

Research Article

## **Performance Analysis and Control Strategy of a Grid-Integrated Solar PV Electric Vehicle Charging Station**

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### **Abstract**

As the global energy paradigm shifts toward sustainable electric mobility, the integration of solar photovoltaic (PV) generation into electric vehicle (EV) charging infrastructure has emerged as a critical research frontier. This paper presents a comprehensive performance analysis and coordinated control framework for a DC-coupled microgrid designed for EV charging applications. The proposed system architecture integrates a 4-kW solar PV array interfaced through a two-phase interleaved buck converter, a bidirectional DC-DC converter for energy storage system (ESS) management, and a grid-connected single-phase inverter. To ensure optimal energy harvesting under variable environmental conditions, an Incremental Conductance (IC)-based Maximum Power Point Tracking (MPPT) algorithm is employed. System stability and grid synchronization are achieved using a DQ0-based current control strategy incorporating Park's transformation and sinusoidal pulse-width modulation (SPWM). The complete system is modeled and simulated in MATLAB/Simulink under a wide range of irradiance conditions varying from 1000 W/m<sup>2</sup> to 0 W/m<sup>2</sup>. Simulation results validate the effectiveness of the proposed energy management strategy. The interleaved buck converter significantly reduces current ripple at the DC bus, thereby enhancing battery lifetime and system stability. The results confirm the suitability of the proposed DC-coupled microgrid architecture for reliable, efficient, and grid-friendly EV charging applications.

### **Keywords**

Photovoltaic Systems, Interleaved Buck Converter, Electric Vehicle Charging, Incremental Conductance MPPT, Grid Integration

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## I. Introduction

The accelerating global transition toward electric mobility necessitates a fundamental restructuring of conventional power distribution networks to accommodate high-power and stochastic EV charging demands. While EV adoption significantly reduces tailpipe emissions, uncontrolled charging can impose severe peak-load stress, voltage instability, and power quality degradation on distribution grids. Consequently, the integration of renewable energy sources—particularly solar photovoltaic (PV) systems—into EV charging infrastructure has become essential for achieving both environmental sustainability and grid resilience.

DC-coupled microgrids provide an effective platform for integrating PV generation, energy storage systems, EV chargers, and grid interfaces within a common DC bus. However, managing such systems requires precise power electronic interfaces and robust control strategies capable of ensuring stable bidirectional power flow between the PV array, stationary energy storage, EV batteries, and the utility grid. Fig. 1 shows the EV charging architecture.

One of the primary challenges in PV-powered EV charging stations is the inherent intermittency of solar irradiance and the associated current ripple generated by conventional step-down conversion stages. Excessive current ripple adversely affects battery health by increasing thermal stress and accelerating aging. Additionally, maintaining a regulated 400 V DC bus under fluctuating load and generation conditions presents a complex control problem requiring high-bandwidth voltage regulation.

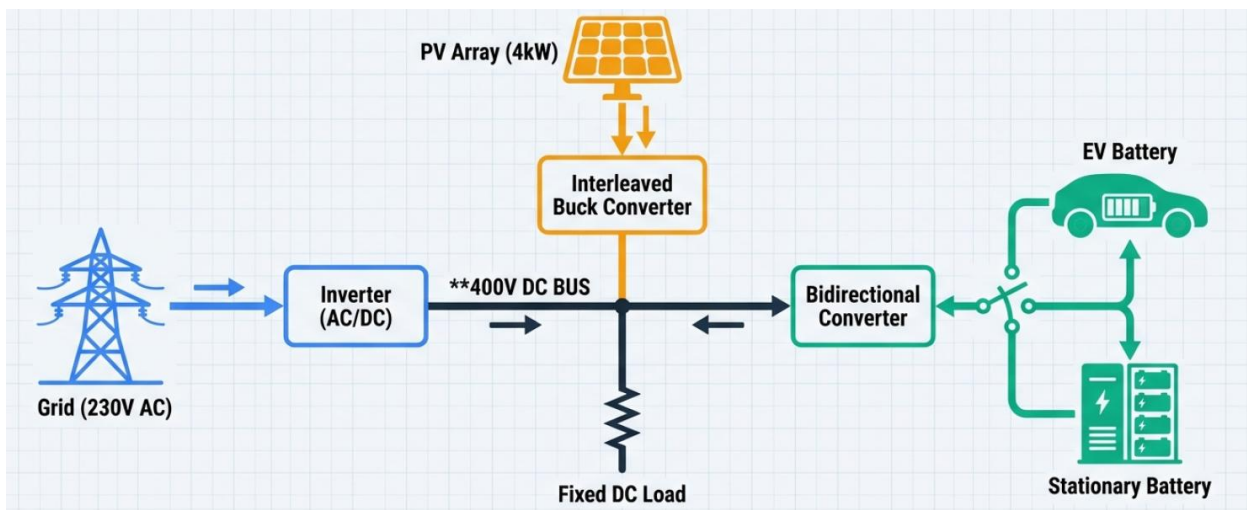


Fig. 1 EV Charging Architecture

To address these challenges, this research proposes a DC-coupled EV charging architecture utilizing a two-phase interleaved buck converter for PV interfacing. The interleaved topology inherently reduces current ripple through phase-shifted operation and avoids discontinuous conduction mode

(DCM) at low power levels. A dual-battery management strategy is introduced to prioritize energy flow between the EV battery and stationary ESS based on vehicle availability. This coordinated approach improves system efficiency, reduces grid dependency, and minimizes total harmonic distortion (THD) at the grid interface.

The primary objective of this study is to evaluate the coordinated control of a PV–EV–Grid system using MATLAB/Simulink. The analysis focuses on MPPT tracking performance, DC bus voltage stability, bidirectional converter dynamics, and grid synchronization under variable irradiance and load conditions.

The integration of solar photovoltaic (PV) systems with electric vehicle charging stations (EVCS) has emerged as a key solution for reducing grid dependency and enhancing renewable energy utilization. Recent research has focused on grid-supportive control, intelligent energy management, and system resilience to address the challenges associated with high-power EV charging and intermittent renewable generation.

Saha *et al.* [1] proposed an adaptive grid-supportive control strategy for solar-powered fast EV charging stations. Their approach enables voltage and frequency regulation under dynamic grid conditions, allowing the charging station to actively participate in ancillary grid services. The results demonstrated improved power quality and stable operation during rapid charging and fluctuating solar generation.

Energy management strategies for grid-integrated PV and battery energy storage-based EV charging stations were comprehensively analyzed by Ali and El Haini *et al.* [2]. The study compared conventional rule-based techniques with neural network-based approaches and showed that intelligent controllers provide enhanced adaptability and robustness under uncertain irradiance and load variations. This work highlights the growing relevance of data-driven methods in modern EV charging infrastructures.

Hybrid control techniques have been introduced to improve coordination among PV, battery, and grid sources. Sithambaram *et al.* [3] developed a hybrid energy management method for a grid-connected PV-powered EV charging station. Their results indicated improved charging efficiency and reduced grid power consumption, particularly during peak demand periods, demonstrating the effectiveness of hybrid control frameworks.

Bidirectional power exchange and vehicle-to-grid (V2G) functionality were addressed by Rao *et al.* [4], who proposed a solar-integrated energy management system supporting seamless grid-to-vehicle (G2V) and V2G operation. The study reported enhanced DC-link stability and effective power flow coordination, reinforcing the role of EV batteries as distributed energy storage units in smart grid environments.

Jain *et al.* [5] investigated the design and performance of a three-phase grid-connected solar PV-battery energy storage system. Their analysis focused on power quality, system efficiency, and grid compliance, emphasizing the importance of robust inverter control and energy storage integration for reliable EV charging applications.

System resilience under grid disturbances was examined by Mazumdar *et al.* [6], who proposed a resilient EV charging framework integrating solar PV, standby batteries, and advanced control mechanisms. The proposed strategy ensured uninterrupted charging during grid faults and renewable intermittency, highlighting the importance of fault-tolerant energy management in EV charging stations.

In addition to operational strategies, optimal planning of EV charging infrastructure has also been investigated. Deeum *et al.* [7] studied the optimal placement of EV charging stations in active distribution networks with PV and battery energy storage integration. Their optimization-based approach minimized power losses and voltage deviations, underscoring the necessity of coordinated planning for large-scale EVCS deployment.

## II. System Modeling

The proposed DC-coupled microgrid is structured around a centralized DC bus regulated at 400 V. Accurate voltage matching between the PV generation stage and the DC bus is essential to maximize conversion efficiency and ensure stable operation of downstream converters. Fig. 2 illustrates solar PV array specification.

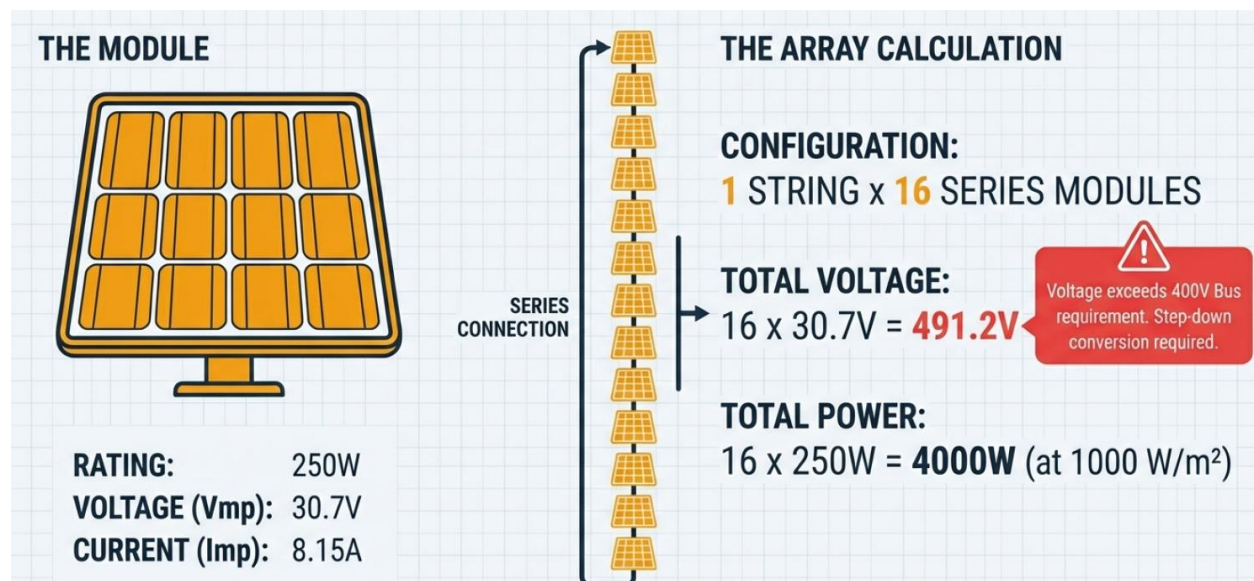


Fig. 2 Solar PV Array Specification

### A. Photovoltaic Generation Unit

The PV generation unit consists of 16 series-connected modules, each rated at 250 W, yielding a total peak power capacity of 4 kW under Standard Test Conditions (STC). Each module exhibits a maximum power point voltage of 30.7 V and a current of 8.15 A. Consequently, the PV string produces an approximate MPP voltage of 491.2 V, necessitating step-down conversion to match the 400 V DC bus.

### B. Interleaved Buck Converter

An interleaved buck converter is employed to interface the PV array with the DC bus. The converter comprises two identical buck stages operating in parallel with a 180° phase shift between their switching signals. This interleaving effect results in partial cancellation of current ripples at both the input and output, significantly improving current quality delivered to the DC bus and connected storage systems. Fig. 3 shows interleaved buck converter.

The output voltage of the converter is governed by the duty cycle  $D$ , expressed as

$$V_{\text{out}} = D \cdot V_{\text{in}}$$

By distributing current across multiple phases, the interleaved converter mitigates the risk of DCM operation, enhances control linearity, and improves thermal performance.

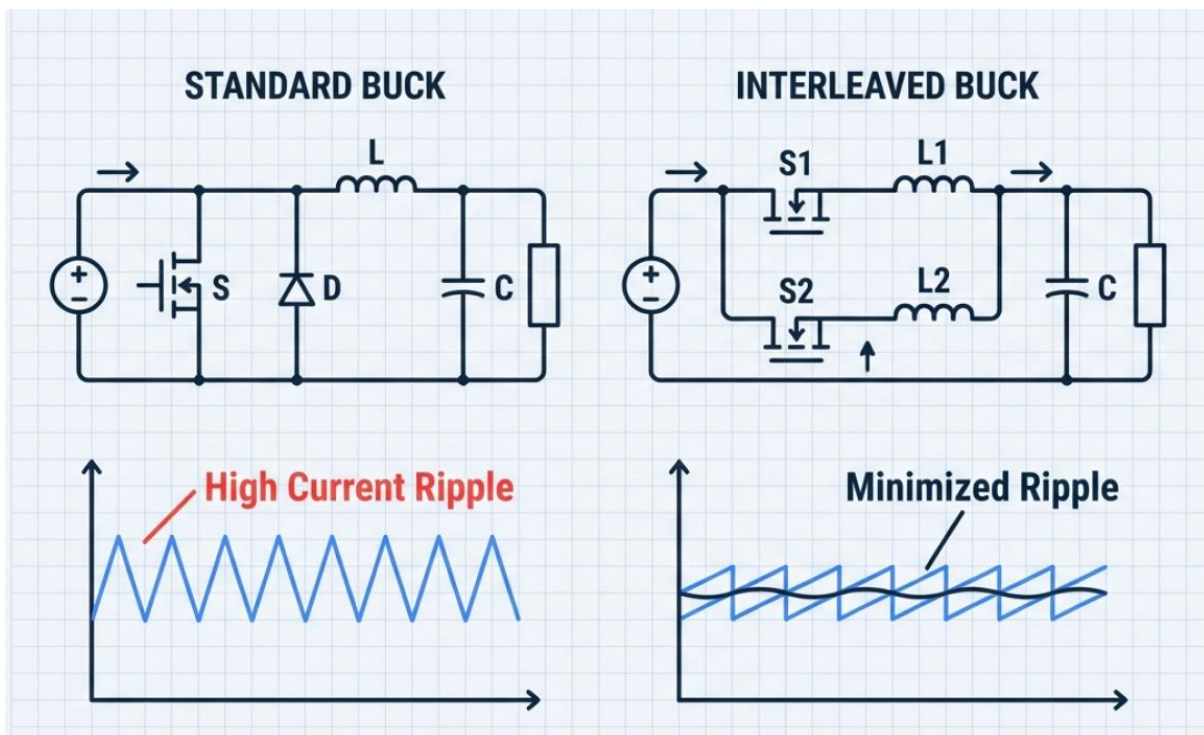


Fig. 3 Interleaved Buck Converter

### C. Energy Storage and EV Interface

Energy storage is integrated via a bidirectional DC-DC converter that regulates power flow between the DC bus and connected storage assets. A logical control signal governs a circuit breaker that selects either the EV battery or stationary ESS as the active storage unit. This configuration ensures that only one primary storage asset is prioritized at a given time, improving control simplicity and operational safety.

## III. Control Methodology and Mathematical Modeling

The control framework is designed to achieve three primary objectives: maximum power extraction from the PV array, stable DC bus voltage regulation, and synchronized grid interaction.

### A. Incremental Conductance MPPT

Maximum Power Point Tracking is implemented using the Incremental Conductance (IC) method, which exploits the condition that the derivative of PV power with respect to voltage is zero at the maximum power point:

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V}$$

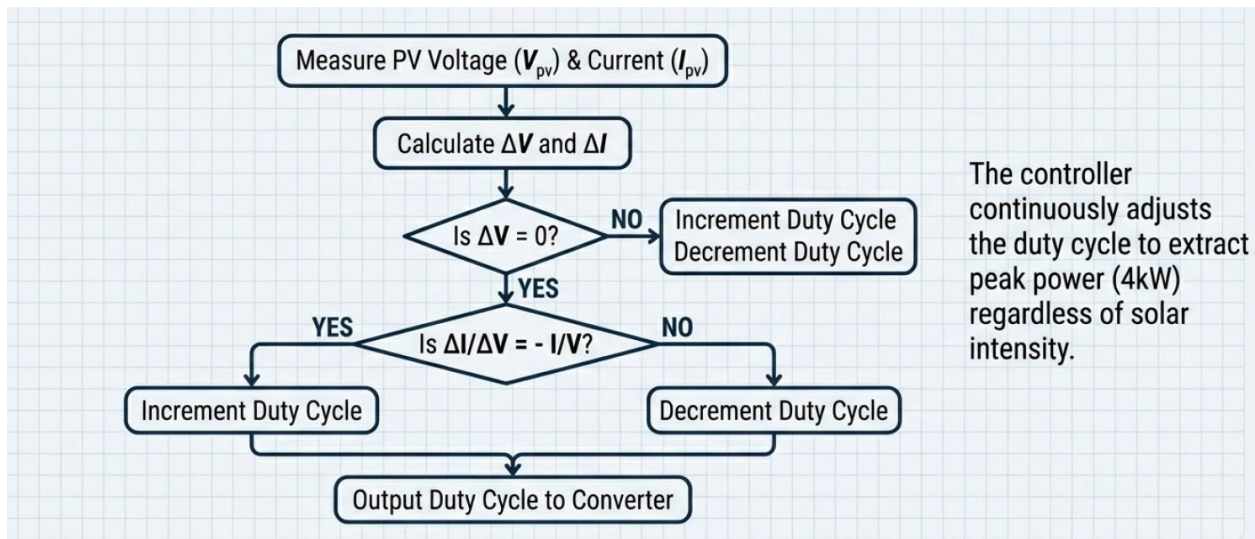


Fig. 4 Flowchart of Incremental Conductance MPPT

Fig. 4 shows the flowchart of incremental conductance MPPT. The algorithm continuously evaluates the instantaneous PV voltage and current to determine the direction of duty-cycle adjustment. If

$$\frac{dI}{dV} > -\frac{I}{V}$$

the duty cycle is increased; otherwise, it is decreased. This approach ensures rapid and accurate MPP tracking under dynamic irradiance conditions.

### B. Grid-Side Control Strategy

Grid synchronization is achieved using a DQ0 current control strategy based on Park's transformation. Measured grid currents are transformed into the rotating reference frame, where PI controllers regulate the d- and q-axis current components. The controlled voltage references are transformed back to the stationary frame and applied to a sinusoidal PWM generator to produce inverter gating signals. Fig. 5 shows the grid integration with inverter control.

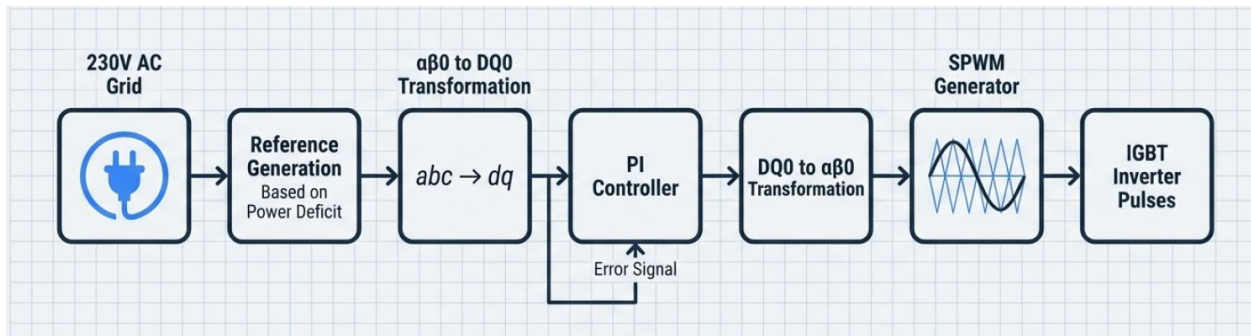


Fig. 5 Grid Integration with Inverter Control

### C. Energy Management Logic

A rule-based state machine governs energy flow using PV current magnitude and EV availability as decision variables. Table I and Fig. 6 represents grid dispatch logic.

TABLE I  
GRID DISPATCH LOGIC

Condition	Logic State	Action
$I_{pv} < 0.5A$ & EV present	Grid Support Enabled	Grid supplies EV and DC load
$I_{pv} > 2.0A$	Grid Disabled	PV supplies EV directly
EV absent	Stationary Mode	ESS supports DC load; zero-grid operation

This strategy ensures grid engagement only, when necessary, thereby minimizing energy costs and grid stress. Fig. 7 shows the storage logic.

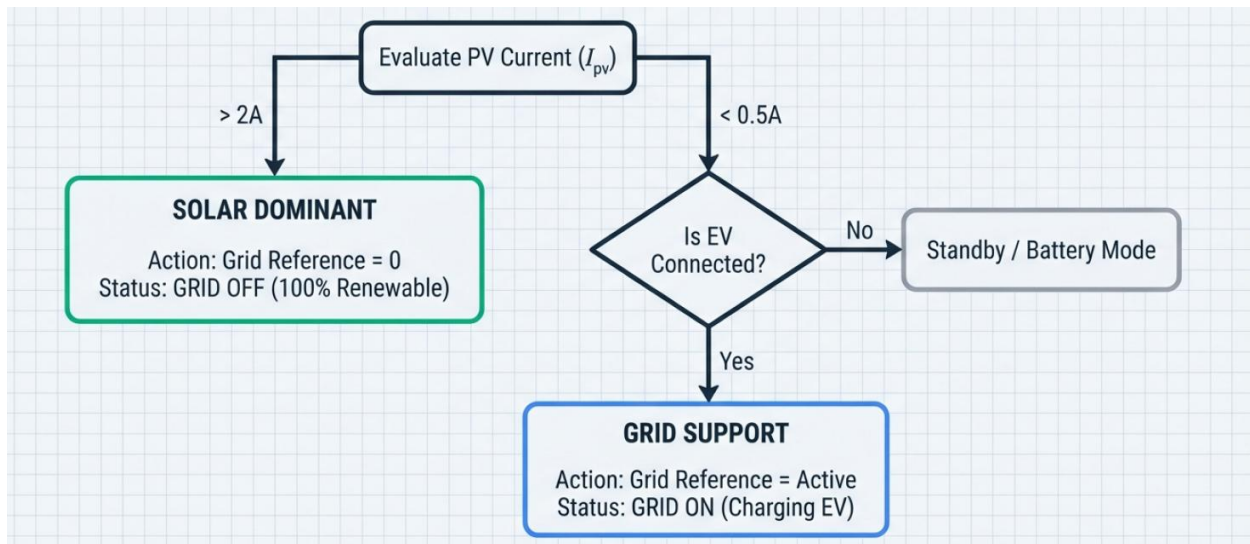


Fig. 6 Grid Dispatch Logic

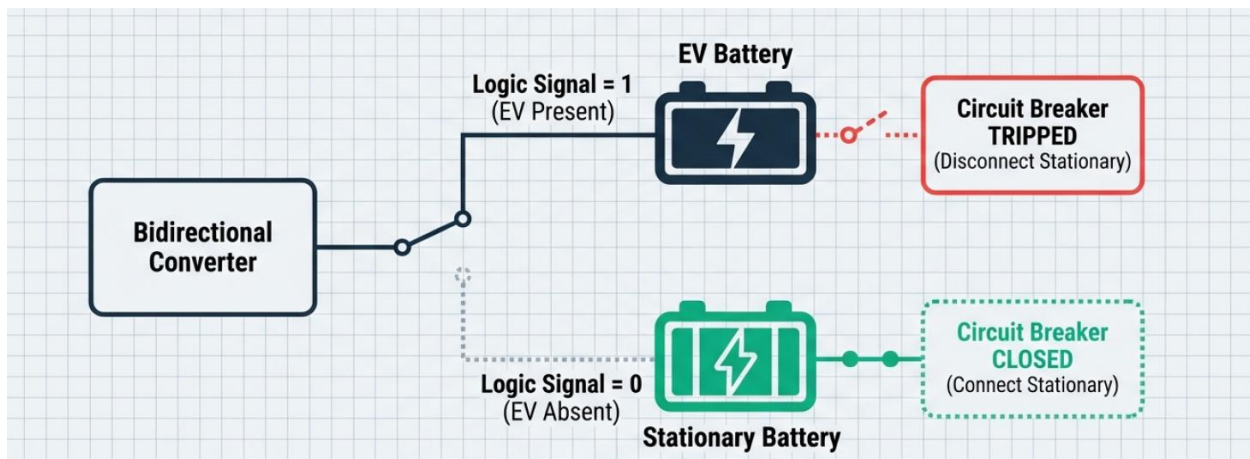


Fig. 7 Storage Logic of EV vs Stationary Battery

#### IV. Simulation Setup and Parameters

Type The complete system is modeled in MATLAB/Simulink to evaluate dynamic behavior under transient irradiance conditions.

TABLE II  
SYSTEM PARAMETERS

Parameter	Value

Parameter	Value
PV Module Rating	250 W
PV Configuration	16 Series Modules
Total PV Power	4 kW
DC Bus Voltage	400 V
Grid Voltage	230 V AC
$V_{mpp}$ (Module)	30.7 V
$I_{mpp}$ (Module)	8.15 A
Interleaving Phase Shift	180°

The simulation employs a stochastic solar irradiance profile to rigorously evaluate the robustness of the Incremental Conductance (IC) MPPT algorithm and the associated energy management logic. The irradiance level is varied in discrete steps, transitioning from 1000 W/m<sup>2</sup>, representing standard peak solar conditions, to 500 W/m<sup>2</sup>, corresponding to partial shading, and finally to 0 W/m<sup>2</sup>, indicating the absence of solar generation. This dynamic irradiance profile enables a comprehensive assessment of the system’s power flow redistribution, DC bus voltage stability, and control responsiveness under realistic and rapidly changing operating conditions. Fig. 8 illustrates voltage control and bidirectional flow.

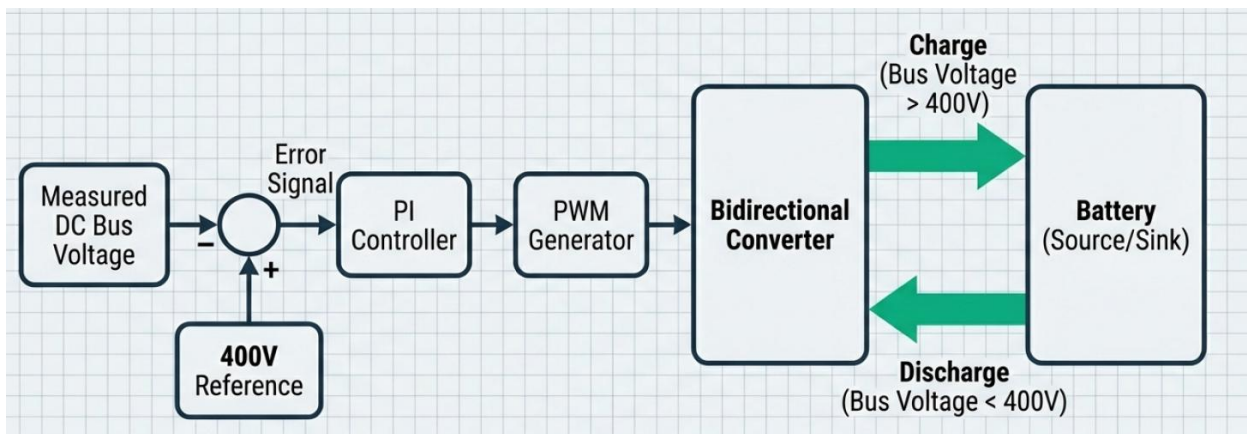


Fig. 8 Voltage Control and Bidirectional Flow

## V. Results and Discussion

The performance analysis focuses on the dynamic response of the proposed system under step variations in solar irradiance, with particular emphasis on the redistribution of power among the photovoltaic array, the utility grid, and the connected energy storage units. These transitions provide insight into the effectiveness of the coordinated control strategy and the stability of the DC-coupled microgrid.

Under peak irradiance conditions of **1000 W/m<sup>2</sup>**, the Incremental Conductance (IC) MPPT algorithm successfully extracts approximately **4 kW** from the PV array. The interleaved buck converter efficiently steps down the PV array voltage from approximately **491 V** to the regulated **400 V DC bus**, while maintaining negligible current ripple due to the phase-shifted operation of the interleaved topology. This confirms the converter’s suitability for battery-coupled EV charging applications where current ripple minimization is critical.

### Case A: EV Connected (Signal = 1).

When an EV is connected, it is assigned the highest priority in the energy management hierarchy. At an irradiance level of **1000 W/m<sup>2</sup>**, the system supplies **1000 W** to the local DC load, while the remaining **3000 W** is allocated to charging the EV battery. As the irradiance decreases to **0 W/m<sup>2</sup>**, the control logic identifies a condition where the PV current falls below **0.5 A**, thereby triggering grid support. In this mode, the utility grid supplies the required power to sustain both EV charging and the DC load, ensuring uninterrupted charging operation and a continuous increase in the EV battery state of charge (SoC). Fig. 9 shows EV Connected (Signal = 1). Fig. 10 shows energy balance analysis.

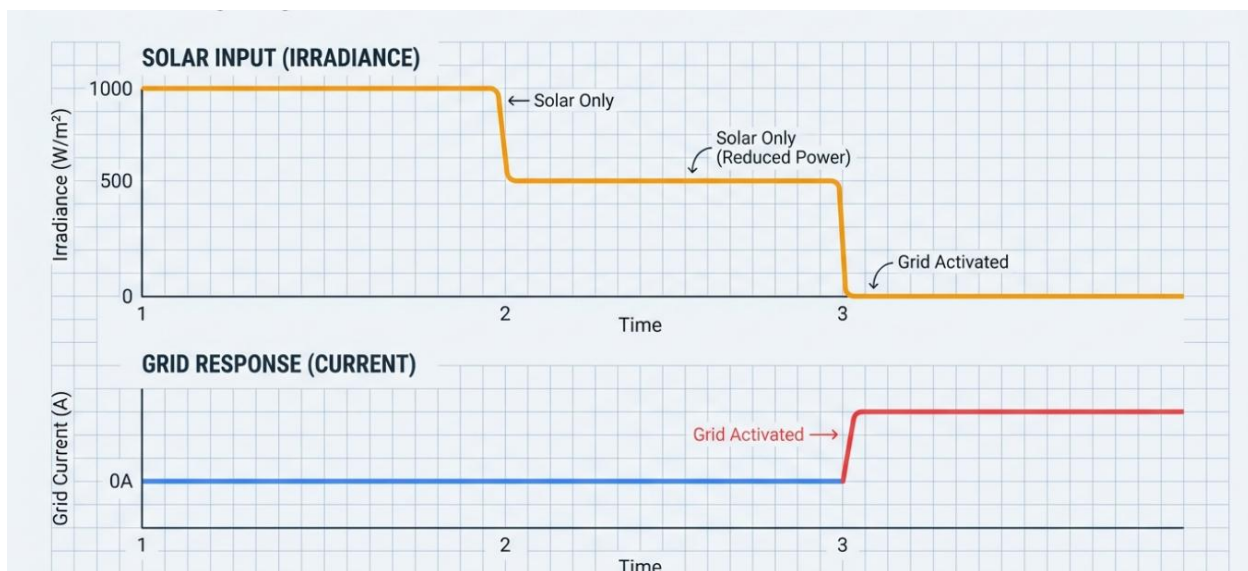


Fig. 9 EV Connected (Signal = 1)

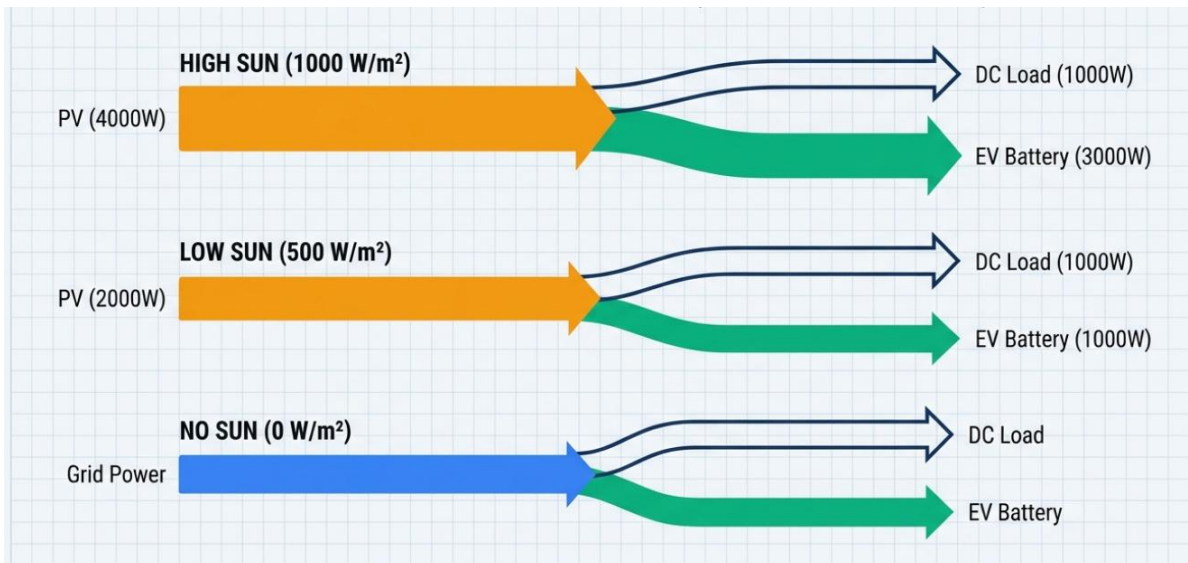


Fig. 10 Energy Balance Analysis

**Case B: Stationary Battery Mode (Signal = 0).**

In the absence of an EV, the control signal isolates the EV charging path via the circuit breaker and activates the stationary energy storage system. Under this operating condition, the system enters a “Zero-Grid” mode. When PV generation is insufficient or drops to zero, the stationary battery discharges to support the local DC load without drawing power from the grid. Grid participation remains at **0 W**, the proposed architecture to operate as an autonomous DC microgrid when EV charging is not required. Fig. 11 shows stationary battery mode (Signal = 0)

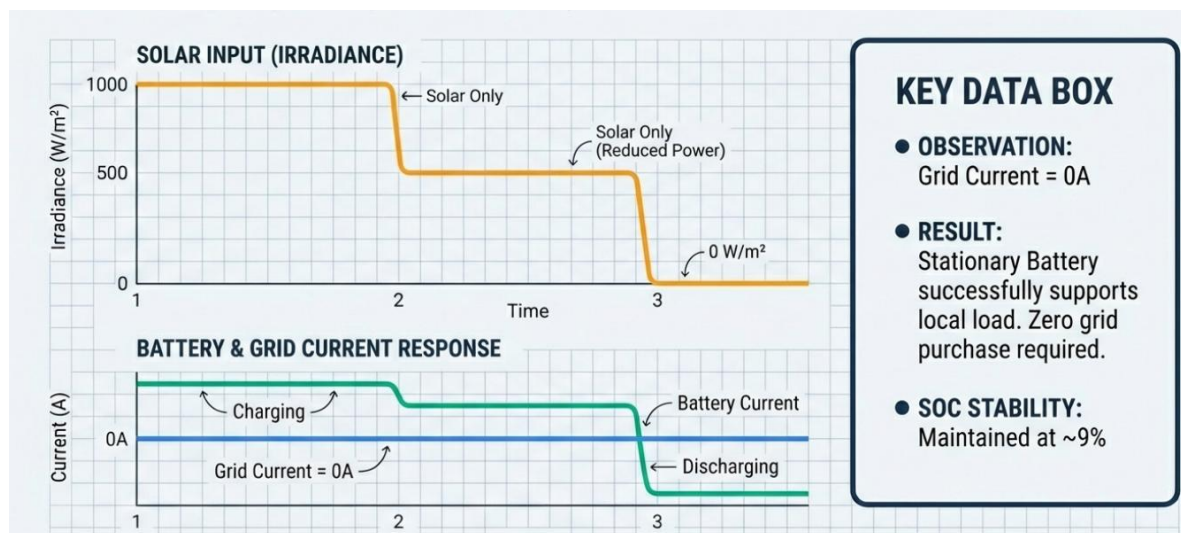


Fig. 11 Stationary Battery Mode (Signal = 0)

Throughout all irradiance transitions and operating modes, the bidirectional DC–DC converter effectively regulates the **400 V DC bus** using a PI-based voltage control loop. Simultaneously, the grid-side inverter maintains a sinusoidal current waveform with low Total Harmonic Distortion (THD) and precise phase synchronization with the **230 V AC utility grid**, validating the robustness of the DQ0-based current control strategy. Fig. 12 shows comparative analysis of grid dependency.

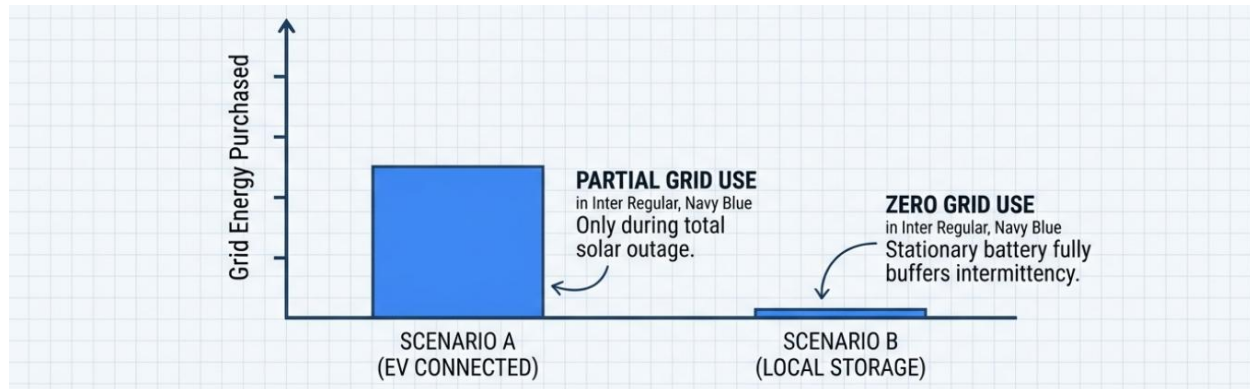


Fig. 12 Comparative Analysis of Grid Dependency

## VI. Conclusion and Future Scope

This research confirms that a DC-coupled microgrid architecture employing interleaved buck converters and an Incremental Conductance (IC) MPPT algorithm provides a stable, efficient, and scalable solution for electric vehicle charging applications. The proposed coordinated control framework successfully manages multi-source power flow among the photovoltaic array, energy storage systems, EV load, and utility grid, thereby ensuring reliable charging operation while simultaneously optimizing grid dependency and economic performance.

The use of a two-phase interleaved buck converter with a 180° phase shift significantly mitigates input and output current ripple, which is critical for protecting battery health and extending storage system lifetime. Moreover, the interleaved topology effectively prevents operation in discontinuous conduction mode (DCM), enhancing control linearity and improving dynamic response under low-power conditions.

From an operational perspective, the logic-driven energy management strategy minimizes reliance on the utility grid by prioritizing renewable energy utilization. Grid participation is selectively enabled only when photovoltaic generation becomes negligible and an electric vehicle is actively connected, thereby reducing electricity purchase costs and alleviating stress on the distribution network.

In terms of power quality, the implementation of DQ0-based current control combined with bidirectional DC-bus voltage regulation ensures a tightly regulated 400 V DC bus and high-quality

sinusoidal grid currents with low harmonic distortion across a wide range of irradiance profiles. This confirms the robustness of the proposed control approach for seamless grid integration and compliance with power quality standards.

Future research will extend the proposed framework to support Vehicle-to-Grid (V2G) operation, enabling EVs to provide ancillary services such as peak shaving and frequency regulation during high-demand periods. Additionally, the incorporation of artificial intelligence-based MPPT and predictive energy management algorithms may further enhance tracking accuracy and system responsiveness under rapid and stochastic irradiance variations.

## Acknowledgment

Nil

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