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Research Article

Power Management Strategy for PV-Battery-Supercapacitor Hybrid Energy Storage Systems in DC Microgrids

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Abstract

The integration of solar photovoltaic (PV) systems into DC microgrids is frequently challenged by the stochastic volatility of solar irradiation, which threatens the stability of the DC bus. This paper proposes an enhanced power management strategy utilizing a Hybrid Energy Storage System (HESS) that combines the high energy density of lead-acid batteries with the high-power density of supercapacitors. The system architecture employs an Incremental Conductance (IncCond) Maximum Power Point Tracking (MPPT) algorithm to optimize power extraction from a 2kW PV array. To regulate the DC bus at a constant 400V, a multi-tiered control scheme is implemented, featuring a double-loop proportional-integral (PI) control architecture and a low-pass filter (LPF) for current splitting. Simulation results in MATLAB/Simulink demonstrate that while the battery handles steady-state power requirements, the supercapacitor effectively mitigates high-frequency transients during rapid irradiation step-changes. This coordinated approach ensures superior voltage stability and protects the battery from high-rate discharge cycles, thereby extending the operational lifespan of the storage units and ensuring grid resilience.

Keywords

DC Microgrid; Hybrid Energy Storage System; Incremental Conductance MPPT; Low-Pass Filter; Power Management Strategy; Supercapacitor.

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I. Introduction

The transition toward decentralized renewable energy infrastructure has positioned DC microgrids as a primary solution for efficient power distribution. By eliminating the multiple conversion stages required for DC-native sources like solar PV and electrochemical storage, these systems significantly reduce transmission losses. However, the inherent intermittency of solar irradiation necessitates robust storage solutions to maintain the power balance. Fig. 1 illustrates the power management strategy.

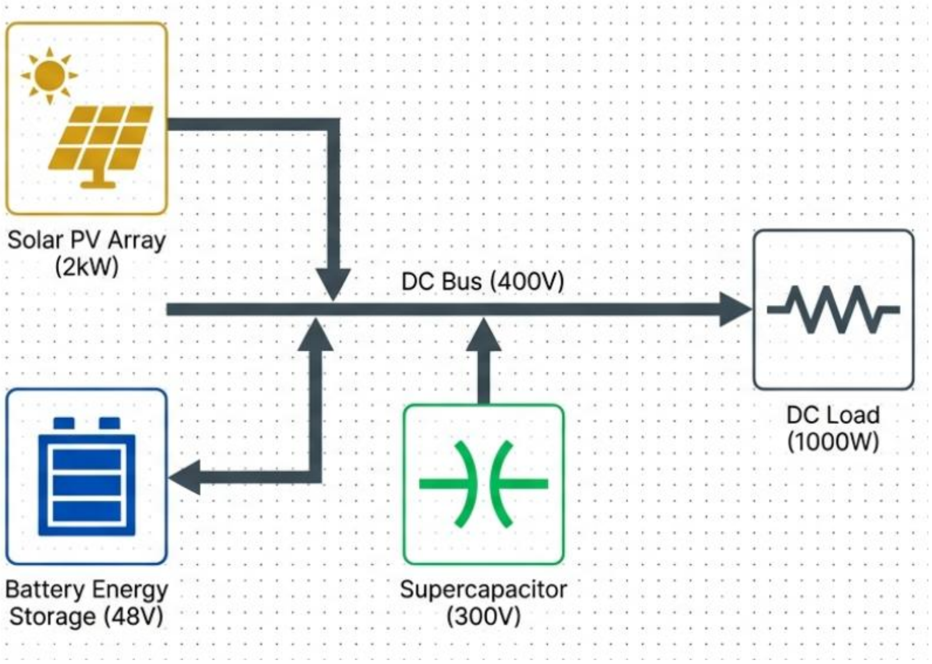


Fig. 1 Power Management Strategy

Single-source storage systems often fail to satisfy the conflicting requirements of energy and power density. While batteries provide the high energy density required for long-term load following, their limited cycle life and thermal sensitivity make them poorly suited for the rapid power fluctuations typical of intermittent PV generation. Supercapacitors, conversely, offer high power density and rapid response times but lack the capacity for sustained discharge. This study implements a Hybrid Energy Storage System (HESS) to leverage the complementary strengths of both technologies. The primary objective is the implementation of an integrated control scheme to manage power flow among a 2kW PV array, a battery bank, and a supercapacitor unit, maintaining a rigid 400V DC bus.

The increasing penetration of renewable energy sources and the variability associated with solar photovoltaic (PV) generation have motivated extensive research on hybrid energy storage systems

(HESS) integrating batteries and supercapacitors. Such hybrid configurations aim to enhance system reliability, power quality, and dynamic performance while extending battery lifespan.

Kurtoğlu [1] proposed a novel energy management control scheme for a solar PV–integrated hybrid energy storage system, focusing on operational performance improvement under dynamic operating conditions. The study demonstrated effective power sharing between storage elements, resulting in enhanced system stability and reduced stress on the battery. Similarly, Buduma et al. [2] investigated power coordination and control strategies for a DC microgrid incorporating PV and hybrid energy storage, highlighting improved voltage regulation and seamless power balance during load and generation variations.

In isolated and grid-independent microgrid environments, advanced control techniques have been widely explored. Arunkumar and Manthati [3] developed a hybrid controller–assisted voltage regulation and power splitting strategy for battery–supercapacitor systems in isolated DC microgrids. Their results showed superior transient response and effective decoupling of high-frequency power fluctuations from the battery. Zdiri et al. [4] introduced a sliding-mode artificial neural network–based control strategy for a hybrid PV–battery–supercapacitor system, achieving robust performance under uncertainties and nonlinear operating conditions.

For grid-connected systems, Jena and Ray [5] presented a power management approach for a three-phase grid-integrated PV system with hybrid energy storage, emphasizing coordinated control to support grid stability and power quality. The use of intelligent optimization and learning-based techniques has further improved energy management effectiveness. Sandeep and Mohanty [6] employed an artificial rabbits optimized neural network for energy management in an isolated DC microgrid, demonstrating enhanced load-following capability and reduced system losses.

Optimization-based energy management strategies have also gained attention in multi-source hybrid renewable systems. Alhumade et al. [7] proposed an advanced energy management strategy for a PV/PEMFC/lithium-ion battery/supercapacitor hybrid system using a white shark optimizer, achieving improved efficiency and optimized power distribution among sources. In applications involving highly dynamic loads, Aghmadi et al. [8] addressed pulsed load mitigation using a hybrid PI–neural network controller, effectively reducing voltage deviations and improving transient response in PV–battery–supercapacitor systems.

Aboukhris et al. [9] presented a detailed review of energy management strategies in grid-connected hybrid PV–battery–supercapacitor systems, emphasizing optimization, intelligent control, and grid-support functionalities.

The paper is organized as follows: Section II details the system architecture and hardware specifications; Section III provides the mathematical modeling of the IncCond MPPT and the double-loop control strategy; Section IV outlines the simulation parameters; Section V evaluates the performance results; and Section VI concludes the study with a summary of findings and future research directions.

II. System Configuration and Proposed Architecture

The proposed DC microgrid architecture is centered on a high-voltage 400V DC bus. A 2,000W PV array serves as the primary generation source, interfaced via a unidirectional boost converter. The HESS, comprising a battery bank and a supercapacitor, is connected to the bus through bi-directional DC-DC converters to allow for both charging (Buck mode) and discharging (Boost mode) operations. Fig. 2 shows the system topology and specifications.

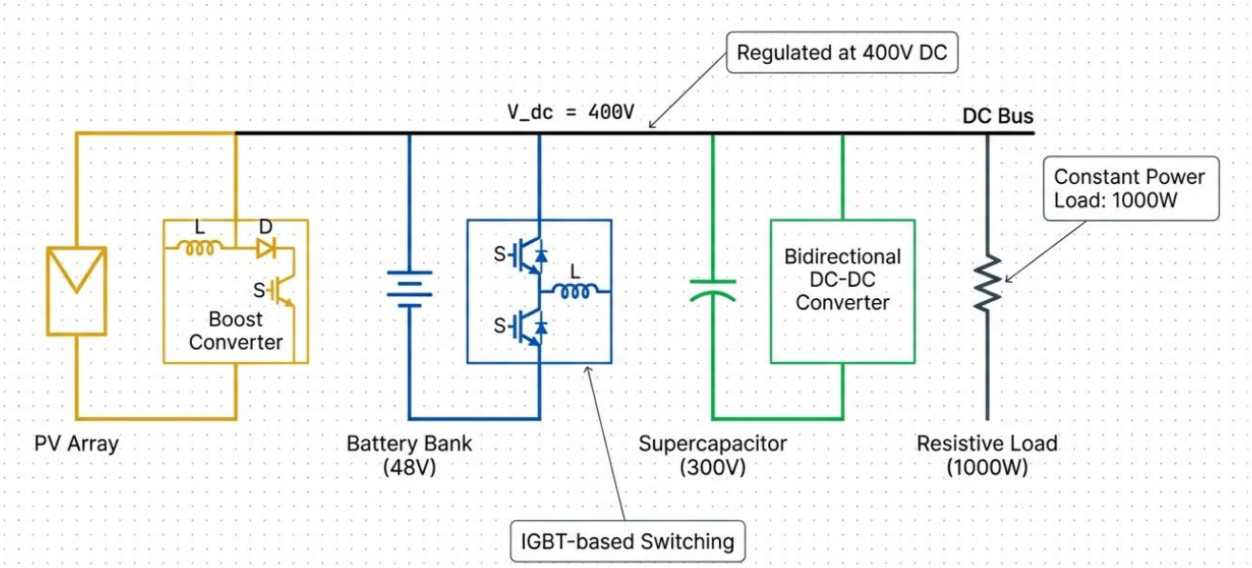


Fig. 2 System Topology and Specifications

Solar PV Specifications

The PV array consists of eight 250W panels. Precise technical parameters are required to calibrate the MPPT algorithm for peak efficiency. Table I shows the PV array specifications.

TABLE I
SOLAR PV ARRAY TECHNICAL SPECIFICATIONS

Parameter	Value
Total Rated Power	2000 W
Single Panel Rated Power	250 W
Open Circuit Voltage	37.3 V
Voltage at Max Power Point	30.7 V
Short Circuit Current	8.66 A
Current at Max Power Point	8.15 A

Storage and Converter Topologies

The battery storage system is configured with 20 units of 12V batteries in series, resulting in a nominal voltage of 240V. This 240V system has a rated capacity of 480Ah and an initial State of Charge (SoC) of 50%. The supercapacitor bank is rated at 99.5F with a 300V rated voltage and an initial voltage of 295V.

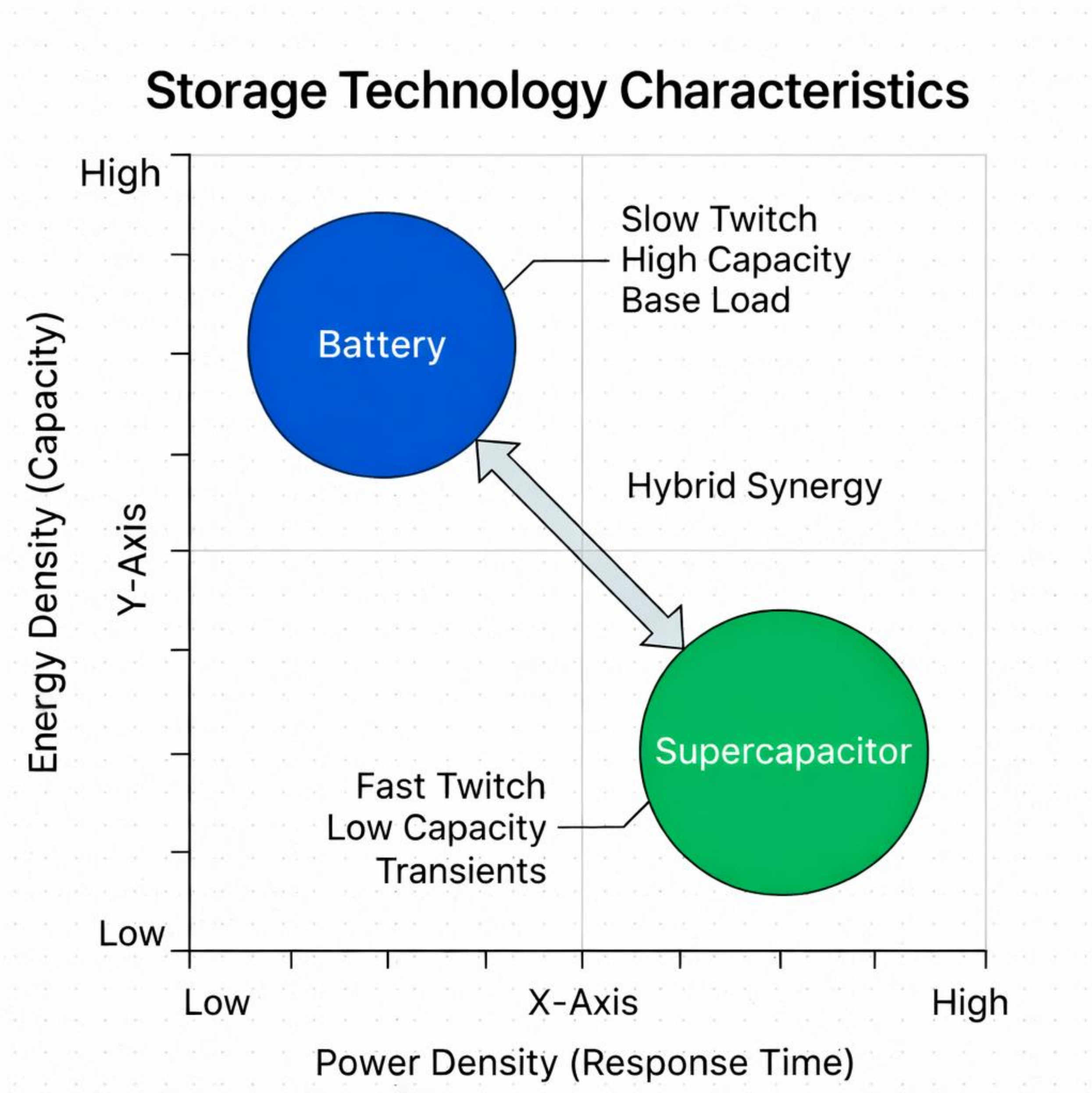


Fig. 3 Storage Technology Characteristics

The storage units are interfaced with the 400V DC bus via bi-directional converters. For the supercapacitor, the converter must manage a 105V differential (from 295V to 400V) while responding to high-speed transients. The bi-directional nature of these converters is essential for current sharing; they operate in Buck mode during PV surplus (charging) and Boost mode during PV deficit (discharging). Fig. 3 depicts the storage technology characteristics.

III. Control Strategy and Mathematical Modeling

Effective power management requires a multi-tiered control strategy to ensure maximum power extraction while simultaneously providing transient power compensation.

Incremental Conductance MPPT

The system utilizes the Incremental Conductance (IncCond) algorithm to track the maximum power point (MPP) under varying irradiation. The logic is governed by the derivative of the power-voltage curve, where at the MPP. The algorithm compares the instantaneous conductance to the incremental conductance:

By monitoring these variables, the controller adjusts the boost converter's duty cycle to maintain operation at the peak of the PV curve, even during stochastic environmental shifts.

Double-Loop PI Control and Current Splitting

Bus regulation is achieved through a double-loop control architecture. The outer Voltage Control Loop compares the actual DC bus voltage against the 400V reference. A PI controller processes the voltage error to generate the total reference current required to stabilize the bus.

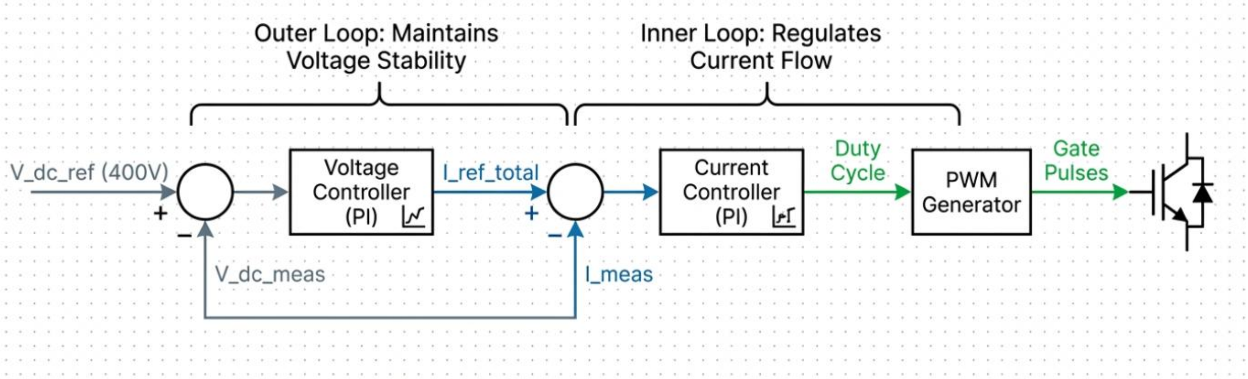


Fig. 4 Double Loop Control Strategy

Fig. 4 illustrates the double loop control strategy. Crucially, this is processed through a Low-Pass Filter (LPF) to bifurcate the demand. The low-frequency component is assigned to the battery current controller, while the high-frequency residue (the difference between and the filtered current) is directed to the supercapacitor. This current-splitting logic ensures that the supercapacitor handles rapid changes, providing transient support and mitigating high-rate discharge cycles on the battery. The inner Current Control Loop then generates PWM signals for the IGBTs of the respective bi-directional converters.

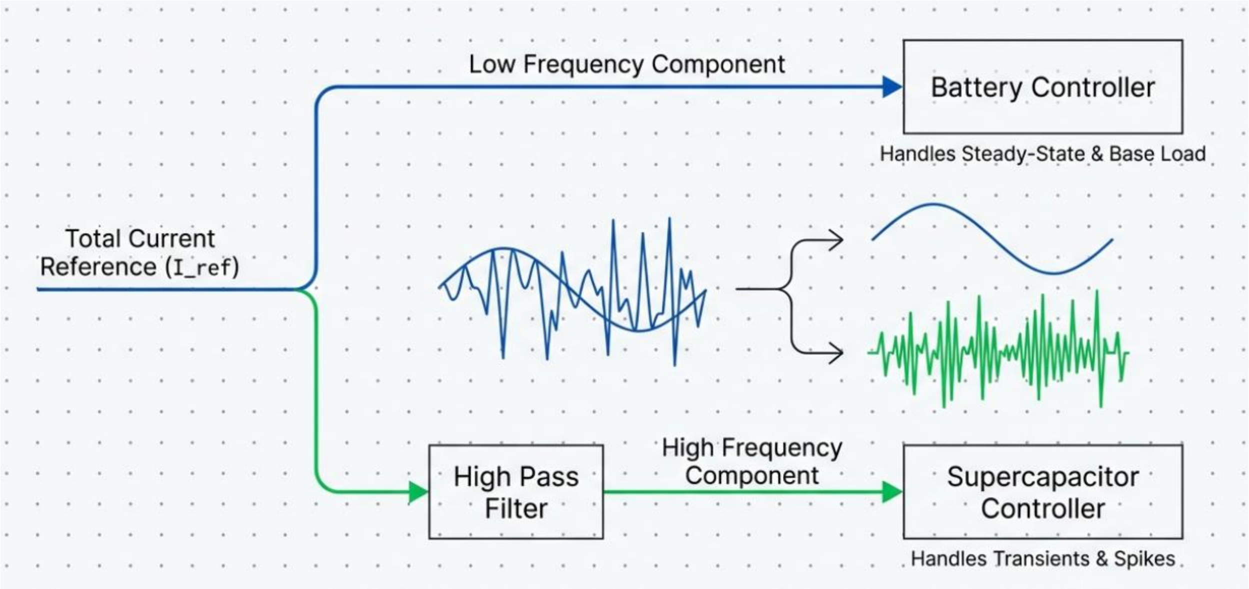


Fig. 5 Frequency based power distribution

IV. Simulation Setup and Parameters

The system was modeled in MATLAB/Simulink using PWM generators to drive the IGBT-based converters, allowing for high-fidelity analysis of switching dynamics and transient response. Table II represents the simulation system parameters.

TABLE III
SIMULATION SYSTEM PARAMETERS

Parameter	**Value**
DC Bus Reference Voltage	400 V
System Load	1000 W
Nominal Battery Voltage	240 V (20 x 12V units)
Supercapacitor Rating	99.5 F / 300 V
Irradiation Step Profile	1000, 800, 500, 300, 100 W/m^2
Simulation Duration	5.0 Seconds

The irradiation profile simulates a series of rapid degradation steps to test the HESS's ability to transition between charging and discharging modes while maintaining bus stability.

V. Results and Discussion

PV Performance Analysis

The IncCond MPPT demonstrated high precision across the irradiation profile. The extracted power closely matched the theoretical peaks identified in the PV characteristics. Fig. 6 shows the simulation scenario.

- 1000 W/m^2: 2002 W extracted
- 800 W/m^2: 1599 W extracted
- 500 W/m^2: 1000 W extracted
- 300 W/m^2: 350 W extracted
- 100 W/m^2: 100 W extracted

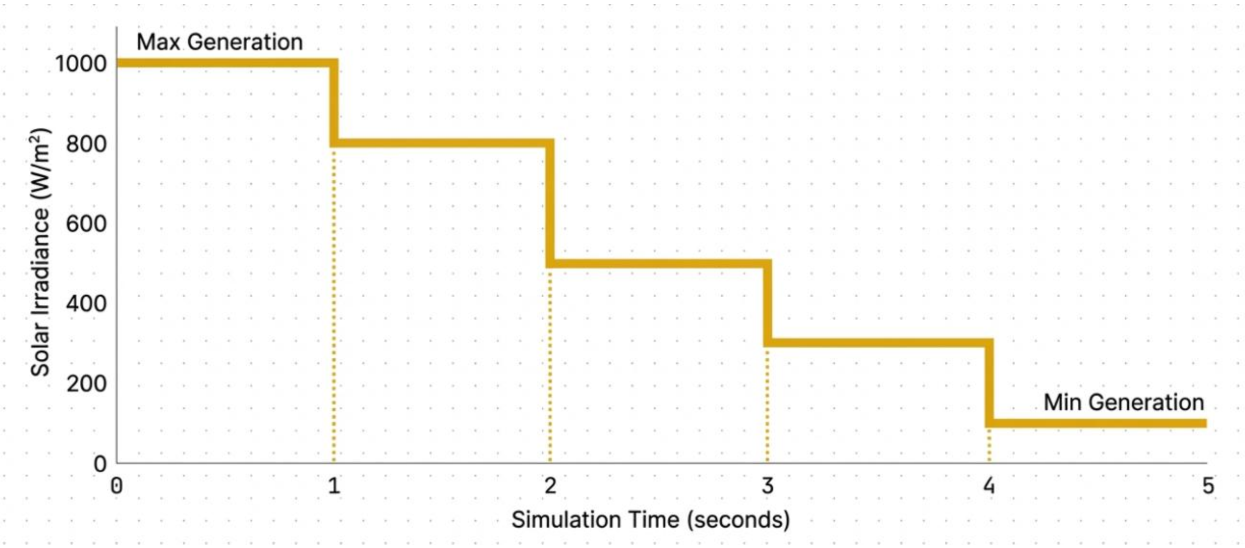


Fig. 6 Simulation Scenario

Power Management and Transient Mitigation

The effectiveness of the double-loop logic is evident in the transition phases. Between 0 and 2 seconds, with irradiation at 1000–800 W/m^2, the PV output exceeds the 1000W load. The battery and supercapacitor exhibit negative current and power, indicating they are in charging mode (Buck operation). Fig. 7 depicts surplus power generation (PV power > load power).

At the 3-second mark, irradiation drops to 500 W/m^2, and PV power (1000W) equals the load. Here, the supercapacitor current returns to zero, and the battery enters a neutral state. When irradiation drops further (300 W/m^2 and 100 W/m^2), the PV power (350W and 100W) is insufficient to meet the load. The battery assumes the primary load-following role, entering discharging mode (Boost operation). Fig. 8 depicts transition from charging to discharging.

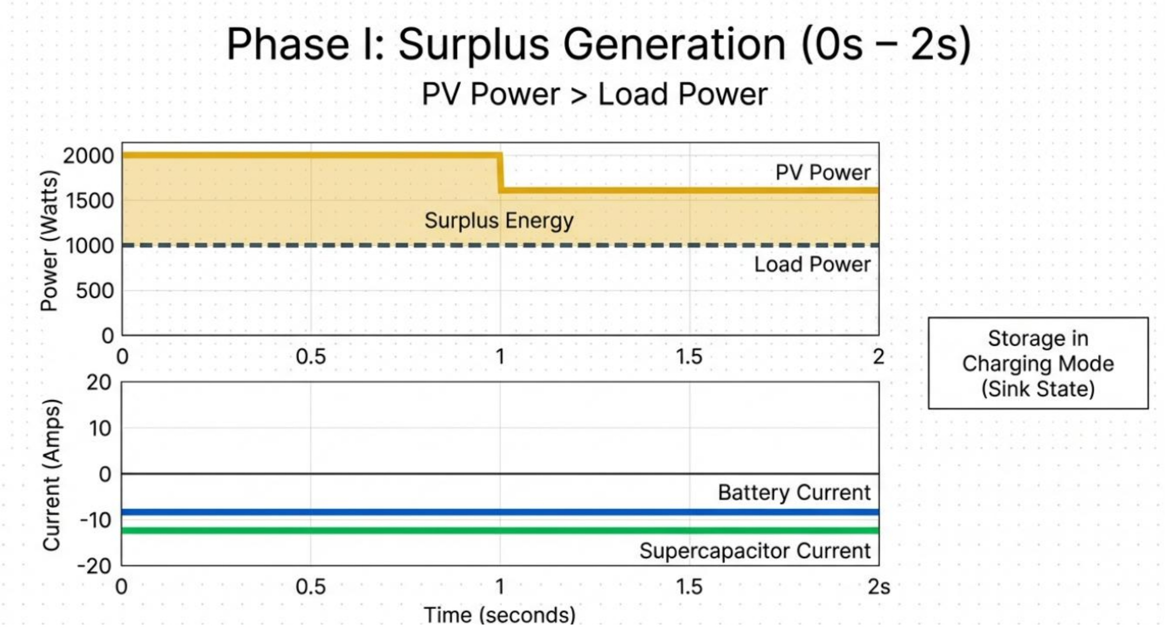


Fig. 7 Surplus power generation (PV power > load power)

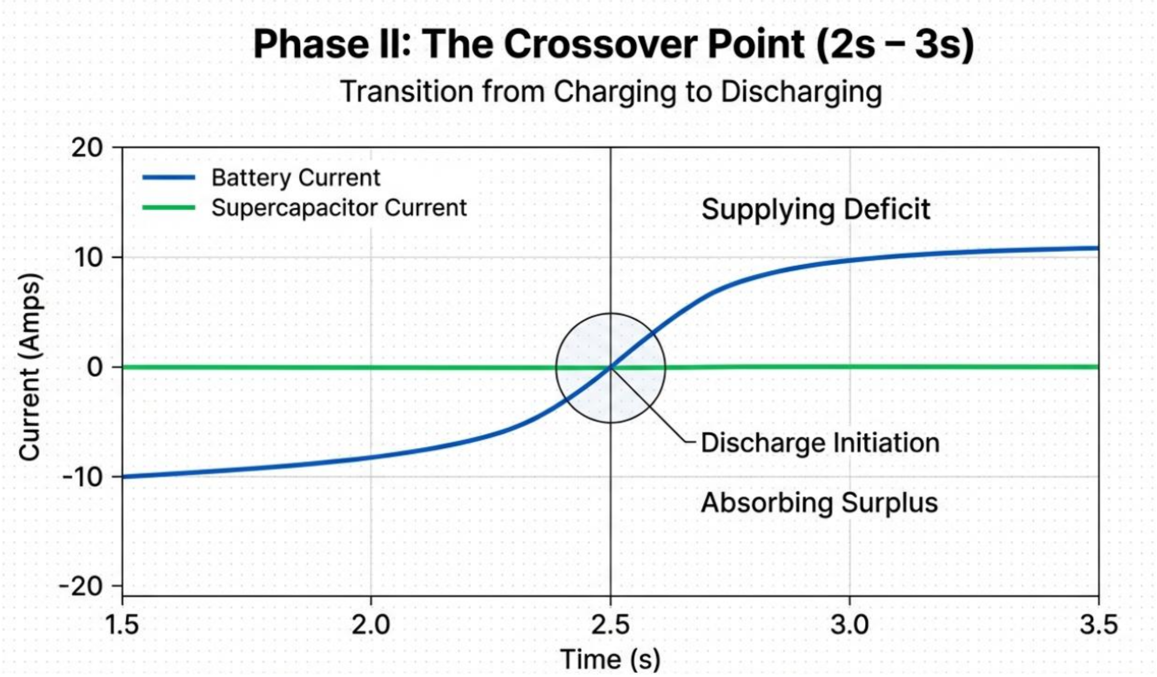


Fig. 8 Transition from charging to discharging

The architecture is highlighted during the transients at 3 and 4 seconds. During these rapid drops, the supercapacitor provides an instantaneous power burst to compensate for the high and demand. This "peak shaving" of the transient current prevents the battery from experiencing the chemical and thermal stress of rapid discharge, thereby preserving its state-of-health (SoH). Fig. 9 illustrate the transient response analysis

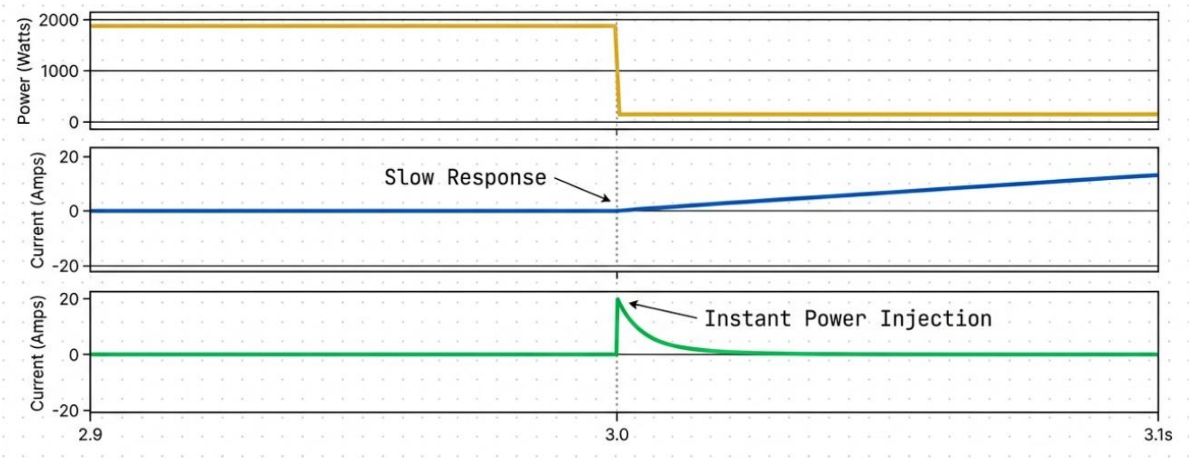
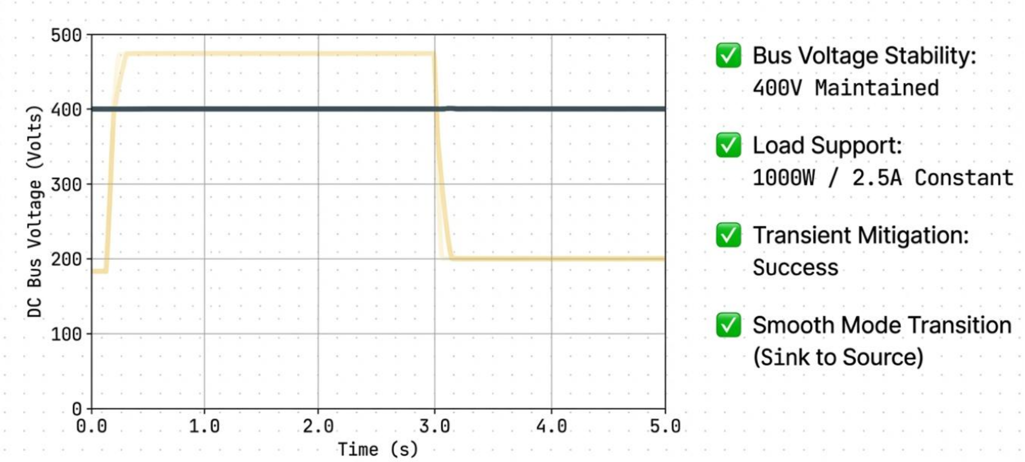


Fig. 9 Transient response analysis

DC Bus Stability

Despite the aggressive irradiation changes, the DC bus voltage was maintained consistently at 400V. The supercapacitor's ability to provide transient power compensation allows the battery's slower control loop to ramp up without causing significant voltage dips, validating the robustness of the double-loop PI and LPF control strategy. Fig. 10 shows the DC bus voltage stability.



✅ Bus Voltage Stability:
400V Maintained

✅ Load Support:
1000W / 2.5A Constant

✅ Transient Mitigation:
Success

✅ Smooth Mode Transition
(Sink to Source)

Fig. 10 DC bus voltage stability

VI. Conclusion and Future Scope

This research successfully validated an enhanced power management strategy for a hybrid PV-Battery-Supercapacitor DC microgrid. By integrating diverse control methodologies, the system ensures both high-efficiency energy harvesting and robust storage protection.

The study concludes with three critical takeaways:

1. MPPT Precision: The IncCond algorithm maintains optimal power extraction, achieving 2002W at peak irradiation and tracking down to 100W with high accuracy.

2. Double-Loop Efficacy: The PI-based voltage regulation loop, coupled with an LPF for current splitting, maintains a stable 400V DC bus regardless of irradiation volatility.

3. Transient Mitigation: The supercapacitor effectively manages high-frequency power gaps, protecting the battery from high-rate discharge and enhancing the overall reliability of the HESS.

Future research will explore the integration of fuzzy logic controllers to adaptively tune the LPF cutoff frequency based on the battery's SoC. Furthermore, hardware-in-the-loop (HIL) testing is planned to validate these results against real-world communication latencies and switching losses in a physical microgrid environment.

Acknowledgment

Nil

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