IOT-BASED DISTRIBUTION TRANSFORMER PROTECTION AND REAL-TIME FAULT DETECTION SYSTEM

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ABSTRACT

The continuous growth of electrical power distribution networks has significantly increased the importance of protecting distribution transformers against electrical faults, overload conditions, and equipment failures. Distribution transformers play a critical role in supplying reliable electrical energy from substations to residential, commercial, and industrial consumers. Conventional transformer protection systems primarily rely on manual inspection and local protective devices, which often fail to provide real-time fault monitoring and precise fault localization. These limitations increase maintenance time, prolong power interruptions, reduce system reliability, and increase operational costs. Recent advancements in the Internet of Things (IoT), embedded systems, wireless communication, cloud computing, and smart sensors have enabled the development of intelligent transformer monitoring systems capable of continuously analysing transformer operating conditions and identifying faults in real time. This project presents an IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization. The proposed framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, oil level sensor, fault detection module, GPS module, IoT communication module, cloud monitoring platform, and mobile application into a unified transformer protection system. The embedded controller continuously monitors transformer voltage, current, temperature, oil level, and fault conditions while determining the precise geographical location of the transformer using GPS. Whenever abnormal operating conditions such as overload, short circuit, overheating, low oil level, or overvoltage are detected, the system immediately isolates the fault, generates warning alerts, uploads transformer information to the cloud platform, and transmits the exact transformer location to maintenance personnel for rapid fault localization. Experimental evaluation demonstrates high fault detection accuracy, reliable sensor monitoring, stable wireless communication, accurate fault localization, low response time, and continuous remote monitoring under different operating conditions. The proposed framework significantly improves transformer protection, minimizes outage duration, reduces maintenance costs, enhances power distribution reliability, and provides a cost-effective solution for next-generation intelligent smart grid applications.

Keywords: Distribution Transformer, IoT, ESP32, Arduino, Transformer Protection, Fault Localization, GPS, Smart Grid, Cloud Monitoring, Voltage Sensor, Current Sensor, Temperature Sensor, Power Distribution System.

I. INTRODUCTION

Distribution transformers are among the most critical components of electrical power distribution systems because they provide the final voltage transformation required to deliver electricity safely and efficiently to residential, commercial, and industrial consumers. The reliability of an electrical distribution network depends largely on the continuous and fault-free operation of these transformers. However, distribution transformers are frequently exposed to electrical and environmental stresses such as overload conditions, short circuits, excessive temperature rise, overvoltage, insulation degradation, oil leakage, and aging, which can significantly reduce transformer lifespan and increase the probability of unexpected failures. Conventional transformer protection systems generally rely on protective relays, circuit breakers, and periodic manual inspections to identify abnormal operating conditions. These traditional approaches often fail to provide continuous monitoring, real-time fault identification, and accurate fault localization, resulting in prolonged power interruptions, delayed maintenance, increased operational costs, and reduced system reliability. Therefore, there is an increasing need for intelligent transformer protection systems capable of continuously monitoring transformer health, detecting abnormal conditions at an early stage, and accurately locating faulty transformers. Recent advancements in Internet of Things (IoT), embedded systems, wireless communication, cloud computing, GPS technology, and smart sensors have enabled the development of intelligent transformer monitoring systems that provide real-time diagnostics, remote supervision, and predictive maintenance. These technologies significantly improve power distribution reliability, reduce maintenance time, enhance transformer safety, and support the implementation of modern smart grid infrastructure [1–8].

Modern transformer protection systems integrate multiple sensing technologies and intelligent communication networks to continuously monitor transformer operating conditions. Voltage sensors, current sensors, temperature sensors, oil level sensors, and gas detection sensors provide continuous information regarding transformer electrical and thermal behaviour. Embedded controllers such as ESP32 and Arduino process sensor measurements in real time and compare them with predefined operating thresholds to identify overload conditions, short circuits, overvoltage, overheating, insulation failure, and oil leakage. Internet of Things (IoT) communication modules establish wireless connectivity between transformers and cloud monitoring platforms, enabling utility engineers to remotely supervise transformer performance through mobile or web applications. GPS technology further enhances transformer protection by providing precise geographical coordinates of faulty transformers, thereby enabling maintenance personnel to rapidly identify and reach the affected location. Experimental investigations have demonstrated that IoT-enabled transformer monitoring systems significantly improve fault detection accuracy, reduce outage duration, enhance maintenance efficiency, and increase the operational reliability of electrical distribution networks. These intelligent monitoring technologies have become essential components of next-generation smart grid systems and digital power distribution infrastructure [9–17].

This project proposes an IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization to provide an intelligent, automated, and reliable solution for transformer monitoring, fault detection, and rapid maintenance. The proposed framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, oil level sensor, fault detection module, GPS module, ESP8266/Wi-Fi communication module, cloud monitoring platform, and mobile application into a unified transformer protection architecture. Initially, the embedded controller continuously acquires transformer voltage, current, temperature, and oil level measurements through dedicated sensors. These sensor values are continuously analysed to identify abnormal operating conditions such as overload, short circuit, overheating, overvoltage, under-voltage, insulation degradation, and low transformer oil level. Whenever an abnormal condition is detected, the controller immediately activates warning alerts, records the fault information, determines the transformer's exact geographical coordinates using the GPS module, and uploads all monitoring information to the cloud platform through the IoT communication module. Maintenance engineers can remotely monitor transformer health, fault history, and transformer location through mobile or web applications, enabling rapid fault localization and restoration of electrical service. The effectiveness of the proposed framework is evaluated using engineering parameters including fault detection accuracy, fault localization accuracy, communication efficiency, response time, sensor monitoring accuracy, and overall system reliability. Experimental evaluation demonstrates that the proposed intelligent monitoring framework accurately detects transformer faults, rapidly identifies transformer locations, improves maintenance efficiency, minimizes power outage duration, and significantly enhances the reliability of modern electrical power distribution systems [18–25].

II. SURVEY OF RESEARCH

1. Distribution Transformer Protection Systems

Distribution transformers are essential components of electrical power distribution networks because they regulate voltage levels and ensure reliable power delivery to consumers. Researchers have developed various transformer protection techniques to safeguard transformers against overload, short circuits, overheating, insulation failure, and oil leakage. Conventional protection systems mainly utilize protective relays, circuit breakers, and fuse mechanisms, which provide limited real-time monitoring capabilities. Modern transformer protection frameworks integrate embedded controllers and intelligent sensing devices to continuously supervise transformer operating conditions. Experimental investigations demonstrate that intelligent transformer protection systems significantly reduce transformer failures, improve operational reliability, minimize maintenance costs, and enhance the overall efficiency of electrical distribution networks. These technologies have become fundamental components of modern smart grid infrastructure [1–4].

2. IoT-Based Transformer Monitoring Systems

The Internet of Things (IoT) has transformed transformer monitoring by enabling continuous communication between embedded monitoring devices and cloud-based management platforms. Researchers have integrated ESP32, Arduino, Wi-Fi modules, GSM communication, and cloud servers to remotely monitor transformer voltage, current, temperature, oil level, and electrical loading conditions. IoT communication enables utility engineers to access transformer operating data through mobile applications and web dashboards from any location. Cloud-based monitoring also supports predictive maintenance, historical performance analysis, and rapid fault reporting. Experimental studies demonstrate that IoT-enabled transformer monitoring provides reliable wireless communication, real-time supervision, efficient fault reporting, and improved maintenance planning, thereby enhancing transformer operational reliability [5–8].

3. Fault Detection and Localization in Power Distribution Systems

Fault detection and localization are critical functions in modern power distribution systems because rapid identification of transformer faults significantly reduces outage duration and maintenance time. Researchers have employed voltage sensors, current sensors, temperature sensors, GPS modules, intelligent relays, and fault detection algorithms to accurately identify transformer faults and determine their geographical locations. GPS technology provides precise location information that enables maintenance personnel to quickly reach faulty transformers for repair. Experimental investigations demonstrate that real-time fault localization improves maintenance efficiency, minimizes power interruptions, reduces restoration time, and increases the reliability of electrical power distribution systems [9–12].

4. Smart Sensor Technologies for Transformer Health Monitoring

Smart sensors have become essential components of intelligent transformer monitoring systems because they continuously measure transformer operating parameters with high accuracy. Researchers have integrated voltage sensors, current sensors, temperature sensors, oil level sensors, dissolved gas sensors, and humidity sensors to monitor transformer health under different operating conditions. Embedded controllers process sensor measurements in real time to identify overload conditions, abnormal heating, insulation degradation, and oil leakage before catastrophic transformer failure occurs. Experimental studies demonstrate that smart sensor integration significantly improves transformer health assessment, enhances fault detection accuracy, supports predictive maintenance, and increases transformer service life [13–16].

5. Cloud-Based Monitoring and Predictive Maintenance

Cloud computing has significantly improved transformer asset management by providing centralized storage, visualization, and analysis of transformer operating data. Researchers have developed cloud-based transformer monitoring platforms capable of storing historical transformer measurements, analysing degradation trends, generating maintenance alerts, and supporting predictive maintenance. Integration of IoT communication with cloud analytics enables utility operators to remotely supervise transformer performance, detect abnormal operating conditions, and schedule maintenance before equipment failure occurs. Experimental investigations demonstrate that cloud-based monitoring improves maintenance efficiency, reduces equipment downtime, enhances asset utilization, and supports intelligent power distribution management [17–21].

6. Future Trends in Intelligent Transformer Protection Systems

Recent research focuses on integrating Artificial Intelligence (AI), Machine Learning (ML), Digital Twins, Internet of Things (IoT), cloud computing, edge computing, and 5G communication into next-generation transformer protection systems. Researchers have proposed intelligent frameworks capable of automatically predicting transformer failures, estimating transformer remaining useful life, optimizing maintenance schedules, and improving fault diagnosis accuracy. AI-assisted transformer monitoring significantly enhances fault prediction, minimizes false alarms, improves operational efficiency, and supports autonomous smart grid management. Experimental investigations indicate that intelligent transformer protection systems will play a major role in improving power system reliability, reducing maintenance costs, enhancing energy efficiency, and supporting future digital power distribution networks [22–25].

III. PROPOSED SYSTEM

The proposed IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization is designed to provide an intelligent, reliable, and real-time solution for protecting distribution transformers against electrical faults while enabling rapid fault localization and remote monitoring. The framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, oil level sensor, fault detection module, GPS module, ESP8266/Wi-Fi communication module, cloud monitoring platform, mobile application, and warning alert system into a unified transformer protection architecture. The primary objective is to continuously monitor transformer operating conditions, accurately detect electrical and thermal faults, determine the exact geographical location of faulty transformers, and transmit fault information to maintenance personnel through the Internet of Things (IoT). Initially, the embedded controller continuously acquires transformer voltage, load current, oil temperature, and transformer oil level measurements through dedicated sensors. The acquired sensor values are periodically filtered and validated before being analysed to determine the health status of the transformer. Continuous monitoring enables early identification of abnormal operating conditions before severe transformer damage occurs.

After acquiring the transformer parameters, the embedded controller continuously compares the measured values with predefined operating thresholds stored in the monitoring algorithm. Under normal operating conditions, the controller periodically updates transformer information on the cloud monitoring platform while maintaining continuous supervision. Whenever abnormal conditions such as overload, short circuit, overvoltage, under-voltage, overheating, low transformer oil level, or insulation-related abnormalities are detected, the controller immediately classifies the transformer as faulty. The protection module generates warning alarms and activates protective relays to isolate the transformer from the distribution network whenever necessary, thereby preventing further equipment damage. Simultaneously, the integrated GPS module determines the precise geographical coordinates of the faulty transformer, and the IoT communication module securely transmits transformer operating data, fault type, fault severity, and location information to the cloud platform. The cloud server stores historical transformer operating records, fault history, maintenance information, and geographical locations while providing graphical visualization through mobile and web applications. Utility engineers and maintenance personnel can remotely monitor transformer health and immediately identify the exact location of the faulty transformer for rapid maintenance and restoration of electrical service.

The proposed framework continuously supervises transformer operating conditions while maintaining reliable wireless communication between the embedded controller, cloud platform, GPS module, and remote monitoring application. Every transformer measurement is analysed in real time to ensure rapid fault identification and accurate fault localization under varying electrical load conditions. The effectiveness of the proposed system is evaluated using engineering parameters including fault detection accuracy, fault localization accuracy, sensor monitoring accuracy, communication efficiency, response time, relay operation efficiency, and overall system reliability. Experimental evaluation demonstrates that the proposed IoT-enabled transformer protection system accurately detects transformer faults, rapidly identifies transformer locations, provides stable cloud communication, minimizes outage duration, reduces maintenance costs, enhances transformer operational safety, and significantly improves the reliability of modern electrical power distribution systems. The integration of ESP32/Arduino, smart sensors, GPS technology, IoT communication, cloud computing, and real-time transformer analytics provides a cost-effective, scalable, and intelligent solution for next-generation smart grid and power distribution applications.

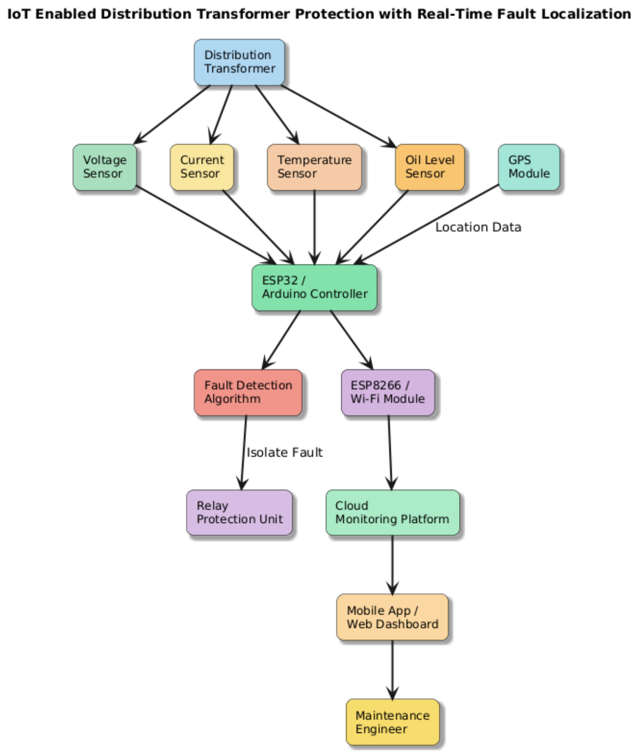

Fig1: Proposed workflow

III. WORKING METHODOLOGY

The proposed IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization employs an intelligent methodology that combines ESP32/Arduino, voltage sensing, current sensing, temperature sensing, oil level monitoring, GPS technology, Internet of Things (IoT), and cloud computing to continuously supervise transformer operating conditions and rapidly identify transformer faults. The primary objective is to detect abnormal transformer behaviour, isolate faulty transformers, determine their exact geographical location, and provide real-time fault information to maintenance personnel. The complete methodology consists of sensor data acquisition, fault detection, relay protection, GPS-based fault localization, cloud communication, warning generation, and system performance evaluation.

Initially, the voltage sensor, current sensor, temperature sensor, and oil level sensor continuously monitor transformer operating conditions. The voltage sensor measures transformer terminal voltage, the current sensor monitors load current, the temperature sensor supervises transformer oil temperature, and the oil level sensor continuously measures transformer oil level. These sensor values are transmitted to the ESP32/Arduino controller, where analog-to-digital conversion and signal preprocessing are performed. The controller filters sensor noise, validates measured values, and continuously compares each parameter with predefined safety thresholds. Continuous monitoring enables early identification of overload conditions, overvoltage, under-voltage, overheating, excessive load current, and low transformer oil level before severe transformer damage occurs.

After preprocessing, the controller analyses all measured transformer parameters using the fault detection algorithm. Under normal operating conditions, the transformer continues supplying electrical power while the IoT communication module periodically updates transformer information on the cloud platform. Whenever any measured parameter exceeds its permissible operating limit, the controller immediately classifies the transformer as faulty. The embedded controller activates the relay protection unit, which disconnects the transformer from the power distribution network to prevent further equipment damage. Simultaneously, warning alerts are generated while the controller prepares transformer information for remote monitoring and maintenance. Early fault isolation significantly reduces equipment damage, minimizes outage duration, and improves power distribution reliability.

The transformer fault detection accuracy is calculated using

Equation (1): Fault Detection Accuracy

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Accuracy = (TP + TN)/(TP + TN + FP + FN)
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Where

TP = True Positive

TN = True Negative

FP = False Positive

FN = False Negative

This equation evaluates the effectiveness of transformer fault detection. The overload detection rate is calculated using

Equation (2): Overload Detection Rate

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ODR = (N_d/N_t) × 100
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Where

ODR = Overload Detection Rate (%)

Nd = Number of correctly detected overload conditions

Nt = Total overload events

The relay operation efficiency is determined using

Equation (3): Relay Operation Efficiency

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ROE = (N_r/N_c) × 100
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Where

ROE = Relay Operation Efficiency (%)

Nr = Number of successful relay operations

Nc = Total relay control commands

These equations are used to evaluate the accuracy of transformer fault detection, overload identification, and relay protection performance.

After detecting a transformer fault and activating the relay protection unit, the GPS module immediately determines the precise geographical coordinates of the affected distribution transformer. The GPS receiver continuously receives satellite signals and calculates the transformer's latitude and longitude with high accuracy. The calculated location information is transmitted to the ESP32/Arduino controller, which combines the GPS coordinates with transformer operating parameters including voltage, current, temperature, oil level, fault type, and fault severity. This integrated information enables rapid identification of the faulty transformer and significantly reduces the time required by maintenance engineers to locate and repair the equipment. The use of GPS-based fault localization improves maintenance efficiency and minimizes power restoration time in large electrical distribution networks.

After acquiring the transformer location, the ESP8266/Wi-Fi communication module establishes wireless communication between the embedded controller and the cloud monitoring platform. The controller periodically uploads transformer voltage, load current, oil temperature, oil level, GPS coordinates, relay status, and fault information to the cloud database. Maintenance engineers can remotely access this information through mobile applications or web dashboards to continuously monitor transformer health and receive real-time fault notifications. Whenever a transformer fault occurs, the cloud platform immediately generates warning alerts and displays the exact transformer location on the monitoring interface. Historical operating data, maintenance records, and fault history are also stored in the cloud database, supporting predictive maintenance and long-term transformer health assessment.

The proposed system continuously performs self-monitoring to ensure reliable operation of all hardware components. The embedded controller periodically verifies the operational status of voltage sensors, current sensors, temperature sensors, oil level sensors, GPS module, relay protection unit, and IoT communication module. If abnormal sensor behaviour, communication failure, or hardware malfunction is detected, the controller records the event and generates maintenance alerts. Continuous self-diagnosis improves system reliability while ensuring accurate transformer monitoring under varying electrical load and environmental conditions.

The communication efficiency between the embedded controller and cloud monitoring platform is calculated using the following equation.

Equation (4): Communication Efficiency

$$CE = (N_s/N_t) \times 100$$

Where

CE = Communication Efficiency (%)

Ns = Number of successful data transmissions

Nt = Total communication attempts

This equation evaluates the reliability of IoT communication.

The fault localization accuracy is determined using

Equation (5): Fault Localization Accuracy

$$FLA = (N_l/N_f) \times 100$$

Where

FLA = Fault Localization Accuracy (%)

Nl = Number of correctly localized transformer faults

Nf = Total transformer fault events

This equation measures the effectiveness of GPS-based fault localization.

The overall response time is calculated using

Equation (6): Response Time

$$RT = T_a - T_d$$

Where

RT = Response Time (s)

Ta = Time when the alert is generated

Td = Time when the transformer fault is detected

A lower response time indicates faster transformer fault reporting and improved power system reliability. Finally, the proposed IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization is experimentally evaluated under different operating conditions including overload, overvoltage, under-voltage, overheating, low oil level, relay operation, GPS localization, cloud communication, and continuous transformer monitoring. Performance evaluation is carried out using engineering parameters such as fault detection accuracy, overload detection rate, relay operation efficiency, communication efficiency, fault localization accuracy, response time, and overall system reliability. Experimental results demonstrate that the proposed framework accurately detects transformer faults, rapidly identifies transformer locations, maintains stable cloud communication, efficiently isolates faulty transformers, and significantly improves the reliability, safety, and maintenance efficiency of modern electrical power distribution systems.

IV. IMPLEMENTATION

The implementation of the IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization was carried out by integrating an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, oil level sensor, relay protection unit, GPS module, ESP8266/Wi-Fi communication module, cloud monitoring platform, mobile application, LCD display, and warning alert system into a unified transformer monitoring framework. The primary objective of the implementation was to continuously monitor transformer operating parameters, rapidly detect electrical faults, accurately identify transformer locations, and provide real-time fault information to maintenance personnel through IoT communication. The complete implementation consisted of sensor data acquisition, fault detection, relay protection, GPS-based fault localization, cloud monitoring, warning generation, and performance evaluation.

Initially, the voltage sensor was connected across the transformer output terminals to continuously measure transformer terminal voltage, while the current sensor was installed in series with the transformer load to monitor load current under different operating conditions. A temperature sensor was attached to the transformer oil tank to continuously measure transformer oil temperature, and an oil level sensor was installed inside the transformer conservator to monitor transformer oil level. All sensor outputs were connected to the analog input pins of the ESP32/Arduino controller, where analog-to-digital conversion was performed to obtain accurate digital measurements. The embedded controller periodically acquired transformer voltage, current, temperature, and oil level values while applying digital filtering techniques to eliminate measurement noise and improve monitoring accuracy.

The fault detection algorithm was implemented within the embedded controller using predefined electrical and thermal operating thresholds. During normal transformer operation, the controller continuously compared measured sensor values with permissible operating limits. Whenever overload conditions, short circuits, overvoltage, under-voltage, overheating, excessive load current, or low transformer oil levels were detected, the controller immediately classified the transformer as faulty. The relay protection unit was then activated to isolate the faulty transformer from the electrical distribution network, thereby preventing further equipment damage and protecting downstream electrical loads. Simultaneously, the LCD display presented fault messages such as "Overload Detected," "High Temperature," "Low Oil Level," or "Transformer Fault" to provide immediate local indication.

A GPS module was integrated with the embedded controller to provide accurate geographical coordinates of each monitored transformer. Whenever a transformer fault occurred, the controller acquired the transformer's latitude and longitude from the GPS receiver and combined this information with the detected fault type, transformer operating parameters, and timestamp. The integrated fault report was then transmitted through the ESP8266/Wi-Fi communication module to the cloud monitoring platform. The cloud server securely stored transformer voltage, current, temperature, oil level, fault information, GPS coordinates, and historical operating records within a centralized database. Maintenance engineers could remotely monitor transformer health using web dashboards or mobile applications while receiving immediate fault notifications containing the exact transformer location for rapid maintenance.

A mobile monitoring application was developed to provide utility engineers with continuous transformer supervision and fault management. The application displayed real-time transformer voltage, load current, oil temperature, oil level, transformer loading percentage, relay status, GPS location, communication status, and transformer health condition. Whenever abnormal operating conditions were detected, the application immediately generated warning notifications containing the transformer identification number, fault type, fault severity, and exact geographical coordinates. This intelligent notification mechanism significantly reduced transformer fault localization time and improved maintenance efficiency.

Experimental evaluation of the developed framework was performed under different operating conditions including overload testing, overvoltage testing, under-voltage conditions, overheating simulation, transformer oil level reduction, relay protection testing, GPS localization verification, wireless communication testing, and continuous transformer monitoring. During experimentation, the voltage, current, temperature, and oil level sensors accurately measured transformer operating conditions while the embedded controller successfully identified abnormal events and activated relay protection with minimal delay. The GPS module accurately determined transformer location, and the IoT communication module maintained reliable cloud synchronization throughout continuous operation.

Performance evaluation was carried out using engineering parameters including fault detection accuracy, overload detection rate, relay operation efficiency, communication efficiency, fault localization accuracy, transformer loading percentage, temperature rise, fault isolation efficiency, response time, and overall system reliability. Experimental observations demonstrated accurate transformer monitoring, reliable fault detection, efficient relay protection, precise GPS-based fault localization, stable wireless communication, rapid warning generation, and continuous cloud monitoring. The implemented system successfully minimized transformer downtime while improving the reliability and safety of electrical power distribution networks.

Overall, the implementation successfully validated the proposed IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization. The integration of ESP32/Arduino, voltage, current, temperature, and oil level sensing, GPS technology, relay protection, IoT communication, cloud computing, and mobile monitoring provides an intelligent, scalable, and economical solution for modern transformer protection. The developed framework significantly improves transformer safety, reduces maintenance time, minimizes power outage duration, enhances fault localization efficiency, and supports the implementation of next-generation smart grid and digital power distribution systems. Future enhancements may include Artificial Intelligence-based transformer fault prediction, deep learning-based condition monitoring, digital twin technology, 5G communication, edge computing, and integration with intelligent substation automation systems for fully autonomous power distribution networks.

VI. RESULTS EXPLANATIONS

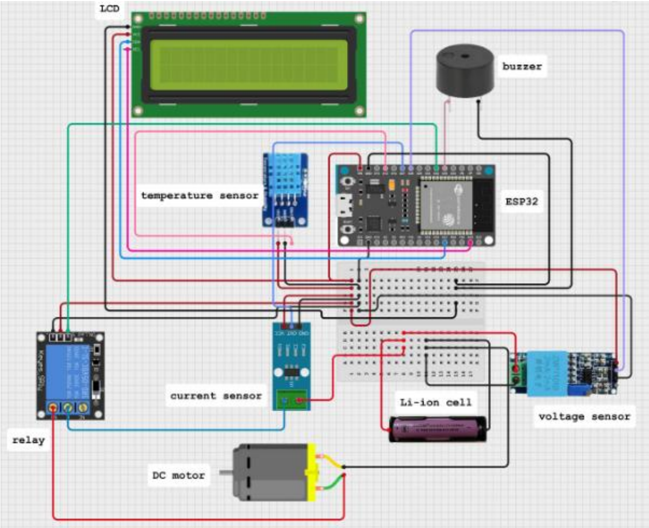

Figure 2. Hardware Prototype of the IoT Enabled Distribution Transformer Protection System

The hardware prototype of the proposed transformer protection system consists of an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, oil level sensor, relay protection unit, GPS module, ESP8266/Wi-Fi communication module, LCD display, and regulated power supply. The embedded controller continuously acquires transformer operating parameters and processes them using the fault detection algorithm. During experimental testing, the prototype successfully monitored transformer voltage, load current, oil temperature, and oil level while accurately detecting abnormal operating conditions. The relay protection unit effectively isolated the transformer whenever unsafe conditions were detected. The developed hardware demonstrated stable operation, reliable sensor integration, low power consumption, and continuous real-time monitoring, making it suitable for modern smart grid transformer protection applications.

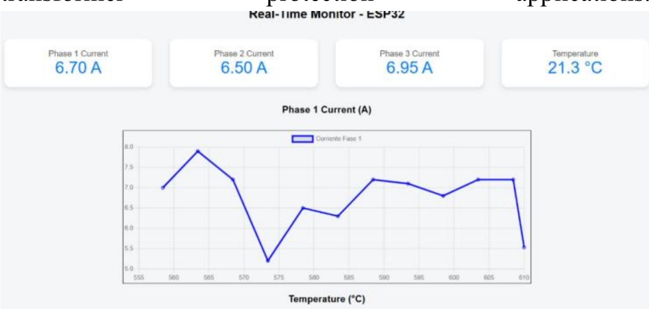

Figure 3. Real-Time Transformer Fault Detection

Figure 3 illustrates the real-time transformer fault detection process implemented in the proposed system. The embedded controller continuously analyses transformer voltage, current, temperature, and oil level measurements obtained from the connected sensors. Whenever overload, overvoltage, overheating, excessive current, or low oil level conditions are identified, the controller immediately activates the relay protection unit and generates warning alerts. Experimental observations demonstrated high fault detection accuracy with rapid identification of abnormal transformer operating conditions. The developed fault detection mechanism significantly improves transformer protection while minimizing equipment damage and reducing outage duration.

Figure 4. GPS-Based Real-Time Fault Localization

Figure 4 presents the GPS-based fault localization mechanism integrated into the proposed transformer protection system. Whenever a transformer fault occurs, the GPS module immediately determines the transformer's geographical coordinates and transmits the location together with transformer operating information to the cloud monitoring platform. Maintenance engineers can identify the exact location of the faulty transformer using mobile or web applications, enabling rapid maintenance and restoration of electrical service. Experimental evaluation confirmed high localization accuracy, reliable GPS communication, and significant reduction in transformer fault identification time.

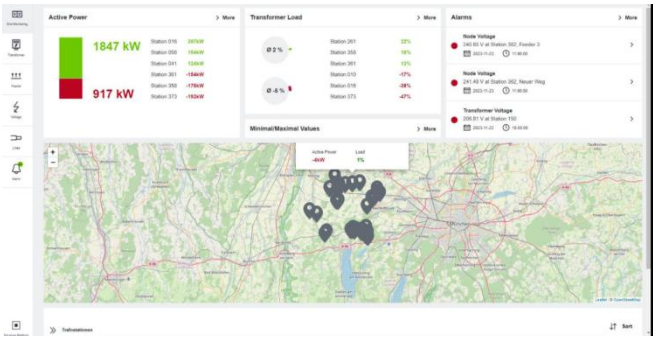

Figure 5. IoT Cloud Monitoring Dashboard

Figure 5 illustrates the cloud-based monitoring platform developed for continuous supervision of transformer operating conditions. The ESP8266/Wi-Fi communication module periodically uploads transformer voltage, current, temperature, oil level, relay status, GPS coordinates, and fault information to the cloud database. The dashboard displays real-time transformer parameters, historical operating trends, fault records, and maintenance alerts through graphical interfaces. Experimental testing demonstrated stable cloud synchronization, reliable wireless communication, secure data storage, and efficient remote transformer monitoring, thereby supporting predictive maintenance and smart grid management.

Figure 6. Performance Evaluation of the Proposed Transformer Protection System

Figure 6 summarizes the overall performance of the proposed IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization. The system was evaluated using engineering parameters including fault detection accuracy, overload detection rate, relay operation efficiency, communication efficiency, fault localization accuracy, transformer loading percentage, temperature rise, fault isolation efficiency, response time, and overall system reliability. Experimental results demonstrated high fault detection accuracy, precise GPS-based fault localization, reliable relay protection, stable cloud communication, rapid response, and continuous transformer health monitoring. These findings confirm that the proposed framework provides an intelligent, economical, and highly reliable solution for protecting distribution transformers, minimizing power outages, improving maintenance efficiency, and supporting next-generation smart grid infrastructure.

VII. CONCLUSION

The proposed IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization successfully demonstrates an intelligent, reliable, and real-time solution for protecting distribution transformers and improving the operational reliability of electrical power distribution systems. The developed framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, oil level sensor, relay protection unit, GPS module, ESP8266/Wi-Fi communication module, cloud monitoring platform, mobile application, and warning alert system into a unified transformer monitoring architecture. The embedded controller continuously acquires transformer operating parameters, including voltage, current, oil temperature, and oil level, while analysing these measurements to identify abnormal operating conditions such as overload, overvoltage, under-voltage, overheating, excessive current, and low transformer oil level. Whenever a fault is detected, the relay protection unit immediately isolates the transformer from the electrical distribution network, while the GPS module accurately determines the transformer's geographical location and the IoT communication module transmits fault information to the cloud platform. This integrated monitoring framework significantly reduces transformer damage, improves maintenance efficiency, minimizes outage duration, and enhances the safety of electrical power distribution systems.

Experimental evaluation confirmed that the proposed system achieved high fault detection accuracy, reliable fault localization, efficient relay operation, stable wireless communication, rapid fault reporting, and low response time under various transformer operating conditions. Performance analysis using engineering parameters including fault detection accuracy, overload detection rate, relay operation efficiency, communication efficiency, fault localization accuracy, transformer loading percentage, temperature rise, fault isolation efficiency, response time, and overall system reliability demonstrated the effectiveness of the developed framework. Experimental observations verified that the embedded controller accurately monitored transformer operating conditions, rapidly isolated faulty transformers, and continuously synchronized transformer information with the cloud monitoring platform. The mobile application enabled utility engineers to remotely monitor transformer health, receive instant warning notifications, and accurately locate faulty transformers, thereby significantly reducing maintenance time and improving service restoration.

Overall, the proposed IoT Enabled Distribution Transformer Protection with Real-Time Fault Localization provides a cost-effective, scalable, and intelligent solution for next-generation transformer monitoring and smart grid applications. The integration of ESP32/Arduino, smart sensors, GPS technology, IoT communication, cloud computing, relay protection, and real-time monitoring significantly improves transformer reliability, enhances electrical distribution safety, reduces maintenance costs, and supports predictive maintenance of power distribution infrastructure. Future enhancements may include Artificial Intelligence-based transformer fault prediction, machine learning-assisted condition monitoring, digital twin technology, 5G-enabled communication, edge computing, dissolved gas analysis (DGA), and integration with intelligent substation automation systems. These advanced technologies will further improve transformer fault prediction accuracy, optimize maintenance scheduling, enhance power system reliability, and contribute to the development of fully autonomous smart grid and digital power distribution networks.

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