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Research Article

Design and Performance Analysis of a DC Microgrid-Based EV Charging Station with Hybrid PV-Wind and Battery Energy Storage Systems

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Abstract

This research presents the design and rigorous performance evaluation of a DC microgrid architecture tailored for electric vehicle (EV) charging, integrating hybrid renewable energy sources and stationary energy storage. To mitigate the operational challenges posed by the stochastic nature of solar and wind energy, a coordinated power electronic framework is developed, featuring a 2.0 kW Photovoltaic (PV) array, a 3.0 kW Wind Energy Conversion System (WECS), and a 240V Battery Energy Storage System (BESS). The study implements specialized Maximum Power Point Tracking (MPPT) algorithms—specifically Perturb and Observe (P&O) for the wind turbine and Incremental Conductance (INC) for the PV system—to optimize energy extraction across varying environmental conditions. Centralized 400V DC link regulation is achieved via a bidirectional converter utilizing a Proportional-Integral (PI) control strategy, ensuring a robust power balancing equilibrium. Simulation-based validation, conducted in MATLAB/Simulink, demonstrates high transient stability and a steady-state error near zero, maintaining a constant 1.5 kW charging rate per vehicle despite significant irradiation and wind speed fluctuations. The results confirm the technical viability of the proposed system in providing reliable, high-efficiency power delivery for modern green transport infrastructure.

Keywords

DC Microgrid, Photovoltaic Systems, Wind Energy Conversion, Battery Energy Storage System (BESS), Electric Vehicle Charging.

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I. Introduction

The global shift toward sustainable transportation mandates the development of electric vehicle (EV) charging infrastructure that reduces reliance on carbon-intensive utility grids. Integrating renewable energy sources (RES) directly into charging stations offers a strategic pathway to decarbonization. However, the inherent intermittency of solar and wind generation introduces significant challenges regarding power quality and supply consistency. The Fig. 1 shows integration of PV wind and battery ESS for EV charging.

In addressing these challenges, the DC microgrid architecture emerges as a superior technical solution compared to traditional AC-coupled systems. By utilizing a common DC bus, the system eliminates multiple AC-DC conversion stages, thereby reducing conversion losses and avoiding complex synchronization issues. This streamlined architecture is particularly well-suited for DC-native components, including PV panels, battery storage, and EV battery packs.

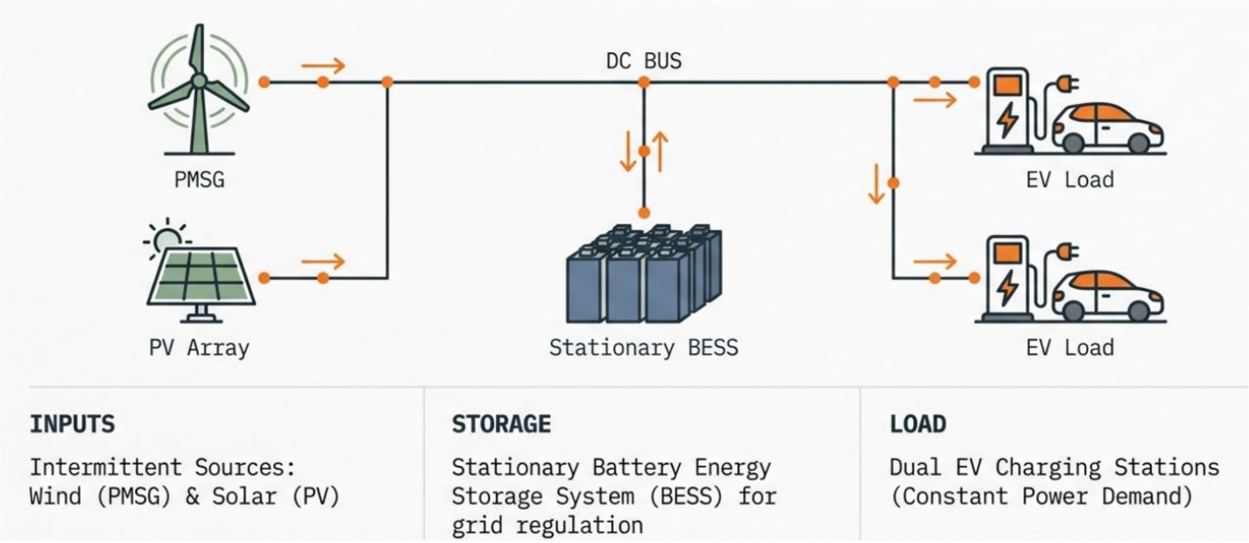


Fig. 1 Integration of PV Wind and Battery ESS for EV Charging

The primary contribution of this study is the implementation and analysis of a multi-source hybrid system that utilizes coordinated bidirectional converters to maintain bus stability. By harmonizing stochastic generation with fixed demand, the proposed control layer ensures operational reliability. The hardware's operational efficiency is fundamentally dependent on the control layer's ability to process these specifications in real-time, as detailed in the following sections.

The integration of renewable energy–based microgrids with electric vehicle (EV) charging infrastructure has gained significant attention due to increasing EV penetration and grid decarbonization goals. In this context, Haffaf et al. experimentally investigated a real-time grid-connected microgrid comprising photovoltaic (PV) generation, battery storage, and EV charging loads [1]. Their study provided valuable insights into system efficiency, energy flow coordination, and grid interaction under practical operating conditions. The results demonstrated that battery-assisted microgrids can effectively mitigate PV intermittency while maintaining grid compliance, highlighting the importance of experimental validation beyond simulation-based analyses.

Focusing on planning and sizing aspects, Khazali et al. addressed the optimal configuration of hybrid battery energy storage systems for EV charging station microgrids [2]. Their work emphasized techno-economic planning by considering load uncertainty, charging demand profiles, and storage capacity trade-offs. The study showed that appropriately sized battery systems significantly reduce peak grid demand and operational costs, underscoring the necessity of strategic planning frameworks for large-scale EV charging deployments.

The operational control of DC microgrids supporting EV charging was explored by Mohan and Dash, who proposed a renewable energy–based DC microgrid with a hybrid energy management system (EMS) [3]. Their work demonstrated coordinated control among PV sources, storage units, and EV loads, ensuring stable DC bus regulation and improved power-sharing performance. The proposed EMS enhanced system reliability and reduced dependency on the utility grid, particularly under fluctuating renewable generation and variable EV charging demands.

From a broader hybrid microgrid perspective, Al-Quraan and Al-Qaisi presented a detailed modeling, design, and control framework for a standalone PV–wind microgrid system [4]. Their study addressed dynamic interactions between renewable sources and control loops, providing fundamental insights into voltage regulation and power balance in hybrid configurations. Although EV charging was not the primary focus, the modeling and control principles established in this work are directly applicable to EV-integrated microgrids requiring stable standalone or islanded operation.

Recently, intelligent control strategies have been increasingly adopted to enhance microgrid performance. Sai Eswar et al. proposed a hybrid Dragonfly Optimization Algorithm–Shallow Backpropagation Neural Network (DOA–SBNN) approach for renewable-integrated EV charging microgrids [5]. Their method improved energy management decisions under uncertain generation and load conditions, demonstrating superior adaptability and reduced operational cost compared to conventional controllers. This work highlights the growing role of AI-based hybrid optimization techniques in next-generation EV charging microgrids.

Complementing intelligent EMS approaches, Hosny et al. conducted a comparative optimization study of PV–wind–battery microgrids using various metaheuristic algorithms [6]. Their analysis revealed that algorithm selection significantly influences convergence speed, solution quality, and system cost-effectiveness. The study reinforced the effectiveness of bio-inspired optimization methods for sizing and operational optimization of hybrid microgrids, particularly when multiple conflicting objectives such as cost, reliability, and renewable penetration are considered.

Early feasibility analysis of renewable-powered EV charging infrastructure was carried out by Singh et al., who evaluated a grid-connected solar–wind hybrid system supplying EV charging stations [7]. Their findings confirmed the technical and economic viability of such systems while highlighting challenges related to intermittency and grid coordination. This work laid foundational groundwork for subsequent studies focusing on advanced control, storage integration, and intelligent energy management in EV-oriented microgrids.

II. System Modeling and Methodology

The proposed DC microgrid is engineered to facilitate a high-efficiency energy value chain from generation to consumption. Each hardware component is integrated via specific power electronic interfaces to maintain the 400V DC link as the stable backbone of the station. The Fig. 2 illustrate the central topology of 400 DC link.

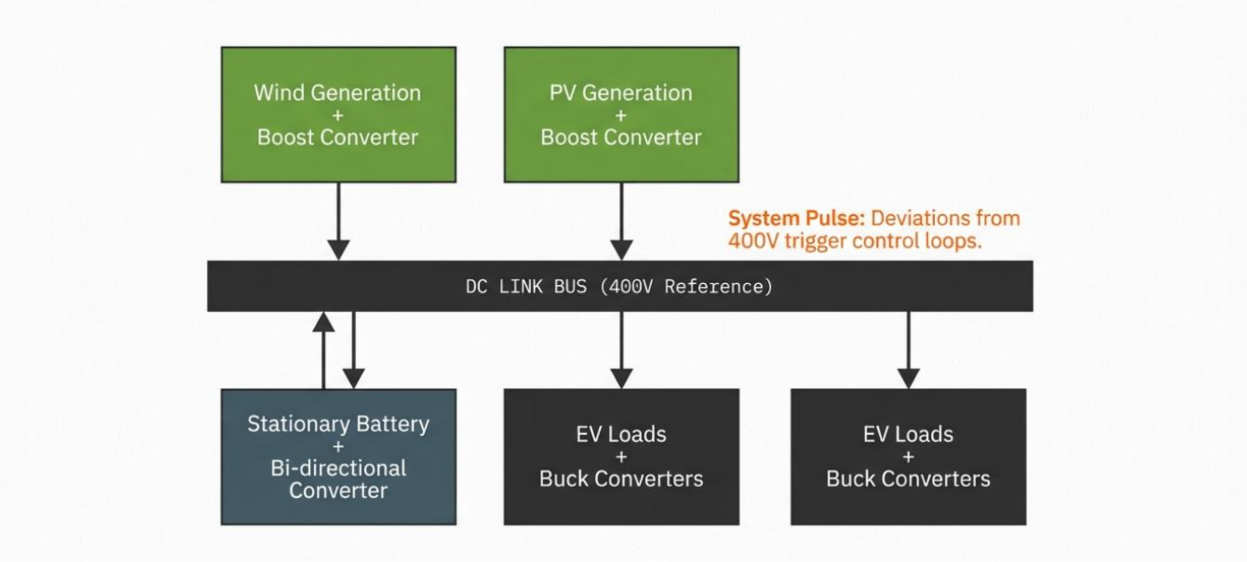


Fig. 2 Central topology of 400 DC link

Wind Energy Conversion System (WECS)

The WECS employs a 2.5–3.0 kW wind turbine coupled with a Permanent Magnet Synchronous Generator (PMSG). The variable-frequency AC output is converted to a rectified DC bus via a three-phase diode rectifier. A boost converter subsequently interfaces this rectified voltage with the 400V DC link, performing duty cycle modulation to extract maximum power regardless of wind velocity. Fig. 3 depicts wind turbine sub system.

Photovoltaic (PV) System

The PV segment consists of a 2.0 kW array (at Standard Test Conditions). The array produces an output of approximately 245.6V at peak power. Integration into the 400V DC bus is managed through a dedicated boost converter, which utilizes an advanced tracking algorithm to maintain peak efficiency.

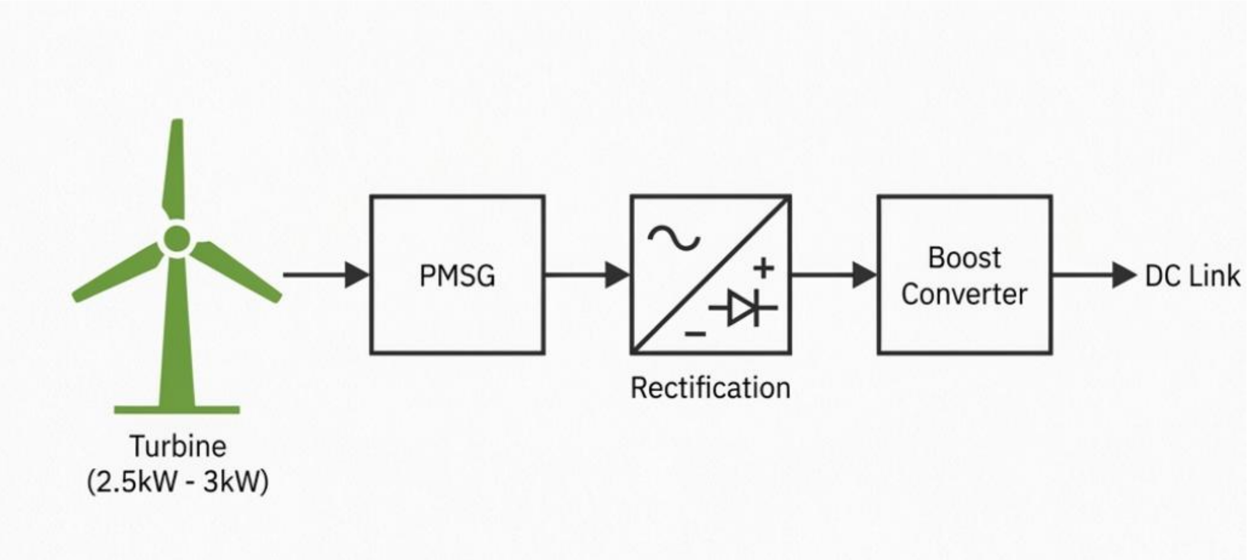
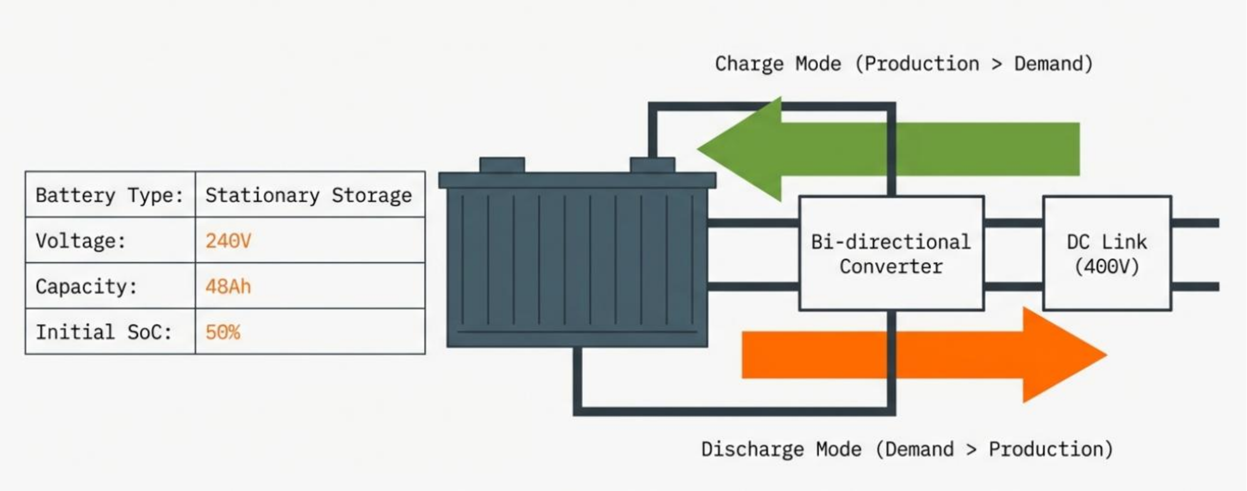


Fig. 3 Wind turbine sub system



Battery Type:	Stationary Storage
Voltage:	240V
Capacity:	48Ah
Initial SoC:	50%

Fig. 4 Stationary Battery Energy Storage System

Energy Storage and EV Interface

The system incorporates a stationary BESS (240V/48Ah) with an initial State of Charge (SoC) of 50%. This unit serves as the dynamic buffer for the DC link. The load profile consists of two EV battery units, each rated at 320V and 22 kWh. These are connected via buck converters that regulate the charging process to meet specific power targets. Table I shows the system component parameters. Fig. 4 shows the stationary battery energy storage system.

TABLE I
SYSTEM COMPONENT SPECIFICATIONS

Component	**Parameter**	**Rating / Value**
Wind Turbine	Rated Power	2.5 – 3.0 kW
PV Array	Rated Power (STC)	2.0 kW
PV Array	Nominal Output Voltage	245.6 V
DC Link	Reference Voltage	400 V
Stationary BESS	Voltage / Capacity	240 V / 48 Ah (Initial SoC: 50%)
EV Battery (x2)	Voltage / Capacity	320 V / 22 kWh (Per Unit)
Charging Power	Per Vehicle Target	1.5 kW

The coordination of these hardware components is governed by a sophisticated control layer, which is essential for maintaining the power balancing equilibrium.

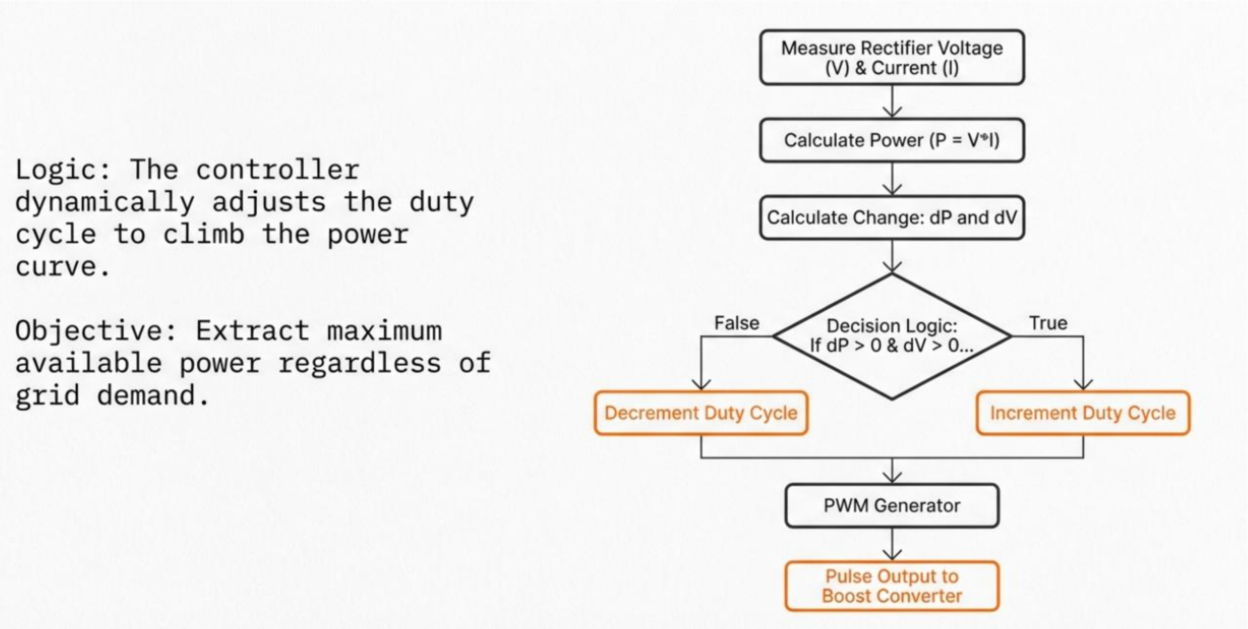
III. Control Strategy and Mathematical Modeling

Coordinated control is vital for managing the mismatch between stochastic renewable generation and the continuous 3.0 kW aggregate load of the EV units.

Renewable Energy MPPT Algorithms

To ensure maximum energy harvest, the system employs two distinct MPPT strategies:

- **Wind System (P&O Logic):** The Perturb and Observe algorithm monitors the rectified voltage and current. By evaluating the change in power and voltage, the controller determines the sign of two iteratively adjust the duty cycle. This ensures the PMSG operates at the peak of its power-speed curve. Fig. 5 represents wind control logic of P&O MPPT algorithm.



Logic: The controller dynamically adjusts the duty cycle to climb the power curve.

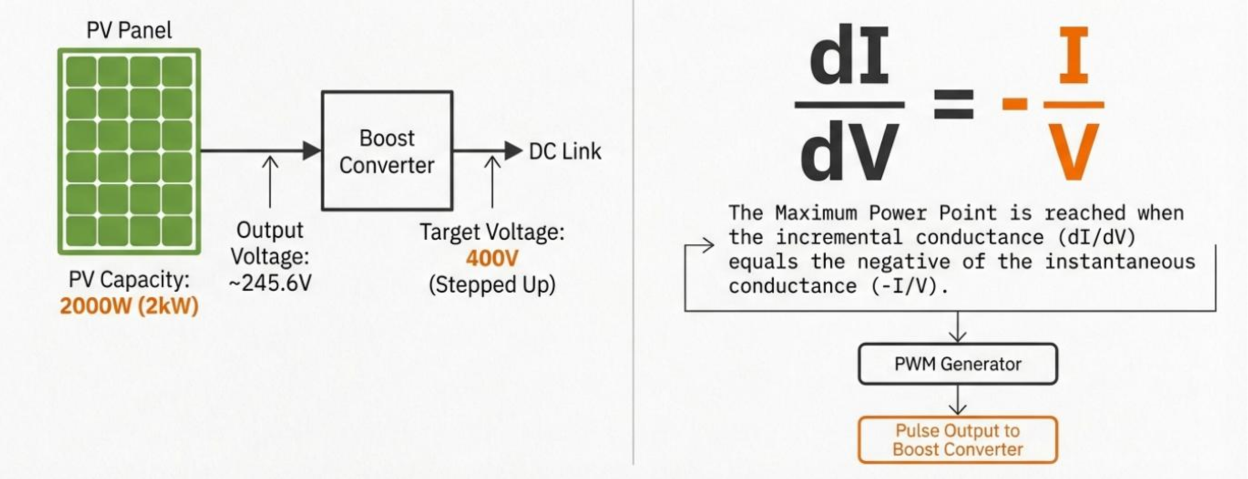
Objective: Extract maximum available power regardless of grid demand.

Fig. 5 Wind Control Logic: P&O MPPT Algorithm

- **PV System (INC Algorithm):** The Incremental Conductance algorithm is utilized for the PV boost converter. It operates on the principle that the derivative of power with respect to voltage is zero at the maximum power point. Fig. 6 shows PV Array with Incremental Conductance. The governing condition is:

$$dI/dV = -I/V$$

Where I and V are instantaneous current and voltage, dI and dV represent incremental changes. The controller modulates the duty cycle to satisfy this equilibrium.



The Maximum Power Point is reached when the incremental conductance (dI/dV) equals the negative of the instantaneous conductance (-I/V).

Fig. 6 PV Array with Incremental Conductance

DC Link Voltage Regulation

The 400V DC link stability is maintained by a bidirectional DC-DC converter connected to the stationary battery. A PI controller processes the error between the 400V reference and the measured bus voltage. This control loop achieves dynamic decoupling of the sources and loads, allowing the battery to charge during surplus generation and discharge during deficits, effectively clamping the bus voltage. Fig. 7 shows the voltage regulation with PI controller.

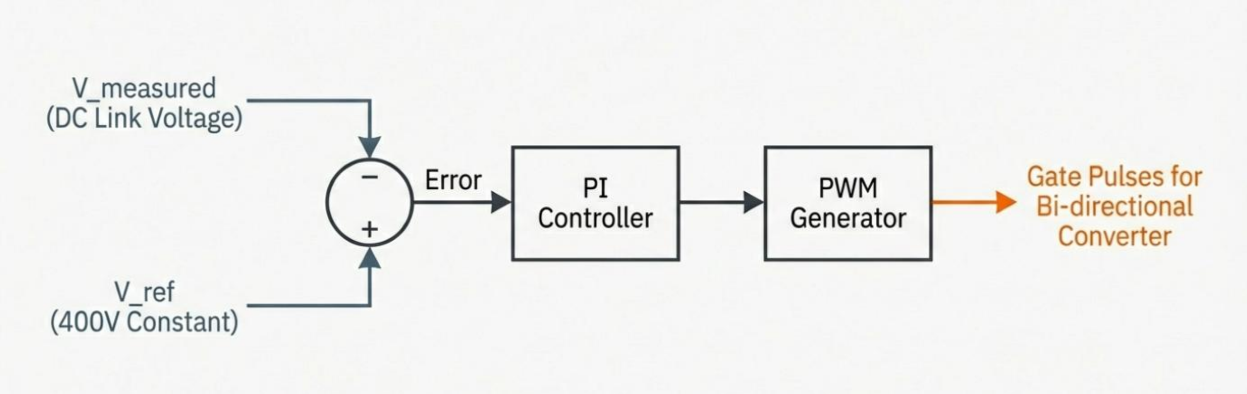


Fig. 7 Voltage Regulation with PI Controller

EV Charging Control

To ensure a consistent 1.5 kW charging rate per vehicle, each EV interface utilizes a buck converter governed by a PI-based current control loop. Crucially, the reference current is derived by dividing the target power (1500 W) by the DC link voltage (400 V), resulting in a precise current setpoint of 3.75 A. This strategy ensures that charging remains independent of the EV's instantaneous battery voltage. These control loops are translated into the simulation environment to validate system performance.

IV. Simulation Model and Parameters

The dynamic response and transient stability of the microgrid were validated using MATLAB/Simulink. This platform facilitates high-fidelity switching analysis of the power electronic converters and the observation of the system's reaction to rapid environmental changes.

Simulation Step-Change Profiles

The simulation subjects the system to rigorous transients in irradiation and wind speed to evaluate the robustness of the PI and MPPT controllers.

TABLE III
IRRADIATION AND WIND SPEED WITH TIME INTERVALS

Time Interval (s)	Irradiation (W/m^2)	Wind Speed (m/s)
0.0 – 0.3	1000	12.0
0.3 – 0.6	500	12.0
0.6 – 1.0	10	12.0
1.0 – 1.6	500	12.0
1.6 – 2.0	1000	12.0
2.0+	1000	10.8

V. Results and Discussion

The simulation results elucidate the system's ability to maintain load requirements despite significant environmental transients.

Renewable Power Extraction and Wind Step-Change

The PV array successfully tracked the irradiation profile, producing 2 kW at STC and dropping to near 0W during the 0.6s–1.0s interval. The wind system extracted approximately 3 kW at 12 m/s. At, a step-change in wind speed from 12 m/s to 10.8 m/s was introduced. The P&O controller adjusted the duty cycle with minimal settling time, reflecting the system’s high transient stability. Fig. 8 represents the system with severe solar dropout and wind speed reduction.

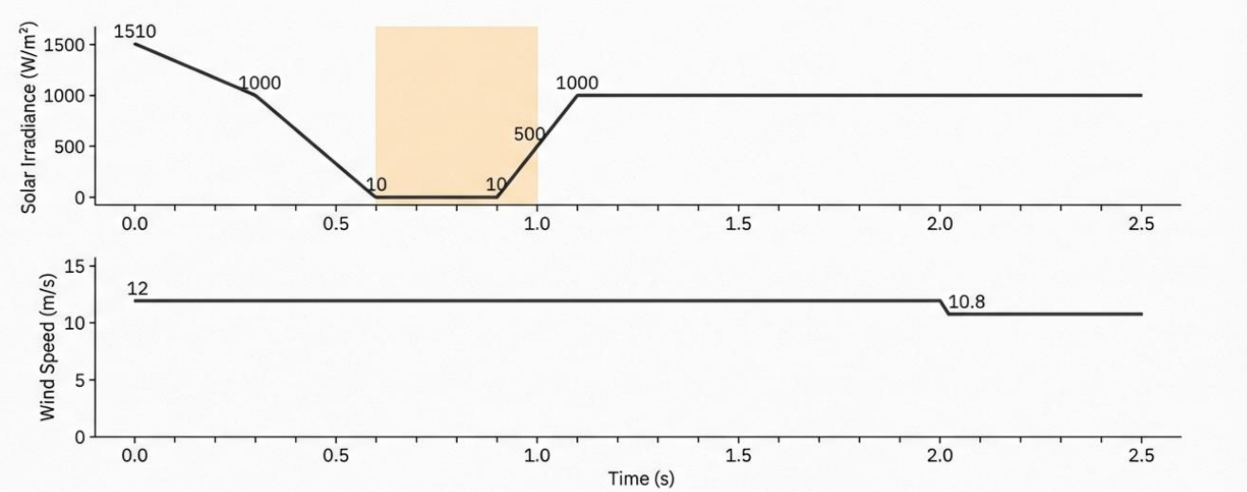


Fig. 8 System with Severe Solar Dropout and Wind Speed Reduction

BESS Dynamic Response and Power Balancing

The stationary BESS proved effective as the primary balancing mechanism. With an initial SoC of 50%, the battery transitioned between charging and discharging modes based on the generation-load gap. During the irradiation drop, the BESS instantly transitioned to discharge mode to compensate for the lost solar power. Similarly, when wind power dropped at, the BESS compensated for the reduction in generation, ensuring the power balancing equilibrium was maintained. Fig. 9 and Fig. 10 shows performance analysis of generation response and battery as grid balancer.

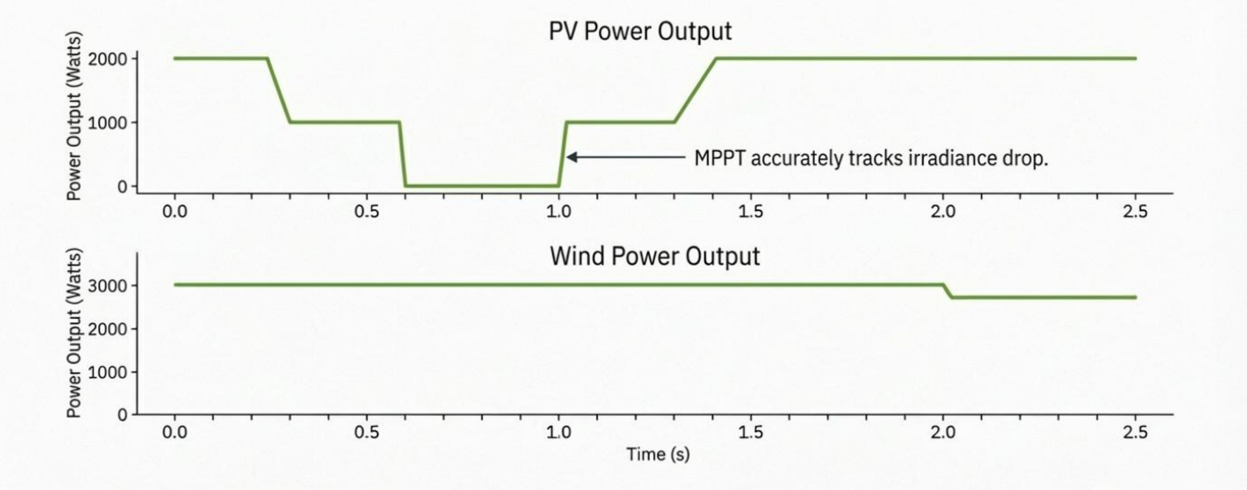


Fig. 9 Performance Analysis of Generation Response

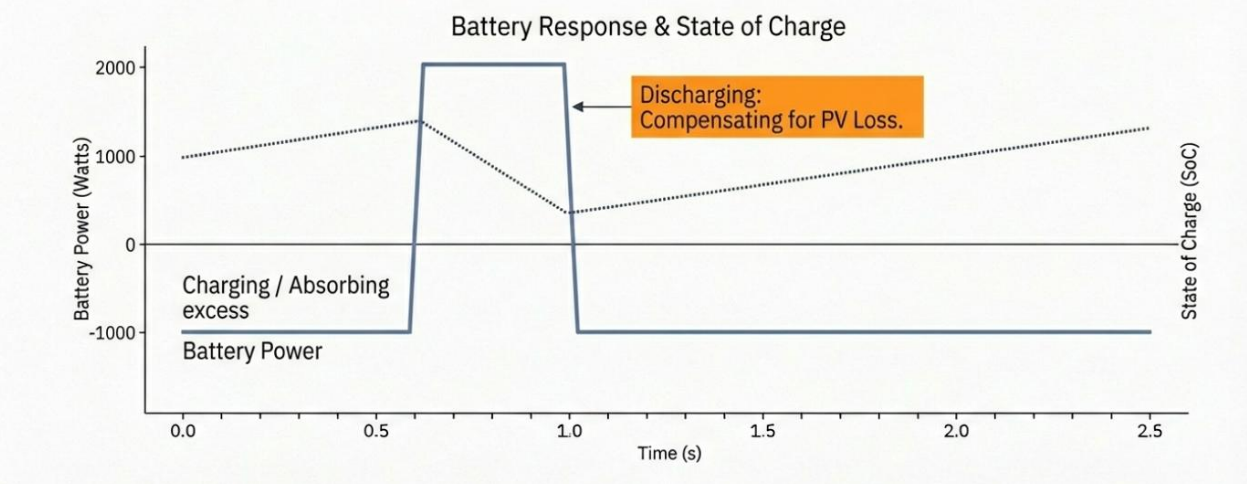
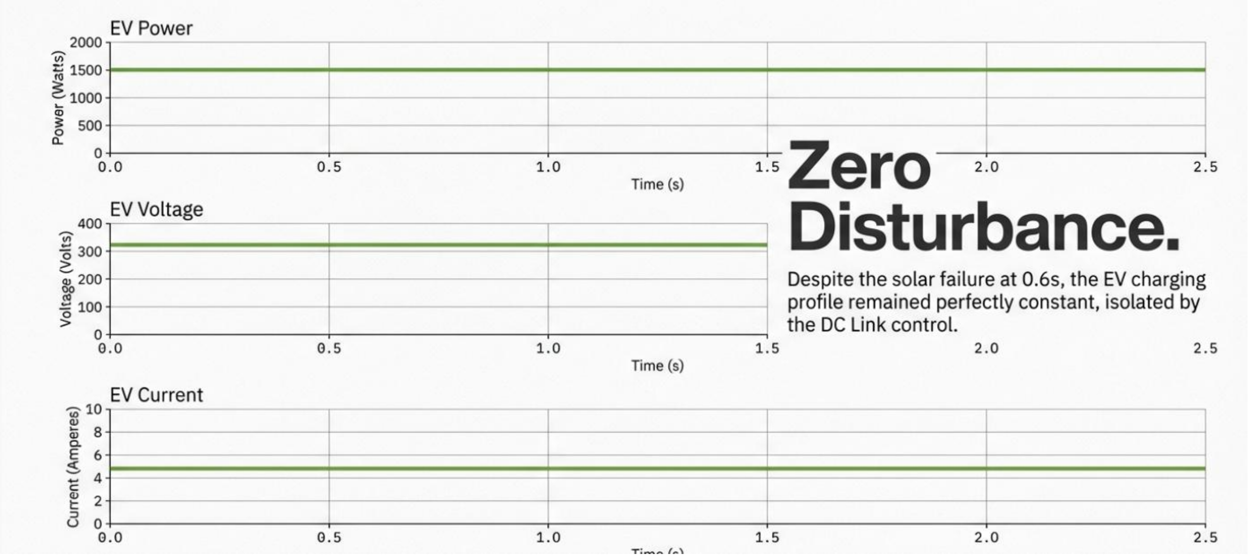


Fig. 10 Performance Analysis of Battery as Grid Balancer

EV Charging Stability and DC Link Regulation

A paramount finding is the absolute stability of the EV charging rate. Throughout all transients—including the total loss of solar power and the wind speed step-change—both EV batteries maintained a constant 1.5 kW charging target. This consistency is attributed to the 400V DC link regulation, where the PI controller maintained the bus voltage with negligible steady-state error. This confirms the effectiveness of using the DC link voltage as the basis for the EV current reference. Fig. 11 depicts performance analysis of load stability.



Zero Disturbance.

Despite the solar failure at 0.6s, the EV charging profile remained perfectly constant, isolated by the DC Link control.

Fig. 11 Performance Analysis of Load Stability

VI. Conclusion and Future Scope

This study validates the technical success of a hybrid DC microgrid-based charging station in managing multi-source inputs and prioritized charging loads. The integration of INC and P&O algorithms demonstrated high efficiency in energy extraction, while the PI-controlled bidirectional converter ensured the 400V DC link remained stable under diverse transient conditions. The system successfully maintained a 1.5 kW charging rate per vehicle, regardless of the 50% drop in wind speed or the near-total loss of solar irradiation.

Future research directions will explore:

- **V2G Capability:** The implementation of Vehicle-to-Grid protocols to allow EV batteries to support the microgrid during peak demand.

- **Advanced MPPT:** The application of AI-based or fuzzy logic MPPT controllers to further reduce tracking time during extreme environmental volatility.

In conclusion, the proposed architecture represents a robust and scalable framework for real-world green transport infrastructure, offering a highly reliable solution for the next generation of electric mobility.

Acknowledgment

Nil

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