 https://doi.org/10.1051/e3sconf/202568000145

Energy management system for an Islanded Micro-grid combining PV, battery and variable load

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Abstract. This paper proposes a Perturb and Observe (P&O)-based Energy Management System (EMS) for an islanded micro-grid composed of photovoltaic (PV) generation, battery storage, and variable load demand. The EMS employs a hierarchical control strategy that leverages the P&O algorithm to optimize PV power extraction while coordinating battery charging and discharging operations. Specifically, when the battery state of charge (SOC) is low and the system encounters a power shortfall, the EMS directs all available renewable energy exclusively to recharge the battery, thereby improving resilience and extending autonomous operation. Conversely, in the case of energy surplus and a high SOC, the EMS suspends maximum power tracking and limits PV generation to balance production with demand, thus preventing overcharging and ensuring system safety. Under normal conditions, the EMS dynamically allocates PV generation between direct load supply and storage through P&O-based maximum power point tracking, ensuring efficient energy use and minimizing curtailment. Simulation results demonstrate that the proposed P&O-based EMS effectively stabilizes the micro-grid, enhances energy self-sufficiency, and guarantees reliable operation under variable solar irradiance and load conditions.
Keywords. Energy Management System (EMS), Perturb and Observe (P&O), Maximum Power Point Tracking (MPPT), Islanded Micro-grid, Battery Storage, State of Charge (SOC)

1 Introduction

The growing global demand for sustainable and decentralized energy solutions has accelerated the deployment of micro-grids as a promising pathway to enhance energy access and reduce reliance on fossil fuels. Micro-grids integrate distributed generation units, storage systems, and local loads into a coordinated network capable of operating either in grid-connected or islanded mode [1], [2]. Among these, islanded micro-grids, operating independently from the main grid have become crucial for powering remote, rural, and off-grid regions where centralized grid extension is economically or technically unfeasible [3], [4]. By integrating renewable energy resources with local storage and demand management, islanded micro-grids offer a reliable and environmentally friendly alternative to conventional diesel-based generation, contributing both to energy security and carbon emission reduction [5].

Photovoltaic (PV) systems are among the most widely adopted renewable energy technologies in islanded micro-grids due to their scalability, modularity, and rapidly declining installation costs [6], [7]. Global PV deployment has expanded significantly, with capacity doubling over the past decade, making it a cornerstone of clean electrification strategies [8]. However, the intermittent and variable nature of solar irradiance presents substantial challenges in maintaining the supply-demand balance, particularly in microgrids with fluctuating and variable load profiles. In the absence of appropriate control strategies, such variability can lead to voltage instability, frequency deviations, and reduced system reliability [9], [10].

To mitigate intermittency, PV generation in micro-grids is typically complemented by Battery Energy Storage Systems (BESS), which provide flexibility by storing surplus energy during periods of excess generation and discharging during deficits [11]. Beyond balancing generation and demand, BESS play a critical role in frequency regulation, voltage support, and black-start capability [12]. Nevertheless, the operational performance and lifetime of batteries are highly dependent on State of Charge (SOC) management, as frequent deep discharges or underutilization may degrade battery capacity and compromise system reliability [13], [14].

The Energy Management System (EMS) forms the core of efficient micro-grid operation, coordinating power flows among generation, storage, and load while ensuring economic operation and reliable supply [15]. Various EMS approaches have been explored in the literature. Rule-based EMS are simple, transparent, and suitable for real-time applications, but they may lack adaptability to rapidly changing operating conditions [16]. Optimization-based EMS, including Mixed-Integer Linear Programming (MILP), Genetic Algorithms (GA), and Particle Swarm Optimization (PSO), aim to minimize costs, emissions, or degradation while maximizing renewable utilization [17], [18]. More recently, predictive and intelligent control strategies, such as Model Predictive Control (MPC) and artificial intelligence (AI)-based algorithms, have been introduced to enhance decision-making under uncertainty [19], [20]. While these advanced methods improve adaptability, they often require accurate forecasts and significant computational resources, limiting their applicability in small-scale or real-time islanded systems.

Despite these advancements, a persistent challenge arises under deficit conditions combined with low battery SOC. In such cases, conventional EMS strategies often attempt to distribute renewable energy between direct load supply and storage. This compromises the rapid recovery of the battery, reduces system resilience, and risks premature load shedding or blackout [21].

This work introduces a Perturb and Observe (P&O) based EMS that integrates MPPT control with adaptive energy allocation policies. Unlike conventional approaches that maintain maximum PV extraction at all times, the proposed strategy dynamically adapts to system conditions: it enforces priority charging of the battery during deficit periods with low SOC, and it deliberately reduces PV output under surplus conditions to prevent overcharging. Thus avoiding the inclusion dump load within the micro-grid and reducing the cost. This flexible coordination between power generation, storage, and demand improves overall system autonomy and safeguards reliable operation. Simulation studies verify that the method not only maintains micro-grid stability but also enhances energy self-sufficiency under fluctuating irradiance and load scenarios.

2 Methodology

2.1 Micro-grid construction

The islanded micro-grid (Figure 1) integrates renewable generation, storage, and demand through a common DC bus. It consists of a PV array interfaced with a downstream DC/DC boost converter, a Battery Energy Storage System (BESS) comprising a battery pack and a bidirectional converter governed by a Battery Charging and Discharging Controller (BCDC), a variable DC load, the switch S1, and a supervisory Energy Management System (EMS). The boost converter adapts is controlled by a PWM duty cycle generated by the EMS. The BESS absorbs surplus energy or compensates for renewable shortfalls according to the SOC, while the BCDC regulates charge and discharge currents and DC voltage. The DC bus acts as the central node for power exchange, ensuring voltage stability under variable operating conditions. Switch S1 allows the EMS to isolate the load from the micro-grid when safety constraints arise.

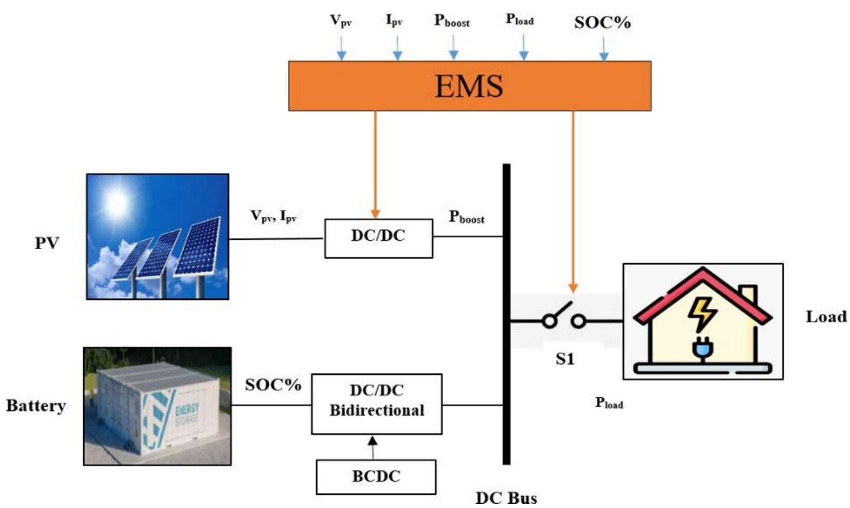

Fig. 1. Micro-grid architecture

2.2 Mathematical modelling of Micro-grid components and MPPT controller

2.2.1 Photovoltaic system and Boost converter

The electrical behavior of a photovoltaic (PV) array comprising Ns modules in series and Np strings in parallel can be modeled using a simplified single-diode equation, which captures the main effects of irradiance and temperature while remaining computationally efficient [22-23]. The array current is expressed in the following equation:

$$\boldsymbol{I = N_p \left(I_{ph}(G,T) - I_s(T) \left[exp\left(\frac{qV}{N_s n_m kT} \right) - 1 \right] \right)}$$

In this formulation, I represents the output current of the PV array, while V denotes the output voltage (V). The photocurrent I_{ph}(G,T) is a function of the incident solar irradiance **G** and the cell temperature T, whereas the reverse saturation current of the diode, Is(T) varies with temperature and n_m is the diode ideality factor. The physical constants involved are the electron charge q=1.602×10^{-19} C and Boltzmann's constant k=1.381×10−23 J/K.

To interface the PV array with the DC bus, a boost converter is commonly used. The average voltage and current relationships of an ideal boost converter are:

$$\boldsymbol{V_{out} = \frac{V_{in}}{1-D}, \quad I_{out} = I_{in}.(1-D)}$$

Where V_{in} I_{in} are the PV array voltage and current, V_{out}, I_{out} are the DC-link voltage and current, and $D$is the duty cycle.

The dynamic behavior of the inductor $L$and capacitor C *can* be described by:

$$L\frac{dI_L}{dt} = V_{in} - (1-D).V_{out} \text{ and } C\frac{dV_{out}}{dt} = (1-D).I_L - I_{out}$$

These equations form the basis for modeling and control of PV systems integrated with a boost converter for maximum power point tracking (MPPT) and voltage regulation.

2.2.2 Battery with bidirectional converter and charge and discharge controller

The BESS is used to store excess renewable energy and supply power during generation shortfalls. It is modelled using a dynamic equivalent circuit model that includes internal resistance and open-circuit voltage. The battery state of charge (SOC) evolves according to [24-25]:

$$SOC(t+\Delta t) = SOC(t) + \frac{(\eta_{ch}P_{ch}(t) - P_{dis}(t)/\eta_{dis})}{E_{bat}}.\Delta t$$

where η_{ch} and η_{dis} are the charging and discharging efficiencies, P_{ch} andP_{dis} are the charging and discharging powers, E_{bat} is the nominal energy capacity, and Δt is the sampling interval. SOC is bounded within operational limits (19.5%-90%) to avoid deep discharge and overcharging. The bidirectional DC–DC converter interfaces the battery with the DC bus, enabling bidirectional power flow according to system requirements. In charging mode, it functions as a buck converter to step down the DC-bus voltage, while in discharging mode, it operates as a boost converter to regulate the DC-link voltage. Its control structure typically employs a dual-loop scheme: an outer loop regulates the battery current or state of charge (SOC) to follow energy management set points, while an inner loop ensures fast voltage or current tracking through pulse-width modulation (PWM). The controller also enforces voltage and current limits to protect the battery and maximize efficiency during charging, while stabilizing the DC-link and supplying load demand during discharging [26].

2.2.3 Power balance in DC Bus

The power balance of the hybrid micro-grid at the DC bus level can be expressed as a function of time t, capturing the interaction between the photovoltaic (PV) generation, energy storage units, and the load demand. The instantaneous power balance is given by:

$$P_{PV}(t) + P_{dis}(t) = P_{Load}(t) + P_{ch}(t)$$

Where $\boldsymbol{P_{PV}}$ is the power delivered by PV and $\boldsymbol{P_{Load}}$ the load demand.

2.2.4 MPPT Controller

The Perturb and Observe (P&O) method is one of the most widely used MPPT algorithms for PV systems due to its simplicity, ease of implementation, minimal parameter requirements, and potential for high efficiency [26-28]. It operates by analysing the relationship between PV output power and voltage. As illustrated in Figure 2, when the operating point lies to the left of the maximum power point ($\Delta P/\Delta V > 0$), the duty cycle is decreased to move toward the MPP, whereas on the right side ($\Delta P/\Delta V < 0$), the duty cycle is increased to track the MPP.

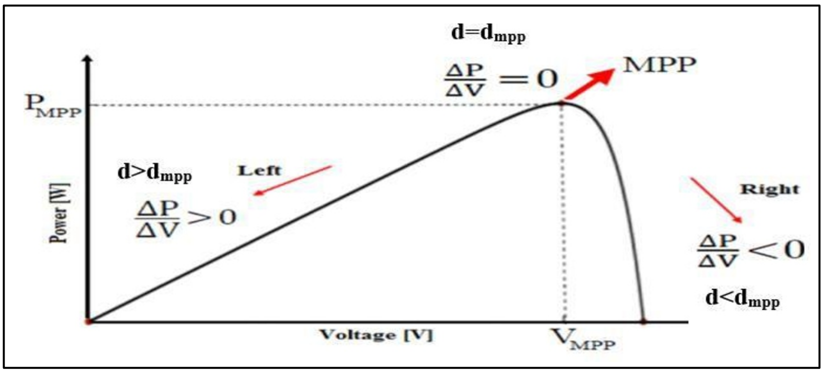

Fig. 2. Operating principle of the MPP for a PV panel

2.3 Energy management strategy

The primary function of the Energy Management System (EMS) is to maintain a balance between generation, storage, and consumption while ensuring that the battery operates within safe state-of-charge (SOC) limits. Effective energy management can be characterized by the following operational scenarios:

Scenario 1: When the generated power exceeds the load demand, the excess energy is used to charge the battery until it reaches its maximum SOC limit.

Scenario 2: If the battery is fully charged and the generated power still exceeds consumption, the PV output is curtailed to prevent overcharging.

Scenario 3: When the load demand exceeds the generated power, the battery supplies the deficit until its SOC reaches the minimum threshold.

Scenario 4: If the load demand surpasses generation and the battery SOC has already reached its minimum threshold, the load is temporarily disconnected from the micro-grid to allow the battery to recharge to a safe SOC level before reconnecting.

2.4 P&O Energy management design

The proposed EMS integrates the (P&O) technique within a real-time energy management framework for the hybrid PV-Battery-Load system. It simultaneously ensures maximum renewable power extraction and efficient energy flow control according to the system's operating state. The EMS as illustrated in Figure 3 receives as inputs the PV voltage (V_{PV}), current (I_{PV}), boost converter power (P_{PV}), load demand (P_{Load}) and the battery state of

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charge (SOC%). One embedded MPPT module compute the optimal duty cycles for the PV based on the P&O technique.

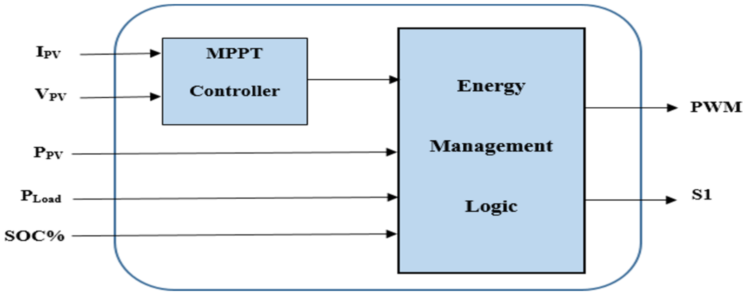

Fig. 3. Block diagram of the proposed EMS

The Energy Management Logic then evaluates the power balance (PPV PLoad) and Battery SOC to determine the appropriate system mode. When PV generation exceeds the load

(PPV PLoad > 0) and the SOC surpasses its upper limit (SOC>90%), the controller slightly increases the duty cycle to limit further charging. Conversely, when a power deficit occurs

(PPV PLoad < 0) and the battery SOC drops below its critical threshold (SOC < 19.5%), the load is temporarily disconnected (S1=0) to preserve battery life. Once the SOC recovers above the resume level (SOC > 20.5%), the load is reconnected (S1=1). This coordinated control structure ensures optimal power harvesting, battery protection, and load reliability under dynamic environmental and demand conditions. Figure 4 shows the algorithm implemented within the EMS.

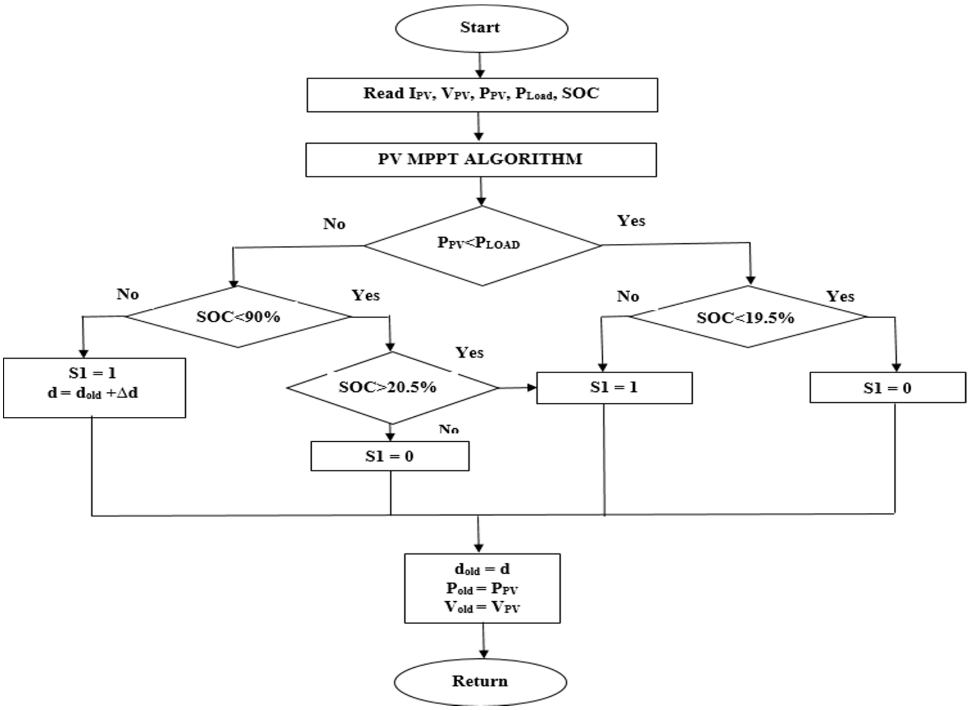

Fig. 4. EMS algorithm flowchart

3 Simulation and discussion

To assess the performance and effectiveness of the proposed Energy Management System (EMS), a 24-seconds simulation was conducted in MATLAB/Simulink. The simulation model, shown in Figure 5, incorporates all components of the islanded microgrid, including the EMS.

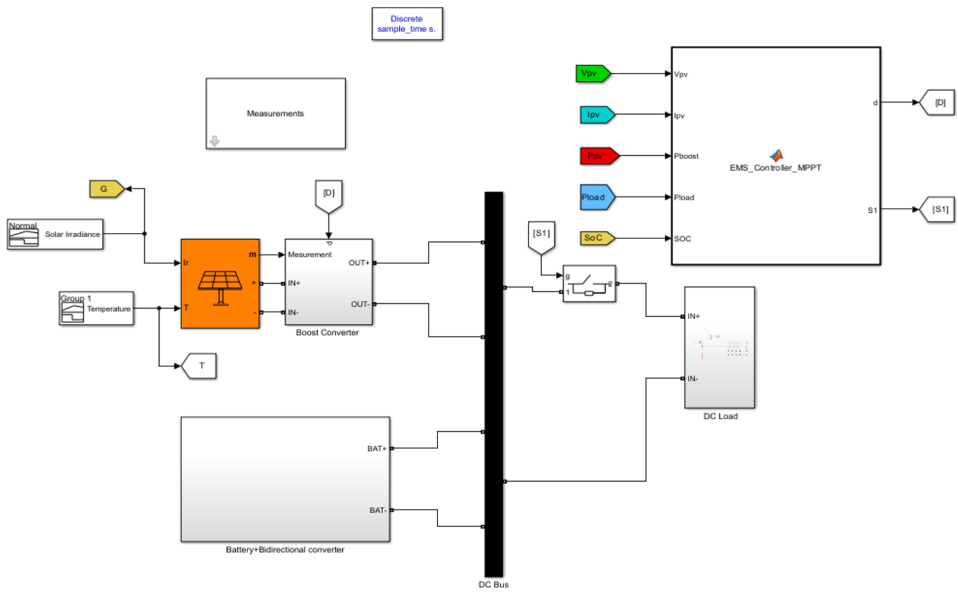

Fig. 5. Micro-grid modelling in Matlab Simulink

The hybrid micro-grid case study incorporates a photovoltaic (PV) array, a battery energy storage system (BESS), and a dynamic load profile under variable environmental conditions. The PV array consists of seven series-connected modules (parameters summarized in Table 1), delivering up to 1960 W at 250 V under standard test conditions (STC: 1000 W/m², 25 °C. The BESS is implemented using a 48 V, 10 Ah lithium-ion battery, selected for its high energy density and efficiency [29]. Battery specifications are summarized in Table 2.

Table 1. PV module parameters.

PV module name	**HSL72P6-PA-0-280T**
Maximum Power	280 W
Open-circuit voltage	44.6 V
Voltage at MPP	35.7 V
Cells per module	72
Short-circuit current	8.43 A
Current at MPP	7.84 A

Table 2. Battery characteristics.

Battery type	**Lithium-ion**
Maximum capacity	10 Ah
Nominal voltage	48 V
Cut-off voltage	36 V
Fully charged voltage	55.87 V
Nominal discharge current	4.34 A
Internal resistance	0.0048 Ω
Capacity at nominal voltage	9.0435 Ah
Exponential zone	(51.86 V, 0.49 Ah)

The system is subjected to time varying solar irradiance and ambient temperature profiles. Furthermore, the load demand is modelled using a dynamic profile, together with a dynamic load profile, as illustrated in Figure 6. All these inputs serve as the basis for evaluating the performance of the proposed EMS

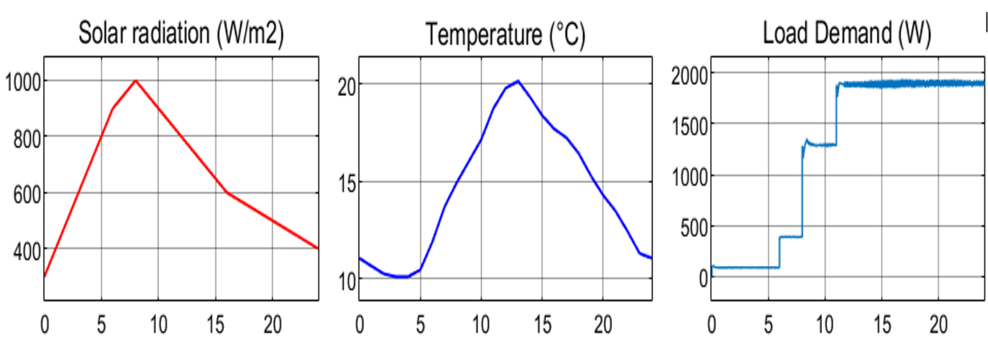

Fig. 6. Solar irradiance, temperature, and dynamic load demand

To capture different operational conditions, three scenarios were considered based on the initial state of charge (SOC): a high SOC of 90.1%, representing a nearly fully charged battery; and a low SOC of 19.5%, simulating a depleted storage state.
Upon completing the simulations for each scenario, a series of graphs (**Figures 7,8**) was generated to provide a comprehensive view of the system's dynamic behavior. These figures illustrate the temporal evolution of the battery state of charge (SOC), highlighting how the Energy Management System (EMS) maintains the SOC within safe operational limits under varying generation and load conditions. The comparison between the boost power output and the load demand is presented, demonstrating the EMS's ability to balance energy supply and consumption efficiently. The variations in the boost converter duty cycle reflect the interaction between the Maximum Power Point Tracking (MPPT) algorithm and the EMS, showing how the system modulates PV extraction in response to battery SOC and load requirements. Additionally, the control signal of switch S1 is displayed, indicating periods when the load is temporarily disconnected to prioritize battery charging and prevent

 https://doi.org/10.1051/e3sconf/202568000145

deep discharge. Collectively, these graphs provide a clear visualization of the EMS's effectiveness in managing energy flows and ensuring reliable operation of the PV-battery system across different scenarios.

3.1 High initial SOC scenario (SOC=90.1%)

From 0 to 0.15 second, the Boost converter power rises rapidly, reaching a peak of 400 W before dropping to approximately 100 W. During this period, the converter power exceeds the load demand, and the battery state of charge (SOC) is above 90%. As a result, the duty cycle increases sharply up to 0.9, with the EMS deliberately incrementing it to move the operating point away from the maximum power point, which explains the significant drop in the boost power. Between 0.15 and 11 seconds, the difference between boost converter power and load demand remains very small, sometimes favouring generation and sometimes consumption. A slight decrease in the battery SOC is observed. During this phase, the duty cycle decreases. The smaller the gap between PV power at the maximum power point and the load demand, the closer the duty cycle value approaches 0.1, which corresponds to the maximum power point. From 11 to 24 seconds, the load demand consistently exceeds PV generation. The EMS then focuses on maximum power point tracking, resulting in a stable duty cycle with a value 0.1. In this scenario, switch S1 remains continuously closed.

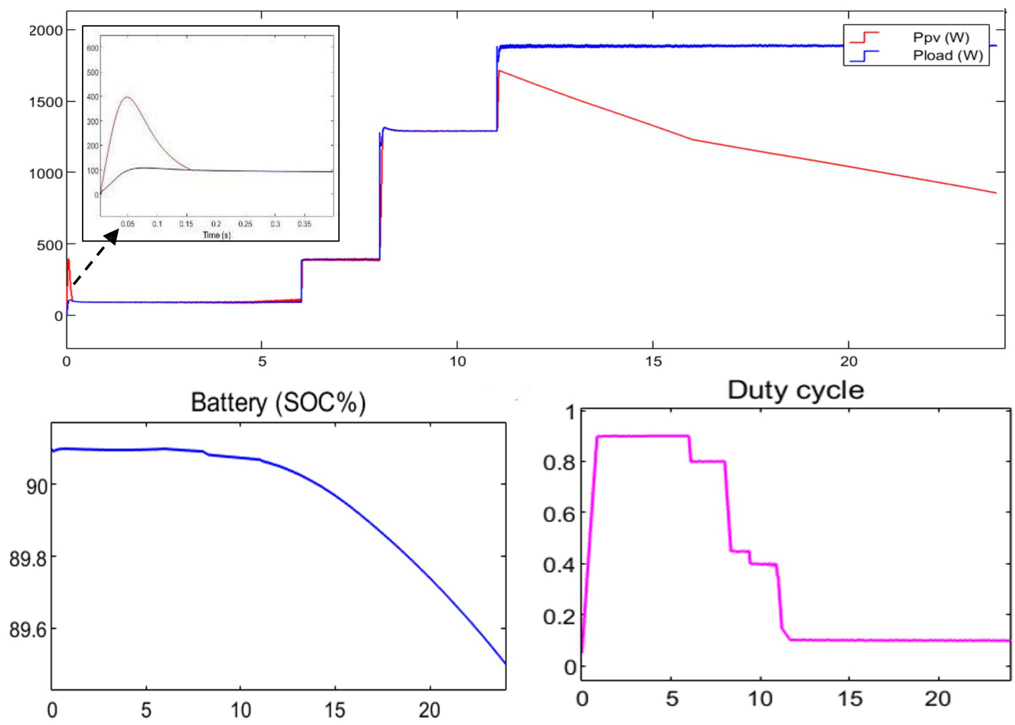

Fig. 7. High initial SOC scenario simulation results

3.2 Low initial SOC scenario (SOC=19.5%)

From 0 to 14.07 seconds, switch S1 remains open, directing all the available PV energy to the battery in order to accelerate charging until the SOC reaches the 20.5% threshold. During this period, the load receives no power (P_{Load} = 0), and the duty cycle remains constant at a value corresponding to the maximum power point. Once the threshold is reached at 14.07 seconds, the EMS closes the switch, reconnecting the load. At this stage, the load demand exceeds the boost converter output, resulting in battery discharge. The switch remains closed thereafter, as the battery SOC does not fall below the critical 19.5% threshold. A brief perturbation in the duty cycle is observed at the instant the switch is activated, reflecting the transient response of the system.

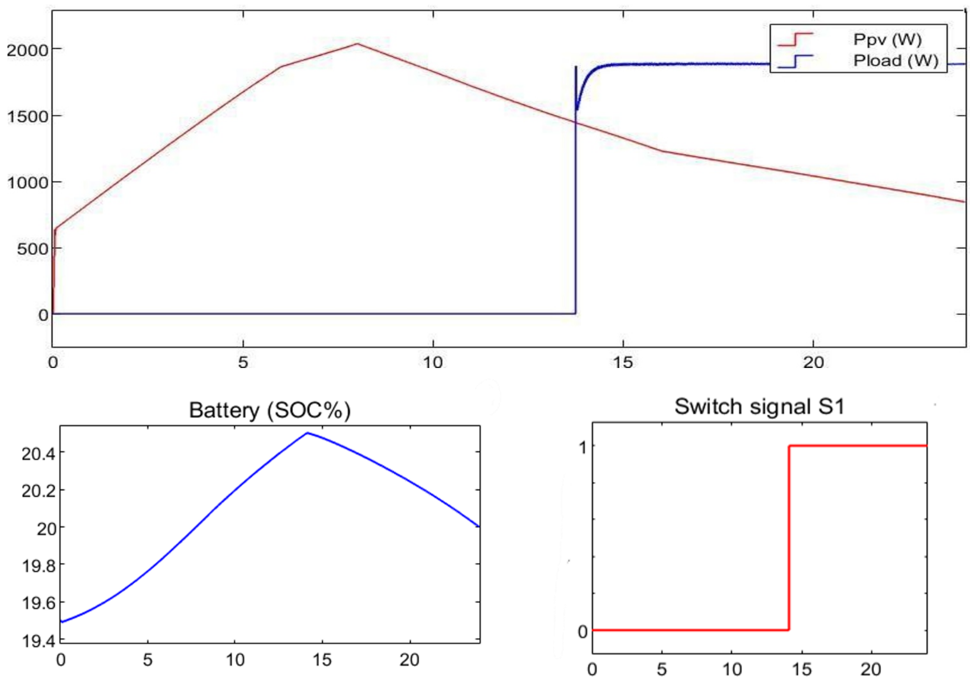

Fig. 8. Low initial SOC scenario simulation results

4 Conclusion

The simulation results across the two scenarios clearly validate the effectiveness of the proposed energy management strategy for the PV–battery micro-grid. In Scenario 1, the EMS successfully avoided battery overcharging by deliberately increasing the duty cycle to move the operating point away from the maximum power point, thereby limiting PV energy extraction once the SOC exceeded the upper threshold. Scenario 2 highlighted the EMS's capability to safeguard the battery under low SOC conditions by disconnecting the load, prioritizing SOC recovery until the 20.5% threshold was reached.
Overall, the results confirm that the EMS effectively combines maximum power point tracking with SOC driven decision-making to regulate power flows, preserve system stability, and extend battery lifetime. By coordinating duty cycle modulation and load switching, the system optimizes renewable energy utilization, ensures load supply when feasible, and enhances the reliability of the storage unit. Nonetheless, it should be noted that the current EMS does not guarantee an uninterrupted power supply to the load, as its primary objective is to prevent deep battery discharge rather than ensure continuous power

delivery. To overcome this limitation, the integration of a backup source, such as a diesel generator, would be required to support the micro-grid under critical conditions.

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