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Microcontroller for Temperature Condition Monitoring Systems on Transformers: Enabling Predictive Maintenance for Aviation

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ABSTRACT

Airports heavily rely on stable electricity, with transformers as essential components for converting electrical voltage. High temperatures in transformers can cause degradation of the cooling oil, insulation damage, and a reduction in the transformer's lifespan that coul be degrade aviation safety standard. The incident on the transformer at SS2 Sultan Mahmud Badaruddin II Airport in Palembang due to overheating caused a significant impact on airport operations. This research aims to develop microcontroller technology to identify and predict potential issues in critical electrical components, particularly transformers, before failures occur and conduct the system testing. This effort is relevant to a safety strategy based on predictive maintenance to prevent accidents. This research using the fourth stage of the Maxim's model of R&D method includes planning, development, and testing under conditions that resemble real-life situations. The research began by identifying needs through interviews and observations, which indicated the necessity of monitoring transformer temperature with early notifications and automatic exhaust fan control. The test results show that the system functions well in detecting temperature, activating the exhaust fan when the temperature reaches the threshold, and sending alarm notifications through the Blynk application. Suitability aspect testing indicate that the prototype received a positive response regarding functionality with an average score of 2.67, which falls into the valid feasibility category. It is expected to significantly contribute to developing microcontroller technology in safety, provide databased for predictive maintenance and offer practical solutions for improving the reliability and operational efficiency of electrical distribution systems at airports.

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1. Introduction

Airports are essential infrastructures in the aviation world that serve as major transit points for aircraft, passengers, and cargo [1]. The existence of an efficient airport is essential to support the mobility and economy of a country. In addition to physical facilities such as runways and terminals, airports require complex supporting infrastructure, including a reliable electrical system, to ensure smooth operations. A stable electricity supply is the key to ensuring that all services at the airport function correctly. According to [2] electrical failure is one of the most significant risks for flight safety.

One of the critical components in the airport's electrical distribution system is the transformer, which adjusts the electrical voltage of the facilities according to operational needs [3]. Transformer ensures that each facility at the airport receives an appropriate electricity supply, maintaining the efficiency and safety of the equipment and distributing power to various areas, such as terminals, hangars, and other facilities. Transformers that fail due to overheating can cut off power to vital systems, such as communication systems, navigation, and airport lighting. According to [4], reliable transformer performance is critical to prevent system failures that could impact the continuity of operations.

Several studies have emphasized the importance of transformer management and maintenance in critical environments such as aviation. Research by [5] demonstrates that overheating and insulation degradation are the leading causes of transformer failures that can disrupt airport operations or flight control systems. Research by [6] states that uncontrolled temperature is one factor that accelerates the aging of insulating materials in transformers, which increases the risk of failure. Real-time temperature monitoring technology enables early detection of overheating. Effective temperature monitoring can reduce potential failures [7], thereby playing an essential role in improving the reliability of electrical systems.

Predictive maintenance is a data-driven maintenance strategy gaining popularity in various industries, including aviation. Unlike preventive maintenance, where maintenance is performed at regular intervals based on a fixed schedule, predictive maintenance is based on the actual condition of the equipment and its predicted damage. According to [8] predictive maintenance has the potential to reduce operational costs and increase system reliability.

The use of microcontrollers in transformer temperature monitoring systems plays a vital role in the implementation of predictive maintenance. [9] It highlights that microcontroller-based monitoring systems also have additional benefits, such as integration with supervisory control and data acquisition (SCADA), which are used to manage and control electricity distribution systems on a large scale. The microcontroller's temperature data collected in real-time can be analyzed to predict when a failure is a microcontroller's. Thus, repair measures or component replacement can be carried out before the transformers experience a complete failure, potentially reducing downtime and maintaining smooth airport and flight operations. Research [10] shows that microcontroller-based monitoring is more efficient than conventional methods, providing faster results and more accurate data. The system can monitor the transformer temperature continuously and send out warning signals when the temperature rises close to a critical threshold. This allows system managers to take immediate preventive action before damage occurs.

Internet of Things (IoT), one example of microcontroller development has brought significant advancements in industrial maintenance [11]. IoT enables real-time data collection from various sensors installed on equipment, including in the transformer room [12]. Implementing IoT in transformer maintenance opens up opportunities for more efficient maintenance by analyzing temperature, humidity, and other operational parameters. With this technology, implementing predictive maintenance becomes more accessible [13]. Maintenance is carried out based on data generated by the monitoring system, thereby preventing failure before it occurs and increasing efficiency and safety.

In 2019, there was a trip incident on the transformer at Sultan Mahmud Badaruddin II Airport (SMB II) Palembang due to overheating. The leading causes are the weather and poor air circulation in the transformer room, which causes the transformer temperature to exceed normal limits. This causes physical changes in the oil, increased pressure, and leaks in the transformer seal. As a result, airport operations were disrupted because the SS2 transformer supplying electricity to the passenger terminal experienced a malfunction, causing activities in the terminal to halt temporarily and leading to flight delays and cancellations. To address the incident, immediate repairs were made by replacing the leaking seal and increasing the on-time of the exhaust fan on the timer. However, the increase in on-time on the timer is still inefficient because the exhaust fan will only operate based on the timer settings, not the actual temperature conditions of the transformer. This incident emphasizes the urgency of monitoring temperature and having an efficient cooling system on transformers to prevent potential overheating. Regulations from the American National Standards Institute (ANSI) and the Institute of Electrical and Electronics Engineers (IEEE) C57.12.00, as well as the Indonesian National Standard (SNI) related to transformers, also mandate temperature monitoring and cooling systems as an integral part of transformer maintenance requirements. These regulatory standards emphasize the critical importance of implementing comprehensive monitoring systems for transformer safety and reliability.

Routine maintenance of transformers is essential to ensure their reliability and longevity, prevent damage, and minimize the risk of system failure [14]. One of the routine maintenance tasks for the transformer is monitoring the temperature and controlling the exhaust fan in the transformer room to keep the temperature safe and prevent overheating that could cause damage [15]. The exhaust fan ensures good air circulation, so the transformer performance remains optimal. Many studies have discussed the design and implementation of microcontroller-based temperature monitoring systems. According to [16], these systems can be implemented with digital temperature sensors such as DS18B20 or NTC thermistors connected to microcontrollers such as Arduino or Raspberry Pi. Data from the sensors can be processed and displayed through a graphical user interface (GUI) or sent to the cloud for further analysis.

In previous research, several IoT-based monitoring systems have been developed for various applications, for the IT-Telkom Surabaya server room [17], and an IoT-based distribution transformer monitoring system was also developed for PT. PLN [18], and there is also similar research that developed an IoT-based control and temperature monitoring system for the Sub Distribution Panel (SDP) to reduce overheating [19]. Research by [20], [21] develops a transformer's health monitoring using IoT. [22] Conduct real-time monitoring of a database for predictive maintenance to reach sustainability improvement. However, no research has yet focused on designing an IoT-based transformer temperature monitoring system with an exhaust fan controller in transformer rooms so that transformers can continue to operate at safe temperatures and prevent thermal issues caused by poor room insulation quality.

This represents a significant gap in the current literature, particularly for aviation applications where continuous operation is critical for safety and operational continuity. Our research addresses the identified gap by developing a comprehensive system that combines to: 1) Real-time Temperature Monitoring by using NTC Thermistor temperature sensors that measure the temperature on the transformer, 2) Automated fan Control with ESP8266 microcontroller acts to control the exhaust fan based on actual temperature conditions rather than timer-based operation, 3) IoT Integration where IoT signals allow devices to connect to the internet and control them through applications or commands wirelessly, and 4) Aviation-Specific Application, focused specifically on airport transformer rooms with consideration for poor room insulation quality issues. This research aims to: 1) Plan and develop microcontroller technology to identify and predict potential issues that may arise in critical electrical components, particularly transformers, before failures occur, 2) Conduct response system testing and system suitability evaluation by experts to ensure system reliability and effectiveness.

The research design uses an NTC Thermistor temperature sensor that measures the temperature on the transformer, and the temperature data will be sent to the ESP8266 microcontroller. The ESP8266 microcontroller will act to control the exhaust fan. This happens with the help of IoT signals that allow devices to connect to the internet and control them through applications or commands wirelessly. It is expected that this system can improve the reliability and performance of the transformer and prevent thermal issues caused by poor room insulation quality. This research is relevant to a safety strategy based on predictive maintenance to prevent accidents. The system addresses the critical need for continuous, automated monitoring and control in aviation environments where system failures can have serious safety and operational consequences. The key innovation of this research lies in its integration of real-time monitoring with automated environmental control specifically designed for aviation applications. Unlike previous research that focused on monitoring alone or general industrial applications. This comprehensive approach fills the identified research gap and provides a practical solution for improving transformer reliability in critical aviation infrastructure.

2. Method

The research method used in this study adopts Pressman and Maxim's (2019) Research and Development (R&D) prototype model approach. In this development method, Maxim creates an initial model or prototype of the system to be developed [23]. Through this approach, system development becomes an iterative process, allowing researchers to create an initial version of the temperature monitoring and exhaust fan control system on the transformer, test its functionality, and improve based on the feedback received.

Fig. 1. Prototype Model

The prototype method involves a series of essential steps in prototype development , where each stage plays a crucial role in understanding user needs, identifying problems, and creating an effective prototype. This research uses a prototyping method limited to the fourth stage, the system testing stage, focusing on developing a microcontroller for the Temperature Condition Monitoring System on Transformers in Predictive Maintenance for Flight Safety.

The first stage in the prototype method is to identify and understand user needs, which refers to electrical technicians at Sultan Mahmud Badaruddin II Airport in Palembang as the research site. This is achieved through interviews and observations to obtain in-depth information about the transformer issues. At this stage, the needs identification process is carried out through two main techniques, namely interviews and observations. The interview was conducted with the airport electrical supervisor, and 2 technicians who has direct responsibility for the operation and maintenance of the airport's electrical systems. The topic limited to transformers maintenance and troubleshooting. The questions discussed include the challenges that often arise, the solutions airports have implemented, and their needs and expectations. At this stage, data collection of transformer temperatures is also conducted over a period of time as a reference in the system development.

The second stage in this research is the planning stage, which involves several necessary steps. First, an initial design was carried out by creating a system configuration to understand the concept of the system that will be developed. Then, a schematic design of the tool is created, which serves as a guide in the assembly process at the next development stage. After that, a flowchart or workflow diagram was created to depict the operational steps of the system visually. This flowchart is very important because it helps visualize the logic and sequence of processes, making it easier to understand and implement the designed system.

The third stage is the development stage, where the design is further developed into a prototype ready for use. At this stage, the development process includes assembling hardware, creating the system interface using the Blynk application, and writing programming code to operate the system through the Arduino IDE application. This stage ensures all components work together according to the designed plan so that the prototype can function according to the system's objectives.

The fourth stage is testing, an essential part of the prototype method. This system's transformer temperature monitoring system and exhaust fan control prototype will be tested to ensure all its features and functionalities work well. This testing aims to verify whether the prototype meets the previously specified specifications and requirements and to identify and fix any issues that may arise before the system is fully implemented.

3. Results and Discussion

The initial stage of this research is the identification of needs or initial requirements, which is conducted to delve into in-depth information about the issues faced by electrical technicians and to identify and understand the existing needs. The interview results revealed that the transformer at SS2 often experiences overheating due to suboptimal air circulation. The use of timer-based exhaust fans is considered less efficient because the fans only operate according to a schedule, not based on the actual temperature conditions of the transformer. Respondents also expressed the desire to monitor the transformer temperature in real-time to ensure the smoothness and safety of operations at Sultan Mahmud Badaruddin II Airport in Palembang.

Next, observations were also conducted in the SS2 transformer room to directly observe the physical condition of the transformer, the cooling system, and the surrounding environment. The main focus of this observation is to obtain empirical data about the actual conditions in the field that may be partially revealed through interviews. Several essential aspects observed include the type of transformer, the operational temperature of the transformer, the condition of the exhaust fan, and the quality of room insulation.

3.1. Planning

After the first stage, identifying needs, the next step is to plan the transformer temperature monitoring system and exhaust fan control. This planning stage is vital to ensure that the system design to be developed can meet the identified needs and effectively and efficiently solve existing constraints.

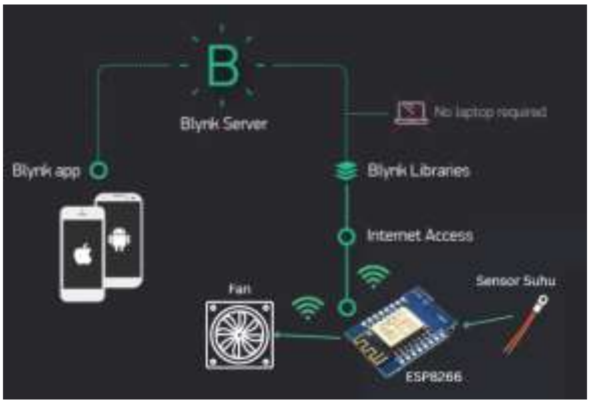

Fig. 2. System Configuration

The image above shows the design configuration of the system to be developed. This system starts with the Blynk application installed on iOS or Android devices, allowing users to monitor temperature and control the fan in real time. The microcontroller collects data from temperature sensors placed on the transformer, sending the data to the Blynk server via an internet connection using the Blynk library. The temperature data sent to the Blynk server can be accessed by users through the Blynk application, enabling them to monitor the transformer temperature in real time and control the exhaust fan. Thus, this system ensures effective and responsive temperature monitoring and automatic exhaust fan control to prevent transformer overheating due to poor room air circulation.

After understanding the system configuration, the next step is determining the main components needed and creating a schematic of the device circuit using the Fritzing application. The purpose of creating this schematic is to map the relationships between components, making the assembly process more accessible and reducing the risk of errors. With Fritzing, the circuit connectivity can be accurately visualized, ensuring the correct layout of components and allowing for the creation of detailed documentation. Here is the schematic diagram of the designed circuit.

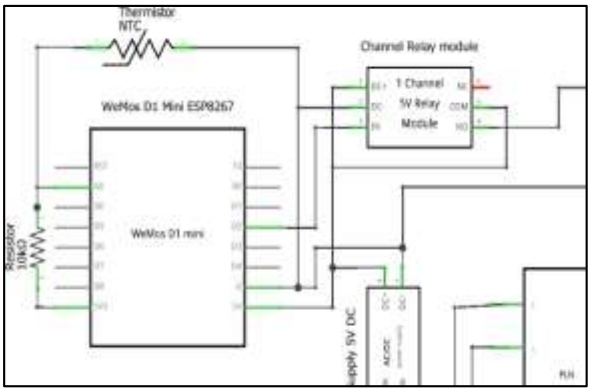

Fig. 3. Schematic Circuit Diagram

Next, create a flowchart visually representing how the IoT-based transformer temperature monitoring and exhaust fan control system works. This flowchart will illustrate each stage of the process from start to finish. With the flowchart, this system is expected to be easily and understood.

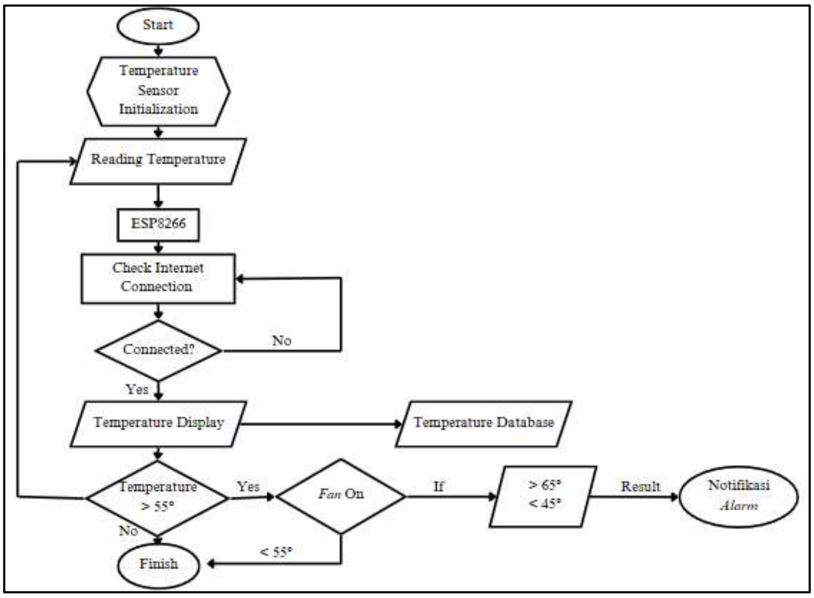

Fig. 4. Flowchart System

The system starts with initialization and temperature readings by the sensor. Temperature data is processed by the ESP8266 microcontroller and displayed in real-time on the server, provided the device is connected to Wi-Fi. When the temperature reaches 55°C, the fan will automatically turn on; when the temperature stabilizes at less than 55°C, the fan will automatically turn off. When the temperature exceeds 65°C, indicating an overheating condition, an alarm notification will be activated on the server. Similarly, when the temperature falls below 45°C, an under-temperature alarm notification will be triggered, allowing technicians to respond more efficiently.

3.2. Development

The next stage is the development stage, which aims to realize the system according to the design to meet the needs and address the problems that have been previously identified. The development begins with preparing all the necessary components, hardware (such as microcontroller, temperature sensor, relay, resistor, fan, cable, and power supply) and software (such as Arduino IDE and the Blynk application). Once all components are ready, the hardware is assembled and connected according to the previously created schematic design. The assembly process is carried out meticulously to ensure that every connection and component functions appropriately so the system can operate according to the expected objectives.

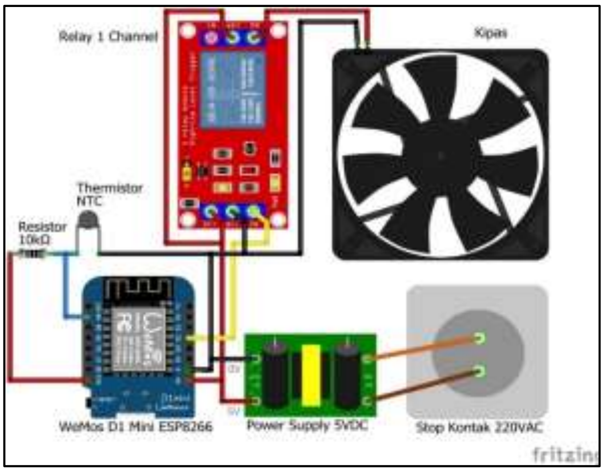

Fig. 5. Prototype Circuit

After the hardware is assembled, the next step is to develop the software using the Blynk application. Blynk was chosen because it provides a user-friendly interface, broad compatibility with various IoT hardware [11], [24], and the ability to integrate various widgets for real-time monitoring and control. Here is the interface for the temperature monitoring and exhaust fan control system created using Blynk.

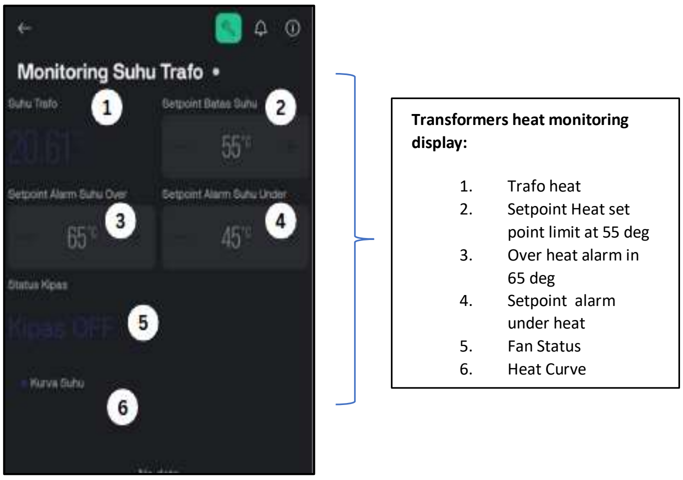

Fig. 6. Interface System

From the interface image above, users will be presented with several prominent features, namely: (1) Real-time transformer temperature display, which continuously updates the transformer temperature so that users can monitor the transformer condition at any time; (2) Temperature limit setpoint, which allows users to set threshold temperatures to turn the fan on and off, helping to keep the transformer temperature stable; (3) Over temperature alarm setpoint, where users can set the maximum temperature limit on the transformer that will trigger a notification if exceeded, to prevent overheating; (4) Under temperature alarm setpoint, which allows users to set the minimum temperature limit that will also trigger an alarm if exceeded, thus avoiding unsafe operating conditions; (5) Fan status, which indicates whether the fan is on or off, helping technicians ensure the fan operates as needed; and (6) Temperature curve, which displays a graph of the transformer temperature over a certain period, providing historical data valid for technicians to analyze temperature trends and plan subsequent maintenance more effectively and timely.

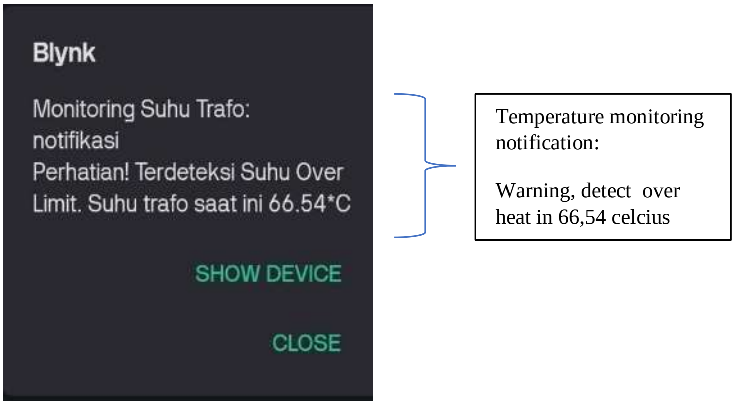

Fig. 7. Alarm Notification

The image above shows the alarm notification interface, designed to provide users with immediate information about abnormal conditions on the transformer. With this notification, users can quickly identify issues, such as the transformer's temperature exceeding or falling below the established thresholds. This allows users to take the necessary corrective actions, thereby minimizing the risk of further damage and maintaining the transformer's operational stability.

Fig. 8. Test Simulation

The prototype of this system is transformers under conditions that simulate real situations to ensure its performance and reliability. The experiment was conducted in an aquarium container that served as a simulation space, where candles were used to heat a beverage can that acted as a heat source, representing the transformer condition during overheating. This setup is designed to test the response of the temperature monitoring system and exhaust fan control in detecting temperature increases and activating necessary control measures, such as cooling fans, to keep the temperature within safe limits.

Table 1. Results of The System Response Test to Temperature Changes

Temperature ^{0}C	Temperature initialization time	Exhaust Fan	Notification
26,1	03.77	Off	ON
35,32	03.10	Off	ON
46,57	04.34	Off	Off
55,73	01.53	ON	Off

The functional testing results of the components indicate that the prototype of the transformer temperature monitoring system and exhaust fan control functions well under simulated conditions, resembling the actual situation. The system has proven capable of responding to temperature changes quickly, where the exhaust fan turns on and off according to the predetermined temperature threshold. Additionally, alarm notifications appear promptly when the temperature reaches or falls below the set threshold. These results indicate that the system can be relied upon for use in real-world environments, providing adequate protection against potential overheating and maintaining the operational stability of the equipment. Additionally, the Functional Suitability Aspect has been tested using a questionnaire focused on the prototype's functionality. This questionnaire was prepared based on the ISO 25010 standard [25] and the field prototype's three respondents, who are system experts. Respondents provide their assessments using a checklist method to evaluate the extent to which the prototype meets the specified functionality criteria. The data collected from the respondents serves as an essential source of information regarding the prototype's ability to perform the designed functions. The table below shows the evaluation results from the prototype's respondents regarding the functionality of this system prototype.

Table 2. Results of The System Expert Evaluation

Number of assessment aspects	Score (User 1)	Score (User 2)	Skor (User 3)	Average
1	2	2	3	2,34
2	3	3	2	2,67
3	2	3	3	2,67
4	3	3	2	2,67
5	3	3	3	3
Total Score	13	14	13	
Average Score	2,6	2,8	2,6	2,67
	Criteria			**Valid**

Eligibility Criteria:
Valid = 2,36 – 3,00
Enough = 1,68 – 2,35
Not Valid = 1,00 – 1,67

Based on system experts' functional suitability aspect testing results in the table above, the temperature monitoring and exhaust fan control system prototype received a valid feasibility criterion with an average score of 2,67.

This research successfully developed and tested a transformer temperature monitoring system based on the ESP8266 microcontroller with an NTC Thermistor sensor and automatic exhaust fan control integrated with Internet of Things (IoT) technology. The main findings show that this system is able to monitor the transformer temperature in real-time and control the cooling fan based on the actual temperature, not just based on a timer like the system previously used at Sultan Mahmud Badaruddin II Airport, Palembang. This significantly increases cooling efficiency and reduces the risk of overheating which can cause transformer failure and disrupt airport operations. The prototype test results show that the system can function according to the design, namely sending temperature data in real-time to an IoT-based application and activating the exhaust fan automatically when the temperature reaches a critical threshold. Thus, this system not only provides accurate and fast monitoring data, but is also able to take preventive actions automatically to keep the transformer temperature within safe limits. Testing also shows that this system can be operated easily and can be accessed remotely, making it easier for technicians to monitor and control.

When compared to other studies that are used as references, this system has quite prominent advantages. Several previous studies, such as those conducted by IoT research in the IT-Telkom [17], and an IoT-based distribution transformer monitoring system was also developed for PT. PLN [18], and monitoring system for the Sub Distribution Panel (SDP) to reduce overheating [19]. Research by [20], [21] and [22] Surabaya server room and the PT PLN distribution transformer monitoring system, generally only focus on temperature monitoring without integrating automatic fan control based on actual temperature. Studies [16], that develop transformer temperature monitoring using digital sensors such as DS18B20 or NTC thermistors with Arduino or Raspberry Pi microcontrollers have also not combined automatic exhaust fan control that is responsive to real temperature conditions. In addition, studies that focus on predictive maintenance in the electrical field have not applied many IoT-based systems with exhaust fan control in transformer rooms specifically for airport applications, which have very critical operational needs. Our research closes the gap by combining four main aspects: real-time temperature monitoring using NTC Thermistor sensors, automatic fan control based on ESP8266 microcontroller, IoT integration for remote monitoring and control, and application focus on airport transformer rooms with poor room insulation conditions.

This approach is in line with the recommendations of ANSI, IEEE C57.12.00, and SNI standards that emphasize the importance of temperature monitoring and cooling systems as part of transformer maintenance to maintain operational reliability and safety.

In addition, this study supports findings from the literature stating that overheating and insulation degradation are the main causes of transformer failures that can disrupt critical operations such as at airports. With an IoT-based automatic monitoring and control system, potential failures can be detected and addressed early, thereby reducing downtime and improving flight safety. Overall, the results of this study provide an important contribution to the development of a more responsive and efficient predictive maintenance system for transformers in aviation environments. This system not only improves the reliability and safety of transformers, but can also be a model for the development of similar systems in other critical facilities that require real-time IoT-based temperature monitoring and control.

4. Conclusion

This study successfully developed an IoT-based transformer temperature monitoring system using the ESP8266 microcontroller and NTC Thermistor sensor, equipped with an automatic exhaust fan control. The system was tested at Sultan Mahmud Badaruddin II Airport in Palembang and proved capable of real-time temperature monitoring and automatic fan activation when the temperature reached a critical threshold, unlike the previous timer-based system. Testing results showed that the system functioned optimally in transmitting temperature data and controlling the fan, thereby preventing transformer overheating. Compared to other referenced studies, the advantage of this system lies in its integration of automatic fan control responsive to actual temperature rather than just monitoring. Its application in a critical airport environment supports predictive maintenance and enhances transformer operational reliability. The conclusion from these results is that the developed system effectively improves the monitoring and automatic control of transformer temperature in real-time, preventing damage caused by excessive heat. The system also provides remote monitoring convenience via IoT, which is crucial for critical facilities such as airports. Therefore, this system offers a practical and efficient solution to maintain the reliability and safety of transformers in high-stability operational environments. Overall, this system contributes significantly to enhancing the safety and efficiency of transformers, especially in vital facilities like airports, by providing a smarter and more responsive temperature monitoring and control solution.

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