Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 7, No.1, July : 2025

AN ADAPTIVE CONTROL STRATEGY FOR SOLAR ENERGY CONVERSION AND BATTERY STORAGE IN STANDALONE PV SYSTEMS

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ABSTRACT

This paper presents a solar energy-based battery charging system designed for standalone applications. The system uses a hybrid Maximum Power Point Tracking (MPPT) method that combines Incremental Conductance (Inc-Cond) and Perturb & Observe (P&O) techniques to improve tracking speed and accuracy during changes in sunlight. A synchronous boost converter is used to increase the voltage from the solar panel to a suitable level for charging a lithium-ion battery. This converter reduces losses by replacing the traditional diode with a controlled MOSFET.

The battery is charged using a Constant Current–Constant Voltage (CC–CV) method to ensure safe and efficient operation. The system is modeled and tested in MATLAB/Simulink under different sunlight conditions. Simulation results show stable voltage output, effective MPPT performance, and smooth battery charging even when sunlight levels vary. The system also supports battery discharging during low solar availability, ensuring continuous power to the load. This design is suitable for off-grid and remote solar power applications.

Keywords: Solar Photo-Voltaic (SPV) system, Hybrid MPPT Algorithm, Perturb and Observe (P&O), Incremental conductance (IncCond), Synchronous Boost Converter, Lithium-ion Battery, Matlab/Simulink Modeling.

I. INTRODUCTION

As the demand for sustainable energy grows, photovoltaic (PV) solar power systems have emerged as a key element of renewable energy solutions, particularly for off-grid and programs that are decentralized. Because its power production is nonlinear and very sensitive to environmental variations like temperatures and sunlight exposure, sophisticated control systems are required for efficient energy harvesting. For standalone PV systems to ensure a consistent power supply, energy storage batteries are necessary.

The variable voltage of the PV is increased to the proper battery level. Charging levels with the use of the DC-DC boost converter, that is managed by an integrated controller to ensure reliable and safe operation. maximum power points tracking techniques are necessary for peak power extraction in dynamic circumstances. The P&O method is commonly used because of its simplicity, even though the Incremental Conductance (INC) approach offers more accuracy and a faster reaction in dynamic settings.

Recent studies have shown that variable step-size INC approaches outperform fixed step size variations in terms of tracking speed, stability, and charging efficiency. For instance, MATLAB/Simulink simulations were utilized in one study to determine that INC-based control had a system efficiency of almost 96%. Based on these results, this study offers a hybrid MPPT strategy that combines the simplicity of P&O with the flexibility of INC. The system, which consists of the PV, boost conversion device, MPPT controller, and battery with SOC monitoring, is modeled and then analyzed by using MATLAB/Simulink.

[1] investigated the efficacy of several Incremental Conductance (INC) MPPT strategies for PV system battery charging. Their study compared fixed and variable step-size implementations and

demonstrated that an adjustable step-size INC approach significantly improved tracking of the maximum power point by offering faster convergence, reduced current ripple, and more dependable charging in dynamic solar conditions. A standalone PV system with battery was designed and modeled using MATLAB/Simulink and a bidirectional DC-DC converter managed by an INC-based MPPT controller [2]. Their findings showed that under various temperature and irradiation circumstances, the system's efficiency may reach 96%, highlighting the importance of precise MPPT management and converter tuning for reliable energy transmission in off-grid photovoltaic systems.

II. SYSTEM DESIGN AND METHODOLOGY

A solar photovoltaic (PV) array coupled with a DC-DC power converter makes up the entire system, managed by the MPPT hybrid algorithm. Using a regulated current and voltage profile, a lithium-ion battery is charged using the converter's output. When solar energy is not enough, the battery also acts as a power source for the load.

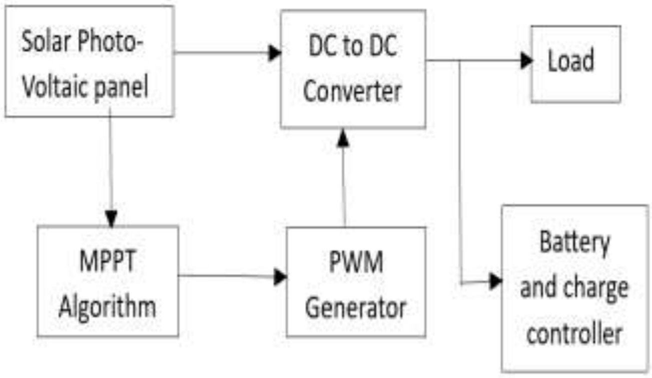

Fig. 1: The suggested system's block diagram

The system employs a hybrid MPPT algorithm that integrates key aspects of Perturb & Observe and Incremental Conductance to enhance tracking accuracy under varying irradiance. Voltage perturbations guide the operating point, while slope analysis refines convergence toward the MPP. A synchronous boost converter, implemented in Simulink using Simscape Electrical, steps up the PV voltage for battery charging. A MOSFET-based freewheeling path minimizes conduction losses and improves efficiency at low input levels, with PWM control regulating switching. A 48 V lithium-ion battery is used for its high energy density, fast charging, and long life.

Charging follows a CC–CV profile, and SOC monitoring ensures safe operation by preventing overcharge or deep discharge. This closed-loop control maintains safe and effective battery charging while ensuring everything operates at or close to the maximum power point.

The complete model was implemented together and simulated using MATLAB/Simulink in order to assess the performance of the suggested solar energy harvesting and battery charging system. Key performance metrics such tracking accuracy, converter voltage boosting behavior, battery charging response, and system adaptability under different irradiance levels were the main focus of the simulation. To replicate real-time power flow
regulation, every subsystem—including the PV module, MPPT controller, boost converter, and battery was linked in a closed-loop mode.

Industrial Engineering Journal
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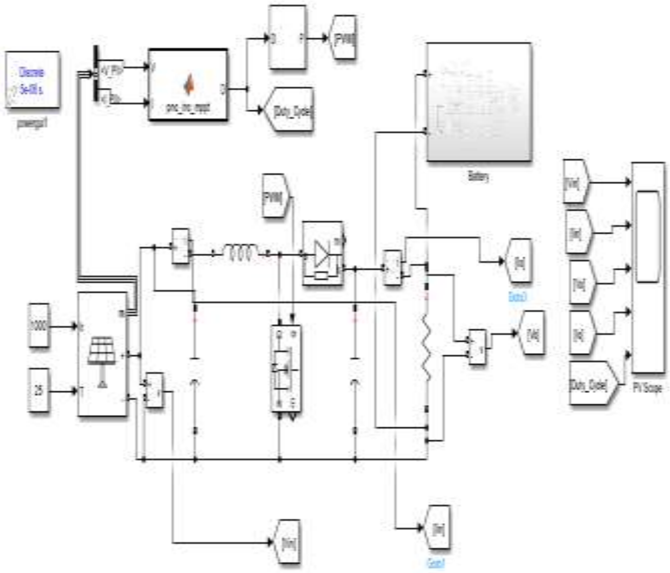

Fig 2: The specified system's simulation

A fixed-step simulation methodology and discrete solver parameters were used in the MATLAB/Simulink simulation. A typical test was used to configure the PV array. standard test condition of 25°C and 1000 W/m² of irradiance. To confirm MPPT performance and system stability, additional scenarios were developed to test the system under various irradiance levels (such as 800 W/m² and 500 W/m²).

III. SIMULATION RESULTS

Depending on the amount of solar irradiation during the simulation, the PV panel generates a variable DC voltage. The hybrid MPPT controller uses an incremental conductance check in conjunction with perturb and observe logic to determine the optimal operating point.

A PWM generator is then utilized to control the synchronous boost converter based on the determined duty cycle. To increase the PV voltage to an extent appropriate for charging lithium-ion batteries, the converter modifies its switching operation. To guarantee safe operation, the battery's voltage, electrical current, and the state of charge (or SOC) are continuously monitored while it is charged using a CC–CV profile. Stable voltage and current output were attained by the PV system under constant irradiation (1000 W/m²).

The operating conditions are:

a. Stable PV Output at Constant Irradiance
b. Adaptive Response to Irradiance Fluctuations
c. Efficient Battery Charging – Under constant irradiance and Varying irradiance.
d. Battery Discharging mode.

3.1 Stable PV output at constant irradiance

The converter effectively raises the changing PV voltage to a steady, higher level appropriate for battery input, as shown by the Fig 5. The PV system maintains consistent voltage and power output at 1000 W/m² as shown in Fig 3 and Fig 4.

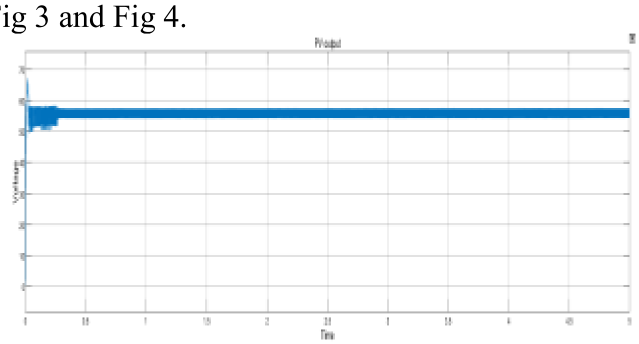

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Fig. 3: PV system's voltage response

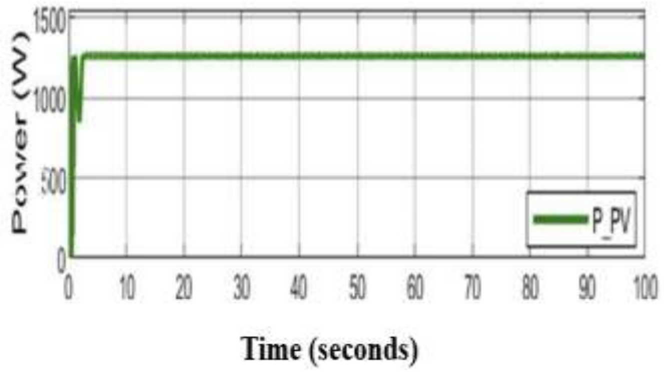

Fig. 4: PV output power at Constant irradiance

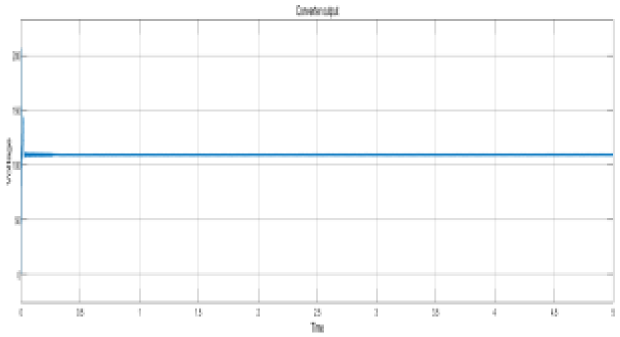

Fig. 5: Boost converter's voltage response

3.2 Adaptive Response to Irradiance Fluctuations

The PV array was subjected to a step-by-step change in irradiance throughout a single simulation cycle in order to assess the dynamic performance of the suggested system. The brightness was 1000 W/m² was the initial setting, which was subsequently lowered to 800 W/m², then to 500 W/m², and eventually back to 1000 W/m². Realistic solar conditions, like cloud movement or partial shadowing, were simulated using this version.

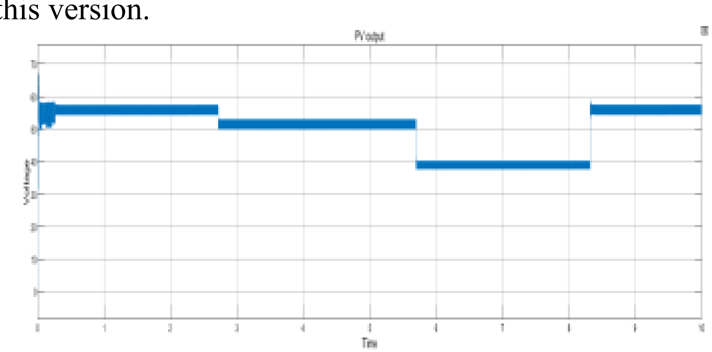

Fig. 6: PV Output Voltage response Under Varying Irradiance

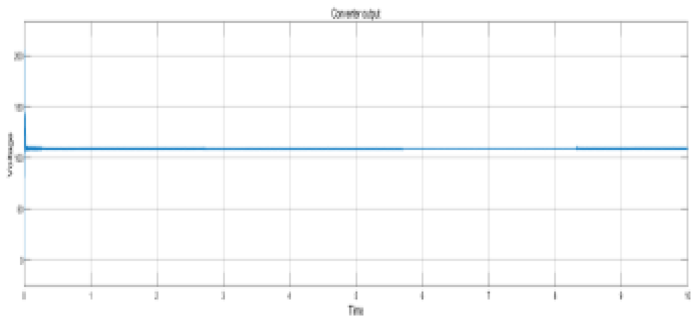

Fig. 7: Converter response Under Varying Irradiance

The waveform shows that at each stage of irradiance reduction, the PV voltage and current decrease correspondingly. The new maximum power point is determined by the hybrid MPPT algorithm following to sustain effective energy extraction, the duty cycle is modified and adjusted for each. Despite variations in the solar input, the battery receives a steady charging input because to the synchronous boost converter's quick response and output voltage regulation.

During the low irradiance interval (500 W/m²), the PV output power decreases significantly, yet the converter maintains voltage boosting functionality, though the charging current to the battery is reduced. Once irradiance returns to 1000 W/m², the controller rapidly re-converges to the optimal point, and the system resumes full-power charging operation.

This simulation confirms that the proposed system maintains continuous operation and exhibits strong adaptability under rapidly changing environmental conditions.

3.3 Efficient Battery Charging – Under constant irradiance and Varying irradiance.

3.3.1. Battery Charging under constant Irradiance

During charging, the battery voltage increased gradually and then levelled off, indicating a shift from constant current to constant voltage mode.

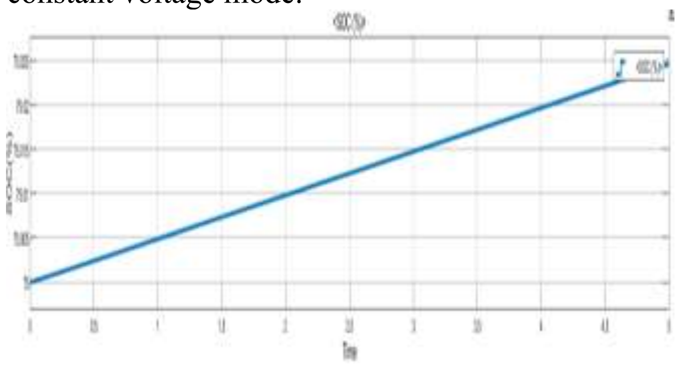

Fig. 8: SOC progression during the simulation (Charging)

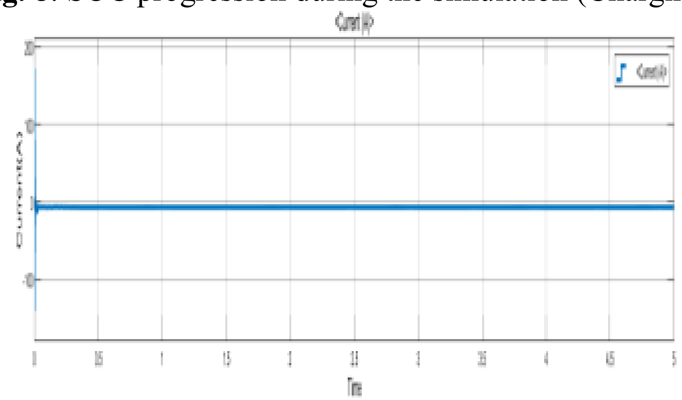

Fig. 9: Battery current during the simulation (Charging)

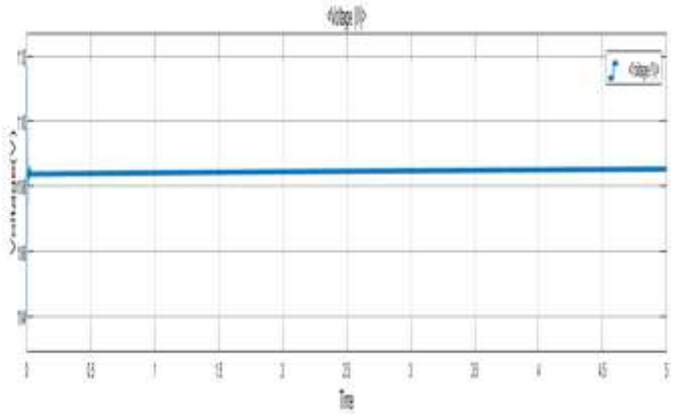

Fig. 10: Battery voltage during the simulation (charging)

Throughout the simulation time, the SOC grew steadily, demonstrating that the MPPT controller and converter provided reliable and secure energy transmission from the solar source to the battery.

3.3.2 Battery Charging under Varying Irradiance

During the simulation, the battery charging behavior closely followed the irradiance variations applied to the PV array. There was a corresponding drop in charging current as the solar irradiation dropped from 1000 W/m² to 800 W/m² and finally to 500 W/m² because of lower power generation.

Despite the lower input, the boost converter maintained a stable output voltage, enabling the battery to continue charging. Although the rate of charging slowed during low irradiance periods, the battery voltage continued to rise, and the SOC showed a steady upward trend.

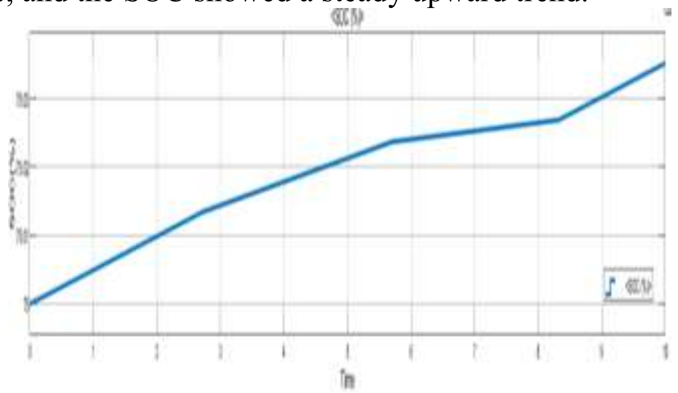

Fig. 11: SOC progression during the simulation (Charging)

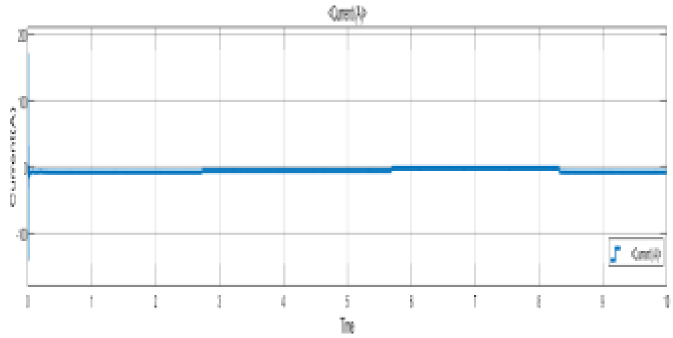

Fig. 12: Battery current during the simulation

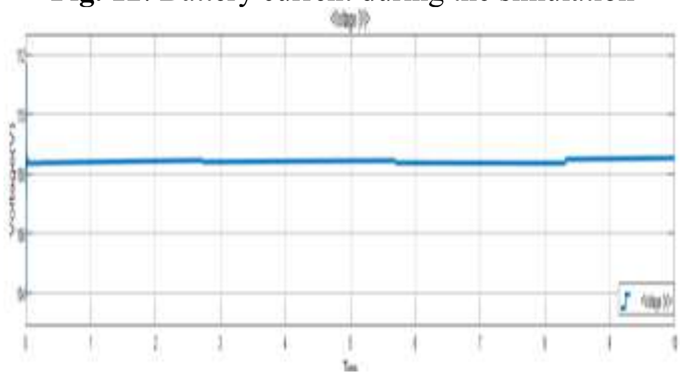

Fig. 13: Battery voltage during the simulation

The charging current increased once more and the SOC increased faster when the irradiance reached 1000 W/m². The system switched from constant electrical current to constant voltage mode when the battery got closer to its full charge level. This slow change in charging behavior shows how the system can adjust to changing solar circumstances while maintaining a steady and secure energy transfer to the battery.

3.4 Battery Discharging mode

In the absence of sufficient solar energy, the converter operated in reverse to discharge the battery. The converter maintained output voltage stability to supply the load during these periods.

When the solar irradiance drops below the level required to meet the connected load demand, the system transitions into discharging mode. In this condition, the synchronous boost converter operates in reverse, enabling the battery to deliver stored energy to the load.

The discharging is not continuous but occurs only when the instantaneous load exceeds the available PV power, making the system load-dependent in its battery support strategy.

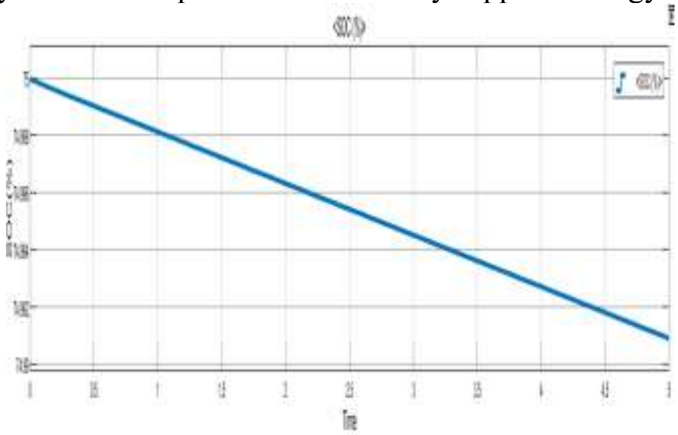

Fig. 14: SOC during the battery discharging

The converter maintains a stable output voltage during this period, ensuring uninterrupted power supply to the load despite reduced solar generation. Once the irradiance improves and PV power becomes sufficient to both supply the load and charge the battery, the system automatically switches back to charging mode. This switching behavior enhances overall energy utilization and enables reliable system operation even during partial shading or low sunlight.

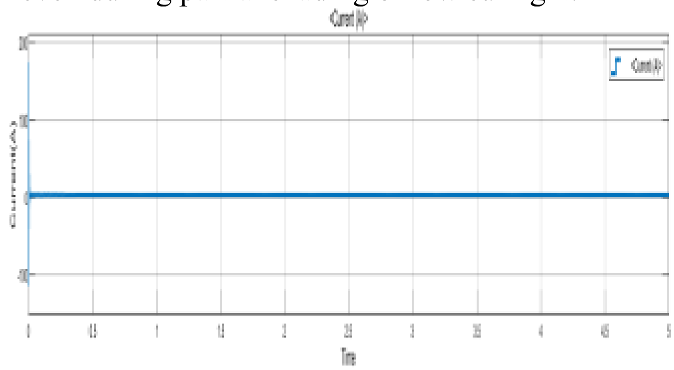

Fig. 15: Battery voltage and current during discharging

This behavior highlights the bidirectional functionality of the converter and the system's capability to manage both charging during solar surplus and discharging during power deficit, ensuring smooth energy flow and increased autonomy in standalone or weak-grid applications.

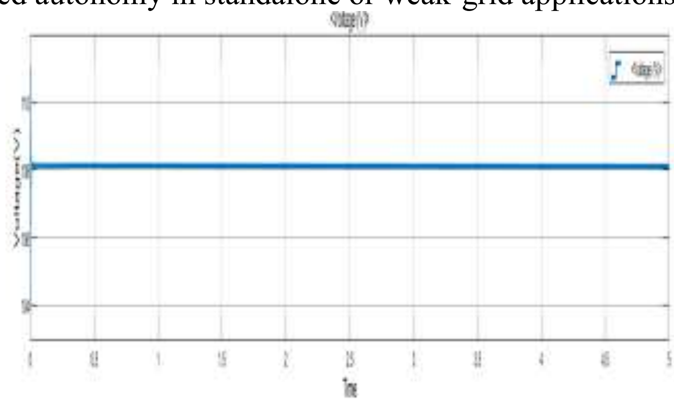

Fig. 16: Battery voltage and current during discharging

This mode validates the system's bidirectional capability, improving energy utilization and autonomy during nighttime or shading events.

V. CONCLUSION

The design and simulation of a solar-powered battery charging system are discussed in this work. The system combines a synchronous boost converter with a hybrid Maximum Power Point Tracking (MPPT) technique. The characteristics of the Incremental Conductance (Inc-Cond) and Perturb and Observe (P&O) algorithms are combined in the hybrid MPPT. This combination makes it easier for the system to react to variations in temperature and sunlight. Overall efficiency is increased with the employment of a synchronous boost converter. It lowers switching losses by substituting a second MOSFET for the conventional diode. The voltage from the solar panel is raised by this converter to the required amount for battery charging. The system uses a Li-ion battery because of its long life-cycle and high energy density.

To safeguard the battery and increase its longevity, the charging procedure adheres to the constant current–constant voltages (CC-CV) profile. The battery's current state of charge (SOC) is tracked using a straightforward battery management technique. It guarantees safe operation and stops overcharging.

The hybrid MPPT approach discovers the maximum power point faster and more precisely than individual approaches, according to simulation data. Additionally, the system maintains a steady output voltage even in the event of a shift in the sun's circumstances, such as partial shadowing.

Overall, the proposed design is efficient and reliable. It can be applied in off-grid solar systems, remote power applications, and standalone renewable energy setups. The combination of a fast MPPT controller, an efficient converter, and reliable storage makes the system suitable for real-world use in sustainable energy projects.

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