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Fuzzy Logic-Based Degradation Fault Identification In Photovoltaic Arrays

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Abstract

The development of renewable energy technology, particularly photovoltaic (PV) systems, has increased due to the growing demand for environmentally friendly energy sources. However, PV performance may decrease due to degradation faults caused by changes in electrical characteristics and environmental conditions. This study aims to identify degradation faults in a photovoltaic array using the Fuzzy Logic method based on voltage and temperature parameters. The experimental data were collected using a sensor-based monitoring system integrated with the Blynk platform. The results demonstrate that the proposed Fuzzy Logic method can effectively classify PV operating conditions into normal, warning, and degradation fault categories. Therefore, the developed system can support real-time monitoring and improve the reliability of PV system maintenance.

Keywords: Photovoltaic Array; Degradation Fault; Fuzzy Logic; Voltage; Temperature ; Blynk

INTRODUCTION

The advancement of renewable energy technology continues to increase along with the rising demand for electrical energy and efforts to reduce dependence on fossil fuels. One of the rapidly developing technologies is photovoltaic (PV), which utilizes solar cells to convert sunlight into electrical energy. PV technology is considered a promising solution due to its abundant energy

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resources, environmental friendliness, and relatively low operational and maintenance costs (Mellit & Kalogirou, 2008; Green et al., 2024; Wohlgemuth, 2008).

However, during its operational period, photovoltaic arrays may experience performance degradation due to various degradation faults such as microcracks, hot spots, delamination, corrosion, and semiconductor material degradation. These faults cause changes in electrical characteristics, including reductions in current, voltage, output power, and system efficiency. Therefore, early fault identification is essential to improve the reliability, lifespan, and performance of PV systems (Madeti & Singh, 2017; Skoczek et al., 2009; Jordan & Kurtz, 2013; Dhimish & Holmes, 2016).

Various methods have been developed to identify faults in PV systems, including electrical characteristic analysis, data processing techniques, and Artificial Intelligence (AI)-based approaches capable of recognizing patterns and handling complex data. One widely applied AI method is Fuzzy Logic because it can handle uncertainty through IF–THEN rules and membership functions, enabling more flexible decision-making under varying system conditions. By utilizing electrical parameters such as current, voltage, output power, and efficiency as input data, Fuzzy Logic can effectively identify and classify degradation fault levels in photovoltaic arrays (Zadeh, 1965; Chine et al., 2016; Mellit & Kalogirou, 2008).

The increasing implementation of photovoltaic systems as renewable energy sources requires monitoring and fault detection systems capable of maintaining PV module performance and reliability. One common issue is degradation fault, which reduces efficiency, output power, and the operational lifetime of PV systems. Therefore, a fast and accurate fault identification method is required to detect performance degradation at an early stage (Madeti & Singh, 2017; Silvestre et al., 2014).

Previous studies have developed PV fault identification methods using artificial intelligence techniques such as Artificial Neural Networks (ANN), machine learning, and complex electrical parameter analysis. However, these methods often require large training datasets, high computational resources, and relatively complex implementation for small-scale monitoring systems. Moreover, studies concerning degradation fault identification using a Fuzzy Logic approach based on simple parameter combinations, such as voltage and temperature, remain limited (Chine et al., 2016; Mellit & Kalogirou, 2008).

Based on these challenges, this research proposes a degradation fault identification method for photovoltaic arrays using a Fuzzy Logic approach with voltage and temperature as input variables. The proposed method is designed to provide a simpler identification process,

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easier implementation, and applicability to real-time PV monitoring systems without requiring complex data training procedures (Zadeh, 1965; Chine et al., 2016).

METHODS

This study employs a Fuzzy Logic approach to identify potential degradation fault conditions in a photovoltaic (PV) array based on variations in electrical parameters and environmental conditions. The input parameters used in this study are voltage (V) and temperature (T), which were obtained from measurements under various PV operating conditions. These parameters were utilized as indicators to determine the operational status of the PV system, including normal conditions and indications of degradation. The Fuzzy Logic approach was selected due to its ability to handle uncertainty and provide decisions based on linguistic rules that resemble human reasoning (Zadeh, 1965; Chine et al., 2016).

The acquired voltage and temperature data were subsequently processed using a Fuzzy Inference System (FIS). During the fuzzification stage, the input values were converted into fuzzy membership sets, including low, normal, and high categories. The inference process was then performed using IF–THEN rules established based on the relationship between variations in voltage, temperature, and PV operating conditions. A decrease in output voltage combined with changes in operating temperature can indicate a reduction in PV performance, which may be associated with degradation phenomena (Madeti & Singh, 2017; Silvestre et al., 2014).

The hardware design of the monitoring system consists of a voltage sensor, temperature sensor, microcontroller, and the Blynk application, as illustrated in Figure 1.

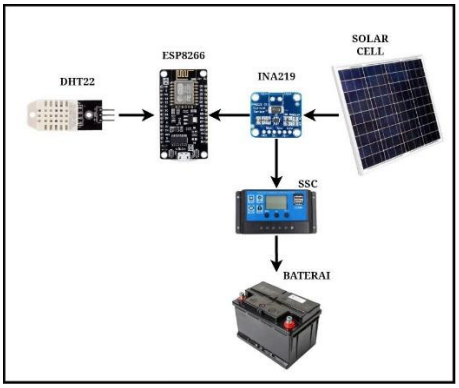


Figure 1. Hardware Design of the Monitoring System

The next stage is the defuzzification process, where the fuzzy output is transformed into a specific decision value representing the PV operating condition, such as normal, warning, or

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indication of degradation fault. This approach allows the system to classify PV conditions with a simple computational process and good flexibility compared to conventional approaches, making it suitable for real-time PV monitoring applications (Chine et al., 2016; Zadeh, 1965).

To achieve reliable identification results, the design of the membership functions and fuzzy rules was developed based on the relationship between temperature variations and the output voltage characteristics of the PV module. Increased operating temperature and changes in the electrical characteristics of the PV module may affect its performance. Therefore, the analysis of these two parameters was used as the basis for identifying potential degradation conditions in the PV system (Skoczek et al., 2009; Jordan & Kurtz, 2013).

RESULT AND DISCUSSION

The experimental testing was conducted on June 3, 2026, at the Electrical Power Simulation Laboratory, Department of Electrical Engineering, Politeknik Negeri Bengkalis. The measured voltage and temperature data of the photovoltaic array are presented in Table 1. Based on the measurement results, a voltage range of approximately 15–20 V generally indicates a normal operating condition, whereas a voltage reduction to approximately 10–15 V may indicate a decrease in PV performance.

Table 1. Comparison of Photovoltaic Array Performance

Voltage	Temperature	Condition
19,18 V	35,0 °C	No fault indication
13,51 V	34,4 °C	Potential degradation indication
18,96 V	34,6 °C	No fault indication
17,46 V	34,7 °C	No fault indication
16,50 V	34,5 °C	No fault indication
14,71 V	34,2 °C	Potential degradation indication
14,73 V	34,1 °C	Potential degradation indication
12,47 V	34,5 °C	Potential degradation indication
10,92 V	33,5 °C	Potential degradation indication
15,28 V	33,8 °C	No fault indication
16,16 V	33,8 °C	No fault indication
14,78 V	33,8 °C	Potential degradation indication

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19,52 V	33,8 °C	No fault indication
20,00 V	33,9 °C	No fault indication

Based on the experimental results of voltage and temperature measurements in the photovoltaic array, it was observed that changes in voltage values have a significant influence on the operating condition of the PV system. Under normal voltage conditions and certain operating temperatures, the PV system demonstrates stable performance. Conversely, a reduction in voltage may indicate a decline in PV performance, which can be associated with degradation-related conditions (Madeti & Singh, 2017; Dhimish & Holmes, 2016).

The measurement results indicate that a voltage range of approximately 15–20 V with an operating temperature of around 33–35 °C generally represents a normal condition. In contrast, voltage values within the range of approximately 10–15 V indicate potential abnormalities, even though the temperature remains relatively stable. These findings suggest that voltage acts as the primary parameter in evaluating PV operational conditions, while temperature serves as a supporting parameter affecting the electrical characteristics of the module (Silvestre et al., 2014; Jordan & Kurtz, 2013).

The monitoring data obtained through the Blynk application were then used as input parameters for the Fuzzy Logic system to identify the PV operating condition. The voltage and temperature data were processed through fuzzification, IF–THEN rule-based inference, and defuzzification stages to produce a final decision regarding the PV condition. The results demonstrate that the Fuzzy Logic method can effectively classify PV operating conditions based on variations in the measured electrical parameters (Zadeh, 1965; Chine et al., 2016).

The real-time monitoring interface of voltage and temperature parameters using the Blynk application is shown in Figure 2.

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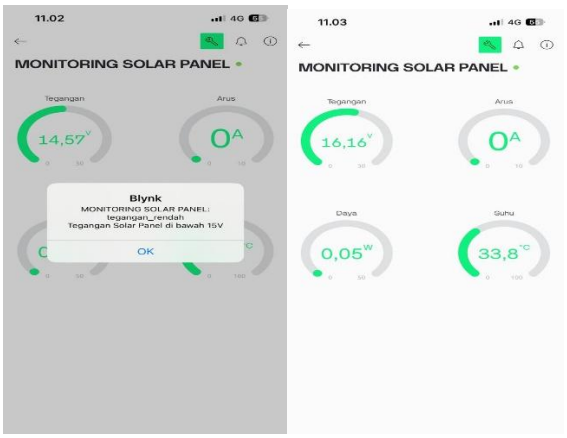
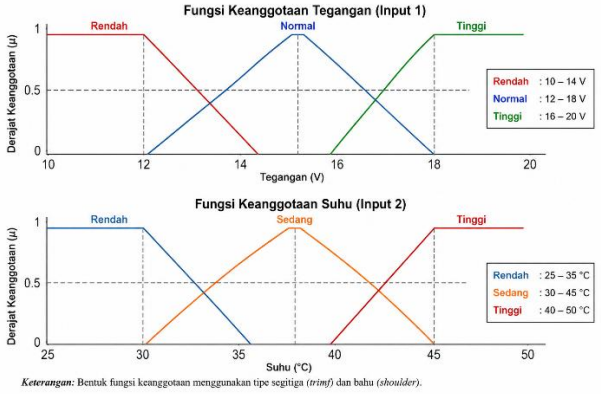


Figure 2. Real-Time Monitoring Interface of Voltage and Temperature Parameters Using the Blynk Application

The monitoring data obtained from the Blynk application were further processed as input variables in the Fuzzy Logic system to determine the operating condition of the photovoltaic array. The voltage and temperature parameters were processed through the stages of fuzzification, IF–THEN rule-based inference, and defuzzification to generate a final classification of the PV condition, namely normal, warning, or potential degradation indication. This process demonstrates that the Fuzzy Logic approach is capable of identifying changes in PV operating conditions based on variations in measured electrical parameters (Zadeh, 1965; Chine et al., 2016).

The membership functions used to classify the voltage and temperature values into linguistic variables are illustrated in Figure 3.



Keterangan: Bentuk fungsi keanggotaan menggunakan tipe segitiga *(trimf)* dan bahu *(shoulder)*.

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Based on Figure 3, the designed membership functions divide the voltage and temperature values into several linguistic categories, namely low, normal, and high. This categorization enables the system to determine the degree of membership of each input parameter before entering the inference stage. Consequently, the Fuzzy Logic system can provide a more flexible and adaptive decision-making process when handling variations in PV operating conditions (Zadeh, 1965).

Overall, the experimental results indicate that the proposed Fuzzy Logic-based identification system using voltage and temperature parameters can effectively determine the operating condition of the photovoltaic array and provide indications of potential degradation. The developed system is capable of providing real-time information regarding PV performance with a relatively simple computational process, making it suitable for implementation in practical PV monitoring applications (Chine et al., 2016; Zadeh, 1965).

CONCLUSION

Based on the research conducted, the Fuzzy Logic approach can be utilized to identify potential degradation conditions in photovoltaic (PV) arrays based on voltage and temperature parameters. The monitoring data obtained through the Blynk application were utilized as input to the Fuzzy Inference System (FIS), which consists of fuzzification, IF–THEN rule-based inference, and defuzzification stages to determine the PV operating condition. The identification results indicate that variations in voltage and temperature can be utilized as indicators for distinguishing normal operating conditions and potential degradation indications. Therefore, the developed Fuzzy Logic-based identification system is capable of providing effective real-time monitoring information regarding the condition of photovoltaic arrays and can be considered a practical approach for supporting PV maintenance and performance evaluation

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