Battery management system using Jaya maximum power point tracking technique

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ABSTRACT

This paper introduces the development of a battery management system (BMS) utilizing the Jaya-based maximum power point tracking (MPPT) technique. Previous studies have combined various MPPT techniques with switching methods, each having its pros and cons. Traditional MPPT methods are common but have limited performance. Therefore, artificial intelligence (AI)-based approaches are introduced to enhance and reduce the limitations faced. The Jaya technique is straightforward and easy to implement, making it an attractive choice for MPPT in photovoltaic systems. It is recognized for its effectiveness in eliminating the worst solutions and identifying the best solution with only a few control parameters required for operation. The proposed work aims to develop a BMS using a DC-DC buck converter and the Jaya MPPT technique. The objective is to find the MPP to achieve the desired performance level and ensure the effectiveness of maintaining battery quality, preventing overcharging or undercharging. The system is modeled in MATLAB/Simulink. The findings indicate that the Jaya MPPT demonstrates a tracking speed of less than 1 second to locate the maximum power point (MPP). Furthermore, the BMS is capable of monitoring changes in state of charge (SoC) to determine whether the system is in charging or discharging mode.

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1. INTRODUCTION

The escalating global demand for energy, driven by population growth and increased utilization of electrical and electronic technology, has placed unprecedented pressure on the power sector to deliver sufficient electricity. This demand, coupled with the finite nature of conventional energy sources such as uranium, coal, kerosene, oil, and natural gas, necessitates a shift towards efficient and sustainable energy solutions [1]. Conventional energy sources, while historically abundant and cost-effective, present environmental challenges such as pollution, global warming, and adverse effects on human health. The combustion of fossil fuels releases substantial amounts of carbon dioxide (CO2), nitrogen oxide (NO2), and sulfur oxide (SO2), contributing to these environmental concerns [2]. In response to these challenges, researchers are increasingly turning to renewable energy sources, with solar energy gaining prominence due to its cleanliness, cost-effectiveness, abundance, and low carbon emissions [3]. However, integrating renewable energy, particularly solar power, into existing grids introduces complexities. The non-linear characteristics of photovoltaic (PV) systems, influenced by atmospheric conditions like solar irradiance and temperature variations, result in fluctuating output power [4]. To address this, DC-DC converters play a pivotal role in regulating and optimizing power transfer between PV arrays and loads or energy storage systems [5].

The inherent non-linear characteristics of PV systems, influenced by fluctuations in atmospheric conditions like solar irradiance and temperature, result in unpredictable variations in output power. These fluctuations pose challenges to the effective management of energy storage devices, particularly batteries, leading to regular operation at low state-of-charge (SoC), frequent partial cycling, and suboptimal recharging conditions [6], [7]. This, in turn, adversely impacts the longevity of batteries, posing a significant hurdle to the reliable performance of solar power systems [8]. Additionally, conventional MPPT techniques used in PV systems exhibit limitations, including slower convergence speed, higher steady-state oscillation, and lower efficiency when compared to emerging AI-based MPPT techniques [9], [10]. The inadequate adaptation of conventional techniques to changing weather conditions results in inaccurate tracking of the MPP, reducing overall PV system efficiency [11].

Conventional control techniques for MPPT, the perturbation and observation (P&O) method, widely employed for its simplicity is scrutinized for its inherent drawbacks such as sluggish tracking and oscillations around the MPP [12]. In contrast, the incremental conductance (IC) methodology is introduced, demonstrating superior accuracy and efficiency by utilizing instantaneous conductance to ascertain the MPP direction [13]. Additionally, the hill climbing (HC) approach, characterized by perturbing the duty cycle and deemed suitable for less dynamic applications, is critically examined, revealing challenges related to slow convergence and oscillations [14]. The subsequent section delves into AI control techniques, elucidating the applicability of fuzzy logic control (FLC) for addressing nonlinear variations and the efficacy of artificial neural networks (ANN) in achieving self-adaptation for efficient MPPT-based power harvesting [15], [16].

This paper addresses these challenges by focusing on the development and implementation of a battery management system utilizing the Jaya MPPT technique. The objectives include constructing a BMS integrated with a DC-DC buck converter for optimized charging processes and developing adaptive Jaya MPPT techniques to maximize PV module power output under diverse weather conditions. The significance of this research lies in its potential to enhance the efficiency of photovoltaic systems, especially in regions like Malaysia, where abundant sunlight presents an opportunity for robust solar energy harnessing. The project's scope encompasses modelling a battery, a DC-DC buck converter, and developing control algorithms to govern the charging process, ultimately contributing to optimized power generation, and improved energy utilization.

2. METHODOLOGY

2.1. Overview of the system

Figure 1 (see Appendix) depicts the flow of the standalone PV system design. The PV module optimizes its performance by using solar irradiation and cell temperature as inputs. The DC-DC buck converter takes the output voltage and current from the PV module as input, allowing for optimization of voltage or current levels to maintain peak performance in varying environmental conditions. The Jaya MPPT achieves this optimization by analyzing current and voltage measurements to determine the PV module MPP output. Using this information, the Jaya MPPT calculates adjustments to the circuit, specifically modifying the duty cycle that governs the DC-DC buck converter's operation. This modification in the duty cycle leads to changes in the output voltage based on prevailing conditions. Ultimately, the generated energy is stored in a Battery, providing power during periods without sunlight or unexpected power outages. A BMS controls the charging and discharging operations to ensure the battery's lifespan. The simulation of this PV system is conducted using MATLAB/Simulink.

2.2. Overall system design

Figure 2 outlines the structure of the PV system created with MATLAB/Simulink. It comprises a PV array, a DC-DC buck converter with MPPT governing the duty cycle, and a gate for the MOSFET in the converter. The DC-DC buck converter is linked to a battery management system, which is integrated to oversee the charging and discharging of the battery.

2.3. PV module

For this study, Malaysian solar resources MYS-60P/B3/CF-235 solar PV module has been chosen as the power source. Table 1 shows the PV module specifications including the electrical characteristics. The PV array is configured with one series-connected module per string and one parallel string.

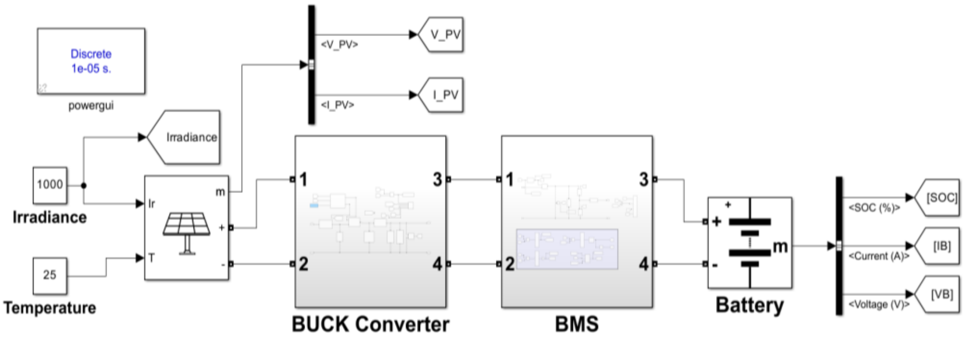


Figure 2. Overall simulation system using MATLAB/Simulink

Table 1. Specification of PV module

Parameter	Value
Maximum power (P_{max})	235 W
Voltage at max power (V_{mpp})	30.6 V
Current at max power (I_{mpp})	7.68 A
Open circuit voltage (V_{oc})	37.02 V
Short circuit current (I_{sc})	8.22 A
Total number of cells per module (N_{cell})	60
Number of parallel string (N_P)	1
Number of PV module in series per string (N_S)	1

2.4. DC-DC boost converter

To optimize the PV system's operation at its MPP, a power electronic interface is indispensable between the PV module and the load, allowing for the control of circuit parameters. In PV systems, DC-DC buck converters, commonly known as step-down converters, play a pivotal role [17], [18]. These converters, serving as power electronic devices, are designed to decrease voltage from the input side to the load output while simultaneously increasing the current. DC-DC buck converters enable the regulation of both the output voltage and the current drawn from the source, thereby controlling the input impedance of the converter through duty cycle adjustment [19], [20]. Duty cycle control is achieved using the pulse width modulation (PWM) technique, and the specific value of the duty cycle can be determined using any MPPT algorithm.

Figure 3 shows the buck converter circuit in MATLAB/Simulink. The fundamental operation of a buck converter revolves around the rapid switching of an electronic component, such as a MOSFET, between an 'on' and 'off' state to regulate the amount of energy delivered to the load. This switching process is governed by PWM, wherein the duration of the 'on' time of the switch determines the average power supplied to the load. A longer 'on' time results in a higher average output voltage. In the 'on' phase, energy is stored in an inductor and subsequently transferred to the load. When the switch is 'off,' the energy stored in the inductor is released to the load, ensuring a continuous power flow. Diodes within the circuit prevent the backflow of current, guaranteeing that energy moves solely from the source to the load. Capacitors are also integrated to smooth out the output voltage and reduce voltage ripples [21].

2.5. Implementation of Jaya MPPT technique

The Jaya algorithm, proposed by Rao [22], stands out as a simple and effective population-based technique. Noteworthy for its parameter simplicity, the algorithm relies on just two parameters which is iterations and population size [23]. Its fundamental approach involves iteratively converging toward the optimal solution, designated as the best solution, while actively avoiding the worst solution [23], [24]. The objective function for MPPT endeavors to maximize power output from the PV module, as defined in (1). In this context, the particle solutions are characterized by the duty cycle Di.

$$P(D_{i,j}^{k+1}) > P(D_i^k) \quad (1)$$

Where, P(D) represents the instantaneous power at duty cycle Di, as defined by (2). The power of each duty cycle, calculated using this formula, serves as a basis for comparing duty cycles with those from the previous iteration.

$$D'_{i,j} = D_{i,j} + r1(D_{i,best} - |Di,j|) - r2(D_{i,worst} - |D_{i,j}|) \quad (2)$$

$$P = VI \quad (3)$$

Where, D_i^k and D_i^{k+1} represent the current and updated values of the particle position (Duty), respectively. Di, worst, and Di, best indicate the worst and best positions of the particles. The variables r1 and r2 are uniformly distributed random numbers. The term ri,1 (Di, best − |Di,j |) s utilized to guide the candidate solution towards the best solution, while the term −ri,2 (Di, worst − |Di,j |) is intended to aid a candidate solution in moving away from the worst solution [25].

Figure 4 illustrates the Jaya MPPT technique flowchart. The process initiates with the system using initial duty cycle values as a reference to identify the best and worst duty cycles. Each power corresponding to the initial duty cycle is calculated using (3) and stored for future reference in determining the best and worst solutions. After selecting the best and worst duty cycles based on power comparison, the system proceeds to the Jaya algorithm to compute the new duty cycle. The modified duty cycle is stored, and its corresponding power is calculated and stored. Following the modification of all initial duty cycles using (2), the powers of the modified duty cycle are compared with those of the initial duty cycle or the previous iteration. The three highest powers are then chosen as the new initial duty cycle, replacing the old values. From this new initial duty cycle, the best and worst solutions are reselected, marking the completion of the first iteration. The system iteratively updates the duty cycle until all power values are equal, indicating convergence.

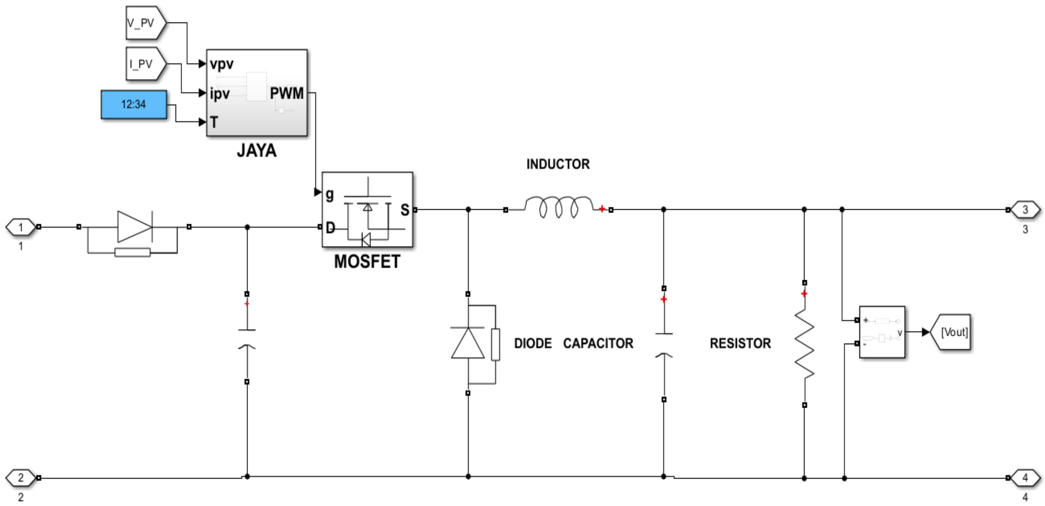


Figure 3. Buck converter circuit in MATLAB/Simulink

2.5.1. Jaya MPPT optimization process

In this study, the Jaya algorithm is utilized to identify the maximum input power until the MPP is attained. The underlying principle of this algorithm is grounded in the notion that the solution derived for a specific problem should progress toward the best solution while steering clear of the worst solution [22]. Considering a population size of 3, representing candidate solutions, and two design variables duty cycle and input power—the initial duty cycle population is established within the range of 0.1 to 0.95. The associated objective function values are presented in Table 2. As the objective is a maximization function, the highest input power is identified as the optimal or best solution, while the lowest value is deemed the worst solution.

From Table 2, the best solution aligns to the 2nd candidate and the worst solution corresponds to the 1st candidate. The new values of the duty cycle are calculated using (2) and will be compared with variables in Table 1. If the input power from the PV is greater than the previous value, the new duty cycle values will replace the existing ones. Table 2 shows the new values of the duty cycle and the corresponding values of the objective function. From Table 2, it is evident that the best solution corresponds to the 2nd candidate, while the worst solution aligns with the 1st candidate. Utilizing (2), new duty cycle values are calculated and compared with the variables in Table 1. If the input power from the PV system surpasses the previous value, the new duty cycle values replace the existing ones. Table 2 presents these updated duty cycle values along with their corresponding objective function values. The values of input power of Tables 2 and 3 are compared and the best and worst values of power are considered placed in Table 4. This completes the first iteration of the Jaya algorithm.

Table 3 presents the updated values of variables and the objective function after the first iteration's completion. The best solution is associated with the 2nd candidate, while the worst solution corresponds to the 1st candidate. This overview outlines the functioning of the Jaya algorithm in pursuing the MPP. The system continuously monitors power values until reaching and stabilizing at the MPP. The system successfully identifies the MPP when all power values among the three candidates are equal.

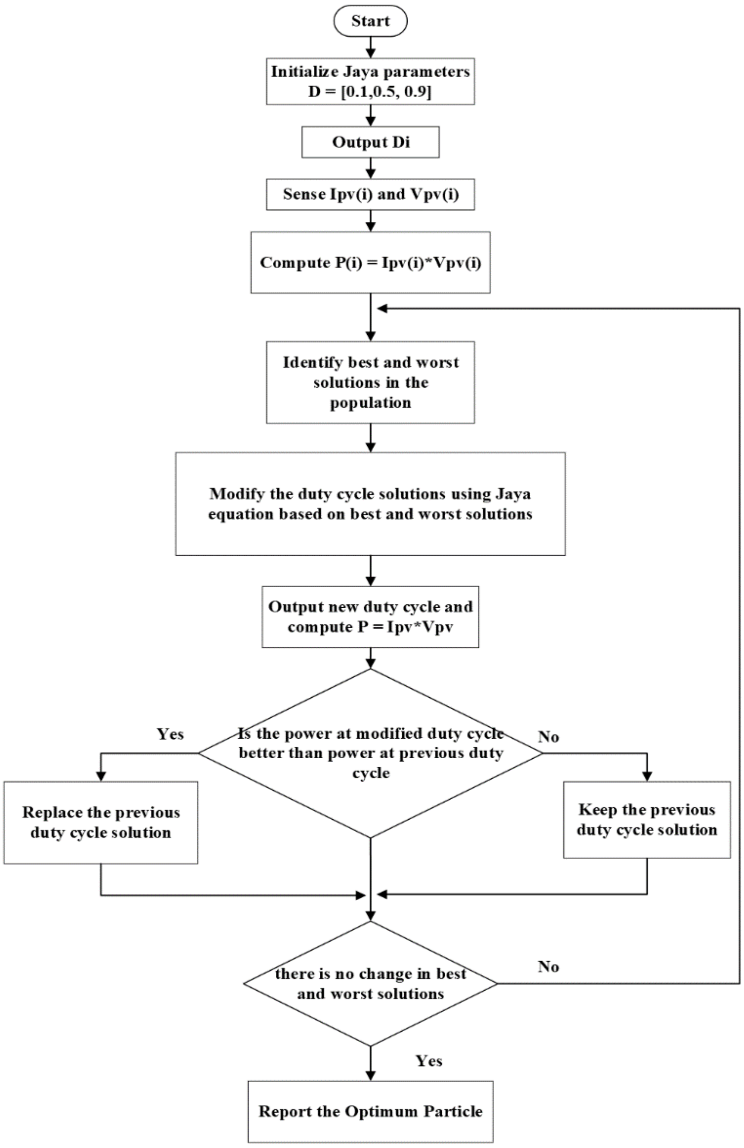


Figure 4. Flowchart of Jaya MPPT

Table 2. Initial population

Candidate	Duty cycle	Input power	Status
1	0.1	1.252	Worst
2	0.5	227.8	Best
3	0.9	128.7	-

Table 3. New values of the duty cycle

Candidate	Duty cycle	Input power
1	0.4259	227.7
2	0.5677	197
3	0.7361	157.7

Table 4. Updated values of the duty cycle

Candidate	Duty cycle	Input power	Status
1	0.4259	227.7	-
2	0.5	227.8	Best
3	0.7361	157.7	Worst

2.6. Battery management system (BMS)

The primary goal of a BMS is to optimize battery energy utilization, mitigating the risk of degradation. This involves careful oversight of charging and discharging to prevent overcharging and extend battery life. The BMS monitors discharge, halting when the battery is depleted to prevent damage. Constant assessment of the battery's SoC allows the BMS to adjust charging and discharging, ensuring proper handling, and protecting against misuse. Figure 5 illustrates the BMS circuit in MATLAB/Simulink. The system operates in two modes: charge and discharge. Currently, the battery's SoC is at 80%.

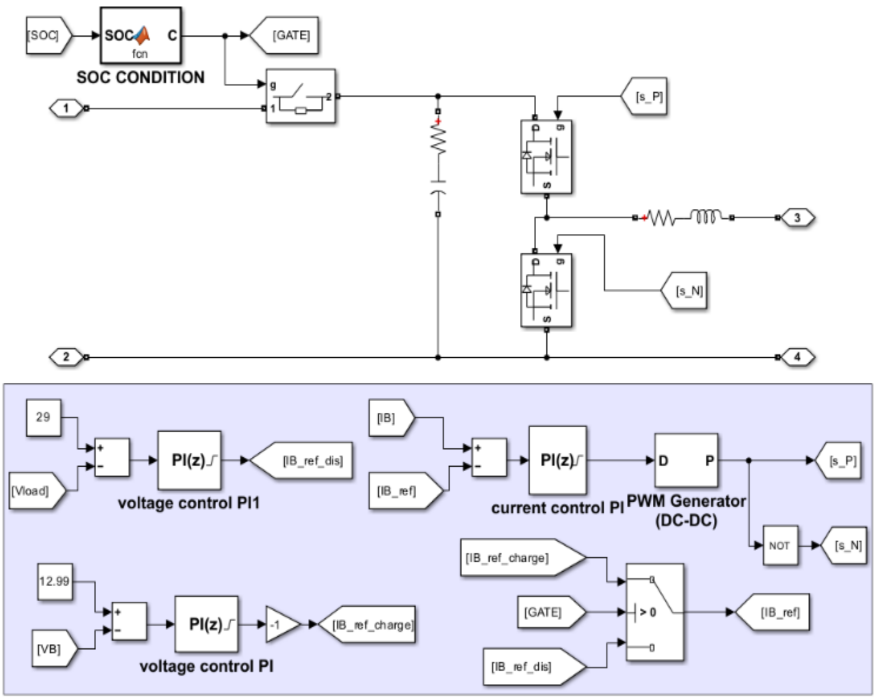


Figure 5. Battery controller circuit in MATLAB/Simulink

3. RESULTS AND DISCUSSION

The proposed BMS employs the Jaya MPPT algorithm, simulated using MATLAB/Simulink. The term steady state refers to the MPPT algorithm's performance under constant conditions of solar irradiance and temperature. In this setup, the PV module consists of a single module that generates an output of 235 W under a consistent irradiance of 1000 W/m² and a cell temperature of 25 °C, as depicted in Figure 6. The DC input voltage from the PV module is reduced through a buck converter, adapting it to a 14V battery voltage level. The Jaya MPPT effectively tracks the MPP of 235 W, achieving this in less than 1 second which is 0.45 s as shown in Figure 6. Overall, the results presented in this section affirm the Jaya algorithm's efficiency, characterized by its rapid response time and stability during steady-state operations.

Figure 7 demonstrates the simulation of the PV system under varying irradiance conditions, mirroring the fluctuating solar intensity typical of Malaysia's climate. In these simulations, the solar irradiance levels are altered between 1000, 800, 600, and 200 W/m², while maintaining a constant temperature of 25 °C. The Jaya algorithm is shown to successfully track the MPP for each change in solar irradiance. The irradiance levels in the simulation shift from 1000 to 800, back to 1000, then to 600, and finally 200 W/m² at a consistent temperature of 25 °C, as depicted in Figure 7. These simulations were conducted to evaluate the Jaya algorithm's response time in tracking the MPP, which was consistently less than 1 second under these conditions.

Figure 8 illustrates the state where the battery's SoC is at 80% and it is in discharging mode, leading to a decrease in SoC. This scenario suggests that the battery is actively discharging its stored energy. Throughout this discharging stage, the battery maintains a constant current, while the voltage gradually diminishes as the energy level decreases. This phase is essential for understanding the discharge behavior of the battery, particularly how the voltage and current interact with the diminishing SoC.

Figure 9 demonstrates that an increasing SoC indicates the battery is in charging mode. The system initiates the charging mode when the SoC is below 20%. Throughout this process, the battery voltage rises, while the current remains constant and negative, indicating a continuous inflow of charge to the battery.

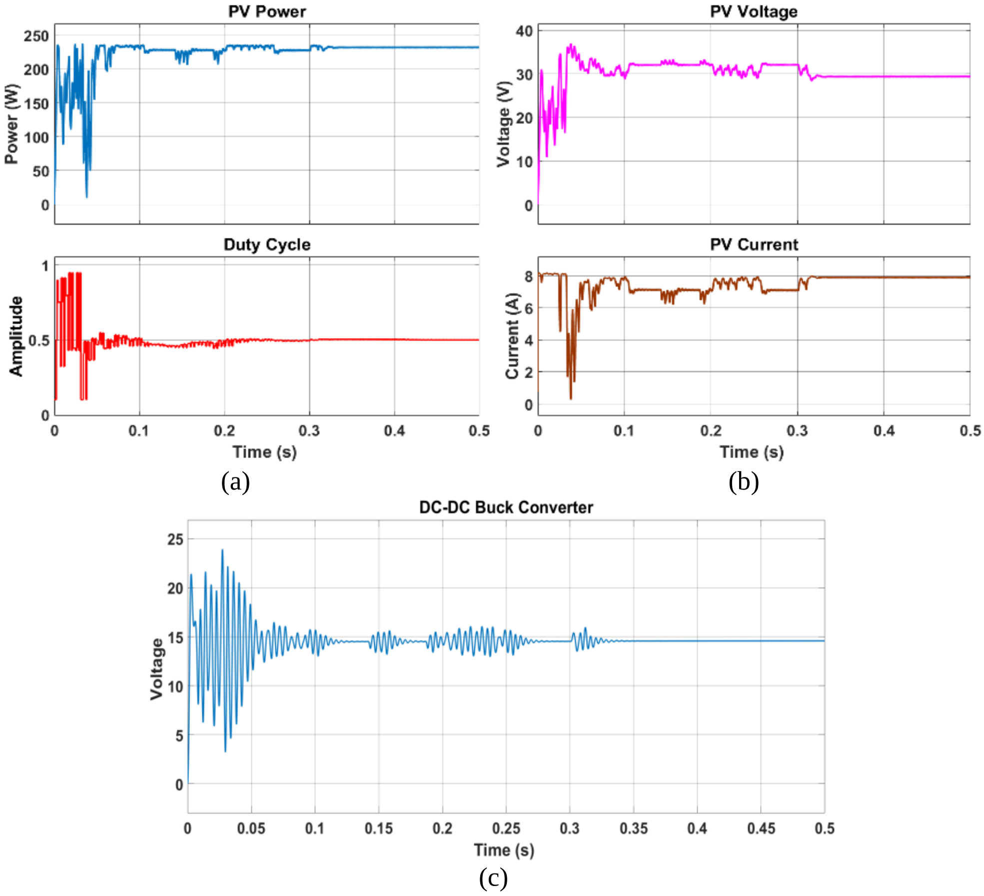


Figure 6. Output waveform of (a) power of PV & duty cycle, (b) voltage & current of PV module, and (c) DC-DC buck converter voltage during the fixed condition

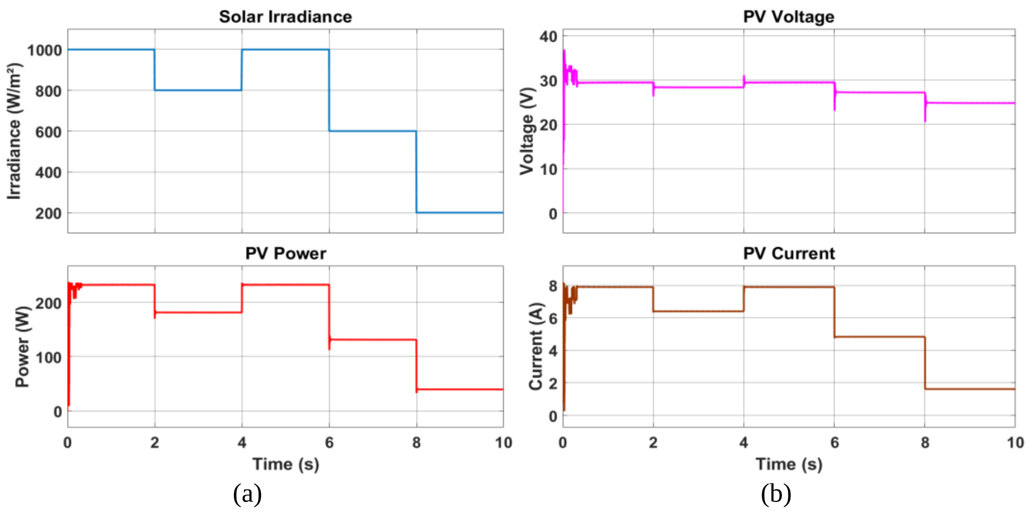
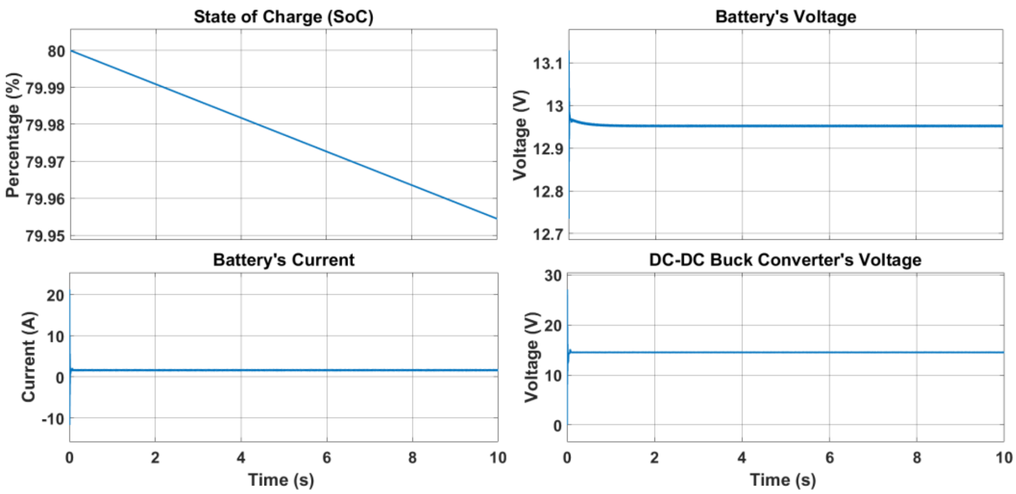
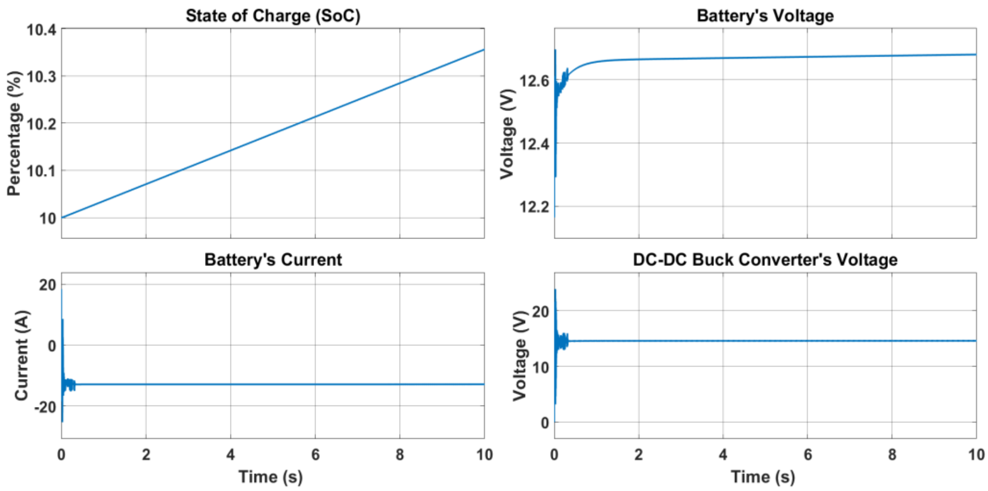


Figure 7. Output waveforms of (a) irradiance and power of PV and (b) voltage and current of PV during variations in irradiance conditions



(a) (b)

Figure 8. The output waveform of (a) SOC, battery's current, and (b) battery's voltage, DC-DC buck converter voltage during the discharging process



(a) (b)

Figure 9. Output waveform of (a) SOC & battery's current, and (b) battery's voltage & DC-DC buck converter voltage during the charging process

4. CONCLUSION

The proposed Jaya MPPT system combined with a BMS for PV applications has been identified as a simple and efficient solution for tracking MPP and energy conversion. This system employs a buck converter to reduce the output DC voltage from a PV module. To boost energy conversion efficiency, an advanced control technique utilizing the Jaya algorithm has been integrated into the MPPT controller in this study. The MPPT control algorithm optimizes the operation of the PV module at its MPP ensuring the maximum energy produced is stored in the battery connected across the output terminal of the buck converter. The advantages of this proposed method include reduced system complexity, a more compact size, and enhanced efficiency. Simulation results show that the Jaya MPPT system achieves superior maximum power point tracking and demonstrates a quicker convergence speed. In conclusion, for future advancements, it is recommended to increase the number of variables for the duty cycle, which could further improve the accuracy of the Jaya algorithm in MPPT systems.

APPENDIX

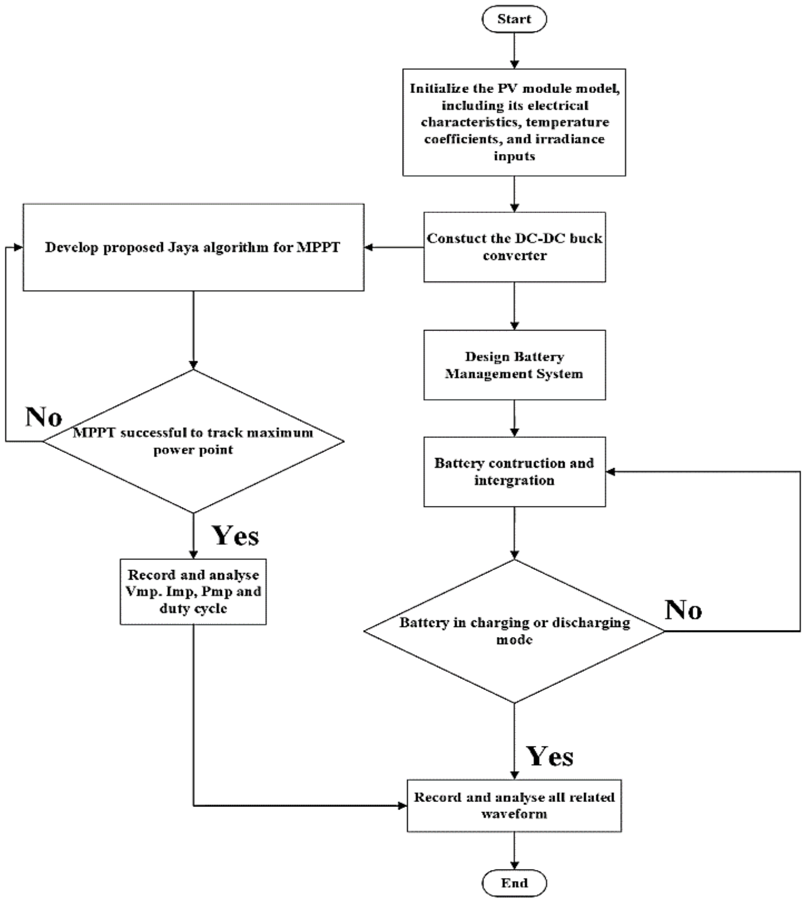


Figure 1. Overview of the system

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