Transformer Winding Alert & Temperature Control Hub (T-WATCH)

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Abstract- *T-WATCH (Transformer Winding Alert Temperature Control Hub) is an IoT-based transformer monitoring and control system designed to improve reliability, safety, and operational efficiency. The system uses a NodeMCU ESP32s to continuously monitor key transformer parameters such as temperature, voltage, and current through dedicated sensors. Real-time processing enables power calculation, fault de-tection, and automatic relay tripping when predefined thresholds are exceeded, ensuring fail-safe operation. The system employs MQTT-based bidirectional communication through HiveMQ Cloud, enabling real-time data transmission and remote control functions such as transformer trip and reset. A cross-platform React Native application provides live monitoring, data visual-ization, diagnostic analysis, and system health assessment. The application also supports offline data storage, cloud synchroniza-tion via Firebase, and PDF report generation for maintenance purposes. By integrating real-time sensing, cloud communication, and intelligent diagnostics, T-WATCH offers a scalable and cost-effective solution for modern transformer management. The system enhances fault detection, enables predictive maintenance, and contributes to improved asset performance and lifecycle management.*

Keywords: Assistive Technology, Object Detection, Computer Vision, Indoor Navigation, College Campus Assistance

I. INTRODUCTION

Electrical transformers are essential elements of modern power distribution networks, ensuring the efficient transmis-sion and regulation of electrical energy across industrial, commercial, and utility sectors. Since transformers operate continuously under varying electrical and environmental con-ditions, they are susceptible to issues such as thermal stress, insulation deterioration, and electrical faults. Transformer fail-ures can result in equipment damage, extended power outages, safety hazards, and significant economic losses. Therefore, continuous monitoring of transformer health is crucial for maintaining reliability and preventing unexpected failures.

Conventional transformer monitoring approaches primarily depend on periodic manual inspections and standalone protection devices such as relays and circuit breakers. While these methods provide a basic level of protection, they lack real-time visibility, remote accessibility, and predictive maintenance capabilities. Most traditional systems detect faults only after they occur, making them reactive rather than proactive. With the emergence of Industry 4.0 and smart-grid technologies, there is an increasing demand for intelligent monitoring solutions capable of real-time sensing, analysis, and control.

To address these limitations, this paper presents T-WATCH (Transformer Winding Alert Temperature Control Hub), an IoT-enabled transformer monitoring and management system. The proposed solution integrates embedded hardware, cloud communication, and mobile-based software to provide real-time monitoring, predictive diagnostics, and secure remote control. The primary objective is to improve operational efficiency while reducing downtime and maintenance costs.

The hardware platform is built around the NodeMCU ESP32S, which functions as both the processing and communication unit. Various sensors are connected to monitor important transformer parameters, including temperature, voltage, and current. These parameters are continuously sampled and processed in real time. The embedded firmware performs data acquisition, transmission, power estimation, and threshold-based fault detection to ensure reliable operation.

Whenever abnormal operating conditions such as excessive temperature, overcurrent, or voltage irregularities are detected, the system automatically activates a relay mechanism to dis-connect the transformer. This autonomous protection feature minimizes the risk of equipment damage and enables fail-safe operation without requiring immediate human intervention.

A key feature of the proposed system is its bidirectional communication capability implemented through the MQTT protocol using HiveMQ Cloud as the message broker. The ESP32S publishes real-time sensor readings to predefined topics while simultaneously subscribing to control topics for receiving user commands. This architecture enables operators to monitor transformer status remotely and perform actions such as tripping or resetting the transformer through secure control mechanisms.

On the software side, the T-WATCH application is developed using React Native with Expo and serves as the primary user interface. The application provides an interactive dashboard displaying live sensor values, graphical trends, and system status indicators. To enhance decision-making, the software calculates advanced performance metrics such as efficiency, power losses, voltage regulation, and transformer health indices. These insights help users identify potential issues before they develop into critical failures.

In addition to monitoring functions, the application offers alert notifications, user authentication, access control, and secure remote operation with built-in safety confirmations. The system also supports offline data storage through local databases, allowing uninterrupted operation in areas with lim-ited internet connectivity. Once connectivity is restored, the stored data is automatically synchronized with cloud services for long-term storage and analysis. Furthermore, the platform can generate detailed reports to assist in maintenance planning and performance evaluation.

Overall, T-WATCH provides an intelligent and scalable approach to transformer monitoring by combining IoT-based sensing, embedded processing, cloud connectivity, and user-focused application design. Through real-time monitoring, automated protection, predictive maintenance, and remote ac-cessibility, the system improves transformer reliability, reduces maintenance costs, and supports the transition toward smarter and more sustainable power distribution infrastructures.

II. RELATED WORK

Related Work

Transformer monitoring and protection systems have be-come increasingly important in modern power distribution networks due to the growing demand for reliable and uninter-rupted electricity supply. Traditional transformer maintenance methods are generally based on periodic inspections, which often fail to detect faults at an early stage. To overcome these limitations, researchers have developed various IoT-based monitoring systems that enable real-time data acqui-sition, remote supervision, and predictive maintenance.

Several studies have utilized microcontroller platforms such as Arduino, ESP8266, and ESP32 for monitoring transformer parameters including temperature, voltage, current, oil level, and humidity. These systems collect sensor data and trans-mit it to cloud platforms through wireless communication technologies. Real-time monitoring helps operators identify abnormal conditions before they develop into severe faults, thereby reducing downtime and maintenance costs.

Recent research has focused on integrating Internet of Things (IoT) technologies with transformer health monitoring. IoT-based solutions provide continuous access to transformer operating data through web dashboards and mobile applica-tions. Many systems employ cloud services such as ThingS-peak, Blynk, Firebase, and MQTT brokers for data storage and communication. These platforms allow utility personnel to monitor transformer conditions remotely and receive instant alerts when critical parameters exceed safe limits.

A number of researchers have also explored the use of MQTT (Message Queuing Telemetry Transport) due to its lightweight architecture and suitability for low-bandwidth industrial environments. MQTT enables efficient real-time communication between monitoring devices and cloud servers while minimizing network overhead. Studies have demon-strated that MQTT-based systems provide faster data transmis-sion and improved scalability compared to traditional HTTP-based approaches.

In addition to monitoring, several transformer protection systems incorporate automatic control mechanisms. These sys-tems use relays to disconnect transformers during overloading, overheating, or fault conditions. Automatic protection reduces the risk of equipment damage and enhances operational safety. However, many existing solutions offer only local protection and limited remote control capabilities.

Mobile application-based transformer monitoring has gained popularity in recent years. Researchers have developed An-droid applications that display live transformer data, histori-cal trends, and alarm notifications. While these applications improve accessibility, many lack advanced diagnostic features such as efficiency analysis, voltage regulation assessment, loss calculation, and transformer health scoring.

The proposed T-WATCH (Transformer Winding Alert Tem-perature Control Hub) system extends existing research by combining real-time monitoring, intelligent diagnostics, re-mote control, and cloud-based communication within a single platform. Unlike conventional systems, T-WATCH utilizes an ESP32-based monitoring unit, MQTT communication through HiveMQ Cloud, and a cross-platform React Native application. The system not only monitors transformer parameters but also performs automated protection, health analysis, report generation, and offline data synchronization. These enhance-ments contribute to improved transformer reliability, predictive maintenance, and efficient asset management in modern power distribution environments.

III. PROPOSED SYSTEM

Proposed System

The proposed T-WATCH (Transformer Winding Alert Tem-perature Control Hub) system is an IoT-based transformer monitoring and control solution designed to improve the reli-ability, safety, and operational efficiency of power distribution systems. The system integrates embedded hardware, cloud communication, and a mobile application to provide real-time monitoring, automated protection, remote control, and performance analysis of transformers. The primary objective of the proposed system is to continuously monitor critical transformer parameters, detect abnormal operating conditions, and enable timely intervention to prevent equipment failures and service interruptions.

The hardware component of the system is built around the NodeMCU ESP32S microcontroller, which serves as the central processing and communication unit. Various sensors are connected to the ESP32S to measure important trans-former parameters such as temperature, voltage, and current.

These parameters are continuously sampled and processed to determine the operational condition of the transformer. The collected sensor data is converted into meaningful electrical values through calibration and processing techniques, enabling accurate monitoring of transformer performance.

To ensure equipment safety, the system incorporates an automated protection mechanism using a relay module. The relay is controlled by the ESP32S and operates based on pre-defined threshold values. Whenever abnormal conditions such as excessive temperature, overcurrent, or voltage fluctuations are detected, the controller automatically activates the relay to disconnect the transformer from the supply. This protection mechanism minimizes the risk of transformer damage and enhances operational safety even when network connectivity is unavailable.

A major feature of the proposed system is its cloud-enabled communication architecture based on the MQTT protocol. HiveMQ Cloud is utilized as the MQTT broker to establish secure and efficient communication between the hardware module and the mobile application. The ESP32S periodi-cally publishes real-time sensor readings to dedicated MQTT topics, while simultaneously subscribing to control topics for receiving user commands. This publish-subscribe model enables seamless bidirectional communication, allowing users to monitor transformer conditions and perform remote control operations from any location.

The user interface of the system is developed using Re-act Native and Expo, enabling deployment across Android, iOS, and web platforms. The T-WATCH mobile application provides a real-time dashboard displaying temperature, volt-age, current, power consumption, and overall system status through graphical charts and indicators. The application also offers advanced analytical features by calculating transformer efficiency, power losses, voltage regulation, and health scores. These performance indicators assist users in evaluating trans-former conditions and identifying potential issues before they become critical failures.

To improve reliability under varying network conditions, the system supports offline data storage using local databases. Sen-sor data collected during connectivity interruptions is stored locally and automatically synchronized with cloud services once internet access is restored. Additionally, the system gen-erates detailed reports in PDF format, enabling maintenance personnel to review historical performance data, analyze fault events, and plan preventive maintenance activities.

By combining real-time sensing, automated protection, se-cure cloud communication, intelligent analytics, and user-friendly mobile access, the proposed T-WATCH system pro-vides a comprehensive solution for modern transformer moni-toring and management. The system not only enhances opera-tional reliability and safety but also supports predictive main-tenance and efficient asset management, making it suitable for smart power distribution applications.

IV. SYSTEM ARCHITECTURE

Hardware Components

The T-WATCH (Transformer Winding Alert Temperature Control Hub) system is built using a collection of sensors, control devices, and communication modules that work to-gether to monitor transformer operating conditions in real time. The hardware architecture is designed to provide accurate measurement of critical parameters such as temperature, volt-age, and current while ensuring reliable protection and remote monitoring capabilities.

1. ESP32 DevKit V1 / NodeMCU ESP32s

The ESP32 DevKit V1 serves as the central processing unit of the T-WATCH system. It is a powerful microcontroller equipped with dual-core processing capabilities, integrated Wi-Fi, and Bluetooth connectivity. The ESP32 collects data from various sensors, processes the information, and communicates with cloud services through the MQTT protocol.

The microcontroller continuously monitors transformer pa-rameters and compares them with predefined threshold values. When abnormal conditions such as overheating or overcurrent are detected, the ESP32 activates protective mechanisms by controlling the relay module and buzzer. Its built-in wireless communication capability allows seamless transmission of real-time data to HiveMQ Cloud and synchronization with the T-WATCH mobile application.

2. DS18B20 Temperature Sensor

The DS18B20 is a digital temperature sensor used to monitor the transformer winding or oil temperature. It offers high accuracy and supports one-wire communication, reducing wiring complexity and improving reliability.

The sensor measures temperature continuously and sends digital readings directly to the ESP32. These measurements help identify overheating conditions that may indicate exces-sive load, insulation degradation, or cooling system failure. The temperature data is also used for trend analysis and predictive maintenance within the mobile application.

3. ZMPT101B Voltage Sensor Module

The ZMPT101B is an AC voltage sensing module designed for accurate measurement of transformer output voltage. It pro-vides electrical isolation between the high-voltage transformer circuit and the low-voltage monitoring system, ensuring safety during operation.

The sensor converts AC voltage into a proportional analog signal that can be processed by the ESP32. By continuously monitoring voltage levels, the system can detect overvoltage, undervoltage, and voltage fluctuations that may affect trans-former performance and connected equipment. The collected voltage data is further utilized to calculate power, efficiency, and voltage regulation parameters.

4. ACS712 Current Sensor

The ACS712 is a Hall-effect-based current sensor used to measure load current flowing through the transformer. It provides electrical isolation and delivers an analog output proportional to the measured current.

The sensor enables real-time current monitoring and helps identify overload conditions. The measured current values are processed by the ESP32 to calculate power consumption and transformer loading conditions. By tracking current variations, the system can detect abnormal operating patterns and initiate protective actions when necessary.

5. SCT-013 Current Transformer Sensor

The SCT-013 is a non-invasive current transformer sensor used for additional current measurement and load monitoring. It can measure AC current without requiring direct electrical contact with the conductor, making installation safer and more convenient.

The sensor clamps around the conductor and generates a proportional signal based on the current flowing through it. This feature is particularly useful for industrial transformer ap-plications where isolation and safety are critical requirements. The collected data supports load analysis and transformer health assessment.

6. Relay Module

The relay module acts as the primary protection and control device within the T-WATCH system. It enables the ESP32 to control high-voltage transformer circuits using low-voltage

control signals.

When sensor readings exceed predefined safety thresholds, the ESP32 automatically energizes or de-energizes the relay to disconnect the transformer from the load. This protective action helps prevent equipment damage, overheating, and potential electrical hazards. The relay can also be controlled remotely through the mobile application for maintenance and emergency operations.

7. Buzzer

The buzzer serves as an audible alarm system for local fault indication. It provides immediate notification whenever abnormal transformer conditions are detected.

When critical events such as excessive temperature, overcur-rent, or system faults occur, the ESP32 activates the buzzer to alert nearby operators. This ensures rapid response even when network connectivity is unavailable or the mobile application is not being actively monitored.

8. 16×2 LCD Display

The 16×2 LCD display provides a local human-machine interface for real-time visualization of transformer parameters. It displays important information such as temperature, voltage, current, power status, and fault conditions.

The LCD enables operators to monitor system performance directly at the installation site without requiring a smartphone or internet connection. It improves usability and assists tech-nicians during maintenance and troubleshooting activities.

Overall, these hardware components collectively form a robust and intelligent monitoring platform capable of deliver-ing real-time transformer diagnostics, protection, and remote management. Their integration ensures reliable operation, en-hanced safety, and improved transformer asset management.

V. METHODOLOGY AND IMPLEMENTATION

Methodology

The T-WATCH (Transformer Winding Alert and Tempera-ture Control Hub) Transformer Monitoring System was de-veloped through a systematic approach involving hardware

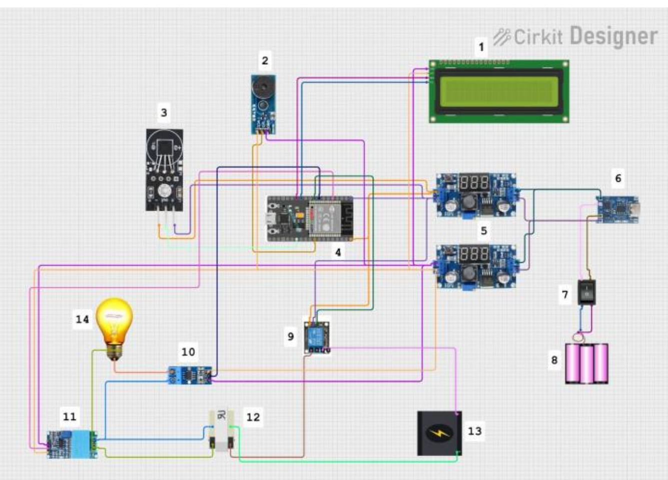

Fig. 1. System Architecture of T-WATCH (Transformer Winding Alert & Temperature Control Hub). (1) 16×2 LCD Display, (2) Buzzer Module, (3) Temperature Sensor Module, (4) ESP32 Development Board, (5) DC-DC Buck Converter Modules, (6) TP4056 Battery Charging Module, (7) Power Switch, (8) Lithium-Ion Battery Pack, (9) Relay Module, (10) AC Load Control Relay, (11) AC-DC Power Supply Module, (12) Current Sensor, (13) Mobile Monitoring Interface (MQTT/Blynk Dashboard), and (14) Transformer Load/Lamp. design, firmware development, wireless communication, mobile application integration, and cloud-based monitoring. The proposed methodology consists of interconnected stages that enable real-time monitoring, remote control, data logging, and intelligent analysis of transformer operating conditions. The complete system architecture is designed to ensure reliability, scalability, and efficient communication between hardware and software components.

1. System Architecture Design

The proposed T-WATCH system follows a three-layer ar-chitecture comprising the Hardware Layer, Messaging Layer, and Application Layer. The Hardware Layer consists of an ESP32-based monitoring unit integrated with sensors, relays, and display modules for data acquisition and local control. The Messaging Layer employs the MQTT protocol using the HiveMQ Cloud platform to facilitate secure and lightweight bidirectional communication between the monitoring device and the mobile application. The Application Layer includes the T-WATCH mobile application developed using React Native, which provides users with a user-friendly interface for monitoring transformer parameters and controlling system operations remotely.

This layered architecture enhances modularity and flexibility, allowing future expansion of system functionalities without affecting existing components.

2. Hardware Implementation

The hardware subsystem is centered around the ESP32 microcontroller, which serves as the primary processing and communication unit. Various sensors are interfaced with the ESP32 to continuously monitor transformer operating condi-tions.

A temperature sensor is utilized to measure winding and ambient temperature levels. Voltage sensing circuits monitor input and output voltage values, while a current sensor measures load current flowing through the transformer. These sensors provide real-time electrical and thermal information essential for transformer condition assessment.

The analog outputs from the sensors are connected to the ESP32 Analog-to-Digital Converter (ADC) pins. The acquired signals are processed using calibration equations to convert raw sensor readings into meaningful engineering units such as volts, amperes, and degrees Celsius.

A relay module is integrated into the system to perform protection and control functions. The relay operates using active-low logic and can disconnect or reconnect the trans-former supply whenever abnormal operating conditions are detected or when remote commands are received from the mobile application.

For local monitoring, a 16×2 I2C LCD display is connected to the ESP32. The display provides instant visualization of important parameters such as temperature, voltage, current, and system status, enabling users to monitor transformer performance directly at the installation site.

3. Firmware Development

The firmware is developed using the Arduino framework and programmed in Embedded C/C++. The firmware performs continuous monitoring, data processing, communication man-agement, and protection operations.

Sensor readings are acquired periodically at predefined in-tervals. The collected data is processed to calculate additional parameters such as power consumption and transformer oper-ating conditions. Threshold values are predefined for critical parameters including temperature, voltage, and current.

Whenever a parameter exceeds its permissible limit, the firmware automatically initiates protective actions by activat-ing the relay mechanism. This ensures the transformer is pro-tected against overheating, overload, and abnormal electrical conditions.

The ESP32 establishes a secure Wi-Fi connection and authenticates itself with the HiveMQ MQTT broker using valid credentials. Through MQTT communication, the device periodically publishes sensor readings while simultaneously subscribing to control topics for receiving remote commands. Incoming MQTT messages are decoded and interpreted by the firmware. Depending on the command received, the relay state is modified accordingly, enabling remote trip and restore functionality.

4. Communication Layer (MQTT Implementation)

The communication infrastructure of the T-WATCH sys-tem is based on the Message Queuing Telemetry Transport (MQTT) protocol. MQTT was selected due to its lightweight nature, low bandwidth requirements, and suitability for Inter-net of Things (IoT) applications.

HiveMQ Cloud serves as the central MQTT broker respon-sible for managing message exchanges between the ESP32 device and the mobile application. Separate MQTT topics are defined for sensor data transmission and control command exchange. Sensor measurements are periodically published to data topics, while remote control instructions are transmitted through command topics.

The publish-subscribe architecture enables real-time bidi-rectional communication. This mechanism allows users to observe transformer conditions instantly and perform remote control actions whenever required. To ensure secure com-munication, Transport Layer Security (TLS) encryption and authenticated access mechanisms are implemented.

5. Mobile Application Development

The T-WATCH mobile application is developed using React Native and Expo to provide cross-platform compatibility and enhanced user experience. The application serves as the pri-mary interface between users and the transformer monitoring system.

The dashboard presents real-time transformer parameters using graphical elements such as gauges, charts, and status indicators. Through MQTT subscriptions, the application re-ceives live sensor updates from the ESP32 and displays them dynamically.

The application also provides remote control capabilities, allowing users to issue trip and restore commands. Confirma-tion prompts are implemented to prevent accidental operations. Advanced analytics modules calculate transformer efficiency, power losses, and health scores based on collected sensor data. For improved reliability, historical records are stored locally using AsyncStorage or SQLite databases. Data synchroniza-tion mechanisms ensure that information is uploaded to cloud storage whenever network connectivity becomes available.

Firebase Authentication is incorporated to provide secure user access and account management.

6. Data Logging and Reporting

The system continuously records transformer operating data both locally and on cloud servers. Historical records are or-ganized and processed to generate daily, weekly, and monthly performance reports in PDF format.

These reports provide valuable insights into transformer be-havior, operational trends, fault occurrences, and maintenance requirements. The generated reports support predictive main-tenance strategies and assist utility personnel in evaluating transformer performance over extended periods.

7. System Workflow

The operational workflow begins with sensor data acquisi-tion from the transformer environment. The ESP32 processes the acquired data, performs threshold analysis, and publishes the information to the MQTT broker. The mobile application subscribes to these updates and displays the information in real time. Users can issue remote commands through the application, which are transmitted back to the ESP32 via MQTT. The controller executes the requested actions through relay operations while simultaneously storing operational data for future analysis and reporting.

8. Testing and Validation

Comprehensive testing was conducted to evaluate the func-tionality and reliability of the proposed system. Individual modules, including sensors, relay circuits, communication interfaces, and display units, were tested independently. End-to-end testing was performed to verify seamless real-time monitoring and remote control functionality.

Various fault scenarios, including over-temperature, over-current, and abnormal voltage conditions, were simulated to validate the protection mechanisms. Experimental results confirmed that the system successfully detects abnormal oper-ating conditions, communicates data efficiently, and responds promptly to control commands, thereby ensuring effective transformer monitoring and protection.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

Experimental Results and Analysis Experimental Setup

The proposed T-WATCH (Transformer Winding Alert and Temperature Control Hub) system was implemented and tested using a NodeMCU ESP32S microcontroller integrated with temperature, voltage, and current sensing modules. The system was connected to the HiveMQ Cloud MQTT broker through a Wi-Fi network, enabling real-time communication between the hardware device and the T-WATCH mobile application developed using React Native.

A relay module was incorporated to provide automatic protection and remote switching capabilities, while a 16×2 LCD display was used for local visualization of operating parameters. Various operating conditions, including normal operation and fault scenarios, were simulated to evaluate system performance, communication reliability, and protection effectiveness.

Sensor Data Acquisition Performance

The first phase of testing focused on verifying the accu-racy and stability of sensor measurements. The temperature, voltage, and current sensors continuously collected real-time transformer parameters and transmitted them to the ESP32 controller.

Experimental observations showed that the sensors provided stable and consistent readings throughout the testing period. The calibration procedures successfully converted raw analog values into meaningful engineering units. Temperature mea-surements accurately reflected environmental and operating conditions, while voltage and current sensors effectively mon-itored electrical parameters under varying load conditions.

The average sensor update interval remained within the de-signed sampling rate, ensuring continuous monitoring without significant data loss. The obtained results confirmed that the sensing subsystem was capable of providing reliable input data for further processing and decision-making.

MQTT Communication Performance

The communication layer was evaluated by analyzing the performance of MQTT-based data transmission between the ESP32 device and the mobile application. Sensor values were periodically published to predefined MQTT topics, while remote control commands were transmitted through separate control topics.

The system demonstrated successful real-time bidirectional communication throughout the testing period. Sensor readings published by the ESP32 were received and displayed on the mobile application with minimal delay. Similarly, control com-mands issued from the application were successfully delivered to the hardware module and executed without communication failures.

The lightweight nature of the MQTT protocol resulted in efficient network utilization and reduced communica-tion overhead. Even during continuous operation, the sys-tem maintained stable connectivity with the HiveMQ Cloud broker. Automatic reconnection mechanisms implemented in the firmware successfully restored communication whenever temporary network interruptions occurred.

The experimental results verified that MQTT is a suitable communication protocol for IoT-based transformer monitoring applications requiring low latency and reliable message deliv-ery.

Mobile Application Performance

The T-WATCH mobile application was tested for functional-ity, responsiveness, and user interaction. Real-time sensor data received through MQTT subscriptions were displayed using interactive dashboards, gauges, and status indicators.

The application successfully visualized live transformer parameters without noticeable delays. Historical records were stored correctly and could be accessed for trend analysis. The implemented Firebase authentication mechanism ensured secure user login and controlled access to system resources.

Remote control functionality was also validated. Users were able to issue trip and restore commands through the application interface, and confirmation dialogs prevented accidental oper-ations. The mobile application maintained stable performance across multiple testing sessions and demonstrated effective integration with the hardware system.

Protection Mechanism Validation

One of the primary objectives of the T-WATCH system is transformer protection. Therefore, several fault conditions were intentionally simulated to verify the effectiveness of the protection algorithms.

Over-Temperature Condition

The temperature sensor value was gradually increased be-yond the predefined threshold. Once the threshold was ex-ceeded, the ESP32 firmware successfully detected the abnor-mal condition and activated the relay protection mechanism. The transformer supply was disconnected automatically, and warning notifications were generated on both the LCD display and mobile application.

Overload Condition

An increased load current was applied to simulate trans-former overloading. The current sensor detected the abnormal rise in current and transmitted the information to the controller. The protection logic responded immediately by triggering the relay and isolating the load from the transformer supply.

Voltage Abnormalities

Various voltage fluctuation conditions were introduced dur-ing testing. The system successfully monitored voltage vari-ations and generated alerts whenever the measured values approached unsafe operating limits. This capability enables early detection of potential transformer faults and improves operational reliability.

The successful execution of all protection scenarios con-firmed the effectiveness of the implemented threshold-based protection strategy.

System Reliability Analysis

Long-duration testing was conducted to evaluate system reliability and operational stability. The system operated continuously for extended periods while monitoring sensor values and maintaining MQTT communication.

The results indicated stable operation without significant performance degradation. Sensor measurements remained consistent, communication links remained active, and data synchronization between the hardware device and mobile application functioned correctly. The implemented error-handling and reconnection routines significantly improved system ro-bustness under varying network conditions.

Overall Performance Evaluation

The experimental results demonstrate that the proposed T-WATCH system effectively achieves real-time transformer monitoring, remote control, automated protection, and cloud-based data management. The integration of ESP32, MQTT communication, HiveMQ Cloud, and the React Native mobile application provides a reliable and scalable solution for transformer condition monitoring.

The system successfully detected abnormal operating conditions, executed protective actions with minimal response time, and provided users with continuous access to transformer information through a user-friendly mobile interface. These results validate the feasibility of the proposed approach and confirm its suitability for practical transformer monitoring and protection applications in modern smart power systems.

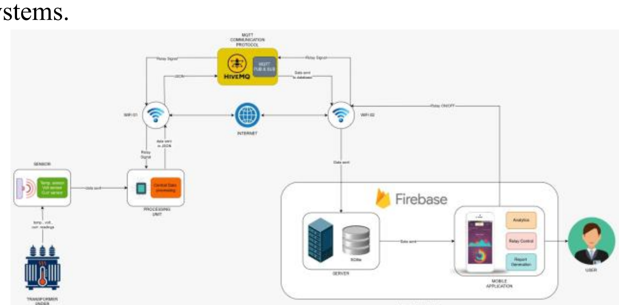

Fig. 2. MQTT-Based Communication Architecture Using HiveMQ Cloud

Fig. ?? illustrates sample detection outputs of the proposed system. The model successfully identifies multiple objects such as chairs, desks, and doors in complex indoor scenes. The bounding boxes and class labels demonstrate the model's ability to handle overlapping objects and varying perspectives. The qualitative results show that the model performs well in structured indoor environments with moderate lighting condi-tions. It effectively detects frequently occurring objects such as chairs and desks with high confidence. Additionally, the system demonstrates robustness in detecting multiple instances of the same object class within a single frame.

However, minor inconsistencies were observed in cases of occlusion and low contrast between objects and background surfaces. These challenges are typical in real-world deploy-ments and can be further mitigated through dataset expansion and augmentation.

The OCR module, implemented using PaddleOCR, was evaluated on text present in classroom labels, signboards, and notices.Performance variations were primarily influenced by factors such as motion blur, skewed text orientation, and illumination changes. Preprocessing techniques such as image enhancement and noise reduction contributed to improved recognition accuracy.

The overall system was evaluated for real-time performance by measuring inference time across modules. The object de-tection module demonstrated efficient processing suitable for real-time applications, while OCR introduced slight additional latency due to text extraction complexity.

The average end-to-end response time was observed to be approximately 1–2 seconds, which is acceptable for assistive navigation systems.

The experimental results demonstrate that the proposed system is capable of accurately detecting indoor obstacles and extracting textual information in real time. The integration of a custom-trained detection model significantly improves performance for environment-specific objects compared to generic models.

The results validate the effectiveness of the system in assist-ing visually impaired users by providing reliable environmen-tal awareness. Future improvements may include expanding the dataset, optimizing model performance, and enhancing robustness under diverse environmental conditions.

VII. DISCUSSION

Discussion

The proposed T-WATCH (Transformer Winding Alert Tem-perature Control Hub) system demonstrates the effectiveness of integrating IoT technologies, embedded systems, cloud communication, and mobile applications for intelligent trans-former monitoring and management. The developed system successfully addresses several limitations associated with con-ventional transformer monitoring methods, particularly the lack of real-time visibility, remote accessibility, and predictive maintenance capabilities.

One of the key strengths of the system is its ability to continuously monitor critical transformer parameters such as temperature, voltage, and current. By utilizing the NodeMCU ESP32S microcontroller and dedicated sensing modules, the system provides real-time acquisition of operational data. Continuous monitoring allows abnormal conditions to be de-tected at an early stage, reducing the possibility of severe equipment damage and unexpected service interruptions. The implementation of threshold-based protection further enhances system reliability by automatically disconnecting the trans-former whenever unsafe operating conditions are detected.

The MQTT-based communication architecture plays a significant role in achieving efficient and reliable data exchange. Through the publish-subscribe model implemented using HiveMQ Cloud, sensor readings are transmitted to the mobile application with minimal delay while allowing control commands to be sent back to the hardware module. This bidirectional communication capability enables remote supervision and control, which is particularly beneficial in industrial environments where transformers may be installed in locations that are difficult to access frequently.

The mobile application developed using React Native provides an intuitive and user-friendly interface for system in-teraction. Real-time visualization of transformer parameters through charts, gauges, and status indicators improves situa-tional awareness and enables operators to make informed deci-sions. The inclusion of advanced performance metrics such as efficiency, power losses, voltage regulation, and transformer health scores further enhances the analytical capabilities of the system. These features allow users to evaluate transformer performance beyond basic monitoring and support condition-based maintenance strategies.

Another significant advantage of the proposed system is its support for offline data storage and cloud synchronization. In practical deployment scenarios, network connectivity may not always be available. The ability to store data locally and synchronize it automatically when connectivity is restored ensures uninterrupted monitoring and prevents data loss. Fur-thermore, automated report generation simplifies maintenance documentation and assists engineers in tracking long-term performance trends.

Testing and validation results indicate that the system per-forms reliably under normal and fault conditions. Simulated over-temperature and over-current scenarios successfully trig-gered the protection mechanism, confirming the effectiveness of the relay-based control strategy. End-to-end communication tests also verified the accuracy of data transmission and command execution between the hardware and application layers.

Despite these advantages, certain limitations remain. The current implementation relies on predefined threshold values for fault detection, which may not capture all complex fault conditions. Future enhancements can incorporate machine learning and predictive analytics techniques to identify hidden patterns and predict failures before critical conditions occur. Additional sensors such as oil level, humidity, and vibration sensors may also be integrated to provide a more comprehen-sive assessment of transformer health.

Overall, the T-WATCH system demonstrates that combin-ing IoT sensing, cloud connectivity, embedded intelligence, and mobile-based monitoring can significantly improve trans-former reliability, operational safety, and maintenance effi-ciency. The proposed solution provides a scalable foundation for next-generation smart transformer management systems and supports the ongoing transition toward intelligent and sustainable power distribution networks. .

VIII. CONCLUSION

The T-WATCH Transformer Monitoring System has proven an integrated and intelligent approach for modern transformer management via Embedded Hardware, Cloud-based Communication, Mobile App for the User. By enabling persistent real-time datum acquisition over long distances, as well as the capacity to be accessed remotely and to provide an automated protection function, the system clearly outmatches traditional monitoring techniques that are incapable of these capabilities. In this paper, multiple sensors are used with the NodeMCU ESP32S microcontroller to continuously read and process important parameters like temperature, voltage and current from EV batteries. With HiveMQ the hardware and the mobile application can communicate with each other bidirectionally and reliably. Finally, the T-WATCH application complements the system with visualization options, comprehensive diagnostics, remote operation and handling of offline data until a WLAN connection is established. A major strength of the system is its ability to provide automatic protection based on threshold conditions, which helps keep it operational even when the network connection becomes compromised. More-over, the performance parameters such as efficiency, losses and health indicators are integrated in predictive maintenance and better decision making. In summary, T-WATCH is a low-cost, scalable and reliable system for performing transformer monitoring over industrial or utility environments. This not only maximizes operating efficiency and minimizes downtime, but also supports improved safety and asset life. Additionally, the project lays a solid groundwork for future advancements like AI-driven faults identification/prediction integration with smart grids and expansion to large scale power networks. Collectively, these performance parameters combine real-time sensing, data analysis, and intelligent decision-making to present an overview of transformer operation. By continuously monitoring these parameters, the T-WATCH system guarantees high reliability, higher efficiency of measurements as well as early fault detection and efficient transformer protection

FUTURE SCOPE AND SCALABILITY OF PROPOSED SYSTEM

T-WATCH Transformer Monitoring System market is ap-plicable for Industrial, Utility and Smart Infrastructure indus-tries that are expandably deployable on a large scale. Indus-trial Scope The technique is used in manufacturing plants, power distribution units and substations to constantly monitor transformers. Minimize dependence on manual assessments, reducing operational costs and increasing maintenance efficiency; More Greater Efficiency and Output: With the aid of Artificial Intelligence (AI) in manufacturing, every equipment is equipped with sensors that analyze their performance data and share them over the internet. In this way AI helps detect problems before they occur. This allows predictive mainte-nance to take place which not only minimizes downtime but also prevents unexpected failures of any kind of equipment. Increases operational safety by providing real-time alerts and self-protection mechanisms. Utility and Smart Grid Applications Appropriate for the smart grid systems, live data acquisition with remote asset monitoring. Allows for centralised monitoring of many geographically distributed transformers. Scalable deployment cloud-based communication (MQTT) for utility-grade infrastructure. Global (Worldwide) Scope Has the potential to be used in all regions of the world —developed and developing, especially in areas with limited maintenance resources. With offline capability, it can be used in poor-connectivity or remote areas and hence globally adaptable.

Enabling energy sustainability by improving transformer performance and avoiding losses The groundwork before allowing future integration with AI-driven predictive analytics, digital twins and smart energy ecosystems. Future Expansion Scope Connect additional sensors (oil and humidity level, gas anal-ysis) for better diagnosis. Development of machine learning models for fault prediction and outlier detection. Multi-device monitoring offers an entire end-to-end network management capability from one interface.

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