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Smart MPPT Controlled Solar Power with Temperature & Battery Health Sensing

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ABSTRACT : The increasing demand for clean and sustainable energy has encouraged the adoption of solar photovoltaic (PV) systems in many power generation applications. However, the efficiency of photovoltaic systems is highly dependent on environmental conditions such as solar irradiance and temperature. To improve the performance of solar energy systems, this work proposes a smart solar charging system that integrates Maximum Power Point Tracking (MPPT) with temperature and battery health monitoring.

The proposed system employs the Incremental Conductance MPPT algorithm to ensure that the photovoltaic panel operates at its maximum power point under varying atmospheric conditions. Important electrical parameters including photovoltaic voltage, current, battery voltage, and charging current are continuously monitored using dedicated sensors. Temperature monitoring is also incorporated to enhance battery safety and system reliability.

An ESP32 microcontroller is used as the central control unit for implementing MPPT control, sensor data acquisition, and system monitoring. The system also provides real-time visualization through a lightweight web interface and a Python-based monitoring platform. Simulation and hardware results demonstrate that the Incremental Conductance algorithm provides improved tracking accuracy compared with conventional MPPT techniques. The proposed system provides an efficient and economical solution for intelligent solar energy management.

KEYWORDS : Solar energy, MPPT, ESP32, Incremental Conductance, Battery monitoring, IoT

I. INTRODUCTION

The global demand for electrical energy has increased rapidly due to population growth and technological development. At the same time, the depletion of conventional fossil fuels and environmental concerns have accelerated the transition toward renewable energy sources. Among the available renewable resources, solar energy is considered one of the most promising alternatives because it is abundant, environmentally friendly, and widely available [1].

Photovoltaic (PV) systems convert solar radiation directly into electrical energy using semiconductor devices. These systems are widely used in standalone power generation, rural electrification, and distributed energy systems. However, the power output of photovoltaic panels is strongly influenced by environmental parameters such as solar irradiance and operating temperature [2]. These variations cause changes in the voltage–current characteristics of PV modules, which may prevent the system from operating at maximum efficiency.

To overcome this limitation, Maximum Power Point Tracking (MPPT) techniques are used in solar energy systems. MPPT algorithms continuously adjust the operating point of the PV module to extract the maximum available power under changing environmental conditions [3]. Various MPPT techniques such as Perturb and Observe, Incremental Conductance, fuzzy logic, and neural network-based methods have been proposed in the literature.

Energy storage is another important component of solar power systems. Lithium-ion batteries are commonly used due to their high energy density, longer cycle life, and better charging efficiency. However, improper charging conditions and excessive temperatures may lead to battery degradation and reduced system reliability [4].

Therefore, monitoring battery parameters such as voltage, current, and temperature is essential for safe and efficient operation.

In this work, a smart solar charging system based on the Incremental Conductance MPPT algorithm is developed using an ESP32 microcontroller. The system integrates photovoltaic power conversion, battery monitoring, and real-time visualization to improve the performance and reliability of solar energy systems.

II. LITERATURE REVIEW

Several researchers have investigated techniques for improving the performance and efficiency of photovoltaic energy systems. MPPT algorithms are widely used to ensure maximum power extraction from PV modules under varying environmental conditions. A comparative study of different MPPT techniques shows that methods such as Perturb and Observe and Incremental Conductance are commonly used due to their simplicity and effectiveness [5].

Advanced MPPT techniques including fuzzy logic controllers and adaptive control methods have also been proposed to enhance tracking performance in rapidly changing environmental conditions. These approaches provide improved accuracy but often require complex computation and hardware implementation [6].

Battery management systems are also an important research area in renewable energy systems. Modern battery monitoring systems continuously observe parameters such as voltage, current, and temperature in order to prevent overcharging, overheating, and deep discharge conditions [7]. These monitoring techniques help extend battery life and improve system reliability.

Recent research has also explored the use of artificial intelligence and machine learning algorithms for predictive monitoring of battery health. These methods are capable of detecting abnormal operating conditions and estimating battery state of charge and state of health more accurately [2]. However, these solutions generally require high computational power and expensive hardware platforms.

Therefore, there is a need for a compact and cost- effective solution that integrates efficient MPPT control and real-time monitoring for small-scale solar applications. The proposed system addresses this requirement by using an ESP32 microcontroller to implement MPPT control and system monitoring functions.

III. SYSTEM ARCHITECTURE

The proposed solar energy monitoring system integrates power conversion, sensing, control, and monitoring functions within a single embedded platform. The system mainly consists of a photovoltaic panel, sensing modules, a DC-DC buck converter, an ESP32 microcontroller, and a lithium- ion battery storage unit.

The photovoltaic panel acts as the primary source of energy in the system. The generated DC power is processed through a DC-DC buck converter which regulates the voltage supplied to the battery. The converter also allows adjustment of the PV operating point according to the MPPT control algorithm.

The ESP32 microcontroller serves as the main controller of the system. It collects data from various sensors, performs MPPT calculations, and manages system monitoring tasks. Voltage and current sensors are placed on both the PV panel side and the battery side to measure electrical parameters in real time.

A temperature sensor is included to monitor thermal conditions near the battery and power conversion circuits. These measurements help improve battery safety and ensure reliable operation of the system.

The overall system architecture includes four major functional modules: Solar power generation module, Sensor and data acquisition module, MPPT control module, Monitoring and communication module

The Overall Structure of the Proposed System is Illustrated in Fig.1.

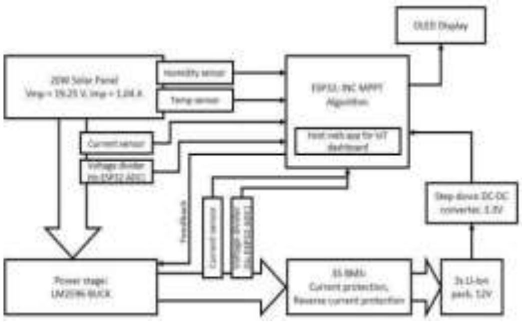

Fig.1 – System Block Diagram

IV. HARDWARE DESIGN

The hardware implementation consists of sensing circuits, power conversion components, and the ESP32 microcontroller. The photovoltaic voltage is measured using a resistor divider circuit which scales the voltage to the acceptable input range of the ESP32 analog-to-digital converter.

Photovoltaic current is measured using an INA219 current sensor which provides precise digital measurements through an I²C interface. This sensor determines the current by measuring the voltage drop across a shunt resistor.

The power conversion stage is implemented using an LM2596-based DC-DC buck converter. This converter regulates the output voltage supplied to the battery while allowing control of the PV operating point through the MPPT algorithm.

Battery current is monitored using a MAX471 current sensor connected to the ESP32 analog input. Additionally, a DHT11 temperature sensor is used to monitor ambient temperature around the battery and power electronics components.

These sensors enable continuous monitoring of electrical and environmental parameters within the solar charging system.

The major hardware components used in the implementation of the proposed system are shown in Table 1.

COMPONENT	SPECIFICATIONS
Solar Panel	12v, 20w
Buck Converter	Dc-Dc Converter for MPPT Control
Battery	12v Li-Ion (18650 x 3 cells)
Battery BMS	3S, Li-ion, 1A
ESP32	ESP32 WROOM module
Voltage Sensor	Resistor voltage divider
Current Sensor	MAX471, INA219
Temperature Sensor	DHT11
OLED Display	IoT Dashboard for Status Monitoring
IoT module	ESP32 WROOM Dev module
Connecting Wires, PCB	Circuit Implementation and Testing

Table 1 – Components Used in the System

The circuit implementation of the MPPT-based solar charging system is shown in Fig. 2.

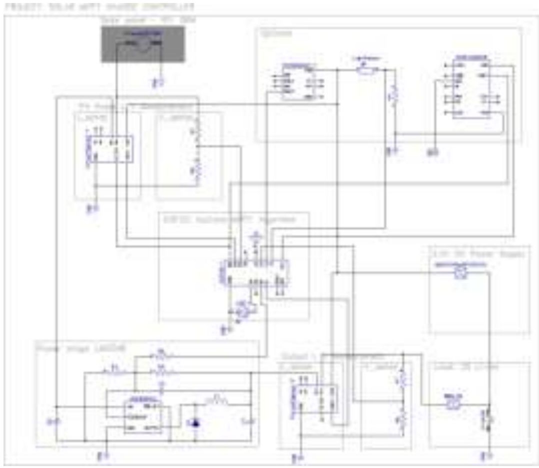

Fig. 2 – MPPT Circuit Diagram

V. SOFTWARE DESIGN

The system software is developed using the Arduino programming framework for the ESP32 microcontroller. The firmware consists of several functional modules responsible for data acquisition, MPPT control, battery monitoring, and communication with the monitoring interface.

Analog signals from voltage and current sensors are sampled using the ESP32's 12-bit analog-to-digital converter. Calibration factors are applied to compensate for measurement errors and sensor offsets. The processed data is then used to calculate electrical power and implement MPPT control.

The ESP32 also hosts a lightweight web server that enables real-time monitoring through a web browser. System parameters such as PV voltage, PV current, battery voltage, battery current, and temperature are displayed on the monitoring interface.

This feature allows users to observe system performance and battery conditions remotely.

VI. MPPT CONTROL METHODOLOGY

The Incremental Conductance (IC) method is used in the proposed system to track the maximum power point of the photovoltaic panel. This technique determines the optimal operating point by comparing incremental conductance with instantaneous conductance.

The algorithm calculates incremental changes in voltage and current by comparing present measurements with previous values. Based on this comparison, the controller determines whether the operating point is located to the left or right of the maximum power point.

The reference voltage of the DC-DC converter is then adjusted accordingly to move the operating point toward the maximum power point. This process continues until the optimal operating condition is achieved.

The Incremental Conductance method offers improved tracking accuracy and faster response compared to traditional MPPT techniques [5].

The operational logic of the Incremental Conductance MPPT algorithm implemented in the ESP32 controller is illustrated in Fig. 3.

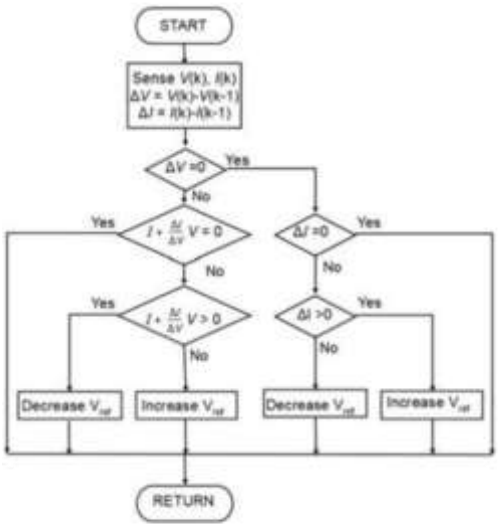

Fig. 3 - Flowchart of Incremental Conductance MPPT Algorithm

As shown in Fig. 3, the algorithm begins by sensing the photovoltaic voltage and current values. The incremental changes in voltage (ΔV) and current (ΔI) are calculated by comparing the present measurements with the previous values. Based on the relationship between incremental conductance and instantaneous conductance, the controller determines whether the operating point is to the left or right of the maximum power point. Accordingly, the reference voltage of the converter is increased or decreased until the system reaches the maximum power point condition.

VII. RESULTS & DISCUSSION

The performance of the proposed system was evaluated using MATLAB/Simulink simulations and hardware implementation. Different MPPT techniques including Incremental Conductance, Perturb and Observe, and Fixed Voltage methods were analyzed under varying environmental conditions.

Simulation results showed that the Incremental Conductance algorithm provides better tracking performance and reduced oscillations around the maximum power point. The Perturb and Observe method exhibited higher oscillations, while the Fixed Voltage technique showed lower efficiency when environmental conditions changed.

A hardware prototype of the system was developed using an ESP32 microcontroller and associated sensors. Experimental observations confirmed that the proposed system can efficiently extract power from the photovoltaic panel while maintaining stable battery charging conditions.

The hardware prototype of the proposed system, which was developed, is shown in Fig. 4.

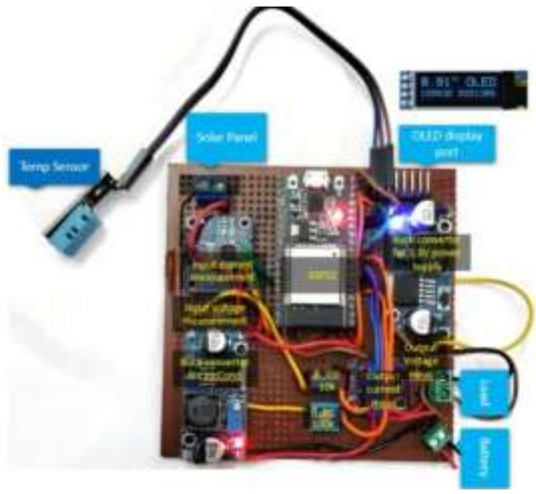

Fig. 4 – ESP32 Based Hardware Prototype

The MATLAB/Simulink model used for comparing different MPPT techniques is shown in Fig. 5.

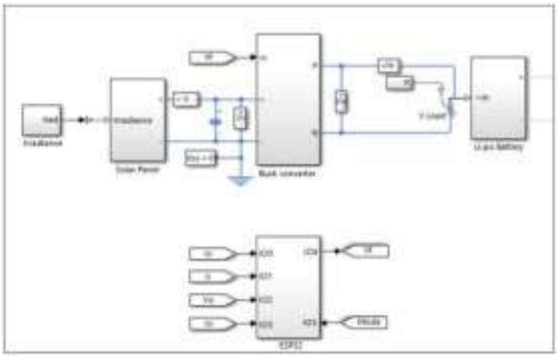

Fig. 5 – Simulink Model for MPPT Analysis

A comparative analysis of different MPPT techniques is summarized in Table 2.

Test Condition	Battery Voltage (avg)	Theoretical Available PV Power	P&O Power	P&O Charge Current	IncCond Power	IncCond Charge Current	Fixed Voltage Power	Fixed Voltage Charge Current
1000 W/m², 25°C	11.8 V	17.6 W	16.5 W	1.29 A	17.1 W	1.33 A	14.7 W	1.15 A
600 W/m², 25°C	12.0 V	10.6 W	9.8 W	0.75 A	10.2 W	0.78 A	8.6 W	0.66 A
600 W/m², 50°C	12.2 V	9.7 W	8.9 W	0.67 A	9.3 W	0.70 A	7.9 W	0.60 A
900 W/m², 50°C	12.3 V	14.6 W	13.4 W	1.00 A	14.0 W	1.05 A	11.8 W	0.88 A

Table 2 – Performance Comparison of MPPT Methods

These results confirm that the Incremental Conductance method provides improved power extraction efficiency and more stable battery charging performance for the proposed solar charging system.

VIII. ADVANTAGES

The proposed system offers several advantages:

- Improved energy extraction using Incremental Conductance MPPT algorithm
- Real-time monitoring of photovoltaic and battery parameters
- Integration of sensing, control, and communication within a single microcontroller
- Web-based monitoring without requiring external cloud services
- Modular design allowing future system upgrades
- Enhanced battery safety through voltage, current, and temperature monitoring

IX. DISADVANTAGES

The system also has certain limitations:

- Increased complexity due to integration of multiple sensors
- Dependence on accurate sensor calibration
- Limited graphical capability in the embedded web interface
- Remote monitoring requires stable Wi-Fi connectivity

X. FUTURE SCOPE

Future improvements may include the implementation of artificial intelligence-based MPPT algorithms for better tracking performance under rapidly changing environmental conditions. A more advanced battery management system can also be integrated to estimate battery state of charge and state of health more accurately.

Cloud-based data storage can be incorporated to allow long-term monitoring and analysis of system performance. In addition, the development of a mobile application could further improve system usability and accessibility.

XI. CONCLUSIONS

This work presented the design and implementation of a smart solar charging system with MPPT control and real-time monitoring capabilities. The system integrates photovoltaic power generation, sensor- based monitoring, and control functions within a compact embedded platform.

The Incremental Conductance MPPT algorithm implemented using the ESP32 microcontroller enables efficient energy extraction from the photovoltaic panel while maintaining stable battery charging conditions. Continuous monitoring of voltage, current, and temperature improves system safety and reliability.

Overall, the proposed system provides a cost- effective solution for intelligent solar energy management in renewable energy applications.

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