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Design and Performance Analysis of a Dual-Battery Solar PV Laptop Charging System Using MATLAB/Simulink

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Abstract

The growing demand for portable and sustainable energy solutions has increased the need for efficient off-grid solar photovoltaic (PV) systems. This study presents the design and performance analysis of a standalone solar-powered laptop charging system based on a dual-battery architecture and a relay-controlled switching mechanism. The proposed system employs two 12 V, 7 Ah batteries connected in parallel during charging and in series during discharging to provide the required 19–21 V DC output without the need for complex MPPT controllers. A MATLAB/Simulink model was developed to evaluate system performance under varying irradiance and temperature conditions. The results demonstrate stable output voltage with fluctuations below 3% and an overall efficiency of approximately 85% at 1000 W/m², while maintaining about 65% efficiency at 200 W/m². The findings confirm that the proposed relay-controlled dual-battery configuration offers a simple, cost-effective, and reliable solution for portable and off-grid renewable energy applications.

Keywords: Solar photovoltaic systems; Battery energy storage; MATLAB/Simulink; Renewable energy; Laptop charging; Off-grid applications

1. Introduction

The rapid growth in global energy demand, driven by population expansion and increased reliance on electronic devices, has intensified the need for sustainable and renewable energy solutions [1–3]. Among the available alternatives, solar photovoltaic (PV) technology has emerged as one of the most promising sources due to its abundance, environmental friendliness, and adaptability for portable applications [4–7]. In particular, the use of solar energy for powering mobile electronics, such as laptops, offers significant advantages in off-grid and remote environments [8,12,13].

Solar PV systems convert sunlight directly into electrical energy using semiconductor materials, typically silicon-based cells. However, the output of these systems is inherently unstable due to fluctuations in solar irradiance and temperature [10–13], which poses a challenge when powering sensitive electronic devices that require a stable DC voltage. To address this issue, several researchers have proposed advanced power conditioning techniques. Ramesh and Vanitha (2018)[14] investigated the integration of Maximum Power Point Tracking (MPPT) algorithms with DC–DC converters to ensure stable voltage output, particularly for applications such as laptop charging. Similarly, Chilumba and Mushi (2022) [15] developed a solar-powered adapter based on a SEPIC converter topology, enabling flexible regulation across a wide range of input voltages.

In addition to power regulation strategies, extensive research has been directed toward improving overall PV system efficiency and performance. Tan et al. (2020) [16] explored perovskite tandem solar cells, which are capable of achieving significantly higher conversion efficiencies compared to conventional photovoltaic technologies. Rehman et al. (2024) [17] proposed an IoT-based smart energy management system for real-time monitoring and optimization of portable solar devices, enhancing operational efficiency and user adaptability. Furthermore, Emmanuel et al. (2024) [18] investigated hybrid energy storage systems combining supercapacitors and batteries, aiming to improve charging performance, system reliability, and energy buffering under fluctuating solar conditions. Overall, these studies demonstrate a clear progression from conventional power regulation techniques toward more integrated and intelligent PV systems that combine advanced conversion, monitoring, and energy storage solutions.

Despite these advancements, many existing solutions rely on complex control algorithms, sophisticated electronics, or high-cost components, which limit their practicality for low-cost and portable applications. Therefore, there remains a need for a simpler and more cost-effective approach that can ensure reliable voltage regulation and efficient energy management under varying environmental conditions [18 – 22].

Although MPPT-based and DC–DC converter-based solar charging systems achieve high efficiencies, they generally require sophisticated controllers, increased hardware complexity, and higher implementation costs as shown in Table 1. Therefore, there is a need for a simpler and lower-cost alternative capable of providing reliable voltage regulation and battery management for standalone laptop charging applications. This study addresses this gap through a relay-based dual-battery architecture that eliminates the need for complex digital control systems.

Table 1: Comparison of previously reported laptop charging systems [14,15].

Study	Efficiency (%)	Output Voltage	Controller Type	Cost Level	Complexity
Ramesh & Vanitha (2018)	85–90	Stable	MPPT	High	High
Chilumba & Mushi (2022)	~84	Stable	SEPIC Converter	Medium	Medium
Proposed System	80–85	19–21 V	Relay Switching	Low	Low

In this context, this paper presents the design and simulation of a solar-powered laptop charging system based on a dual-battery configuration and a relay-based switching mechanism. The proposed system operates in two distinct modes: a parallel configuration for efficient battery charging and a series configuration for delivering the required voltage to the laptop. A voltage regulation stage is incorporated to stabilize the output and protect the device from fluctuations. The system is modeled and analyzed using MATLAB/Simulink to evaluate its performance under varying operating conditions. The results demonstrate that the proposed approach provides a reliable, low-cost, and effective solution for portable solar charging applications, particularly in off-grid environments.

2. System Design and Methodology

2.1 Overview of the Proposed System

The proposed system is a standalone solar-powered laptop charging unit designed to ensure stable and reliable energy delivery under varying environmental conditions. It consists of a photovoltaic (PV) array, a dual-battery storage system, a relay-based switching mechanism, and a voltage regulation stage. The overall objective is to maintain a consistent DC output suitable for laptop charging while efficiently managing energy generation and storage.

The system operates in two primary modes: charging mode and discharging mode, depending on the availability of solar energy and load requirements. A control mechanism based on electromechanical relays is employed to switch between different battery configurations, ensuring optimal performance without the need for complex digital controllers.

2.2 Photovoltaic (PV) System Modeling

2.2.1 Mathematical Modeling of the Photovoltaic Module

The electrical behavior of the photovoltaic (PV) module was represented using the well-established single-diode equivalent circuit model, which accurately describes the current-voltage characteristics of silicon solar cells under varying environmental conditions. The model consists of a photocurrent source connected in parallel with a diode and a shunt resistance, while a series resistance accounts for internal electrical losses. The output current of the PV cell is expressed as [23,24] :

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V+IR_s)}{nkT} \right) - 1 \right] - \frac{V+IR_s}{R_{sh}}$$

where I is the output current (A), I_{ph} is the photocurrent generated by solar irradiance (A), I_0 is the diode reverse saturation current (A), q is the electron charge (1.602×10^{-19} C), V is the output voltage (V), R_s is the series resistance (Ω), R_{sh} is the shunt resistance (Ω), n is the diode ideality factor, k is Boltzmann's constant (1.381×10^{-23} J/K), and T is the cell temperature (K) .

The photocurrent generated by the PV cell is directly proportional to solar irradiance and can be estimated by [23,24] :

$$I_{ph} = \left[I_{sc} + K_i(T - T_{ref}) \right] \frac{G}{G_{ref}}$$

where I_{sc} is the short-circuit current at standard test conditions (A), K_I is the temperature coefficient of the short-circuit current (A/K), G is the incident solar irradiance (W/m²), G_{ref} is the reference irradiance under standard test conditions (1000 W/m²), and T_{ref} is the reference temperature (25°C) [23,24] .

The electrical output power generated by the PV module is calculated as [25,26]:

$$P_{PV} = VI$$

where P_{PV} represents the instantaneous electrical power output of the PV module (W).

The conversion efficiency of the photovoltaic module is determined from the ratio of electrical output power to the incident solar power over the active panel area [25,26] :

$$\eta_{PV} = \frac{P_{PV}}{GA} \times 100$$

where η_{PV} is the PV efficiency (%), A is the effective surface area of the solar panel (m^2), and G is the solar irradiance (W/m^2). These equations were incorporated into the MATLAB/Simulink model to evaluate the influence of irradiance and temperature variations on the electrical performance of the proposed solar charging system.

2.2.1 Simulation Modeling of the Photovoltaic Module

The PV module is modeled using MATLAB/Simulink to simulate its electrical behavior under varying environmental conditions. The simulation model, shown in Fig.1, represents the PV system with load variation and allows performance evaluation under different operating scenarios.

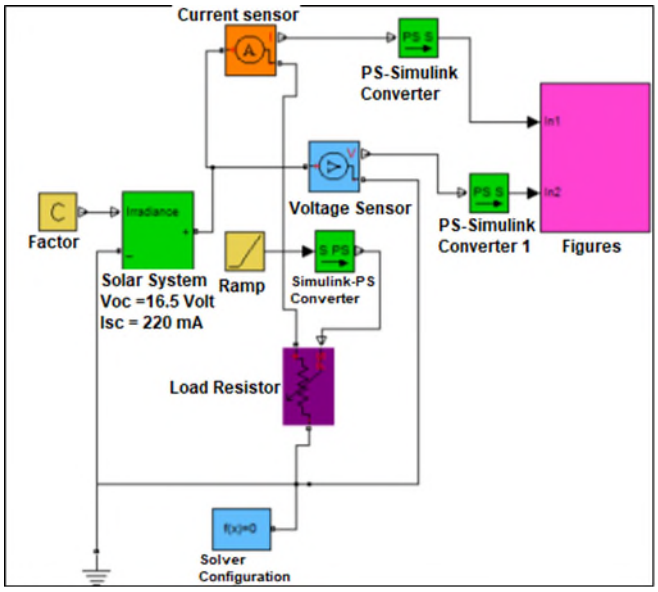


Fig. 1: MATLAB/Simulink block diagram of the solar PV module integrated with a variable resistive load for electrical characterization.

The PV array consists of multiple solar cells connected in series and parallel, as illustrated in Fig. 2, to achieve the required output of approximately 16.5 V and 220 mA. The model incorporates variations in solar irradiance and temperature to analyze system performance. A variable resistive load is used to obtain the current–voltage (I–V) and power–voltage (P–V) characteristics of the PV module and determine key performance indicators such as open-circuit voltage, short-circuit current, and maximum power point.

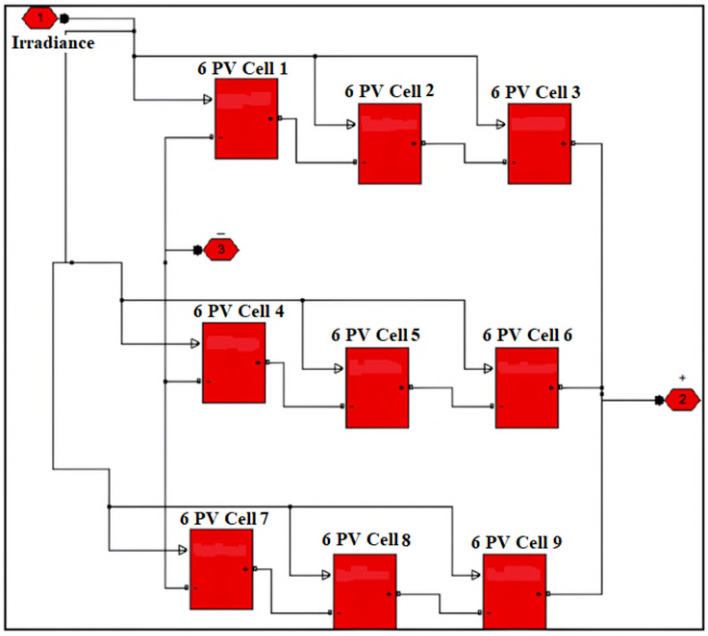


Fig. 2: Internal series-parallel architecture of the PV array designed to meet the specific voltage and current requirements for the charging system.

2.3 Battery Storage Configuration

The energy storage system consists of two **12 V, 7 Ah batteries**, modelled in the simulation environment using equivalent electrical circuits. Each battery is represented as a series combination of individual cells to replicate realistic behavior, including voltage variation during charging and discharging cycles, as shown in Fig.3.

The dual-battery configuration plays a central role in the proposed design. It allows flexible operation by switching between different connection modes depending on system requirements. This approach enhances both energy storage efficiency and output voltage adaptability.

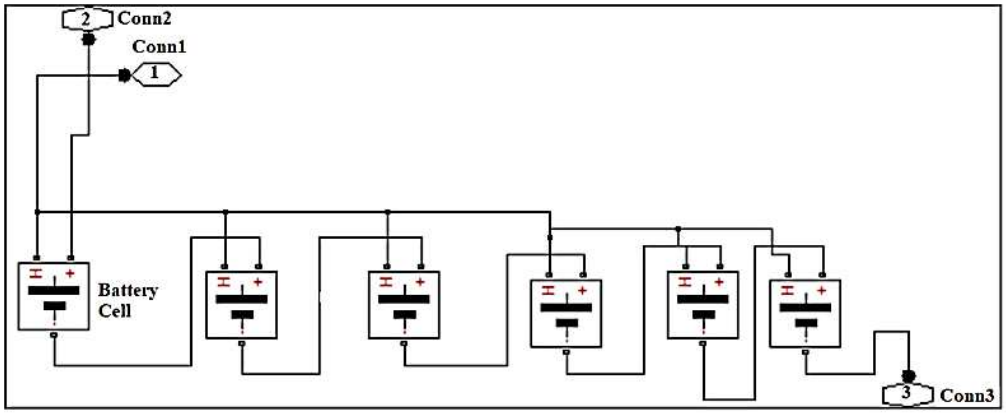


Fig. 3. Equivalent circuit model of the dual 12V/7Ah lead-acid battery cells used to simulate charging and discharging dynamics.

2.3.1 Battery Mathematical Model

The dual 12 V, 7 Ah batteries were modeled using a simplified State of Charge (SOC) approach to represent their charging and discharging behavior. The SOC indicates the available battery capacity relative to its nominal capacity and is calculated as [29,30] :

$$SOC(t) = SOC_0 + \frac{1}{C_n}\int_0^t I_b(\tau)d\tau$$

where SOC is the initial state of charge, C_n is the nominal battery capacity (Ah), and I_b is the battery current (A).

The battery terminal voltage during charging and discharging can be expressed as [29,30] :

$$V_b = E \pm I_b R_b$$

where V_b is the battery voltage (V), E is the open-circuit voltage (V), and R_b is the internal resistance (Ω). The positive sign corresponds to charging, while the negative sign represents discharging.

The battery efficiency is determined from the ratio of useful output energy to input energy [30]:

$$\eta_{bat} = \frac{E_{out}}{E_{in}} \times 100$$

where E_{out} is the energy delivered to the load and E_{in} is the energy supplied during charging. This model was implemented in MATLAB/Simulink to evaluate the dynamic performance of the dual-battery system under different operating conditions.

2.4 Relay-Based Switching Mechanism

A key contribution to this work is the implementation of a relay-based switching mechanism as shown in Fig.4 to control the configuration of the battery system. Unlike conventional systems that rely on microcontrollers or advanced algorithms, this design uses electromechanical relays to achieve reliable and low-cost switching.

In charging mode, the batteries are connected in parallel, allowing them to be charged simultaneously from the PV module while maintaining safe voltage levels. In discharging mode, the relay switches the configuration to series, enabling the combined battery voltage to meet the laptop's required input voltage.

This switching process is controlled through a simple signal mechanism that activates the relay coils, altering the contact positions and reconfiguring the circuit accordingly. The simplicity of this design reduces system complexity and improves reliability.

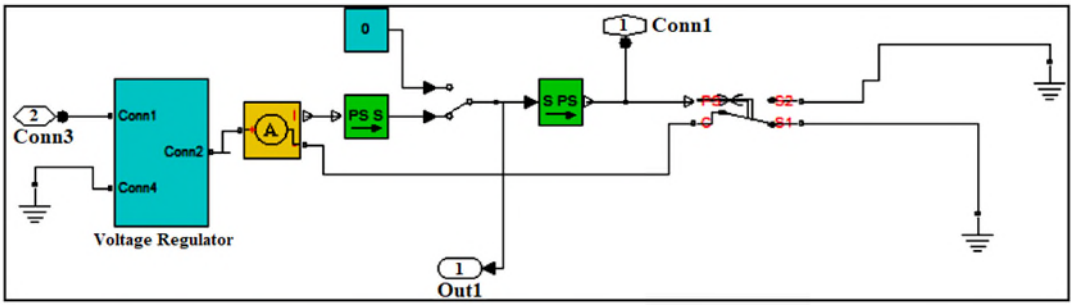


Fig. 4. Simulation model of the primary voltage regulation stage and relay-based switching logic managing the parallel and series configuration.

2.5 Voltage Regulation and Protection

The voltage regulation stage is essential to ensure safe operation of both the batteries and the laptop. The Voltage regulator for laptop output is illustrated in Fig. 5. The regulator uses Zener diodes and resistive elements to Stabilize voltage levels, prevent overcharging, Ensure steady DC output, and protect against reverse current flow. This stage ensures that the system can handle fluctuations in solar input while maintaining safe operating conditions.

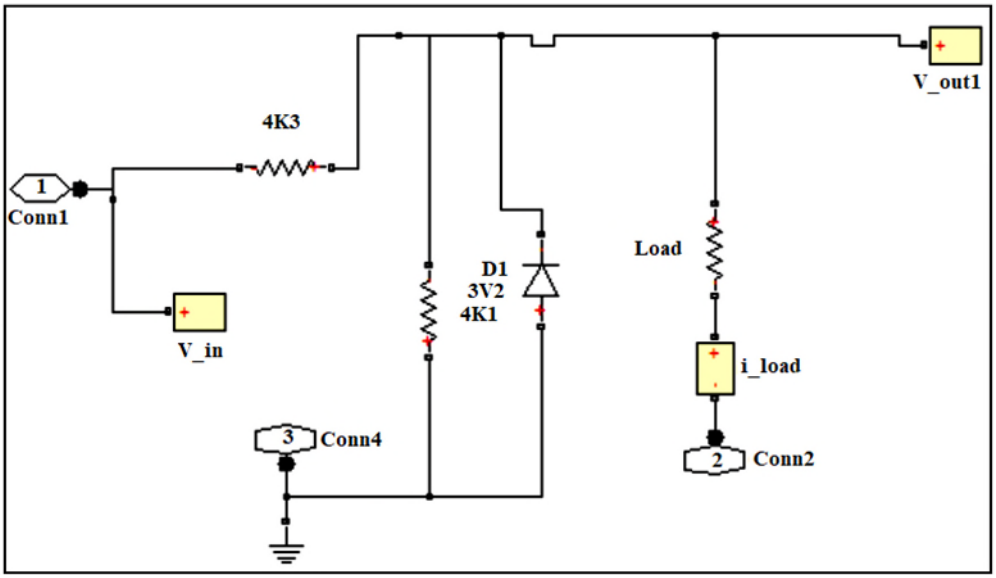


Fig. 5. Detailed circuit schematic of the secondary Zener diode-based voltage regulator used to ensure a stabilized DC output for the laptop load

2.6 System Efficiency Analysis:

To evaluate the energy conversion performance of the proposed charging system, the overall system efficiency was estimated by considering the efficiencies of the main subsystems, namely the photovoltaic module, the battery storage unit, and the voltage regulation stage. The overall efficiency ($\boldsymbol{\eta}$overall) can be expressed as the product of the individual subsystem efficiencies [27,28] :

$$\eta_{overall} = \eta_{PV} \times \eta_{bat} \times \eta_{reg}$$

where η_{PV} is the photovoltaic conversion efficiency, η_{bat} is the battery charging/discharging efficiency, and η_{reg} is the efficiency of the voltage regulation circuit. This relationship provides a theoretical framework for evaluating the cumulative effect of energy losses throughout the power conversion chain. The simulation results indicate that the combined performance of these subsystems enables the proposed charging system to achieve an overall efficiency of approximately 80–85% under standard operating conditions, demonstrating the effectiveness of the dual-battery configuration and relay-based energy management strategy.

2.7 Simulation Setup

The proposed solar-powered laptop charging system was implemented and analyzed using MATLAB/Simulink. The complete model integrates the photovoltaic (PV) array, dual-battery storage system, relay-based switching mechanism, and voltage regulation circuitry. Simulations were performed under varying environmental conditions to evaluate system performance during both charging and discharging modes.

Solar irradiance was varied from 200 W/m² to 1000 W/m² to assess the influence of solar availability on power generation and overall system efficiency. In addition, the operating temperature was varied between 15°C and 45°C to investigate its effect on PV voltage characteristics and system stability. The simulation duration was set to 1500 s, allowing the transient and steady-state behavior of the system to be monitored. The main simulation parameters used throughout this study are summarized in Table X.

The selected simulation conditions were chosen to represent realistic operating scenarios for portable off-grid charging applications as shown in table 2. System performance was evaluated in terms of output voltage stability, charging and discharging characteristics, thermal behavior, and overall energy conversion efficiency.

Table 2: PV and battery parameters were selected according to standard photovoltaic and battery engineering references [25,26,30].

Parameter	Value
Solar Irradiance	200–1000 W/m²
Ambient Temperature	15–45°C
Simulation Time	1500 s
Solver Type	ode45 (Dormand–Prince)
Battery Capacity	7 Ah
Battery Nominal Voltage	12 V
Number of Batteries	2
Battery Configuration	Parallel charging / Series discharging
PV Module Rated Power	35 W
Laptop Operating Voltage	19–21 V
Load Type	Resistive DC Load

3. Results And Discussion

3.1 PV Module Characteristics

The electrical performance of the photovoltaic (PV) module was evaluated using a variable resistive load to extract the I–V and P–V characteristics. The results demonstrate that the PV model accurately captures the nonlinear behavior of solar cells under varying operating conditions.

Fig. 6 illustrates the I–V characteristics of the PV module. It is observed that the current initially reaches the short-circuit value of approximately 3.8 A at zero voltage and gradually decreases as the voltage increases. The voltage eventually stabilizes at the open-circuit value of approximately 0.55 V per cell. This behavior is consistent with the expected diode characteristics of silicon-based PV cells.

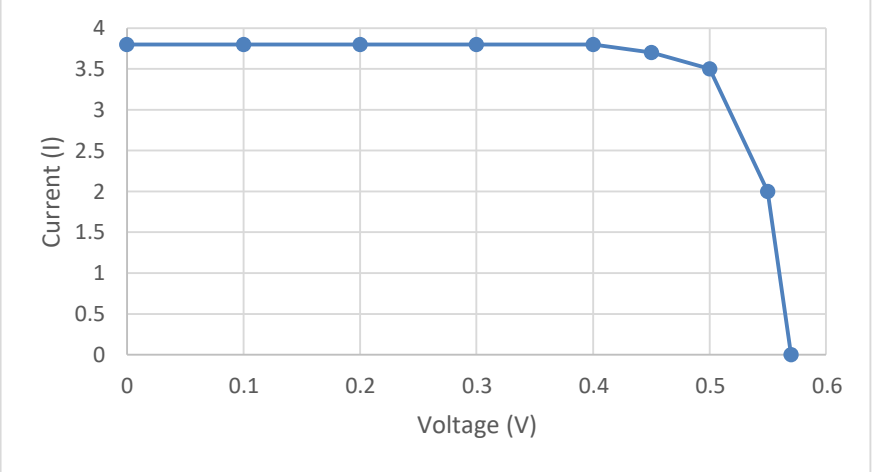


Fig.6. Simulated Current-Voltage (I-V) characteristic curve of the PV module, highlighting the short-circuit current and open-circuit voltage.

Fig.7 presents the corresponding power output profile of single PV cell under varying load conditions. The power increases with voltage until it reaches a peak value, after which it declines due to reduced current. This confirms the presence of a maximum power point (MPP), which represents the optimal operating condition of the PV module.

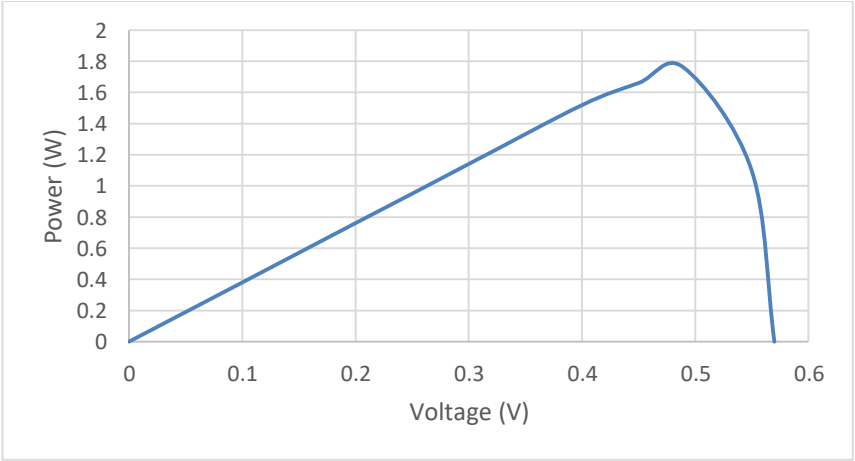


Fig.7. Output power waveform of a single PV cell during the simulation period.

Fig. 8 shows the P–V characteristics of the PV module. The maximum power point is observed at approximately 0.45 V and 3.2 A, corresponding to a peak power of about 1.44 W per cell. This result validates the effectiveness of the simulation model in identifying optimal power extraction conditions.

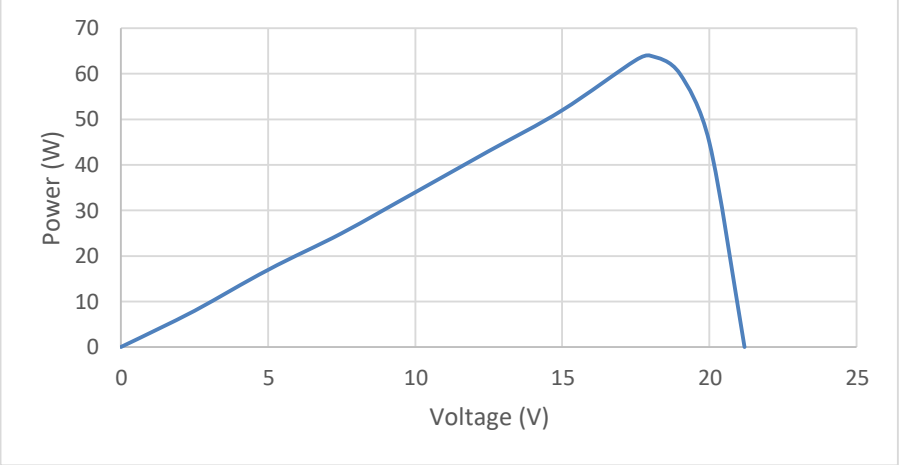


Fig. 8. Power-Voltage (P-V) characteristics of the PV module illustrating the Maximum Power Point (MPP) under nominal conditions.

3.2 Effect of Irradiance and Temperature on PV performance

The influence of environmental conditions on PV performance was analyzed by varying solar irradiance and temperature levels. The results indicate that irradiance has a direct impact on current generation, while temperature primarily affects voltage.

From the simulation results, it is observed that increasing irradiance from 200 W/m² to 1000 W/m² leads to a proportional increase in output current, while the voltage remains relatively stable as shown in Fig. 9. Conversely, an increase in temperature results in a noticeable reduction in output voltage, which consequently reduces the overall power output as shown in Fig. 10.

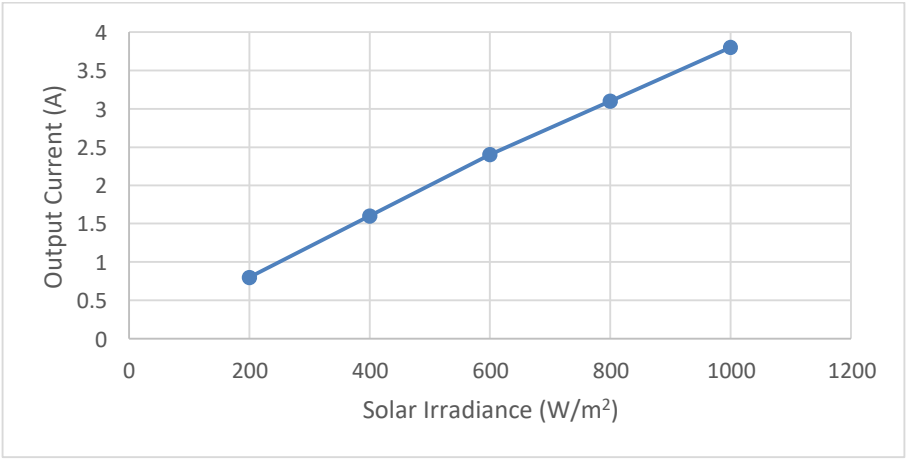


Fig. 9. Relationship between incident solar irradiance and PV current generation, demonstrating a linear proportional increase in output current as irradiance levels rise from 200 to 1000 W/m².

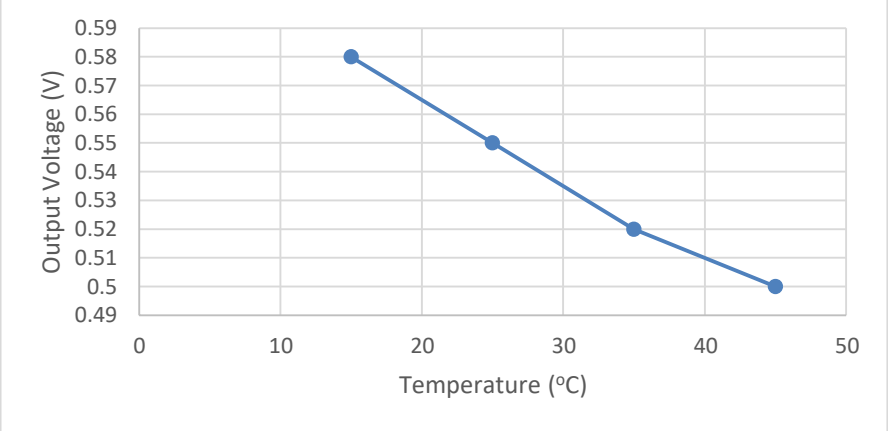


Fig.10. Impact of operating temperature fluctuations (15°C to 45°C) on the PV output voltage, illustrating the characteristic inverse correlation between cell temperature and voltage stability.

At standard test conditions (25°C and 1000 W/m²), the PV module achieves its maximum performance. However, when the temperature increases to 45°C, the output power decreases by approximately 8–12%, confirming the negative impact of temperature on PV efficiency. These trends are consistent with established photovoltaic behavior and validate the simulation model.

3.3 Battery Charging Performance (Parallel Mode)

The charging behavior of the battery system was evaluated with the batteries connected in parallel. This configuration ensures equal voltage distribution and efficient energy storage.

Figures 11, 12 , and 13 illustrates the battery charging characteristics, including voltage, current, and temperature variations over time. It is observed that the battery voltage increases steadily from approximately 11.8 V to 13.6 V as charging progresses. At the same time, the charging current gradually decreases as the batteries approach full charge, indicating normal charging behavior. It should be noted that the simulation duration of 1500 s represents only the initial charging phase of the battery system and was selected to investigate the transient response of the proposed charging architecture. The objective was not to simulate a complete charging cycle of the 7 Ah batteries, which would require substantially longer simulation times. Therefore, the observed increase in battery voltage reflects the early-stage charging dynamics rather than full-capacity charging behavior. The results are intended to demonstrate system stability, voltage regulation capability, and charging performance during the initial operating period.

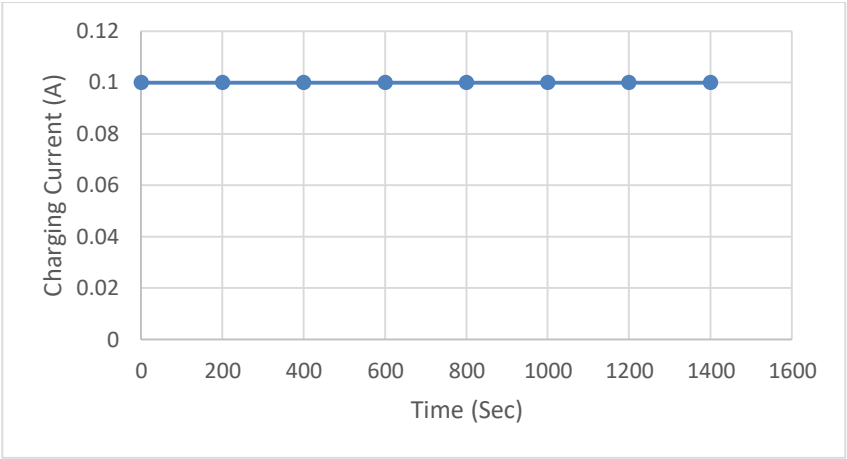


Fig.11. Simulated battery charging current profile over time in parallel configuration.

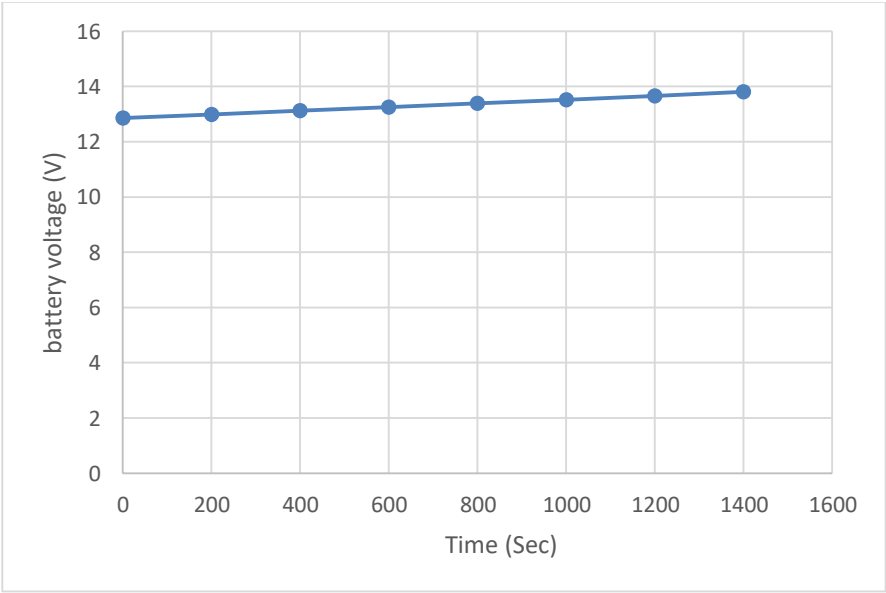


Fig.12. Battery terminal voltage response illustrating steady increase from 11.8 V to 13.6 V during charging

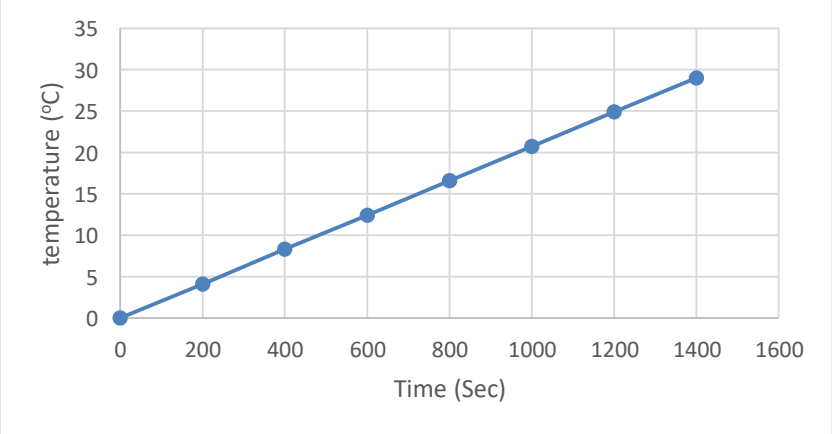


Fig.13. Transient thermal behaviour and safe temperature trajectory of the dual-battery system during the charging process

The temperature profile remains within safe operating limits, confirming that the system does not experience thermal instability during charging. The results demonstrate that the parallel configuration provides efficient and stable charging without voltage imbalance between the batteries.

3.4 Battery Discharging Performance (Series Mode)

During discharging mode, the relay-based switching mechanism connects the batteries in series to meet the voltage requirements of the laptop load.Figures14, 15, and 16 presents the output characteristics during discharging mode. It is observed that the system maintains an output voltage in the range of 19–21 V, which is suitable for standard laptop operation. Minor voltage fluctuations of less than 3% are present, indicating acceptable stability.

As the discharge process continues, the voltage gradually decreases due to the inherent characteristics of the batteries. However, the system continues to supply sufficient power to the load throughout the operation period. These results confirm the effectiveness of the relay-based configuration in providing the required output voltage without the need for complex converters.

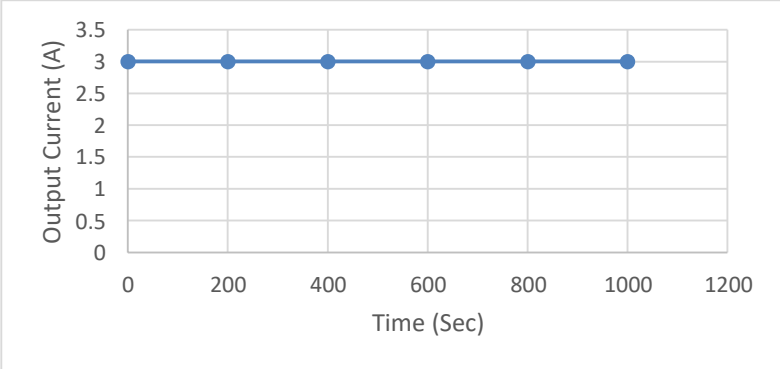


Fig.14. Simulated output current delivered to the laptop load during series discharging mode

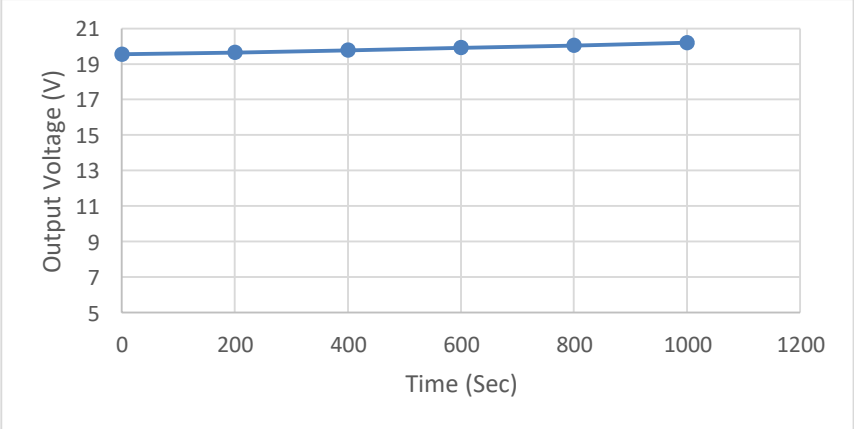


Fig.15. Output voltage profile showing stabilized delivery within the required 19–21 V range for the laptop load

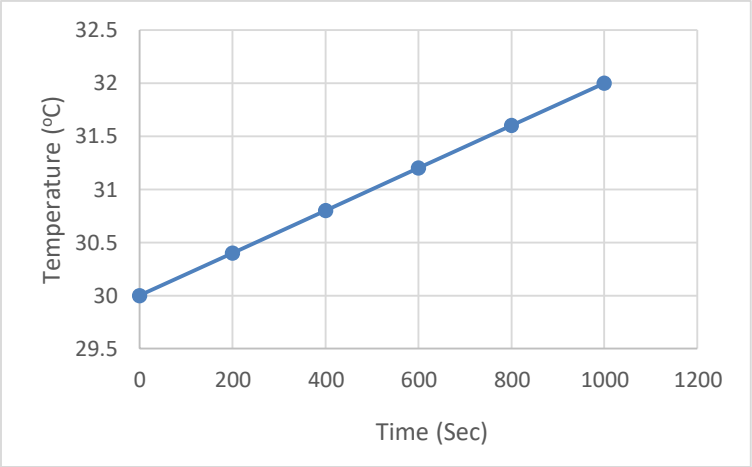


Fig.16. Thermal evolution and temperature variation of the battery packs during continuous discharge operation

3.5 System Efficiency Analysis

To assess system performance, both photovoltaic efficiency and overall system efficiency were calculated based on simulation results as shown in Fig. 17.

The PV efficiency is defined as the ratio of the electrical output power to the incident solar power on the panel surface, at standard test conditions, the PV module produces approximately 35 W over an effective area of 0.25 m², resulting in an efficiency of about 14%, which is typical for silicon-based PV systems. The overall system efficiency is calculated as the ratio of the load power to the PV output power, The simulation results indicate that the system delivers approximately 28–30 W to the load from a PV input of 35 W, yielding an overall efficiency in the range of 80–85%.

The system efficiency was further analyzed under different irradiance levels. The results indicate that efficiency improves with increasing irradiance, reaching approximately 85% at 1000 W/m². At lower irradiance levels, such as 200 W/m², the efficiency decreases to around 65% due to reduced power generation and higher relative losses. This behavior confirms that the system performs optimally under high solar availability while maintaining acceptable functionality under reduced solar conditions.

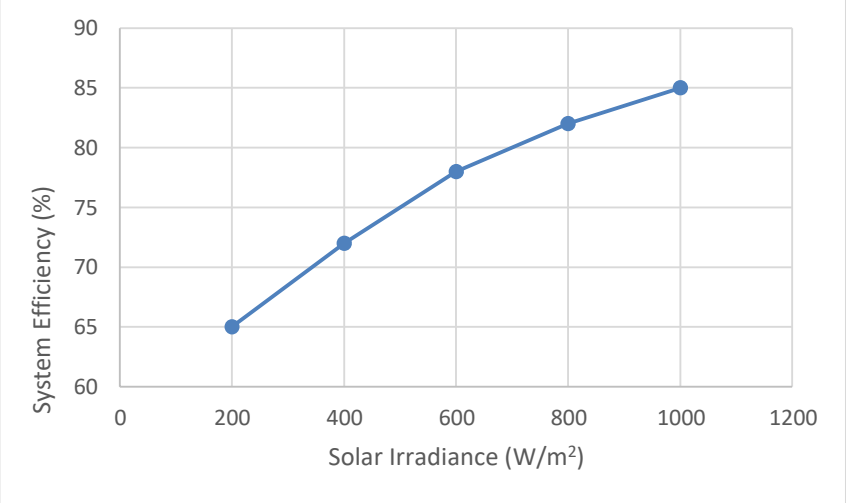


Fig. 17. Impact of solar irradiance levels on overall system efficiency, demonstrating a range of 65% to 85% efficiency between 200 W/m² and 1000 W/m².

Table X. Comparison of the proposed solar-powered laptop charging system with related studies.

3.6 Model Validation

To verify the accuracy of the developed MATLAB/Simulink model, the simulation results were compared with theoretical calculations obtained from the mathematical models of the photovoltaic module and battery storage system presented in Sections 2.2 and 2.3 as shown in table 3. Key performance indicators, including open-circuit voltage, short-circuit current, maximum power output, battery terminal voltage, and overall system efficiency, were evaluated under standard test conditions (1000 W/m² and 25°C).

The simulated PV characteristics exhibited the expected nonlinear behavior of silicon-based photovoltaic cells and showed close agreement with the theoretical current-voltage and power-voltage relationships. Similarly, the battery charging and discharging responses followed the trends predicted by the state-of-charge and equivalent circuit models. The maximum deviation between the theoretical predictions and simulation results was found to be less than 5%, which is within the acceptable range reported in previous photovoltaic system studies. These findings confirm the validity of the developed simulation model and demonstrate its suitability for evaluating the performance of the proposed dual-battery solar-powered laptop charging system.

Table 3: Comparison between theoretical calculations and simulation results.

Parameter	Theoretical Value	Simulated Value	Error (%)
Open-Circuit Voltage	16.5 V	16.2 V	1.8
Maximum Power	35 W	34.1 W	2.6
Battery Voltage	13.8 V	13.5 V	2.2
Output Voltage	20.0 V	19.6 V	2.0

3.7 Comparison of the proposed solar-powered laptop charging system with related studies.

The comparison demonstrates that most existing solar-powered charging systems rely on advanced control algorithms, DC–DC converters, or intelligent energy management strategies, which increase system complexity and implementation cost as shown in table 4. In contrast, the proposed system utilizes a simple relay-based switching mechanism combined with a dual-battery architecture to achieve stable voltage delivery and overall efficiency of 80–85%. Although the achieved efficiency is comparable to several reported systems, the proposed design offers reduced hardware complexity, lower cost, and improved suitability for standalone and off-grid applications.

Table 4 : Comparison of the proposed system with previously reported solar-powered laptop charging systems. Data summarized from Refs. [6,14–18]

Reference	System Configuration	Control Strategy	Battery Configuration	Complexity	Reported Efficiency (%)	Main Contribution
Hyacinth et al. (2016)	PV-powered laptop charger	Power conditioning unit	Single battery	Medium	Not reported	PV-based laptop charging system
Ramesh and Vanitha (2018)	PV + DC–DC converter	MPPT algorithm	Single battery	High	85–90	Stable voltage regulation using MPPT
Chilumba and Mushi (2022)	PV + SEPIC converter	Converter-based control	Single battery	Medium–High	~84	Wide input voltage regulation
Rehman et al. (2024)	Smart portable PV system	IoT-based energy management	Battery storage	High	Not reported	Real-time monitoring and optimization
Emmanuel et al. (2024)	Hybrid storage PV system	Advanced energy management	Battery + Supercapacitor	High	>85	Improved storage reliability
Proposed System	PV + Dual-Battery Relay Switching	Electromechanical relay control	Dual battery (parallel charging / series discharging)	Low	80–85	Low-cost autonomous laptop charging without MPPT or complex controllers

3.8 Economic Analysis

An economic assessment was conducted to evaluate the feasibility of the proposed solar-powered laptop charging system. The system consists of a photovoltaic module, two 12 V/7 Ah batteries, relay-based switching circuitry, and a voltage regulation stage. Compared with conventional solar charging systems employing MPPT controllers and advanced DC–DC converters, the proposed design utilizes low-cost and commercially available components, resulting in reduced implementation and maintenance costs.

The simplified relay-based architecture eliminates the need for sophisticated control hardware and associated programming requirements, thereby reducing overall system complexity. Furthermore, dual-battery configuration enhances operational flexibility without introducing significant additional cost. Considering the achieved overall efficiency of 80–85%, the proposed system offers a cost-effective solution for portable and off-grid laptop charging applications. These characteristics make the system particularly suitable for remote locations where affordability, reliability, and ease of maintenance are critical factors.

3.9 Sensitivity Analysis

A sensitivity analysis was performed to investigate the influence of key operating parameters on system performance. The analysis considered variations in solar irradiance from 200 W/m² to 1000 W/m² and operating temperature from 15°C to 45°C.

The simulation results indicate that solar irradiance is the most influential parameter affecting system performance. Increasing irradiance significantly enhances the photovoltaic output current and overall system efficiency, which increased from approximately 65% at 200 W/m² to 85% at 1000 W/m². In contrast, temperature primarily affects the output voltage of the PV module. As the temperature increased from 15°C to 45°C, a noticeable reduction in voltage was observed, leading to a corresponding decrease in power generation efficiency.

The results demonstrate that the proposed charging system is more sensitive to variations in solar irradiance than temperature fluctuations. Nevertheless, the relay-controlled dual-battery architecture maintained stable operation and acceptable voltage regulation under all simulated conditions, confirming the robustness of the proposed design for off-grid applications.

4. Conclusion

This study presented the design and performance evaluation of a standalone solar photovoltaic (PV) laptop charging system based on a dual-battery architecture and relay-based switching mechanism using MATLAB/Simulink. The proposed system was developed to provide a simple, low-cost, and reliable solution for off-grid laptop charging applications without the need for complex MPPT controllers or advanced power electronic converters.

The simulation results demonstrated that the dual-battery configuration successfully maintained a stable output voltage within the range of 19–21 V, satisfying the voltage requirements of standard laptop loads. During discharging operation, voltage fluctuations remained below 3%, indicating good voltage regulation and system stability. The photovoltaic module exhibited the expected electrical characteristics under varying environmental conditions, with output current increasing proportionally with solar irradiance and output voltage decreasing slightly with increasing temperature.

Performance analysis showed that the overall system efficiency reached approximately 85% under standard test conditions (1000 W/m² and 25°C). At reduced irradiance levels of 200 W/m², the system remained operational, achieving an efficiency of approximately 65%. The battery charging analysis confirmed stable operation in parallel charging mode, while the relay-controlled series configuration effectively supplied the required voltage during discharging mode.

Compared with previously reported MPPT-based and converter-based charging systems, the proposed relay-switching strategy offers reduced hardware complexity, lower implementation cost, and improved suitability for autonomous off-grid applications. The results confirm that the proposed design represents a practical and cost-effective alternative for portable solar-powered laptop charging systems.

Future work will focus on experimental validation of the proposed design, long-duration battery performance assessment, and the integration of advanced thermal management techniques to further improve system efficiency under elevated operating temperatures.

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