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Original Article

Development of an IoT-Based Monitoring System for Preventing Oil Spills in Single-Phase Transformers within Rural Distribution Grids in Peru

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Abstract *- The paper describes developing an innovative monitoring system based on the Internet of Things (IoT) aimed at single-phase distribution transformers of rural type. These types of transformers are threatened by adverse weather conditions in conjunction with the increasing energy demand, which puts them at high risk of overheating, overloading, and other operational eventualities that could ultimately lead to a highly polluting oil spill. The proposal incorporates a single-phase energy meter PZEM-004T, capable of measuring in real time. It also includes an infrared sensor, MLX90614, for continuous surface temperature monitoring. For its part, the available A9G communication module makes it possible to have fluid communication with a central IoT platform, in addition to allowing the visualization and geopositioning in real time of the transformers at risk and the proactive control of the infrastructure. The experimental results show the accurate and timely diagnosis of overload and overheating, thus enunciating the easy creation of alerts to improve intervention and prevent failure. This effectively means that the proposed approach improves transformers' operational safety and reliability in rural areas and lays the foundation for future developments in electrical infrastructure management using IoT technologies.*

Keywords *- Wireless communication, Internet of things, Transformer monitoring, Electrical overload.*

1. Introduction

Single-phase transformers are critical for electrical power distribution in rural areas of Peru, where infrastructure lags and operational vulnerability are high [1]. In these contexts, such transformers face severe weather conditions and additional power demands during peak periods, increasing the risk of overloads and overheating [2]. These conditions can lead to operational failures and, in extreme cases, oil spills, with severe environmental and economic implications. Placing transformers outdoors, which characterizes rural areas, increases their susceptibility to extreme weather conditions [3]. The cooling oil serves a very important function for peak performance and the longevity of the equipment [4]. Nevertheless, the oxidation and contamination of the oil results in severe degradation of critical electrical parameters like voltage and current, compromising safe operation engineering and safety engineering and increasing the likelihood of incidents [5]. Historically, monitoring has relied on manual inspections and periodic maintenance cycles [6]. Traditionally, implementing more robust materials and optimized maintenance practices has failed to solve the underlying problems systemically [7], evidencing the demand for advanced monitoring systems with real-time data for detecting early failures [8]. The emergence of IoT technologies offers a new range of possibilities for managing electrical infrastructures [9]. Critical information can be obtained and analyzed in real-time with IoT through sensor networks and communication platforms, allowing immediate attention to certain anomalies [10]. However, even in rural areas, these solutions become additional challenges due to the underdeveloped communication infrastructure and the low-consumption design. In response to these challenges, this study proposes developing an IoT-enabled monitoring system to prevent oil spills and improve the operational efficiency of single-phase transformers in rural distribution networks in Peru. The system continuously measures critical parameters such as voltage, current, and temperature, allowing for early warning notifications for timely interventions.

2. Literature Review

This section reviews articles published in specialized scientific journals that emphasize the importance of single-phase transformers in relation to the distribution of electrical power, particularly in rural regions where infrastructure is underdeveloped and maintenance resources are limited. Monitoring such transformers has become an area of active interest because it is critical to the stability and security of power grids [11]. Many studies have investigated the implementation of new technologies, especially those related to IoT, to improve these systems' operational efficiency and reliability [12]. The work presented in [13] developed an IoT framework for monitoring and controlling distribution transformers over LoRa WAN. This research recorded key operational parameters using integrated sensors such as voltage, charging current, winding temperature, and oil quality, enabling continuous monitoring and real-time alerting. The block diagram in Figure 1 illustrates the system's structure in the form of a block diagram, which helped to increase the transformer's life and contributed to the early detection of faults.Another significant study [14] mentions another critical study proposing an IoT-based online monitoring system for diagnosing and managing transformer failures. This system uses voltage, current, and temperature sensors that send their data through an Arduino microcontroller to a mobile application, guaranteeing improvements in reliability, operational stability, and incident response time. Likewise, [15] research proposed wireless sensors and electromagnetic energy transmission systems, which made non-contact temperature and gas concentration possible. Although this proposal is technologically distant from those embodied in [13, 14], the robust real-time monitoring system improves the proposed solutions.

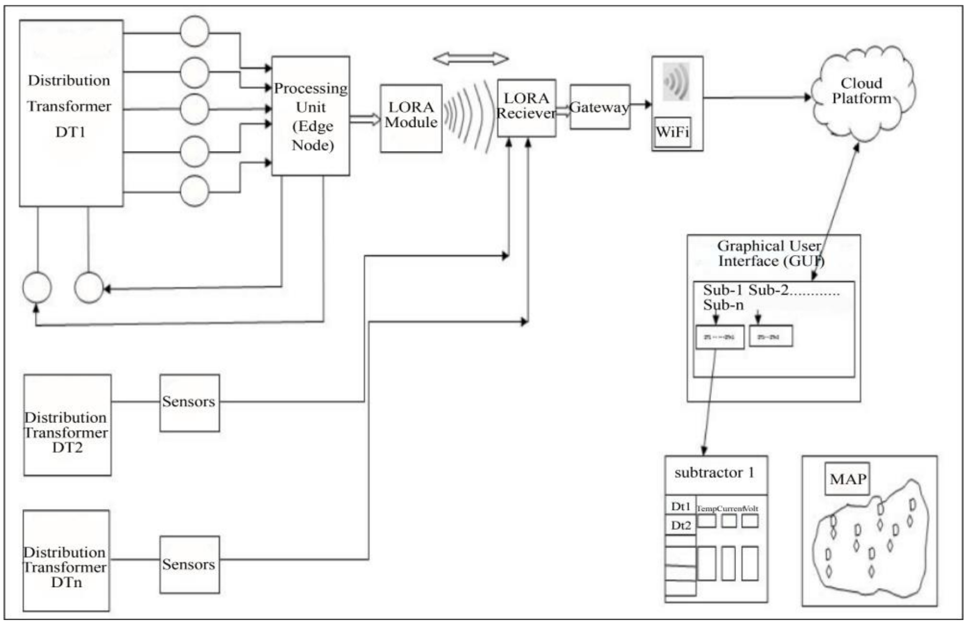

Fig. 1 LoRa-based block diagram [13]

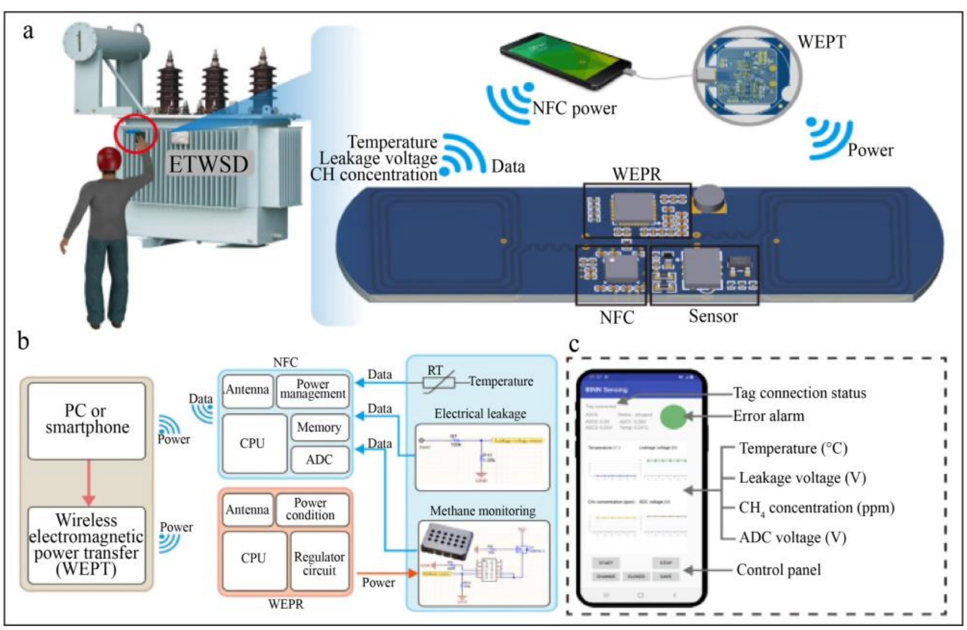

Fig. 2 Diagrams of the ETWSD [15]

Figure 2 presents the conceptual and schematic diagrams of the ETWSD system, where its accuracy in the prevention of failures is tested.This research, taken together, demonstrates the ability of IoT technologies to improve transformer monitoring [16]. However, the consulted bibliography has important time gaps. In most cases, the proposed systems have not been subjected to validation in real environments or in high-power transformers, which avoids the generalization of the findings in active distribution districts.

It also requires the design of a high-reliability communication network and low-power solutions, especially in peripheral areas. Another important detail is the implementation of other auxiliary parameters, such as oil quality control and the type of oil used [17, 18] which are important for the anticipated monitoring of circumstances that may cause oil leaks. Indeed, although the possibility of integrating IoT into transformer monitoring is highly promising, the reliability of these systems must be assessed through extensive studies in real-life scenarios.

These studies must address rural particularities and the design of spill prevention indicators, thus giving a broad perspective instead of the axiomatic methods that predominate in the subject.

3. Materials and Methods

This section describes the materials, methods, and technical fundamentals used to develop and implement the proposed system, highlighting the integration of diagrams that facilitate understanding of the methodology.

3.1. Monitoring System Components

3.1.1. PZEM 004T Single-Phase Energy Meter

The PZEM-004T single-phase energy meter accurately measured key electrical parameters such as voltage, current, active power, and accumulated energy in transformers [19]. Its operating voltage range is 80 to 260 VAC, which makes it appropriate for the usual voltage conditions in rural areas.

The nominal voltage is 220 V and has a tolerance of 7.5%, according to the NTCSE (Technical Standard for the Quality of Electrical Services) [20]. In addition, this device measures currents up to 100 A, which translates into a maximum active power of approximately 20 kW. The block diagram of the module depicting its internal structure is shown in Figure 3.

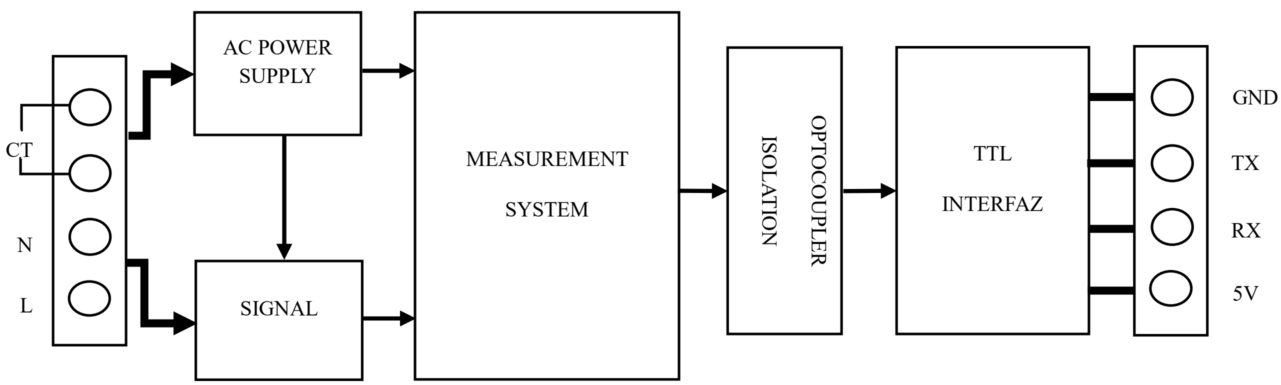

Fig. 3 PZEM 004T Block diagram

Rural transformers are usually rated at 15 kVA, so the PZEM-004T is ideal for monitoring. The key specifications are described below:

- Voltage Operating Range: 80-260V AC
- Current Range: 0-100A

3.1.2. ESP32 Microcontroller

As the core of the monitoring system, the ESP32 is responsible for data acquisition, processing, and transmission. This microcontroller has two interfaces (Wi-Fi and Bluetooth) that make it stand out regarding energy efficiency, which is important in IoT applications in rural areas with limited connectivity. It is configured to obtain data from the PZEM-004T meter and the MLX90614 temperature sensor; the connection blocks are shown in Figure 4. The processed information triggers alarms and transmits information to the IoT platform, allowing remote monitoring of transformers.

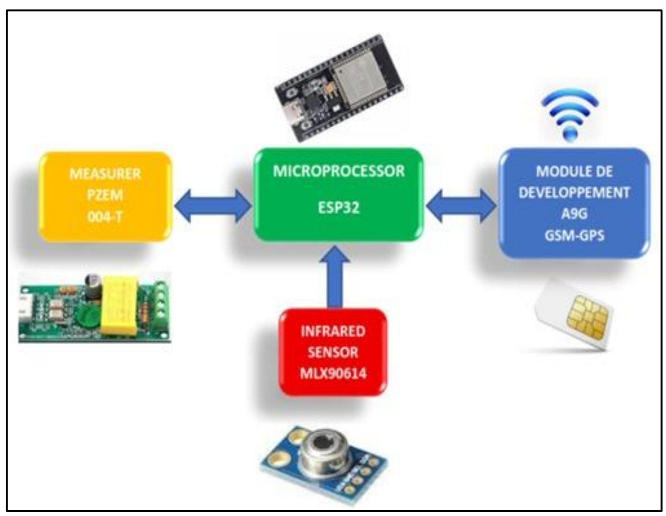

Fig. 4 Connection blocks

3.1.3. Infrared Sensor MLX90614

The MLX90614 can measure the temperature of the transformer's external surface without making physical contact, which is critical when assessing its operating condition. Its specifications are given in Table 1, along with the measurable range:

Table 1. Sensor specifications MLX90614

Specification	Details
Temperature Measurement	-70°C a +380°C
Precision	±0.5°C
Communication	I2C

According to IEC 60076, a transformer's temperature under normal conditions should not exceed 70°C [21]; additionally, a margin for oil should be considered. The MLX90614 sensor is programmed to trigger an alarm when the temperature exceeds this limit, alerting possible overheating scenarios that could lead to an oil spill.

3.1.4. A9G Communication Module

The A9G module combines GSM/GPRS and GPS; it allows the transmission of real-time data to a centralized IoT platform and the precise geolocation of transformers. This was particularly useful for maintenance planning and rapid response to failures. The module guaranteed continuous connectivity even in remote areas, and its GPS function allowed for quick identification of the affected transformer, optimizing maintenance interventions. Figure 5 shows the connection between the microcontroller and the module.

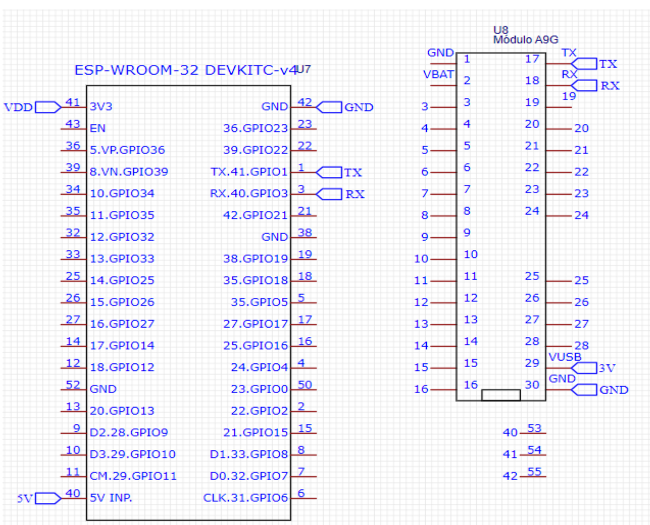

Fig. 5 Electronic circuit connection blocks

3.2. Implementation Methodology

3.2.1. System Installation and Configuration

The system is designed to be installed without interrupting the power supply and uses hot connectors and installation techniques that minimize the risk of failures during assembly. The installation was performed on selected transformers in rural areas, where their performance was evaluated under various climatic and load conditions. Figure 6 shows the installation that was applied to the transformer.

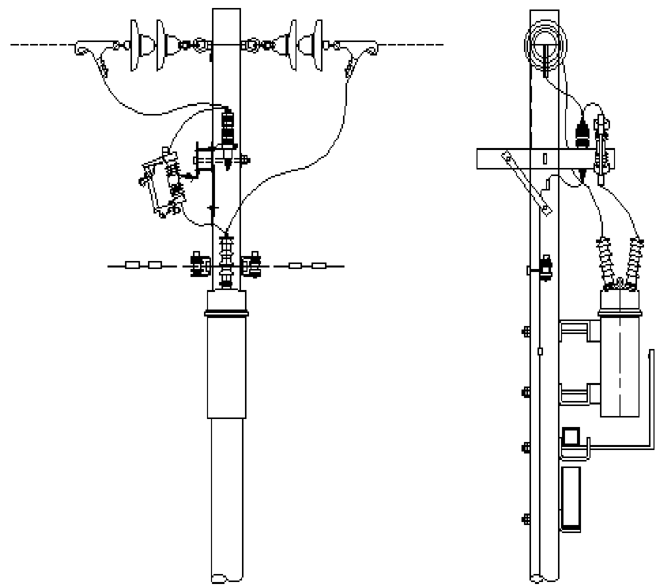

Fig. 6 System installation drawing

3.2.2. Continuous Monitoring and Alert Management

The system allows continuous monitoring of electrical and thermal variables, generating real-time alerts when critical parameters exceed the established limits. By IEC 60076 [22], an alarm has been programmed to be triggered when the transformer temperature exceeds 70°C, indicating an overheating state. The system's database will record the duration and frequency of these events, providing valuable information for predictive maintenance.

3.2.3. Integration with IoT Platform

All the data collected by the system was sent to an IoT platform explicitly designed for transformer management in rural areas. The communication was carried out through the A9G module, which sent the data through GSM/GPRS networks. The platform made it possible to visualize the location and status of each transformer in real-time, facilitating maintenance planning and identifying network expansion needs.

3.2.4. System Flow Diagram

For a better interpretation of the entire process, Figure 7 graphically describes each action carried out in the monitoring system. This includes data capture by PZEM-004T meter and MLX90614 sensor, information processing and transmission by ESP32 microcontroller along with A9G communication module, and implementation in IoT. This diagram allows you to visualize more effectively the relationship between the different elements of the system, helping to locate each part of the process accurately.

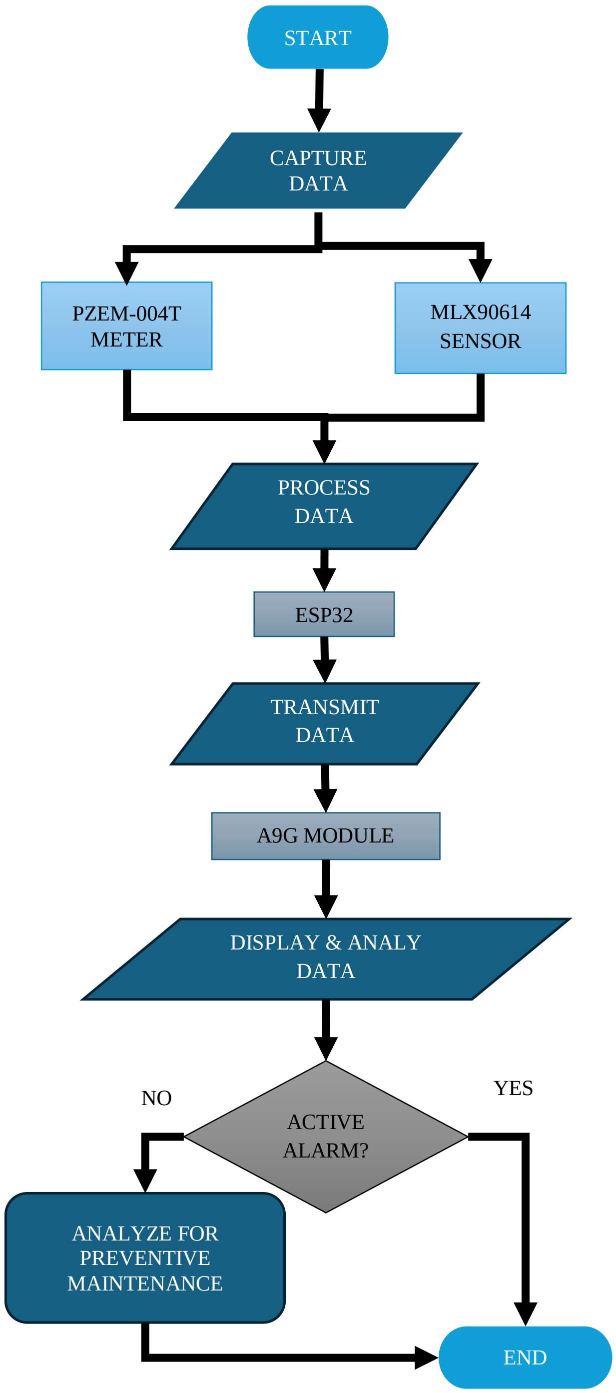

Fig. 7 System flowchart

3.3. Technical Measurements

3.3.1. Heat Transfer and Overload

Overheating is a factor that affects the life of transformers. The efficiency in heat transfer from the windings to the cooling oil largely determines the transformer's ability to operate safely under load conditions. Using the basic Equation (1) of convection heat transfer:

$$Q = h * A(T_S - T_\infty) \quad (1)$$

It was determined that a significant increase in Ts (surface temperature) versus T∞ (surrounding oil temperature) indicates a deterioration in cooling capacity, warranting alert triggering and maintenance intervention.

3.3.2. Transformer Overload and Protection

The system monitors the load current to calculate the overload factor using the following Equation (2):

$$Overload\ Factor = \frac{I_{measure}}{I_{nominal}} \quad (2)$$

When this factor exceeds 1.2, the transformer is considered at risk, and an alarm is activated to prevent damage. This calculation is based on the transformer specifications and the margins allowed by the NTCSE.

The research was conducted in the “Viñas” Village Center in the Pampas province of Tayacaja, Huancavelica region, Peru. This place is located at a latitude of 12° 25' 0.5” S and a longitude of 74° 51' 36.4” W, at 3412 meters above sea level. The corresponding time zone is UTC-5. This location presents particular geographical and altitudinal characteristics that will be considered in the development of the study. Figure 8 shows the transformer installed for the distribution of electrical energy in that sector.

Fig. 8 Transformer where measurements were made

4. Results

4.1. Electrical Parameter Monitoring

The PZEM-004T single-phase energy meter was integrated into the system to monitor electrical parameters continuously. As shown in Figure 9, this device made it possible to measure the voltage and current at the transformers' output point with high accuracy.

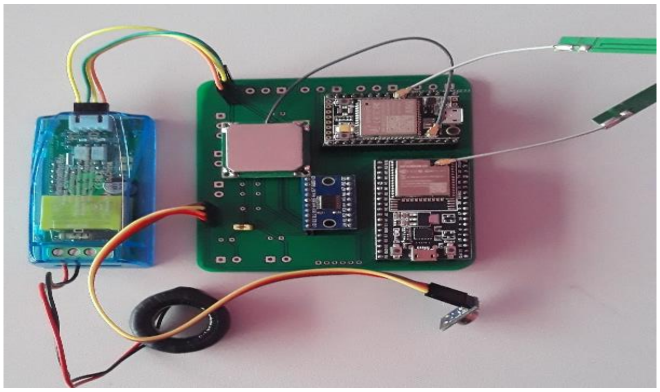

Fig. 9 PZEM 004T meters installed in the device

Data were collected over a period of two days, revealing the variation of these parameters as a function of the system's variable load. The average, maximum, and minimum values recorded are detailed in Table 2, offering a quantitative perspective of electrical behavior under real conditions. The results demonstrate the system's ability to accurately record variations in voltage, as shown in Figure 10, and current variations, as shown in Figure 11. The system can identify critical events, such as current peaks that exceed normal operating limits, suggesting the presence of temporary overloads.

Table 2. Electrical parameters

Parameters	Measurement
Voltage Average	223.62 V
Maximum Voltage	224.28 V
Minimum Voltage	222.21 V
Average Current	25.96 A
Maximum Current	40.6495 A
Minimum Current	15.8634 A

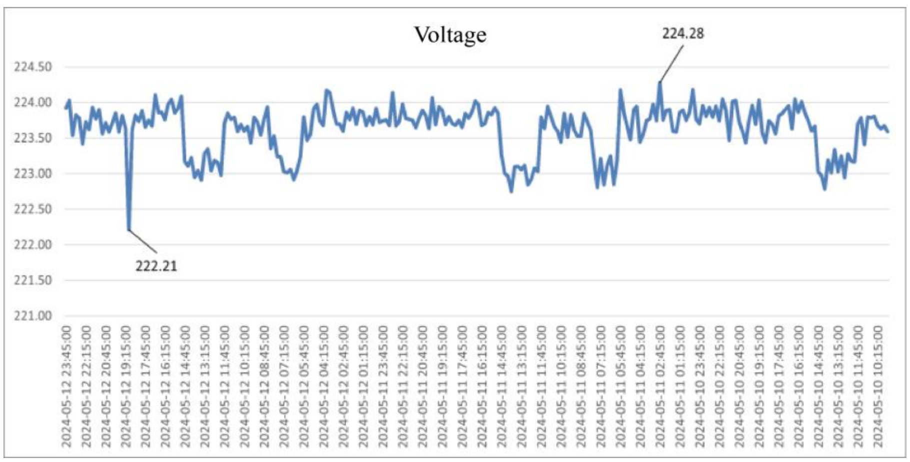

Fig. 10 Graph of voltage measurements

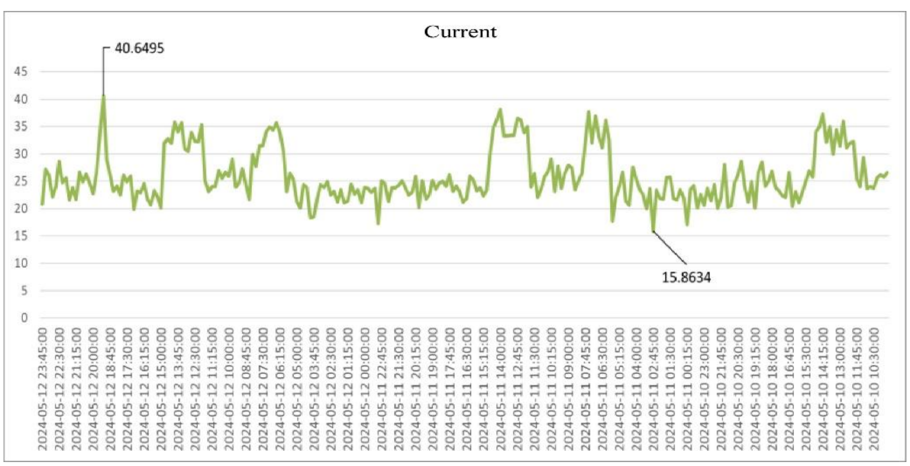

Fig. 11 Graph of current measurements

4.2. Overload Detection and Alerting

The system effectively detected overload conditions, automatically generating alerts when the measured power exceeded the 20-kW threshold. As Figure 12 illustrates, exceeding this limit triggers alerts, which is critical to preventing potential damage. A direct correlation between power increases and temperature variations was also observed, indicating the importance of monitoring various critical parameters simultaneously.

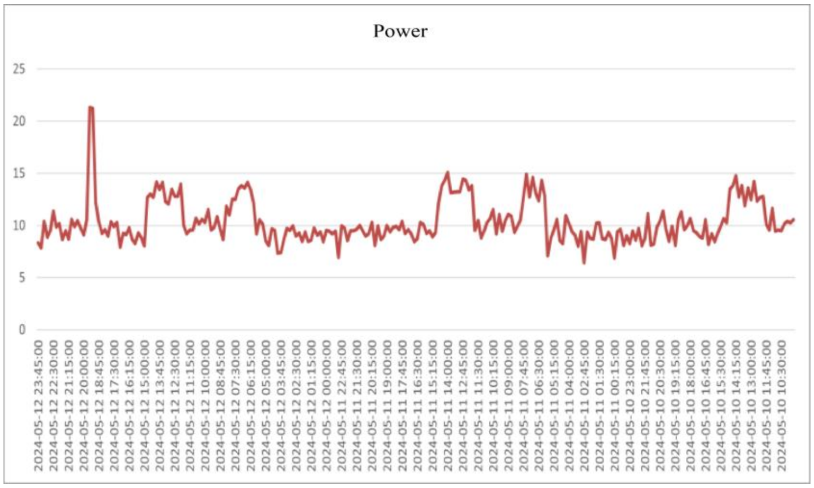

Fig. 12 Transformer overload graph using power

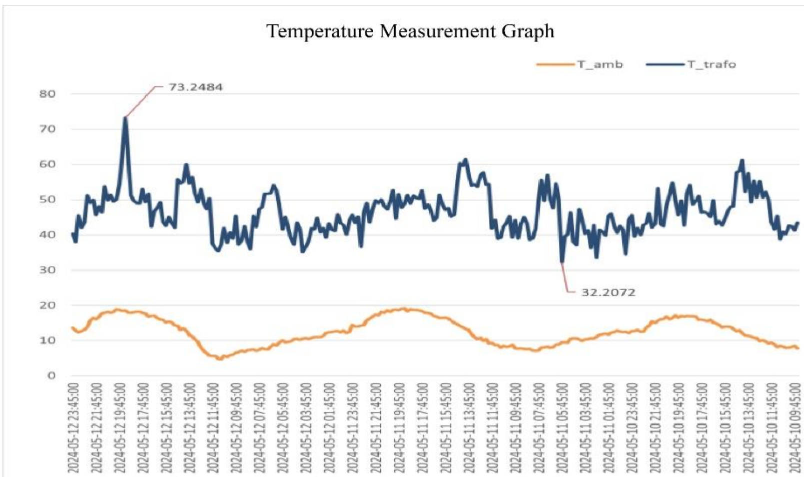

Fig. 13 Temperature measurement graph

During the measurement period, critical events were recorded mainly during peak hours (between 6:00 p.m. and 8:00 p.m.). Although short-lived, these events were crucial to verifying the system's ability to respond to sudden increases in demand.

Table 3. Temperature measurements

Parameters	Measurement
Average Temperature	46.54 °C
Maximum Temperature	73.2484 °C
Minimum Temperature	32.2072°C

4.3. Transformer Temperature Monitoring

The infrared sensor allowed MLX90614 to measure the transformer's surface temperature non-intrusively. During the study, temperatures close to the limit of 70°C established by the IEC 60076 standard were observed. Figure 13 shows the temperature variations, highlighting the periods when critical levels were reached. Table 3 summarizes the thermal data, which includes average, maximum, and minimum values. This information is essential to evaluate the transformer's thermal performance and prevent overheating, which can lead to oil spills.

4.4. Data Transmission Efficiency and Response

The A9G communication module showed high efficiency in transmitting real-time data to the IoT platform, even in areas with limited network coverage. Over a period of four days, response times to the alerts generated varied between 2 and 5 minutes, as detailed in Table 4.

These response times allow early interventions in transformers that present anomalies. Figure 14 shows the prototype installed in the transformer, evidencing the system's physical integration into the real environment.

Table 4. System alerts and response time

Parameter	minutes
The Total of Alerts Generated	3
Average Response Time	3.2
Maximum Response Time	5
Minimum Response Time	2

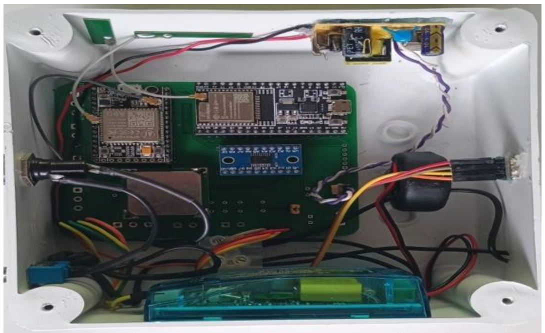

Fig. 14 Device installed on the transformer

4.5. IoT Platform Evaluation

The IoT platform developed allowed the comprehensive and real-time visualization of the data collected, facilitating the proactive management of the transformers. Incorporating geolocation information through the A9G module made it possible to accurately identify those transformers at risk, optimizing maintenance work and expansion planning in areas with growing demand. In addition, the platform enables data export to Excel, and the graphs presented were generated using Excel. Figure 15 illustrates the platform's interface, showing the different parameters monitored in real-time.

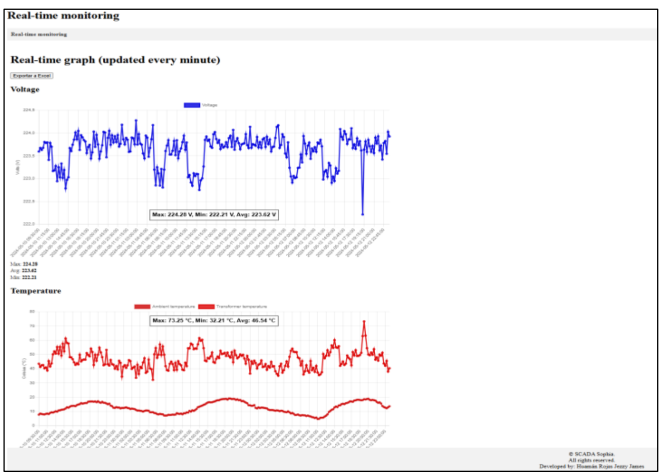

Fig. 15 IoT interface for monitoring the different parameters

5. Discussion

The IoT-based monitoring system developed in this study shows a remarkable capacity for detecting anomalies in distribution transformers operating in rural environments. Accurate measurements of electrical parameters, such as voltage and current, combined with continuous surface temperature monitoring using infrared sensors, aid in the timely identification of critical conditions, such as overloads and overheating. Notably, the calculation of the overload factor that sometimes approaches pre-set thresholds and the recognition of temperature readings exceeding 70°C (the limit defined by IEC 60076) emphasize the system's effectiveness in preventing potential failures and extending the operational life of transformers.

Compared to traditional methodologies that still rely on manual inspections and scheduled maintenance routines, the IoT-based approach presents substantially more accuracy, reliability, and responsiveness advantages. Integrating multiple sensors and real-time data transmission over GSM/GPRS networks allows for the generation of immediate alerts, allowing timely interventions that mitigate severe damage to equipment. Las redes GSM y GPRS son fundamentales. Sin embargo, su dependencia de los sistemas de vigilancia, normalmente en lugares remotos y de difícil acceso, puede plantear un grave problema, especialmente si la infraestructura de comunicación no está disponible. Esto nos permite postular formas alternativas de conectividad, como el satélite en capas, otras redes como LPWAN, o incluso la estrategia de almacenamiento en el borde, que aseguran un monitoreo continuo en tiempo real.

On the other hand, the effective systematization of data obtained with monitoring also supports the system's ability to maintain alerts in real-time, automatically executing active maintenance management. Other studies, such as [23], which used infrared to diagnose the oil degradation of insulating oil, argued that complementing with additional techniques to evaluate the system improved the assessment of the transformer's condition and refined predictive maintenance planning. Similarly, together with [24], IoT integrations reinforce the sustainability paradigm of implementation, focusing on modernizing the management infrastructure for electricity systems in rural and under-resourced areas.

In addition, a complementary implementation proposal for a system in the future is suggested. Currently, the system incorporates the PZEM-004T meter, the MLX90614 sensor, the ESP32, and the A9G module. However, it is always possible to enrich it with other sensors, such as those that evaluate the quality of the coolant oil. Inspired by the ETWSD methodology, this extension would allow several critical factors for transformer control to be simultaneously correlated, such as voltage, current, temperature, and even the oil itself, providing an accurate snapshot of the transformer's state.

It could help improve the early detection of anomalies and optimize maintenance intervention plans, thereby improving the reliability and operational safety of the system. In this context, the IoT is consolidated as a modern, sustainable, and efficient alternative to control and manage electrical infrastructures, improve maintenance, and increase the helpful life of transformers in rural areas.

6. Conclusion

This IoT monitoring system manages and controls single-phase distribution transformers in rural regions. The results demonstrate that the system delivers operational reliability by detecting critical conditions, such as overload and overheating, in real time. This is essential to avoid system failures and service interruptions. However, the reliance on system connectivity in remote areas highlights the need to investigate alternative communication technologies, such as satellite networks or LPWANs, to ensure consistent operational capability across environments.

Future research should focus on validating the system with a broader range of operating conditions to test its versatility and resilience. In addition, applying advanced diagnostic techniques, such as infrared spectroscopy, could improve achievable diagnostic accuracy and expand the system's applicability in predictive maintenance strategies.

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