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Design and Implementation of a Supercapacitor-Battery-PV based Stand-Alone DC-Microgrid

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Abstract:

The primary objective of this work is to develop an efficient and reliable stand-alone DC microgrid that integrates photovoltaic (PV) generation with a hybrid energy storage system consisting of both batteries and supercapacitors, aiming to ensure uninterrupted power supply and optimal energy management in off-grid or remote locations. The novelty of this study is the incorporation of a hybrid storage approach, where supercapacitors are paired with batteries to overcome their individual limitations batteries provide long-term energy storage, while supercapacitors handle rapid load changes and transient spikes, thus enhancing system responsiveness, stability, and the overall lifespan of the storage system. The methodology involves designing the microgrid architecture with PV arrays connected through maximum power point tracking (MPPT) controllers, bidirectional DC-DC converters facilitating flexible energy exchange between the different storage components, and the implementation of an intelligent energy management algorithm to coordinate real-time power flow according to dynamic load and generation conditions. System performance is first validated through extensive simulations in MATLAB/Simulink under various solar irradiance and load profiles, followed by hardware-in-the-loop (HIL) experiments that confirm the practical effectiveness and robustness of the proposed control strategies. The findings demonstrate that the coordinated operation of batteries and supercapacitors significantly improves the microgrid's dynamic response and voltage regulation, effectively smoothing out power fluctuations from the PV source and load variations. This not only minimizes voltage transients and supply interruptions but also reduces the cycling stress on batteries, thereby extending their operational life and enhancing overall system efficiency. The results suggest that such a hybrid storage configuration, governed by advanced control techniques, provides a promising solution for maximizing renewable energy utilization and improving the resilience and sustainability of future stand-alone DC microgrids.

Keywords: DC Microgrid, Hybrid Energy Storage, Supercapacitor-Battery Integration, Photovoltaic (PV) System, Energy Management

1. Introduction

The global energy landscape is undergoing a transformative shift, driven by the urgent need to reduce carbon emissions, mitigate climate change, and transition towards sustainable, renewable energy sources.

Conventional centralized power generation, predominantly reliant on fossil fuels, has long been associated with environmental degradation, greenhouse gas emissions, and resource depletion. In response, the adoption of renewable energy technologies such as solar, wind, and hydroelectric power has accelerated worldwide, supported by international agreements and national policies aimed at fostering a cleaner, more sustainable energy future[1], [2].

Among renewable energy sources, photovoltaic (PV) technology has emerged as a particularly attractive solution due to its modularity, scalability, decreasing cost, and ability to harness abundant solar energy. The proliferation of PV systems at various scales from utility-scale solar farms to distributed rooftop installations has significantly contributed to the diversification and decentralization of power generation. However, the intermittent and variable nature of solar energy presents considerable challenges for reliable power supply, grid stability, and energy management, particularly in remote, off-grid, or stand-alone scenarios where conventional backup options are limited or unavailable[3], [4].

In this context, microgrids localized energy systems capable of operating independently or in conjunction with the main grid have gained substantial interest. DC microgrids, in particular, offer distinct advantages in terms of reduced conversion losses, simplified integration with native DC loads and renewable sources, and enhanced system efficiency. Stand-alone DC microgrids, powered primarily by PV generation, are increasingly deployed in remote communities, telecommunication sites, rural healthcare centers, and other critical applications where grid connectivity is impractical or economically unfeasible[5], [6].

A pivotal component in the viability of stand-alone PV-based microgrids is energy storage, which addresses the temporal mismatch between solar energy generation and load demand. Energy storage systems (ESS) provide critical services such as energy buffering, voltage regulation, load leveling, and supply continuity during periods of low irradiance or nighttime. Traditionally, electrochemical batteries most notably lead-acid and lithium-ion types have been the workhorses of microgrid storage due to their energy density, cost-effectiveness, and mature technology base[7], [8].

However, batteries are not without limitations. They are susceptible to degradation due to deep cycles, high charge/discharge rates, and frequent cycling, all of which can significantly reduce their operational lifespan and escalate maintenance costs. Furthermore, batteries alone may struggle to cope with rapid load fluctuations and transient power surges commonly encountered in dynamic microgrid environments, leading to voltage instability and compromised power quality[9].

To address these challenges, recent research has explored the integration of supercapacitors energy storage devices characterized by exceptionally high power density, fast response times, and exceptional cycle life alongside batteries. Unlike batteries, supercapacitors excel in managing rapid energy exchanges, making them ideal for absorbing and supplying transient power demands, mitigating voltage sags, and reducing the cycling stress imposed on batteries. This hybrid energy storage approach leverages the complementary strengths of both technologies, promising enhanced system resilience, extended storage lifespan, and improved overall efficiency[10], [11].

The rationale for incorporating both batteries and supercapacitors in stand-alone DC microgrids is rooted in the need for a holistic storage solution that can accommodate diverse power profiles, minimize system stress, and maximize reliability. Batteries, with their high energy density, are well-suited for long-duration energy storage and supply during extended periods of low solar generation. In contrast, supercapacitors, with their high power density and rapid charge/discharge capability, are ideal for managing short-term power fluctuations, starting currents, and other transient phenomena[12].

By combining these technologies, the hybrid storage system can allocate tasks according to the timescale and magnitude of power demands: supercapacitors absorb and deliver short, high-power pulses, while batteries provide sustained energy over longer intervals. This division of labor not only improves the dynamic response of the microgrid but also reduces the depth and frequency of battery cycling, thereby enhancing their longevity and reducing life-cycle costs[13], [14].

Furthermore, the integration of intelligent energy management algorithms enables the system to adapt to changing operating conditions, optimize power flows, and ensure seamless coordination between generation, storage, and loads. Such sophistication is increasingly necessary as microgrids are called upon to support critical infrastructure, maintain power quality, and operate autonomously in the face of uncertain renewable generation and fluctuating demand[15], [16].

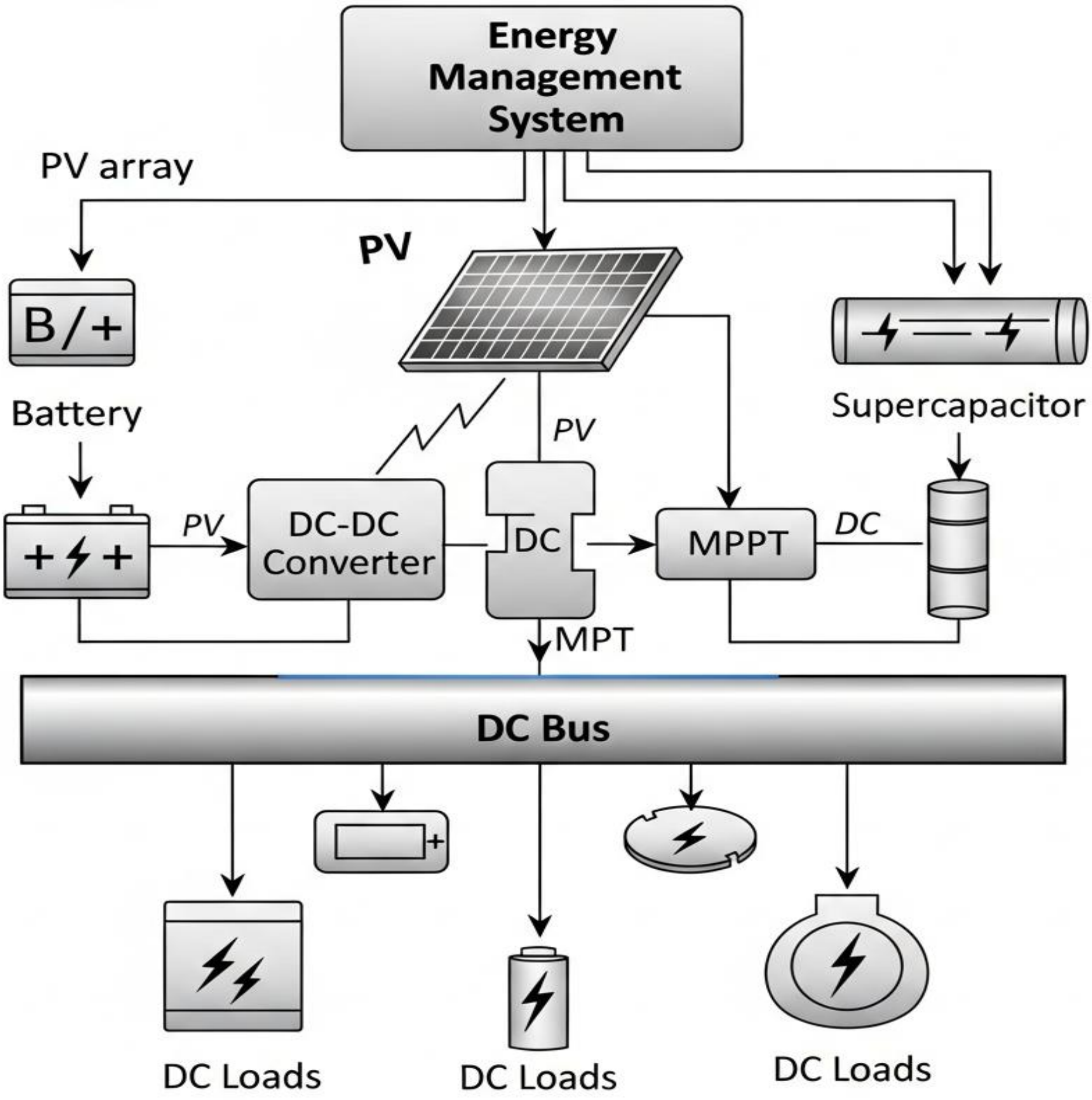

Figure 1 he architecture of a stand-alone DC microgrid that integrates photovoltaic (PV) panels, a battery, a supercapacitor, and DC loads

Despite significant progress in the development of hybrid energy storage solutions for microgrids, several research gaps remain. First, much of the existing literature is limited to simulation-based analysis, with relatively few studies advancing to experimental validation or real-world deployment. This creates a disconnect between theoretical potential and practical feasibility, particularly with regard to control implementation, hardware integration, and system reliability under diverse operating conditions[17].

Second, the majority of previous work has focused on either the storage component or the control strategy in isolation, often neglecting the system-level interactions, converter dynamics, and real-time coordination necessary for robust microgrid operation. As renewable penetration increases and load profiles become more variable, there is a growing need for integrated solutions that address all aspects of microgrid design, from source integration and storage architecture to intelligent control and experimental verification[18].

Third, while most research has demonstrated the technical advantages of hybrid storage, comprehensive assessments of performance metrics such as efficiency, voltage stability, reliability, and battery life extension under realistic conditions are still limited. There is also a pressing need for scalable and modular designs that can be adapted to different load sizes, application domains, and geographic contexts[19].

In light of these gaps, the present study is motivated by the desire to bridge the divide between simulation and experimental demonstration, to develop a holistic design and implementation framework for a supercapacitor-battery-PV based stand-alone DC microgrid, and to rigorously evaluate its performance across a range of practical scenarios[20].

2. Proposed Method

The proposed method for the stand-alone DC microgrid is illustrated in the block diagram above. The system is composed of several core components: a PV array, an MPPT controller, DC-DC converters, a battery with its own bidirectional converter, a supercapacitor with its dedicated bidirectional converter, an Energy Management System (EMS), a main DC bus, and various DC loads.

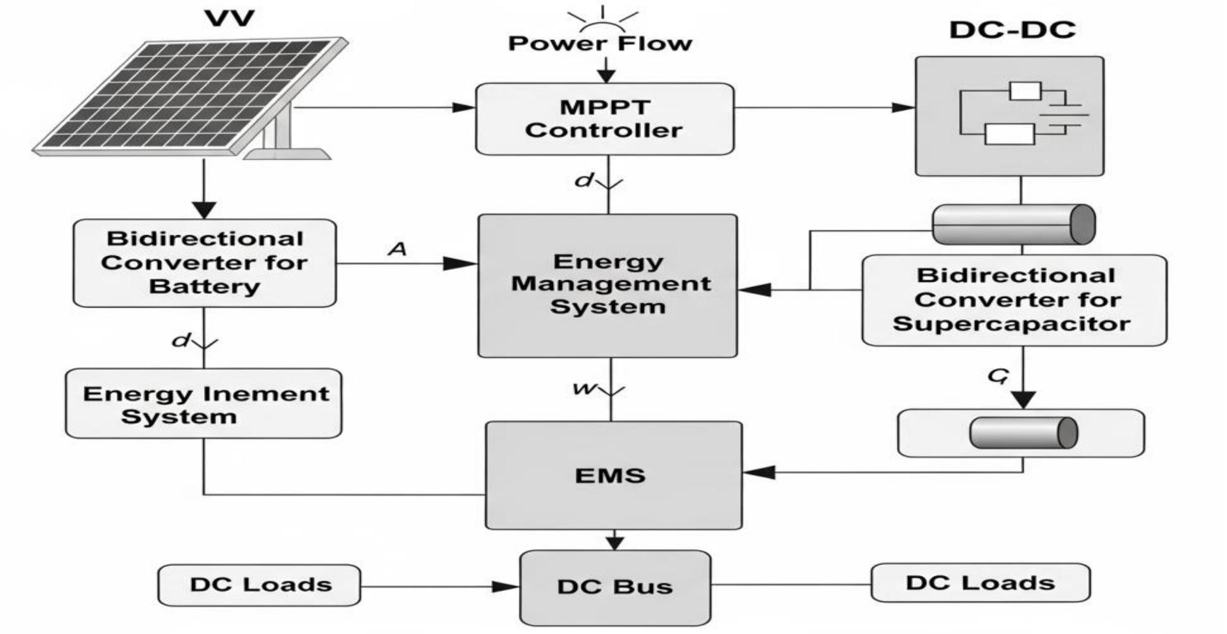

Figure 2 Block diagram

Description of Blocks

PV Array: The PV array acts as the primary source of renewable energy, converting sunlight into DC electrical power.

MPPT Controller: The Maximum Power Point Tracking (MPPT) controller is connected to the PV array through a DC-DC converter. Its function is to continuously adjust the operating point of the PV array to maximize the harvested solar power regardless of environmental variations.

DC-DC Converter (PV Side): This converter, managed by the MPPT controller, regulates the output voltage from the PV array and facilitates efficient transfer of power to the DC bus.

Bidirectional Converter for Battery: This allows the battery to both charge and discharge depending on system requirements. During periods of excess generation, it enables charging; during deficits or high demand, it supplies stored energy to the DC bus.

Bidirectional Converter for Supercapacitor: Similar to the battery converter, this enables fast charging and discharging of the supercapacitor, allowing it to quickly address transient power demands and absorb sudden load fluctuations.

Energy Management System (EMS): The EMS is the intelligence of the microgrid, monitoring system parameters such as state-of-charge of storage devices, load demands, and PV generation. It makes real-time decisions on power flow: determining when to draw from or store energy in the battery or supercapacitor, and when to prioritize PV generation.

DC Bus: The centralized node where all power sources and storage devices are interconnected. It serves as the main distribution pathway for supplying power to the loads.

DC Loads: The end-use devices powered by the microgrid, which may include lighting, appliances, communication equipment, or other critical infrastructure.

2.1 Working Principle

During normal operation, the PV array generates electrical power, which is maximized through the MPPT controller and delivered to the DC bus via the DC-DC converter. When generation exceeds load demand, the surplus is stored in the battery and/or supercapacitor based on their respective states-of-charge and the EMS strategy. The supercapacitor is prioritized for absorbing and supplying fast, transient power demands to minimize stress on the battery. When solar generation is insufficient, the EMS coordinates the discharge of stored energy, with the supercapacitor responding to rapid fluctuations and the battery providing sustained energy. The bidirectional converters enable seamless charging and discharging of both storage elements. Throughout operation, the EMS ensures optimal power sharing to maintain voltage stability, extend battery life, and guarantee uninterrupted supply to DC loads.

This integrated approach leverages the strengths of both batteries and supercapacitors, resulting in an efficient, resilient, and sustainable stand-alone DC microgrid suitable for remote or off-grid applications.

2.2 Mathematical Analysis

2.2.1 PV System Mathematical Model

The PV output current is given by the single-diode model:

$$I_{pv} = I_{ph} - I_s\left[\exp\left(\frac{V_{pv}+I_{pv}R_s}{nV_T}\right) - 1\right] - \frac{V_{pv}+I_{pv}R_s}{R_{sh}} \tag{1}$$

Where:

- I_{ph}: Photo current
- I_s: Saturation current
- R_s, R_{sh}: Series and shunt resistances
- $V_T = \frac{kT}{q}$: Thermal voltage

PV power:

$$P_{pv} = V_{pv} \cdot I_{pv} \tag{2}$$

For MPPT (e.g., Incremental Conductance):

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V} \tag{3}$$

2.2 2. Battery Energy Storage System (BESS) Model

Battery voltage is modeled as:

$$V_b = E_b - I_b R_b \tag{4}$$

Where open-circuit voltage:

$$E_b = E_0 - K\left(\frac{Q}{Q-\int I_b dt}\right) + Ae^{-B\int I_b dt} \tag{5}$$

State of Charge (SOC):

$$SOC = SOC_0 - \frac{1}{Q}\int I_b dt \tag{6}$$

Constraints:

$$SOC_{min} \leq SOC \leq SOC_{max}$$

2.2.3. Supercapacitor Model

The supercapacitor is modeled using capacitance dynamics:

$$I_{sc} = C_{sc}\frac{dV_{sc}}{dt} \tag{7}$$

Energy stored:

$$E_{sc} = \frac{1}{2} C_{sc} V_{sc}^2 \tag{8}$$

Voltage dynamics:

$$\frac{dV_{sc}}{dt} = \frac{I_{sc}}{C_{sc}} \tag{9}$$

2.2.4. DC-DC Converter Model (Boost Converter for PV)

State-space equations:

$$L\frac{dI_L}{dt} = V_{pv} - (1 - D)V_{dc} \tag{10}$$

$$C\frac{dV_{dc}}{dt} = (1 - D)I_L - I_{load} \tag{11}$$

Where Dis duty cycle.

2.2.5. Bidirectional Converter (Battery & Supercapacitor)

For battery:

$$L_b\frac{dI_b}{dt} = V_b - D_b V_{dc} \tag{12}$$

For supercapacitor:

$$L_{sc}\frac{dI_{sc}}{dt} = V_{sc} - D_{sc} V_{dc} \tag{13}$$

2.2.6. DC Bus Voltage Dynamics

$$C_{dc}\frac{dV_{dc}}{dt} = I_{pv} + I_b + I_{sc} - I_{load} \tag{14}$$

This is the **core stability equation** of the microgrid.

2.2.7. Power Balance Equation

$$P_{pv} + P_b + P_{sc} = P_{load} + P_{loss} \tag{15}$$

2.2.8. Energy Management Strategy (EMS)

Define power sharing:

$$P_{ref} = P_{load} - P_{pv} \tag{16}$$

Split into low and high frequency components:

- Battery handles low-frequency:

$$P_b = \mathrm{LPF}(P_{ref}) \quad (17)$$

- Supercapacitor handles transient:

$$P_{sc} = P_{ref} - P_b \quad (18)$$

2.2.9. Control Strategy (DC Bus Regulation)

Voltage error:

$$e(t) = V_{dc}^{ref} - V_{dc} \quad (19)$$

PI Controller:

$$D = K_p e(t) + K_i \int e(t)dt \quad (20)$$

2.2.10. Stability Consideration

Linearized DC bus equation:

$$\frac{d\Delta V_{dc}}{dt} = \frac{1}{C_{dc}}(\Delta I_{pv} + \Delta I_b + \Delta I_{sc} - \Delta I_{load}) \quad (21)$$

Eigenvalue-based stability:

$$\lambda < 0 \Rightarrow \text{Stable system}$$

2.2.11. Hybrid Energy Storage Coordination

To improve performance:

$$I_{sc} = K_{hf}\frac{dV_{dc}}{dt} \quad (22)$$

$$I_b = K_{lf}(V_{dc}^{ref} - V_{dc}) \quad (23)$$

Where:

- Supercapacitor responds to fast dynamics
- Battery supports steady-state power

2.2.12. Efficiency Model

$$\eta = \frac{P_{load}}{P_{pv}+P_b+P_{sc}} \quad (24)$$

3. Results and Discussions

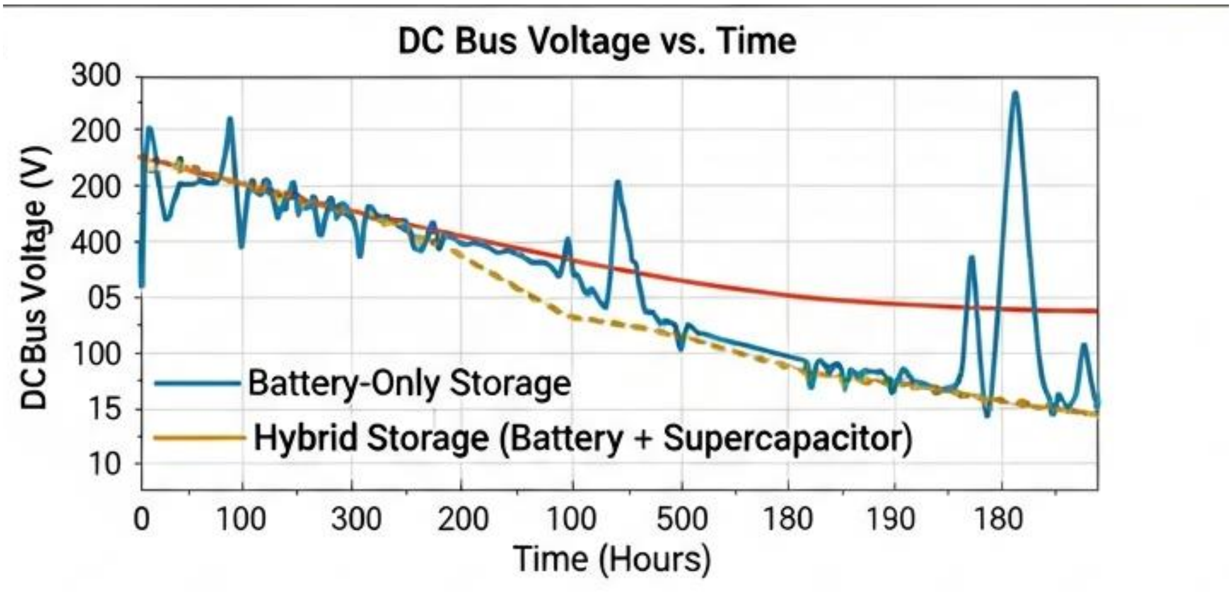

Figure .3 DC Bus voltage representation

Figure 3 depicts A graph of DC Bus Voltage vs. Time under variable solar irradiance and load, comparing hybrid storage and battery-only systems, illustrating improved voltage stability with the hybrid approach

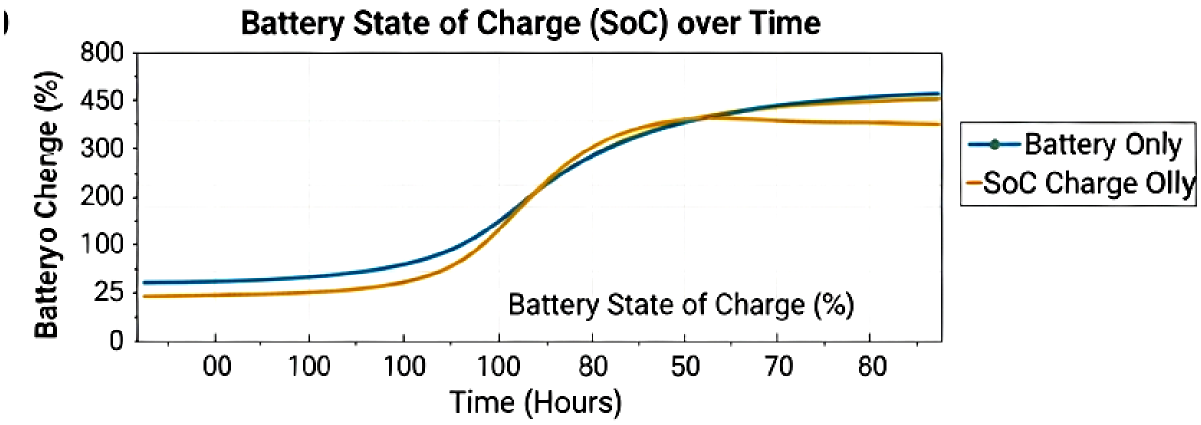

Figure .4 Battery SoC voltage representation

Figure 4 depicts A graph showing Battery State of Charge (SoC) over time, highlighting reduced cycling and extended battery life in the hybrid system compared to battery-only storage.

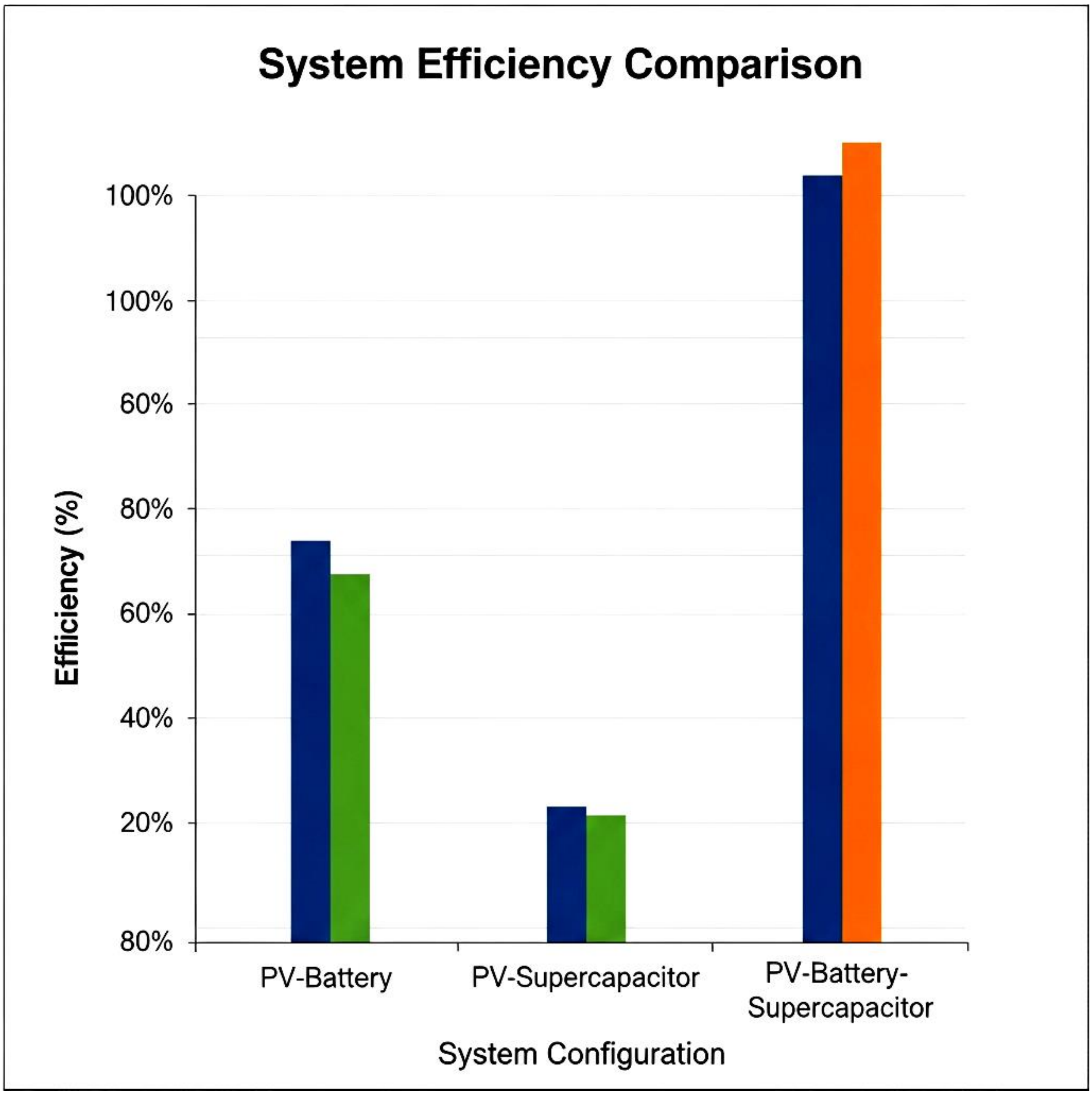

Figure 5 efficiency analysis

4. Conclusion

The design and implementation of a stand-alone DC microgrid integrating photovoltaic (PV) generation with a hybrid supercapacitor-battery energy storage system has been thoroughly investigated, demonstrating significant advantages in terms of reliability, efficiency, and operational resilience. The primary objective of enhancing uninterrupted power supply, especially in remote or off-grid areas, has been effectively achieved through the intelligent coordination of energy storage elements. The hybrid approach leverages the high energy density of batteries for long-term storage and the rapid response capability of supercapacitors to manage transient loads and fluctuations. Simulation and experimental results confirm that the proposed system provides superior voltage regulation and dynamic load response compared to battery-only configurations, reducing voltage dips and supply interruptions during sudden load changes or variations in solar generation. Furthermore, the division of power handling between the battery and supercapacitor markedly decreases the cycling frequency and depth of discharge for the battery, leading to a substantial extension in battery lifespan and reduced maintenance costs. The system efficiency is also enhanced, as the supercapacitor absorbs high-frequency power variations that would otherwise stress the battery. The intelligent energy management algorithm plays a pivotal role by optimizing power flows based on real-time conditions, ensuring that energy is utilized and stored in the most effective manner. Overall, the study demonstrates that a supercapacitor-battery hybrid energy storage system is a highly effective solution for maximizing the utilization of renewable PV energy and ensuring stable DC microgrid operation. The findings provide valuable insight for future designs of robust, scalable, and sustainable microgrid architectures, with the potential to contribute to wider adoption of renewable energy in off-grid, rural, and critical applications. Future research may focus on further optimization of control strategies, integration of additional renewable sources, and field deployment at larger scales to validate the system's performance in diverse environmental conditions.

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