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AN IOT-BASED ADAPTIVE PHOTOVOLTAIC SYSTEM EMPLOYING FUZZY MPPT AND DUAL-AXIS TRACKING TO MAINTAIN POWER STABILITY UNDER NON-UNIFORM IRRADIANCE CONDITIONS

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ABSTRACT

This study presents an adaptive photovoltaic system integrated with Internet of Things (IoT) technology, which combines a Fuzzy Logic–based Maximum Power Point Tracking (MPPT) algorithm with a dual-axis solar tracking mechanism to maintain stable power generation under non-uniform irradiance conditions. The system is experimentally implemented with real-time monitoring and data transmission through an IoT platform, enabling continuous performance evaluation in dynamic outdoor environments. Experimental results indicate that the proposed system improves MPPT tracking efficiency from 96% to 99.98%, with optimal operation achieved within a Pulse Width Modulation (PWM) duty cycle range of 71.8%–72.2%. The most rapid transient response and stable oscillatory behavior are observed at a duty cycle of 0.03, ensuring consistent operation at the maximum power point. Compared to a system without Fuzzy Logic control, the proposed approach increases output power by 1.6%, and achieves up to a 15% improvement relative to a conventional MPPT system without Fuzzy Logic and dual-axis tracking under unfavorable weather conditions. These findings confirm that the proposed IoT-based adaptive photovoltaic system effectively enhances energy harvesting efficiency and operational reliability in real-world applications.

Keywords*: Photovoltaic System, Fuzzy Logic MPPT, Internet Of Things, Irregular Irradiance, Dual Axis Solar Tracker.*

INTRODUCTION

Renewable energy is defined as energy generated from natural resources that are continuously replenished and do not diminish over time. Supported by rapid technological progress, renewable energy has increasingly been developed as a substitute for conventional energy sources. Various forms of renewable energy include solar, wind, hydropower, ocean waves, ocean thermal energy, and other sustainable resources [1]. Among these options, solar energy can be converted into electrical power through photovoltaic (PV) cells, which transform solar radiation directly into electricity. However, PV cells exhibit non-linear current–voltage characteristics, and their output power is highly dependent on solar irradiance levels and operating temperature [2].

Solar energy has been extensively applied in electricity generation, particularly through solar power plants (PLTS). On a global scale, PLTS have been implemented in approximately 183 countries, with an installed capacity of 755 GW out of a projected total of 1,745 GW [3]. This extensive adoption highlights solar energy as a viable alternative to fossil fuel–based power generation, including coal, petroleum, and natural gas.

In Indonesia, there are currently 26 operational PLTS facilities distributed across various regions. According to data from the Ministry of Energy and Mineral Resources (ESDM), the total installed PLTS capacity has reached 548.48 MW, comprising 244.00 MW from utility-scale systems and 304.48 MW from rooftop installations [4]. Despite this progress, Indonesia’s theoretical solar energy potential is estimated at 16,530 GW if fully optimized [3].

Nevertheless, the development of PLTS in Indonesia still encounters several challenges, such as limited infrastructure, economic and commercial barriers, and complex regulatory and licensing processes. Additionally, low public awareness and insufficient educational dissemination continue to hinder the widespread adoption of solar energy systems [5].

Another critical issue in PLTS operation is the variability of weather conditions, which causes fluctuations in solar irradiance and light intensity. Solar energy availability also varies geographically. Based on data from the Meteorology, Climatology, and Geophysics Agency (BMKG), Indonesia’s solar irradiation ranges between 1.2 and 7.5 kWh/m², indicating strong potential for nationwide PLTS deployment [6].

To mitigate irradiance fluctuations and maintain optimal system performance, Maximum Power Point Tracking (MPPT) techniques are widely employed. MPPT algorithms are designed to continuously adjust the operating point of photovoltaic modules to ensure maximum power output under varying environmental conditions [7]. Rapid weather changes often prevent PV systems from operating at their optimal point, leading to the development of various MPPT methods, such as Perturb and Observe (P&O), genetic algorithms, fuzzy logic, and other intelligent approaches.

Fuzzy logic is a control methodology well suited for addressing complex problems through rule-based reasoning. It transforms numerical inputs into linguistic variables, enabling flexible and intuitive decision-making processes [8]. Unlike conventional binary logic, which operates strictly on two states, fuzzy logic utilizes degrees of membership ranging from 0 to 1, allowing uncertainty and imprecision to be effectively modeled. For instance, vehicle speed can be expressed linguistically as slow, medium, fast, or very fast [9].

Consequently, MPPT systems based on a Fuzzy Logic Controller (FLC) feature a simple structure and do not require explicit mathematical modeling, making them highly adaptable to changing environmental conditions. In this research, an Arduino microcontroller is employed to implement the FLC, resulting in a compact, efficient, and cost-effective control system.

Beyond MPPT control, the implementation of a dual-axis solar tracking system can further improve energy harvesting efficiency. By adjusting the photovoltaic panel orientation along both azimuth and elevation axes, the system maintains an optimal angle relative to the sun throughout the day, thereby maximizing solar radiation absorption [10].

To support real-time monitoring and remote accessibility, Internet of Things (IoT) technology is integrated into the MPPT system. IoT refers to a network framework in which devices equipped with unique identifiers can collect and transmit data via communication networks to users or computing platforms [11]. Technologies such as Wi-Fi, Long Range (LoRa), and other internet-based communication methods may be utilized. Through cloud servers or online platforms, the system can be monitored and controlled remotely as long as internet connectivity is available.

METHODOLOGY

1. Methodology Content

This study presents the design and implementation of a Fuzzy Logic–based Maximum Power Point Tracking (MPPT) system integrated with a dual-axis solar tracking mechanism to improve the performance of photovoltaic (PV) panels. The proposed system architecture consists of several electronic modules and supporting components that are centrally managed by a microcontroller serving as the main control unit. The system is developed to maximize solar energy utilization by enhancing electrical power extraction while simultaneously adjusting the physical orientation of the PV module in response to changing environmental conditions.

The MPPT subsystem operates as a solar charge controller and is implemented using an Arduino Nano microcontroller. The photovoltaic panel serves as the primary energy source, while the MPPT circuit regulates the panel output to provide a stable charging voltage of 13.7 V for battery storage. In addition, a regulated 5 V power supply is used to support the Arduino Nano and peripheral devices, including Light Dependent Resistor (LDR) sensors, an ACS712 current sensor, an LCD module, and servo motors. Electrical output parameters, such as voltage and current, are continuously monitored through the ACS712 sensor to facilitate real-time system performance evaluation.

To ensure optimal operating conditions under varying environmental influences, a Fuzzy Logic Controller (FLC) is embedded within the MPPT algorithm. The controller adaptively adjusts the MPPT duty cycle based on real-time feedback from the sensors, allowing the system to maintain operation near the maximum power point. This adaptive control approach enables effective compensation for fluctuations in solar irradiance and temperature, resulting in higher energy conversion efficiency compared to conventional MPPT methods.

In addition to electrical optimization, a dual-axis solar tracking system is employed to further enhance energy harvesting throughout the day. The tracking mechanism utilizes LDR sensors to detect the direction and intensity of incoming solar radiation, enabling the Arduino Nano to control servo motors that adjust the PV panel orientation along both azimuth and elevation axes. This two-degree-of-freedom movement allows the panel to continuously align with the sun’s trajectory, thereby maximizing solar radiation absorption.

The overall system is configured as a closed-loop control structure, where feedback from the LDR sensors and the ACS712 current sensor is continuously processed by the microcontroller to regulate both the MPPT operation and the dual-axis tracking mechanism. Key parameters, including voltage, current, and light intensity, are displayed locally on an LCD and transmitted wirelessly via an Internet of Things (IoT) platform using an ESP32 module. With an active internet connection, the system enables real-time remote monitoring and performance analysis, allowing users to assess energy optimization outcomes from any location.

2. Study Literature

Maximum Power Point Tracking (MPPT) is a commonly implemented control strategy in solar and wind energy charge controllers to maximize the electrical power extracted from renewable energy sources. MPPT enables a system to continuously determine the optimal operating condition at which a photovoltaic (PV) module can deliver its highest power output. This is achieved by controlling the PV output voltage via a DC–DC converter so that the operating point remains close to the region of maximum power [12].

The main objective of MPPT is to ensure that the PV module operates at its Maximum Power Point (MPP), which varies continuously due to changes in solar irradiance, ambient temperature, and shading conditions. When MPPT is effectively applied, the amount of energy generated is significantly higher than that of PV systems operating without power point optimization. Numerous studies and review papers have reported that conventional MPPT algorithms, such as Perturb and Observe (P&O) and Incremental Conductance, have gradually evolved into more advanced hybrid and intelligent techniques. Methods based on fuzzy logic, artificial neural networks, and metaheuristic optimization have demonstrated improved tracking accuracy and faster dynamic response, particularly under partial shading and rapidly changing environmental conditions [13].

In certain applications where the solar-powered load operates intermittently and does not require continuous maximum power delivery, a simplified operational strategy may be employed. In this method, the load is activated at an initial operating point (Point 1) and deactivated at a second operating point (Point 2), allowing the system to function at approximately 90% of the MPP. When the load is connected, the increased current demand causes the PV voltage to decrease, shifting the operating point from Point 1 through the MPP toward Point 2. Once the load is disconnected, the PV voltage increases again toward its initial value. Although this approach offers simplicity, it still presents certain performance limitations and control challenges that must be carefully addressed [14].

The performance of the MPPT scheme is evaluated using specific performance indicators. In this research, tracking efficiency is determined by comparing the power successfully extracted by the MPPT controller (P_tracked) with the actual maximum available power of the PV module under the given test conditions (P_maxreal). For a more comprehensive assessment of energy performance, additional metrics such as the Performance Ratio (PR) may also be considered. The experimental evaluation follows established methodologies, where the true maximum power (P_maxreal) is obtained either through current–voltage (I–V) curve measurements or through irradiance-based estimation with temperature compensation. Meanwhile, the tracked power (P_tracked) is directly calculated from the measured voltage and current values at the MPPT input terminals [15].

3. Block Diagram

During the design stage, a flowchart is developed to describe the overall operating procedure of the system, in which solar irradiance is captured and converted into electrical energy for battery charging and load supply. The schematic illustrating the integration of the MPPT system with the Internet of Things (IoT) platform via an ESP32 module is shown in Figure 1.

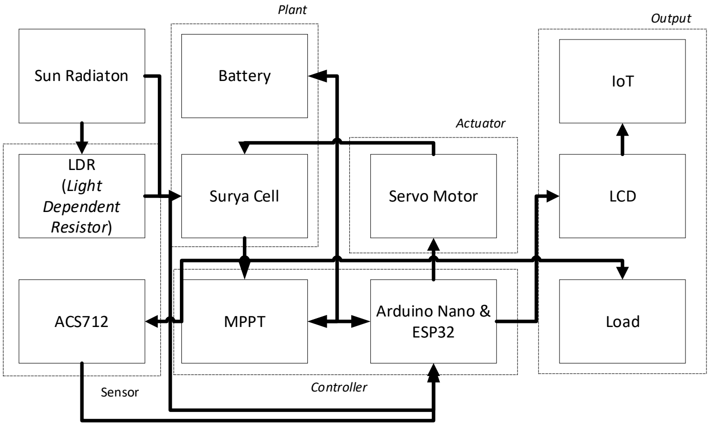


Figure 1. System Design Block Diagram

As depicted in Figure 1, the photovoltaic panel functions as the primary input source for the MPPT system, which operates as a solar charge controller implemented using an Arduino Nano microcontroller. The MPPT unit generates a regulated output voltage of 13.7 V for battery charging, while also providing a 5 V supply to power the Arduino Nano and supporting components, including Light Dependent Resistor (LDR) sensors, an ACS712 current sensor, an LCD module, and servo motors. After the MPPT stage, the output voltage and current are continuously monitored using the ACS712 sensor to evaluate the electrical performance of the system. Based on these measurements, a fuzzy logic–based control algorithm is applied to regulate the MPPT operation, ensuring that the voltage and current remain at their optimal operating points.

To further enhance solar energy utilization, a dual-axis solar tracking mechanism is incorporated into the system. This tracking subsystem utilizes LDR sensors connected to the Arduino Nano to detect both the intensity and direction of incident sunlight. The acquired sensor data are processed to control servo motors that adjust the orientation of the photovoltaic panel along two rotational axes. In addition, measurement data obtained from the ACS712 and LDR sensors are displayed locally on an LCD and transmitted wirelessly to an Internet of Things (IoT) platform through an ESP32 module. This configuration enables continuous real-time monitoring of system parameters and operational performance. The overall closed-loop architecture of the proposed system is illustrated in Figure 2.

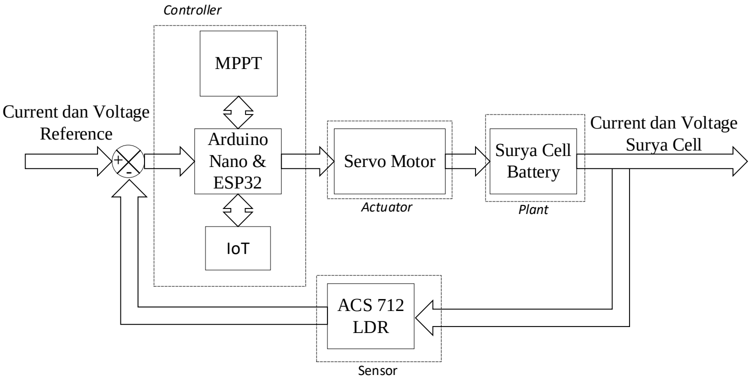


Figure 2. Closed-Loop Block Diagram

Figure 2 shows that solar radiation acts as the primary energy input to the system and is directly received by the photovoltaic panel. The panel converts the incoming solar energy into electrical power, which is supplied to both the MPPT module and the microcontroller. The MPPT unit regulates the generated electrical energy to produce a stable output voltage of 13.7 V for battery charging, while the battery simultaneously provides power to support the operation of the MPPT system.

The microcontroller processes feedback signals from the LDR and ACS712 sensors to control the servo motors at predefined angular positions, thereby adjusting the panel orientation and regulating the MPPT operation to maintain the system at the maximum power point. In the final stage, the measured and processed data are transmitted to an Internet of Things (IoT) platform via an internet connection, enabling remote data acquisition and real-time monitoring of the system.

4. Flowchart

During the system design and implementation stages, a flowchart is developed to support and clarify the overall research procedure. The flowchart representing the system operation is shown in Figure 3.

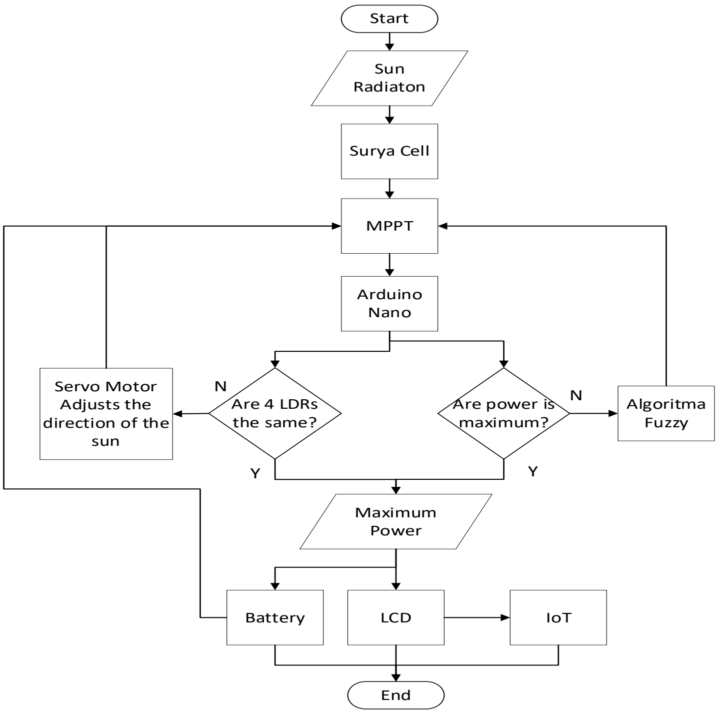


Figure 3. Flowchart

In this study, solar irradiance is treated as the main system input and is converted into electrical energy by the photovoltaic panel. The generated electrical output is then processed by the MPPT unit, which adjusts the operating voltage toward its optimal value using an Arduino Nano microcontroller. After this stage, both the output voltage and the measured solar irradiance are evaluated to determine whether the system has reached its maximum operating condition. If the detected irradiance is below the optimal threshold, the orientation of the servo motors is adjusted to improve solar exposure. Conversely, when the output voltage has not yet reached its maximum value, a fuzzy logic–based control algorithm is applied to optimize power extraction.

Once optimal voltage and irradiance conditions are achieved, the generated electrical energy is directed to charge the battery, and key system parameters are displayed on the LCD for local monitoring. The efficiency of the MPPT system is calculated by comparing the input power and output power of the MPPT unit, resulting in an overall efficiency percentage. In addition, the dynamic behavior of the MPPT controller is evaluated by analyzing the response time required for the system to return to the maximum power operating point following changes in environmental conditions and disturbances in solar irradiance experienced by the photovoltaic module.

This research is expected to improve MPPT efficiency through the implementation of a fuzzy logic–based control approach, increasing performance from approximately 96% to a range of 98–99%. Compared with the conventional Perturb and Observe (P&O) method, the proposed technique offers better adaptability while avoiding the extensive data requirements and long training periods associated with neural network–based MPPT algorithms. Consequently, the proposed MPPT strategy demonstrates enhanced efficiency and robustness under fluctuating environmental conditions

RESULT AND DISCUSSION

The solar tracking system is designed to operate with two degrees of freedom, comprising horizontal motion along the azimuth+ and azimuth− axes, and vertical motion along the elevation+ and elevation− axes. To obtain the optimal tracking position, the combined outputs of the sensors on each axis are regulated so that their resultant value approaches zero. Electrical parameters are monitored using an ACS712 current sensor, which supplies input data to the fuzzy logic controller. The fuzzy control variables consist of ΔP, representing the change in output power, and ΔV, representing the corresponding voltage variation within a specific time interval.

Before conducting experimental tests, all sensors are calibrated using standardized measuring instruments to ensure accurate data acquisition and reliable system operation. The experimental procedure begins with validation of the solar tracking subsystem, followed by performance evaluation of the MPPT controller. During MPPT testing, two input variables are processed to generate ΔD in the form of a Pulse Width Modulation (PWM) signal, which is then translated into a duty cycle to regulate the MPPT output power.

Performance evaluation is conducted concurrently by comparing the proposed system with a conventional MPPT method based on the Perturb and Observe (P&O) algorithm. This assessment is carried out by varying the duty cycle membership function within a range of 0.01 to 0.05 to examine its influence on system behavior. To ensure a fair comparison, both systems utilize identical photovoltaic modules, specifically 10 Wp polycrystalline solar panels. The complete circuit configuration of the proposed system is illustrated in Figure 4.

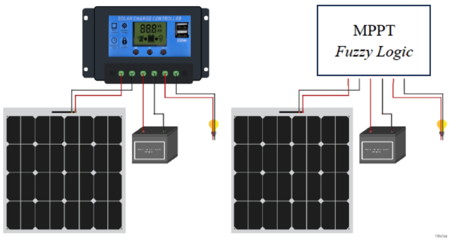
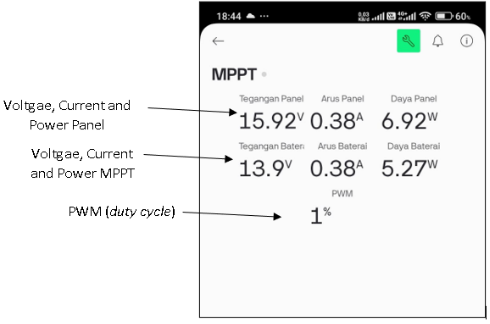


Figure 4. Fuzzy Logic–Based MPPT Testing

Figure 4 shows the physical prototype of the developed system, which was constructed in accordance with the predefined design specifications. The prototype is capable of executing a fuzzy logic algorithm using an Arduino microcontroller and acquiring data from Light Dependent Resistor (LDR) sensors as well as an ACS712 current sensor. The collected sensor data are transmitted through an application integrated with an Internet of Things (IoT) platform, namely Blynk. These data are subsequently visualized in real time on the Blynk user interface, as depicted in Figure 5.



Tegangan Panel 15.92 V
Arus Panel 0.38 A
Daya Panel 6.92 W
Tegangan Bateri 13.9 V
Arus Baterai 0.38 A
Daya Baterai 5.27 W
PWM 1 %

Figure 5. Internet of Things Blynk

MPPT performance evaluation is conducted to investigate the system's response to variations in incident solar irradiance. Fluctuations in light intensity received by the photovoltaic panel directly affect the output voltage, leading to voltage variations that influence MPPT behavior. As a result, changes in irradiance are a critical factor in determining the effectiveness of MPPT operation. The evaluation procedure involves measuring voltage, current, and power at both the input and output sides of the MPPT system.

During the assessment, system performance is analyzed based on its input–output electrical characteristics as well as the dynamic behavior of the MPPT controller, particularly its ability to re-establish operation at the Maximum Power Point (MPP) under varying environmental conditions. The duty cycle is varied within a range of 0.02 to 0.05, and the corresponding transient response time is examined to evaluate the MPPT controller's capability to reach optimal operating conditions with minimal oscillations and rapid convergence to the MPP.

The response time analysis is initiated using a defuzzification output value of 0.2, as illustrated in Figure 6, followed by values of 0.3, 0.4, and 0.5, which are shown in Figure 7, Figure 8, and Figure 9, respectively. The transient response of the MPPT system is evaluated using the first ten data samples after system activation. For analytical consistency, the measured values are normalized from an initial range of 0–100 to a scaled range of 0–1.

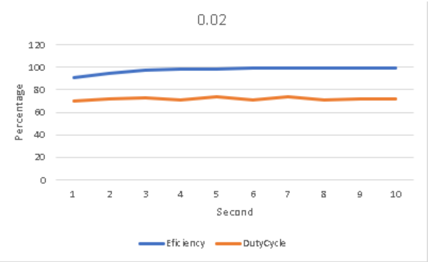


Figure 6. Response Time at Duty Cycle 0.02

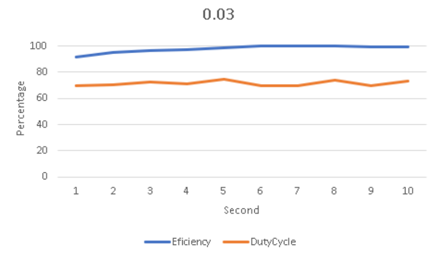


Figure 7. Response Time at Duty Cycle 0.03

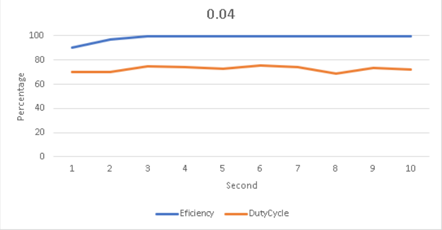


Figure 8. Response Time at Duty Cycle 0.04

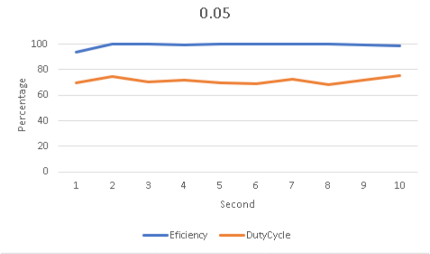


Figure 9. Response Time at Duty Cycle 0.05

Based on the results presented in Figure 6 through Figure 9, the MPPT output demonstrates stable oscillatory behavior at specific duty cycle variations. The fastest response is achieved at duty cycle values of approximately 71.575% for a defuzzification value of 0.02, 71.467% for 0.03, 72.488% for 0.04, and 71.38% for 0.05. These findings indicate that the stable operating range of the MPPT duty cycle is within 71% to 72%, characterized by relatively small oscillations.

The experimental evaluation is conducted by monitoring the MPPT response over a daily operating period, with data acquisition performed for approximately four hours at one-minute intervals. The analysis utilizes defuzzification output values ranging from 0.2 to 0.5 and focuses on observing data variations until the PWM output generated by the microcontroller stabilizes, indicating that steady-state conditions have been achieved. The experimental results corresponding to this evaluation are presented in Figure 10 through Figure 13.

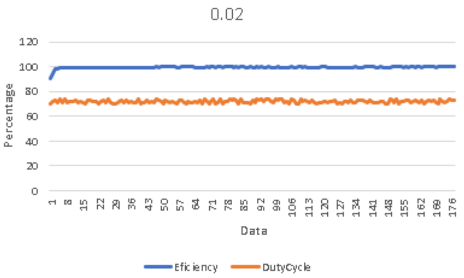


Figure 15. Performance at Duty Cycle 0.02

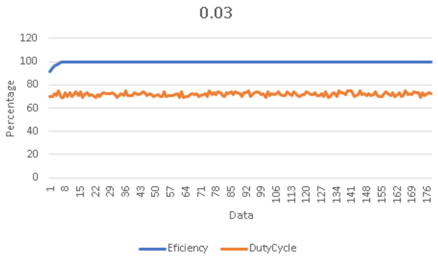


Figure 16. Performance at Duty Cycle 0.03

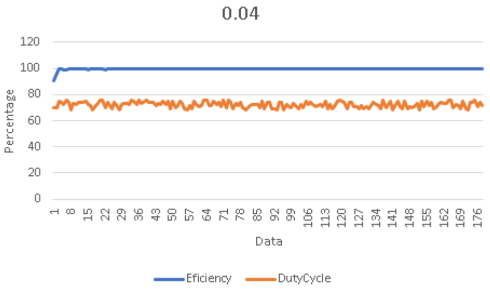


Figure 17. Performance at Duty Cycle 0.04

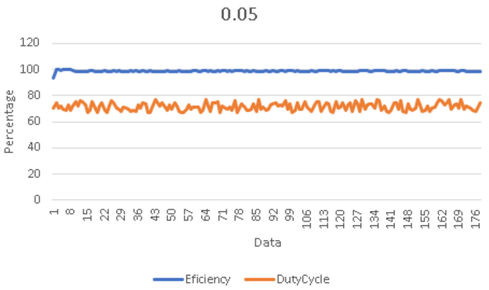


Figure 18. Performance at Duty Cycle 0.05

Long-term performance analysis shows that duty cycle variations of 0.02, 0.03, 0.04, and 0.05 result in MPPT efficiencies of 99.474%, 99.699%, 99.61%, and 98.88%, respectively. Among these configurations, the duty cycle variation of 0.03 achieves the highest efficiency, indicating the most optimal operating condition for the proposed MPPT system.

To further validate the effectiveness of the proposed approach, comparative testing is carried out under unstable weather conditions by operating the fuzzy logic–based MPPT system alongside a conventional MPPT method using the Perturb and Observe (P&O) algorithm. The comparison results are shown in Figure 19.

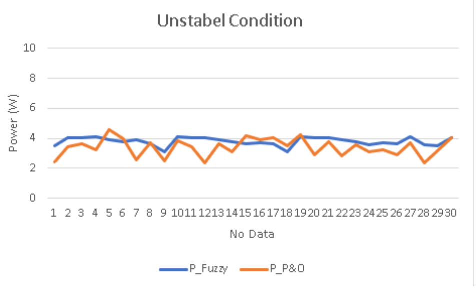


Figure 19. Comparison of Fuzzy Logic MPPT and P&O MPPT

The experimental results indicate that the proposed system produces an average output power of 3.79 W, while the P&O-based MPPT system yields an average power of 3.39 W. Although performance fluctuations are observed under certain conditions due to irradiance variability and partial shading, the overall results demonstrate an average power improvement of approximately 15% achieved through the integration of fuzzy logic control and dual-axis solar tracking.

CONCLUSION

Aplikasi Based on the findings of this research, it can be concluded that the application of a Fuzzy Logic–based algorithm in a Maximum Power Point Tracking (MPPT) system integrated with a dual-axis solar tracking mechanism is able to substantially enhance the performance of photovoltaic systems. Experimental results indicate that the overall system efficiency increases from 96% to 99.98%, with an optimal PWM operating range between 71.8% and 72.2%. In addition, the ACS712 current sensor used in the system demonstrates a relatively low measurement error of 1.46%, confirming the reliability of the acquired electrical data. The most favorable dynamic response is achieved at a duty cycle of 0.03, which provides faster convergence to the maximum power point and stable oscillatory behavior, resulting in the highest observed efficiency.

Furthermore, the proposed system achieves a power output improvement of approximately 15% compared to MPPT configurations that do not employ fuzzy logic control or dual-axis solar tracking, particularly under adverse weather conditions. These results confirm that the integration of a fuzzy logic–based MPPT algorithm with a dual-axis tracking system enables more effective solar energy harvesting, thereby improving both the efficiency and overall performance of the photovoltaic power generation system.

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