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Review Article

Comparative Study of MPPT and PWM Charge Controllers: Designing an Efficient Solution for Small-Scale Solar Installations with Budget Constraints

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Abstract

In the context of the energy transition, optimizing photovoltaic solar systems with charge controllers plays a crucial role in managing the energy produced by solar panels and its storage in batteries. Two dominant technologies are used in this field: MPPT (Maximum Power Point Tracking) and PWM (Pulse Width Modulation). This paper presents an in-depth comparative study of these two technologies, focusing on their efficiency, cost, and suitability for small-scale solar installations, particularly in rural African contexts where budget constraints are significant. The study begins with a detailed literature review, analyzing the operating principles of MPPT and PWM controllers, their respective advantages and disadvantages, and performance under various environmental conditions. Previous studies are examined to identify the conditions under which each type of controller offers the best performance. Empirical data and existing case studies are reviewed to establish a solid comparison base. This analysis is accompanied by tables and graphs illustrating the performance of both types of controllers. Based on the results of this analysis, the paper proposes the design of a PWM charge controller suitable for small solar installations in rural areas with budget constraints. This solution aims to promote energy accessibility while minimizing costs, offering a viable alternative for rural communities with limited resources.

Keywords: MPPT (Maximum Power Point Tracking), PWM (Pulse Width Modulation), Photovoltaic Solar Systems, Budget Constraints, Energy Transition, Charge Controller.

I. INTRODUCTION

According to the International Renewable Energy Agency (IRENA), Africa's population growth is one of the fastest in the world, far exceeding the global average. "By 2050, Africa's population is expected to double, reaching 2.4 billion, compared to the global population growth rate of 29% over the same period" (IRENA, 2020, p. 18). This exponential population increase comes with an increased energy demand, creating an urgent need for sustainable and accessible energy solutions.

Photovoltaic (PV) systems present a viable solution due to the abundant availability of solar radiation in many African regions. The transformation of solar energy into electricity through photovoltaic cells relies on the photovoltaic effect, where light incident on a PV cell generates an electromotive force (Green, 2005, p. 25). The association of multiple PV cells in series and/or parallel forms a photovoltaic generator (PVG), whose current-voltage (I-V) characteristic is nonlinear and has a maximum power point (MPP) (Markvart, 2000, p. 44).

The performance of a PVG is influenced by various factors such as illumination intensity, cell temperature, and component aging. The operating point of the PVG also depends on the load it supplies. To continuously extract the maximum available power, it is necessary to introduce an adaptation device between the generator and the load, usually in the form of a charge controller.

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Charge controllers are essential for optimizing the extraction of energy from PVGs and protecting batteries from potential damage due to overcharging or excessive discharging. There are mainly two types of charge controllers used in PV systems: PWM (Pulse Width Modulation) controllers and MPPT (Maximum Power Point Tracking) controllers. Each type has its own advantages and disadvantages, and the choice between them often depends on budget constraints and the specific requirements of the solar installation.

PWM controllers are known for their simplicity and relatively low cost, making them attractive for small-scale solar installations. However, their efficiency is generally lower than that of MPPT controllers, which continuously optimize the solar panels' maximum power point, especially under variable sunlight conditions, allowing for more energy extraction even in fluctuating light conditions. Nevertheless, MPPT controllers are often more expensive and complex.

The characteristics, performance, and costs of PWM and MPPT charge controllers are addressed in the following lines.

II. Comparison and Advantages of PWM and MPPT Charge Controllers

Photovoltaic (PV) systems use charge controllers to optimize energy extraction and protect batteries from damage. Charge controllers play a crucial role in optimizing energy extraction from photovoltaic generators (PVG) and protecting batteries from potential damage due to overcharging or excessive discharging. According to Smith *et al*., (2020, p. 215), "charge controllers are essential for ensuring efficient and safe use of photovoltaic systems by regulating the flow of energy between solar panels and batteries."

There are primarily two types of charge controllers used in PV systems: PWM (Pulse Width Modulation) controllers and MPPT (Maximum Power Point Tracking) controllers. As explained by Jones and Green (2019, p. 133), "PWM controllers work by modulating the width of voltage pulses to maintain the battery at an optimal charge level, which can be effective but less efficient than MPPT controllers in terms of energy efficiency."

In contrast, MPPT controllers are often preferred for their ability to maximize the power extracted from solar panels by continuously adjusting the load to follow the maximum power point. Williams *et al*., (2018, p. 98) note that "MPPT controllers offer superior efficiency, especially in conditions of varying sunlight and temperature, although they are generally more expensive than PWM controllers."

The choice between these two types of controllers often depends on budget constraints and the specific requirements of the solar installation. Brown (2021, p. 46) highlights that "low-budget or small-scale systems may opt for PWM controllers due to their lower cost, while installations requiring optimal performance and maximum energy efficiency will prefer MPPT controllers despite their higher cost."

Research by Smith *et al*., (2020) and Jones and Green (2019) provides a comprehensive overview of the advantages and disadvantages of PWM and MPPT controllers. Their work highlights that PWM controllers are widely used in small installations due to their simplicity and affordable cost. However, they acknowledge that the energy efficiency of these controllers is limited compared to MPPT.

On the other hand, Williams *et al*., (2018) emphasize the importance of MPPT controllers for large solar installations, where energy efficiency and the ability to handle rapid changes in environmental conditions are crucial. They show that, despite a higher initial cost, MPPT controllers can offer long-term savings through better utilization of solar energy.

Finally, Brown (2021) offers a practical perspective by examining purchasing decisions and financial trade-offs related to the choice of charge controllers. His research highlights the budgetary considerations and specific needs of end-users, providing a balanced approach between cost and performance.

1. Performance Based on Solar Irradiation

The Fig.1 (a) shows the relationship between solar irradiation and the efficiency of both types of controllers. MPPT controllers display superior efficiency even when solar irradiation is low, reaching up to 95% under optimal conditions compared to 85% for PWM controllers (Harris *et al*., 2018, p. 53; Wang *et al*., 2020, p. 47).

2. Average Energy Efficiency by Season

The Fig.1 (b) illustrates the performance of MPPT and PWM controllers over different seasons (winter, spring, summer, autumn). MPPT controllers show effective adaptation to seasonal sunlight variations, with efficiency ranging from 90% in winter to 95% in summer. In contrast, PWM controllers show more consistent but lower performance, ranging between 80% and 85% (Nguyen *et al*., 2019, p. 67; Zhang and Chen, 2019, p. 61).

These graphs demonstrate that MPPT controllers offer better energy efficiency compared to PWM controllers, both in terms of solar irradiation levels and seasonal variations.

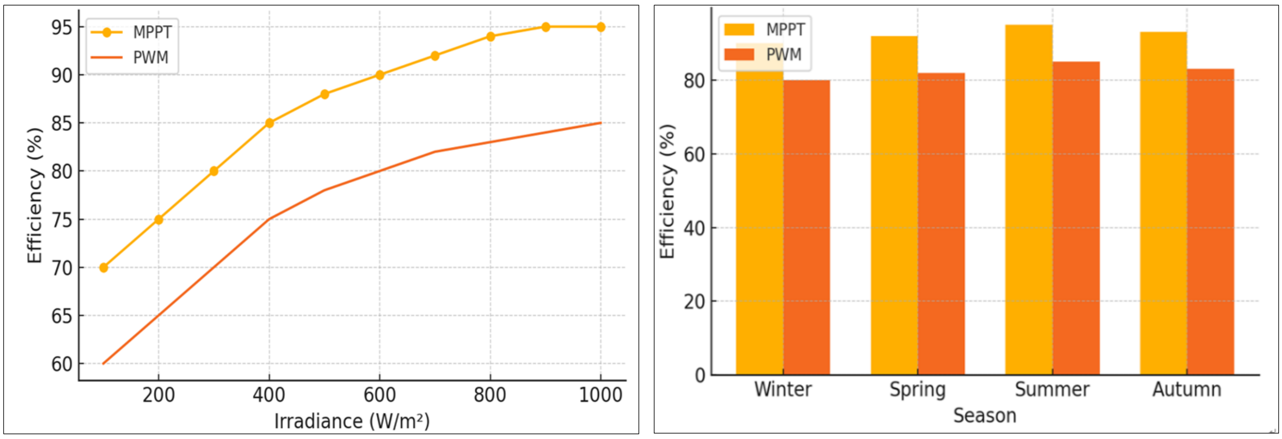

Fig. 1 : Solar irradiance and average efficiency by season : (a) relationship between solar irradiation and the efficiency (b) average energy efficiency by season

The choice between PWM and MPPT controllers largely depends on the specific requirements of the solar installation and budget constraints. PWM controllers are advantageous for small systems with limited budgets, while MPPT controllers are preferred for large installations requiring optimal performance and maximum energy efficiency. The studies by Smith *et al*., (2020), Jones and Green (2019), Williams *et al*., (2018), and Brown (2021) provide a detailed understanding of these technologies and help inform the choice of the most suitable controller for each situation.

III. Operating Principles of PWM and MPPT Controllers

1. Operating Principles PWM Controllers

Pulse Width Modulation (PWM) is a technique used to reduce the average power of an alternating current (AC) signal. It is a method of digitally encoding analog signal levels. It uses a high-resolution counter to modulate the duty cycle of a square wave to encode a specific analog signal level. The PWM signal is always digital and operates by modulating the width of voltage pulses to maintain the battery at an optimal charge level. According to Jones and Green (2019), "PWM controllers continuously adjust the pulse width to regulate the output voltage, thus controlling the amount of energy transferred to the batteries" (p. 133). This process helps to avoid overcharging and prolongs battery life.

The PWM signal is a square wave that alternates between a high (ON) and a low (OFF) level. The duration during which the signal remains high compared to the total cycle duration is called the duty cycle, expressed as a percentage. For example, a 50% duty cycle means the signal is ON half the time and OFF the other half.

Fig.2 is a temporal waveform of a PWM signal, it will resemble the waveform in the following image.

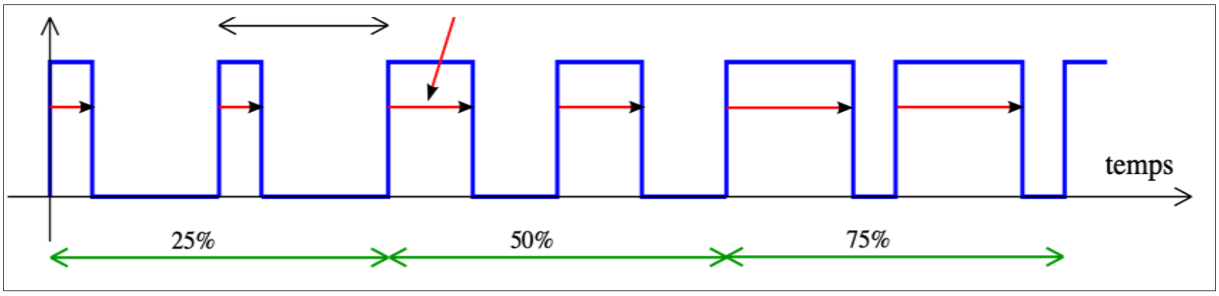

Fig. 2 : Waveform of a PWM signal

As showed in Fig.3, by modulating the duty cycle, the average amount of power delivered to the load is controlled:

- 100% duty cycle: The signal is always ON, delivering maximum power to the load.
- 0% duty cycle: The signal is always OFF, delivering no power.
- Between 0% and 100%: The average power delivered is proportional to the duty cycle. For example, a 25% duty cycle delivers on average 25% of the maximum power.

In the context of charge controllers for solar installations, PWM is used to regulate the charging current sent to the battery, thus optimizing charging efficiency and preserving battery life.

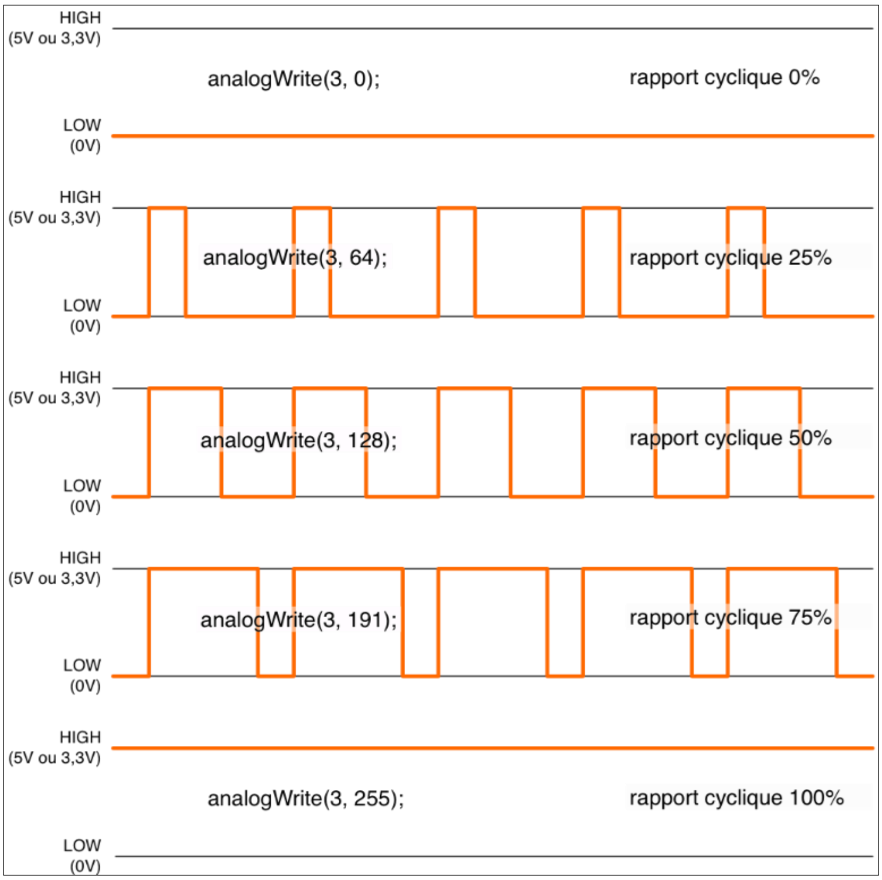

Fig. 3 : PWM waveform by modulating the duty cycle

2. Applications of PWM in Charge Controllers

(a) Steps in the PWM Process in a Charge Controller:

- Battery Voltage Measurement: The controller measures the battery voltage to determine its charge state.
- Comparison with Reference Voltage: The measured voltage is compared to a predefined reference voltage (e.g., the battery's maximum charge voltage).
- PWM Signal Generation: If the battery voltage is below the reference voltage, the controller increases the PWM signal's duty cycle to increase charging power. If the battery voltage reaches or exceeds the reference voltage, the controller decreases the duty cycle to reduce charging power.
- Application of the PWM Signal: The PWM signal is applied to a power transistor (such as a MOSFET) that controls the charging current delivered to the battery. Modulating the duty cycle allows for fine adjustment of the current.

(b) Advantages of PWM:

- Efficiency: Allows fine regulation of the charging current, reducing energy losses.
- Simplicity: Compared to other power regulation methods, PWM is relatively simple to implement.
- Compatibility: Can be used with different types of batteries and solar panels.

3. Operating Principles of MPPT Controllers

MPPT (Maximum Power Point Tracking) controllers are electronic devices used in photovoltaic (PV) systems to maximize the efficiency of converting solar energy into electricity. As the name suggests, Maximum Power Point Tracking maximizes the power extracted from PV systems by ensuring that the solar panels operate at their maximum power point, regardless of environmental variations such as sunlight and temperature.

Williams *et al.*, (2018, p. 98) explain that "MPPT controllers use complex algorithms to track the maximum power point in real-time, thus extracting the maximum available energy from the solar panels." This ability to adapt to rapid changes in sunlight and temperature conditions gives them superior efficiency, especially in dynamic environments.

Other research, such as that by Li and Zhang (2019), confirms that the MPPT algorithm allows for optimized energy yield by adjusting the maximum power point according to climatic variations (Li and Zhang, 2019, p. 77).

The operating principle is based on the I-V (current-voltage) characteristic of the solar panels, where the MPP is the point where the product of current and voltage (P = IV) is maximal. The conditions of light and temperature affect this curve, making dynamic adjustment by the MPPT controller necessary to maintain operation at the MPP.

(a)MPPT Algorithms

MPPT algorithms are mathematical and logical methods used to identify and track the MPP. The main algorithms include:

Perturb and Observe (P&O):

This algorithm perturbs the PV panel voltage and observes the effect on power. If a perturbation leads to an increase in power, the perturbation continues in the same direction; otherwise, it changes direction. Although simple and widely used, this algorithm can oscillate around the MPP due to continuous adjustments.

Incremental Conductance (IncCond):

This algorithm calculates the derivative of power with respect to voltage and compares this value to the instantaneous conductance. It is more precise than P&O because it can determine the direction of the MPP more effectively, even under rapidly changing conditions.

Fraction of Open-Circuit Voltage (FVOC):

This method uses a fraction of the PV panel's open-circuit voltage (VOC) to estimate the MPP. Although faster, it is less accurate because it does not track real-time variations.

Fuzzy Logic Control:

This method uses fuzzy logic rules to adjust the MPP. It is suitable for systems with nonlinear and variable characteristics, offering a quick and efficient response.

(b)MPPT Power Control

MPPT power control is achieved by adjusting the load on the PV panel to reach and maintain the MPP. This involves using a DC-DC converter, such as a Buck or Boost converter, to adjust the PV panel's output voltage. The MPPT controller continuously monitors the output power and adjusts the converter's duty cycle to maintain operation at the MPP.

(c)MPPT Process in a Charge Controller:

Measurement of PV Parameters: The MPPT controller measures the solar panels' voltage and current to calculate the current power.

Analysis of Environmental Conditions: Considering light and temperature variations, the controller adjusts the MPP.

Application of the MPPT Algorithm: The controller uses one of the MPPT algorithms to determine necessary adjustments.

Adjustment of the DC-DC Converter: By adjusting the converter's duty cycle, the controller modifies the voltage and current to reach the MPP.

Continuous Monitoring: The controller continuously monitors parameters to maintain the system at the MPP.

4. Graphical Analysis of VP, VI Curves of MPPT vs. PWM Charger

Fig.4 shows the power-voltage (VP) and current-voltage (VI) curves of a solar panel, as well as the MPP compared to a traditional PWM charger.

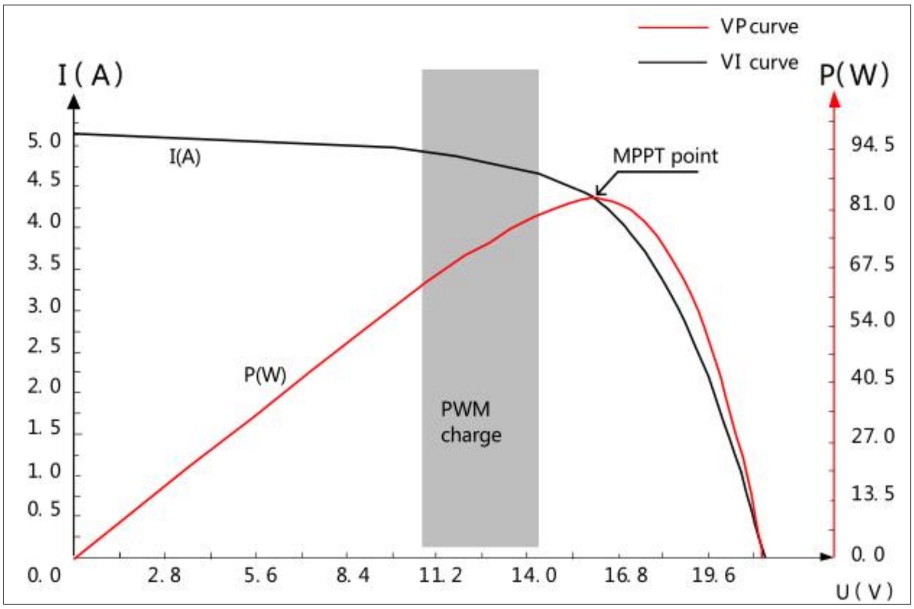

Fig. 1 : Power-voltage (VP) and current-voltage (VI) curves of a solar panel

VP Curve (Red):

Represents power (P) as a function of voltage (U) of the solar panel. Power increases with voltage until it reaches a maximum (MPP), then decreases.

VI Curve (Black):

Represents current (I) as a function of voltage (U). The current remains relatively constant up to a certain voltage, then decreases rapidly.

MPP Point:

The maximum power point (MPP) is where the power curve reaches its maximum. MPPT controllers continuously adjust the panel's operation to remain at this point, maximizing energy efficiency.

PWM Charger:

The traditional PWM charger operates the panel at a voltage close to that of the battery. This results in a loss of efficiency, as the panel does not always operate at its maximum power point. The shaded area on the graph shows where the PWM charger operates, which is suboptimal compared to the MPPT.

IV. Optimized Solution Design of PWM

Based on the literature reviews and analyses, and the results of these analyses, the design of a 24V PWM charge controller has been adopted and realized. The attached schematics represent the detailed circuit design as in Fig.5-8. We will examine the circuit's operation, component by component, explaining each one's role in the overall system. The design includes a thorough analysis of the components, theoretical justifications, and detailed comments on each schematic element.

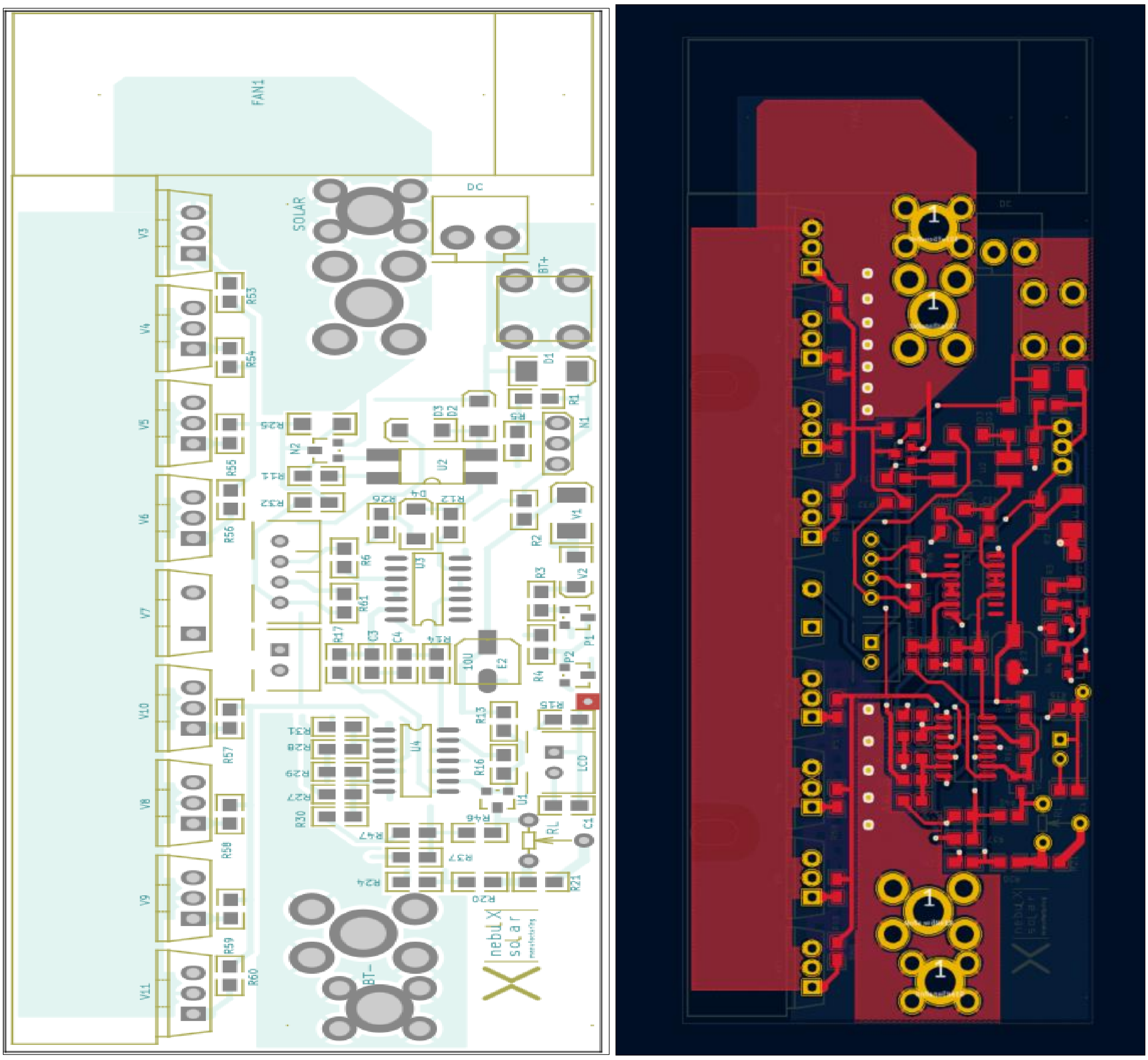

Fig. 5 : Altium design schematic

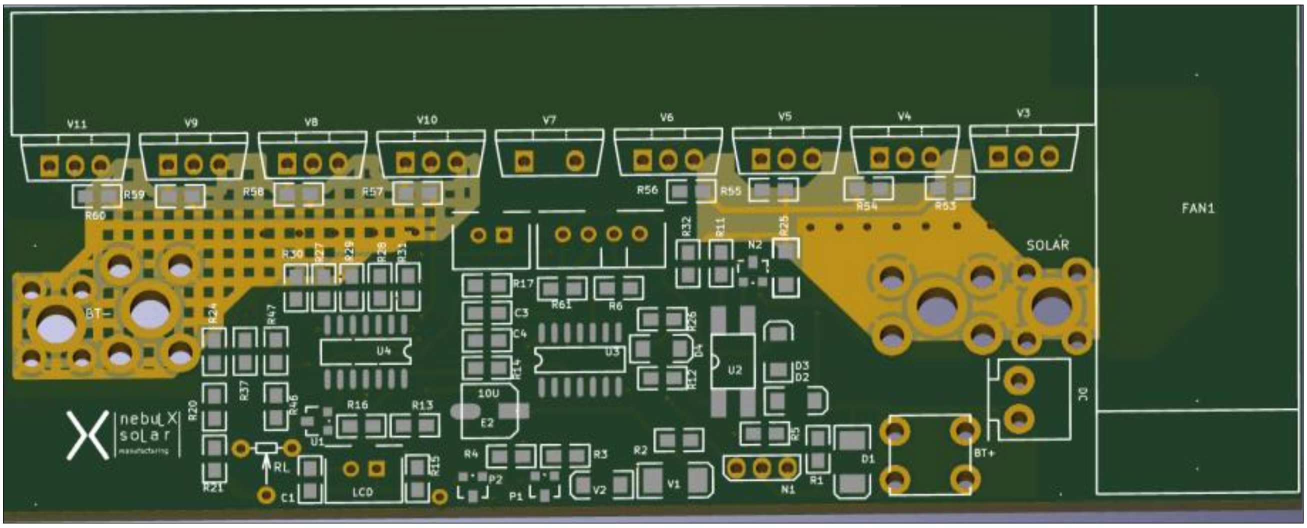

Fig. 6 : Altium design PCB board

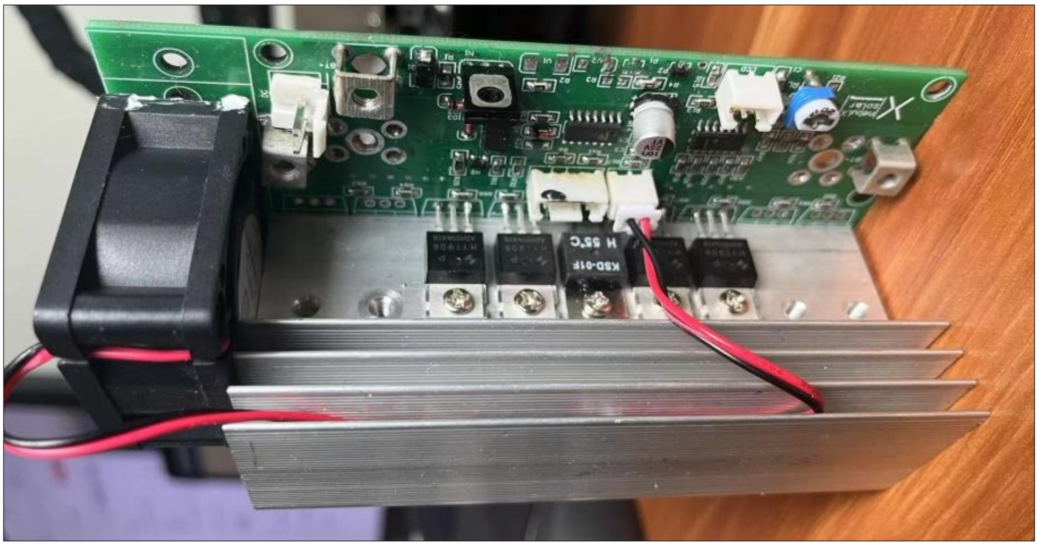

Fig. 7 : PCB prototype

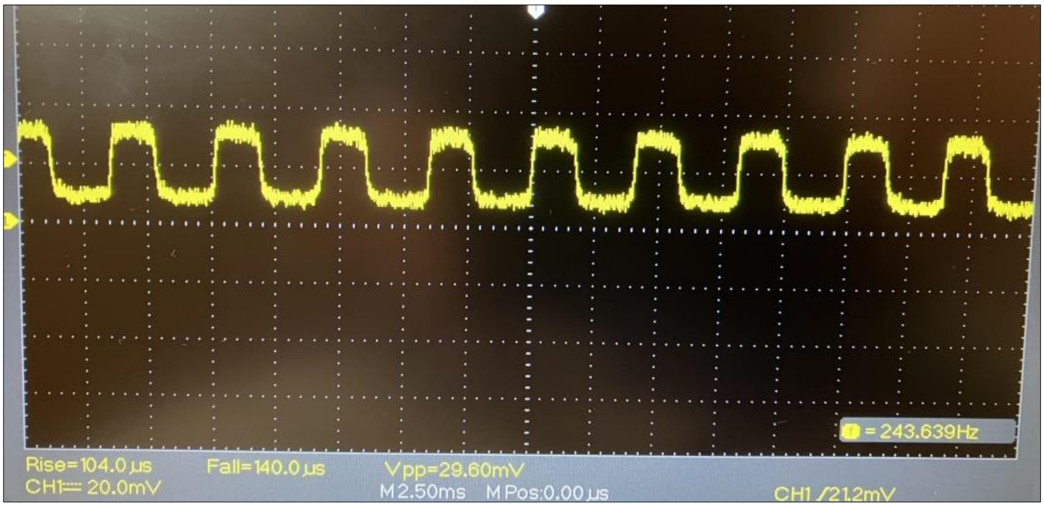

Fig. 8 : Oscilloscope PWM waveform

Using Altium Designer to create the schematic and PCB, and gathered the necessary information on components and generated the Bill of Materials (BOM) via the Octopart website. Using an oscilloscope, a DC load, and a bench multimeter, the circuit is tested for voltage stability during power-up and operation of the charge controller. The PWM with the oscilloscope is measured, and the output noise, load response, and waveform are satisfactory during the power-up and operation of the charge controller as illustrated in Fig.8.

1. Circuit Analysis

Fig.9 is circuit diagram, and you may notice that the two main components of the circuit are the PWM controller chip CD40106BM and the half-bridge MOSFET driver HY1906P.

2. Operational Process of the PWM Regulator

Voltage and Current Sensors: Measure system parameters (output voltage, charging current).

Amplifiers:

Analog signals from these sensors are amplified by operational amplifiers (U4) and then compared to predefined reference voltages using the integrated comparators within the operational amplifiers.

Error Signal Generation: Any deviation of the output voltage or current from reference values generates an error signal.

Microcontroller Processing: The microcontroller (U3 - CD40106BM) processes the error signal to adjust the duty cycle of PWM pulses.

PWM Generation: PWM pulses are generated based on the error magnitude, adjusting power delivery accordingly.

MOSFET Activation: Power MOSFETs (HY1906P) are turned on and off by PWM pulses, controlling power transferred to loads.

PWM Frequency and Duty Cycle: Determine precise power regulation.

Diodes: (SS14, LL4148) protect the circuit from over voltages and ensure rectification.

Resistors and Capacitors: Filter signals, eliminating interference, and stabilizing voltages.

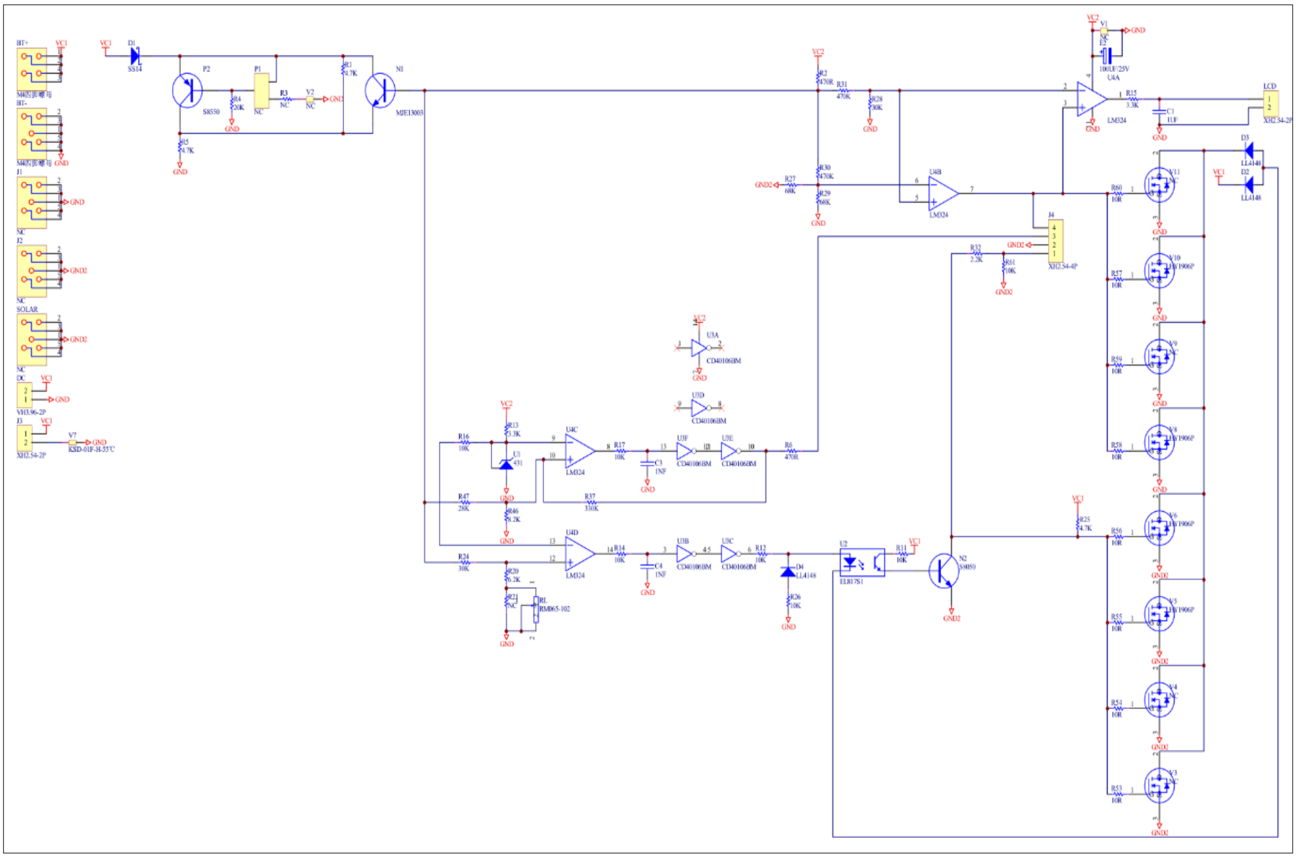

Fig. 9: Circuit diagram

3. Key Components and Their Roles

CD40106BM:

Generates necessary PWM pulses to control power MOSFETs. Uses logic gates to produce square signals with fast transitions, crucial for precise modulation. Schmitt Trigger logic gates eliminate noise from input signals, ensuring clean and precise transitions. Logic gate output signals directly control power MOSFETs (V5, V6, V8, V10).

LM324 (U4):

Operational amplifiers amplify feedback and control signals. Amplified signals from voltage and current sensors are compared to reference voltages to generate precise control signals. Outputs from operational amplifiers are then used to adjust the PWM pulse duty cycle.

HY1906P (V5, V6, V8, V10):

Power MOSFETs are used for power switching and regulation in the circuit. They act as electronic switches, controlled by PWM signals to regulate power delivered to the load. MOSFETs are turned on and off at high frequency by PWM pulses generated by the microcontroller. When activated, they allow current to flow from the solar panel to the battery or load. The duration they remain activated (duty cycle) determines the amount of power transferred. They have low on-state resistance, minimizing power losses and improving overall efficiency.

Diodes (D1 - SS14, D2, D3, D4 - LL4148):

Protection and Rectification. Diodes SS14 and LL4148 protect components against over voltages and allow AC-DC conversion. The SS14 diode, a Schottky diode, is used for its low forward voltage drop, reducing power losses. LL4148 diodes are used for rectification and overvoltage protection, ensuring circuit reliability and durability.

Resistors and Capacitors (R1 to R61, C1 to C4, E2):

Filter and stabilize signals. Configured as filtering, decoupling, and feedback networks. Resistors and capacitors smooth PWM signals and eliminate unwanted fluctuations. Resistors configure the circuit's time constants and frequency characteristics, ensuring stable system response. Decoupling capacitors (like C1 and E2) stabilize supply voltages by eliminating high-frequency interference.

V. CONCLUSION

The presented PWM charge regulator offers an efficient and economical solution for small solar installations. The integration of low-cost, high-performance components such as CD40106BM microcontrollers, LM324 operational amplifiers, and HY1906P MOSFETs ensures precise power regulation and high energy efficiency. This design is particularly suited for rural contexts with budget constraints, offering a viable solution for optimizing solar energy conversion systems.

Incorporate a regulator to manage multiple voltages, including 12V, 24V, and 48V, to adapt the system to different battery and solar installation configurations. A multi-voltage regulator could be incorporated into the DC-DC switching regulator to manually adjust the output voltage based on battery needs.

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