Design and Analysis of Standalone Solar PV system with MPPT and Battery energy system

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***Abstract*— This paper presents the circuit modelling of a solar power system integrating maximum power point tracking (MPPT) and a battery energy storage system. The MPPT functionality is achieved using the Perturb and Observe algorithm, which ensures the photovoltaic (PV) panel operates at its maximum power output. A bidirectional DC-DC converter facilitates this, which adjusts the voltage level according to the MPPT requirements. The converter operates through an adjustable duty cycle that governs its switching mechanism. The battery is an energy storage component, connected to the bidirectional DC-DC converter. The converter dynamically charges or discharges the battery based on the load profile, ensuring efficient energy management. This model is designed to provide benchmark sizing for the PV module and battery storage, catering specifically to standalone PV operations. It effectively harnesses maximum power with minimal oscillations, reduces system losses, and enhances overall efficiency in the energy management system.**

***Index Terms*—Maximum Power Point Tracking (MPPT), Boost converter, Bidirectional DC-DC converter, Perturb and Observe algorithm, Photovoltaic panel, Inverter, Battery energy system.**

I. INTRODUCTION

[Font: Times New Roman, Size:10] Highlight The global transition toward sustainable energy has positioned solar energy as a cornerstone in reducing reliance on fossil fuels. Current trends highlight rapid advancements in solar photovoltaic (PV) technology, resulting in increased efficiency and reduced costs, making solar power more accessible than ever before.
The adoption of large-scale solar farms, urban rooftop installations, and innovative floating solar systems underscores the versatility of solar energy deployment. The adoption of large-scale solar farms, urban rooftop installations, and innovative floating solar systems underscores the versatility of solar energy deployment. A standalone solar photovoltaic (PV) system is a sustainable and versatile solution for providing electricity in areas off the grid or where the extension of the conventional power supply is not economically feasible. These systems harness solar energy through PV modules and convert it into usable electrical power. Unlike grid-connected systems, standalone solar PV setups operate independently, relying on storage components and efficient energy management to meet load demands. The Maximum Power Point Tracking (MPPT) technology is a key element for optimising these systems. It ensures that the PV modules operate at their maximum power point under varying environmental conditions, such as changes in sunlight intensity and temperature. This significantly improves the efficiency and energy yield of the system, making it a reliable energy source for remote applications, households, and industrial setups.

The battery charge controller is central to the operation of a standalone solar PV system, which plays a critical role in regulating the flow of electricity to and from the battery bank. The charge controller prevents overcharging and deep discharging of batteries, which can lead to reduced lifespan and efficiency. Advanced charge controllers, often integrated with MPPT functionality, enhance the system's overall performance by optimizing energy storage and distribution. The battery bank serves as a storage reservoir, ensuring the availability of electricity during periods of low solar irradiation, such as nighttime or cloudy days. Proper management of these batteries is essential to ensure the longevity and reliability of the standalone system.

To enhance system reliability, many standalone solar PV systems incorporate a backup generation source, such as a diesel generator. The backup generator acts as a secondary power source, ensuring an uninterrupted energy supply during prolonged periods of insufficient solar energy or when the battery bank is depleted. This hybrid approach improves the system's resilience and makes it suitable for critical applications where power continuity is essential. However, integrating a backup generator requires careful coordination through control systems to balance the solar, battery, and generator outputs effectively.

An inverter is another vital component of a standalone solar PV system, converting the direct current (DC) electricity produced by the PV modules and stored in the batteries into alternating current (AC) power, which is compatible with most household appliances and industrial equipment. Modern inverters often include intelligent features such as real-time monitoring, load management, and fault detection, further enhancing system performance and user convenience. The integration of MPPT, battery charge controllers, backup generation, and inverters form a cohesive and efficient standalone solar PV system capable of delivering reliable, clean energy across diverse environments.

II. STANDALONE SOLAR PV SYSTEM

This section discusses the circuit topology of a standalone solar PV system where the PV panel is connected to a bidirectional DC-DC converter that interfaces with a battery bank. The bidirectional DC-DC converter facilitates both charging and discharging operations, enabling efficient energy transfer between the PV panel and the battery. The battery is connected to a Maximum Power Point Tracking (MPPT) unit and a battery charge controller, ensuring optimal solar energy harvesting and effective regulation of the battery's charge and discharge cycles. The MPPT maximizes the energy extracted from the PV panel under varying environmental conditions, while the charge controller protects the battery from overcharging or deep discharging. The system also integrates a DC-AC inverter through the battery and converter, converting the stored direct current (DC) energy into alternating current (AC) for powering standard electrical loads. Additionally, a backup generator is incorporated to provide auxiliary power during periods of insufficient solar energy or depleted battery reserves, ensuring an uninterrupted energy supply. This integrated topology offers a robust, efficient, and flexible solution for standalone power generation, catering to diverse energy requirements in off-grid applications.

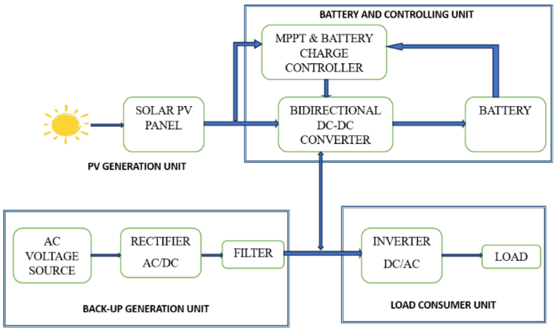

Fig. 1. Schematic diagram of standalone solar PV system

B. Design and Analysis of Photovoltaic cell

The PV cell in the solar panel operates on the principle of the photovoltaic effect, which enables the conversion of solar energy into electrical energy. This process involves the absorption of sunlight by the semiconductor material in the PV cell, causing the release of electrons and generating a flow of electric current. To simulate this mechanism, off-the-shelf Simulink software was utilized to develop a detailed model of the solar PV cell. The electrical equivalent circuit of a PV cell is shown in Figure 2.

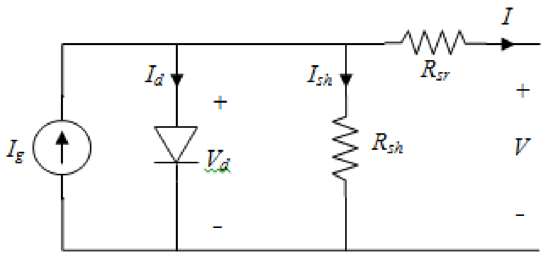

Fig. 2. Equivalent circuit of PV cell

Using this model, individual PV cells were connected in an organized manner to form a solar panel, replicating the functionality and characteristics of a real-world PV system. The Simulink model not only provides a dynamic representation of the PV cell's performance but also facilitates the analysis of its behavior under varying environmental conditions, such as changes in irradiance and temperature.

TABLE I SPECIFICATIONS OF PV CELL PARAMETER

PARAMETERS	SPECIFICATIONS
Parallel strings	02
Series Connected Modules per String	04
Maximum Power (W)	250.29
Cells per Module (N Cell)	60
Open Circuit Voltage V_{oc} (V)	36.6

Short circuit current I_{sc} (A)	8.75
Voltage at Maximum Power Point V_{mp} (V)	30.9
Current at Maximum Power Point I_{mp} (A)	8.1
Temperature Coefficient of V_{oc} (% deg c)	-0.36901
Temperature Coefficient of I_{sc} (% deg c)	0.086998
Light Generated Current IL (A)	8.7587
Diode Saturation Current IO (A)	4.1655e-10
Diode Ideality Factor	1.0003
Shunt Resistance R_{sh} (Ω)	126.1585
Series Resistance R_s (Ω)	0.12527

the following equation can be used to determine the PV current. The equation is derived from the Shockley diode equation and the cell's electrical characteristics:

$$I_{pV} = I_{ph} - I_s\left(e^{\frac{q(v_{pv}+I_{pV}R_s)}{AKT}} - 1\right) - V_{PV} + I_{PV}R_s/R_sh$$

The following terms are used to represent the following quantities: Output current of the PV cell (IPV), Photocurrent generated by the incident sunlight (Iph), Saturation current of the diode (Is), Output voltage of the PV cell (Vpv), Series resistance of the cell (Rs), Shunt resistance of the cell (Rsh), Electron charge (q) (1.602×10^-19), Ideality factor of the diode (A), Boltzmann constant (k) (1.381×10−23 J/K), Cell temperature in Kelvin (T).

C. Current- Voltage and Power- Voltage graph of the module.

The following graph shows the current-voltage characteristics and the power-voltage characteristics considered for the photovoltaic panel array type according to series modules per string and parallel strings. It is used to determine the output of power.

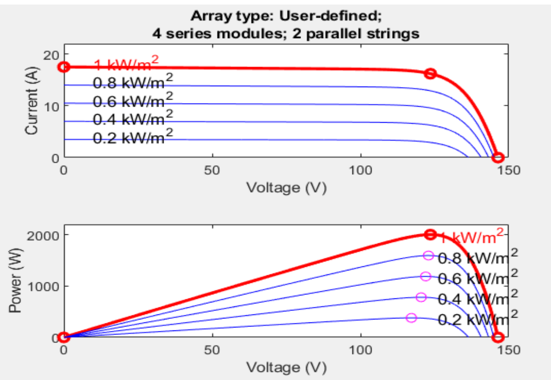

Fig. 3. Current- Voltage and Power- Voltage graph of the module

III. MPPT ALGORITHM USING PERTURB AND OBSERVE METHOD

Due to its straightforward implementation and fast convergence, the Perturb and Observe (P&O) methodology is used as the MPPT algorithm in the proposed solar system. The operating point of the solar panel is adjusted by perturbing the voltage and observing the resulting change in power, which is determined by the following equations:

Calculate Power:

$$P(k)=V(k)\cdot I(k)$$

where:

- P(k) is the power at the current step.
- V(k) is the voltage at the current step.
- I(k) is the current at the current step.

Compare Power Changes:

$$\Delta P=P(k)-P(k-1)$$

where:

- P(k−1) is the power at the previous step.
- ΔP indicates whether the power has increased or decreased.

Adjust Voltage:

- If ΔP>0, the operating point is moving toward the MPP. Continue perturbing in the same direction.
- If ΔP<0, the operating point is moving away from the MPP. Reverse the direction of perturbation.

$$v(k+1) = \begin{cases} v(k) + \Delta V, \text{if } \Delta P > 0 \\ v(k) - \Delta V, \text{if } \Delta P < 0 \end{cases}$$

where ΔV is the voltage perturbation step size.

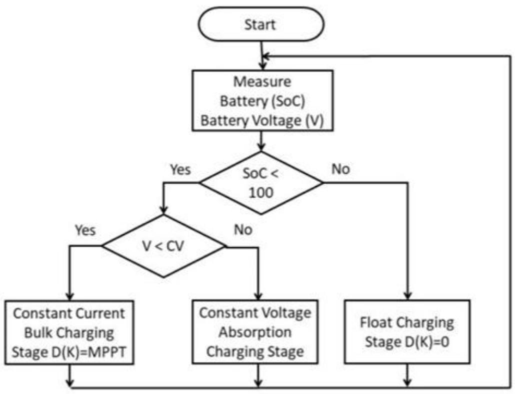

Fig. 4. Perturb & Observe MPPT algorithm flowchart.

The MPPT Perturb & Observe Algorithm in Simulink is shown in Fig. 4. It is implemented by using Simulink blocks and converting the algorithm into scripting code. The MATLAB representation of MPPT with the P&O algorithm and battery charge controller is as follows:

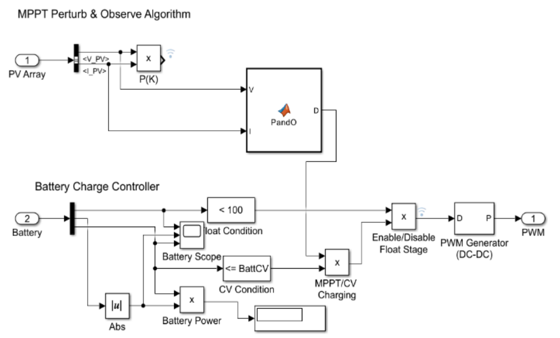

Fig. 5. Perturb & Observe MPPT algorithm implementation in Simulink

IV. BIDIRECTIONAL DC-DC CONVERTER

A bidirectional DC-DC converter is a key component in solar PV systems connected to batteries, enabling efficient energy transfer between the PV array, the battery, and the load. This converter operates in two modes: buck mode (step-down) and boost mode (step-up). In buck mode, it steps down the PV array voltage to charge the battery, ensuring it is charged at the optimal voltage and current. In boost mode, it steps up the battery voltage to supply power to the load or grid during periods of low solar generation. The bidirectional nature of the converter allows for seamless energy flow, facilitating both the charging and discharging of the battery. This enhances the system's flexibility and efficiency, enabling energy storage during excess solar generation and reliable power supply during demand peaks or low solar irradiance. Its ability to regulate power flow ensures the stability of the overall solar PV system, making it an essential component in modern renewable energy solutions.

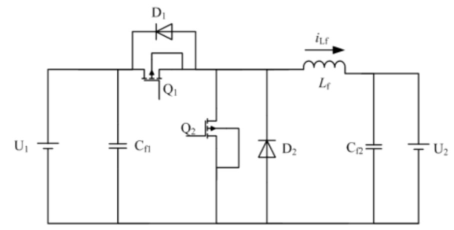

Fig. 6. Bi-directional DC to DC converter Circuit

Modes of operation:

Buck Mode (PV to Battery/Load): The converter steps down the voltage from V_{PV} to V_{battery}.

$$V_{\text{battery}} = D \cdot V_{PV}$$

Where D: Duty cycle (0≤D≤1).

Boost Mode (Battery to Load/PV): The converter steps up the voltage from V_{battery} to V_{load} or V_{PV}.

$$V_{PV} = \frac{V_{\text{battery}}}{1 - D}$$

V. SINGLE PHASE H-BRIDGE INVERTER

A single-phase H-bridge inverter plays a crucial role in solar PV systems by converting the DC power generated by the photovoltaic (PV) panels into AC power suitable for household appliances. The H-bridge inverter consists of four switching devices, typically MOSFETs or IGBTs, arranged in an "H" configuration. These switches are operated in pairs to control the direction of current flow through the load, producing an alternating voltage output. The inverter's operation involves alternately turning on and off the switches in complementary pairs:

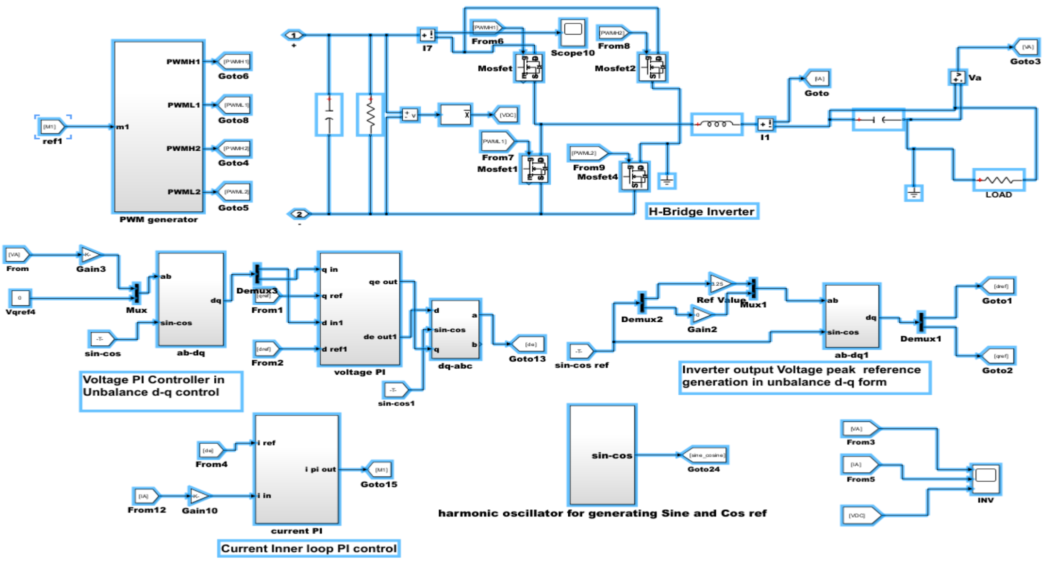

Fig. 7. Simulation diagram of H-Bridge inverter with PWM

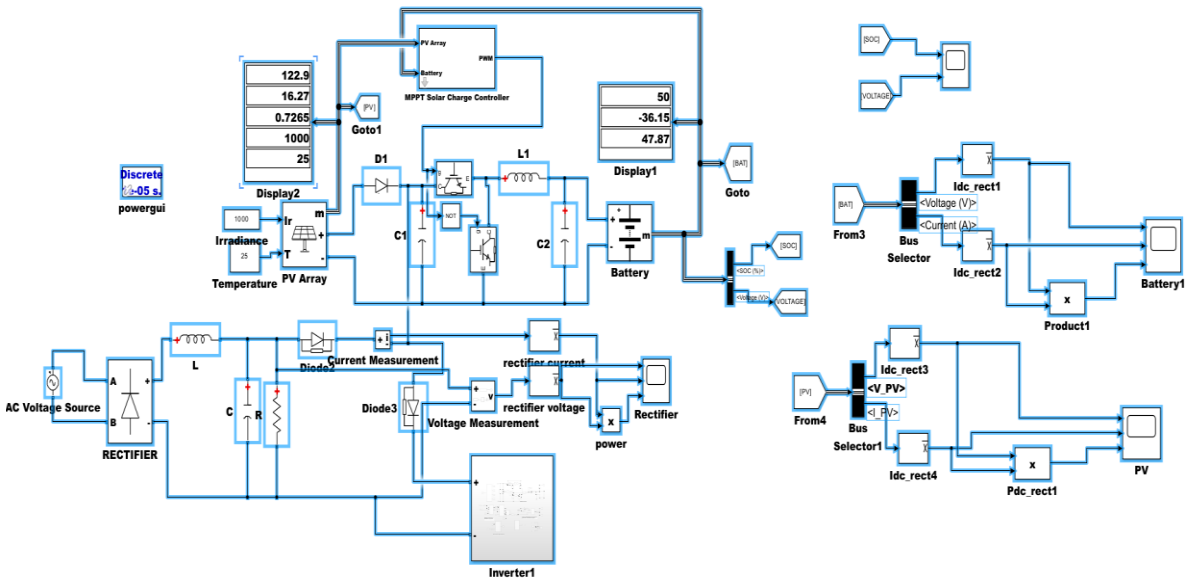

Fig. 8. Simulation of Standalone solar PV system with MPPT and Battery Energy System

- During the first half-cycle, one pair of switches (e.g. S1 and S4) is turned on, causing current to flow in one direction through the load.
- During the second half-cycle, the other pair of switches (e.g., S2 and S3) is activated, reversing the current direction.

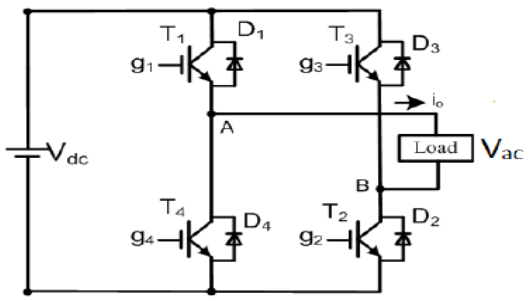

Fig. 9. Single-phase H-Bridge inverter circuit

The inverter is typically integrated with a Maximum Power Point Tracking (MPPT) algorithm to ensure the solar PV panels operate at their maximum power point, optimizing energy extraction. Pulse Width Modulation (PWM) plays a pivotal role in solar PV systems by providing efficient control over the power flow and it controls the switching devices (e.g., MOSFETs or IGBTs) in DC-DC converters, which step up or step down the voltage from the solar PV array to match the required load or battery voltage. It is used to modulate the output waveform, converting DC from the PV system into AC power suitable for appliances and generating a sinusoidal AC waveform by modulating the width of the pulses according to a sine wave reference. This reduces harmonic distortion and improves compatibility with AC loads.

VI SIMULATION RESULTS

The development and analysis of a standalone solar PV system equipped with MPPT and a battery energy storage system focuses on enhancing power quality and maximizing efficiency while minimizing energy losses. A Bidirectional DC-DC converter, recognized for its high reliability and efficiency, is integrated into the solar energy system to ensure superior power performance under varying temperature conditions. The maximum power point tracking (MPPT) technique, implemented using the Perturb and Observe (P&O) algorithm, optimizes energy extraction from solar panels by adapting to changing environmental conditions. Simulation results validate the system's capability to deliver stable power, reduce energy losses, and achieve improved overall efficiency. The above figure shows the simulation diagram of a Standalone solar PV system with MPPT and Battery energy system which is simulated in MATLAB software. The simulation diagram of a standalone solar PV system with a Perturb and Observe (P&O) MPPT, battery controller, and inverter typically illustrates the flow of energy and the operation of various components. A standalone solar PV system with a Perturb and Observe (P&O) MPPT, battery controller, and inverter illustrates the energy flow and operational components of the system.

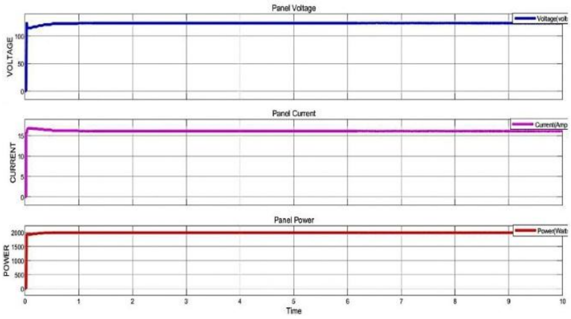

Fig. 10. Result of PV Voltage, PV Current, PV Power with a Variation of Irradiance

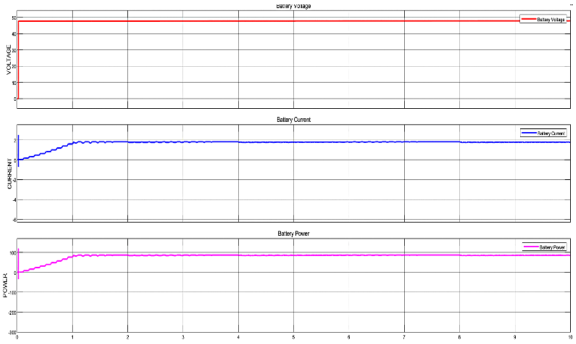

Fig. 11. Battery power, Battery voltage and Battery current characteristics

The battery charge controller was developed to charge a lead-acid battery using the three-stage charging method. The three-stage charging includes the constant current charging, constant voltage charging, and float charging stage. The first stage constant current charging also referred as the bulk charging stage where the charge current is charged at its rated capacity, in this case, the charge current is at MPPT.

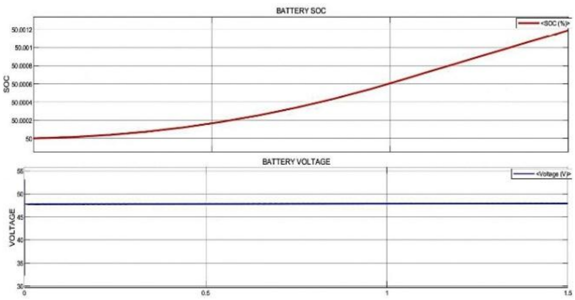

Fig. 12. SOC and Voltage in Battery Charging stage

The second stage constant voltage charging also refers to the absorption charging stage where the battery is charged at a constant voltage, in this stage the MPPT is disabled. Finally, the third stage float charge simply maintains the battery's State of Charge (SoC) at 100 % when the battery is fully charged.

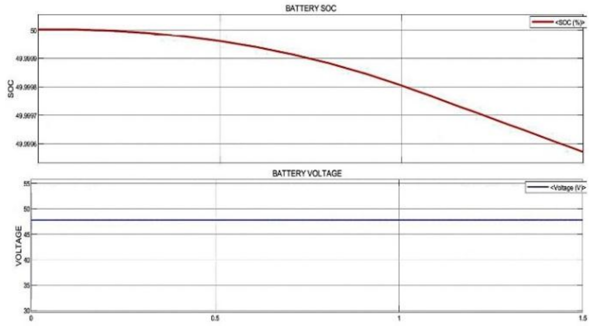

Fig. 13. SOC and Voltage in Battery Discharging State

VII EXPERIMENTAL RESULTS OF H-BRIDGE INVERTER AND RECTIFIER

A rectifier is used as a backup generation for solar photovoltaic (PV) setups. It converts alternating current (AC) from an auxiliary generation source, such as a diesel generator or the grid, into direct current (DC) suitable for charging the system's energy storage or supporting DC loads. When integrated with a bidirectional DC-to-DC converter, the rectifier enhances the system's flexibility and reliability.

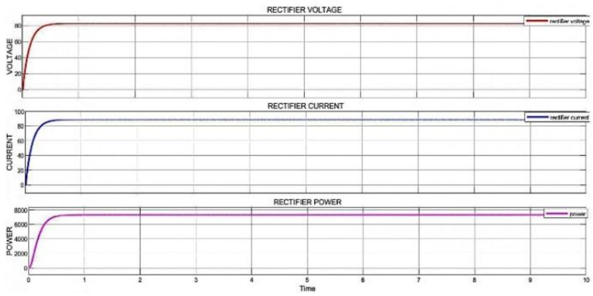

Fig. 14. Voltage, Current and Power characteristics with Rectifier

The bidirectional DC-to-DC converter acts as an interface between the battery bank and the DC bus of the solar PV system. In charging mode, the rectified DC power is regulated and directed toward the battery to restore its state of charge (SoC). Conversely, in discharging mode, the converter allows stored energy to flow from the battery to the DC bus, supplying the load or supporting other system operations.

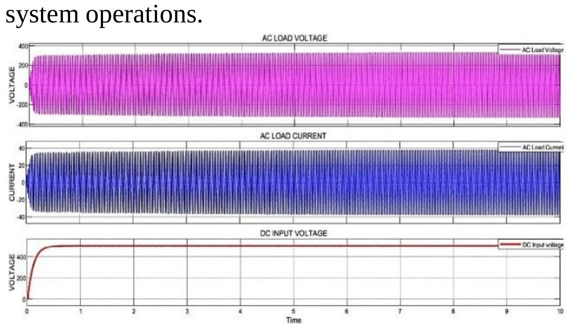

Fig. 15. AC Voltage, Current, and Power characteristics of H-Bridge inverter

VIII CONCLUSION

A detailed circuitry model of a Solar PV MPPT battery charge controller has been developed and presented in Simulink. The model incorporates an MPPT algorithm based on the Perturb and Observe (P&O) method, a buck converter circuit, and a battery charge controller. Each component is thoroughly explained and designed to be fully reproducible. The charge controller is designed to charge a 48V lead-acid battery efficiently by tracking the maximum power point of a 2 kW PV array and employing a three-stage charging strategy. The MPPT battery charge controller achieves an average overall efficiency of 98.3%, comparable to many high-end commercial MPPT charge controllers. This high efficiency demonstrates the capability of the model to meet the stringent performance requirements of modern solar PV systems. The Simulink model is highly flexible and can be adapted to match the topology of commercial MPPT charge controllers with similar design principles. Furthermore, its performance has been validated by comparing the results with a real commercial MPPT charge controller experimental setup. This validated model provides valuable insights for optimizing the sizing of PV panels and battery energy storage, particularly for small- to medium-sized standalone PV systems.

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