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Maximum Power Point Tracking (MPPT) using Fuzzy Logic

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***Abstract*—This paper presents a fuzzy logic control (FLC)-based maximum power point tracking (MPPT) system for photovoltaic (PV) applications implemented using an ESP32 microcontroller and a mobile-based monitoring interface. The proposed method utilizes fuzzy logic to regulate the incremental current in the MPPT algorithm, enabling efficient power extraction under varying environmental conditions. Due to fluctuations in solar irradiance and temperature, PV systems exhibit nonlinear characteristics, reducing the effectiveness of conventional techniques.**

The ESP32 is used for processing and real-time data transmission, while a mobile application is developed to display system parameters such as voltage, current, and power. In the absence of hardware, system outputs are simulated and transmitted to the mobile interface for visualization. The FLC-based approach improves convergence speed, minimizes oscillations around the maximum power point, and enhances overall efficiency. The results demonstrate that the proposed system provides an effective, low-cost, and user-friendly solution for real-time monitoring and optimization of solar energy systems.

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

The increasing demand for energy and the depletion of conventional energy resources have led to a growing interest in renewable energy sources, particularly solar energy. Photovoltaic (PV) systems are widely used due to their clean, sustainable, and environmentally friendly nature. However, the efficiency of PV systems is significantly affected by variations in solar irradiance and temperature, which result in nonlinear output characteristics. Therefore, extracting maximum power from PV systems under varying environmental conditions is a major challenge.

Maximum Power Point Tracking (MPPT) is an essential technique used in PV systems to ensure that the panels operate at their maximum power point (MPP). Unlike mechanical tracking systems that physically align the panels with the sun, MPPT is an electronic method that optimizes the operating point of the PV modules. Conventional MPPT techniques such as Perturb and Observe (PO) and Incremental Conductance (INC) are widely used, but they often suffer from slow response and oscillations around the MPP under rapidly changing conditions.

To overcome these limitations, this paper proposes a fuzzy logic control (FLC)-based MPPT technique. Fuzzy logic provides a robust and adaptive control mechanism that does not require an accurate mathematical model of the system. It improves tracking speed, reduces steady-state oscillations, and enhances overall system performance.

In this project, the proposed MPPT algorithm is implemented using an ESP32 microcontroller, which processes the input parameters and controls the system operation. A mobile-based application interface is developed to monitor real-time parameters such as voltage, current, and power. Due to hardware constraints, system outputs are simulated and transmitted to the mobile application for visualization purposes. This approach provides a cost-effective and user-friendly solution for demonstrating real-time monitoring and control of PV systems.

II. Literature Review

Photovoltaic (PV) systems require efficient maximum power point tracking (MPPT) techniques to extract maximum available power under varying environmental conditions such as irradiance and temperature. Conventional MPPT methods like Perturb and Observe (P&O) and Incremental Conductance (INC) are widely used due to their simplicity, but they suffer from drawbacks such as steady-state oscillations and slow response under dynamic conditions. To overcome these limitations, intelligent techniques such as fuzzy logic, ANFIS, and optimization-based methods have been introduced. These approaches improve tracking accuracy, response speed, and overall system efficiency. Additionally, recent developments focus on integrating MPPT systems with IoT-based platforms for real-time monitoring and control.

A. Maximum Power Point Tracking using Perturb and Observe, Fuzzy Logic and ANFIS

A. S. Mahdi *et al.* presented a comparative analysis of conventional and intelligent MPPT techniques including P&O, fuzzy logic control (FLC), and adaptive neuro-fuzzy inference system (ANFIS). The study shows that the P&O method suffers from oscillations and fails under partial shading conditions, whereas FLC and ANFIS provide better tracking efficiency and faster response [1].

B. Fuzzy Logic Based Control Technique using MPPT for Solar PV System

R. K. Rai and O. P. Rahi proposed a fuzzy logic-based MPPT controller using error and change in error as input variables. The results indicate that fuzzy logic effectively handles nonlinear PV characteristics and improves tracking accuracy, reduces oscillations, and increases overall efficiency [2].

C. Fuzzy-Based Maximum Power Point Tracking (MPPT) Control System

Kifayat Ullah *et al.* developed a fuzzy-based MPPT system using MATLAB/Simulink. The proposed method enhances system stability and reduces power fluctuations under varying weather conditions. The results demonstrate improved efficiency and faster convergence to the maximum power point [3].

D. IoT Based I-V and P-V Curve Analyzer System for Small PV Panels

T. Sapaklom *et al.* presented an IoT-based PV monitoring system using an ESP32 microcontroller. The system measures voltage and current parameters and transmits data to a cloud platform for real-time analysis and visualization, demonstrating effective integration of IoT with PV systems [4].

From the above literature, it is observed that fuzzy logic-based MPPT provides better performance compared to conventional techniques. Hence, this work proposes an FLC-based MPPT system integrated with ESP32 and a mobile monitoring interface.

III. Project Objectives

The main objectives of this project are as follows:

- To design and implement a fuzzy logic control (FLC)-based MPPT algorithm for efficient extraction of maximum power from photovoltaic (PV) systems.
- To improve the tracking speed and accuracy of the MPPT system under varying environmental conditions such as irradiance and temperature.
- To reduce steady-state oscillations around the maximum power point (MPP) compared to conventional MPPT techniques.
- To implement the proposed MPPT algorithm using an ESP32 microcontroller for real-time processing and control.
- To develop a mobile-based monitoring interface for displaying PV parameters such as voltage, current, and power.
- To simulate PV system outputs in the absence of hardware and demonstrate real-time data visualization on the mobile platform.
- To provide a cost-effective, efficient, and user-friendly solution for solar energy monitoring and optimization.

IV. Proposed Methodology

This section describes the design and implementation of the proposed fuzzy logic control (FLC)-based maximum power point tracking (MPPT) system using an ESP32 microcontroller and a mobile-based monitoring interface.

A. System Overview

The proposed system consists of a photovoltaic (PV) panel, MPPT controller, ESP32 microcontroller, and a mobile monitoring application. The PV panel generates electrical energy depending on solar irradiance and temperature. The MPPT controller ensures that the system operates at its maximum power point (MPP). The ESP32 processes the data and transmits it to the mobile application for real-time monitoring.

B. MPPT Principle

The output characteristics of a PV system are nonlinear and vary with environmental conditions. There exists a unique point called the maximum power point (MPP) at which the product of voltage and current is maximum. MPPT techniques are used to track this point continuously and extract maximum power. In this work, a fuzzy logic-based approach is used for better performance under dynamic conditions.

C. Fuzzy Logic Controller

The fuzzy logic controller (FLC) uses two input parameters: change in power (ΔP) and change in voltage (ΔV). Based on these inputs, the controller generates an output that adjusts the duty cycle.

The FLC consists of three stages:

- Fuzzification: Converts input values into linguistic variables such as NB, NS, ZE, PS, and PB.
- Rule Base: A set of IF-THEN rules is used to determine the control action.
- Defuzzification: Converts the fuzzy output into a crisp value.

This approach improves tracking speed and reduces oscillations around the MPP.

D. ESP32 Implementation

The ESP32 microcontroller is used to implement the MPPT algorithm. It processes input parameters such as voltage and current and transmits data to the mobile application using Wi-Fi. Its low cost and built-in connectivity make it suitable for IoT-based applications.

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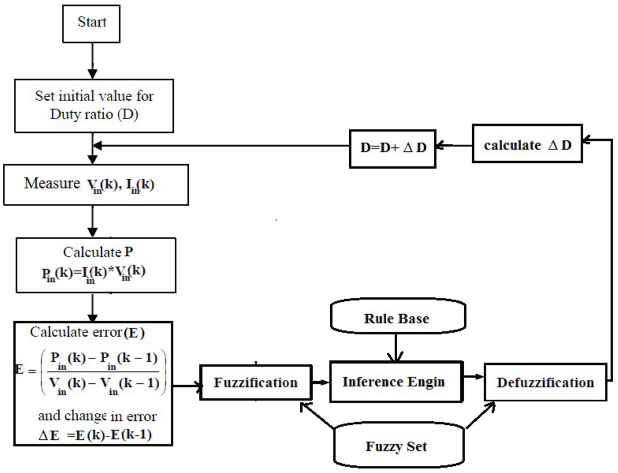

Fig. 1. Flowchart of fuzzy Logic-based MPPT algorithm

E. *Mobile Application*

A mobile-based interface is developed to display real-time parameters such as voltage, current, and power. This enables remote monitoring of the PV system.

F. *Simulation Approach*

Due to hardware limitations, the PV parameters are simulated. The generated values are processed using ESP32 and transmitted to the mobile application for visualization.

G. *System Block Diagram*

The overall working of the proposed system is illustrated in Fig. 2.

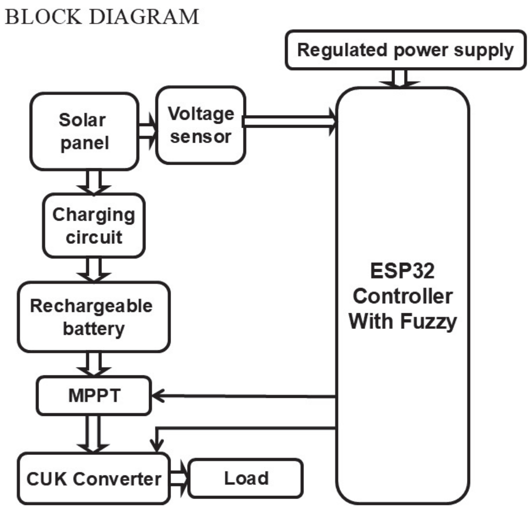

Fig. 2. Proposed System Block Diagram

V. Results and Discussion

This section presents the performance analysis of the proposed fuzzy logic control (FLC)-based MPPT system implemented using ESP32 and a mobile-based monitoring interface.

A. *Mobile Application Output*

The developed mobile application displays real-time photovoltaic (PV) parameters such as voltage, current, and power. Due to hardware limitations, the values are generated through simulation and processed using the ESP32 microcontroller.

The results shown in Fig. 3 and Fig. 4 demonstrate the successful transmission and visualization of system parameters on the mobile interface. The variation in output values indicates the dynamic behavior of the MPPT system under different conditions.

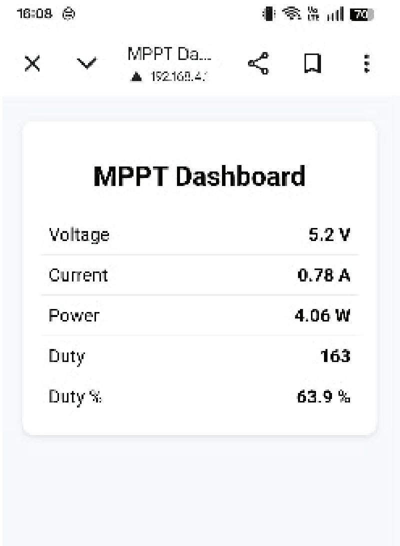

Fig. 3. Mobile Application Output (Case 1)

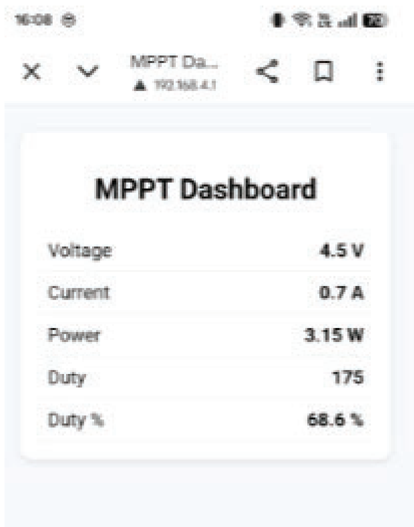

Fig. 4. Mobile Application Output (Case 2)

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B. Discussion

The results indicate that the fuzzy logic-based MPPT approach provides better tracking efficiency and response compared to conventional techniques. Even in the absence of physical hardware, the system effectively demonstrates the working of MPPT and real-time monitoring using ESP32 and IoT-based applications.

VI. Conclusion

This paper presents a fuzzy logic control (FLC)-based maximum power point tracking (MPPT) system for photovoltaic (PV) applications using an ESP32 microcontroller and a mobile-based monitoring interface. The proposed system effectively tracks the maximum power point under varying environmental conditions.

The use of fuzzy logic improves the tracking performance by reducing oscillations around the maximum power point and providing faster convergence compared to conventional techniques. The ESP32 enables real-time data processing and wireless transmission, making the system suitable for IoT-based applications.

Due to hardware limitations, the system was demonstrated using simulated data; however, the results successfully validate the effectiveness of the proposed approach. The mobile application provides a user-friendly interface for monitoring PV parameters such as voltage, current, and power.

In future work, the system can be implemented with real hardware components to further enhance accuracy and practical applicability.

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