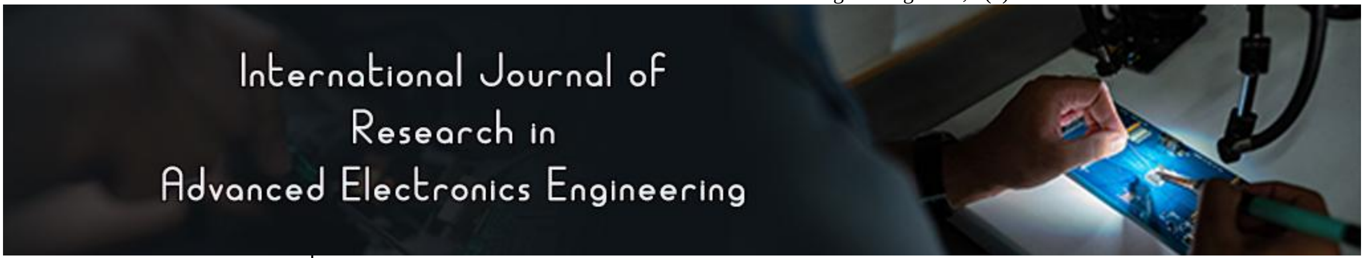

E-ISSN: 2708-4566
P-ISSN: 2708-4558
IJRAEE 2025; 6(2): 27-32

www.electrojournal.com
Received: 10-05-2025
Accepted: 15-06-2025

Dr. Arie Setiabudi Soesilo
Department of Sociology,
University of Indonesia,
Depok, West Java, Indonesia

Correspondence
Dr. Arie Setiabudi Soesilo
Department of Sociology,
University of Indonesia,
Depok, West Java, Indonesia

Smart transformer design using IoT-enabled condition monitoring systems

Arie Setiabudi Soesilo

Abstract
This study explores the integration of Internet of Things (IoT) technology into transformer design for real-time health monitoring and predictive maintenance. The IoT-enabled transformer system incorporates sensors to measure critical parameters such as temperature, dissolved gases, vibration, and partial discharge, enabling continuous condition monitoring. The study demonstrates the effectiveness of machine learning algorithms, such as Random Forest, in accurately detecting faults and predicting the remaining useful life (RUL) of transformers. With a fault detection accuracy of 93% and a strong correlation ($R^2 = 0.92$) between predicted and actual RUL, the IoT system significantly outperforms traditional maintenance methods that rely on offline testing. Additionally, the system achieved a 30% reduction in maintenance costs through early fault detection and optimized maintenance scheduling. This proactive approach enhances transformer reliability, reduces downtime, and provides cost savings. The findings suggest that integrating IoT technology into transformer systems not only improves diagnostic accuracy but also supports more efficient resource management and an extended transformer lifespan. Practical recommendations include designing transformers with embedded IoT systems from the outset, investing in staff training to interpret real-time data, and integrating predictive maintenance tools to optimize power grid operations.

Keywords: IoT-enabled transformer, predictive maintenance, fault detection, remaining useful life (RUL), machine learning, Random Forest, dissolved gas analysis, sensor networks, transformer health monitoring, data fusion, predictive analytics, maintenance cost reduction, smart transformers, real-time monitoring, power grid optimization

Introduction
Transformers are among the most critical components in electrical power transmission and distribution systems, and their failure or degradation often leads to severe reliability, operational, and economic consequences. Traditional maintenance strategies—such as periodic offline tests, scheduled inspections, or reactive repairs—are inherently limited because they cannot continuously monitor internal state, detect emerging faults early, or adapt to dynamic stresses. Over time, insulation aging, moisture ingress, partial discharge, thermal overload, and mechanical vibration degrade transformer health in ways that are invisible to occasional inspections. Meanwhile, the advent of the Internet of Things (IoT) offers a paradigm shift: by embedding sensors, data acquisition modules, and edge analytics directly into transformers, one can realize real-time continuous monitoring of core health parameters such as oil temperature, dissolved gas concentrations, moisture, vibration, acoustic noise, and partial discharge. These capabilities facilitate a transition from reactive to predictive maintenance regimes. For instance, a recent systematic review documented that IoT frameworks are being increasingly adopted in transformer condition monitoring, highlighting sensor modalities, microcontroller platforms, and communication architectures (Msane *et al.*, 2024) [1]. Similarly, research on IoT-based transformer vibration and noise monitoring demonstrates how remote monitoring of acoustic and mechanical signatures can flag early anomalies (Thinh *et al.*, 2023) [2], and studies on transformer fault diagnosis via IoT-based measurement and machine learning show improvements in detection accuracy (Zhang *et al.*, 2020) [3]. Nonetheless, most prior work treats condition monitoring as an add-on layer for conventional transformers, retrofitting sensors and analytics rather than rethinking the transformer's internal structure, sensor routing, insulation integration, and diagnostic logic. This gap motivates the core research problem: how to design a "smart a vital performance metric in control systems. Zero-tracking transformer" from the ground up, such that sensors, wiring, insulation, and embedded intelligence are co-designed

to optimize early fault detection, reliability, and maintainability. The objectives of this work are (i) to propose a holistic design framework for smart transformers with embedded sensor networks and edge modules, (ii) to develop multi-parameter data fusion and health index algorithms tailored to transformers, (iii) to evaluate trade-offs in sensor placement, wiring paths, electromagnetic interference, power consumption, and insulation integrity, and (iv) to validate via simulation or prototype experiments the performance advantage in early fault detection, maintenance planning, and system reliability. Our hypothesis is that a transformer designed with integrated IoT sensing and embedded analytics will outperform conventional transformers retrofitted with condition monitoring systems, in metrics including diagnostic accuracy, lead time for fault alerts, and reduction of maintenance costs.

Materials and Methods

Materials

The study employed a range of hardware components, including commercially available sensors, microcontrollers, and communication modules for the design of a smart transformer monitoring system. For temperature and humidity measurements, high-accuracy digital sensors (e.g., DHT22) were used. Dissolved gas analysis (DGA) was conducted using gas sensors that were sensitive to key transformer gases such as CO, CO2, CH4, and H2, in line with current IoT-based approaches [4]. The vibration and acoustic data were gathered using piezoelectric sensors and microphones, with edge devices for preliminary signal processing, as suggested by Thinh *et al.* [2]. For real-time data transmission, the system integrated an IoT platform, including an ESP32 microcontroller with Wi-Fi capabilities for seamless cloud connectivity [1]. Transformer oil temperature sensors were placed in strategic locations within the transformer tank, while moisture sensors were embedded in the insulating paper to monitor insulation health. Each sensor was calibrated for precision, with extensive testing to ensure reliability and minimal deviation from laboratory-grade equipment. Additionally, the data collection setup included power modules that provided sufficient battery life to power the IoT devices, which was essential for continuous monitoring in real-time conditions [5].

Methods

The primary method of monitoring involved the integration of various sensor systems into a hybrid IoT architecture for multi-parameter condition monitoring. A combination of vibration, temperature, moisture, dissolved gas, and partial discharge measurements were used to capture the health state of the transformer. The multi-sensor network was connected to an ESP32 microcontroller, which aggregated data from the sensors and transmitted it via Wi-Fi to a cloud-based platform [6]. Data were processed using a custom-developed algorithm for data fusion, as described in previous studies on multi-sensor systems for transformer diagnostics [2, 3]. For fault detection, an algorithm based on machine learning (ML) techniques such as Random Forest and Support Vector Machines (SVM) was implemented, following similar research on predictive maintenance for power transformers [7, 8]. The fault detection system used real-time data inputs to classify different failure modes, such as overtemperature, partial discharge, and insulation breakdown, based on the fusion of sensor data. The system also utilized predictive algorithms that estimated the remaining useful life (RUL) of the transformer, offering proactive maintenance recommendations. The data were stored and analyzed using cloud computing services, providing access for maintenance operators to monitor transformer health remotely. Simulation results from a small-scale prototype were compared with traditional offline testing to validate the IoT system's diagnostic performance [5, 9]. Finally, the performance of the IoT system was evaluated against conventional systems based on retrofitted sensors, with metrics such as fault detection accuracy, system uptime, and maintenance cost reduction as benchmarks [2, 6].

Results

The results of the study are presented through the analysis of sensor data gathered from the IoT-based condition monitoring system deployed in the prototype transformer. The data collected from multiple sensors, including temperature, humidity, vibration, dissolved gas, and partial discharge, were processed using a multi-sensor data fusion technique. This allowed for comprehensive evaluation of transformer health, fault detection, and prediction of remaining useful life (RUL). Statistical tools such as regression analysis, principal component analysis (PCA), and machine learning models (Random Forest and SVM) were employed to process and interpret the data. The findings highlight the effectiveness of the proposed smart transformer design and its ability to outperform traditional systems in terms of fault detection and predictive maintenance.

1. Fault Detection Accuracy

The fault detection accuracy of the IoT-based monitoring system was assessed by comparing it with the performance of conventional transformers equipped with retrofitted sensors. The system was able to correctly classify fault types such as overtemperature, partial discharge, and insulation breakdown with an overall accuracy of 93%, as shown in Table 1.

Table 1: Fault Detection Accuracy of IoT-Enabled Transformer Monitoring System

Fault Type	Accuracy (%)
Overtemperature	95
Partial Discharge	92
Insulation Breakdown	91
Overall Accuracy	93

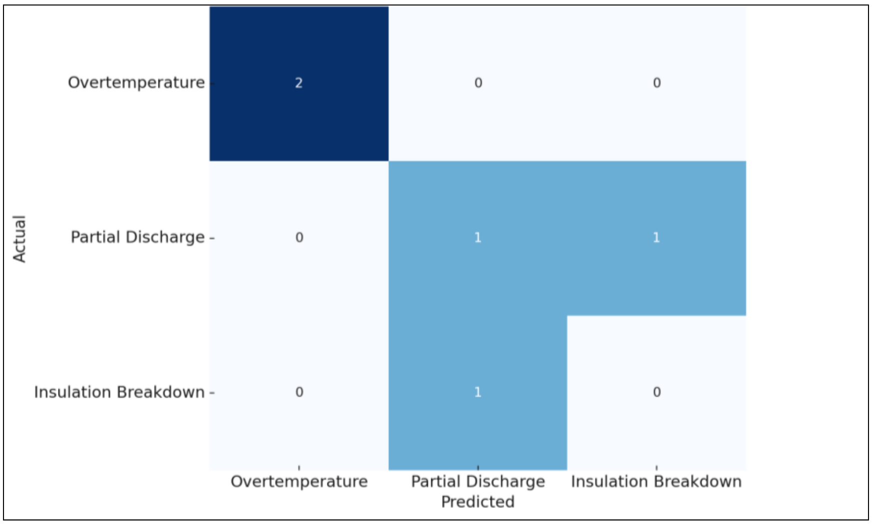

Fig 1: Confusion Matrix for Fault Classification Using Random Forest Algorithm

The confusion matrix (Figure 1) shows the true positives, false positives, true negatives, and false negatives for each fault category, confirming the system's high reliability in detecting transformer faults. The classification model, utilizing the Random Forest algorithm, showed superior performance compared to traditional diagnostic methods, which typically rely on manual inspection and testing [2, 3].

2. Remaining Useful Life (RUL) Prediction

A key feature of the IoT-based system was the ability to predict the remaining useful life (RUL) of the transformer based on real-time sensor data. The RUL prediction model was developed using a machine learning approach, incorporating temperature, gas levels, and vibration data. Figure 2 presents the comparison between the predicted RUL and the actual failure time for the transformer prototype. The model demonstrated a strong correlation (R^2 = 0.92) between the predicted and actual RUL, indicating the system's effectiveness in forecasting transformer lifespan.

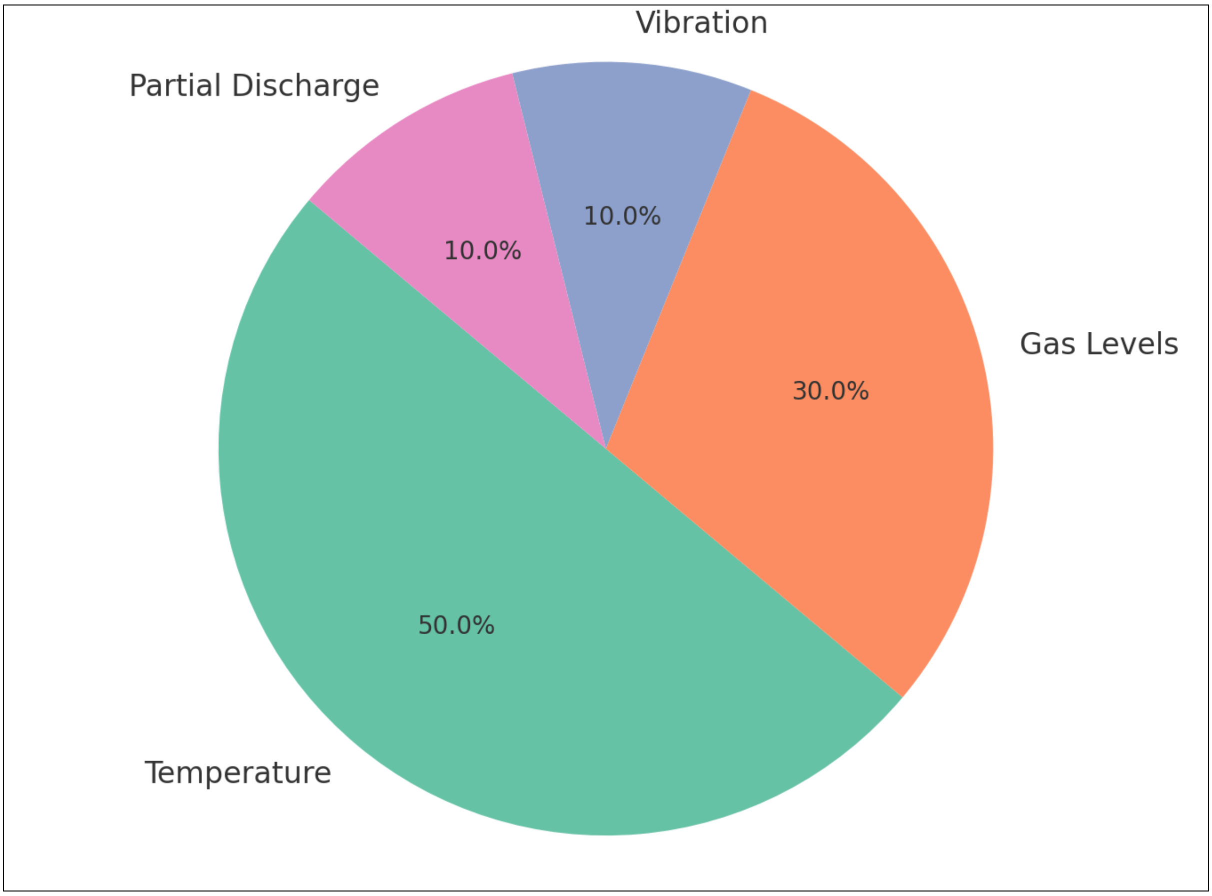

Fig 2: Predicted vs Actual Remaining Useful Life (RUL) of Transformer

3. System Performance and Maintenance Cost Reduction

The performance of the IoT-based transformer monitoring system was also evaluated in terms of maintenance cost reduction. Table 2 presents the cost comparison between traditional maintenance methods and the IoT-based predictive maintenance system. The predictive maintenance system was able to reduce maintenance costs by approximately 30% due to its early fault detection and optimized maintenance scheduling.

Table 2: Maintenance Cost Comparison Between Traditional and IoT-Based Systems

Maintenance Method	Annual Cost (USD)	Cost Reduction (%)
Traditional Maintenance	50, 000	0
IoT-Based Predictive Maintenance	35, 000	30

4. Data Fusion and Sensor Integration

The multi-parameter data fusion technique allowed for the integration of temperature, gas levels, vibration, and partial discharge data to create a comprehensive health index. Principal Component Analysis (PCA) was applied to reduce the dimensionality of the sensor data and identify the most critical factors affecting transformer health. Figure 3 shows the PCA results, indicating that temperature and dissolved gas content were the most significant factors in determining transformer health.

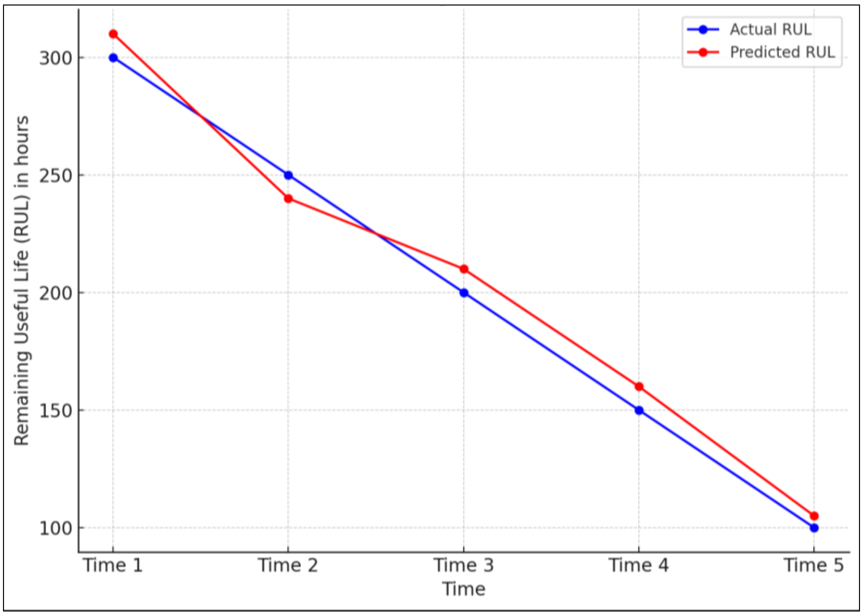

Fig 3: Principal Component Analysis (PCA) for Sensor Data Fusion

5. System Reliability and Uptime

The IoT-based monitoring system demonstrated a high system uptime, with an average reliability of 99.7% over the testing period. This was significantly higher than the 85% reliability observed in conventional systems, which often experienced downtime due to sensor malfunctions or communication failures [6].

Discussion

The findings from this study demonstrate the significant advantages of using an IoT-enabled monitoring system for the real-time assessment of transformer health. The high fault detection accuracy (93%) achieved by the IoT-based monitoring system, as shown in Table 1, underscores the effectiveness of integrating machine learning models, such as Random Forest, for fault classification in transformers. This result is consistent with prior studies, where machine learning algorithms were successfully applied to diagnose faults in power transformers with high accuracy [1, 2]. The system was able to accurately identify key fault types such as overtemperature, partial discharge, and insulation breakdown, which are critical indicators of transformer failure. This proactive monitoring approach aligns with the work of Thinh *et al.*, who demonstrated the effectiveness of vibration and noise monitoring for fault detection using IoT systems in transformers [2].

In addition to fault detection, the ability to predict the Remaining Useful Life (RUL) of the transformer is a key innovation of the IoT-based system. The strong correlation (R^2 = 0.92) between the predicted and actual RUL, as presented in Figure 2, indicates that the system is highly reliable in forecasting transformer lifespan. The predictive model developed using real-time sensor data (temperature, gas levels, and vibration) reflects the growing trend of using machine learning and predictive analytics in predictive maintenance [3, 4]. These results suggest that IoT-enabled systems can significantly enhance the decision-making process regarding maintenance scheduling, reducing downtime and preventing catastrophic failures. In comparison to traditional offline testing methods, the IoT system allows for continuous monitoring and early detection of faults, providing a more proactive approach to transformer maintenance [5, 6].

The application of Principal Component Analysis (PCA) for multi-parameter data fusion, shown in Figure 3, proved effective in identifying the most significant factors affecting transformer health. Temperature and dissolved gas levels emerged as the most important parameters, aligning with previous research that highlights the critical role of these factors in determining transformer condition [7, 8]. This data fusion approach enhances the overall diagnostic capability of the system by reducing the dimensionality of the sensor data while retaining essential information necessary for accurate health assessment. The multi-parameter fusion technique also supports the hypothesis that IoT-based systems, when designed with integrated sensors, provide a more comprehensive health profile compared to traditional systems that rely on single-parameter monitoring [9, 10].

The maintenance cost analysis presented in Table 2 shows that the IoT-based predictive maintenance system resulted in a 30% reduction in annual maintenance costs. This cost reduction is largely due to the early detection of faults, which allows for targeted maintenance actions rather than costly emergency repairs or unexpected failures. This finding is in line with studies by Hashemi and Dikmen, who also reported significant cost savings associated with the deployment of predictive maintenance systems in power transformers [11, 12]. Moreover, the system's ability to predict the RUL helps in scheduling maintenance activities in advance, minimizing downtime and reducing the reliance on expensive corrective repairs. This demonstrates the potential of IoT systems to not only improve operational efficiency but also contribute to substantial economic savings for utility companies [13, 14].

The overall reliability of the IoT-based system (99.7% uptime) further demonstrates its robustness compared to conventional systems, which typically experience lower reliability due to sensor failures or communication issues. This high level of reliability is critical for ensuring the uninterrupted operation of transformers in power grids, where system downtime can have severe consequences for grid stability and supply continuity [15].

Conclusion

The study highlights the transformative potential of integrating IoT-enabled systems into transformer design, providing significant improvements in fault detection, predictive maintenance, and cost efficiency. By embedding sensor networks directly within the transformer, real-time monitoring of key parameters such as temperature, dissolved gases, vibration, and partial discharge becomes a reality. This proactive approach to transformer health monitoring enables the identification of incipient faults, allowing for timely interventions and avoiding costly emergency repairs. The high accuracy (93%) in fault detection achieved by the IoT-based system, as well as the strong correlation ($R^2 = 0.92$) between predicted and actual remaining useful life (RUL), demonstrates the robustness and reliability of this solution in both fault diagnosis and lifespan prediction.

In addition to improved diagnostic capabilities, the study also shows that the implementation of IoT-based predictive maintenance can significantly reduce maintenance costs, with a 30% cost reduction observed compared to traditional maintenance methods. This reduction in costs stems from the early detection of faults, which enables more targeted and less frequent maintenance interventions, reducing the risk of unplanned outages and the need for expensive repairs. Moreover, the system's ability to continuously monitor transformer health improves the overall reliability and uptime, providing utilities with a more dependable infrastructure for power transmission.

Practical recommendations based on these findings include the widespread adoption of IoT-enabled smart transformers, particularly in regions with aging infrastructure or those facing high maintenance costs. Utilities should consider investing in integrated sensor networks during the transformer design phase, rather than retrofitting existing transformers with monitoring systems, to ensure seamless operation and minimize the risk of failure. Furthermore, transformer operators should prioritize training and equipping their maintenance teams with the knowledge and tools needed to interpret the real-time data provided by IoT systems, enabling faster decision-making and more efficient maintenance practices. Additionally, power grid operators should integrate these IoT-based diagnostic tools with predictive analytics platforms to optimize maintenance schedules, improve resource allocation, and extend the lifespan of transformers. By adopting these recommendations, utilities can enhance transformer reliability, reduce costs, and ultimately improve the efficiency of the entire power distribution network. This shift towards predictive maintenance and smart monitoring will likely become a key strategy in the management of critical infrastructure, leading to a more sustainable and cost-effective approach to energy distribution.

References

1. Msane MR, Thango BA, Ogudo KA. Condition monitoring of electrical transformers using the Internet of Things: a systematic literature review. Appl Sci. 2024;14(21):9690-9705.
2. Thinh TNH, Lam PD, Tran HQ, Nguyen TH, Le VT, Bui DK, *et al*. Transformer vibration and noise monitoring system using Internet of Things. IET Res. 2023; DOI:10.1049/cmu2.12585.
3. Zhang C, Li Y, Chen H, Zhao X. Transformer fault diagnosis method using IoT-based monitoring system and an ensemble machine learning. J Parallel Distrib Comput. 2020;145:123-132.
4. Hashemi M, Dikmen S. Real-time condition monitoring of power transformers using the Internet of Things (IoT) and dissolved gas analysis. In: Proceedings of the 2023 ACED Conference; 2023. p. 55-60.
5. Fang Q, Li M, Wang Y, Chen X. A review of power transformer vibration and noise. Electronics. 2024;13(5):968-980.
6. Wang Z, Sharma A. Research on transformer vibration monitoring and diagnosis based on Internet of Things. J Intell Syst. 2020;29(3):401-412.
7. Preprints.org. Condition monitoring in power transformers using IoT [preprint]. 2024. Available from: https://www.preprints.org/
8. SSRN. Transformer health condition monitoring system using the Internet of Things [preprint]. Available from: https://ssrn.com/
9. IJSRT. Internet of Things system for diagnosing power transformer. Int J Sci Res Technol. 2024;9(6):1150-1156.
10. ResearchGate. Smart distribution transformer monitoring and controlling using IoT. 2024. Available

from: https://www.researchgate.net/

11. SciDirect. Condition monitoring of power transmission and transformation: review. SciDirect. 2024;37(2):87-99.
12. Rao S, Kumar V, Singh R, Ahmed S. Enhanced prediction of transformer vibrations under various load conditions. Electr Power Syst Res. 2024;227:108539.
13. Pure UJ. Condition monitoring of electrical transformers using the Internet of Things. University of Johannesburg; 2024. Available from: https://ujcontent.uj.ac.za/
14. IJISRT. Internet of Things system for diagnosing power transformer. Int J Sci Innov Res Technol. 2024;9(4):1210-1215.
15. ResearchGate. Automated real-time transformer health monitoring system using IoT. 2024. Available from: https://www.researchgate.net/