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PERFORMANCE ANALYSIS OF A SOLAR BATTERY CHARGE CONTROLLER FOR TYPICAL RESIDENTIAL PV SYSTEMS IN NIGERIA: A SIMULATION APPROACH

Gerard Nonso Obiora*, Okanlawon Oluwamayomikun Oluwantimilehin and Collins Belouebi Fiemobebefa

Department of Electrical/Electronics & Telecommunication Engineering, Bells University of Technology, Ota, Ogun State, Nigeria

*Corresponding Author Email: gnobiora@bellsuniversity.edu.ng
Corresponding Author Mobile No.: +2348036565846

Abstract

The performance analysis of a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) based solar battery charge controller suitable for typical residential photovoltaic (PV) systems in Nigeria was carried out in this study. The system was modelled using MATLAB/Simulink environment, with specific attention given to modelling and observing a lead-acid battery behaviour in terms of State of Charge (SOC) and Depth of Discharge (DoD). The system comprises of a PV array, MPPT controller, buck converter, lead-acid battery, inverter, and Alternating Current (AC) load. The simulation results demonstrated a gradual charging and discharging pattern. A +0.97 and +0.69 SOC change was observed for SOC of 50.97% and 90.69% under 33 minutes for both cases. The system also performed satisfactorily under varying irradiance levels – a stable 32V output PV voltage was obtained under high solar irradiance (1000W/m^2), medium irradiance (700 W/m^2), and low irradiance (390 W/m^2). The findings support the utilization of MPPT-based controllers for Nigeria's residential solar systems as such controllers ensures improved battery life and efficient energy capture, as well as reduces energy waste. This research also highlights the importance of tailoring PV systems to local load demands and environmental conditions, and thus, contributes to the deployment of off-grid renewable energy solutions in Nigeria.

Keywords: State of Charge, Depth of Discharge, Perturb and Observe, Maximum Power Point Tracking, Solar Irradiance.

1.0 INTRODUCTION

Inconsistent power supply is the major problem of many developing countries, and Nigeria is not an exception. The persistent problems with Nigeria's national grid are multifaceted with factors such as corruption, insufficient investment, poor maintenance, reliance on fossil fuels, aging infrastructure, insufficient generation capacity, politics, conflicting and inconsistent policies, operational inefficiencies, vandalization of power equipment, being major contributors to the grid failure. Nigeria has great potential for Renewable Energy (RE) specifically solar energy. With the fast advancement in photovoltaic technologies, residential solar systems are essentially needed for energy independence especially given the country's energy crisis (Nkalo, 2025; Dinneya-Onuoha, 2025; Adebayo & Ainah, 2024; Somoye, 2023). For instance, the study by Ogunjirin et al. (2020) elaborated on the unreliable electricity supply in Nigeria where a sample case study done for two local government areas in Lagos state showed that eighty-one percent of the two hundred and eighteen sample residents experience power outages three times daily on the average and have less than seven-hour supply. The authors also cited substantial gap in terms of power supply and the service delivered. Thus, residents usually resort to the use of generators to make-up for the power supply shortfalls, and this essentially leads to noise and air pollution. Meanwhile, Owosho (2025) reported that power supply shortfalls and perturbations resulted to 45% fossil fuel generator utilization, 20% equipment damage, 20% income loss and 15% food spoilage of residents and commercial outlets. Then, according to Obele (2025), about 26-29 billion US dollars is lost yearly in Nigeria as a result of erratic power supply. This amounts to about two percent of Nigeria's Gross Domestic Product (GDP) not to mention the daily struggle by residents and businesses that strive to carry out their operations in spite of the country's electricity crisis. The shortcomings of Nigeria's national grid power supply have fueled increased dependence on decentralized power systems like solar PV systems especially in off grid and rural settlements. PV systems are thus, a good alternative for homes and indeed, Nigerian residential power consumers, who seek energy independence and reliability (Yusuff, 2024; Chanchangi et. al., 2023; Tansu, Ogungbemi & Hocanın, 2022). The effectiveness of solar systems mostly depends on the performance of the battery charge controllers, which regulate both charging and discharging of the batteries to maximize the lifespan as well as efficiency. Charge controllers are important in managing the energy from solar panels, especially for off-grid residential application. The design and performance of charge controllers can remarkably impact the overall productivity of PV systems, and thus, affects energy acceptance, user satisfaction and dependency on the system (Hasan, Sabry & Altinoluk, 2024; Villapana, Lagarde, & Oquino, 2023; Apeh, Meyer & Overen, 2021). Since Nigeria is plagued with incessant grid power outages alongside other issues, efficient solar charge controllers are indeed needed so that the energy harvested from the sun is delivered to the load. The country's high solar irradiance levels present an opportunity for solar energy exploitation; however, the lack of suitable and efficient charge management solutions pose challenge for residential users.

The current advancements in technology have led to developments of different charge controllers. These include but not limited to Pulse Width Modulation (PWM), MPPT, and linear controllers. Each type has its merits as well as demerits and this depends on the specific expectations of the photovoltaic system and the battery configuration (Acharya & Aithal, 2020; Laguado-Serrano et al., 2019). PWM controllers are inexpensive and therefore, utilized in smaller, less complex systems because of their affordability. They operate by modulating the width of voltage pulses in order to keep the battery at an optimum charge level. Furthermore, PWM controllers do not fully use the energy produced by the solar panels, especially under variable weather conditions. MPPT controllers on the other hand, are capable of properly optimizing energy consumption by continuously adjusting the operation point of the PV system to the MPP even under changing irradiance levels, temperature and other weather conditions. Although expensive, MPPT controllers are better for residential systems seeking to maximize energy yield (Christian, Shuting & Bolin, 2024; Pathare et al., 2017). Compared to PWM and MPPT controllers, linear controllers are designed to regulate either voltage or current in a continuous way. They maintain constant operation which may give rise to low energy yield, especially in fluctuating atmospheric conditions like changing sunlight intensity or temperature.

The diversity of solar energy potential across different regions necessitates tailored solutions that consider local conditions, which are often overlooked in generic designs (Bamisile et al., 2025; Eze et al., 2024). The integration of charge controllers with various system components including inverters and energy storage systems, ensures seamless operation. The performance of these integrated systems is vital for achieving the desired efficiency and reliability of residential PV installations (Saad, 2025; Maka & Chaudhary, 2024). In many Nigerian homes, despite the increased adoption of solar PV systems, most existing solar battery charge controllers are not designed to accommodate local climatic conditions especially high ambient temperatures. This usually leads to poor performance and user dissatisfaction (Haruna, Ikot & Big-Alabo, 2024; Usman et al., 2020) Thus, the model and analysis of battery charge controllers for residential PV systems constitutes a crucial part of research and development in Nigeria. By tackling the specific challenges faced by users, it is feasible to optimize the efficiency of PV systems. In this present study, computer-based simulation of the performance of a solar battery charge controller will be carried out. And the objectives of this study are as follows:

i. To model a P&O MPPT based solar battery charge controller for residential utilization in Nigeria
ii. Assess the performance of the developed system in terms of SOC, DOD and solar irradiance variation

Specifically, the study targets low-income and remote residential power consumers as the end users of this solution. Nigeria's unique climatic condition in terms of her average ambient temperature (Ajiere & Weli, 2018) will be considered while selecting the system model parameters

2.0 SURVEY OF RELATED WORKS

A number of related studies have been executed in relation to this present research. And a survey of a few of them will be done in this section. Akinsipe, Moya, & Kaparaju (2021) examined the practicability of deploying a freestanding PV system for household utilization in a northern state in Nigeria, owing to the epileptic nature of supply from the country's power grid. Their research provided a framework for PV system deployment within the country especially for residential buildings. It is noteworthy that the study followed a mathematical model-based approach. Part of Hasan & Altinoluk (2023) study was the analytical review of PV battery system charge controllers and their chances of failing. The authors also recommended areas in existing charge controllers that need some form of corrections so that the chances of failure will be reduced and that, such controllers will further help to optimize the efficiency of the systems they are tied to. Part of the authors review was on the general overview of controller types, their algorithms and topologies but specific geographical challenges tied to the utilization of the solar controllers was largely not considered.

Carrera et al. (2025) on their part, analyzed the diverse factors capable of influencing solar PV systems performance. The factors can be installation-based, environmental-based, technological-based or design-based. The review considered environmental factors like contaminants and temperature as part of the factors influencing PV operation but there was no geographic specificity.
Kadeval & Patel (2024) designed and physically implemented an MPPT-based solar charge controller for solar PV system enhancement. However, emphasis on the operation of the system or its durability under specific environment stresses was not done. The study done by Aboagye et al. (2022) illustrated how PV system efficiency is undermined by maintenance and design, as well as charge controllers' function in deep discharge prevention if properly installed. While the study cites maloperation of charge controllers and utilization of low-quality components as the major cause of abandoned systems, the technical analysis of which components fail and why was not done. Oyedepo et al. (2019) executed an economic as well as technical assessment of a Hybrid Energy System (HES) for electricity production in remote communities in Nigeria. The six geopolitical zones in Nigeria were considered and the study's model was based on five hundred rural homes. Results from the study shows that the northern part of the country has a very high potential of RE Sources (RESs), and proper utilization of such resources will help meet the energy needs of the end-users in that location. Impact of weather and environmental factors were not analyzed by the authors for the said focus location of their study. Although no field or experimental data was utilized, Afolabi & Farzaneh (2023) study focused on the optimal design of a freestanding Hybrid RE (HRE) system for a Nigerian community using fuzzy logic control. And the outcome of their research is significant for the implementation of mini-grids in Nigeria's rural communities.
Comparative analysis of different MPPT techniques with respect to battery charging for solar PV systems was executed by Kumar et al. (2022). In their study, diverse charging circuits were compared with the MPPT techniques. The study thus gives useful insights of the MPPT method that is best suited for a given solar charge controller for a specific local application. Meanwhile, the financial implications of the techniques were not considered. Khan et al. (2022) discussed the management, control and sizing strategies of HRE systems. The study is useful, in that, diverse system design optimization strategies were also discussed. However, though MPPT was highlighted as a crucial control strategy but focus was on intelligent and metaheuristic methods. In addition, these methods are sophisticated and are computationally intensive.
Reddy & Reddy (2024) gave a comparison of PV-based SEPIC (Single Ended Primary Inductor Converter) and ZETA DC-DC converter topologies for Electric Vehicles (EVs) charging system. Although the study was not focused on residential utilization of their proposed system but provided valuable information regarding the specific strengths of both considered topologies that can be adapted to other context of PV application. The result of the study shows that SEPIC DC-DC converter is the ideal option for EV charging applications. The study by Pooja et al. (2022) was on the model of an MPPT based solar PV battery charge controller. Of the three techniques considered – P&O, fuzzy logic (FL) and Incremental Conductance (IC), the P&O technique was the best in terms of the time response, output power and efficiency results but the operation of the system with respect to partial shading scenario was not considered. Meanwhile, three MPPT techniques was also examined by Atri, Modi & Gujar (2021) but in their case, fractional open-circuit voltage was the third technique investigated in place of FL. The methods were subjected to varying

irradiance conditions and the corresponding results analyzed. Inclusive in their study, was the hardware execution of the solar charge controller. The hardware implementation and test environment of the system was rather generic than specific especially considering regions with high temperatures exceeding 25°C.

Deepika et al. (2023) proposed an MPPT-based charge controller for fast battery charging, with the end goal geared towards PV system efficiency. Faster charging rates and better energy extraction were some of the results of the research. This is vital for household utilization as it will aid in meeting the consistent energy needs of residents of developing countries such as Nigeria. The end result of the study also confirmed the strength of MPPT controllers over PWM controllers, as the better outcomes were obtained with the former. Meanwhile, no cost-benefit analysis was done in the study. Abraham et al. (2023) on their part, implemented a solar charge controller for household charging stations which was further tailored for low-speed e-scooters. The implemented controller guaranteed the system dependability and battery life. Khera et al. (2015) analyzed the performance of a microcontroller-based charge regulator that was incorporated to a solar PV system. The aim of the authors' study was to enhance the discharging as well as charging of the battery of the modelled system. The designed charge controller demonstrated satisfactory performance as observed from the obtained results but the study lacks solar irradiance variation tests to further ascertain the operation of the designed regulator under such conditions. For Putra, Afianti & Watiasih (2022), the authors did a comparison of PWM-based and MPPT-based solar controllers in order to determine which one amongst the two, is better. The end result showed that on some occasions, the PWM controller was better while for some other occasions, the MPPT controller was better.

For Ratnani & Joshi (2021), the authors proposed a cost-effective solar charge regulator that was neither PWM or MPPT based but was rather on Programmable Intelligent Control (PIC). The function of the PIC of the charge controller is to regulate and coordinate the operation of the proposed system. The end result of the authors' study showed that the designed system is reliable, works optimally and as well, cost effective. In Santosa, Anam & Pamuji (2020) study, it was discovered that the MPPT based approach fast-tracked the battery charging time and enhanced more power input. But on the other hand, the proposed solution of the study is more of for an onshore rather than offshore application. Table 1 shows the summary survey for only the solar charge controller studies.

Table 1: Summary survey for the solar charge controller-based studies alone

Reference	Study focus	Key findings	Limitation(s)/research gap(s) identified
Khera et al. (2015)	Solar charge controller (SCC) design for PV systems	✓ Enhanced control of the battery charging and discharging operation tied to the system was attained ✓ Battery overcharge protection was achieved ✓ Reverse current flow prevention was also attained	The study lacks solar irradiance variation tests to further ascertain the operation of the designed regulator

Santosa, Anam & Pamuji (2020)	Model and execution of a P&O MPPT based SCC for light fishing	✓ Improved battery charging time ✓ Enhanced power input	The proposed solution is more of for an onshore rather than offshore application
Atri, Modi & Gujar (2021)	Assessment of the performance of three MPPT technique tied to the modelled SCC	The IC MPPT method outperformed other techniques as 89.96 percent efficiency was achieved with it	The hardware implementation and test environment of the system was rather generic than specific especially considering regions with high temperatures exceeding 25°C
Ratnani & Joshi (2021)	Design of a SCC for utilization in rural areas	A cost-effective solution was proposed and its performance successfully tested	The proposed regulator was neither PWM or MPPT based
Putra et al. (2022)	Comparison of PWM and MPPT based SCCs	The obtained results indicated the merits and demerits of the compared control techniques in specific applications	The demerits of each control method were brought to light in specific application contexts
Kumar et al. (2022)	Assessment of different battery charging topologies	The assessed methods can be utilized for freestanding, EV battery and remote solar PV applications	✓ The financial implications of the techniques were not considered ✓ Simulation of the system considering partial shading conditions and varying solar irradiance levels was not done
Pooja et al. (2022)	Assessment of the performance of three MPPT technique tied to the modelled SCC	Of all the MPPT methods assessed, the P&O technique was the best in terms of the time response, output power and efficiency results	Simulation of the system considering partial shading conditions was not considered
Hasan & Altinoluk (2023)	Survey of SCCs	Recommendations were made on areas that need some form of corrections in the SCCs in order to prevent failure	The geographical challenges tied to the utilization of the reviewed SCC was largely not considered

Deepika et al. (2023)	Attainment of fast charging rates with a suggested MPPT based SCC	Satisfactory energy extraction and enhanced battery charging rates was attained	Cost-benefit analysis was not done
Abraham et al. (2023)	Development and verification of a SCC for home-based e-scooter charging stations	The designed system was for slow-moving e-scooters	Focus was on e-scooter charging stations
Kadeval & Patel (2024)	Development of a SCC for the enhancement of PV systems	Improvement of the efficiency of PV systems was the study's aim	Emphasis on the operation of the system or its durability under specific environment stresses was not done

From the related works reviewed, it thus shows research efforts by scholars in proffering various frameworks that can be adapted for location specific local PV system development and installation.

3.0 MATERIALS AND METHODS

In this section, the MATLAB/Simulink model of a residential solar power system with MPPT charge controller and lead-acid battery storage will be presented. The model consists of the following key units: solar PV panels, battery bank, charge regulator, and inverter subsystems. Ode15s solver type was utilized and the components of the system were configured with focus on Nigeria's climatic and geographic location needs especially with respect to the average ambient temperature of the country (Ajiere & Weli, 2018).

3.1 System Block Diagram

The block diagram of the developed system is depicted in Figure 1.

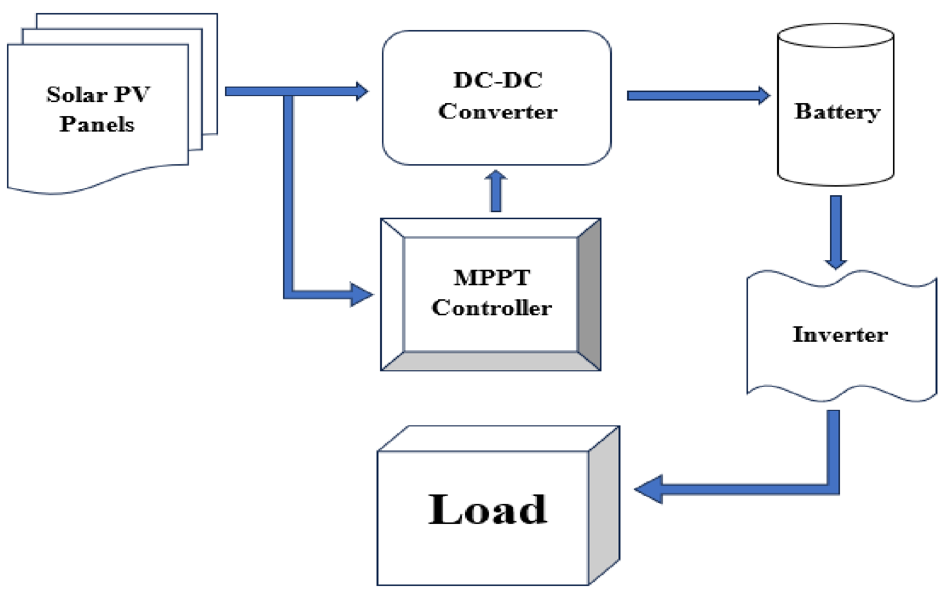

Figure 1: Block diagram of the modelled system

3.2 Subsystems of the Developed System

The aforementioned units are the key component parts of the overall developed system. Thus, these component parts will be discussed in this section.

i. Solar PV Panel Model: In this study, the required parameters of the PV panels such as irradiance and temperature were considered in order to provide realistic simulation of the environment. The goal being to replicate the electrical dynamic nature of a real residential solar PV system. The panel parameters are shown in Table 2 while the PV panel subsystem is shown in Figure 2.

Table 2: Solar panel parameters with their corresponding description

Panel Parameter	Description
PV Array	Incident irradiance & Temperature (1000 W/m^2 at 30°C)
Nominal Voltage	32V
Panel Power	300W
Open Circuit Voltage	39.83Volt
Short Circuit Current	9.74A

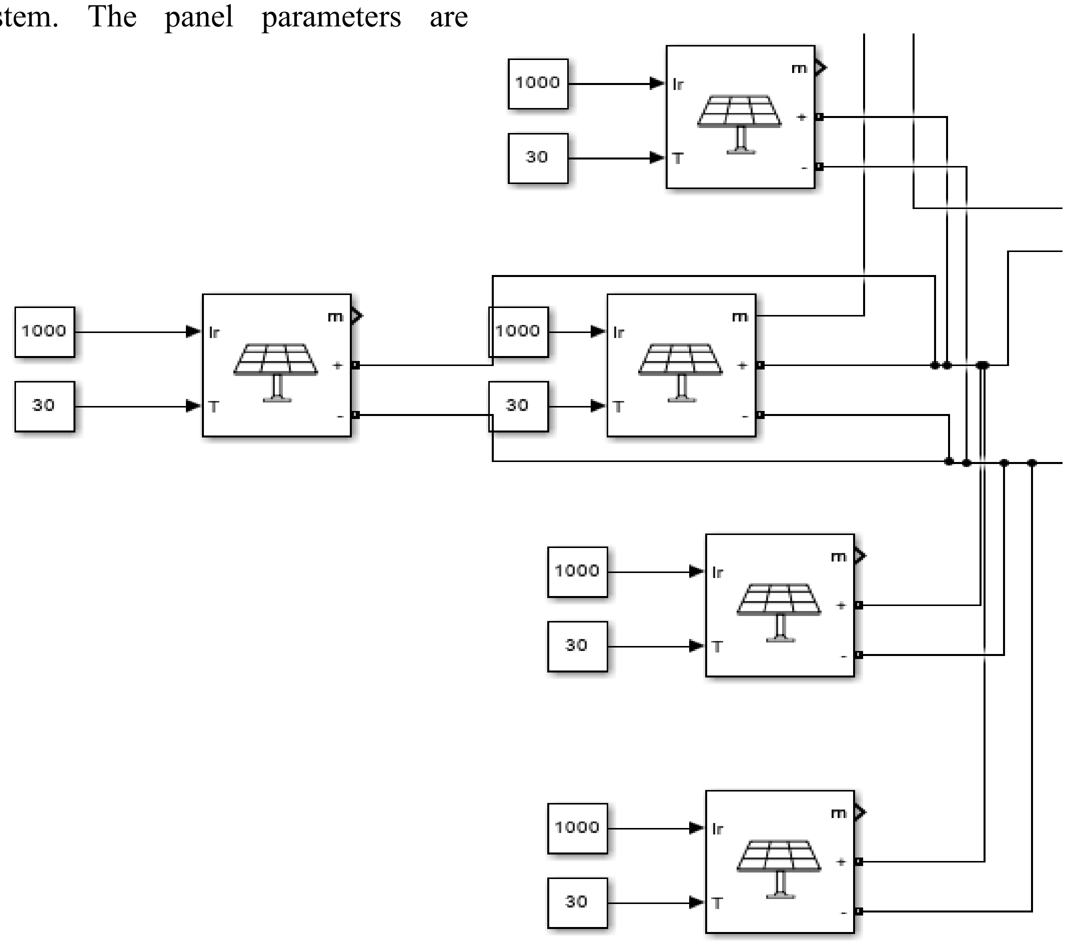

Figure 2: The PV panel model subsystem

ii. Charge Controller and DC-DC Converter Model: The features of the charge controller were modelled to aid control the charging and discharging of the battery. It helps to prevent over charging or drastic discharging of the battery, and hence, maximizes the battery life as well as the overall system reliability. Linked to the controller, is a DC-DC buck converter, which adapts the voltage to the corresponding required level, so that the power provided by the PV array, can effectively charge the connected battery of the system. This unit is critical in power conditioning and efficiency optimization with respect to the designed system and responds to alterations in solar generation, battery SOC and the loads.

The succeeding parts of this section further explains this unit in detail.

When sunlight is incident on the PV panels, the captured power is DC. The panels' output varies depending on environmental conditions like the sunlight intensity and ambient temperature. This in turn, determines the cumulative power produced by the panels. At the heart of the system lies the MPPT controller, a crucial component that unceasingly adapts the converter's duty cycle. This intelligent regulation ensures the solar panels consistently deliver their maximum available power, even as sunlight conditions change throughout the day. It involves two parts:

a. MPPT Control Block: The MPPT controller guarantees that the solar panel's output is always at the MPP by unceasingly monitoring the panel's current and voltage in order to calculate the power in real time. Since P&O is simple to implement and has low computational burden, it was utilized in this study to determine the best duty cycle needed for efficient tracking. This duty cycle is dynamically adjusted to correspond to variations of the prevalent environmental conditions. By optimizing the duty cycle, the controller maintains peak power extraction from the PV array. The resulting duty cycle is then sent to the DC-DC buck converter to regulate the output voltage accordingly. The P&O algorithm is depicted in Figure 3. The duty cycle range is 0-0.95 and the step size, 0.0091.
b. Buck Converter: This reduces the high voltage output from the PV panel to a lower voltage value suitable for charging the battery. It has the following components as part of its make-up: diode, MOSFET (Metal Oxide Semiconductor Field Effect Transistor) switch, a capacitor and an inductor. The converter receives the duty cycle signal from the MPPT controller and adjusts its output accordingly. This thus ensures stable battery charging while maintaining high system efficiency. The output voltage is governed by Equation (1).

$$V_{Output} = D \, x \, V_{Input} \qquad (1)$$

where D is the duty cycle.

Figure 4 shows the combined representation of the DC-DC buck converter and MPPT block (at 30kHz switching frequency).

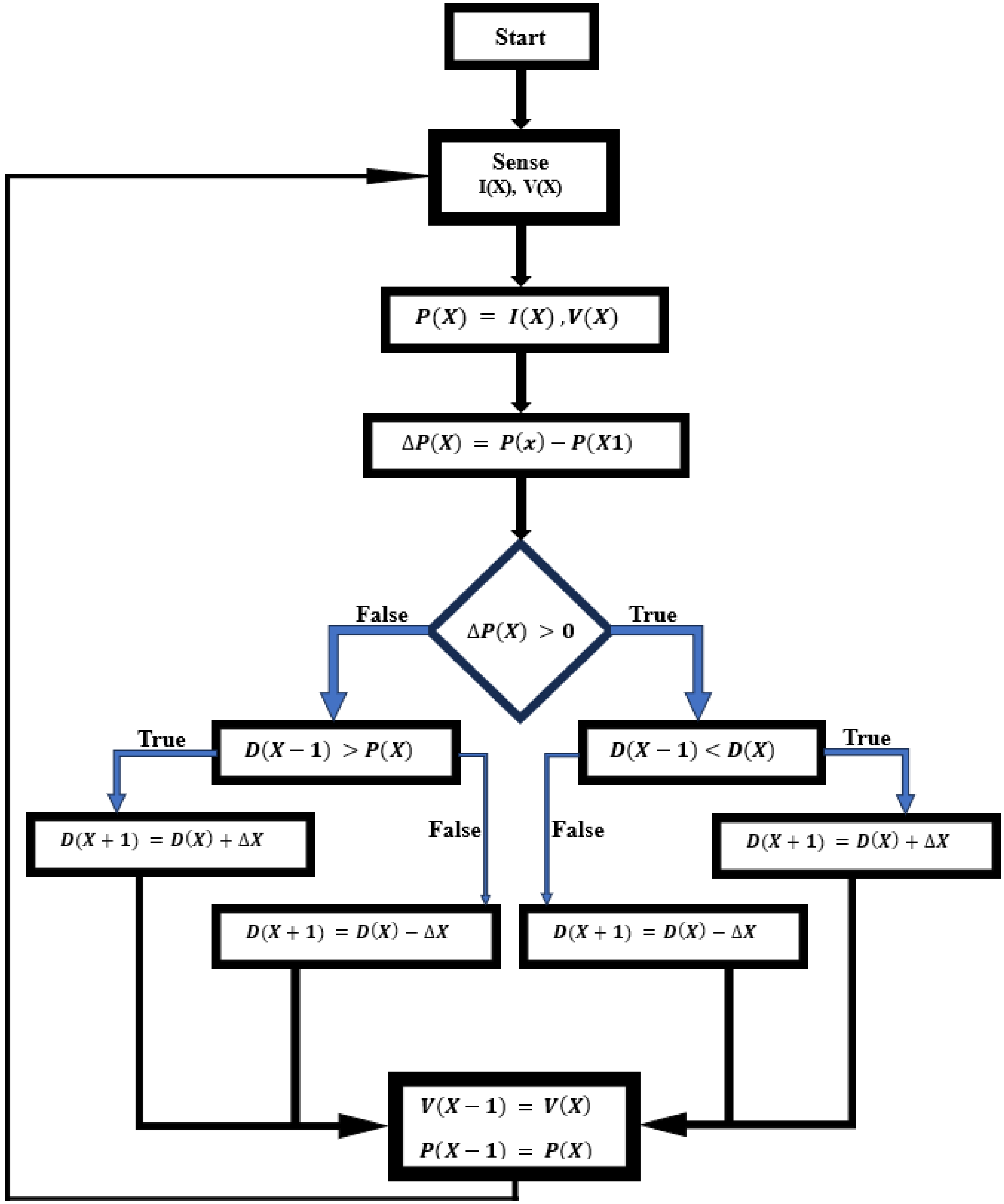

Figure 3: P&O algorithm flowchart for the modelled system

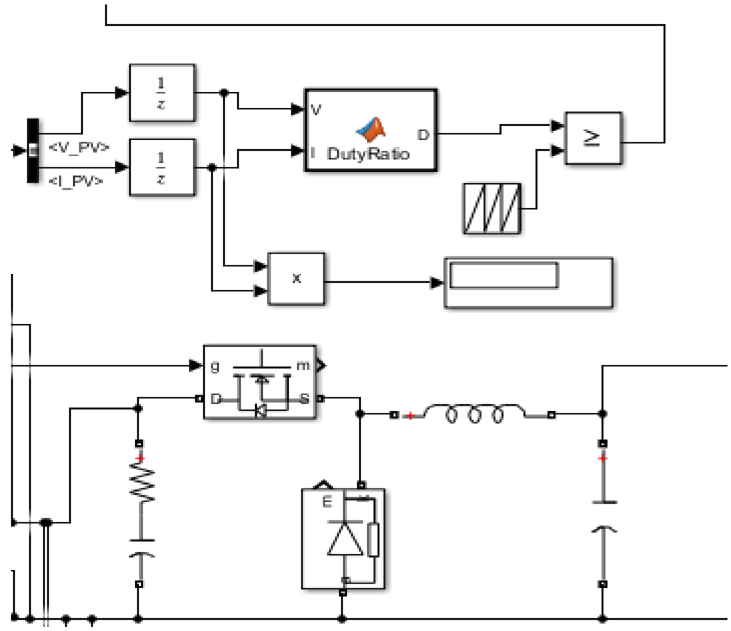

Figure 4: DC-DC buck converter unit + MPPT block

iii. Energy Storage System (ESS) Subunit: In this study, lead acid battery was utilized because it is affordable and as well, suitable for homes with a limited budget. Furthermore, this system was executed with remote residential units in mind, and with such home units situated mostly in tough environments. Some of the notable parameters of this unit are listed in Table 3 and Figure 5 shows the corresponding model diagram of the ESS subsystem.

Table 3: Notable parameters of the ESS subunit

Parameter	Description
Maximum Capacity	1200Ah
Nominal Voltage (NV)	12V
Cutoff Voltage	9V
Voltage at full charge	13.0658V
Nominal Discharge Current	240A
Internal Resistance	0.0004Ω
Capacity @NV	372.3330Ah

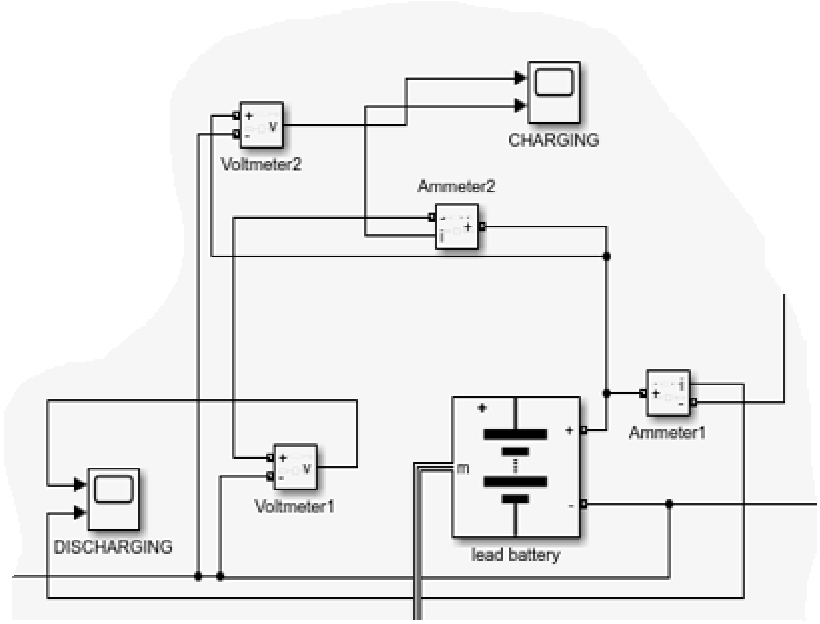

Figure 5: ESS unit of the modelled system

iv. Inverter Unit: 2-pulse generator and 4-MOSFET blocks was utilized in this study to build a square wave PWM inverter unit for powering a 4.41Ω (49.86A at $220V_{AC}$) load. This unit is responsible for the conversion of the DC power from the battery to AC power needed by the connected load. Specifically, the MOSFET enables optimal DC-to-AC power conversion with low power loss. Their purpose is to optimize energy conversion, minimize heat dissipation, and improve the overall system efficiency of the model. While the pulse generators produce precise switching signals to control the four MOSFETs. These timed pulses determine the output AC wave-form's frequency, voltage, and shape. Thus, its representation is shown in Figure 6.

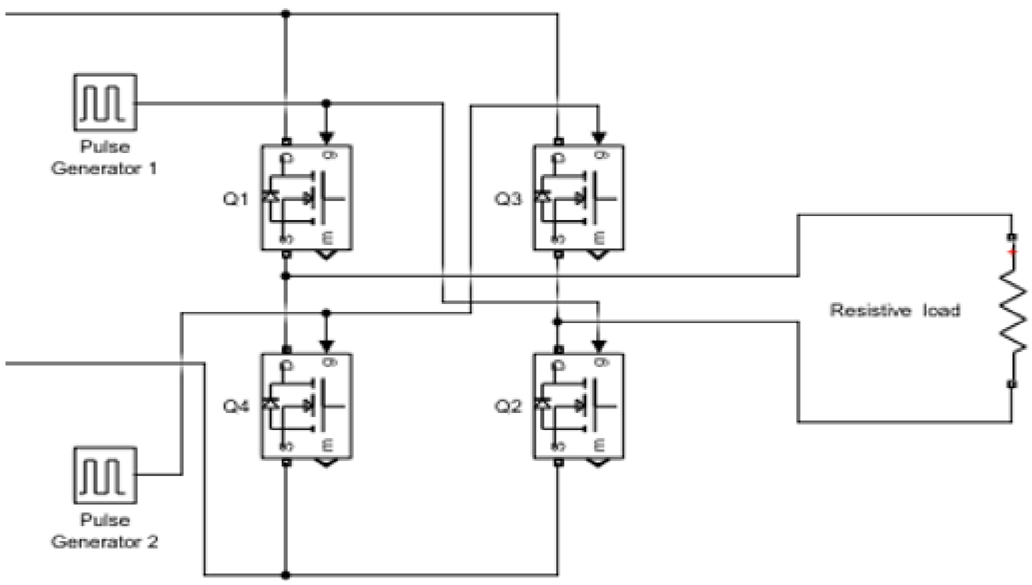

Figure 6: The modelled inverter unit with a connected resistive load

3.3 System Operation

The PV array, configured with the optimal test condition of the concerned geographical location - Nigeria (1000W/m² irradiance at 30°C), serves as the DC power source. Its output is linked to a DC-DC buck converter through an MPPT controller (P&O), necessary for stepping down the panel's voltage to 12Vdc required for charging the lead acid battery. The converter's output was fed into the lead-acid battery bank. For MPPT control, the PV voltage and current measurements was passed through a bus to a delay block. This was further fed into a custom MATLAB function containing the MPPT algorithm, which processes the data with the aid of conditional logic and relational operators. The algorithm's output controls the buck converter's switching MOSFET through pulse signals, while a product block calculates the PV output power. Linked to the lead acid battery unit is a 1Ø H-bridge inverter topology. This inverter consists of 4-MOSFETs and 2-pulse generators that is phase-shifted by 0.01 seconds. This drives the MOSFET gates in complementary pairs (Q1/Q2 and Q3/Q4) to generate a square wave output. And this configuration alternates the conduction paths during the positive and negative half-cycles. Then, connected to the inverter unit, is the consumer load. The overall system configuration is designed to facilitate optimal regulation of the battery charging and discharge according to prevailing atmospheric conditions. The overall modelled system circuit is thus shown in Figure 7.

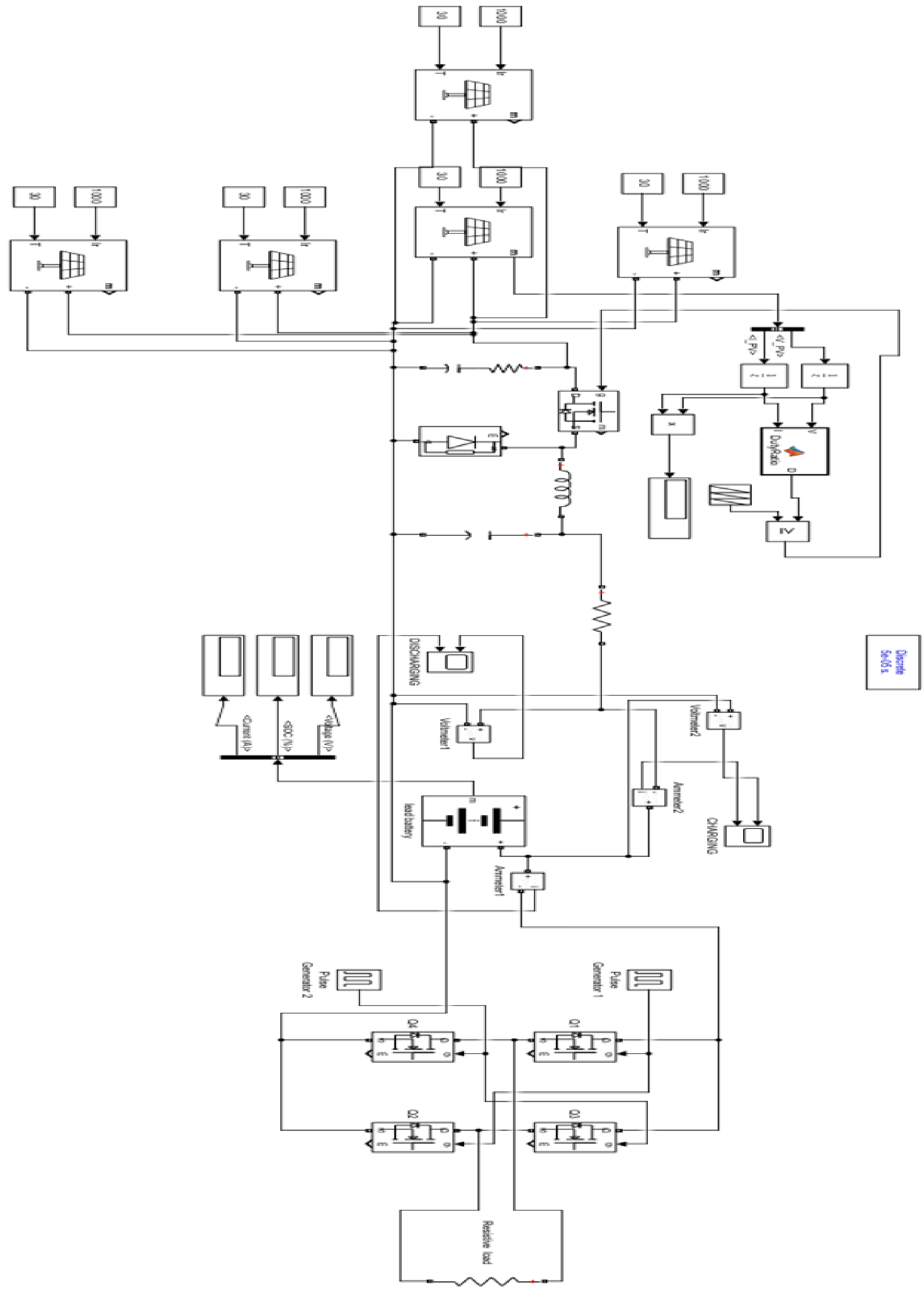

Figure 7: Overall modelled system circuit diagram

4.0 RESULTS AND DISCUSSIONS

The performance of the developed model will be evaluated in this section. The developed system was subjected to three test case scenarios: State of Charge (SOC), Depth of Discharge (DoD) and varying solar irradiance.

- **SOC Test**

SOC is a term that quantifies the amount of electrical energy remaining in a battery relative to its maximum capacity. For instance, a 0% SOC denotes a fully discharged battery (that is, one that is completely empty) while a 100% SOC denotes a fully charged battery. The change in the SOC of the lead battery utilized was monitored for 33 minutes for two test cases, with the details depicted in Table 4.

Table 4: SOC analysis of the lead acid battery (1000 W/m^2 at 30°C)

Charging Test Number	Initial SOC (%)	Final SOC (%)	SOC Change	Simulation Time (Minutes)
1	50	50.97	+0.97	33
2	90	90.69	+0.69	33

For the first test, the observed change in SOC (0.97 percent) in 33 minutes indicates a slow but steady charging rate. This progressive growth validates the combined efficiency of the buck converter and the P&O MPPT charge regulator in maximizing power extraction from the PV arrays, and subsequent transformation and transfer to the lead acid battery. Meanwhile, the choice of the initial SOC of 50 percent represents the linear and stable operating range of the battery's voltage region and thus, it is ideal for testing how efficient the battery is, as well as for peak current acceptance. Furthermore, the reduced charging rate is due to the dynamic nature of lead-acid batteries, and this decreased charging rate aids in guaranteeing the longevity and overall health of the battery.

In the second test, the 0.69% SOC change in the same 2000 seconds for the 90 percent SOC range, is a clear empirical expression of the absorption phase of lead-acid batteries, during which the regulator slows down current in order to avoid overcharging the battery. The SOC change from 0.97 to 0.69 percent affirms the modelled regulator's ability to dynamically transition between the charging phases (bulk charging stage [Test 1] and the absorption stage [Test 2]). This was possible as a result of the control loop's accuracy in adjusting the duty cycle of the buck converter not only in tracking the MPP but also to restrict the charging rate based on the lead acid battery needs as it nears full capacity.

These findings confirm some of the major points in the system design. To begin with, the change in SOC (0.97% versus 0.69%) confirms the non-linear charging behaviour of lead acid batteries when they approach full capacity. This further validates the precision of the modelled battery's SOC. Secondly, it demonstrates the MPPT controller's dynamic response ability, as it is capable of aligning its operation in accordance with the battery's varying conditions (absorption and bulk charging stages) while at the same time, maintaining uninterrupted MPPT. In the case of residential applications in Nigeria, where solar irradiance changes continuously over the course of the day, this steady charging rate is critical in establishing power dependability as well as battery life expectancy. The fact that the controller can slow down the charging rate when the battery is almost fully charged follows best practices in ensuring that off grid solar systems do not experience overcharging and that the battery lasts longer.

- **DoD Test**

DoD is a term that describes the percentage of a battery's total capacity that has been used up (that is, discharged). It is a critical parameter in battery management and essentially, the complement of the SOC. For example, a 100% DoD denotes a fully depleted battery, 50% SOC denotes a 50% DoD – a half empty battery, and a 100% SOC denotes a fully charged battery with DoD being 0%. The DoD percentage of the lead battery utilized was also monitored for two discharge test scenarios. Table 5 shows the details of the two tests.

Table 5: DoD analysis of the lead acid battery (1000 W/m^2 at 30°C)

Discharge Test Number	Initial SOC (%)	Final SOC (%)	DoD (%)	Simulation Time (Seconds)
1	100	94.78	5.22	5000.00
2	100	50.00	50.00	47892.72

The DoD tests give valuable insights on the performance of the system under load conditions. The discharge features indicate firm linearity across the test range, and from the DoD of 50% in 47897.72 seconds, the discharge rate is 0.001044%/s (DoD percent/time). Applying this rate to the first test, we have that 0.001044%/s times 5000 seconds, gives a DoD percent of 5.22, and this conforms with the DoD observed in Test 1. The discharge rate from 100 percent SOC to 50 percent, demonstrates that the power output from the battery was consistent as well as the stable operation of the modelled system inverter in DC to AC power transformation. Furthermore, this discharge rate implies that the terminal voltage of the battery remained within the operational limit of the connected load. Meanwhile, for Test 2, the attainment of 50 percent DoD in 13.3 hours under the same conditions suggests that the modelled system is reliable, and can serve the typical loads of residential buildings for a long duration while maintaining the battery health. Furthermore, the findings support the design parameters of the system and emphasizes the significance of correct DoD management for off-grid solar systems. In addition, the results highlight the importance of controlling the load and optimizing charge controllers to achieve maximum battery life for real world applications, where the daily DoD cycles may be 20-50% with respect to system design and operational cycles.

- **Varying Solar Irradiance Test**

The aim of this test is to examine how change in solar irradiance will influence the PV output voltage, current, power and charging behaviour of the battery. Table 6 depicts three solar irradiance conditions investigated and the results obtained respectively.

Table 6: Analysis of different solar irradiance (at SOC of 50% and voltage of 11.94V)

Solar Irradiance (W/m^2) at 30°C	Power Generated (W)	PV Voltage (V)	Battey Voltage (V)	Battery Current (A)	Simulation Time (Seconds)
1000 (High)	232.00	32	12.12	22.26	50
700 (Medium)	151.10	32	12.11	21.33	50
390 (Low)	115.50	32	12.09	18.06	50

Table 6 shows the solar irradiance result of the modelled system at varying conditions of the sun. The high solar irradiance (1000W/m^2) indicates that the sun intensity was highest during that period. For the medium irradiance (700W/m^2), the intensity of sunshine was lower while the low irradiance (390W/m^2) indicates a cloudy weather condition or evening period when the sunlight intensity is very low. The maximum power output of the system was 232W at high irradiance, and 151.1W and 115.5W at medium and low irradiance respectively. This indicates that the intensity of the sun rays influences power output.

The starting voltage was approximately 11.94V due to the fact that the battery was at a half SOC whereas the final voltages were 12.09V, 12.11V and 12.12V at low, medium and high irradiance respectively. The linear rise in voltage with increase in solar irradiance means that the battery was charged at a satisfactory rate. The rate of charge was highest during the high irradiance period and lowest during the low irradiance period. This trend clearly indicates that the MPPT controller was able to adapt well to changing weather conditions. The current was found to vary significantly with variation in the intensity of sunlight. Under high irradiance, current was 22.26A, it decreased to 21.33A at medium irradiance and further decreased to 18.06A at the lowest irradiance. It can be seen that this behavior is the natural decline in current generation due to decrease in solar irradiance levels. This means that decrease in solar irradiance leads to decrease in current and vice-versa.

Overall, the results as depicted in Table 6 shows that the MPPT charge controller was able to maintain a steady voltage (32V) regulation. This further indicates that MPP was achieved with respect to varying solar irradiance levels. The system was also able to maximize the available solar energy in charging the lead acid battery even in the presence of solar irradiance fluctuations, which indicates that the system is stable and reliable.

4.4 Economic Overview of the Modelled MPPT Controller

From the results on the performance of the modelled system, it indicates that the study is of paramount importance given Nigeria's persistent power supply challenges, that leave many residences (especially remote locations) without power. Solar energy is a viable and economical alternative for households in Nigeria since supply from the national grid is bereft with a lot of challenges such as regular grid power outages, and other issues such as dependence on fossil fuel generators. Despite the fact that the country has an abundance of solar irradiance supply, the performance of solar systems is however usually limited by poor power harvesting. Hence, the need for efficient solar battery charge controllers. The modelled system ability to dynamically regulate the duty cycle in order to keep the MPP, means that useful power is continuously obtained. Thus, even when irradiance is not constant, the solar power available is not wasted but converted into useful power.

Furthermore, the results from the performance analysis of the developed system confirms a number of advantages an MPPT controller has over other controllers such as the PWM and linear controllers. Firstly, the main advantage of the MPPT controller is its MPPT capability. Since, a solar panel's peak power output point varies constantly with solar irradiance and temperature. The MPPT controller solves this problem by utilizing an algorithm (in the case of this present study, P&O algorithm) to unceasingly find this optimal operating point and thus, convert the solar-PV panels high voltage and low current output, to the lead battery's required voltage and corresponding current. This conversion ensures that the panel delivers its full potential power, leading to an increase in energy capture compared to other controllers such as the PWM type especially when the battery is low and the incident temperature is cold.

The initial cost of MPPT charge controllers is rather high but the payback period (called return on investment) in the long run is worthwhile especially given the Nigerian situation where diesel or fuel prices are constantly on the rise or unstable (Okpo, Okonkwo & Nwafor, 2025), coupled with regular and unexpected grid power outage that can affect operations as well as the exorbitant bills from the electricity distribution companies that consumers struggle to pay on a monthly basis (Obiora, Igbinosa & Fiemobebefa, 2025). The capability of the MPPT based system to control the high panel voltages and ensures that about 12V is delivered to the lead acid battery, helps to boost the life of the battery and ensures stability of the system. Furthermore, the cost of PV systems maintenance is lower in the long-term, added to the fact that the system can be deployed and utilized in off-grid locations such as rural communities with limited or no access to the national grid.

5.0 CONCLUSION

This study was carried with the target end users in mind – rural communities with little or no access to electricity. Residents of these communities need some form of power supply for their day-to-day activities. Hence, power supply is needed for general illumination of the environment at night, for cooking, for navigating the home environment at night especially for breast feeding mothers, for charging of phones and other mini-power consuming gadgets used in such communities.

With the above said, the MATLAB/Simulink model of a P&O MPPT charge controller was modelled and simulated in this study with an average ambient temperature of 30°C utilized considering Nigeria's solar irradiance temperature profile. Furthermore, useful insight on important performance parameters such as SOC and DoD was given. These parameters are necessary for maximizing the life and efficiency of the solar battery and the overall system. Meanwhile, the system was also simulated considering three solar irradiance levels that is usually experienced in the country at different times of the day, and the irradiance levels were categorized as low, medium and high for testing purpose. The modelled system was subjected to only varying solar irradiance, DoD and SOC tests but the performance of the system can be analyzed considering other metrics. These other metrics can be explored as well as the hardware implementation of the system in future research.

Author's Contribution Statement

Gerard Nonso Obiora: Conceptualization, Supervision, Investigation, Validation, Writing – original draft, Writing – review & editing. **Okanlawon Oluwamayomikun Oluwantimilehin:** Conceptualization, Formal analysis, Methodology, Software, Resources, Validation. **Collins Belouebi Fiemobebefa:** Writing – review & editing.

Declaration of Competing Interest

The authors have no competing interest to declare.

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