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IoT-Driven Transformer Health Monitoring and Fault Detection: Advancing Reliability in Emerging Power Systems

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ABSTRACT

Transformers in electrical systems constitute basic devices in any modern power generation system because they allow efficient transfer of energy and they also contribute greatly toward the stability of the entire electrical system. The fact that they are using aging infrastructure with heavy overloading, however, is among the factors that significantly contribute to the risk that transformer failures might take place, thus cause a service outage and cause major economic losses. To address such challenges, this paper introduces Transformer Health Monitoring System (THMS) which is an Internet of Things (IoT) based system. The suggested system will include a NodeMCU platform and a set of sensors to continuously monitor key parameters, including temperature, voltage, current, and oil level. The obtained information is stored in a Firebase cloud database to enable real-time monitoring, and in case of surpassing operating limits, automated messages to mobile devices are dispatched. In addition, geolocation applications enable the detection and location of faults in distributed installations in a very short time. The experimental findings demonstrate that the proposed solution increases fault detection efficiency, reduces response time, and lowers maintenance costs compared to traditional monitoring practices, thereby enhancing the reliability and efficiency of transformer operation.

INTRODUCTION

Electrical transformers are an essential element of modern power systems which make possible the transfer of power between various voltage levels and, thus, stabilize the whole grid. However, the invaluable role is accompanied by vulnerability to various operational factors, such as overloading, equipment ageing, insulation damage, and excessive thermal stress. This can lead to a condition of impaired performance and culminate in sudden failures and hence loss of power and significant economic losses (Alinma Bank, 2026). Despite these challenges being global, they are especially severe in Pakistan due to the heterogeneity in the generation portfolio of electricity. As shown in Fig. 1, national power supply includes natural gas (47.0 TWh), hydropower (34.6 TWh), oil-based generation (28.7 TWh), coal (27.5 TWh), nuclear energy (26.9 TWh), wind (6.3 TWh), and solar power (0.9 TWh). This different combination creates complicated operating conditions of the transmission-distribution network, as the variability of output of both thermal plants and renewable energy sources creates the dynamism and high-frequency load changes. As a result, the transformers as key grid components become more vulnerable to overloading and early ageing. Consequently, continuous monitoring of transformer health has become essential to improve system reliability and extend the service life of these critical assets (Tripathi, 2018), (K. Hazarika, 2021).

Traditional transformer monitoring techniques such as scheduled manual tests and reactive maintenance are slow, expensive and do not in most cases identify issues before they escalate (Daniel Kumi Owusu, 2026). Modern solutions have been aimed at compensating these deficiencies and in that regard, Internet of Things (IoT)-based systems have been proposed as offering real-time monitoring and early fault detection (S. Rahman, 2017). Transformer Health Monitoring System is an IoT-based Transformer Health Monitoring system designed on the principles of utilizing a collection of sensors, microcontrollers, and cloud systems to collect, store, and process data concerned with important transformer parameters. These parameters are temperature, voltage, current, oil level, and humidity, which are very crucial information on the transformer status. Through constant monitoring of these aspects, IoT systems can determine problems like insulation failure or overheating and provide a prompt notification to the operator so that

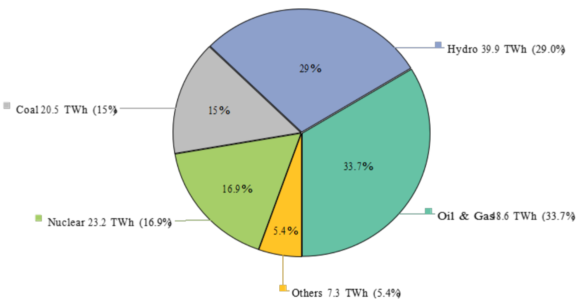

Figure 1: Pakistan's electricity generation in 2025, "Others" aggregates wind, solar PV, and biofuels (Renewables, 2025).

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corrective actions can be taken (Deosarkar, 2017).

It has been proved that IoT solutions can be used in transformer monitoring. The system proposed by Srivastava *et al*. (2018) integrates both IoT and sensors to leverage real-time fault detection to be able to demonstrate better performance in comparison with the traditional monitoring methodology. The article by Hazarika *et al*. (2021) conducted a comprehensive survey of the evolution, benefits, and concerns of IoT-based monitoring of transformers. The other means of saving is utilizing smaller GSM- based monitoring systems suggested by (S. Rahman, 2017)and less expensive than a contemporary IoT framework; nevertheless, they lack the same level of analytics or scalability (K. Hazarika, 2021).

Mobile and cloud-based solutions have also been added to the usability and accessibility of the monitoring systems. Indicatively, live sensor data processing and alerts through the assistance of mobile applications have been successfully deployed using NodeMCU and Blynk-based frameworks (S. Aralikatti, 2021) According to (Yuvaraj, 2021) Android applications are important in enhancing consumer interaction, and ease of doing business. On the same note, the title of research article Condition Monitoring of Electrical Transformers using IoT: A Systematic Literature Review has emphasized the paramount significance of cloud technologies in supporting real-time diagnostics and predictive maintenance (Mzamo R. Msane, 2024). (Kepa, 2021) also reported that GSM-based systems could be used to monitor the health of transformers which meant that such systems can transmit important information via the wireless network.

More advanced sensing technologies have also played part on the precision of monitoring systems on IoT. On the example of (Kuroda, 2025), Fiber Bragg Grating (FBG) sensors were employed, which allowed monitoring the temperature accurately to prove that with the creation of the modern sensors, the accuracy of data and the reliability of the system could be enhanced. (Hassan N. Noura, 2025) focused on the issues and the positive aspects of using the internet to monitor substations in the manner of transformer monitoring systems and therefore contributed more evidence to the scalability and usefulness of the IoT structures. In attempt to solve the issues of power distribution systems, recent studies have given consideration to the issues of scalability and predictive analytics. (Perumal B, 2022) proposed a complex IoT construction of real-time monitoring, with flexibility in various scenarios, and predictive abilities. Further and encompassed the integration of IoT gadgets in transformer health care to deliver the information about cost-effective implementation and future innovation (B. Durai Babu, 2022).

Considering these developments, the current paper proposes a complex IoT-based Transformer Health Monitoring System (THMS) with real-time monitoring, fault-detecting on the basis of the threshold, and the geolocation capabilities. Unlike the conventional systems, this system entails the deployment of NodeMCU as the processing central microcontroller of the system with different sensors to feed on it and then send data to Firebase, a cloud platform where information will be stored and synchronized with to enable real-time analysis. The system contains mobile notification to ensure that users are promptly mitigated and that the transformers located in the distributed networks can be properly localized.

The results of this paper are:

1.Creation of a scalable IoT-based real-time transformer health monitor.

2.Installation of geolocation to enhance fault detection.

3.Threshold based alert and mobile notification to initiate timely intervention.

4.Assessment of the reliability, accuracy, and the responsiveness of the system under operational conditions.

The paper could be regarded as aligned with the existing trends and covering the gaps of scalability, in-time fault detection, and usability. It aims to offer an affordable and efficient system to monitor the health of transformers using Internet of Things (IoT) technology to achieve a high degree of reliability and grid stability. Considering that Pakistan is dependent on this diversified energy base and that there is pressure on distribution transformers, there is a need to adopt sophisticated monitoring systems. The Transformer Health Monitoring System (THMS) proposed will meet this requirement by providing real-time diagnostics, predictive services, and geolocation features through the use of IoT.

MATERIALS AND METHODS

Figure 2 summarizes the chain of generation-transmission-distribution and downstream consumers to place the proposed solution in the electrical network. The THMS concentrates on distribution transformers in the feeder/consumer interface, where loading diversity, ambient conditions, and common switching events increase the probability of failure. Implementation of sensing and communication at the junction would allow localization of faults in real time, as well as predictive grid maintenance of the final grid mile.

Basic Operation

Transformer Health Monitoring System is a comprehensive solution for real-time monitoring, data processing, and decision making that will guarantee the effective and safe operation of power transformers. The process will start with the collection of data by various sensors that are designated to measure particular parameters that are paramount to the health of the transformers, as shown in the block diagram of Figure 3. The DS18B20 temperature sensor is used to measure temperature to prevent overheating, and the DHT11 humidity sensor is used to measure the health of insulation.

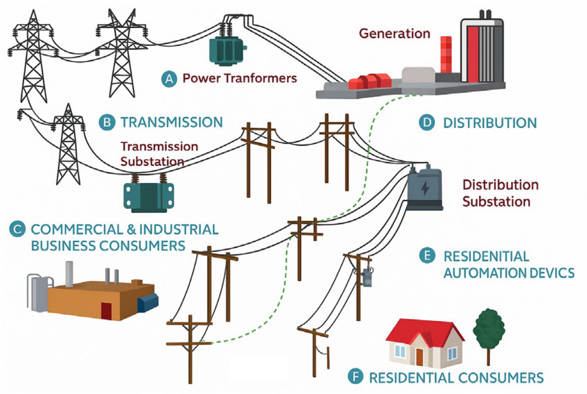

Figure 2: Electricity power network system context: Generation, transmission, and distribution to commercial/industrial and residential consumers. The THMS is installed at the distribution transformers below the distribution substation.

With electrical parameters, the ACS712 current sensor and ZMPT101 voltage sensor are used to get real-time current and voltage values and this guarantees the power stability and the detection of overload condition or short circuit. The ultrasonic level sensor continuously measures the fluid level inside the transformer which helps in detecting a potential leakage of the coolant or the low fluid volume in the transformer that could lead to overheating. Simultaneously, the position can be calculated, and the fault can be detected, and the assets can be tracked; it is possible since the GPS unit sends information via the UART. The THMS in general offers an effective system of transformer health monitoring. By aggregating data offered by multiple sensors and applying the threshold-based policies, as well as communicating with the cloud infrastructure, the system could detect faults earlier and reduce the downtime of the operations and make the operations more efficient overall.

Implementation

The Transformer Health Monitoring System hardware design based on the IoT employs a large number of components that are embedded within a unit to measure, process, and transmit vital transformer data. It is meant to be reliable and stable in the field with reliable and stable monitoring of transformer parameters. The system incorporates different sensors, which are all supposed to detect some areas of transformer performance. As an example, the DS18B20 temperature sensor is very precise in temperature measurement on the transformer and, hence, gives a hint of possible overheating at the initial stage. It is a sensor that uses a one-wire communication protocol with the Arduino UNO, making it easy to wire and efficient. The DHT11 humidity sensor measures the humidity of the air and provides a clue about the insulation wellbeing of the transformer; the digital readings are handled by the Arduino UNO.

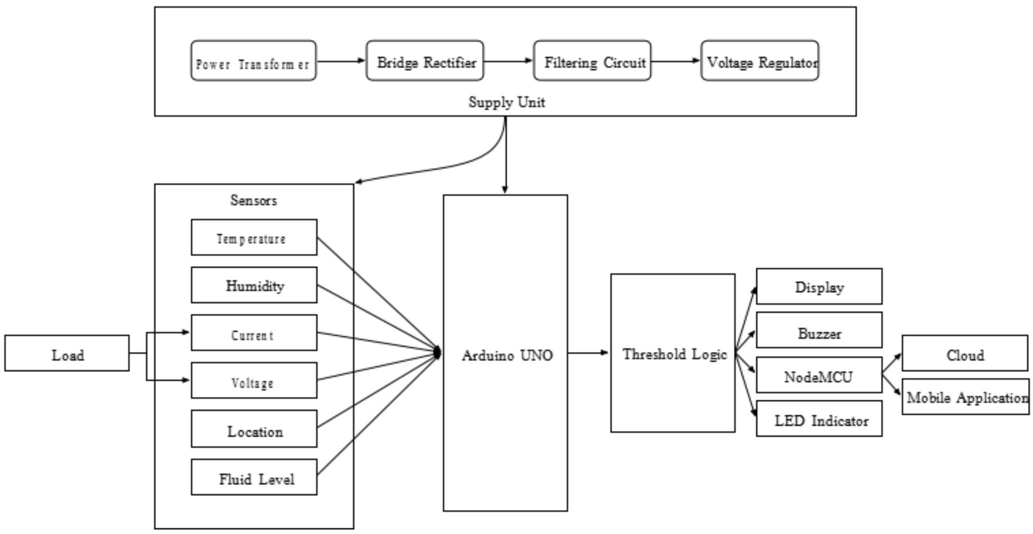

Figure 3: Overall architecture of the IoT-based Transformer Health Monitoring System (THMS)

The ACS712 current sensor is connected across the load and detects the current flowing through the transformer and delivers an analog voltage proportional to the current flowing through it, which is converted by the Arduino UNO through its internal built-in ADC. The ZMPT101 voltage sensor measures the voltage across the transformer, using a resistive divider and amplifier to

Table 1: Down sampled Logged Data from THMS with GPS Location, Voltage, Current, Winding Temperature and Oil Level

Timestamp	Voltage	I(A)	Oil Level (%)	Winding Temp (°C)	Location
2025-08-28 12:00	228.71	14.3	63.15	51.67	33.6844, 73.0479
2025-08-28 12:30	229.69	14.86	63.49	53.52	33.6844, 73.0479

2025-08-28 13:00	222.93	17.33	63.47	56.20	33.6844, 73.0479
2025-08-28 13:30	229.80	16.85	64.19	55.24	33.6844, 73.0479
2025-08-28 14:00	224.69	15.15	64.01	53.61	33.6844, 73.0479
2025-08-28 14:30	223.71	15.36	64.54	54.32	33.6844, 73.0479
2025-08-28 15:00	225.38	15.01	64.65	54.17	33.6844, 73.0479
2025-08-28 15:30	229.69	17.50	64.81	57.09	33.6844, 73.0479
2025-08-28 16:00	220.77	16.90	64.55	56.41	33.6844, 73.0479
2025-08-28 16:30	220.95	16.34	64.78	55.77	33.6844, 73.0479
2025-08-28 17:00	229.18	17.73	65.10	57.95	33.6844, 73.0479
2025-08-28 17:30	222.30	17.74	65.39	58.52	33.6844, 73.0479
2025-08-28 18:00	228.59	19.58	65.91	60.59	33.6844, 73.0479
2025-08-28 18:30	225.08	19.42	65.90	60.27	33.6844, 73.0479
2025-08-28 19:00	229.20	19.74	66.23	60.98	33.6844, 73.0479
2025-08-28 19:30	224.34	20.61	66.16	61.83	33.6844, 73.0479
2025-08-28 20:00	220.70	21.31	66.63	62.57	33.6844, 73.0479
2025-08-28 20:30	221.09	20.65	66.70	62.15	33.6844, 73.0479
2025-08-28 21:00	224.02	21.69	67.03	63.30	33.6844, 73.0479
2025-08-28 21:30	225.87	20.58	66.88	62.37	33.6844, 73.0479
2025-08-28 22:00	226.39	21.32	67.11	63.09	33.6844, 73.0479
2025-08-28 22:30	220.28	20.94	67.01	62.54	33.6844, 73.0479
2025-08-28 23:00	221.46	20.49	67.18	62.32	33.6844, 73.0479
2025-08-28 23:30	220.01	19.54	67.16	61.40	33.6844, 73.0479
2025-08-29 00:00	224.72	18.76	66.91	60.64	33.6844, 73.0479
2025-08-29 00:30	225.11	19.20	67.05	61.08	33.6844, 73.0479
2025-08-29 01:00	222.99	18.65	67.14	60.77	33.6844, 73.0479
2025-08-29 01:30	224.17	19.10	67.34	61.15	33.6844, 73.0479
2025-08-29 02:00	229.10	18.23	67.12	60.22	33.6844, 73.0479
2025-08-29 02:30	223.43	18.07	67.20	60.14	33.6844, 73.0479
2025-08-29 03:00	222.59	17.92	67.08	60.05	33.6844, 73.0479
2025-08-29 03:30	225.56	18.44	67.24	60.39	33.6844, 73.0479
2025-08-29 04:00	228.41	17.66	67.30	59.88	33.6844, 73.0479
2025-08-29 04:30	224.08	17.34	67.12	59.50	33.6844, 73.0479
2025-08-29 05:00	221.27	17.85	67.19	60.07	33.6844, 73.0479
2025-08-29 05:30	223.92	18.05	67.38	60.25	33.6844, 73.0479
2025-08-29 06:00	225.11	19.45	67.44	61.43	33.6844, 73.0479
2025-08-29 06:30	222.20	19.05	67.61	61.02	33.6844, 73.0479
2025-08-29 07:00	220.82	19.72	67.70	61.65	33.6844, 73.0479
2025-08-29 07:30	226.74	20.10	67.88	62.17	33.6844, 73.0479
2025-08-29 08:00	227.51	20.64	68.05	62.81	33.6844, 73.0479
2025-08-29 08:30	224.36	20.19	68.14	62.45	33.6844, 73.0479
2025-08-29 09:00	228.12	21.25	68.28	63.40	33.6844, 73.0479
2025-08-29 09:30	225.66	20.77	68.33	62.94	33.6844, 73.0479
2025-08-29 10:00	220.98	21.60	68.55	63.72	33.6844, 73.0479
2025-08-29 10:30	223.84	21.05	68.70	63.29	33.6844, 73.0479
2025-08-29 11:00	222.43	22.15	68.89	64.18	33.6844, 73.0479

reduce the voltage to a safe operating range which is then measured by the Arduino; the voltage is then maintained constant by the Arduino. A level sensor is the ultrasonic level sensor reading the fluid levels (oil or coolant) in the transformer and indicates possible leakages or lack of fluid by sending out ultrasonic pulses and measuring the echo times to determine the level of fluid. In addition, the GPS module (NEO-6M) provides accurate transformer positioning information and transfers the data to the Arduino UNO through a UART interface, which gives dependable geolocation data.

Firebase is the base of cloud-based storage and analysis of data. It uses a real-time database to save sensor data in a hierarchical manner, which allows quick storage and retrieval. Notifications caused by critical states are recorded and currently aligned to the mobile application. Firebase also provides historical data logging capabilities, which allow one to analyse trends and plan maintenance. Live synchronization between the system and the mobile application makes sure that sensor data and alerts received by Firebase are immediately reflected on the app, where push notifications are received based on critical alerts, e.g., overheating or low fluid levels, and the information is displayed in detail, including transformer ID, location, parameter details, and timestamps. The interactive dashboard retrieves organized data in Firebase in order to show real-time sensor values and historical trends so that a user can keep track of parameters, which include temperature, voltage, current, and fluid levels. This is because the parameter thresholds and notification settings can be changed directly within the mobile application, and Firebase is automatically adjusted to the preferences of the user. The local caching of Firebase provides the app with the ability to access data even when it does not have an internet connection. Security is handled in a way that Firebase Authentication controls the authorized users who can view or edit data, and access controls determine what actions can be performed depending on the user role.

Created based on platforms like MIT App Inventor, the mobile application is simple and easy to use to track the health of transformers. It shows real-time sensor values, sends push notifications when there is a critical situation, and shows trends in past data and general transformer operation. The user can change the threshold values and alert setting, thus enhancing the system usage.

The NodeMCU is also the main component in the Transformer Health Monitoring System (THMS) that facilitates a smooth communication and data management process. It maintains a steady internet connection, sends processed information and signals from the Arduino to Firebase, shapes the data into the real-time database, and includes reconnection logic, a move to reduce the impact of Wi-Fi interruptions or connectivity problems. Every NodeMCU can be used as a separate communication node, which in turn gives the system the opportunity to expand and connect to various transformers located in different locations.

To evaluate the system of Transformer Health Monitoring (THMS), a representative data set was created through aggregating the data collected at periodic intervals of five minutes of a simulated household load profile. Its parameters were voltage, current, temperature of winding, and oil level along with GPS coordinates of the monitoring location. The dataset was down sampled in order to make it clearer and more concise, instead of showing all of the 288 samples, one sample was retained every five measurements. This process resulted in 48 representative records and the preservation of the daily pattern of the variation in loads and thermal behaviour. Table I shows the sampled data that is down sampled where the readings record the various load states of the house throughout the day thus representing the common domestic energy-consumption patterns, which include early-morning activity, day-time air-conditioning, evening high demand, and constant night operation.

RESULTS AND DISCUSSION

Transformer Health Monitoring System (THMS), which is based on IoT, showed high functionality in all its operations through extensive testing and actual implementation. The application of trusted hardware, carefully crafted computer code, and cloud computing technologies allowed the system to resolve the main issues of transformer surveillance. It was more successful, especially in real-time capture of the various critical parameters so that faults could be detected and timely action could be taken. As an illustration, the DS18B20 temperature sensor accurately monitored the operating temperature of the transformer and would alert the operators quickly to the dangers of overheating, which would otherwise result in insulation being damaged or extreme failures. Voltage and current sensors provided real- time access to electrical stability, enabling overloads, short circuiting or under voltages to be found before they occur, potentially compromising transformer efficiency. The ultrasonic level sensor gave correct values of the coolant level in the user system, hence the cooling system is able to sustain its operation. Inclusion of DHT11 to measure humidity in the system assisted to keep track of ambient conditions, which were imperative in determining insulation deterioration by high moisture content. These streams have all collaborated in harmony to give a wholesome picture of transformer health.

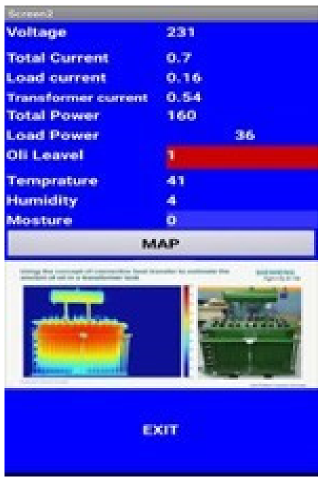

Figure 4: App Interface

The THMS implemented a hierarchical system of alert to inform the maintenance teams about some essential events. Visual and auditory cues were created immediately by the on-board device: red LED light on and buzzer sound to attract the attention of local staff. with the help of Firebase integration these alerts were sent to the remote users via the mobile application. Figures 4 and 5 give this process. The alerts had all the necessary information (where the damaged transformer was located, the fault nature, and the exact values of the parameters). Such detail assisted maintenance crews to know of the problem before getting on location, therefore raising their response efficiency and accuracy.

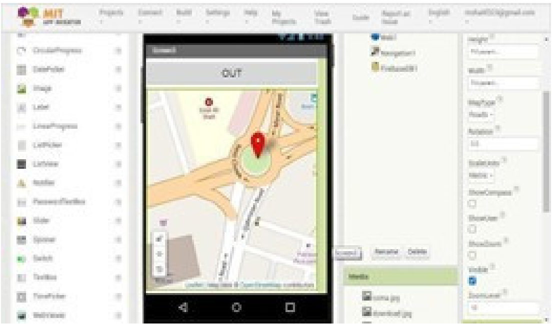

Figure 5: Geo Location

The THMS was designed to be modular to support greater scale in transformer networks. The real-time database of Firebase was capable of receiving a data stream from several transformers at once and remained consistently stable even when the number of active transformers was large. This scalability was confirmed by a simulation of twenty transformers where this system was able to maintain data synchronization and stay alert without compromising its performance.

The developed mobile application in the THMS had an easy user interface that was customizable and flexible. The users were able to track parameters instantly, check past trends, and they were alerted on their device. The fact that threshold values could be adjusted and the choice of preferred types of alerts enabled the system to be adapted to operational needs. As an example, the maintenance managers might want to focus on high-risk transformer alarms and reduce the number of notifications in case of small variations. The trends of the data in the app were displayed in simple, easy-to-read graphs so that the user would be able to make an informed decision and plan maintenance on time.

Table 2: Threshold parameters and their remarks for THMS

Parameter	**Threshold Value**	**Remarks**
Temperature	≤80°C	Overheating risk beyond this.
Voltage	±10% of nominal voltage	Indicates voltage stability.
Current	≤ 110% of rated current	Highlights potential overload.
Humidity	≤ 60% RH	Affects insulation health.
Fluid Level	≥ 25% of tank capacity	Ensures proper cooling.

The THMS assisted predictive maintenance plans by acquiring accurate real-time monitoring and historical data analysis. The monitoring of trends in temperature and voltage variations gave early notifications about possible malfunctions, thus allowing the operators to plan their work so that they could repair the problem before it got out of control. This proactive strategy minimized unplanned interruptions and maintenance expenses, which optimized the general reliability and efficiency.

The traditional approaches to the monitoring of transformers have never been anything other than manual inspection, regular maintenance and the responsive measures once the symptoms of fault have manifested themselves. Although these methods have been in use to produce grid stability long enough, they are increasingly becoming unsuitable towards the requirements of modern-day power systems. The manual process itself can also result in faults being diagnosed late since the more serious ones such as overheating, insulation damage or oil loss cannot be detected until it is too late and the failures are extremely dangerous. Due to the absence of constant monitoring, some unforeseen malfunctions occur that break the supply of electricity and cause serious financial losses. To add to this, operational costs are heightened by the need to use regular physical checks, which require utilities to spend a lot of resources on labor and repair. Traditional monitoring is also limited by scalability, where it is not appropriate to manually monitor and rate large numbers of transformers spread over extensive and, in many cases, remote geographic areas.

The Transformer Health Monitoring System (THMS) presented in the current paper addresses these limitations by combining sensors, microcontrollers, cloud services, and mobile applications into a single system, the IoT. Contrary to traditional approaches, the THMS offers real-time observations of important parameters such as voltage, current, temperature, humidity, and oil level. This data is automatically transmitted to a cloud server where it is synchronized and analyzed on a continual basis. Notifications issued based on thresholds are directly transferred to mobile devices of users, so operators can be informed about possible risks immediately. Inclusion of geolocation capability also enhances the system as it enables maintenance teams to know the exact location of a fault and respond faster and more effectively.

Table 3: Performance Test Results for THMS

Test Parameter	Expected Outcome	Observed Outcome	Remarks
Temperature	≤80◦C	78◦C	Normal
Voltage	360V–440V	370V	Within range
Current	≤ 110% of rated	102%	No overload
Fluid Level	≥ 25%	30%	Adequate cooling

In addition to real-time monitoring, the THMS enables predictive maintenance based on past analysis of data. The trends in changes in temperature, the volatility of currents, or the slow decrease in oil level may be identified in advance to take timely measures before the development of critical defects. This proactive mode not only enhances the reliability of the transformers but also minimizes unexpected downtime and total maintenance expenses. The system provides a less expensive alternative to traditional practices through minimizing the frequency of manual inspection. Moreover, its modular scalable design renders it very flexible in large transformer connections wherein every NodeMCU can be used as a hub independently, which guarantees that multiple sites can be monitored concurrently without performance degradation.

The difference between traditional monitoring and IoT-based monitoring is clear as shown in Fig. 6. Traditional approaches are restricted by delayed fault identification, increased operational expenses, and lack of scalability whereas the suggested THMS provides continuous monitoring, quick fault localization, predictive maintenance, and low cost. This comparison highlights the need to implement IoT technologies in transformer health management, especially in emerging power systems like Pakistan, where reliability and cost efficiency of infrastructure are essential.

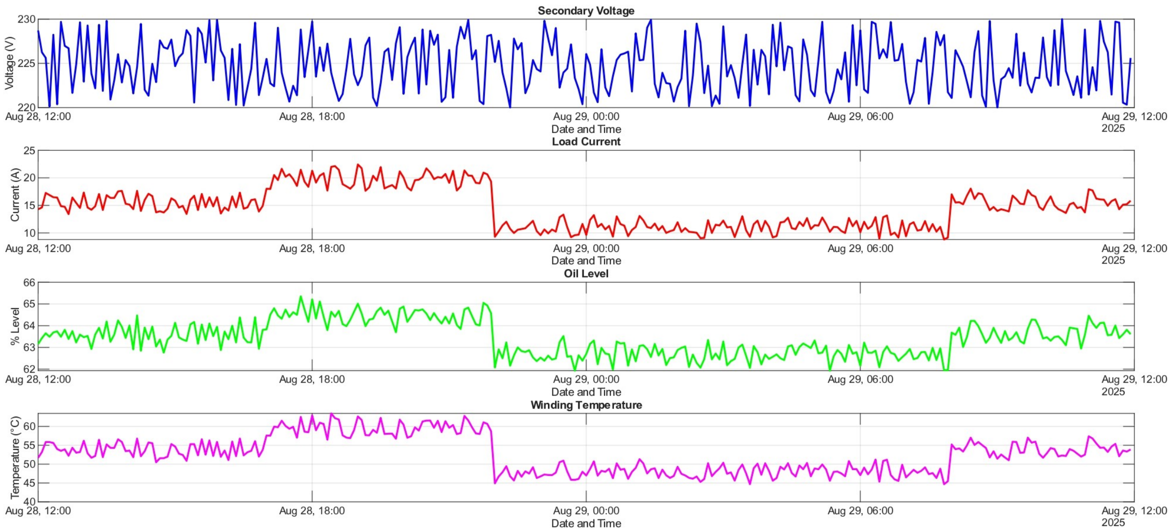

Figure 6: Real-time variations in voltage, current, oil level, and winding temperature of the monitored transformer.

The modular design, combined with efficient cloud integration, allowed the system to scale easily for both small installations and large, distributed transformer networks. Testing demonstrated that the system maintained reliable performance even as network loads increased. It also performed consistently under challenging conditions, such as high humidity and extreme temperatures, ensuring dependable monitoring and fault detection in remote or harsh environments. By leveraging Firebase's real-time database along with local caching, the system maintained continuous data access during connectivity interruptions, supporting uninterrupted operation in areas with unstable network infrastructure. Overall, this robust and scalable setup effectively addressed the key challenges of transformer monitoring (Table 2) while enabling predictive maintenance practices (Table 3).

CONCLUSION

Transformer management is provided by the Transformer Health Monitoring System (THMS) using the described methodology, which is developed as an IoT-based solution that can be considered comprehensive and reliable. The system incorporates advanced sensors, wireless communication, and cloud computing, thus addressing the major challenges of transformer monitoring. Its capability to collect data and detect faults in real time makes it suitable for performing proactive maintenance, minimizing unplanned outages, and improving overall operational performance. The system can be used in a wide variety of deployment scenarios because of its scalable, modular design; it can be configured to support small installations or large, distributed networks. The user-friendly interface of the mobile application allows operators to have clear, actionable insights that aid quicker and informed decision-making during critical events. Predictive maintenance, which is developed on the basis of historical data analysis, also adds value to the system by increasing equipment life and reducing maintenance costs. The scalability of THMS is validated by the inclusion of timestamped and geo-tagged datasets, which ensures real-time fault detection as well as historical records that can be used for predictive analytics. Overall, THMS has performed exemplarily in its functionality, reliability, and flexibility, making it one of the state-of-the-art solutions for contemporary power distribution systems. Future enhancements could involve adding more types of sensors, refining fault detection using AI-based approaches, and exploring other communication protocols to further enhance the capabilities of the system.

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