IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 3, May 2025
Impact Factor: 7.67

IoT And MPPT Based Charge Converter for PV System

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Abstract: *Maximum Power Point Tracking plays a vital role in extracting the highest possible energy from photovoltaic systems under varying environmental conditions. This project presents a practical implementation of an IoT-enabled MPPT-based charge controller that enhances the efficiency of solar energy harvesting. The system uses real-time monitoring and control, where the ESP32 microcontroller adjusts the duty cycle of a custom-designed boost converter to track the maximum power point. Input and output parameters are measured using dual INA219 sensors, and live data is visualized through an OLED display. The MPPT logic is implemented through a perturb and observe algorithm. The controller ensures optimized battery charging, making it suitable for small-scale off-grid renewable applications. The integration of cloud-based data logging adds an intelligent edge for performance analysis and diagnostics.*

Keywords: Maximum Power Point Tracking (MPPT), Photovoltaic System, Boost Converter, IoT-enabled Controller, ESP32 Microcontroller, Perturb and Observe Algorithm, Real-time Monitoring

I. INTRODUCTION

Solar energy is a widely adopted renewable energy source due to its abundance and sustainability. However, the energy output from a solar photovoltaic (PV) system varies significantly with environmental conditions such as sunlight intensity and temperature. To overcome this limitation and utilize solar power efficiently, Maximum Power Point Tracking (MPPT) is employed. MPPT is a technique used to extract the maximum possible power from a PV module by continuously adjusting the operating point of the system.

This project aims to develop an intelligent and cost-effective MPPT-based solar charge controller integrated with an IoT platform for real-time monitoring. The system uses a boost converter topology controlled by an ESP32 microcontroller. The controller dynamically adjusts the PWM signal to track the maximum power point using the Perturb and Observe (P&O) algorithm. Input and output voltages and currents are accurately measured using dual INA219 sensors. An OLED display is included for live data visualization, and optional cloud connectivity allows remote performance monitoring.

Such a system is highly beneficial for rural and off-grid energy applications where battery-based storage is essential. It ensures efficient charging of batteries, reduces energy loss, and enhances the overall reliability of solar power systems. The project not only focuses on the hardware design of the charge controller but also emphasizes efficient software implementation of MPPT and sensor integration for precise control.

The rest of the paper is organized as follows: Section II discusses the overall system architecture and hardware implementation. Section III explains the software design, including the MPPT algorithm and data acquisition. Section IV presents the experimental setup and results with observed performance metrics. Finally, Section V concludes the paper with insights and future enhancement possibilities.

II. LITERATURE SURVEY

The concept of Maximum Power Point Tracking (MPPT) has been widely studied to enhance the efficiency of photovoltaic (PV) systems. One of the earliest and most commonly used MPPT techniques is the Perturb and Observe (P&O) algorithm, introduced in [1], where the operating voltage is incrementally perturbed and the direction of power change is used to track the maximum point. Incremental Conductance (INC) method, as discussed in [2], improves the tracking accuracy by comparing the instantaneous conductance with the incremental conductance to determine the direction of the MPP.

A comparative study in [3] evaluated different MPPT algorithms including P&O, INC, and Fuzzy Logic Control, highlighting that while P&O is simple and easy to implement, its performance degrades under rapidly changing irradiance. In [4], the authors proposed a modified P&O method to reduce oscillations around the MPP and improve convergence speed. The use of microcontrollers like Arduino and ESP32 for MPPT implementation has been explored in [5], where real-time monitoring and PWM control were used to adjust the duty cycle of a boost converter effectively.

Sensor-based feedback systems using voltage and current sensors such as INA219 for precise power calculation have been applied in [6]. Additionally, [7] discusses IoT integration with MPPT systems for remote monitoring, data logging, and analytics using platforms like ThingSpeak. OLED and LCD displays are commonly integrated to provide real-time feedback to users, as noted in [8].

III. MPPT TECHNIQUE FOR CHARGE CONTROLLERS

Maximum Power Point Tracking (MPPT) is an essential technique employed in solar photovoltaic (PV) systems to ensure that the system consistently operates at its highest efficiency. Solar panels exhibit a non-linear current-voltage (I-V) characteristic, which means the power output does not increase linearly with 18 sunlight or temperature. Instead, there exists a unique point on the I-V curve known as the Maximum Power Point (MPP), where the product of current and voltage—and hence the power—is maximum. As sunlight intensity and temperature fluctuate throughout the day, the MPP shifts, making real-time tracking essential for optimal energy harvest. Among the several MPPT algorithms developed, the Perturb and Observe (P&O) algorithm is one of the most widely used due to its simplicity, ease of implementation, and satisfactory performance under slowly changing environmental conditions. In this method, the operating voltage of the PV panel is periodically perturbed (i.e., increased or decreased), and the corresponding change in output power is observed. If a small increase in voltage results in an increase in power, the controller continues increasing the voltage in the same direction. Conversely, if the power decreases, the voltage is perturbed in the opposite direction. This iterative approach ensures that the system hovers around the maximum power point. The process is repeated continuously to track the changing MPP due to varying irradiance and temperature. However, the P&O method is not without limitations. One of the primary challenges is the oscillation around the MPP, which leads to power loss. Additionally, under rapidly changing environmental conditions, the algorithm might respond incorrectly, moving the operating point away from the true MPP. Despite these drawbacks, the P&O method remains a popular choice in commercial and academic applications due to its effectiveness in stable conditions and its ease of coding in embedded systems. In the context of MPPT-based charge controllers, especially when combined with microcontrollers like the ESP32, the P&O algorithm can be implemented efficiently using analog voltage/current sensors and PWM control for regulating the switching of a DC-DC converter.

Implementation of P&O Using ESP32

The implementation of the Perturb and Observe (P&O) algorithm using the ESP32 microcontroller provides a cost-effective and efficient solution for real-time Maximum Power Point Tracking (MPPT) in solar charge controller systems. The ESP32, with its dual-core processor, built-in Wi-Fi, multiple analog-to-digital converters (ADCs), and PWM (Pulse Width Modulation) support, is well-suited for embedded energy applications such as solar charge controllers. 19 In a typical MPPT system, the ESP32 performs several critical functions: sampling voltage and current from the photovoltaic (PV) panel, calculating power, applying the P&O logic, and generating appropriate PWM signals to control the DC-DC converter (boost or buck type). The converter then adjusts the operating point of the solar panel to match the maximum power point

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Procedure For Implementation

The voltage and current from the solar panel are measured using sensors. Voltage sensors detect the potential difference between two points, and current sensors measure the flow of electrons. These sensors provide the necessary data to assess the solar panel's energy generation capabilities. Power is calculated by multiplying the measured voltage and current, yielding the instantaneous power output of the solar panel. The formula used is Power (W) = Voltage (V) × Current (A).

This value is crucial for determining the efficiency and performance of the solar panel, as it reflects how much energy is being harvested at any given time. The calculated power is then compared to the previously recorded value to determine if the power has increased or decreased. If the power has increased, it indicates that the system is approaching its maximum power point. If the power has decreased, it suggests that the system is not performing optimally, and adjustments are necessary.

To optimize the system's power output, the Pulse Width Modulation (PWM) signal is adjusted by slightly modifying the duty cycle. The duty cycle determines how long the PWM signal remains "on" during each cycle, controlling the energy transfer between the solar panel and the load. By fine-tuning the duty cycle, the system can improve or reduce the power delivered, helping to reach the optimal power point. The adjusted PWM signal is then sent to the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) in the converter. The MOSFET acts as a switch, regulating the flow of power through the converter. By switching the MOSFET on and off according to the PWM signal, the system controls the amount of power supplied to the load, ensuring efficient power conversion.

This process is iterative. The system continuously measures the solar panel's power output and adjusts the PWM duty cycle to maintain maximum efficiency. As environmental conditions, such as sunlight intensity, fluctuate, the system tracks the maximum power point to adapt to these changes. 20 Optionally, the collected data (voltage, current, and power) can be sent to cloud platforms for remote monitoring and analysis.

This enables users to track the system's performance in real-time, perform maintenance, and identify potential issues. Cloud integration offers enhanced visibility into the system's status, enabling efficient troubleshooting and predictive maintenance to ensure continued optimal performance.

IV. ARCHITECTURE AND DESIGN OF IoT AND MPPT BASED SOLAR CHARGE CONTROLLER FOR PV SYSTEM

System Architecture

Voltage and current sensors are used to measure the output of the solar panel, providing real-time data to calculate power using $P=V\times I$. This power value indicates the panel's performance and helps in identifying the Maximum Power Point (MPP). By comparing the current power with the previous value, the system determines if it is moving toward or away from the MPP.

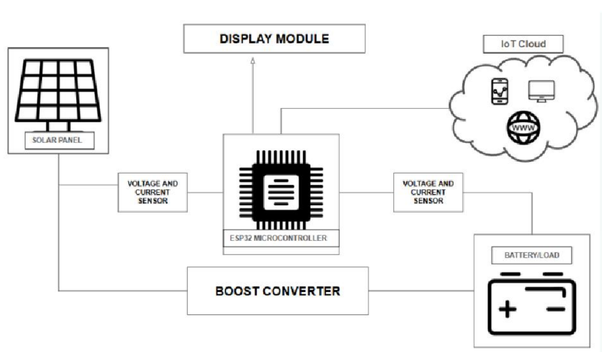

Figure 4.1: Architecture of Charge Controller System

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To optimize output, the Pulse Width Modulation (PWM) duty cycle is adjusted, controlling the on-time of the MOSFET in the boost converter. This regulates energy transfer to the load, ensuring efficient power conversion. The system continuously iterates this process to adapt to changing environmental conditions.

Additionally, measured parameters (voltage, current, and power) can be uploaded to a cloud platform for real-time monitoring, performance analysis, and predictive maintenance.

BLOCK DIAGRAM OF CHARGE CONTROLLER

The proposed MPPT-based solar charge controller maximizes power extraction from photovoltaic (PV) panels by continuously adjusting the operating point in real time. Two 6 V solar panels connected in series serve as the energy source, with output voltage varying due to environmental conditions.

To ensure efficient energy tracking, the system utilizes an INA219 sensor to measure voltage and current, providing input to the MPPT algorithm executed by the ESP32 microcontroller. The Perturb and Observe (P&O) algorithm is employed to dynamically tune the duty cycle and maintain operation at the maximum power point (MPP).

A high-frequency PWM signal generated by the ESP32 controls a boost converter via the HCPL-3131 opto-isolated gate driver, which drives an IRFZ44N MOSFET. This isolation enhances system safety and noise immunity. The converter includes a 100 µH inductor, SS34 Schottky diode, and 1000 µF capacitor to step up and regulate the output voltage. A 20 Ω resistor is used as a test load.

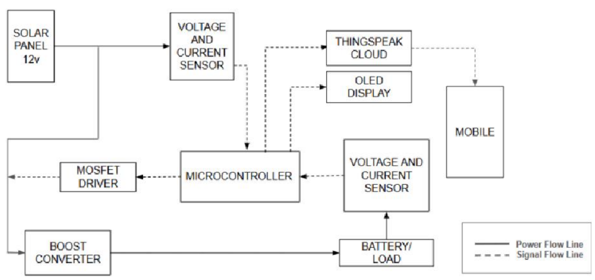

Figure 4.2 Block Diagram of MPPT based Charge Controller

System parameters such as voltage, current, power, and output voltage are displayed locally on an OLED screen and transmitted to the ThingSpeak cloud for real-time remote monitoring and analysis. The integrated design enables adaptive MPP tracking and efficient power conversion, offering a scalable and cost-effective solution for intelligent solar energy systems.

DESIGN PARAMETERS OF BOOST CONVERTER CIRCUIT

Calculation of Inductance

$$L = \frac{Vin \cdot D}{f_s \cdot \Delta I_L}$$

$$D = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{12}{14} \approx 0.143$$

$$D = 14.3\%$$

Duty Cycle: Desired ripple current ΔIL = 20–40% of Iout Let's Assume 30% of Ripple.

$$\Delta I_L = 0.3 \cdot 5A = 1.5A$$

DOI: 10.48175/IJARSCT-26309

$$L = \frac{12V \cdot 0.143}{50 \times 10^3 \cdot 1.5A} = \frac{1.716}{75{,}000} = 22.88\mu\text{H}$$

We have taken Inductor of 100uH for better reduction of Inductor Current Ripple and Better Charging Capability

Calculation of Capacitance:
For a Ripple Voltage ΔVout, typically 1-2% of Vout.
The 1.2% of ΔVout is, ΔVout = 0.02 * 14 = 0.28V

$$C_{out} = \frac{I_{out} \cdot D}{f_s \cdot \Delta V_{out}} = \frac{5 \cdot 0.143}{50 \times 10^3 \cdot 0.28} \approx 510\mu F$$

$$C_{out} = 510\mu F$$

We have taken 1000uF Capacitor in order to have better Filtering in Circuit, For Safer Operations and to Reduce Capacitor Voltage Ripple

Role of Boost Converter

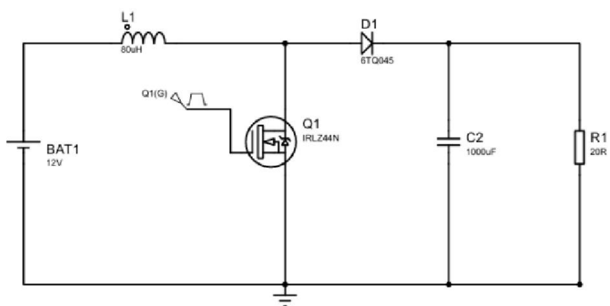

Fig:4.3: Boost Converter Circuit

The boost converter elevates the solar panel's variable voltage to a suitable level for battery charging or load supply, enabling efficient energy harvesting in MPPT-based systems. Controlled by a microcontroller running an MPPT algorithm, it adjusts the duty cycle in real-time based on voltage and current feedback.
A gate driver interfaces the low-voltage microcontroller with the power MOSFET, providing appropriate switching levels and ensuring electrical isolation. This setup ensures safe, stable, and efficient power conversion essential for reliable solar energy management

V. SIMULATION FOR IoT AND MPPT BASED SOLAR CHARGE CONVERTER FOR PV SYSTEMS

MATLAB SImulation for MPPT Based Charge Controller

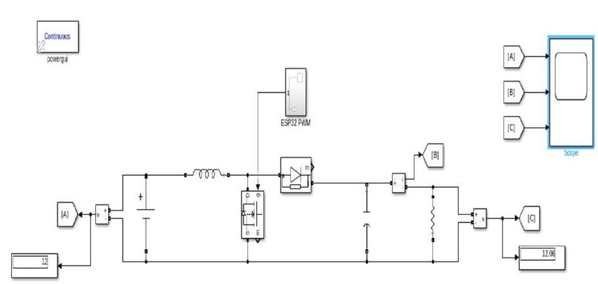

Figure 5.1: MATLAB Simulation for MPPT based Charge Controller

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This circuit has been simulated using MATLAB version R2021 and uses power electronic elements such as MOSFET , Diode and can Immitate the prototype. The charging elements used are carefully designed upon the typical use cases of Indian load standard. So the inductances and Capacitances are used as per our calculation.

Moreover, this circuit provides an outline about how the actual controller will behave under a fixed 12V condition under normal load and normal weather.

Any Abnormal Conditions can be sensed and their respective corrective action will be taken with the help of ESP32.

Let us see the waveforms generated by the circuit, for the dutycycle 14.3% and inductance of 100uH and capacitance of 1000uF. With load of 20Ω

Input voltage(V_{in}), Output Voltage(V_{out}) and Output current waveforms(I_{out})

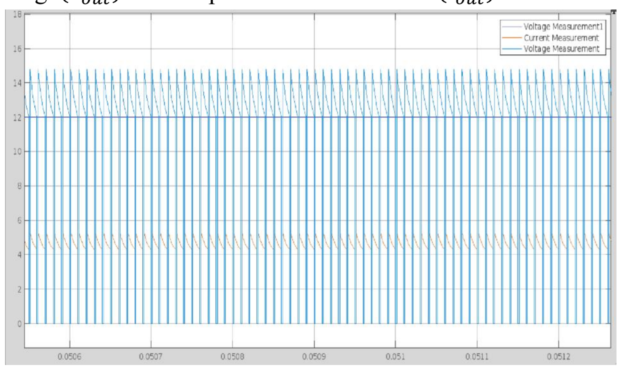

Figure 5.2: Vin,Vout, Iout waveforms for the dutycycle 14.3%

For 50% dutycycle, the Input voltage, Output Voltage and Output current waveforms are given as follows

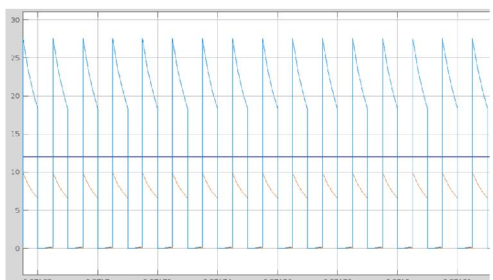

Figure 5.3: Vin,Vout,Iout waveforms for the dutycycle 50%

For the sample of other dutycyles, these following values are obtained as output. The values are given below on the table

S.No	Duty Cycle (%)	Theoretical Vout (V)	Simulated Vout (V)
1	20	20.00	21.3
2	40	30.00	31.5
3	75	65.00	65.0

Calculation of Vout for other dutycycles

VI. CONCLUSION

This project demonstrates the development of a Maximum Power Point Tracking (MPPT) system for efficient solar energy management. The system optimizes power extraction by adjusting to varying environmental conditions. A laboratory setup showed successful power conversion and stable output, with PWM control effectively managing the process. This solution offers a cost-effective approach for solar power management, with potential applications in IoT-based energy systems. Future work will focus on optimizing the MPPT algorithm and integrating real-world loads for enhanced performance.

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