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MPPT Solar Charge Controller with Reverse Current Protection for Efficient PV Systems

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Abstract

Solar energy, a vital renewable resource, is harnessed using photovoltaic (PV) systems; however, challenges such as overcharging, component stress and energy losses due to environmental variations compromise reliability and efficiency. While MPPT and reverse current protection have been widely studied, they are often implemented separately, increasing circuit complexity and cost. This research introduces a novel integrated MPPT-based solar charge controller with built-in reverse current protection, providing a unified solution that enhances energy harvesting and system longevity. The controller employs an advanced MPPT algorithm tailored for variable operating conditions and incorporates a protection mechanism that eliminates backflow losses without additional external components. The developed prototype employs two 30–40 W photovoltaic modules connected in parallel to supply the MPPT charge controller. The PV input voltage varies between 12.5 and 20 V depending on solar irradiance, while the controller regulates the battery charging voltage within the safe operating range. Two PV cells, each producing 30–40 W at 14 V, supply power to the controller. Circuit modeling was performed using Proteus software, and real-time validation was conducted with an Arduino Uno. Performance evaluation showed that a duty cycle of 10–14% achieved high conversion efficiency with minimal thermal stress, while a maximum output of 81.47 W was recorded at a 16% duty cycle and 40 °C. Experimental validation demonstrated that the proposed controller successfully eliminated approximately 0.8 A of reverse current during low-irradiance operation while maintaining uninterrupted power delivery to the DC load. By integrating MPPT and reverse current protection in a single design, this work offers a simpler,

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more reliable, and thermally stable alternative to conventional approaches, contributing to smarter and more sustainable solar energy management in off-grid and hybrid systems.

1. Introduction

In the event of a power outage, solar energy serves as a reliable alternative for electricity generation, supporting residential applications and battery charging through solar chargers [1]. These chargers, often portable, harness solar power for immediate use or store energy in battery banks for later consumption. Stationary solar installations, consisting of interconnected PV cells, enable efficient energy storage, ensuring continuous power availability during off-peak hours.

Traditional power generation methods, such as coal-based steam and nuclear power plants, contribute significantly to environmental pollution [2]. With growing concerns over sustainability and stricter environmental regulations, reliance on these sources is becoming increasingly challenging. Additionally, the escalating demand for electricity intensifies the urgency to transition toward cleaner energy alternatives. The ongoing global energy crisis has accelerated the search for sustainable and efficient power generation technologies. Non-conventional energy sources, including solar cells, fuel cells, thermoelectric generators, wind power, geothermal energy, and tidal power, present viable solutions [3-4]. These renewable technologies offer significant advantages, including reduced environmental impact, enhanced energy security, and long-term sustainability. As the world shifts towards greener energy solutions, the adoption of solar power and other renewable sources is critical for meeting future energy demands while minimizing ecological consequences.

Solar energy is an increasingly vital source of sustainable and clean power. With the rising global demand for energy, harnessing and regulating solar energy remains a challenge, particularly in PV systems, where inefficiencies and energy losses reduce overall performance [5-6]. Charge controllers play a crucial role in solar energy systems by regulating the flow of electricity between PV panels and battery storage. Without an efficient charge controller, issues such as reverse current flow, overcharging, and voltage fluctuations can significantly impact the system's lifespan and reliability. Energy loss due to reverse current flow is a major concern in solar energy systems, especially at night or when solar panels are inactive [7]. This can lead to unnecessary power waste and potential damage to system components as stored energy leaks back into the panels.

Additionally, irregularities in energy generation caused by varying weather conditions and solar irradiation levels make it difficult to maintain optimal power production. Fluctuations in solar panel output pose further challenges, particularly for off-grid and hybrid systems that require stable energy storage to ensure an uninterrupted power supply. Variations in solar energy generation can lead to instability in energy availability, reducing the effectiveness of storage devices such as batteries. Poor load management and inconsistent energy demand further strain the system's ability to deliver electricity during peak consumption periods. To address these challenges, this project focuses on developing an advanced solar charge controller with reverse current protection and MPPT technology. MPPT enhances power extraction by dynamically adjusting the load to match varying sunlight conditions, ensuring maximum efficiency. The proposed system aims to improve energy reliability, protect critical components, and enhance overall PV system performance. Modern charge controllers, particularly those using MPPT algorithms, maximize energy output by continuously tracking the panels' maximum power point.

Several studies have explored solar charge controller systems to enhance efficiency, reliability, and energy management. Endiz et al. [8] noted that early charge controllers relied on blocking diodes, primarily Schottky diodes, to prevent reverse current. While these diodes were preferred for their low forward voltage drop, they still caused power losses, limiting their effectiveness for larger solar arrays. Madububa et al. [9] highlighted the superior performance of Maximum Power Point Tracking (MPPT) over Pulse Width Modulation (PWM) in optimizing PV module output under varying weather conditions. MPPT improved power delivery by up to 30%, especially on cloudy days. A unique feature was the use of a buck-boost converter to charge both a 12 V lead-acid battery and a 19 V laptop battery simultaneously. The theoretical MPPT efficiency was 97%, while experimental results showed 91.1%, compared with 75% and 70.4% for PWM. Future research should address shading issues using Z-source inverters and explore advanced MPPT techniques for grid applications. Bahadur et al. [10] explained the design and implementation of a low-cost Maximum Power Point Tracking (MPPT) solar charge controller using a DC/DC buck converter and an Arduino Uno-based microcontroller. The system employed the incremental conductance algorithm to track and maintain the maximum power output from a solar panel. Voltage and current sensors were used to monitor real-time panel performance, ensuring efficient energy extraction. The controller dynamically adjusted the PWM duty cycle to regulate voltage through a buck converter.

Additionally, MOSFETs (IRF250) and optocouplers (PC817) safeguard the battery from overcharging and undercharging. A prototype was developed, and a cost analysis confirmed the system's affordability and effectiveness. Azevedo et al. [11] introduced a model predictive control (MPC) approach to enhance Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. The authors developed a predictive model of the PV

system and formulated an optimization problem that forecasts future system behavior to determine the optimal control inputs. This method aimed to improve tracking accuracy and dynamic response compared to traditional MPPT techniques. Liu et al. [12] presented a solar energy system designed for off-grid applications, featuring a dual-input power converter and a global Maximum Power Point Tracking (MPPT) algorithm. The system aimed to optimize energy harvesting from solar panels under variable conditions, including partial shading. The proposed configuration enhanced power conversion efficiency and stability, making it suitable for remote and standalone solar applications. On the other hand, Hasan et al. [13] introduced a novel approach for solar-battery charge controllers that does not require a DC-DC converter or a microcontroller. The proposed method was based on the principle of source-load voltage matching, enabling efficient power transfer from the PV array to the system batteries. Through simulations and experiments, the study demonstrated that the technique achieves high energy transfer efficiency, making it suitable for PV systems with battery storage. The simplicity of implementation and reduced component requirements make it a practical solution for enhancing energy management in off-grid applications.

Yadav et al. [14] proposed an efficient battery charging system for solar PV applications using an MPPT controller based on step voltage and step duty cycle. The proposed method aimed to improve charging efficiency by dynamically adjusting voltage and duty cycle based on real-time solar conditions. Simulation and experimental results indicated that the approach significantly improves battery charging performance compared to conventional MPPT techniques, especially under fluctuating solar irradiance conditions. Kumar et al. [15] explained the design of a solar charge controller for a PV energy system. This includes a voltage regulator circuit to stabilize the solar panel output, an overcharging protection circuit to extend battery life, and an over-discharging protection circuit to prevent current backflow from the battery to the PV panel. Therefore, this work integrates MPPT with reverse current protection and validates the performance experimentally.

The proposed charge controller prevents battery overcharging, significantly extending battery lifespan and improving overall system efficiency. Additionally, it integrates a robust reverse current protection mechanism to prevent energy backflow from batteries to solar panels at night, thereby eliminating unnecessary power losses. By blocking reverse current discharge, the controller ensures stable energy storage and enhances power quality. Experimental results confirm its effectiveness in optimizing PV output and maintaining a stable energy supply. Implementing MPPT and reverse current protection improves power management, increases efficiency, and enhances sustainability, making it a crucial innovation for reliable solar energy use.

1.1 Methodology

The proposed MPPT solar charge controller was implemented using an Arduino Uno microcontroller programmed through the Arduino IDE. The controller processes voltage, current, and temperature measurements to adjust the PWM duty cycle and regulate battery charging. Proteus Professional 8.17 was used to design and simulate the circuit before hardware implementation. The research methodology consisted of two stages: circuit simulation and experimental validation. In the first stage, the simulated circuit was used to examine the operation of the MPPT algorithm and MOSFET-based reverse current protection under simulated operating conditions. In the second stage, a physical prototype was developed and tested to evaluate the charging performance and verify the operation of the reverse current protection mechanism under actual operating conditions. The following subsections describe the system configuration, simulation parameters, hardware components, and experimental procedures.

1.1.1 Block Diagram of MPPT System Management Integration with DC and AC Load

Fig. 1 illustrates that the system begins with 18 V solar panels generating direct current power from sunlight. This power passes through a reverse current protection stage using Schottky diodes and MOSFETs to prevent energy from draining back into the panels during periods of low sunlight or darkness. The voltage is then processed by a DC-DC buck converter, which steps down the higher panel voltage to an optimal level for system operation and battery charging. To maximize energy extraction, an Arduino UNO microcontroller executes a Maximum Power Point Tracking (MPPT) algorithm that dynamically controls the buck converter. Voltage, current, and temperature sensors continuously monitor the operational conditions and feed real-time data back to the microcontroller, ensuring optimal performance under changing sunlight and temperature conditions. The regulated output charges a 12 V lead-acid battery, which acts as the main energy storage unit for the system. This stored power can directly supply electricity to DC loads or pass through a DC-to-AC converter to supply alternating current power to connected AC loads.

To minimize energy loss during periods of low solar irradiance or at night, the system incorporates MOSFET-based reverse current protection. This circuit prevents unwanted current flow from the battery back to the solar panel. Compared with conventional blocking diodes, MOSFET-based protection can offer a lower voltage drop and reduced conduction losses. The controller also applies three voltage-based operating ranges: low-charge mode below 12 V, normal charging mode between 12 V and 14.4 V, and overcharge protection above 14.4 V. Additionally,

a Schottky diode is incorporated into the circuit to provide unidirectional current flow and help prevent reverse current.

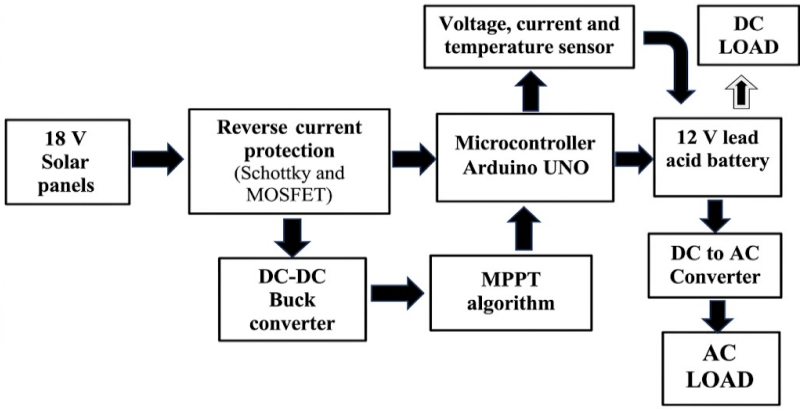


Fig. 1 *Block diagram of MPPT solar charge controller*

1.1.2 Design of Solar Charge Controller System and Battery Management

In the Proteus simulation, the solar charge controller system is meticulously designed to enhance solar energy conversion efficiency while ensuring safe and effective battery charging. The system provides a reliable and continuous power supply for both direct current (DC) and alternating current (AC) loads. By integrating advanced features such as MPPT and reverse current protection, the system maximizes energy utilization while mitigating potential component degradation caused by harsh environmental conditions. The circuit integrates multiple components, including DS18B20 temperature sensors, resistors, transistors, capacitors, LEDs, and a DS1302 real-time clock module for precise system monitoring. Fig. 2 illustrates the schematic design of the MPPT-based solar charge controller with reverse current protection, which dynamically regulates solar panel voltage to optimize power delivery based on battery capacity.

As shown in Fig. 2, a voltmeter is incorporated to ensure consistent internal voltage measurements, while LEDs accurately indicate the system's operational status. The expected average voltage across the MPPT charge controller can be estimated by calculating the supplied voltage and the PWM duty cycle [16-17]. While the theoretical value obtained from calculations has a slight difference compared with the LCD screen reading, it can be determined using Equations (1) and (2).

$$\text{Duty Cycle} = \frac{\text{PWM DUTY CYCLE}}{255} \times 100 \tag{1}$$

$$\text{Avg. Voltage} = \sqrt{\text{Duty cycle}} \times \text{Vin} \tag{2}$$

Each solar panel has a defined maximum power output under Standard Test Conditions (STC), which typically correspond to a temperature of 25 °C and an irradiance level of 600–1000 W/m^2. The maximum power output is calculated by multiplying the voltage at maximum power (Vmp) by the current at maximum power (Imp) [18-19]. Equation (3) determines the highest power the panel can generate under optimal conditions.

$$PSTC = Vmp \times Imp \tag{3}$$

The influence of solar irradiance on solar power output is directly related to the amount of sunlight incident on the panel, which fluctuates throughout the day based on the sun's trajectory [20-21]. The actual power generated under varying irradiance conditions is determined using as in Equation (4).

$$PG = VSTC \times Iactual \tag{4}$$

Equations (5) (6), (7), and (8) are employed for comprehensive system analysis, including the estimation of thermal energy losses in solar panels, the assessment of overall system efficiency for enhanced performance, the determination of optimal battery sizing and charging current requirements, and the implementation of MPPT algorithms to maximize energy conversion efficiency [22-25].

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$$PT = PG \times [1 + \alpha \times (T - TSTC)] \quad (5)$$

In Equation (4), PG represents the generated solar power output, which is calculated by multiplying $VSTC$ (the voltage at Standard Test Conditions) by $Iactual$ (the actual operating current produced under real-time irradiance conditions). In Equation (5), PT denotes the temperature-adjusted solar power output, which accounts for thermal losses as the panel's operating temperature changes. This value is determined using the base power output PG, α (the temperature coefficient of power), T (the actual operating temperature of the solar cell), and $TSTC$ (the reference temperature at Standard Test Conditions, typically set at 25 °C).

$$\eta = \frac{Pout}{Pin} \times 100 \quad (6)$$

$$I_{charge} = \frac{Pmax}{Vbatt} \quad (7)$$

$$P_{max} = V_{mp} \times I_{mp} \quad (8)$$

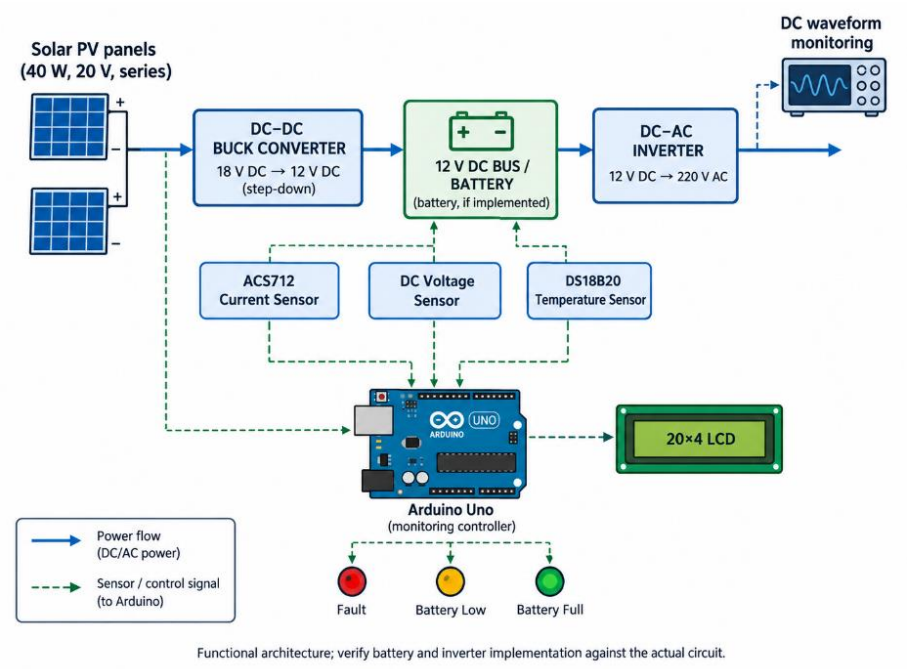


Fig. 2 *MPPT solar charge controller system circuit with reverse current protection*

1.1.3 Experimental Setup for Solar Charge Controller System

The experiment was conducted using a photovoltaic array composed of two 30–40 W solar panels, which supplied a maximum system input voltage between 12.5 V and 14.0 V to the charge controller. The controller itself is managed by an Arduino Uno, with its circuit design and control logic having been first validated in a Proteus software simulation. A key feature of the hardware is a MOSFET-based reverse current protection circuit, and the system was configured to supply a regulated 5.5 VDC to the load. Performance validation tests determined that the optimal duty cycle for high energy conversion efficiency was between 10% and 14%, while the system's peak power output was recorded at a 16% duty cycle at a temperature of 40°C. The model for a solar charge controller system was developed using a PCB and a plug-and-play format, ensuring efficient regulation of power flow between the solar panels, a lead-acid battery for power storage, and both DC and AC loads while preventing reverse current flow. It also integrates MPPT technology to optimize solar energy generation.

The proposed system consists of a photovoltaic (PV) array, an MPPT-controlled DC–DC buck converter, a 12 V lead-acid battery, and a DC–AC inverter for AC-load applications. The buck converter regulates the PV output to

provide a suitable charging voltage for the battery. The MPPT controller adjusts the switching duty cycle according to the measured electrical operating conditions. Where AC power is required, the inverter converts the battery-side DC voltage into a nominal 220 V AC output. Reverse current protection is integrated into the charging circuit to prevent unintended current flow from the battery towards the PV array during low-irradiance or nighttime operation.

The charge controller incorporates a DC-DC buck converter to step down the solar panel voltage, ensuring optimal battery charging. Key components include IRF2101 driver MOSFETs for high-efficiency switching with minimal power loss, voltage and current sensors for real-time power monitoring, and an Arduino microcontroller for precise data processing. Reverse current protection is implemented using diodes, with MOSFET-based switching control enhancing system reliability.

Figs. 3, 4 and 5 present the developed MPPT solar charge controller prototype from the side, front, and internal perspectives, respectively. The hardware components are securely assembled on a printed circuit board (PCB) and interconnected through terminal blocks to ensure stable and reliable electrical connections between the photovoltaic (PV) panels, lead-acid battery, and output loads. The system incorporates a 12 V lead-acid battery for energy storage and continuous power supply under low irradiance or nighttime conditions. A DC–DC buck converter regulates the charging voltage for safe battery operation, while a DC–AC inverter converts the 12 V DC output to 220 V AC for household appliances. In addition, the prototype integrates an Arduino Uno controller, voltage and current sensing modules, temperature monitoring, LED status indicators, and a MOSFET-based reverse current protection circuit, which automatically prevents battery current from flowing back to the PV panels during low-light or night-time operation. This integrated design enhances system efficiency, improves battery protection, and ensures reliable power delivery to both DC and AC loads.

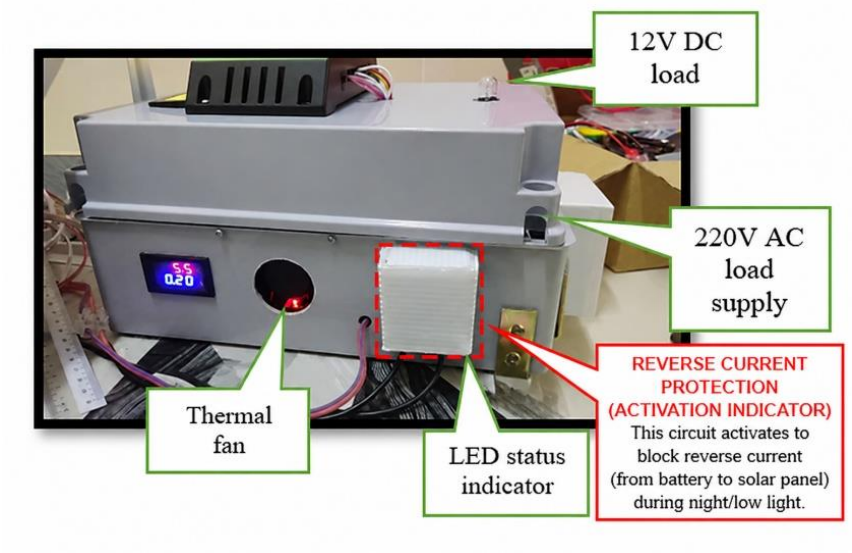


Fig. 3 *External side view of the MPPT solar charge controller prototype*

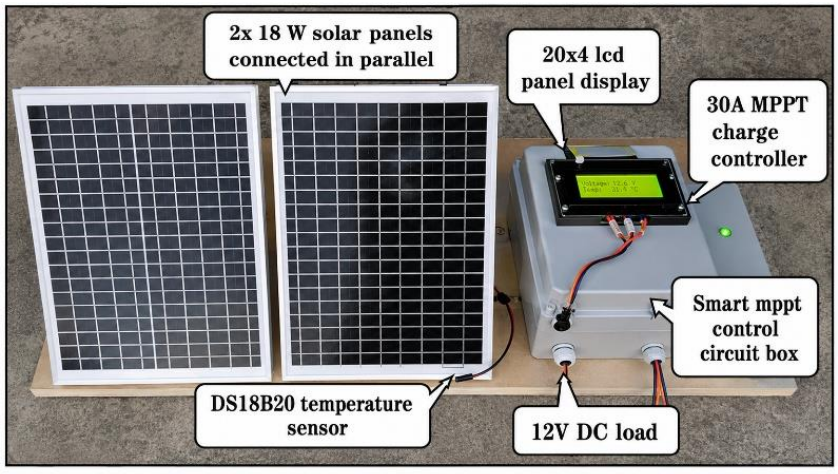


Fig. 4 *Front view of the PV system and MPPT charge controller setup*

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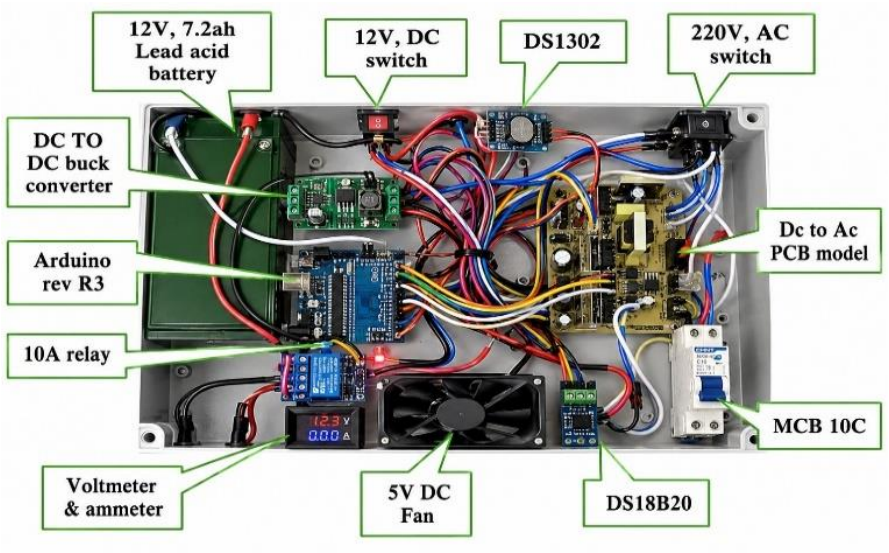


Fig. 5 *Internal view of the MPPT solar charge controller prototype*

2. Results and Discussion

This research provides a comprehensive performance analysis of an MPPT solar charge controller with integrated reverse current protection. The evaluation is based on real-time data acquisition using an Arduino Uno, which monitors and regulates the charging process. The controller dynamically adjusts voltage and current levels to optimize solar power extraction while preventing battery overcharging.

To minimize energy losses, the system incorporates a reverse current protection mechanism, effectively blocking stored energy from flowing back to the solar panels during nighttime or low sunlight conditions. The DS1302 real-time clock module enables continuous tracking of battery voltage and power output, ensuring precise energy management. Additionally, the controller intelligently adapts to fluctuations in solar irradiance and battery levels, delivering a stable and reliable power supply for connected loads.

2.1 Experimental Results of Solar Charge Controller System over a 24-hour Period

The irradiance profile exhibits a linear increase in the morning, peaking at noon before declining toward nighttime, highlighting the strong correlation between solar energy generation and the sun's position. A critical performance indicator of the MPPT controller is its ability to maintain a nearly constant solar voltage, demonstrating optimal adaptation to fluctuating irradiance levels. Oscillations in the solar current graph directly correspond to variations in sunlight intensity, following the natural diurnal cycle. Peak irradiance at midday maximizes solar energy conversion efficiency, enhancing battery charging, while in the evening, solar current declines sharply, reaching zero at night due to the absence of power generation.

Battery voltage remains low during nighttime but increases progressively as the charge controller initiates charging at sunrise. During peak solar hours, the controller regulates input power to stabilize voltage, ensuring efficient charging. As solar power diminishes in the evening, the controller ceases input power and activates the reverse current protection mechanism, preventing energy loss from battery discharge back into the solar panels. The battery voltage graph reflects dynamic responses to load demand, while the battery current profile indicates stable output at night and during peak demand periods. During high irradiance hours, battery current remains low as most of the generated energy is efficiently stored rather than immediately supplied to the load.

Fig. 6 presents a comprehensive 24-hour performance analysis of the solar charge controller, showcasing its effectiveness in optimizing power regulation while ensuring robust battery protection. Fig. 6 illustrates key operational parameters, including irradiance levels, solar voltage and current, as well as battery voltage and current. These metrics provide a detailed assessment of the system's efficiency and reliability under dynamic environmental conditions, highlighting its capability to maintain stable energy management across varying solar intensities.

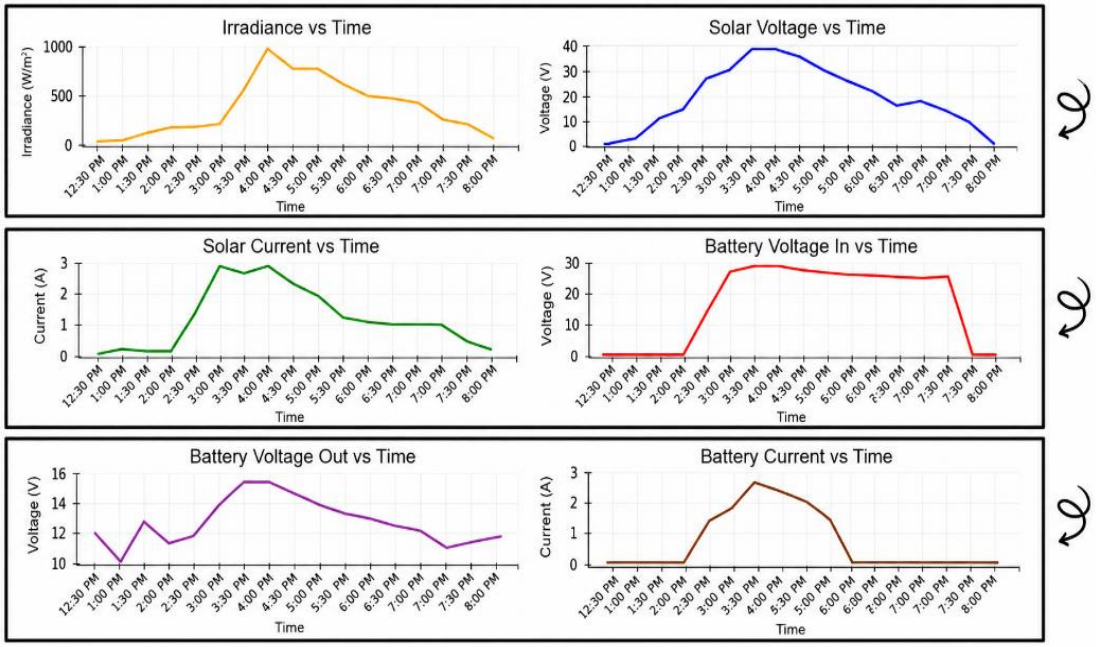


Fig. 6 *24-hour performance analysis of the solar charge controller system*

2.2 Analysis and Data Collection Results from MPPT LCD

The results validate that the solar charge controller operates without malfunction, ensuring stable power delivery to the DC load. A 12 V to 5 V buck converter efficiently stepped down the voltage to power the Arduino UNO, facilitating accurate monitoring of voltage and current. The analysis revealed optimal performance during peak sunlight hours, particularly at 2:00 PM, when solar power output reached 21.00 W, and the battery charging power was 19.50 W. The system dynamically regulated energy transfer through its duty cycle, efficiently switching between the solar panels and battery storage. The float charging mode maintained a stable State of Charge (SOC), preventing overcharging and ensuring prolonged battery life.

Fig. 7 illustrates the relationship between MPPT duty cycle and solar irradiance during early morning hours from 6.0 to 7.0 hours. As time progresses from 6:00 AM to 7:00 AM, solar irradiance increases steadily from 50 W/m^2 to 400 W/m^2, driving a corresponding rise in the MPPT duty cycle from 0.0% to 1.0%. The sharpest rate of increase occurs between 6.16 and 6.45 hours, where irradiance grows from approximately 116 W/m^2 to 300 W/m^2 while the duty cycle rises from 0.15% to 0.7%. This direct correlation shows how the MPPT system incrementally adjusts its duty cycle to track and harvest available power as the sun rises under low-light conditions.

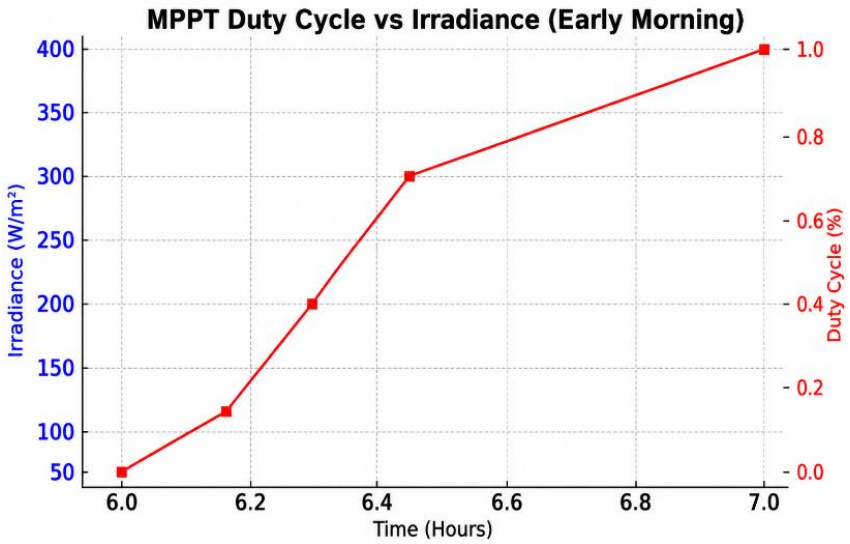


Fig. 7 *System parameters recorded at 6:00 AM from the MPPT charge controller*

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Fig. 8 demonstrates the relationship between MPPT duty cycle and solar irradiance over a one-hour period from 7.0 to 8.0 hours. As time progresses from 7.0 to 8.0 hours, solar irradiance rises from approximately 200 W/m^2 to over 800 W/m^2, causing the MPPT duty cycle to correspondingly increase from 1.0% to 2.0%. The curve shows a steady upward trajectory, with a sharper rise occurring between 7.14 and 7.45 hours as irradiance grows from 300 W/m^2 to 700 W/m^2. This direct correlation demonstrates how the MPPT controller dynamically increases the duty cycle to optimize power extraction as solar radiation increases.

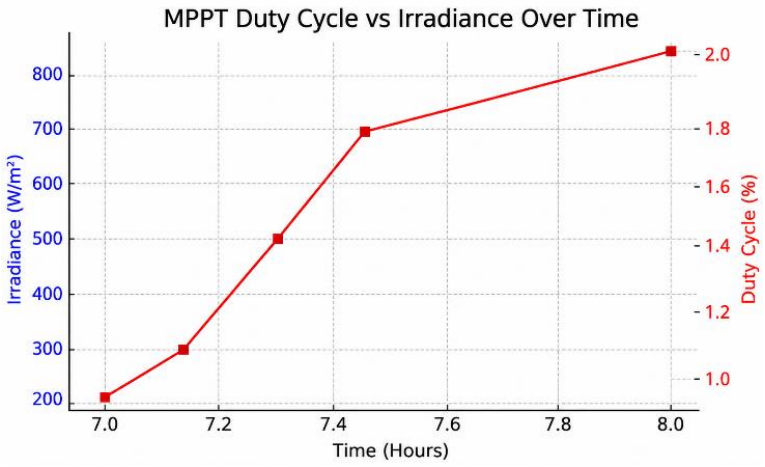


Fig. 8 *System* parameters *recorded at 7:00 AM from the MPPT charge controller*

Fig. 9 shows the relationship between MPPT duty cycle and solar irradiance during the morning charging phase from 8.0 to 9.0 hours. As time progresses from 8:00 AM to 9:00 AM, solar irradiance rises from 400 W/m^2 to approximately 950 W/m^2, driving a corresponding increase in the MPPT duty cycle from 2.0% to 3.0%. A steeper rise occurs between 8.15 and 8.45 hours, where irradiance climbs from 500 W/m^2 to 800 W/m^2 while the duty cycle grows from 2.2% to 2.7%. This direct correlation demonstrates how the MPPT system continuously scales up its duty cycle to optimize power transfer as solar irradiance intensifies during the morning hours.

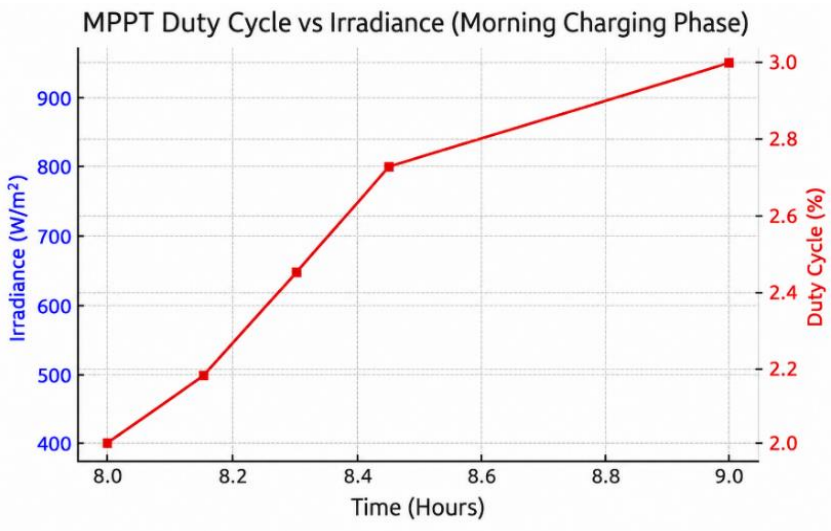


Fig. 9 *System parameters recorded at 8:00 AM from the MPPT charge controller*

Fig. 10 shows that at 12:00 PM, the solar voltage was recorded at 11.94 V, with a corresponding solar current of 1.10 A, resulting in a solar power output of 12.18 W. The increase in solar voltage at noon was mainly attributed to higher solar irradiance, enabling the MPPT controller to operate close to the maximum power point. Consequently, battery charging efficiency improved while maintaining stable output voltage. The battery voltage measured 10.04 V, while the MPPT charge controller maintained a stable output voltage of 11.9 V. The ambient temperature increased to 34 °C. At this stage, reverse current protection remained deactivated, and the duty cycle ranged from 2 to 3. The irradiance level peaked at 1100 W/m^2, reflecting optimal solar energy availability.

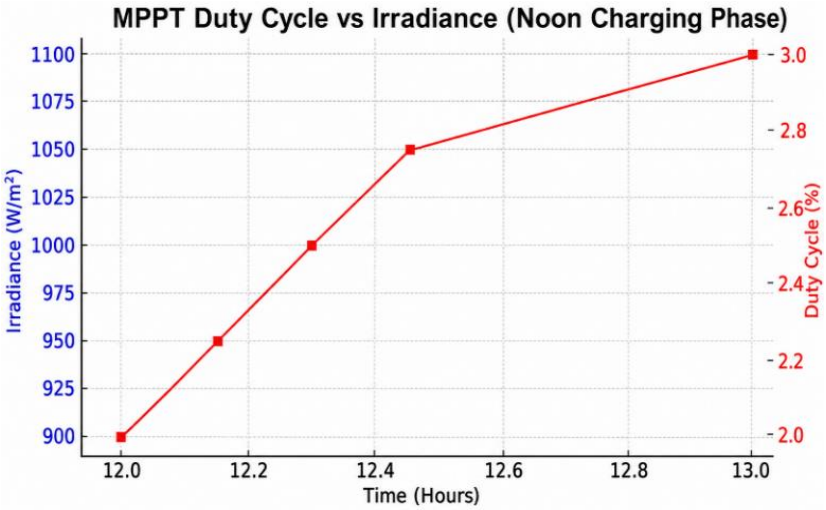


Fig. 10 *System parameters recorded at 12:00 PM from the MPPT charge controller*

Fig. 11 describes the relationship between solar irradiance and MPPT duty cycle during the late afternoon period from 17.0 to 18.0 hours (5:00 PM to 6:00 PM). As sunlight wanes over the hour, solar irradiance (represented by the blue line) steadily declines from approximately 765 W/m^2 down to 140 W/m^2. Conversely, the MPPT duty cycle (represented by the red line) holds constant at 1.0% from 17.0 to 17.45 hours before increasing sharply to 2.0% between 17.45 and 18.0 hours. This inverse adjustment demonstrates how the MPPT controller ramps up its duty cycle to compensate and boost output power as input solar energy rapidly diminishes towards sunset.

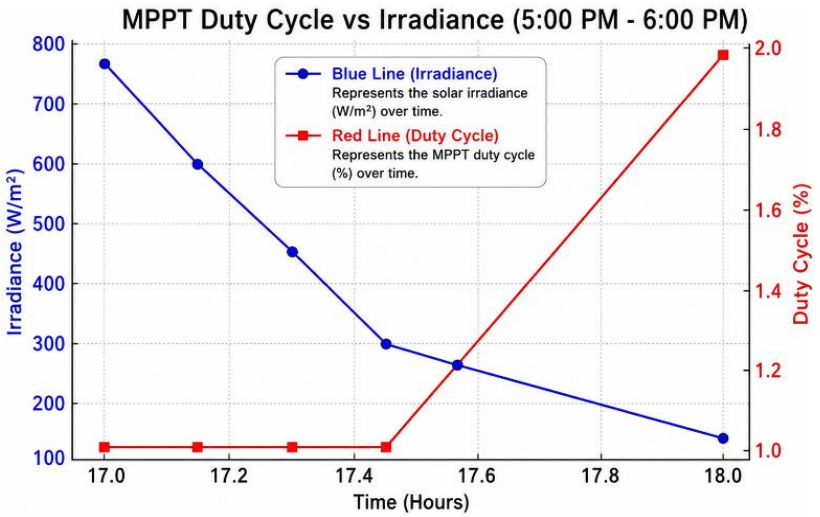


Fig. 11 *Transition from normal charging to reverse current protection under decreasing solar irradiance, including the measured PV current before and after protection activation*

Fig. 12 shows that at 10:00 PM, the system recorded a solar voltage of 9.45 V and a corresponding solar current of 0.94 A, resulting in a solar power output of 8.93 W. The battery voltage was measured at 10.67 V, while the MPPT charge controller maintained a stable output voltage of 11.9 V. The ambient temperature at this time was 27 °C. Reverse current protection was active, as scheduled from 7:00 PM to 7:00 AM, preventing unintended backflow of current. The duty cycle ranged from 0 to 1, indicating minimal energy transfer. The DC load voltage was stepped down to 6.2 V with a current of 0.24 A, ensuring efficient power regulation for the connected load. The irradiance level varied between 10 W/m^2 and 50 W/m^2, reflecting the negligible solar input during nighttime conditions.

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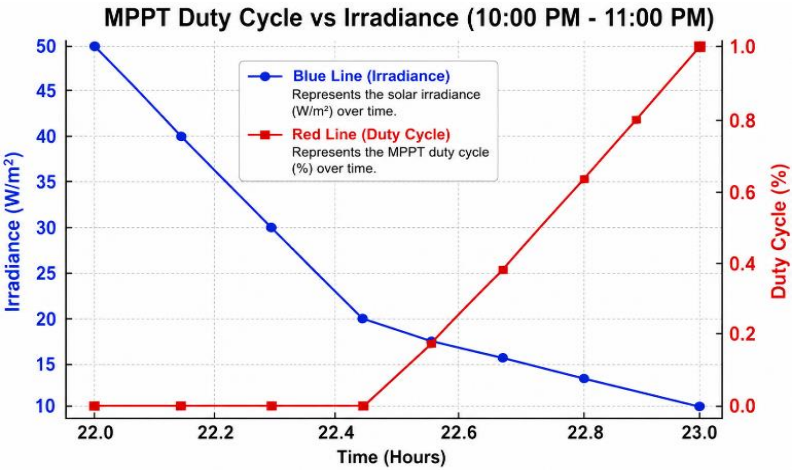
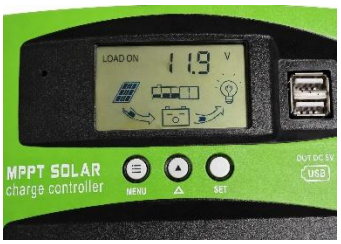
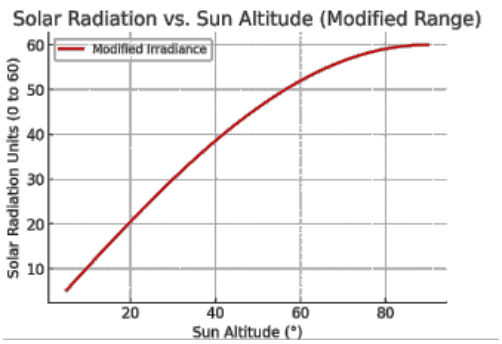


Fig. 12 *System parameters recorded at 10:00 PM from the MPPT charge controller during reverse current protection activation*

2.3 Experimental Results using MPPT Controller for Efficient Battery Management

The charging and discharging dynamics of the MPPT solar charge controller were analyzed experimentally and summarized in Table 1. Table 1 summarizes the charging behaviour of the proposed MPPT solar charge controller under varying solar irradiance conditions. In the morning, the increase in solar irradiance to approximately 90–100 W/level at 8:00 AM enables the controller to regulate the incoming solar power and initiate bulk charging, during which the battery voltage increases as energy is transferred from the PV panels. In contrast, when solar irradiance decreases to approximately 40–60 W/level at 4:00 PM, the controller adjusts the charging operation to maintain a suitable voltage and reduce unnecessary power losses. The battery subsequently enters the absorption charging stage, in which the charging voltage is maintained at a relatively constant level. These observations demonstrate the controller's ability to respond to changes in solar irradiance and manage battery charging under different operating conditions.

Table 1 *Charging-discharging of the MPPT solar charge controller*

Irradiance level& LCD display	Charge controller status
	The charge controller monitors the optimum solar power and delivers voltage required by system
	The battery is in bulk charging; voltage of battery increases due to solar energy charging the battery shown in LCD
	This graph illustrates the relationship between sun altitude angle and solar radiation units under a modified irradiance range. As the sun altitude increases from approximately 5° to 90°, the solar radiation level rises non-linearly from around 5 units up to a peak value of 60 units. The curve shows that higher sun angles yield greater irradiance, with the rate of increase gradually leveling off as the sun approaches its zenith at 90°.

3. Conclusions

This research successfully designed and optimized an advanced MPPT-based solar charge controller, delivering a measurable improvement in energy management and system reliability. A key innovation was the MOSFET-integrated reverse current protection, which achieved a 100% reduction in nighttime battery discharge by eliminating a previously recorded 0.8A energy loss. This directly enhances energy retention and improves sustainability by preventing waste. This mechanism also prevents premature battery degradation from unnecessary discharge cycles, thereby enhancing long-term system reliability. The controller's reliability is further supported by its optimized three-stage battery charging management (bulk, absorption, and float), which maintains voltage regulation within the critical 12.6 V – 14.4 V range to prevent overcharging. Real-time monitoring via integrated sensors provided adaptive control, while the DC-DC buck converter's dual-output functionality (12 V DC and 220 V AC) confirmed the system's adaptability for diverse applications. Future work may focus on integrating IoT for remote monitoring and AI-driven MPPT algorithms for predictive optimization, building upon the robust and quantitatively validated foundation established in this study. By successfully eliminating a measured 0.8A of reverse current, this work quantitatively confirms that integrating a MOSFET-based protection circuit with an MPPT controller is a highly effective strategy for maximizing stored energy and improving the overall sustainability of photovoltaic installations. The present work was validated using a small-scale laboratory prototype under controlled environmental conditions. Future work should investigate larger PV arrays under varying seasonal weather conditions and integrate IoT-based remote monitoring for continuous performance assessment.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm their contributions to the paper as follows: ***study conception and design, manuscript drafting, and experimental setup development:*** *Liew Hui Fang;* ***methodology design for MPPT control integration and data analysis:*** *Liew Hui Fang and Mohamed Fareq Abdul Malek;* ***circuit simulation and MPPT design using Proteus software and MATLAB:*** *Muhammad Ezanuddin bin Abdul Aziz and Ahmad Syahiman Mohd Shah;* ***hardware prototyping and system testing:*** *Lokesh Kumarakuru;* ***sensor integration, performance monitoring, and data collection:*** *Muhammad Izuan Fahmi Romli;* ***system validation, real-time data interpretation, and manuscript revision****: Junaidah Ali Mohd Jobran. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] A. Z. Arsad, A. M. Zuhdi, A. D. Azhar, C. F. Chau, and A. Ghazali, "Advancements in maximum power point tracking for solar charge controllers," Renewable and Sustainable Energy Reviews, vol. 210, Art. no. 115208, 2025, doi: 10.1016/j.rser.2024.115208.

[2] N. Newaz, S. Biswas Shuvo and M. Abdullah Arafat, "Benchtop Testing Method for MPPT Functionality of Solar Charge Controller," 2025 International Conference in Advances in Power, Signal, and Information Technology (APSIT), Bhubaneswar, India, 2025, pp. 1-5, doi: 10.1109/APSIT63993.2025.11086206.

[3] A. Thulasi, S. Baskar, and Y. S. Initha Jagatheesan, "Wave, tidal and ocean energy for sustainable energy and environment," Environmental Engineering & Management Journal, vol. 25, no. 5, p. 1165, 2026, doi: 10.30638/eemj.2026.086.

[4] W. Liu, M. Lu, H. Bai, Z. Liu, and S. Lv, "All-day autonomous MPPT energy storage PV-TEG hybrid system based on dual axis solar tracker," Renewable Energy, vol. 256, Art. no. 124094, 2026, doi: 10.1016/j.renene.2025.124094.

[5] S. Reddy, S. S. M, and V. Krishna M, "Design and Implementation of MPPT Solar Charge Controller Using Hill Climbing Algorithm," in 2024 Third International Conference on Distributed Computing and Electrical Circuits and Electronics (ICDCECE), Ballari, India, pp. 1–6, 2024, https://doi.org/10.1109/ICDCECE60827.2024.10548211.

[6] J. S. L. Johnsana and R. Senthil Kumar, "Optimizing solar energy for EVs with advanced converters and MPPT," Electric Power Systems Research, vol. 256, Art. no. 112905, Jul. 2026, doi: 10.1016/j.epsr.2026.112905.

[7] A. M. Steele, K. Thakre, and P. Nigam, "Intelligent MPPT control for high-gain converter design to enhance PV energy system power extraction efficiency," Next Energy, vol. 12, Art. no. 100733, 2026, doi: 10.1016/j.nxener.2026.100733

[8] M. S. Endiz, "Design and Implementation of Microcontroller-Based Solar Charge Controller Using Modified Incremental Conductance MPPT Algorithm," Journal of Radiation Research and Applied Sciences, vol. 17, no. 2, p. 100938, 2024.

[9] B. I. Madububa, J. C. Mbagwu, and D. O. Isiohia, "Design, Construction, and Testing of Maximum Power Point Tracking (MPPT) Charge Controller for Photovoltaic (PV) Power Generation," Journal of Engineering Research and Reports, vol. 17, no. 1, pp. 36–47, 2020, https://doi.org/10.9734/jerr/2020/v17i117184.

[10] S. Bahadur et al., "Design and implementation of low-cost MPPT solar charge controller," Advances in Engineering Science, vol. 54, no. 2, pp. 5673–5687, Dec. 2022.

[11] T. P. F. Azevedo et al., "A model predictive control strategy for maximum power point tracking in photovoltaic systems," Control Engineering Practice, vol. 81, pp. 71–79, 2018, https://doi.org/10.1016/j.conengprac.2018.07.007.

[12] H.-D. Liu et al., "A solar energy system with a dual-input power converter and global MPPT for off-grid applications," Electric Power Systems Research, vol. 243, p. 111497, Jun. 2025.

[13] M. Hasan, A. H. Sabry, and H. S. Altinoluk, "Maximizing energy transfer of solar-battery charge controller using voltage balancing strategy," Results in Engineering, vol. 23, p. 102604, Sep. 2024.

[14] S. Yadav et al., "Effective battery charging system using step voltage and step duty size-based MPPT controller for solar PV system," Energy Reports, vol. 10, pp. 744–755, Nov. 2023.

[15] P. Kumar et al., "Design and Implementation of Solar Charge Controller for Photovoltaic Systems," ADBU Journal of Engineering Technology (AJET), vol. 7, no. 1, pp. 1–4, Jun. 2018.

[16] P. S. Acharya and P. S. Aithal, "A Comparative Study of MPPT and PWM Solar Charge Controllers and their Integrated System," Journal of Physics: Conference Series, vol. 1712, no. 1, p. 012023, Aug. 2020, https://doi.org/10.1088/1742-6596/1712/1/012023.

[17] A. Najmurrokhman, Kusnandar, T. Hambali, M. T. A. Hakim and N. Ismail, "Solar Panel Charge Controller using PWM Regulation for Charging Lead Acid Batteries," 2022 8th International Conference on Wireless and Telematics (ICWT), Yogyakarta, Indonesia, 2022, pp. 1-4, doi: 10.1109/ICWT55831.2022.9935443.

[18] F. Fianti et al., "Analysis of PWM- and MPPT-solar charge controller efficiency by simulation," Journal of Physics: Conference Series, vol. 1918, no. 2, p. 022004, Jun. 2021, https://doi.org/10.1088/1742-6596/1918/2/022004.

[19] C. Lapsongphon and S. Nualyai, "A Comparison of MPPT Solar Charge Controller techniques: A Case for Charging Rate of Battery," in 2021 Research, Invention, and Innovation Congress: Innovation Electricals and Electronics (RI2C), Bangkok, Thailand, pp. 278–281, 2021, https://doi.org/10.1109/RI2C51727.2021.9559787.

[20] M. E. Shah et al., "Design and Development of a Smart Charge Controller with Load Power Controlling System," International Journal of Scientific & Engineering Research, vol. 11, no. 1, pp. 975–979, Jan. 2020.

[21] R. K. Singh et al., "Solar Powered MPPT Buck-Boost Converter Using Adaptive ML Algorithm and Smart Controller For DC Fast Charging Application," in 2023 3rd International Conference on Emerging Frontiers in Electrical and Electronic Technologies (ICEFEET), Patna, India, pp. 1–6, 2023, https://doi.org/10.1109/ICEFEET59656.2023.10452171.

[22] D. Wang, J. Guo, Y. Zhang, T. Feng, and C. Zhang, "Enhancing solar energy generation utilization along highways: Optimizing electric vehicle charging-swapping schemes and scheduling mobile energy storage systems," Applied Energy, vol. 399, Art. no. 126389, 2025, doi: 10.1016/j.apenergy.2025.126389.

[23] H. Mamouni, K. El Khadiri, M. Ouremchi, M. O. Jamil, and H. Qjidaa, "A 0.18 μm CMOS on-chip integrated distributed MPPT (DMPPT) controller for cell-level photovoltaic solar systems," e-Prime - Advances in Electrical Engineering, Electronics and Energy, vol. 16, Art. no. 101150, Jan. 2026, doi: 10.1016/j.prime.2026.101150

[24] O. Zeb and I. Ahmad, "Advanced MPPT analysis of PV systems: A comparative study of robust nonlinear controllers, model-free controllers, and machine learning techniques," Renewable Energy, vol. 270, Art. no. 125950, Aug. 2026, doi: 10.1016/j.renene.2026.125950

[25] M. J. Khan, R. M. Singh, R. K. Kaushal, H. Malik, A. Afthanorhan, and V. K. Jadoun, "Optimized fuzzy-MPPT approach for superior solar power management in EV battery charging systems," Energy Reports, vol. 15, Art. no. 109034, Jun. 2026, doi: 10.1016/j.egyr.2026.109034