Hybrid energy storage solutions through battery-supercapacitor integration in photovoltaic installations

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Article Info

Article history:

Received Oct 10, 2024
Revised Mar 16, 2025
Accepted Mar 26, 2025

Keywords:

Battery energy storage system
Energy management
Photovoltaic system
Supercapacitors
Sustainable energy transition

ABSTRACT

Batteries integrated into renewable energy storage systems may experience multiple irregular charge and discharge cycles due to the variability of photovoltaic energy production characteristics or load fluctuations. This could negatively impact the battery's longevity and lead to an increase in project costs. This article presents an approach for the sharing of embedded energy between the battery, which serves as the main energy storage system, and the supercapacitors (SC), which act as an auxiliary energy storage system. By delivering or absorbing peak currents according to the load requirements, supercapacitors increase the lifespan of batteries and reduce their stresses. An maximum power point tracking (MPPT) algorithm regulates the connection of the photovoltaic (PV) cells to the DC bus through a boost converter. A buck-boost converter connects supercapacitors and batteries to the DC bus. A DC-AC converter connects the inductive load to the DC bus. The system regulates static converters connected to batteries and supercapacitors based on current. An energy management block supervises the system components. We implement the entire system in the MATLAB/Simulink environment. We present the simulation results to demonstrate the effectiveness of the proposed control strategy for the entire system.

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1. INTRODUCTION

The global integration of renewable energies has grown steadily in recent decades, driven by the urgent need to mitigate climate change, reduce dependence on fossil fuels and limit polluting emissions. The transition toward sustainable energy is further encouraged by technological advancements and policy incentives promoting clean energy adoption. According to data from the International Renewable Energy Agency (IRENA) [1], total global installed renewable energy capacity exceeded 2,351 GW at the close of 2019, with hydropower in first place at 1,172 GW, followed by wind power at 564 GW and solar photovoltaics at 486 GW. Notably, over 80% of the new energy capacity installed in 2018 was derived from solar and wind technologies, highlighting their pivotal role in the decarbonization of the global energy system.

Despite their numerous benefits, renewable energy sources, particularly wind and solar, face significant challenges due to their inherent intermittency and unpredictability. This variability complicates their seamless integration into existing power grids, where energy supply must continuously match demand. To address these challenges, energy storage solutions (ESS) have emerged as essential components for stabilizing electricity supply, improving grid reliability, and enhancing the overall efficiency of renewable energy systems [2]. In remote areas and off-grid communities, where access to centralized electricity networks is limited or nonexistent, decentralized power generation systems provide a viable alternative. Among various renewable technologies, photovoltaic (PV) solar energy has gained widespread attention due to its scalability, low maintenance requirements, and declining installation costs. However, PV energy generation is highly dependent on solar irradiance, which fluctuates throughout the day and is further influenced by weather conditions. In standalone PV systems, where no backup power sources are available [3]-[5], the mismatch between energy production and consumption becomes a critical issue, often necessitating the integration of ESS to ensure a continuous and reliable power supply [6], [7].

Chemical energy storage, particularly batteries, remains the most widely adopted solution in hybrid renewable energy systems due to its high energy storage density. However, standard batteries regularly suffer from limitations such as limited power density, short service life and gradual performance degradation over time [8]-[10]. In contrast, supercapacitors offer significantly higher power density and extended cycle life, making them suitable for applications requiring rapid charge-discharge cycles. However, their lower energy storage capacity limits their ability to function as primary energy storage units. Consequently, supercapacitors are often utilized as complementary storage devices, working in conjunction with batteries to optimize energy management in renewable energy systems [11]-[13]. By utilizing hybrid ESS, the performance and stability of renewable energy systems can be significantly improved, making them more suitable for both grid-based and remote applications. The integration of advanced storage technologies not only facilitates a smoother transition toward sustainable energy but also ensures a more resilient and stable power supply, even in the face of fluctuating renewable energy generation [14]-[18].

This study presents an advanced hybrid energy storage system (HESS) combining batteries and supercapacitors (SC) to improve the performance, efficiency, and lifespan of renewable energy storage. A novel energy-sharing strategy is introduced, where SCs act as auxiliary storage to handle peak power demands, reducing battery stress and mitigating the adverse effects of irregular charge-discharge cycles caused by PV energy fluctuations. A current-based regulation strategy is implemented to dynamically control power flow between the battery and SC, ensuring efficient energy distribution and minimizing storage component degradation. The system architecture incorporates a maximum power point tracking (MPPT) algorithm to optimize PV energy harvesting via a boost converter, a buck-boost converter to regulate energy exchanges between the battery, SCs, and the DC bus, and a DC-AC converter to facilitate power delivery to inductive loads. An energy management block supervises the interactions among system components, optimizing performance under varying load conditions. The entire system is modeled and validated in MATLAB/Simulink, with simulation results confirming that the proposed approach significantly improves battery lifespan, stabilizes power supply, and enhances overall system efficiency. By addressing the limitations of traditional battery-based storage systems, this work advances smart energy management strategies and contributes to the sustainable and cost-effective integration of renewable energy into standalone and grid-connected applications.

2. SYSTEM ARCHITECTURE AND OPERATION

Figure 1 depicts the hybrid energy storage configuration under investigation. The system features a PV generator operating at 34 volts, with batteries and supercapacitors integrated for energy storage. SCs manage rapid current fluctuations, thereby reducing the strain on the batteries, while the batteries serve as long-term energy storage. On the DC bus, the converter associated with the PV generator acts as a voltage booster, increasing the output from 34 V to 50 V. This converter also optimizes power extraction from the solar panels using a MPPT algorithm. A bidirectional buck-boost converter connects the batteries to the DC bus, managing both the battery current and the voltage regulation between the batteries and the DC bus. Another bidirectional buck-boost converter, capable of operating in both charge and discharge modes, also connects the supercapacitors to the DC bus. We link both energy storage devices (batteries and supercapacitors) to a 50 V DC bus, facilitating their interaction [19]-[23]. Additionally, capacitors are utilized on the DC bus to smooth out power irregularities arising from the operation of power conversion units. We have completed and validated the modeling of the various subsystems, ensuring that each component functions as intended within the hybrid energy storage system [24]-[27].

3. ANALYSIS, MODELLING, AND CONTROL OF VARIOUS COMPONENTS

3.1. Photovoltaic system modeling

The functioning mechanism of a solar cell can be modeled using a corresponding electrical diagram, as shown in Figure 2. This model is extensively documented in the literature [28]-[30] and serves as a fundamental reference for PV system analysis. Over the years, numerous studies have contributed to the development of various models for PV cells, modules, and panels. Among these, two primary models are widely referenced: the single-diode and the two-diode models in (1). The single-diode model, known for its effective compromise between precision and manageable computational demands, continues to be the most widely used representation [31], [32], with its corresponding electrical diagram shown in Figure 2.

$$I = I_{ph} - I_s \left(exp\left(\frac{q(V+I*R_S)}{k*A*Tc}\right) - 1\right) - \frac{V+I*R_S}{R_{SH}} \quad (1)$$

Where:
I: flow of current via the solar cell.
I_{ph}: the current generated by light is called photocurrent.
I_S: reverse saturation current, a property of the components used in solar cells.
q: an electron's charge ($q = 1.6.10^{-19} C$).
V: voltage in the solar cell's circuit.
R_s: combining internal resistance with series resistance.
k: Boltzmann constant ($k = 1.3.10^{-23} J/K$).
T_c: temperature in Kelvin.
A: ideality factor of diode.
R_{SH}: parallel resistance.

A PV array has several photovoltaic modules interconnected in series and parallel arrangements. We express the terminal equation for current and voltage in parallel and series configurations as [33]-[35].

$$I = N_P I_{PH} - N_P I_S \left[\exp\left(q\left(\frac{V}{N_S} + \frac{IR_S}{N_P}\right)\frac{1}{kT_CA}\right) - 1\left(\frac{N_PV}{N_S} + IR_S\right)\frac{1}{R_{SH}}\right] \quad (2)$$

The power-voltage (P-V) characteristic of a photovoltaic panel is non-linear, indicating that the output power fluctuates based on irradiance and temperature. The perturbation and observation (P&O) method is the most often used MPPT approach for optimum power extraction, owing to its simplicity, clear design, and ease of practical application [36], [37]. This algorithm was selected for the current investigation.

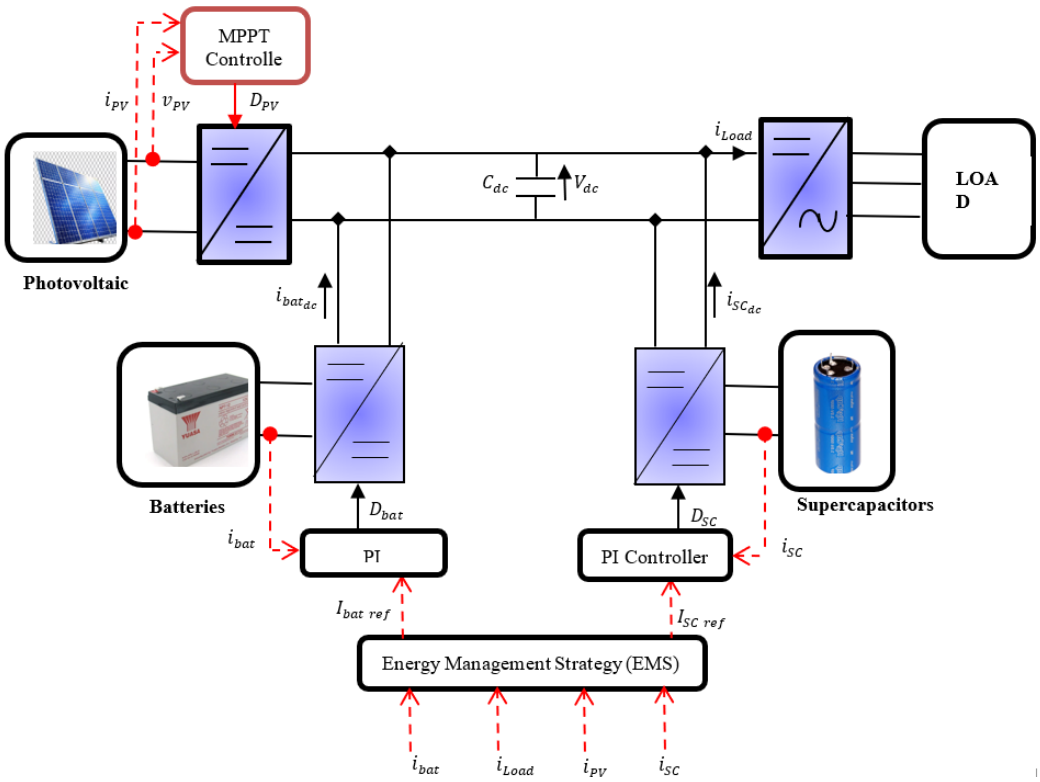

Figure 1. Schematic representation of a photovoltaic system with hybrid storage

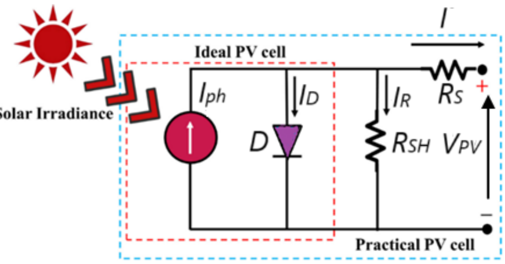

Figure 2. The electrical representation of a PV cell

3.2. Modeling and characteristics of supercapacitors

Supercapacitors, often referred to as ultracapacitors or double-layer electrochemical capacitors, are considered a promising technology due to their advantageous properties. Independent of any chemical reactions, an electric field between two electrodes stores energy. Throughout the charging process, ions that carry an electric charge migrate from the electrolyte to the electrode that has the reverse polarity [38], [39].

Supercapacitors exhibit a low cell voltage, generally reaching up to 3 V. This characteristic requires the construction of supercapacitors from modules of individual cells, interconnected in either series or a combination of series and parallel configurations [40]-[42]. Figure 3 shows the electrical model of a supercapacitor cell. This study examines the two-branch model, comprising the main branch and the slow branch [43].

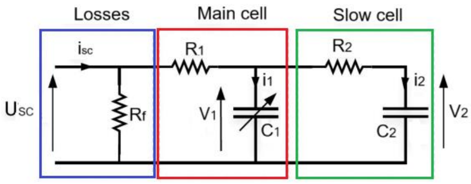

Figure 3. Simplified two-branch model of a supercapacitor cell

The central component of the circuit represents the rapid response of the supercapacitor during charging and discharging, occurring on a timescale of seconds. In this branch, R_1 corresponds to the equivalent series resistance, which accounts for power losses due to internal heating during the charging and discharging processes (measured in milliohms). The capacitor C_1 is governed by the voltage V_1, as described in equation (3). Here, C_0 represents the base (or constant) capacitance in farads (F), and C_V is a voltage-dependent capacitance parameter (measured in F/V) that adjusts for variations in capacitance as a function of the applied voltage [44], [45].

$$C_1 = C_0 + C_v V_1 \tag{3}$$

The gradual branch regulates the energy allocation within the system as the charging or discharging process concludes, usually spanning several minutes. The parallel resistance R_f defines the leakage current present when the supercapacitor is in standby mode, typically within the range of $\Omega \times 10^2$. In the context of rapid charge and discharge cycles, the self-discharge effect can typically be considered negligible [46], [47]. The voltage V_{sc} across the supercapacitor module is defined by (4).

$$V_{sc} = N_s U_{sc} = N_s (V_1 + R_1) \frac{I_{sc}}{N_p} \tag{4}$$

Where N_s and N_p represent respectively the number of supercapacitor cells in series and in parallel. Furthermore, U_{sc} represents the cell voltage and I_{sc} refers to the current of the supercapacitor module. The voltage V_2 can be expressed by the slow cell:

$$V_2 = \frac{1}{C_2} \int i_2 dt = \frac{1}{C_2} \int \frac{1}{R_2} (V_1 - V_2)\, dt \tag{5}$$

the tension V_1 in the main cell is provided by the capacitor C_1:

$$V_1 = \frac{-C_0 + \sqrt{C_0^2 + 2C_v Q_1}}{C_v} \tag{6}$$

where Q_1 represents the instantaneous charge of the capacitor C_1, and it can be calculated as (7).

$$Q_1 = C_0\, V_1 + \frac{1}{2} C_v\, V_1^2 \tag{7}$$

Table 1 [48] provides an overview of the key electrical characteristics of the examined supercapacitor cell (Maxwell BCAP3000). The supercapacitor has a rated voltage of 2.7 V and a nominal capacitance of 3,000 F. Figure 4 illustrates the Simulink model of the supercapacitor.

Table 1. Characteristics of the dual-branch supercapacitor configuration

Parameter	Value
R_1	0.8 $m\Omega$
C_0	2170 F
C_v	520 F/V
R_2	1 Ω
C_2	150 F

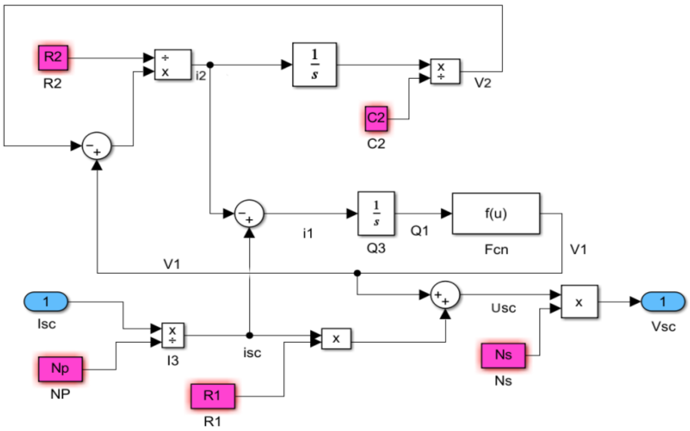

Figure 4. Supercapacitor cell model in Simulink environment

3.3. Modeling and characteristics of battery

Portable electronic devices like laptops and smartphones widely use lithium battery technology, which is also gaining increased attention in hybrid and electric vehicle applications, as well as grid energy systems. Lithium batteries are primarily valued for their significant energy storage capacity (80–200 watt-hours/kg), significant power density (500–2000 watts/kg), remarkable efficiency (90–97%), low self-discharge rate (<5% per month), and the ability to operate over a broad temperature spectrum (from -20 to 60 °C during charging and from -40 to 65 °C during discharging). Furthermore, these batteries possess a substantial lifespan, often ranging from 1,000 to 10,000 cycles. Battery packs consist of many battery modules, each containing numerous cells arranged in series, parallel, or hybrid configurations. Cells arranged in series increase the voltage of the battery pack, whereas parallel configurations increase the current, capacity, and power, thereby augmenting the overall capacity of the pack. This study only examines individual battery cell modeling.

This model is based on the Figure 5 electrical diagram, which solely depicts the battery as a voltage source and internal resistance. For the number of cells connected in series, the relationship can be expressed as (8).

$$V_{bat} = n_b E_b + n_b R_i I_{bat} \tag{8}$$

According to the reception convention, V_{bat} is the voltage and I_{bat} is the current of the battery; E_b is the electromotive force that depends on the state of charge (SOC) of the battery. The element's internal resistance is denoted by R_i. It is possible to see the battery's recovery capability from the average discharge current I_{bat} using the quantitative capacity model C_{bat} [48].

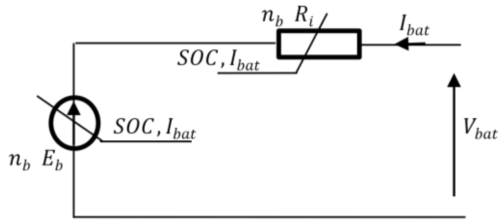

Figure 5. Equivalent circuit diagram of n_b series-connected battery cells

3.4. The PI controller

A regulator based on proportional-integral correction (PI) is used to regulate DC/DC converters. In terms of transformer current regulation, this kind of arrangement yields very good results. The following is the transfer function:

$$PI(S) = K_p\left(1 + \frac{1}{\tau_i S}\right) = \frac{K_p(1+\tau_i S)}{\tau_i S} \tag{9}$$

these equations define the parameters of the controller:

$$K_p = \frac{L}{V_{dc}T_0} \; ; \; \tau_i = \frac{L}{R} \tag{10}$$

T_0: represents the time constant that defines the dynamic behavior of the system.
L and R: refer to the inductance and resistance of the DC/DC converters, respectively.

In the event of a power deficit provided by the photovoltaic panels ($P_{pv} < P_{Load}$) and the batteries' inability to compensate for this shortfall, the supercapacitors come into play by discharging to meet the energy demand. On the other hand, supercapacitors charge up when there is excess solar energy production compared to demand ($P_{pv} > P_{Load}$) and the batteries are unable to absorb this surplus. Supercapacitors respond instantly to load demands by delivering or absorbing current spikes. Figure 6 presents a detailed diagram that illustrates the system's operation.

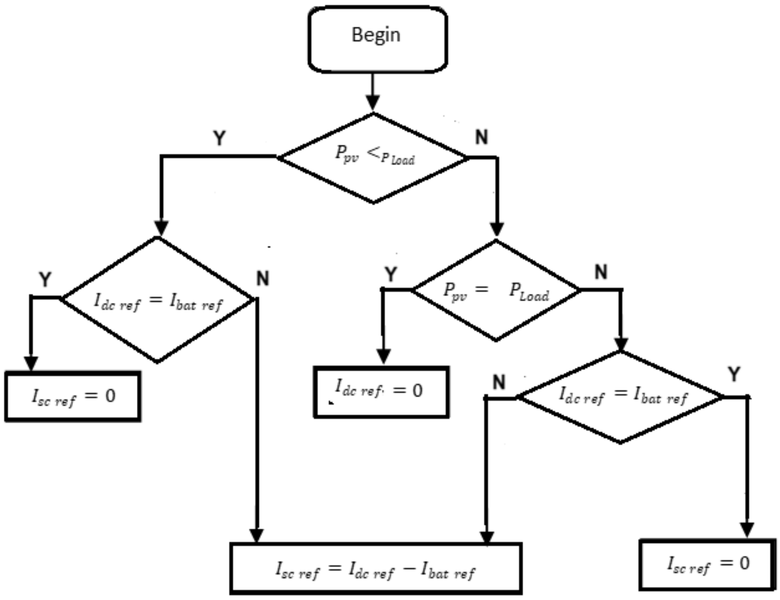

Figure 6. Flowchart for DC bus control

3.5. DC bus management and control

The DC bus voltage is regulated according to the control strategy shown in Figure 7. A PI controller determines the reference current I_{dcref} to keep the bus voltage at the desired level. $V_{ref} = 50\,V$. An energy management strategy (EMS) has been developed to control the DC bus voltage by distributing the reference currents to the static power converters, specifically I_{batref} for the battery and I_{scref} for the supercapacitors. These currents ensure the stability of the bus voltage, irrespective of load variations or fluctuations in the energy harvested from the solar panels. In the event of a component malfunction, the batteries and/or supercapacitors take over the regulation of the DC bus voltage to maintain stability [48]. It is essential that the total of the designated currents, I_{batref} and I_{scref}, always equals I_{dcref}.

$$I_{dcref} = I_{batref} + I_{scref} \quad (11)$$

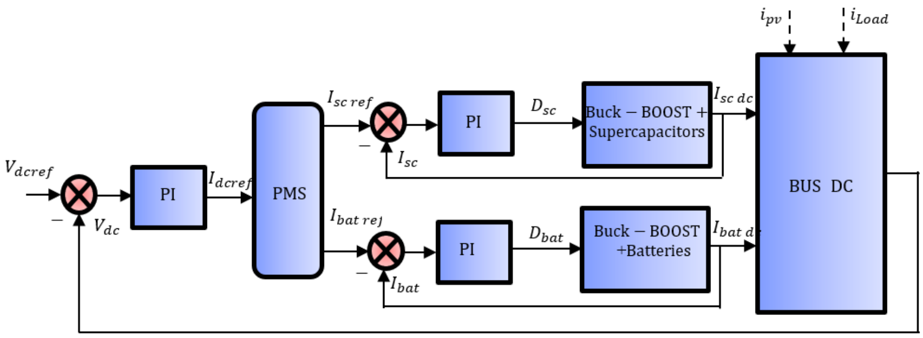

Figure 7. Schematic representation of DC bus control

4. SIMULATION RESULTS AND VALIDATION ANALYSIS

The simulation was conducted in MATLAB/Simulink for a length of 10 seconds, using a two-branch model of SCs to minimize calculation time. The supercapacitors and batteries are presumed to be precharged, exhibiting an initial voltage of 34 V. The level of charge (SoC) of the supercapacitors is 99%, while that of the batteries is 50%.

The simulation was performed under varying levels of solar irradiation [$1{,}000\,W/m^2, 800\,W/m^2, 700\,W/m^2, 500\,W/m^2$], as illustrated in Figure 8, while maintaining a constant load current of $I = 10\,A$. The corresponding variations in photovoltaic cell current I_{pv}, v, battery current I_{bat}, and supercapacitor current I_{sc} are depicted in Figures 9 and 10. During transitions in solar irradiation, the SCs exhibit a rapid dynamic response by supplying or absorbing transient current peaks, as dictated by the reference currents I_{batref} and I_{scref}. In contrast, the battery responds more gradually, as the supercapacitors effectively manage the transient power fluctuations. The DC bus voltage is regulated at $50\,V$, as shown in Figure 11.

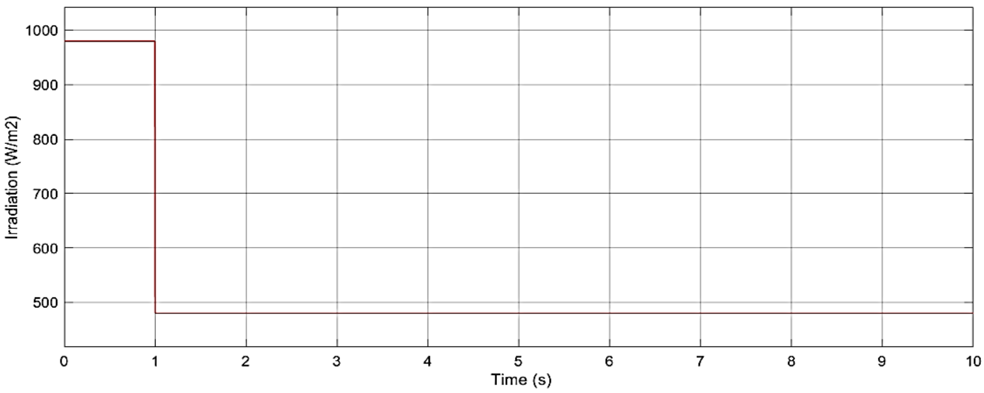

Figure 8. Solar irradiance

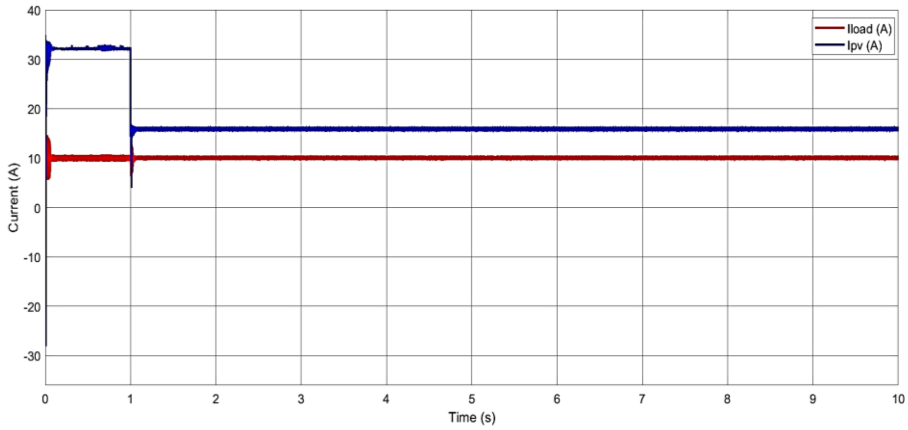

Figure 9. Simulation of I_{pv} and I_{load} under variable solar irradiance

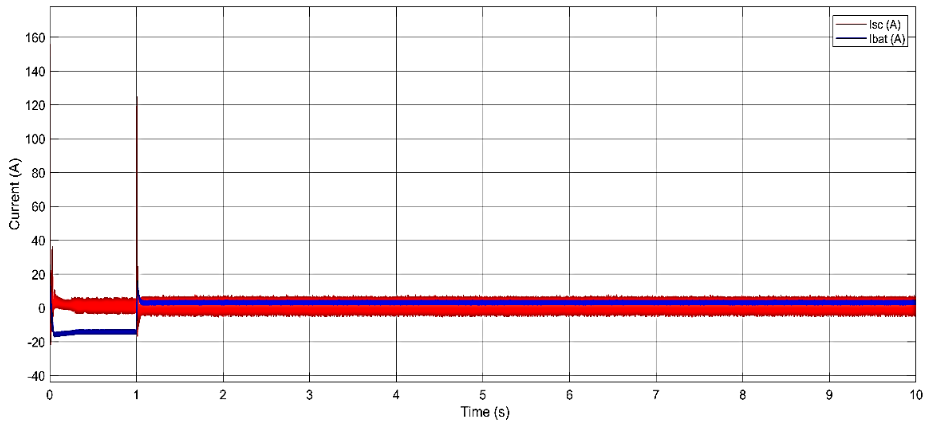

Figure 10. Simulation of I_{SC} and I_{bat} under variable solar irradiance

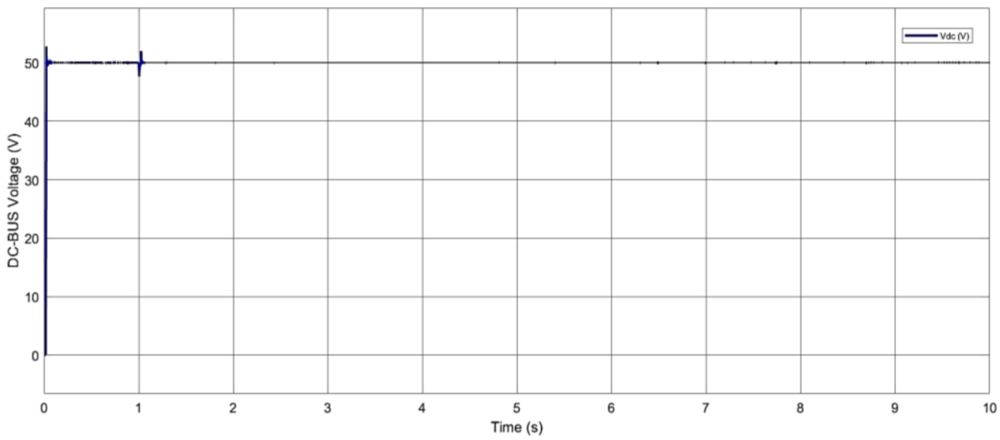

Figure 11. Simulation of V_{dc} under variable solar irradiance

Figure 12 demonstrates that the battery maintains a stable SoC at 50%, while the supercapacitor remains at 99%, ensuring its availability for transient power compensation. This highlights the complementary roles of the battery and supercapacitor in the energy management system, where the battery provides stable baseline power, and the supercapacitor handles short-term power fluctuations. As illustrated in Figure 13, after 1 second, the battery becomes the sole power source, delivering a steady power output of

80 W. During this phase, the supercapacitor remains inactive with an output power of 0 W, suggesting that energy management is primarily handled by the battery. This indicates that the supercapacitor is strategically reserved for transient power demands or future surge management requirements.

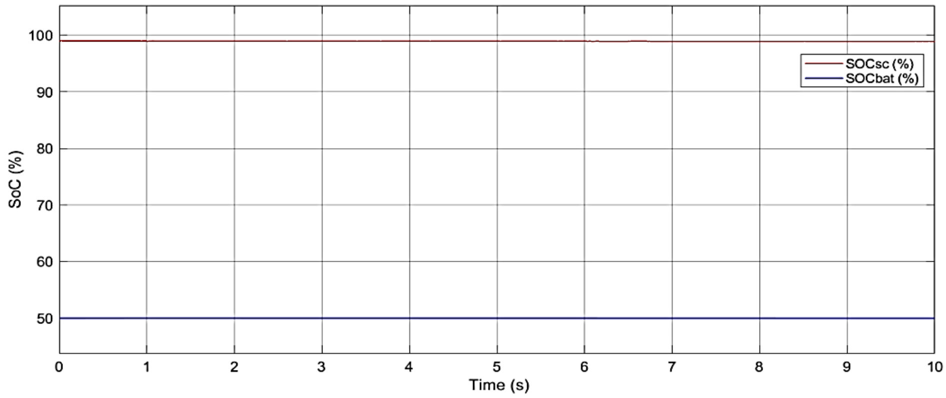

Figure 12. Simulation of SoC_{SC} and SoC_{bat} under variable solar irradiance

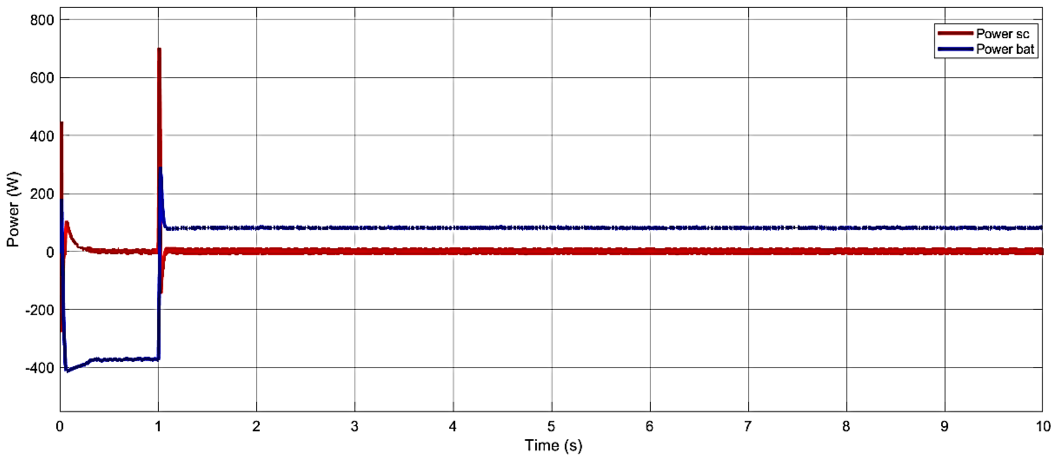

Figure 13. Simulation of P_{SC} and P_{bat} under variable solar irradiance

5. CONCLUSION

Hybrid energy storage systems can be deployed across various applications, offering distinct advantages over single-ESS, particularly in enhancing system efficiency and reliability. This study focused on the mathematical modeling of both supercapacitor and battery cells. The supercapacitor was represented using a two-branch equivalent circuit model, while the battery cell was modeled through the dual-polarization approach, incorporating two resistor-capacitor (RC) networks to accurately capture its dynamic behavior.

This study introduces a photovoltaic energy storage system that integrates a hybrid combination of batteries and supercapacitors. The study begins with the modeling of the system's key components, followed by the development of a control and regulation strategy aimed at stabilizing the DC bus voltage under varying solar irradiation conditions. The proposed control strategy ensures efficient energy management and a stable power supply by employing bidirectional converters: one interfacing the batteries with the DC bus and another linking the supercapacitors to the DC bus, thereby maintaining a regulated voltage of 50 V.

The results from the simulation confirm the efficiency of the introduced control and energy management approaches in providing the necessary power. Furthermore, the findings demonstrate that supercapacitors play a crucial role in absorbing rapid current fluctuations, thereby reducing the load stress on batteries and contributing to their longevity. Future work will focus on further optimizing the control algorithms and extending the experimental validation to real-world operating conditions to enhance system robustness and efficiency.

FUNDING INFORMATION

The authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Abdelkader Yousfi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Fayçal Mehedi	✓	✓			✓	✓		✓	✓	✓	✓	✓		
Youcef Bot	✓		✓	✓			✓		✓	✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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