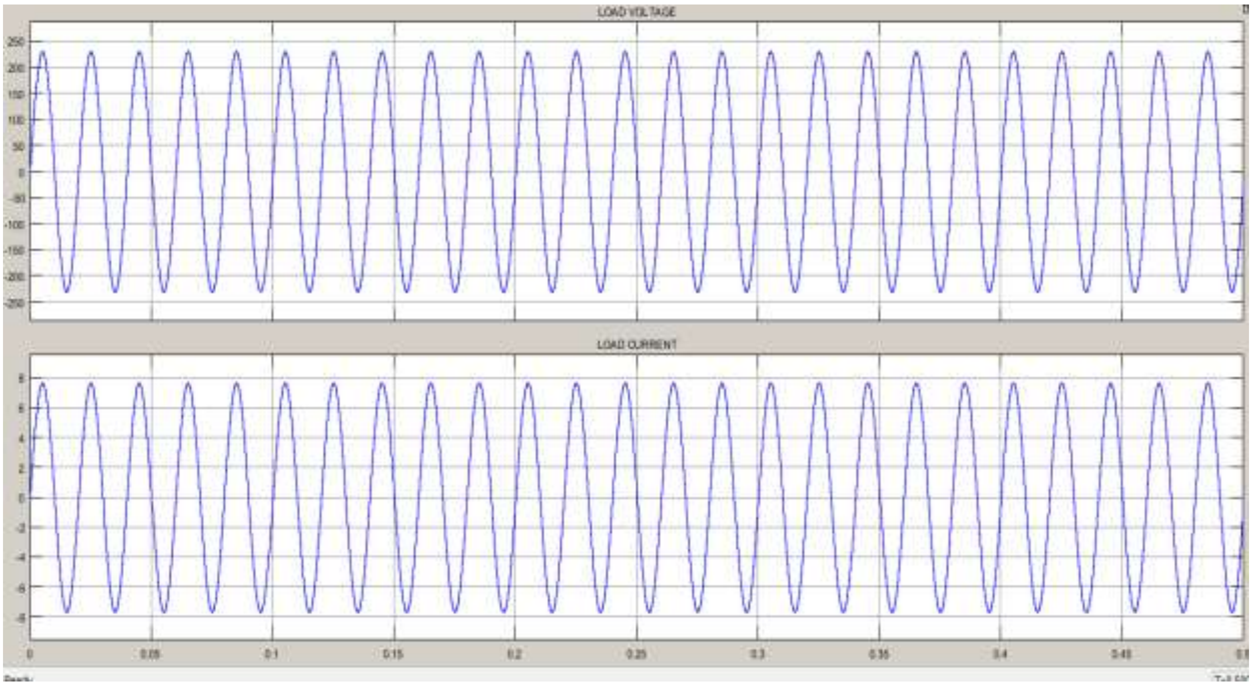

Fig.10 Load Voltage and Current

This figure 10 shows the voltage and current supplied to the load. Both waveforms are stable and sinusoidal, which means the load is receiving high-quality power. There are no fluctuations or distortions, confirming that the inverter and control system are working effectively.

Table: 2 Simulation Waveform Results

Waveform	Observed Value
Grid Current	±5–6 A
Inverter Current	±2–3 A
Load Current	±6–7 A
Battery SOC	~30% (slightly decreasing)
Battery Current	Initially high → ~0 A
Battery Voltage	~110 V
DC Link Voltage	~300 V
Grid Voltage	±230 V
Grid Current	±2–3 A
Load Voltage	±230 V
Load Current	±7–8 A

Table 2 presents the observed values of key electrical parameters obtained from the MATLAB/Simulink simulation of the proposed system. The grid current varies approximately between ±5–6 A, indicating smooth and stable power exchange with the grid. The inverter current is maintained within ±2–3 A, reflecting controlled converter operation. The load current ranges from ±6–7 A, confirming proper power delivery to the load under steady conditions.The battery state of charge (SOC) remains around 30% with a slight decreasing trend, which indicates controlled energy discharge. The battery current initially shows a high transient value and then settles close to zero, demonstrating stable operation without excessive charging or discharging. The battery voltage remains nearly constant at around 110 V, confirming reliable energy storage performance.The DC link voltage is regulated at approximately 300 V with minimal ripple, ensuring stable converter operation. The grid voltage waveform is maintained at ±230 V, which is a standard sinusoidal supply. Similarly, the grid current (±2–3 A) is well synchronized with the voltage, indicating near unity power factor. The load voltage also remains at ±230 V, providing a consistent supply, while the load current varies between ±7–8 A, showing efficient and stable load operation.

V .CONCLUSION

The proposed system demonstrates an effective integration of a photovoltaic (PV) array with the AC grid using a single-stage bidirectional voltage source inverter (VSI). The inclusion of a DC link ensures stable voltage regulation, while the LCL filter significantly reduces harmonic distortion, resulting in a high-quality sinusoidal output. The bidirectional capability of the converter enables flexible power flow, allowing energy to be supplied to the grid or stored in the battery as required.The implemented control strategy, including MPPT, DC link voltage control, and grid current control, ensures optimal system performance under varying operating conditions. The MPPT algorithm successfully extracts maximum power from the PV array, while the grid synchronization mechanism maintains proper phase and frequency alignment with the grid. Simulation results confirm that the system achieves stable DC voltage, efficient energy transfer, and near unity power factor operation.

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