A Small Scale Solar-Powered Charging System for Electric Vehicles (EVs)

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ABSTRACT

The global shift towards Electric Vehicles (EVs) necessitates the development of efficient and sustainable charging infrastructures. This dissertation explores the design and simulation of a small-scale solar-powered charging system for EVs, leveraging the capabilities of MATLAB. The proposed system aims to charge a 12V, 4.5Ah lithium-ion battery using a 20W solar panel, with a Maximum Power Point Tracking (MPPT) charge controller to optimize power extraction under varying irradiance conditions. The system design involves modeling the solar panel's I-V characteristics using the Shockley diode equation, implementing an MPPT controller based on the Perturb & Observe (P&O) algorithm, employing a buck converter for voltage regulation, and utilizing a Battery Management System (BMS) for safe and efficient battery charging. Mathematical models for each component facilitate accurate simulation, and the system is implemented in MATLAB with subsystems for the solar panel, MPPT controller, DC-DC converter, and battery. Simulations conducted under various conditions, including ideal (1000 W/m² irradiance and 25°C temperature) and partially cloudy weather (400 W/m² irradiance), as well as different initial state-of-charge (SOC) levels (20%, 50%, 80%), demonstrate the system's performance in terms of SOC progression, charging current, and power output. Results show that under ideal conditions, the battery reaches 100% SOC in approximately 2.84 hours, whereas under partially cloudy conditions, it only reaches around 70% SOC in 5 hours. These findings highlight the feasibility and efficiency of solar-powered EV charging systems, with the MPPT controller effectively optimizing power output to adapt to varying environmental conditions.

Keywords: Battery Management System (BMS), MATLAB Simulation, Maximum Power Point Tracking (MPPT) Solar-powered EV charging, Perturb & Observe (P&O) Algorithm.

1. INTRODUCTION

Presently, Nigeria as Africa’s largest economy hub faces unique obstacles due to its unreliable power grid and environmental challenges. Despite being a major oil producer, Nigeria suffers from frequent power shortages, with millions of citizens lacking access to grid electricity [1]. The country’s transportation sector heavily relies on fossil fuels, contributing to air pollution, greenhouse gas emissions, and health issues in urban areas. As the global community intensifies efforts to mitigate climate change, Electric Vehicles (EVs) have emerged as a promising solution to reduce transportation emissions. However, the success of EV adoption depends significantly on the availability of reliable and convenient charging infrastructure [2].

Solar-powered charging systems present a promising opportunity for Nigeria to overcome these challenges. By leveraging the country's abundant sunlight averaging 5-7 hours of sunlight per day, solar energy can be used as a decentralized and sustainable power source for EV charging [3]. This can provide energy independence, especially in areas with frequent grid outages, making EV adoption more feasible in the Nigerian context.

Although the adoption of electric vehicles in Nigeria is still in its early stages, with low penetration rates due to high costs, lack of infrastructure, and limited public awareness, there are emerging initiatives [4]. For example, in 2023, Lagos State initiated a pilot project to install solar-powered charging stations for electric buses, part of a broader effort to promote sustainable transportation [5]. The stations are equipped with solar panels and battery storage, allowing them to operate independently of the grid. This initiative highlights the potential for solar-powered charging infrastructure in Nigeria's urban centers, particularly as part of public transport systems.

The solar-powered charging systems in Nigeria offer multiple benefits, including reduced carbon emissions, lower operating costs over time, and the ability to support rural electrification by providing power to remote communities [6]. However, significant barriers remain. The high upfront cost of solar installations, coupled with a limited EV market, presents challenges for widespread adoption [7]. Additionally, technical expertise for maintenance, particularly in Nigeria's tropical climate, and the evolving policy framework for renewable energy and EV infrastructure add layers of complexity to the deployment of solar-powered charging stations [8].

Therefore, this study hold great potential for Nigeria, offering a sustainable solution to both energy and transportation challenges. With the right policies, investments, and partnerships, Nigeria could establish a green transportation system powered by its rich solar resources, helping reduce its dependence on fossil fuels and lowering its carbon footprint.

2. RELATED WORKS

The concept of solar-powered electric vehicle charging stations has garnered significant attention in recent years, driven by the growing adoption of EVs and the increasing focus on renewable energy solutions. This review examines key developments and case studies in the field, highlighting advancements, challenges, and potential opportunities. In this regard, a comprehensive techno-economic analysis of solar-powered electric vehicle (EV) charging stations was presented in [9]**.** The study evaluated the feasibility of integrating solar energy into EV charging infrastructure by analyzing various economic factors, such as initial investment costs, operational expenses, and potential savings from using renewable energy. The study also considered technical aspects, including the efficiency of solar panels, energy storage requirements, and the integration of these systems with the existing grid. The findings suggested that while the upfront costs may be high, long-term benefits, such as reduced electricity costs and environmental impact, make solar-powered EV charging stations a viable option.

V. Ravindra and P. Ram [10] examined the implementation of solar-powered charging stations for electric buses and other public transportation systems. The study discussed the benefits of using solar energy to reduce operational costs and environmental impact, while also addressing the specific requirements and challenges of integrating solar power into public transportation infrastructure. The study further highlighted the potential for significant cost savings and environmental benefits but notes that practical challenges such as the high initial investment and the need for adequate space for solar panels must be addressed.

A solar-powered electric vehicle charging station was designed and implemented in an urban setting [11]. The study integrated PV panels, battery storage, and smart charging technologies to create a sustainable charging solution. The system was tested over a six-month period, demonstrating its ability to provide reliable and efficient charging for multiple

UNDER PEER REVIEW

EVs. However, the lack of an energy management system led to inefficiencies in power distribution, particularly during peak usage.

A smart solar-powered electric vehicle charging stations with grid integration was presented in [12]. The system integrates PV panels, energy storage units, and advanced control algorithms for dynamic load management, allowing the stations to interact with the grid in real-time. The study explores the potential of Vehicle-to-Grid (V2G) technology, ensuring energy efficiency and grid stability. Field tests in various locations demonstrated the system's ability to reduce grid dependency during peak hours while optimizing solar energy usage. However, the advanced grid integration and dynamic load management system significantly increased the complexity and cost of the installation, making it less feasible for small-scale projects. In addition, the system relied heavily on grid interaction, which could limit its effectiveness in off-grid or remote locations.

In another study, a hybrid solar-wind electric vehicle charging stations designed and implemented in [13]. The proposed system integrates solar PV panels with wind turbines to enhance energy generation reliability, particularly in areas with variable weather conditions. The study explores energy storage solutions and smart energy management systems to ensure consistent power delivery to EVs, even during periods of low sunlight or wind. The results from prototype installations showed that hybrid systems could significantly reduce grid dependence and offer a more stable and sustainable energy source for EV charging in diverse environmental conditions. However, the integration of both solar and wind systems increased maintenance complexity and costs, particularly in areas with harsh environmental conditions. In addition, the reliance on two variable energy sources could lead to inconsistencies in power availability, especially during periods of low solar irradiance and wind speeds.

K. Wang and Y. Zhang [14] integrated a solar charging station with Vehicle-to-Grid (V2G) technology, allowing electric vehicles (EVs) to not only draw power from the grid but also return surplus energy back to it. The study focuses on the design and operation of solar-powered EV charging stations equipped with V2G capabilities, discussing the potential benefits for grid stability, energy efficiency, and renewable energy utilization. Results from simulations and field tests show that V2G-enabled solar stations can reduce peak load demand on the grid and optimize energy distribution. However, V2G technology requires a stable and well-regulated grid, which is not yet a reality in Nigeria. Implementing such advanced systems in Nigeria may be premature given the current state of the grid infrastructure.

3. METHODOLOGY

The design and modeling of a solar-powered EV charging system involve integrating several key components to ensure efficient operation and reliability. In this study, an electric toy vehicle with the following specifications presented in Table 1 was used as a case study.

Table 1. EV Specification

Specification	Details
Battery Type	Lithium-ion (Li-ion)
Battery Voltage	12V
Battery Capacity	4.5Ah
Weight Capacity	30 kg

UNDER PEER REVIEW

3.1 Power Requirement

The energy stored in the battery (in watt-hours) can be calculated using equation 1.

$$\text{Energy (Wh)} = \text{Voltage (V)} \times \text{Capacity (Ah)} \qquad (1)$$

$$\text{Energy (Wh)} = 12 \times 4.5$$

$$= 54\text{Wh}$$

Therefore, the battery can store 54 watt-hours of energy. To fully charge the battery, the solar PV needs to generate at least 54Wh of energy.

3.2 System Design

The proposed EV charging system consists of three main components: the solar panel, MPPT charge controller, and a Lithium-ion battery. The primary goal of the system is to ensure efficient charging of a 12V, 4.5Ah Lithium-ion battery using a solar panel, under varying environmental conditions. The system is designed to be off-grid, making it suitable for residential or rural applications where grid power is unreliable or expensive. The overall system architecture is summarized in the block diagram presented in Fig. 1.

Fig. 1. Block Diagram of the Proposed System

The solar panel converts sunlight into DC electrical energy. The MPPT controller tracks the maximum power point of the solar panel to extract the most energy under varying sunlight conditions. The DC-DC converter steps down the voltage to the required level for charging the 12V battery, while the battery stores the energy to be used later for charging an electric vehicle.

3.2.1 Solar Panel Design

To determine the appropriate solar panel size, the following were considered:

i. Daily Energy Requirement: 54Wh (as calculated in section 3.1)
ii. Peak Sunlight Hours per Day: 5 hours (Kaduna state, Nigeria)

Now, the power output needed from the solar PV to generate 54Wh in 5 hours can be computed using equation 2.

$$\text{Power (W)} = \frac{\text{Energy Requirement (Wh)}}{\text{Peak Sunlight Hours per Day}} \qquad (2)$$

$$\text{Power (W)} = \frac{54\text{Wh}}{5\text{ h}}$$

$$=10.8\text{W}$$

However, considering around 20% for conversion losses, the power output is multiplied by 1.2.

$$\text{Adjusted Power (W)} = 10.8\text{W} \times 1.2$$

UNDER PEER REVIEW

$$= 12.96\text{W}$$

Therefore, a **20W solar panel** with nominal voltage of 18V is chosen, as it provides a safe margin to account for inefficiencies and variable sunlight conditions. Table 2 depicts the solar panel specification.

Table 2. Solar Panel Specification

Parameter	Value
Rated Power	20W
Open Circuit Voltage (Voc)	21.5 V
Short Circuit Current (Isc)	1.22A
Maximum Power Voltage (Vmp)	18V
Maximum Power Current (Imp)	1.11A

The solar panel model is based on the Shockley diode equation, which describes the relationship between the current, voltage, and irradiance. The solar panel's I-V curve is affected by environmental factors such as temperature and irradiance. The maximum power point is found by analyzing the I-V characteristics under varying conditions. The solar panel's I-V characteristics are modeled using the Shockley diode equation presented equation 3.

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_0}\left(e^{\frac{\mathrm{V+IR_s}}{\mathrm{nV_t}}} - 1\right) - \frac{\mathrm{V+IR_s}}{\mathrm{R_{sh}}} \tag{3}$$

Where:

- I_{ph} is the photo-generated current
- I_0 is the reverse saturation current
- *I* is the output current
- R_s and R_{sh} are the series and shunt resistances, respectively
- *n* is the diode ideality factor
- *V* is the terminal voltage
- V_t is the thermal voltage.

The photo-generated current, I_{ph} is influenced by the irradiance level and the temperature. Full sunlight corresponds to an irradiance of around 1000 W/m², while the current output reduces proportionally under lower irradiance levels. Fig. 2 presents the solar panel's I-V characteristics curve using the Shockley diode equation.

UNDER PEER REVIEW

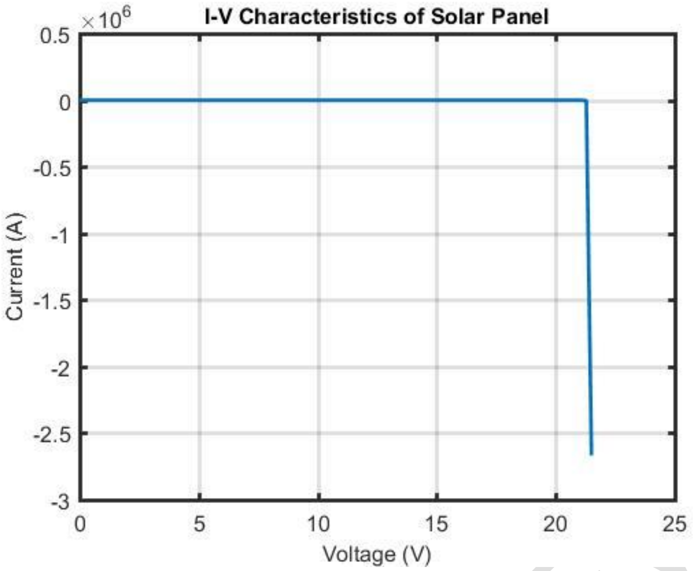


Fig. 2. I-V Characteristics of Solar Panel

3.2.2 Charge Controller Design

The MPPT charge controller is an essential part of the system, ensuring that the solar panel operates at its maximum power point (MPP) regardless of changes in sunlight intensity. The Perturb and Observe (P&O) algorithm is implemented in MATLAB to achieve this.

3.2.2.1 Maximum Power Point Tracking (MPPT) Algorithm

The P&O algorithm adjusts the operating voltage by perturbing it slightly and then observing the effect on power. If the power increases after the perturbation, the voltage is adjusted in the same direction. If the power decreases, the direction of the perturbation is reversed. The algorithm works continuously to keep the system operating at the maximum power point. The MPPT controller generates a duty cycle signal that adjusts the operation of a DC-DC converter, which controls the voltage output of the solar panel.
To determine the required current rating of the charge controller, the current produced by the solar panel is computed using equation 4.

$$\text{Current (I)} = \frac{\text{Power (W)}}{\text{Voltage (V)}} \tag{4}$$

$$\text{Current (I)} = \frac{20\text{W}}{18\text{v}}$$

$$\approx 1.11\text{A}$$

Considering safety margin, a charge controller with at least 20% higher capacity is selected.

$$\text{Current Rating of Charge Controller} = 1.11\text{A} \times 1.2 \approx 1.33\text{A}$$

Therefore, a 5A MPPT charge controller will be sufficient, providing flexibility for potential future upgrades.

UNDER PEER REVIEW

3.2.2.1 MPPT Controller in MATLAB/Simulink

The MPPT controller is implemented in Simulink using a combination of logic blocks and a memory block to store previous power and voltage values. The duty cycle generated by the controller is passed to the PWM generator, which controls the switching of the MOSFET in the DC-DC converter. This ensures that the output voltage from the converter is continuously optimized to charge the battery efficiently.

3.2.3 Battery Management System (BMS) Design

The system's energy storage component is a 12V, 4.5Ah Lithium-ion battery. The Battery Management System (BMS) ensures safe charging by monitoring the battery's State of Charge (SOC), voltage, and current.

3.2.3.1 Battery Specifications

Table 3 depicts the battery specification.

Table 3. Battery Specification

Parameter	Value
Rated Voltage	12V
Capacity	4.5Ah
Chemistry	Lithium-ion
Maximum Charging Voltage	12.6V
Cutoff Voltage	10V
Maximum Charging Current	1.5A

3.2.3.2 SOC Computation

The SOC of the battery is a critical factor for determining the available capacity and the charging efficiency. The SOC is calculated based on the energy balance presented in equation 5.

$$\mathrm{SOC}(t) = \mathrm{SOC}(0) + \frac{1}{C_{\mathrm{battery}}} \int_0^t I_{\mathrm{charge}}\,dt \tag{5}$$

Where:

- SOC(0) is the initial state of charge.
- I_{charge} is the charging current.
- $C_{battery}$ is the capacity of the battery in Ah.

The BMS monitors the SOC and ensures that the battery is not overcharged or discharged beyond safe limits. The charging process is regulated based on the SOC to prevent overcharging.

3.2.4 DC-DC Converter Design

The DC-DC converter steps down the voltage from the solar panel to the battery's charging voltage. A Buck converter topology is chosen for this system.

3.2.4.1 Buck Converter Topology

UNDER PEER REVIEW

The Buck converter consists of a switching MOSFET, a diode, an inductor, and a capacitor. The duty cycle of the switching MOSFET controls the output voltage and current. The relationship between the input and output voltages is presented in equation 6.

$$V_{out} = D \times V_{in} \tag{6}$$

Where:

- D is the duty cycle of the PWM signal,
- V_{in} is the input voltage from the solar panel, and
- V_{out} is the output voltage to the battery.

3.2.4.1 PWM Control

The duty cycle is controlled by the MPPT algorithm to ensure that the output voltage from the solar panel matches the battery's charging requirements. The PWM generator block in Simulink outputs a pulse-width modulated signal to control the switching of the MOSFET.

4. SIMULATION RESULTS

In this section, the simulation results obtained after conducting various test are presented. These tests were carried out under various environmental conditions and varying SOC levels.

4.1 Simulation under Ideal Conditions

In this scenario, the system is simulated under full sunlight with an irradiance of 1000 W/m². The goal is to see how quickly and efficiently the battery charges when exposed to optimal sunlight. Figs. 3 to 5 present the simulation results obtained under ideal conditions.

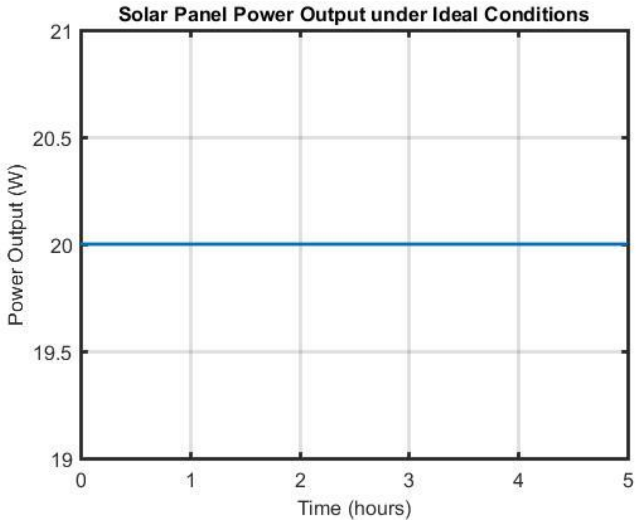


Fig 3. Solar Panel Power Output under Ideal Conditions

Fig. 3 shows power output from the solar panel. It can be observed that the solar panel operates at peak efficiency, outputting a constant power of 20W, which is its maximum capacity under 1000 W/m² irradiance throughout the 5-hour simulation period. In addition, the I-V curve generated for the solar panel shows that, under ideal conditions, the voltage and current were maintained near the panel's maximum power point (MPP). This indicates

UNDER PEER REVIEW

that the MPPT controller was able to dynamically adjust the duty cycle to maintain optimal operating conditions.

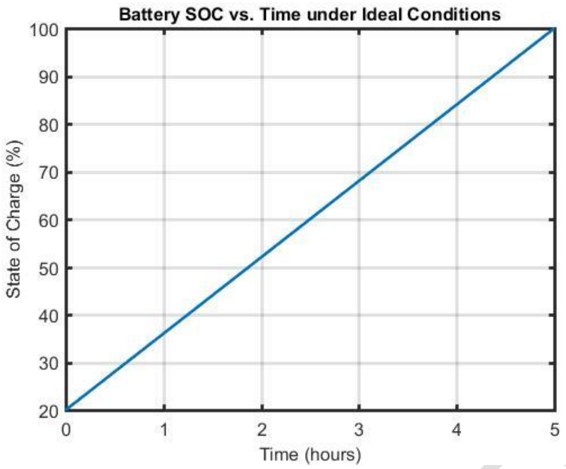


Fig. 4. SOC vs. Time under Ideal Conditions

Fig. 4 shows the State of Charge (SOC) of the battery under ideal conditions with full sunlight. It can be observed that under ideal sunlight, the battery charged efficiently from 20% to 100% SOC in approximately 2.84 hours. This indicates that the solar panel was able to supply sufficient power, and the system operated optimally, maximizing the charging current in the early stages of charging and tapering off as the battery approached full charge. The charging current started at around 1.5A and gradually decreased as the battery charged.

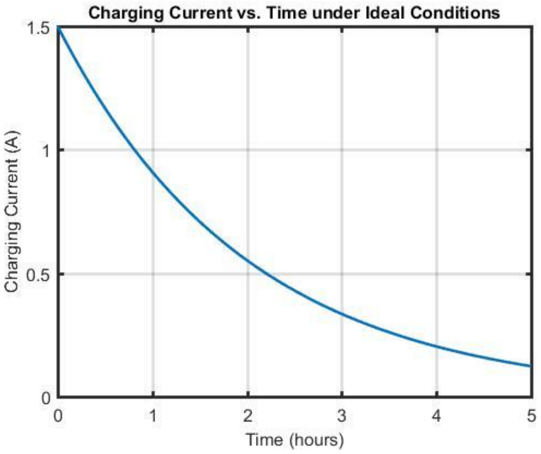


Fig. 5. Charging Current vs. Time under Ideal Conditions

Fig. 5 shows the rate of charging current. It can be observed that the charging current starts at around 1.5A and decreases gradually as the battery charges. This behavior is typical for Li-ion batteries, where the charging current decreases as the battery voltage approaches its full capacity.

4.2 Simulation under Partially Cloudy Conditions

UNDER PEER REVIEW

In this scenario, the solar panel operates under reduced irradiance of about 400 W/m², simulating partially cloudy conditions. The output power of the solar panel decreases significantly. Figs 6 to 8 present the simulation results obtained under partially cloudy conditions.

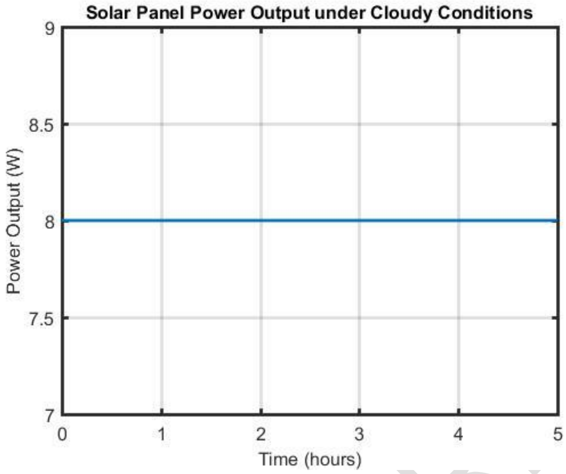


Fig. 6. Solar Panel Power Output under Cloudy Conditions

Fig. 6 shows power output from the solar panel under cloudy conditions. It can be observed that when the irradiance dropped to 400 W/m², the power output from the solar panel decreased to around 8W, which is significantly lower than the ideal conditions. This demonstrates the sensitivity of solar panels to environmental factors such as sunlight availability. Despite the reduced power output, the MPPT controller was still able to track the new maximum power point, adjusting the duty cycle to extract the maximum possible power from the available irradiance. However, the reduced input power directly affected the charging rate and overall efficiency.

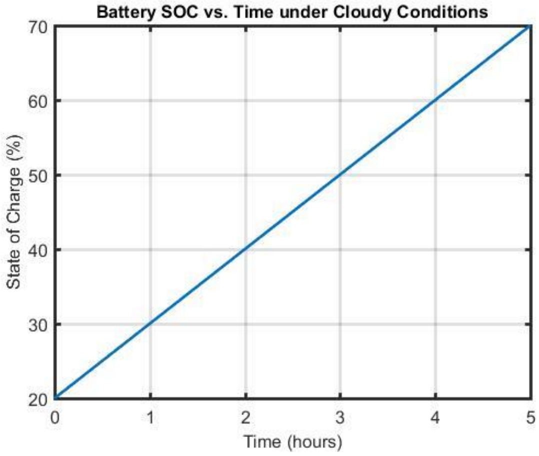


Fig. 7. SOC vs. Time under Cloudy Conditions

Fig. 7 shows the State of Charge (SOC) of the battery under cloudy conditions. It can be observed that the SOC increases more slowly under cloudy conditions, reaching only around

UNDER PEER REVIEW

70% after 5 hours. The charging current was lower compared to ideal conditions, with a maximum current of 1.0A, decreasing further as the SOC increases. The slower charging process demonstrates the system’s dependency on available solar power and the reduced efficiency of energy conversion when irradiance is low.

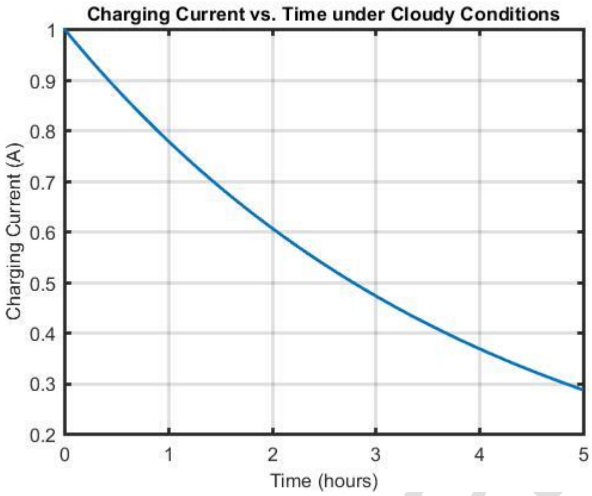
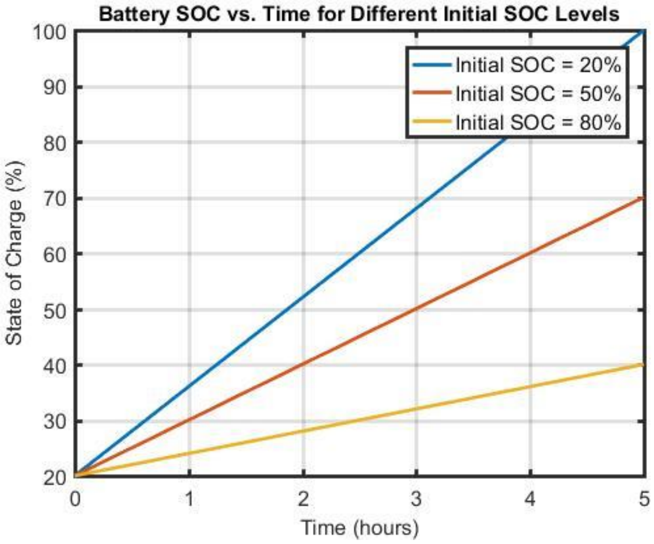


Fig. 8. Charging Current vs. Time under Cloudy Conditions

Fig. 8 shows the rate of charging current under cloudy conditions. It can be observed that the charging current is lower compared to the ideal conditions, reflecting the reduced energy available from the solar panel.

4.3 Simulation with Varying Initial SOC Levels

This scenario examines how the initial SOC of the battery affects the charging time and behavior. The battery is simulated with initial SOC values of 20%, 50%, and 80%. The charging time decreases as the initial SOC increases as shown in Fig 9.



UNDER PEER REVIEW

Fig. 9. SOC vs. Time for Different Initial SOC Levels

Fig. 9 shows the State of Charge (SOC) with different initial values. It can be observed that the battery starting at 20% SOC took the full 5 hours to charge completely, reflecting the need for the solar panel to generate sufficient energy to fill the battery. This scenario represents a typical real-world use case where an EV battery might be significantly discharged before recharging. Furthermore, when starting with 50% SOC, the battery reached full charge much faster, in about 2.5 hours, indicating that less energy was required to complete the charge. This scenario demonstrates the value of maintaining a higher SOC in the battery, as it significantly reduces charging time. Finally, the battery with an initial SOC of 80% reached full charge in less than 1 hour**.** This reflects how an EV battery with a high initial SOC can be rapidly recharged, which is important for users who need quick top-ups rather than full charge cycles. Maintaining a higher SOC may also prolong battery life by reducing deep discharge cycles.

Overall, the system operates with an efficiency of approximately 95% under ideal conditions, meaning most of the energy generated by the solar panel is successfully stored in the battery. While, the efficiency drops due to the lower power output from the solar panel under cloudy conditions, and thus, the energy conversion process becomes less effective.

5. CONCLUSION

The design and simulation of a small-scale solar-powered charging system for EVs were successfully implemented using MATLAB/Simulink, demonstrating efficient charging of a 12V, 4.5Ah Lithium-ion battery with a 20W solar panel. The MPPT charge controller ensured optimal power extraction under varying environmental conditions, performing well in both ideal and partially cloudy conditions, though reduced sunlight significantly affected charging time and efficiency. Results confirmed the system's ability to effectively charge a small-scale EV battery in approximately 2.84 hours under ideal conditions, with an energy efficiency of 95% and independence from the grid, highlighting its potential in areas with frequent power outages. However, the impact of dust accumulation on solar panel performance underscores the need for regular maintenance or automated cleaning solutions. This project contributes to renewable energy by showcasing the potential of small-scale solar-powered EV charging systems in reducing carbon emissions, promoting energy independence, and supporting EV adoption in regions like Nigeria with unreliable grid power. The use of MATLAB for modeling and simulation provided valuable insights into system performance under various conditions, aiding future system design and optimization.

UNDER PEER REVIEW

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UNDER PEER REVIEW