Comparison of adaptive tuning fuzzy PID and Ziegler-Nichols PID for photovoltaic cooling system

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Article Info

ABSTRACT

Renewable energy, particularly solar power, is widely recognized as a clean and sustainable resource, with rooftop photovoltaic (PV) systems playing a vital role in electricity generation. However, high temperatures can significantly reduce their efficiency, making effective cooling systems essential. This study proposes a proportional-integral-derivative (PID) based cooling control system for rooftop PV panels, integrating an adaptive Mamdani fuzzy logic controller to optimize PID parameters dynamically. The methodology includes system modeling, hardware and software implementation, and comparative testing between the Mamdani fuzzy-PID controller and the Ziegler-Nichols PID method. Experimental results show that both controllers effectively regulate PV panel temperature at 36 °C. The Ziegler-Nichols PID achieves faster settling time of 6.45 minutes with a steady-state error of 1.345%, whereas the Mamdani fuzzy-PID reduces the steady-state error to 0.93% but with a longer settling time of 9.15 minutes. These results indicate that the fuzzy-PID controller offers better accuracy and system stability, making it a promising solution for maintaining PV performance under varying environmental conditions. The key novelty of this study lies in its adaptive approach, where the Mamdany fuzzy-PID controller continuously adjust control parameters (Kp, Ki, Kd) in real time, resulting in more consistent and precise temperature regulation than conventional PID tuning methods.

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1. INTRODUCTION

Solar energy is a widely recognized renewable and sustainable energy source, valued for its environmental benefits and economic viability. Among its various applications, rooftop photovoltaic (PV) systems have emerged as a practical solution to meet electricity demands in residential and commercial sectors. However, the efficiency of PV systems is significantly affected by environmental factors, particularly elevated temperatures, which reduce solar energy conversion efficiency and overall power output [1]–[5]. Studies indicate that PV efficiency declines when operating temperatures exceed the optimal range of 25 °C, emphasizing the need for effective cooling strategies [6], [7].

Various cooling techniques have been explored, including passive methods such as phase change materials and active strategies like forced air circulation [8], [9]. While these methods effectively regulate PV module temperatures, their performance can be further optimized using advanced control strategies. The proportional-integral-derivative (PID) controller is widely used for thermal regulation, offering simplicity

and effective control [10]. However, conventional PID tuning methods, such as Ziegler-Nichols, often fail to maintain optimal performance under dynamic environmental conditions, leading to overshooting and slow response times [11]–[13].

To address these limitations, fuzzy logic controllers (FLCs) have been introduced as a more adaptive and robust alternative [14], [15]. Unlike conventional PID controllers, FLCs enable real-time parameter adjustments, allowing better adaptation to fluctuating environmental conditions and enhancing cooling efficiency [16]–[18]. Hybrid approaches, particularly adaptive fuzzy-PID controllers, have shown superior performance in maintaining PV module temperatures while minimizing steady-state errors [19], [20].

Despite these advancements, comparative studies evaluating adaptive fuzzy-PID controllers against conventional PID controllers in rooftop PV cooling applications remain limited. Therefore, this study aims to analyze and compare the effectiveness of an adaptive tuning fuzzy-PID controller and a Ziegler-Nichols PID controller in regulating PV module temperatures. The ESP32 microcontroller is used as the central processing unit, implementing both control strategies. Key performance metrics—including temperature regulation, response time, and steady-state error—are evaluated to determine the most effective approach [21], [22].

Building upon previous research on adaptive fuzzy logic controllers [18], [21], [23], PV cooling strategies [4], [24], and Ziegler-Nichols PID tuning [12], [14], [25] to the development more efficient for rooftop PV cooling control mechanisms systems. By experimentally evaluating both adaptive fuzzy-PID and conventional PID methods under identical conditions, the research fills a notable gap in existing literature. The findings provide valuable insights into each method's ability to reduce steady state errors and enhance energy output, offering practical implications for optimizing photovoltaic system performance in dynamic environmental conditions and advancing smart renewable energy systems.

2.   METHOD
2.1. Rooftop photovoltaic cooling system design
2.1.1. Cooling system circuit design

The circuit configuration of the cooling system is illustrated in Figure 1. As depicted in Figure 1, the system consists of four photovoltaic panels, arranged in two series-connected strings. Each string is equipped with temperature sensors for real-time monitoring: i) The ESP32 microcontroller collects and processes temperature data from the PV panels; ii) When the measured temperature exceeds the predefined limit, the fuzzy-PID controller activates the water pump and motorized valve; iii) The water pump sprays water onto the PV surface, while the motorized valve regulates the flow rate, ensuring efficient cooling; and iv) This process enhances PV performance and prevents overheating, extending the lifespan of the panels.
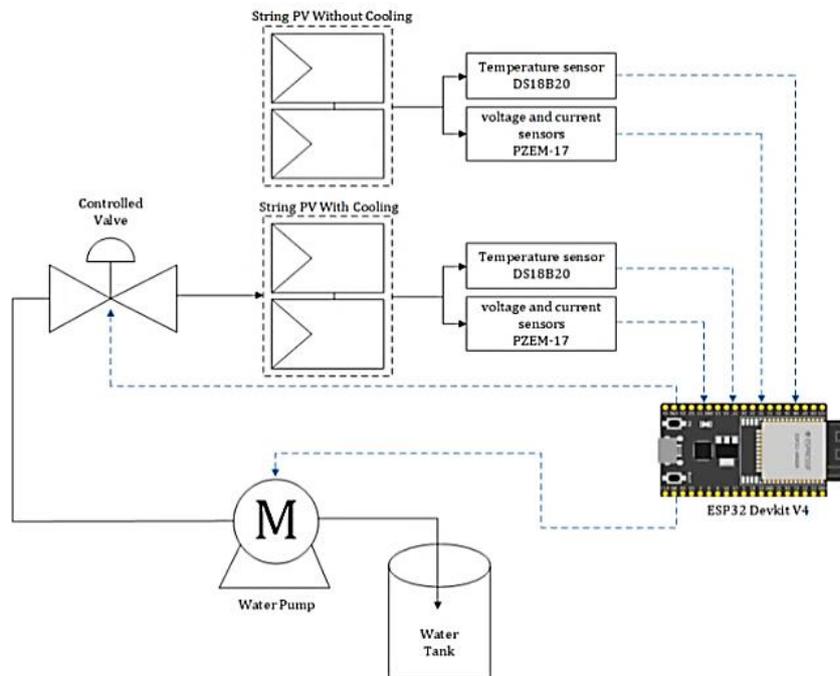

Figure 1. Configuration of the control system module

2.1.2. Cooling system circuit control panel

The following is the configuration of the rooftop PV cooling system installed on the research object. As depicted in Figure 2, The monitoring system utilizes a power supply unit that converts 220 V AC to 5 V DC, enabling continuous operation of the internet of things (IoT) system. The ESP32 microcontroller serves as the central unit, responsible for data acquisition, processing, and transmission to the IoT platform. Communication between sensors and the ESP32 is facilitated by a MAX485 interface to ensure reliable serial data transmission. Voltage and current measurements are performed using PZEM-017 modules with different addresses: 0x001 for PV1, 0x002 for PV2, and 0x003 for the battery. Additionally, a PZEM-016 module with address 0x004 monitors the inverter output. Shunt resistors are used to measure current by producing a proportional voltage drop, allowing the corresponding PZEM modules to calculate current flow for PV1, PV2, and the battery, respectively. Circuit protection is ensured through the use of dedicated DC miniature circuit breakers (MCBs) for PV1, PV2, and the battery, while an AC MCB safeguards the entire IoT monitoring system.

Figure 2. Configuration of the control system module

2.1.3. Internet of things system architecture

The internet of things architecture of the cooling system is depicted in Figure 3. The ESP32 microcontroller serves as the central processing unit, managing temperature data acquisition and cooling system activation. The system connects to the internet via Wi-Fi, using a modem to transmit real-time data to the Blynk cloud server.
a. The Blynk cloud server acts as an intermediary between the microcontroller and the user interface.
b. Users can remotely monitor and control the system via the Blynk mobile app (iOS/Android).
c. Data visualization and storage allow users to analyze system performance trends over time.
This IoT-based architecture ensures real-time monitoring and remote control, optimizing PV cooling system performance.
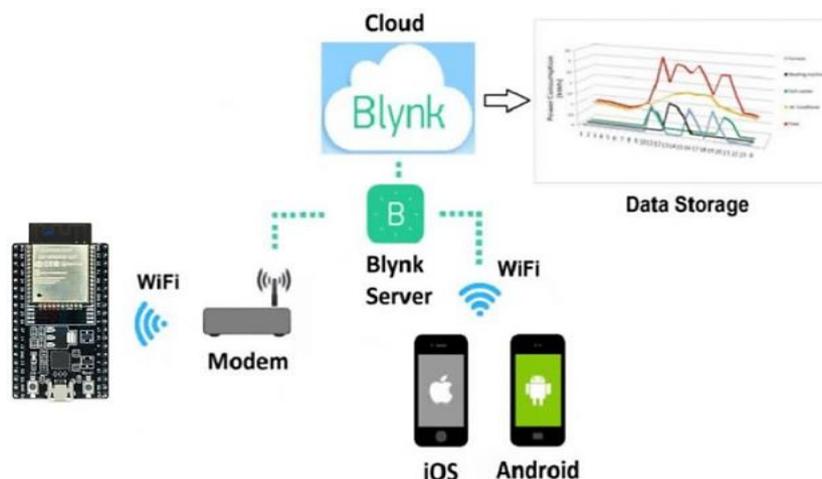

Figure 3. The IoT architecture of the cooling system

2.2. Mathematical modeling of the motorized valve

To facilitate system simulation and control tuning, a mathematical model of the motorized valve is developed through an experimental system identification approach [12]. The relationship between valve opening percentage and PV temperature reduction is determined using MATLAB's system identification toolbox [16].

2.2.1. Experimental setup

The experiment was conducted on June 17-18, 2024, from 12:00 to 13:00 WIB to minimize external variability. The dataset includes various valve opening percentages and corresponding temperature changes, as summarized in Table 1. The results indicate a strong correlation between wider valve openings and greater temperature reduction, confirming that water flow rate significantly influences PV cooling performance [7].

Table 1. Data the effect of valve opening on solar panel temperature

Valve opening degree (%)	Initial temperature (°C)	Final temperature (°C)	Temperature reduction (°C)
5	54.3	52.2	2.1
10	56.4	54	2.4
15	53.6	49.9	3.7
20	56.5	52.1	4.4
25	55.4	50.7	4.7
30	52.8	47.5	5.3
35	54.6	48.8	5.8
40	55.9	48.4	7.5
45	56.1	48.2	7.9
50	54.7	46.4	8.3
55	53.4	44.2	9.2
60	55.2	45.4	9.8
65	54.6	44.4	10.2
70	55.3	44.8	10.5
75	54.6	43.2	11.4
80	52.5	39.4	13.1
85	53.8	40.5	13.3
90	54.6	41.1	13.5
95	53.2	39.4	13.8
100	54.7	40.6	14.1

2.2.2. Model validation and transfer function

To validate the mathematical model, experimental data were processed in MATLAB's system identification toolbox, comparing measured vs. simulated cooling performance as shown in Figure 4. Figure 4 indicates that the simulated temperature reduction using the identified transfer function closely matches the experimental data, thereby validating the accuracy and reliability of the mathematical model derived through MATLAB's system identification toolbox.
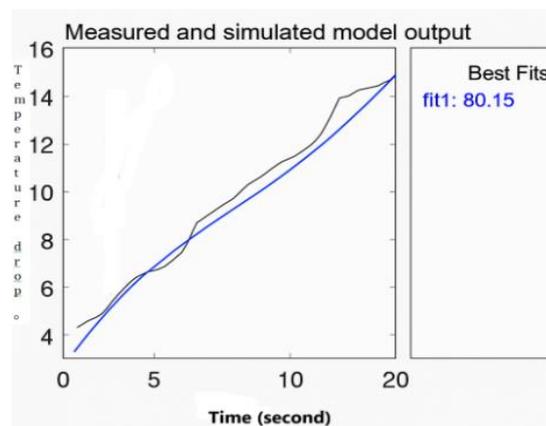

Figure 4. Comparison of measured and simulated cooling performance

The derived transfer function for the motorized valve dynamics is formulated as:

$$G(s) = \frac{0.1568}{s^2 + 4.588e - 10 + 0.09293}$$

(1)

This validated model serves as the foundation for PID controller design and fuzzy adaptive tuning.

2.3. PID control design using the Ziegler-Nichols method

The PID controller is designed to regulate the motorized valve opening based on real-time temperature feedback from DS18B20 sensors. The control system is illustrated in Figure 5. The controller parameters are tuned using the Ziegler-Nichols method, following the approach outlined in "Modern control engineering" by Ogata [21]. The tuning process involves:

a. Initial setup: Setting $Ki = 0$ and $Kd = 0$, increasing Kp gradually.
b. Critical gain determination: Identifying the gain (Kcr) at which the system enters sustained oscillation as shown in Figure 6.
c. Period measurement: The oscillation period, known as Pcr, is measured during the sustained response phase.
d. Parameter calculation: The Ziegler-Nichols formulas are then applied using the obtained values, which are summarized in Table 2.
e. Fine-tuning: The controller parameters are further adjusted to enhance overall system performance, with the final values presented in Table 3.
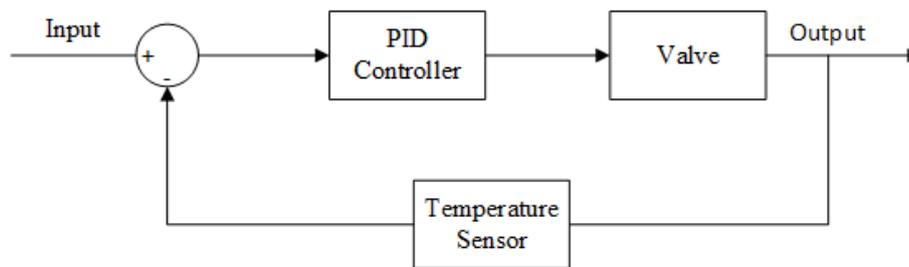

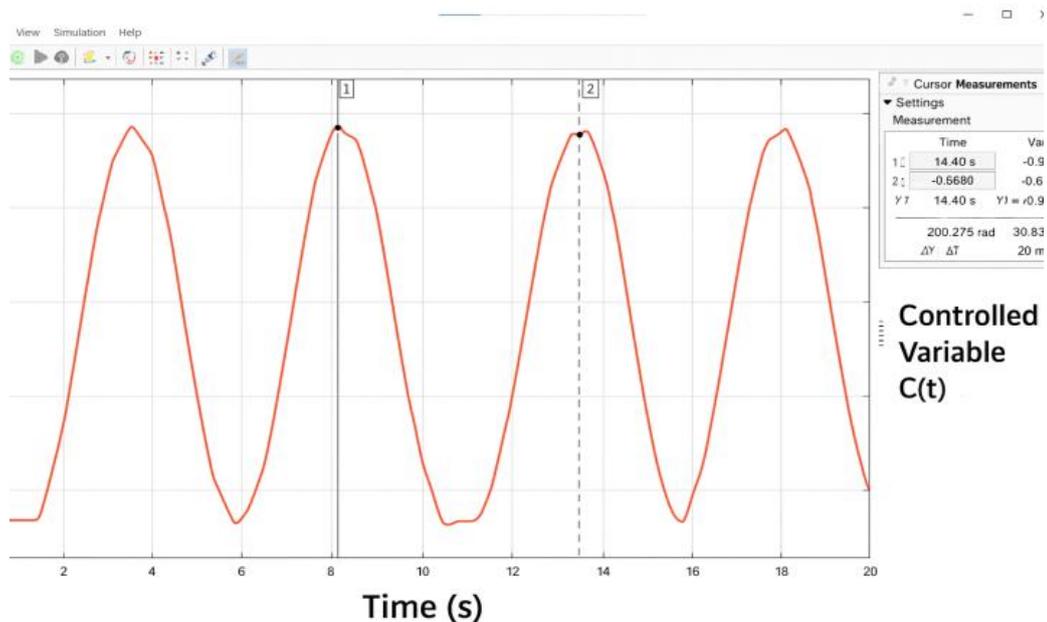Figure 5. Block diagram of the PID control system

Figure 6. Sustained oscillations with $Kp = 10$

Table 2. Ziegler-Nichols formula

Controller	Kp	Ti	Td
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$\dfrac{1}{1.2}Pcr$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

Table 3. Ziegler-Nichols method PID parameter results

Controller	Kp	Ki	Kd
PID	6	0.2	4

2.4. Adaptive tuning fuzzy PID design

To enhance system adaptability under dynamic environmental conditions, an adaptive fuzzy-PID controller is implemented. Figure 7 illustrates its structure. The FLC dynamically adjusts PID parameters (Kp, Ki, Kd) based on:
a. Error $(e(t))$: Difference between setpoint and actual temperature.
b. Error rate (t): Rate of temperature change.

These parameters are continuously updated based on real-time error conditions, allowing the system to adapt to changing environmental factors. The PID controller output, which incorporates the adjusted values of Kp, Ki, and Kd, determines the valve opening percentage, regulating the water flow on the PV panel surface to optimize cooling performance.
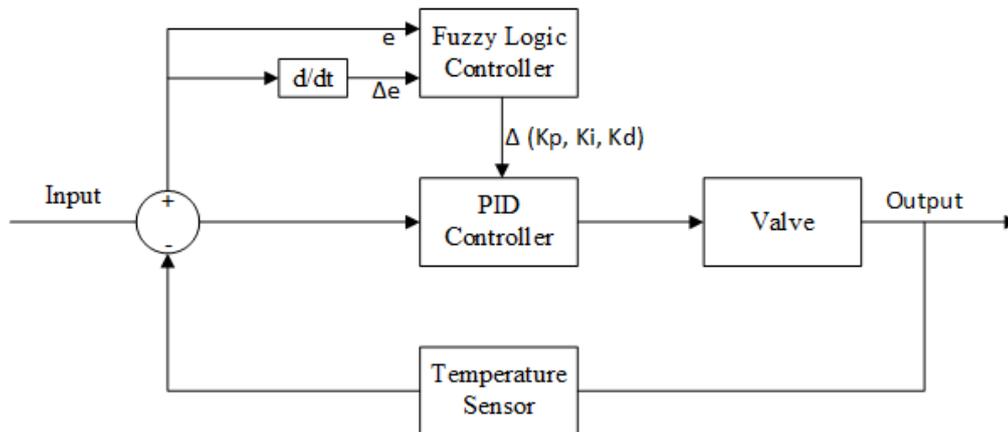

Figure 7. Block diagram of adaptive tuning fuzzy PID

2.4.1. Fuzzy membership functions for inputs

The membership functions for the input variables are illustrated in Figure 8. The linguistic variables for the error (t) and error change $d(t)$ are classified as very small (VS), small (S), medium (M), big (B), and very big (VB).
a. The linguistic variables for the error (t), The universe of discourse ranges from -6 to 22.
b. The linguistic variables for the rate of error change (t), The universe of discourse ranges from -2 to 2.

2.4.2. Fuzzy membership functions for PID outputs

The FLC dynamically adjusts the PID parameters Kp, Ki, and Kd based on the error and its rate of change. The membership functions for these outputs are illustrated in Figure 9. The linguistic variables for both proportional gain (Kp) and integral gain (Ki) are very low (VL), low (L), high (H), and very high (VH).
a. The linguistic variables for proportional gain (Kp), The universe of discourse ranges from 3 to 9.
b. The linguistic variables for integral gain (Ki), The universe of discourse ranges from 0.15 to 0.3.
The derivative gain (Kd) reduces overshoot and enhances system stability. It is defined by four linguistic variables: very low (VL), low (L), high (H), and very high (VH), with a universe of discourse ranging from 2 to 6.
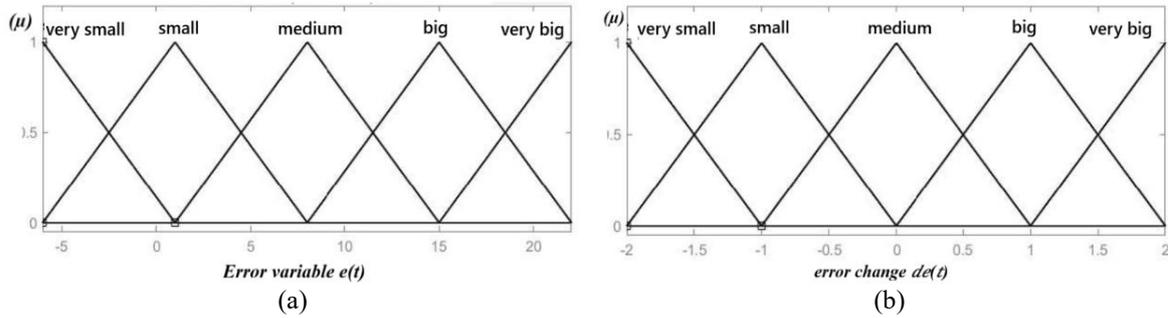
Figure 8. Membership function input (a) $e(t)$ and (b) $de(t)$
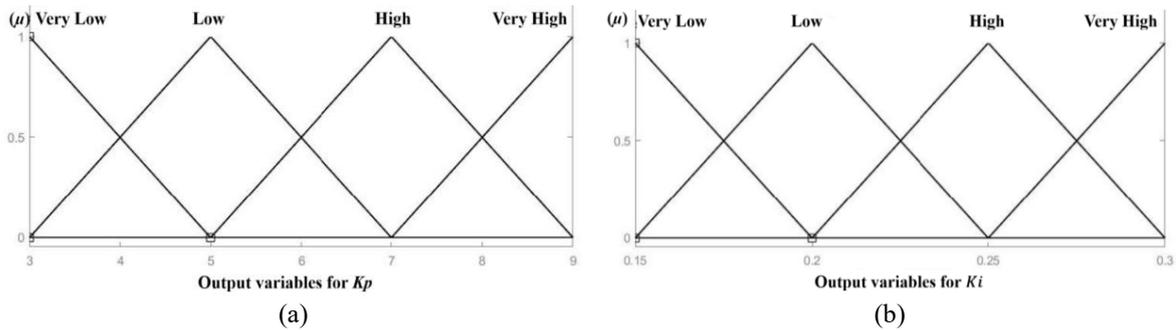
Figure 9. Membership function output (a) Kp and (b) Ki

2.4.3. Fuzzy rule base and adaptive control mechanism

The fuzzy rule base determines how the PID parameters are adjusted based on real-time error conditions. The rule base is structured to: i) Increase Kp when errors are large to accelerate response time, ii) Adjust Ki to reduce steady-state error without causing oscillations, and iii) Modify Kd to minimize overshoot and improve settling time. This adaptive fuzzy tuning approach significantly enhances temperature stability and response time, outperforming conventional PID tuning methods. Unlike static controllers, the adaptive fuzzy-PID system continuously recalibrates itself, ensuring robust operation under varying environmental conditions.

3. RESULTS AND DISCUSSION

This study involved a two-day experimental setup to evaluate the performance of two control strategies in a rooftop PV cooling system. On the first day, the Ziegler-Nichols PID control method was tested, while on the second day, the adaptive fuzzy-PID control using the Mamdani method was implemented. The experiment utilized four 550 Wp solar panels, arranged in two strings: one equipped with a cooling system and the other serving as a control without any cooling intervention. Key data collected included temperature, voltage, and current measurements from both PV strings. The motorized valve opening percentage was controlled based on the PID controller's output.

3.1. PID controller experiment using the Ziegler-Nichols method

The performance of the Ziegler-Nichols PID control system was evaluated in maintaining the PV module temperature at a setpoint of 36 °C. The system response is illustrated in Figure 10. As shown in Figure 10, temperature fluctuations occurred due to uncontrollable variations in solar radiation. To account for these variations, a ±5% tolerance was applied. The PID control effectively maintained the temperature close to the setpoint, achieving a settling time of 6.45 minutes and a steady-state error of 1.345%. To assess the impact of cooling on power output, the generated power from the cooled PV string was compared to the uncooled PV string, as depicted in Figure 11. The results indicate a 9.63% increase in power output due to the implementation of the cooling system, highlighting the effectiveness of PID-based thermal management in reducing temperature-induced efficiency losses.
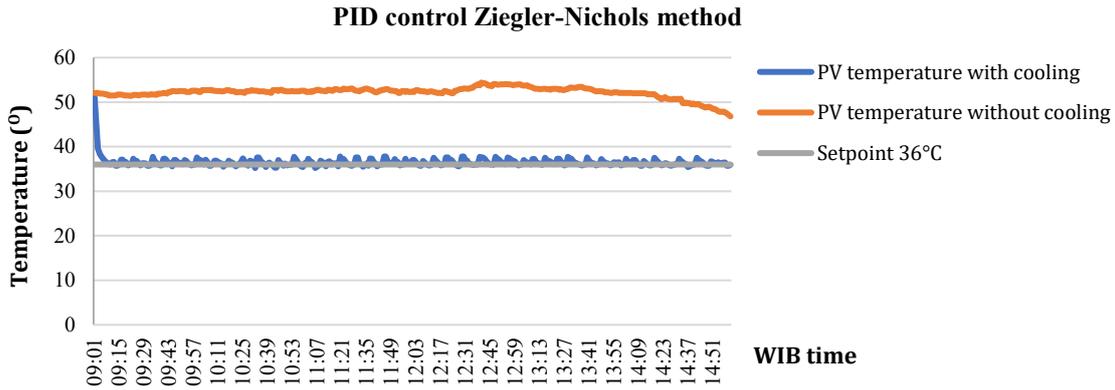
PID control Ziegler-Nichols method

Figure 10. Response system of PID control Ziegler-Nichols method

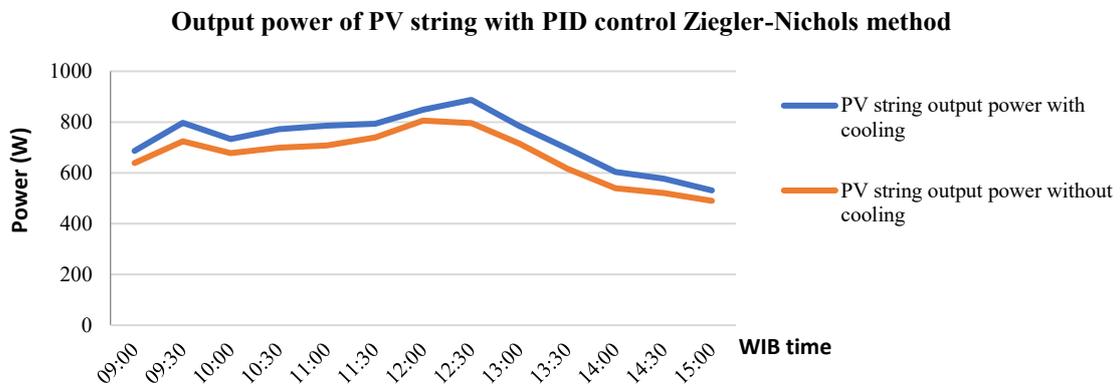**Output power of PV string with PID control Ziegler-Nichols method**

Figure 11. Output power of PV string with PID control Ziegler-Nichols method

3.2. Adaptive fuzzy-PID controller experiment using the Mamdani method

A similar experimental setup was applied to evaluate the adaptive fuzzy-PID controller's performance. The system response is presented in Figure 12. As observed in Figure 12, the adaptive fuzzy-PID controller demonstrated stable temperature regulation with a longer settling time of 9.15 minutes but a lower steady-state error of 0.93%, indicating superior accuracy in maintaining the desired temperature. The impact of cooling on power output was also analyzed, as shown in Figure 13. With an average 10.08% increase in power output, the adaptive fuzzy-PID control method demonstrated a slight improvement over the Ziegler-Nichols PID method.
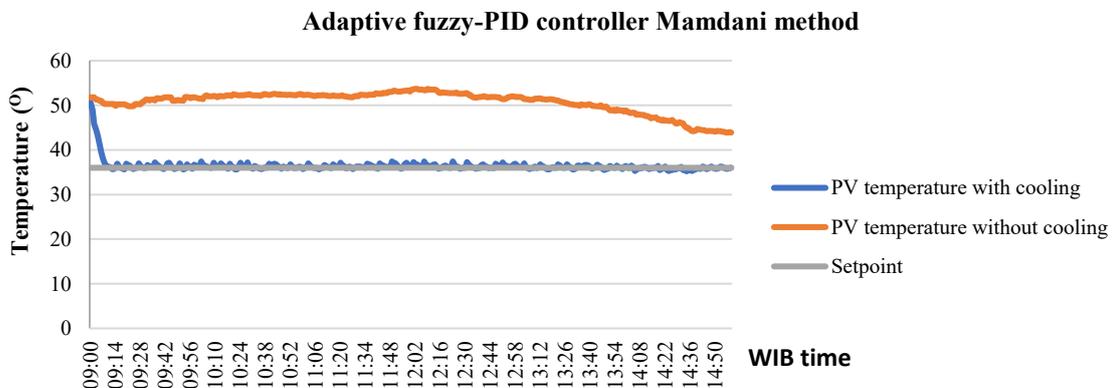
Adaptive fuzzy-PID controller Mamdani method

Figure 12. Response system of adaptive fuzzy-PID controller Mamdani method

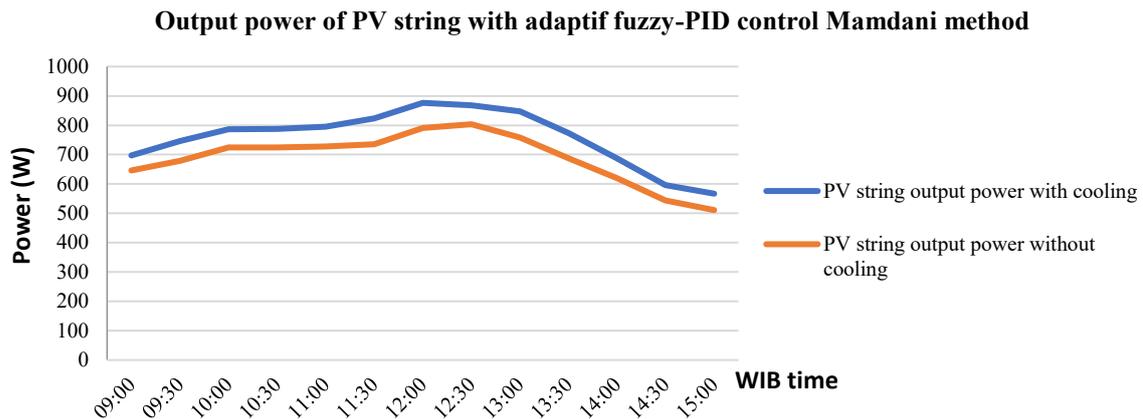**Output power of PV string with adaptif fuzzy-PID control Mamdani method**

Figure 13. Output power of PV string adaptive fuzzy-PID controller Mamdani method

3.3. Controller comparison

To determine the superior control method, a comparative analysis was conducted based on transient response characteristics. Since experiments were performed on different days with varying sunlight intensities, direct power output comparisons were inconclusive. However, temperature regulation performance could be reliably assessed. The transient response metrics for both controllers are presented in Table 4.

Table 4. Comparison of transient response of PID Ziegler-Nichols method and PID Ziegler-Nichols method

Controller	Settling time	Error steady state
PID Ziegler-Nichols method	6.45 minutes	1.345 %
Fuzzy-PID Mamdani method	9.15 minutes	0.93 %

From Table 4, it can be observed that:
a. The Ziegler-Nichols PID controller achieved a faster settling time (6.45 min) but exhibited a higher steady-state error (1.345%).
b. The adaptive fuzzy-PID controller demonstrated better accuracy with a lower steady-state error (0.93%) but required a longer settling time (9.15 min).

These findings suggest that if rapid response is prioritized, the Ziegler-Nichols PID method is preferable, whereas if precise temperature stability is the primary goal, the adaptive fuzzy-PID controller is the superior choice. Since the cooling system operates continuously throughout the day, minimizing steady-state error is more critical, making the adaptive fuzzy-PID method the more effective solution for long-term photovoltaic cooling.

4.   CONCLUSION

This study successfully designed and implemented a cooling system for rooftop PV panels using two different control strategies: Ziegler-Nichols PID control and adaptive fuzzy-PID control based on the Mamdani method. Experimental results demonstrate that implementing a cooling system increases PV power output by 9.63% using the Ziegler-Nichols PID method and 10.08% using the adaptive fuzzy-PID method, compared to an uncooled PV system.

A comparative analysis of the two controllers shows that Adaptive Fuzzy-PID control outperforms in steady-state error reduction, achieving 0.93% compared to 1.345% in the Ziegler-Nichols PID method. This indicates that the fuzzy logic-based approach provides better long-term temperature stability for photovoltaic cooling. However, in terms of response time, the Ziegler-Nichols PID method has a faster settling time of 6.45 minutes, whereas the adaptive fuzzy-PID control requires 9.15 minutes to reach a steady state.

The adaptive fuzzy-PID method proves to be the most effective solution for PV cooling due to its ability to maintain stable temperatures, which is essential for long-term performance. This study contributes by practically validating the method's superior thermal and energy efficiency compared to conventional

approaches. To enhance its performance, future research should focus on optimizing fuzzy rule sets, integrating adaptive tuning mechanisms, and applying machine learning for autonomous and context-aware control under diverse environmental conditions.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Pangestuningtyas Diah Larasati				✓	✓	✓			✓	✓		✓	✓	

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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