Enhancing Energy Flow Management for a Hybrid Grid-Connected Photovoltaic Battery Energy Storage System

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Abstract- This study addresses the energy management challenges within a solar power generation system linked to the grid and equipped with energy storage using batteries. The system comprises a combination of solar panels arranged in series and parallel, a DC/DC boost converter, a DC/AC inverter, a DC/DC buck-boost converter, a Li-ion battery, and a DC load. The periodic nature of solar energy and the variability in load demand pose a challenge, affecting the performance of battery life and charging. To mitigate these issues and guarantee battery safety, a battery energy management algorithm has been created with the subsequent goals: (i) Constant current (CC) mode: This mode is activated when the battery's state of charge (SOC) is below 100% (SOC < 100%). It ensures that the battery current closely follows a constant reference while adhering to permissible limits. (ii) Constant voltage (CV) mode: When the battery is fully charged (SOC = 100%), this mode is activated, allowing the battery voltage to reach its reference value, indicating a fully charged state. Additionally, the study focuses on energy flow management (EFM), aiming to equalize the distribution of energy between the load and different energy resources with the aim of reducing overall system expenses, and enhance grid stability. To attain the desired outcomes, an algorithm for managing the flow of energy is used, resulting in the design of a reliable and flexible energy management strategy that optimizes resource utilization while maintaining system stability. The MATLAB Simulink/SIMPOWER environment is used to assess the performance of this energy management strategy, which demonstrates its capacity to achieve the stated goals.

Keywords PV power system, lithium-ion battery, CC/CV mode, energy flow management (EFM).

1. Introduction

Energy management in hybrid grid-connected photovoltaic battery energy storage systems (BESS) has become a critically important area in the contemporary energy landscape [1, 2]. This innovative system embodies the evolution of energy technology and offers a promising solution to address the pressing challenges of transitioning to cleaner, more reliable, and sustainable energy [3, 4]. The integration of solar photovoltaic technology with a battery energy storage system (BESS) constitutes a noteworthy advancement in maximizing the efficient utilization of renewable energy resources, reducing greenhouse gas emissions, and enhancing the resilience of the electrical grid [5, 6]. The management of energy within this hybrid system holds particular significance. It involves meticulous planning, intelligent regulation, and constant optimization of energy production and consumption. This fine-tuned management is essential for maximizing system efficiency, reducing energy costs, minimizing energy losses, and contributing to the stability of the electrical grid [7, 8]. Furthermore, it can provide significant economic benefits for the owners of these hybrid systems, notably by enabling active participation in energy markets and offering backup solutions in the event of a grid failure [9, 10].

Several energy management methodologies, including nonlinear controllers [11, 12, 13], intelligent controllers based on fuzzy logic (FL) [14, 15] or neural networks (NN) [16, 17], have been proposed in the literature. These

methodologies facilitate smart decision-making, dynamic load distribution, and energy trading [18, 19, 20]. Nevertheless, given their inherent characteristics, these techniques still entail complexity and imprecision, often requiring a substantial number of tuning parameters [21, 22, 23].

In this paper, our primary goal is to establish energy distribution equilibrium between various energy sources and the load. This equilibrium is crucial for maintaining stability in the DC link and enhancing the quality energy within the AC-network. To achieve these goals while accommodating diverse operational modes, we have developed an algorithm that facilitates seamless mode switching based on battery's SOC. The proposed algorithm empowers battery to either converge to a constant reference for current in one mode or maintain a constant reference for voltage in another mode.

The paper is organized as follows: Section 2 provides a comprehensive system description; Section 3 delves into the energy flow management algorithm and Section 4 presents the verification of the proposed EFM. Finally, the paper ends with a conclusion.

2. Studied System Description

The system under investigation is shown in Fig. 1. It consists of a photovoltaic (PV) panel, a BESS, an inverter linked to the grid, and a DC load. The DC/DC boost converter is positioned between the PV panels and the DC-link, enabling the produced power to directly supply the load and transfer any surplus power to the BESS or the grid when the generated power surpasses the load requirements. In cases where the power demand exceeds the PV system's production, excess energy can be sourced either from the battery bank using the buck-boost converter or from the AC-grid via the inverter.

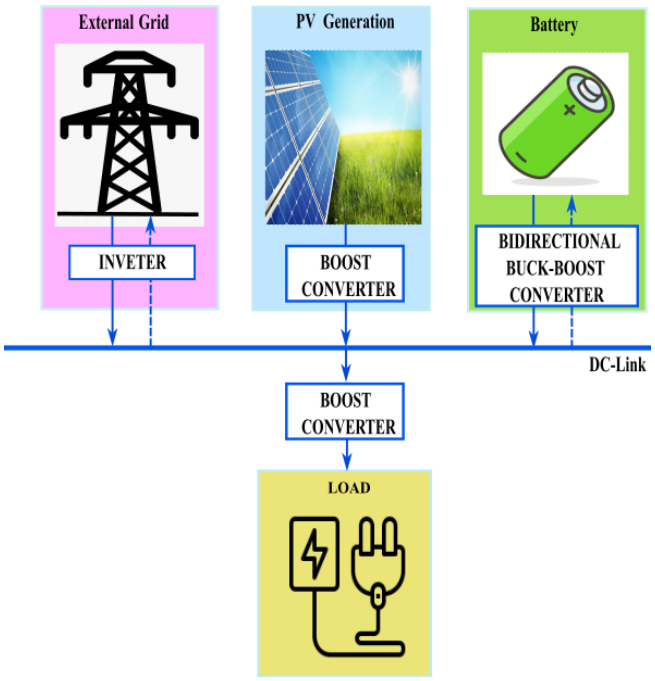


Fig. 1. The proposed photovoltaic system connected to the grid with a battery energy storage system

To attain effective and optimal energy management within the examined system, we have devised an energy management flow algorithm, expounded upon in the subsequent section.

3. Energy Flow Management

Taking into account the optimal photovoltaic power (Ppv), the battery SOC, the power demand of the load (PL), and the availability of the grid; we explore various energy flow management (EFM) scenarios designed to balance the distribution of power among various loads and energy sources. These scenarios are developed with the objectives of cost reduction (economic perspective), grid stability assurance, and enhancement of power quality (technical perspective) in mind. In pursuit of these EFM goals, we introduce a flowchart in Fig, 2, 3 and 4, which succinctly outlines the subsequent operational modes:

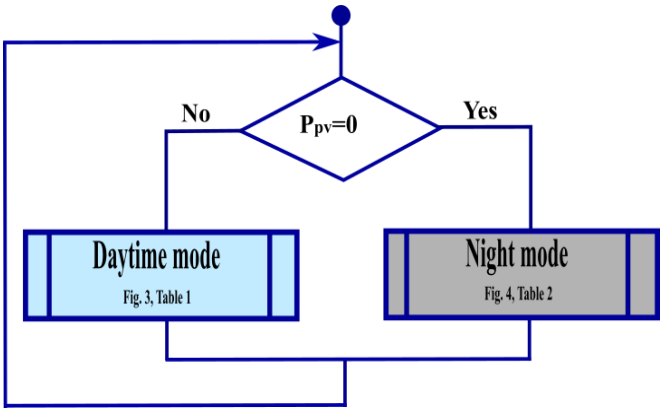


Fig. 2. The energy flow management flowchart.

- **Daytime mode:** This mode is adopted when the photovoltaic panel received power is non-zero, according to the AC-grid state, there are two cases:
  - **Grid ON:** when the grid can be treated as a storage system, the goal is to extract the maximum possible PV power (P_{pv}). The energy management algorithm accomplishes this by setting the boost converter to maximum power point tracking (MPPT) mode. The DC-link voltage is regulated by the DC/AC inverter. There are two scenarios based on the SOC of the BESS. The first scenario occurs when the battery is fully charged. The algorithm of energy management switches to CV charging mode in this case by maintaining the BESS voltage at a constant level. The second scenario occurs when the BESS is not fully charged and the received PV power is greater than the battery's maximum power. In this instance, the algorithm of energy management regulates the DC/DC boost converter to charge the battery at its maximum charging power. ($P_{pv} > P_{bmax} + P_L$), the CC mode will be adopted. In case of the PV power insufficiency ($P_{pv} < P_{bmax} + P_L$), the BESS charging current will be adapted (adaptive constant current (ACC) mode: $i_{bref} = ((P_{pv} - P_L)/V_b)$.

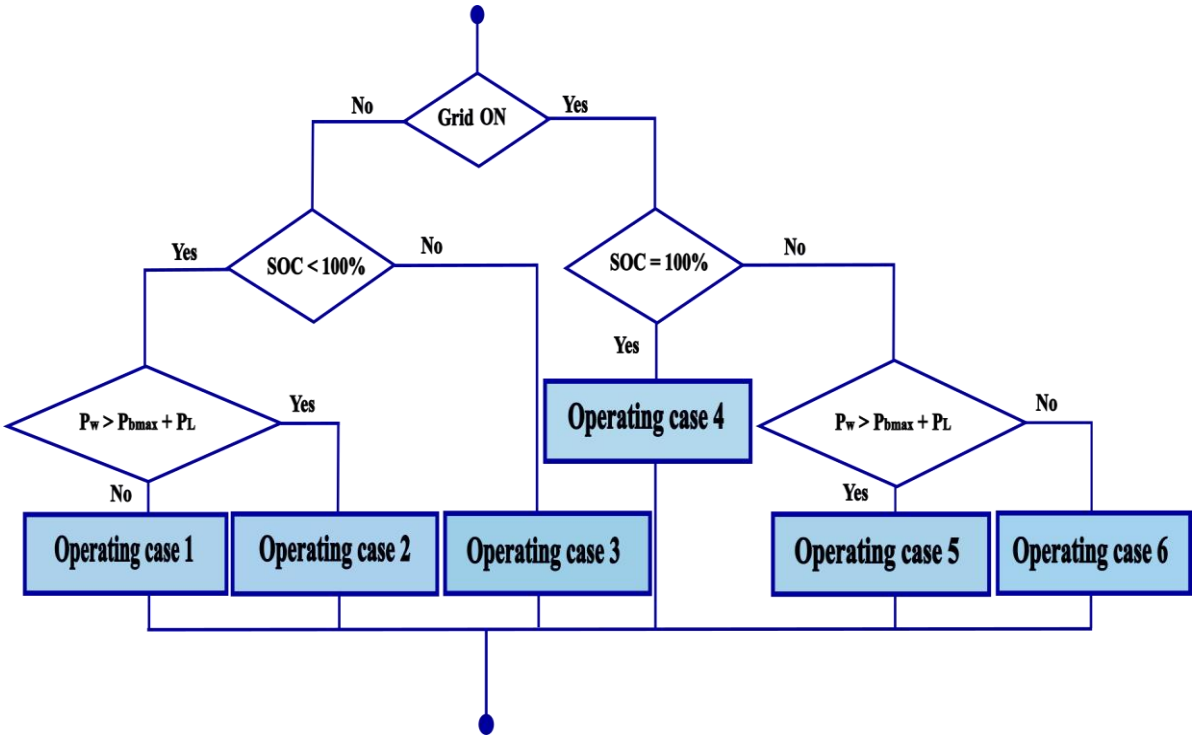


Fig. 3. The energy flow management flowchart in the daytime mode.

Table. 1. Daytime operating modes

Operating mode 1	**Operating mode 2**	**Operating mode 3**
➢ MPPT mode. ➢ DC-link voltage regulation using DC/DC buck boost converter. ➢ ACC charging mode.	➢ APPT mode. ➢ DC-link voltage regulation using DC/DC boost converter. ➢ CC charging mode.	➢ APPT mode. ➢ DC-link voltage regulation using DC/DC boost converter. ➢ CV charging mode.
Operating mode 4	**Operating mode 5**	**Operating mode 6**
➢ MPPT mode. ➢ DC-link voltage regulation using inverter. ➢ CV charging mode.	➢ MPPT mode. ➢ DC-link voltage regulation using inverter. ➢ CC charging mode.	➢ MPPT mode. ➢ DC-link voltage regulation using inverter. ➢ ACC charging mode.

- **Grid OFF:** The system containing PV power and BESS, the flexibility demand is mainly to meet the random fluctuation of load and PV power. We can establish BESS power as the variance between load demand and PV power generation ($P_b = P_{pv} - P_L$). If the battery is not completely charged and $P_b < P_{bmax}$, the energy management algorithm switches to: i) MPPT mode by regulate the DC/DC boost; ii) ACC charging mode; iii) and the DC-link will be regulated by DC/DC Buck-Boost converter. Nonetheless if $P_b > P_{bmax}$ (and BESS is not charged), the EFM algorithm switches to: iv) Adaptive power point tracking (APPT) mode by choosing the CC charging mode; v) and the DC-link will be regulated using DC/DC Boost converter. Upon reaching full charge, the energy management algorithm transitions into the CV charging mode by maintaining a consistent BESS voltage. (APPT mode). The DC-link will be regulated by the DC/DC boost converter.

➢ **Night mode:** this mode is activated at night ($P_{pv} = 0$). To guarantee a high lifetime of the BESS, the discharge depth must be limited. the if $SOC > SOC_{min}$, the DC-link will be controlled by the DC/DC buck-boost converter. However, if the battery state of charge is lower than SOC_{min} two cases appear:

- **Grid ON:** The AC-grid supplies the DC-link through the DC/AC inverter.
- **Grid OFF:** In this condition, the energy management algorithm switches to load shedding mode.

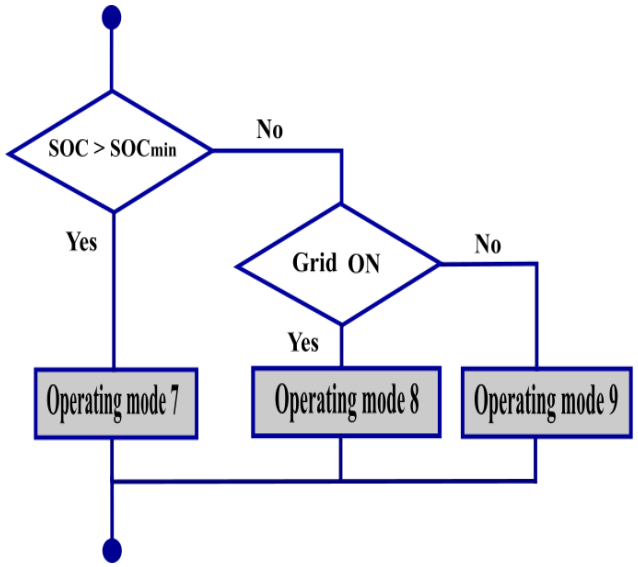


Fig. 4. The energy flow management flowchart in the night mode.

Table. 2. Night mode operating modes

Operating mode 7	Operating mode 8	Operating mode 9
DC-link voltage regulation using DC/DC buck boost converter.	DC-link voltage regulation using inverter.	Load shedding (PL = 0).

4. Verification of the Proposed EFM

In this section, the effectiveness of the suggested energy flow management is evaluated within the MATLAB Simulink/SIMPOWER environment. The system is characterized by the parameters listed in Table. 3.

Table. 3. Electrical characteristics of the system under study

Characteristics	Values
Solar module	
N_{cell}	60
P_m (W)	243.412
I_{SC} (A)	8.81
V_{oc} (V)	38.3
V_{mp} (V)	30.2
I_{mp} (A)	8.06
I Temp coef (%/deg.C)	0.07
Temp coef (%/deg.C)	-0.35601
DC-link voltage reference	
V_{dcref}	700 V
Load power	
P_L	7 Kw
Battery	
CC mode (i_{bref})	30 A
CV mode (V_{bref})	612

4.1. Daytime Energy Flow Management System Performance without Grid Connection

From 0 to 8 seconds, the solar energy conversion system, integrated with a BESS, operates independently from the grid. The initial battery SOC is 99.99%, as shown in Fig. 6. The system's performance is assessed under variable irradiance conditions, detailed in the upper part of Fig. 5. The lower part of the figure presents the available power (Ppv) from the photovoltaic panel and the optimal power output (P_{opt}). Within the initial 3 seconds of this time interval, the power delivered by PV panel falls below both the battery's maximum capacity of power and the load requirement. This is attributed to the battery's SOC being less than 100%, as shown in Fig. 6. Consequently, the system's management algorithm Converts the operation mode to Maximum Power Point Tracking (MPPT), as shown in Fig. 5, and employs the ACC mode as depicted in Fig. 8. The reference current, ibref, is determined by the equation $i_{bref} = (P_{pv} - P_L)/V_b$. Notably, the DC-link voltage (V_{dc}) precisely tracks its reference value (V_{dcref}), presented in Fig. 7. In this scenario, The DC-link voltage is effectively regulated by the DC/DC buck-boost

converter. From 3s to 5.7s, the photovoltaic panel generates more power than the battery can absorb and the load power requirement. As shown in Fig. 5, the battery SOC remains below 100%. Consequently, The energy management algorithm transitions the system to operate in APPT mode, as depicted in Fig. 5, and Constant Current (CC) mode (Fig. 8). Furthermore, the DC-link voltage (V_{dc}) follows its reference value (V_{dcref}), as illustrated in Fig. 7. In this case, the boost DC/DC converter ensures the Vdc voltage regulation. Between 5.7s and 8s, the battery reaches full charge, with the SOC reaching 100% (Fig. 6). The energy management algorithm then transitions the system into constant voltage (CV) operation (see Fig. 8) to safeguard the battery against. overcharging and overheating. The load's power requirement is then sourced from the photovoltaic panel in APPT mode, as presented in Fig. 9. In this instance, the management algorithm governs the boost DC/DC converter to maintain the regulation of the DC-link voltage.

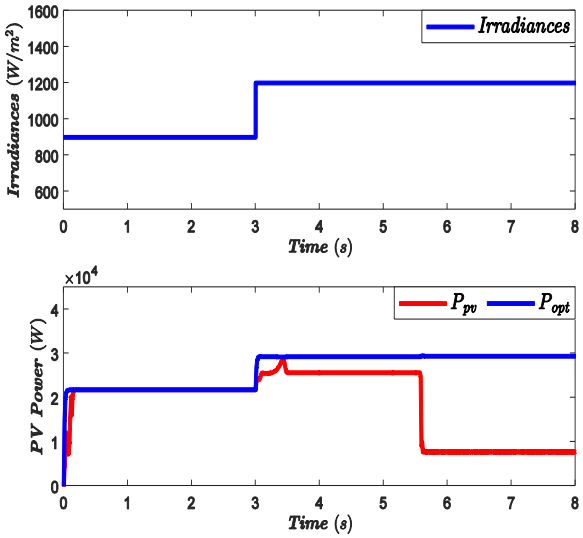


Fig. 5. Top. The irradiances profile. **Bottom.** The PV power.

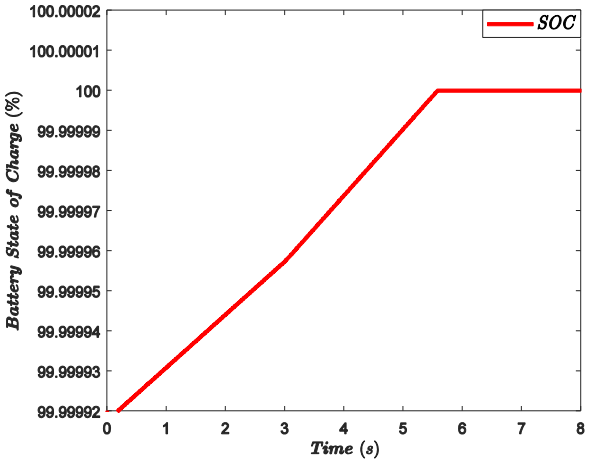


Fig. 6. The battery state of charge.

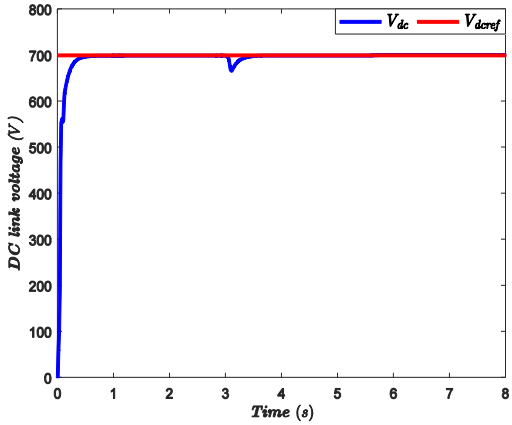


Fig. 7. Blue. The DC-link voltage. **Red.** The optimal DC reference voltage.

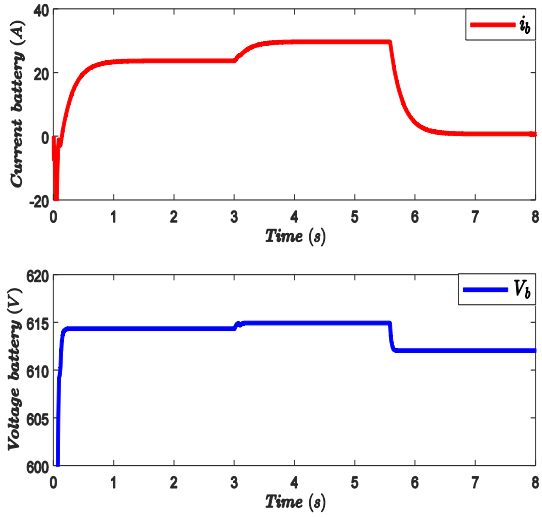


Fig. 8. Top. The current battery. **Bottom.** The voltage battery**.**

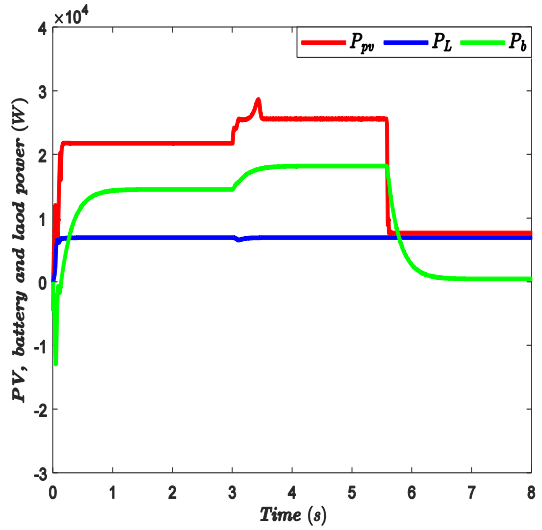


Fig. 9. Red. The PV power**, Blue.** The load power**, Green.** The battery power.

4.2. Daytime Energy Flow Management System Performance with Grid-Connected Operation

In this instance, the grid-connected solar conversion system with BESS is operational. The irradiance is visualized in Fig. 10, and throughout this condition, the management algorithm consistently oversees the operation of the boost converter in MPPT mode, as depicted in Fig. 10. Furthermore, the grid ensures the regulation of the DC-link, illustrated in Fig. 12. During the initial 3s of this time interval, the battery's SOC remains below 100%, and the power delivered by PV panel falls short of the battery's maximum capacity (P_{bmax}) and the power required for the load (P_L), as showcased in Fig. 14. In response, the management algorithm transitions to the ACC mode, with a corresponding current ibref = $(P_{pv}-P_L)/V_b$, as presented in Fig. 13. Between 3s and 5.7s, the power supplied by PV panel exceeds both the battery's maximum capacity and the load demand, and given that the SOC of the battery is still below 100%, the management algorithm shifts to Constant Current mode, as indicated in Fig. 13. Additionally, the surplus power supplied by PV panel is fed back to the main grid, as illustrated in Figure. 14. From 5.7s to 8s, the battery attains a full charge with a SOC of 100%, as represented in Fig. 11. During this phase, the management algorithm takes control of the buck-boost DC/DC converter, operating it in Constant Voltage (CV) mode, as depicted in Fig. 13.

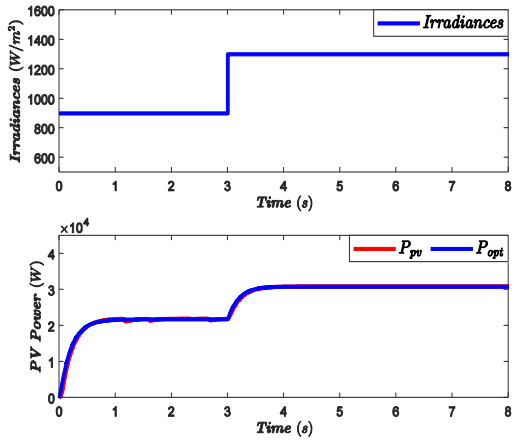


Fig. 10. Top. The irradiances profile. **Bottom.** The PV power.

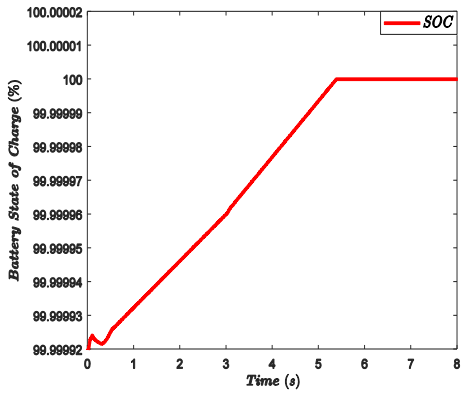


Fig. 11. The battery state of charge.

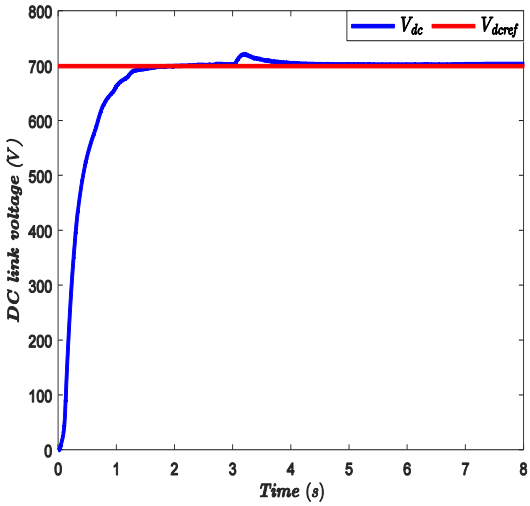


Fig. 12. Blue. The DC-link voltage. **Red.** The optimal DC reference voltage.

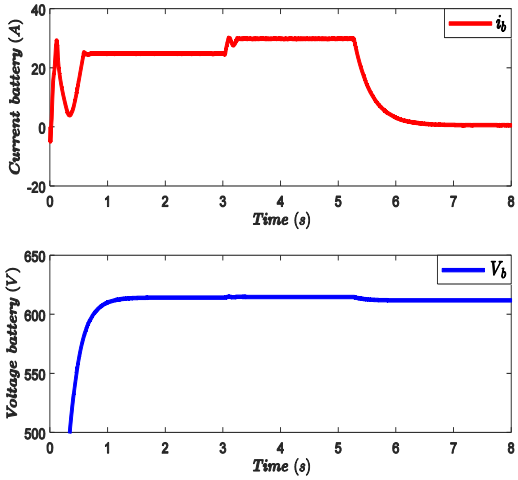


Fig. 13. Top. The battery current. **Bottom.** The battery voltage.

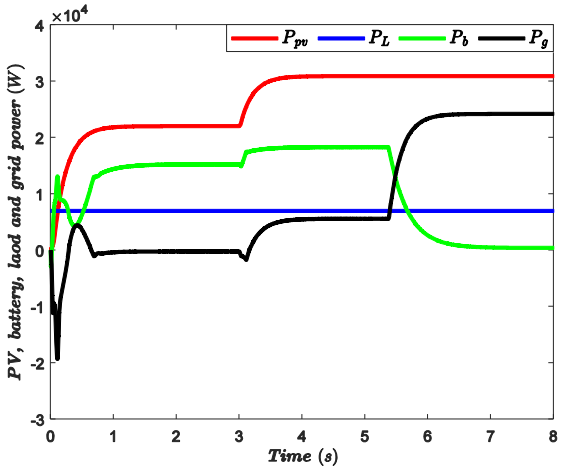


Fig. 14. Red. The PV power**, Blue.** The load power**, Green.** The battery power, **Black.** The grid power**.**

4.2. Night mode energy flow management system performance

During the night mode period, no power is being generated by the photovoltaic panel. Hence, it becomes necessary to address certain critical energy management scenarios within the system. Within the time range of 0 to 2.8s, the battery's State of Charge (SOC) exceeds SOCmin, specifically set at 20%, as depicted in Fig. 15. During this phase, the load power demand is met through the battery, as illustrated in Fig. 17. Additionally, the management algorithm oversees the operation of the DC/DC buck-boost converter, ensuring that the DC-link voltage (V_{dc}) closely tracks its reference value (V_{dcref}), illustrated in Fig. 16. Between 2.8s and 5s, the battery SOC is at 20%, and the main grid is unavailable. In response, the energy management algorithm initiates load-shedding, see Fig. 17, while maintaining a constant DC-link voltage (V_{dc}) equal to the reference value (V_{dcref}). From 5s to 8s, the main grid is reconnected. With battery's SOC at 20%, the grid is responsible for regulating the DC-link voltage (Fig. 16) and delivering the required load power (Fig. 17).

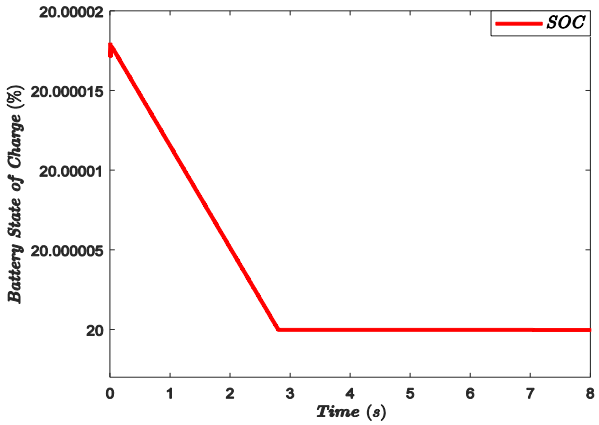


Fig. 15. The battery state of charge.

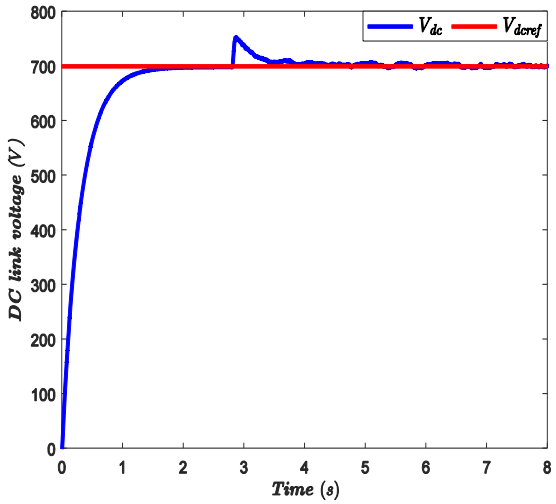


Fig. 16. Blue. The DC-link voltage. **Red.** The optimal DC reference voltage.

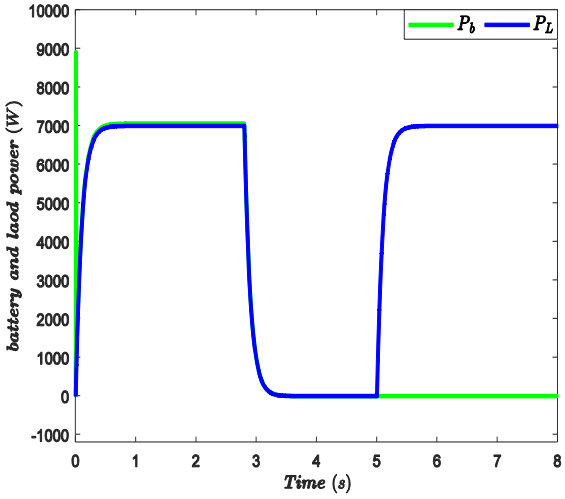


Fig. 17. Blue. The Load power, **Green.** The battery power.

5. Conclusion

This paper has proposed an energy flow management approach for a grid-connected photovoltaic system with battery storage. The system consists of a PV panel, DC/DC boost converter; DC/AC inverter, DC/DC buck-boost converter, Lithium-ion battery, and DC load. The primary objective is to enhance the efficiency of energy distribution between loads and energy sources, with the aim of reducing overall expenses, maintaining DC-link stability, and enhancing energy quality. A novel energy management system has been created to attain these objectives, bolstering performance across all operational states. The simulation results affirm the effectiveness of the introduced energy flow management approach.

In consideration of future studies, our orthcoming work aims to leverage artificial intelligence, particularly in the form of a multi-agent system, to further enhance the energy flow management proposed in this study. The integration of AI technologies is anticipated to bring about advanced adaptive capabilities, enabling more sophisticated decision-making processes for optimizing energy distribution within the grid-connected photovoltaic system with battery energy storage system.

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