IoT-Enabled Arduino-Based Monitoring and Protection System for Three-Phase Transformers

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Abstract. This project presents an accurate and intelligent monitoring and protection system for three-phase transformers, emphasizing real-time data acquisition, advanced safety features, and proactive maintenance. Utilizing an Arduino-based platform, the system continuously monitors vital transformer parameters such as three-phase currents, oil level, oil temperature, and oil quality, while detecting critical conditions like overloading and phase loss. It incorporates load-sharing mechanisms to ensure balanced operation under varying loads, thereby reducing transformer stress and optimizing energy distribution. With both local and remote access capabilities, the system features integrated sensors, LCD visualization, and wireless communication to deliver a user-friendly interface for efficient data management and instant alerts. The project also explores the technical design, implementation strategies, and highlights the economic and environmental advantages of deploying such an innovative solution in modern power systems, ultimately enhancing transformer performance, reliability, and lifespan.

Keywords: Real-time monitoring, Transformer protection, Load-sharing, Arduino-based system

1 Introduction

Transformers are indispensable components in electrical power systems, playing a crucial role in the efficient transmission and distribution of electricity. By stepping voltage levels up or down, transformers help minimize energy losses during long-distance transmission and ensure appropriate voltage levels for consumer use. Despite their robust design, transformers are vulnerable to operational stresses such as overloading, phase imbalance, oil degradation, and overheating. These faults, if undetected, can lead to severe consequences including transformer failure, power outages, system downtime, and safety risks. Conventional transformer monitoring relies heavily on manual inspection and periodic maintenance, which often fails to detect early signs of degradation. This reactive approach contributes to unexpected failures and increased operational costs.

In response to these challenges, the proposed project aims to design and develop a real-time, cost-effective transformer monitoring and protection system using Arduino microcontrollers and various sensors. The system is intended to monitor critical parameters such as three-phase current, oil temperature, oil level, oil quality (density and intensity), overloading conditions, and phase loss. These parameters are essential indicators of transformer health and performance. The collected data will be displayed locally on an LCD for on-site monitoring and simultaneously transmitted to a remote interface using the ESP32 Wi-Fi module, enabling maintenance personnel to access real-time data through mobile devices or computers. Alerts for abnormal conditions will be issued using LEDs to facilitate timely responses.

2 Literature Review

The integration of Internet of Things (IoT) technology in transformer monitoring systems has been explored in numerous recent studies. developed an IoT-based monitoring system using Arduino and ESP8266 to track oil level, temperature, and load current [1] . Their system demonstrated the benefits of remote monitoring and predictive maintenance. However, the ESP8266's limited processing power posed a performance constraint in data-intensive applications. Addressed this issue by implementing an ESP32-based system with dual-core processing [2], which enabled faster data handling and integration with the Blynk IoT platform for real-time visualization. Similarly, used ESP32 and Google Firebase for cloud-based monitoring with push notifications [3], highlighting the importance of user-centric design in modern monitoring systems.

Apart from monitoring, protection mechanisms have also been integrated into microcontroller-based solutions. Designed an Arduino-based transformer protection system that could disconnect the transformer during over-voltage, over-current, and high-temperature conditions [4]. Although effective locally, their system lacked remote access capabilities. Recent advancements now allow seamless integration of monitoring and protection through IoT platforms, enabling immediate alerts and automated protective actions.

Sensor integration plays a key role in determining system reliability. Low-cost sensors such as LM35, DHT11, and current transformers interfaced with Arduino and ESP32 [5] . They concluded that with adequate calibration and filtering, these sensors offer reliable performance suitable for cost-sensitive applications, though environmental resilience remains a concern.

By leveraging these technologies, this project proposes a scalable and affordable solution that addresses the limitations of conventional systems. It not only enhances transformer reliability and maintenance practices but also represents a significant step toward building smarter and more resilient electrical infrastructure through the adoption of embedded systems and IoT technologies.

3 Methodology

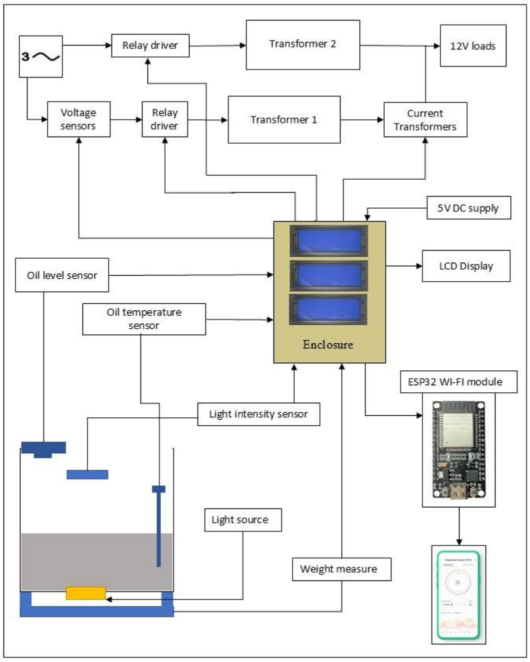

Fig. 1. Block diagram for the prototype design

The prototype design of the Three-Phase Transformer Monitoring and Protection System involved a structured approach to achieve real-time monitoring, fault detection, and preventive maintenance using affordable embedded technology. Key parameters such as voltage, current, oil temperature, oil level, and oil quality were identified due to their critical impact on transformer health. Components including sensors and microcontrollers were selected for their accuracy, range, and compatibility with the Arduino platform. The hardware setup involved circuit design for precise sensor data acquisition and relay-based protection control. Arduino Uno and Mega 2560 were used for system control, with programming in Embedded C, while the ESP32 module facilitated remote monitoring via the Blynk IoT platform. An I2C LCD was integrated for on-site data visualization. Calibration of sensors ensured reliable readings, and modular prototyping allowed for iterative refinement. This holistic integration of hardware and software delivered a scalable, user-friendly, and cost-effective solution for transformer monitoring and protection.

3.1 System Design

This project presents a comprehensive protection system for a three-phase transformer, integrating phase failure detection, load sharing, and oil monitoring. Phase failure is detected using ZMPT101B voltage sensors and an Arduino Uno, which disconnects the load if the voltage drops below the threshold. Load sharing is achieved with SCT013 current sensors, balancing the load between two transformers to prevent overloads. Transformer oil health is monitored via ultrasonic (level), BH1750 (intensity), load cell with HX711 (density), and DS18B20 (temperature) sensors. Real-time data is displayed on an LCD and alerts are triggered for abnormal conditions, ensuring safety, efficiency, and prolonged transformer life (Fig. 1).

Hardware Components

The hardware components are given in Table 1.

Software Development

Used the Blynk Data Monitoring system for our project to remotely monitor and control through a mobile app. Blynk IoT is a user-friendly cloud platform that enables real-time remote monitoring and control of hardware like ESP32 and Arduino via mobile apps or web dashboards. Its virtual pin system simplifies data exchange, supports cross-platform access, live sensor visualization, device control, and integrates with cloud services for enhanced IoT management.

Table 1. Components with Specification

Component	Function/Purpose
Arduino UNO (ATmega328P)	Microcontroller for basic data processing, sensor interfacing, and control in simpler system modules.
Arduino mega 2560 (Atmega2560)	Main microcontroller with more I/O pins and memory for handling complex processing and multiple sensors.
SCT013 30A/1V split-core current transformer	Measures AC current in transformer phases for load monitoring and load sharing control.
ZMPT101B voltage sensor	Measures AC voltage of each transformer phase to detect phase failure and voltage drops.
Relay module	Electrically isolates and switches high-power loads or circuits based on Arduino commands for protection.
Ultrasonic sensor	Measures transformer oil level by detecting the distance to the oil surface.
BH1750 light intensity sensor	Measures light intensity to assess transformer oil clarity or quality via oil transparency.
DS18B20 temperature sensor	Measures transformer oil temperature for thermal condition monitoring.
20x4 I2C LCD display	Provides local, real-time display of sensor readings and system status.
Relay MK3PN	Additional relay used for switching high current loads or multiple relay control in the system.
ESP32 WIFI module	Enables wireless communication for remote monitoring and control via IoT platforms like Blynk.

3.2 Phase Failure Protection System

Phase failure protection is a critical safety feature for 3-phase electrical systems, especially in transformers, motors, and other industrial equipment. It ensures that all three phases (R, Y, B) are present and balanced. If any one of the phases fails (due to a blown fuse, broken wire, or loose connection), it can cause severe damage to the equipment, including overheating, vibration, and insulation failure. To prevent this, a protection mechanism can be implemented using an Arduino Uno, ZMPT101B voltage sensors, and a relay module.

In this system, three ZMPT101B voltage sensors are used to monitor the voltage levels of each of the three phases. These sensors are designed to measure AC voltage and provide a corresponding analog signal to the Arduino. Each ZMPT101B sensor is connected to one of the phases (R, Y, or B), and the Arduino reads the analog voltage values through its analog input pins. These sensors are chosen because they are compact, accurate, and provide electrical isolation between the high-voltage line and the Arduino. The Arduino Uno acts as the central controller. It continuously checks the input from the three

ZMPT101B sensors. Under normal conditions, all three sensors report voltages within an expected range. If the Arduino detects that the voltage from any one phase has dropped significantly below the threshold (indicating a phase loss), it triggers the protection mechanism. To respond to the fault, the Arduino activates a relay module. The relay cuts off the power supply to the transformer or load, thereby isolating the equipment and preventing damage. The Circuit arrangement is shown in Fig. 2.

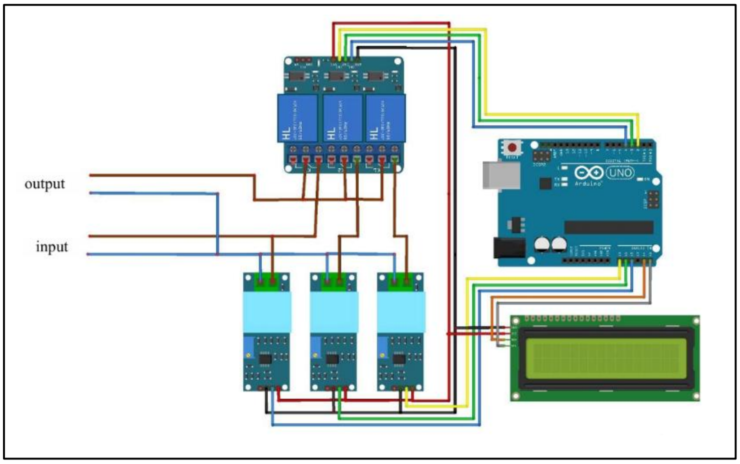

Fig. 2. Phase failure protection system circuit arrangement

3.3 Load Sharing System

In a load-sharing system using two 3-phase transformers, an Arduino Uno can be used to intelligently monitor and control the distribution of electrical load between the transformers to prevent overloading. The setup includes current transformers (CTs), voltage sensors, and protection relays installed on both transformers. The CTs measure the current drawn by each transformer, while the voltage sensors monitor the system voltage. These sensor readings are fed into the Arduino Uno, which continuously analyzes the load on each transformer. If the Arduino detects that one transformer is approaching its rated capacity, it automatically activates relays to transfer a portion of the load to the second transformer, thereby balancing the load between the two units. This method protects the transformers from thermal damage due to overloading and ensures efficient operation. Additionally, this automated system can be programmed to display real-time values on an LCD or transmit data to a monitoring station, enhancing system reliability and operational transparency. The Circuit arrangement is shown in Fig. 3.

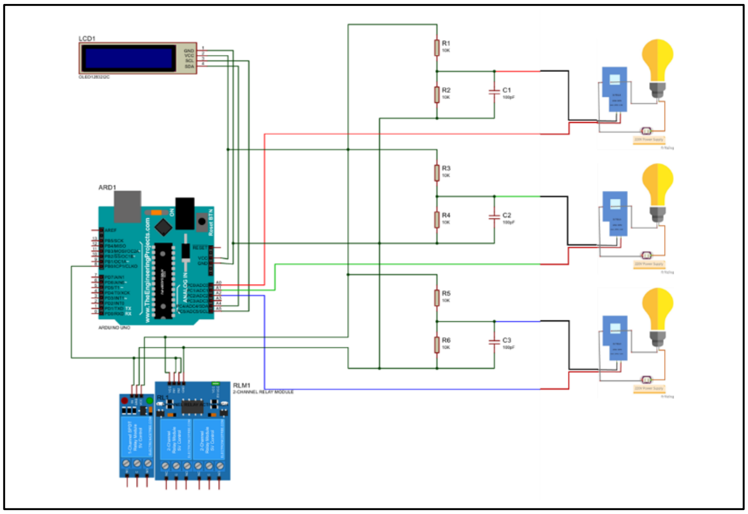

Fig. 3. Load sharing system circuit diagram

3.4 Oil Testing Unit

This system integrates multiple sensors to monitor transformer oil conditions in real-time, measuring oil level (via ultrasonic sensor), light intensity (BH1750 sensor for quality inference), density (load cell and HX711 module), and temperature (DS18B20 sensor). It processes data using an Arduino, displays results on an LCD, and triggers alerts (e.g., buzzer for high temperature or low oil levels) to ensure proactive maintenance. By combining these measurements, the system enhances transformer reliability, prevents failures, and optimizes operational efficiency.

Measure Oil Level

This is done by measuring and displaying the oil level in a tank using an ultrasonic sensor and an LCD. During each loop, the ultrasonic sensor sends a 10-microsecond pulse, and the time taken for the echo to return is measured. This duration is converted to a distance in inches, which represents the empty portion of the tank. The oil level percentage is then calculated using the formula, which is shown in Fig. 4.

$$\text{Percentage} = \frac{\text{Set value} - \text{inches}}{\text{Set value}} \times 110$$

Fig. 4. Percentage formula

- ✓ The set value is the maximum tank height.
- ✓ The factor 110 adjusts for scaling or unit conversion

The calculated percentage is displayed on the LCD along with a status message indicating whether the level is low (below 40%), or full (above 80%).

Measure Oil Intensity

This is done by measuring light intensity using a BH1750 light sensor to infer oil quality and display the results on an LCD. In the setup phase, the BH1750 sensor and LCD are initialized, and a test message is sent to the serial monitor. During each loop, the BH1750 reads ambient light intensity in lux, which is displayed on the first line of the LCD and printed on the serial monitor. The program then checks if the lux value is below a threshold of 800 lx.

Measure Oil Density

This is done by measuring and displaying the density of oil in a tank using a load cell sensor and HX711 module. In the setup, the system initializes the HX711 module and calibrates the scale with a predefined calibration factor. The load cell measures the mass of an object placed on it, and the system subtracts a calibration offset to ensure accurate readings. The density is 13, then calculated by dividing the measured mass by a known volume of 400 ml, using the Fig. 5 formula.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

Fig. 5. Density formula

Measure Oil Temperature

This is done by measuring the oil temperature using a DS18B20 temperature sensor and displaying the results on an LCD display. It continuously reads the temperature from the sensor, converting the raw data to Celsius and Fahrenheit. If the temperature exceeds 100°F, the code activates a trigger that buzzes to alert the user. The sensor communicates with the Arduino through the one-wire protocol, with specific functions to handle reading and writing data. The main loop reads the temperature, displays it on the LCD, and checks if the temperature exceeds the threshold.

4 Results

4.1 Phase Failure Protection System

In this project, this is done by monitoring and protecting a three-phase transformer from phase failure or voltage drops. It calculates RMS voltage values for each phase 230V (R, Y, and B) using ZMPT101B voltage sensors connected to analog pins. The voltage drop checks and compares the RMS voltage of each phase to a predefined threshold and determines if a phase is down or available. If any phase voltage falls below 215V the threshold, the activates all relays, which are connected to digital pins, to protect the transformer. It displays the relay status are 'ON' or 'OFF'. When all phases are normal, the relays are deactivated. The system logs voltage readings and phase status to the Serial Monitor for debugging and updates the LCD in real-time. This setup effectively prevents damage to the transformer in the event of a phase failure or voltage drop.

The system incorporates three switches to simulate phase faults in a three-phase transformer setup. In the current configuration (as shown in Fig. 6), all three switches remain in the "off" position, indicating no simulated faults are active. As a result, the transformer operates normally, delivering uninterrupted power to the output load (as shown in Fig. 7). This design allows for controlled testing of fault conditions.

Fig. 6. Switches to make the faults

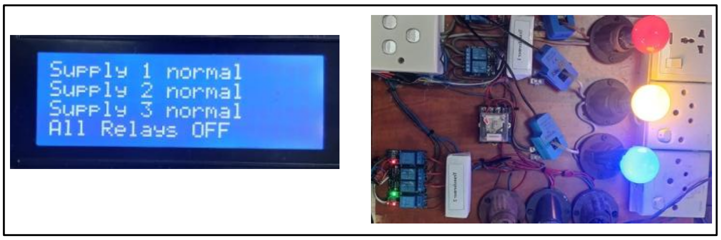

Fig. 7. Delivering power to the output load

When any switch is turned "on" (as shown in Fig. 8), it triggers a corresponding phase fault, enabling the system to demonstrate protective responses to shut down the transformer

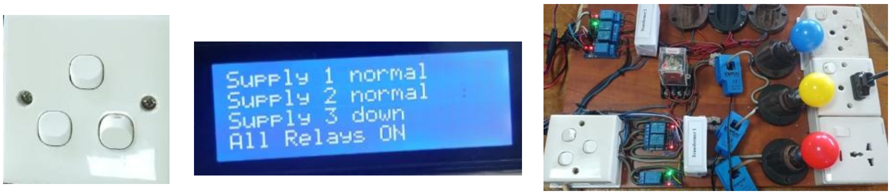

Fig. 8. In-phase fail condition

4.2 Load Sharing System

In this project, this is done by implementing a three-phase transformer load-sharing system by monitoring current and power in each phase (R, Y, B) using SCT013 30A/1V split-core current transformers and adjusting relay states to ensure proper load sharing. If the load current exceeds 5A the relays turn on and activate load-sharing operation. Each phase's current values and relay condition ('ON' or 'OFF') are displayed on an LCD display. The loop function continuously reads current, calculates power, updates relay states, and displays data. This system ensures balanced transformer load distribution by activating relays for overloaded phases, preventing overheating and phase imbalance, and maintaining transformer efficiency.

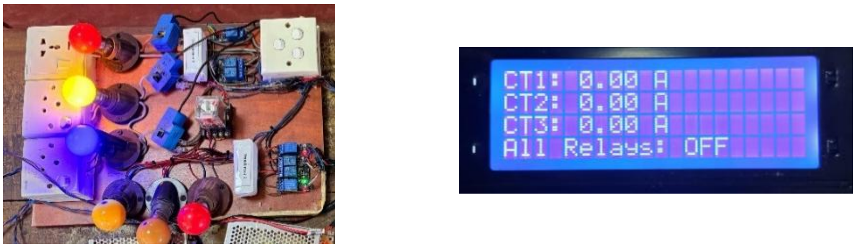

Fig. 9. In the normal condition

In normal conditions where there is no load applied to the transformer and it does not exceed its rated maximum current, then the LCD display indicates that the relays are 'OFF,' as in Fig. 9.

If the high load is applied to the transformer (transformer 1), the load is shared with the other transformer (transformer 2), and it displays as relays are 'ON' and displays each phase current as in Fig. 10.

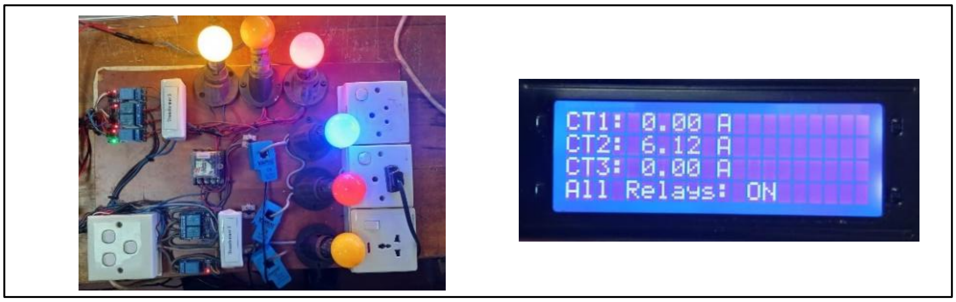

Fig. 10. When a high load is applied to the phase

4.3 Oil Testing Unit

The system successfully monitors four critical parameters of transformer oil to ensure optimal performance and safety. The oil level is accurately measured using an ultrasonic sensor, with results displayed as a percentage on an LCD, including status alerts for low (<40%) or full (>80%) levels. Oil quality is inferred through light intensity measurements via a BH1750 sensor, with readings below 800 lux indicating potential issues. Density is calculated using a load cell and HX711 module, where mass is divided by a known volume (400 ml) to determine oil consistency. Temperature is tracked with a DS18B20 sensor, notify if exceeding 100°F to prevent overheating risks. All data is displayed in real-time on an LCD, providing a comprehensive and user-friendly interface for proactive maintenance and fault detection, as shown in Fig. 11. This integrated approach enhances transformer reliability by addressing key operational factors—level, quality, density, and temperature through precise sensor measurements and timely alerts.

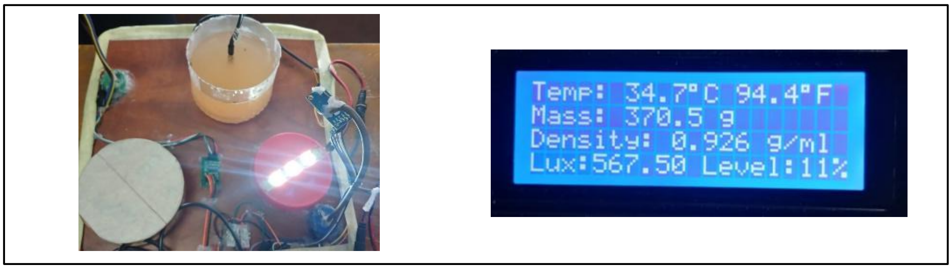

Fig. 11. Oil testing unit and display

Also, oil testing results are displayed and monitored and displayed on mobile or desktop via the Blynk Data Monitoring system show as Fig. 12.

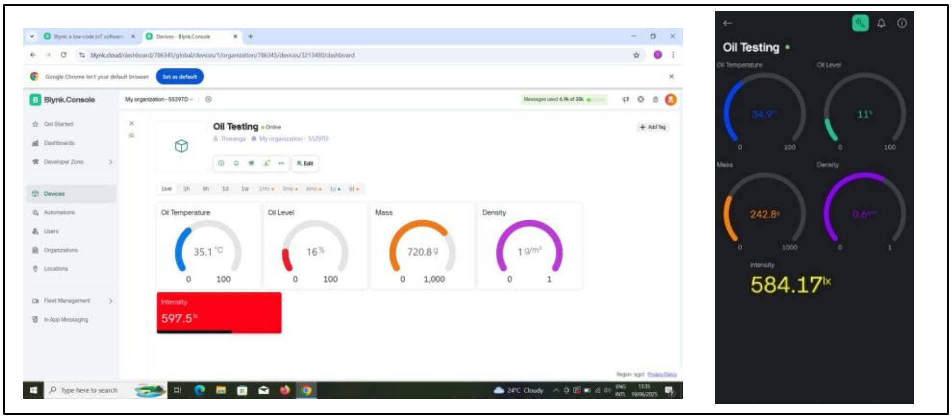

Fig. 12. Oil testing results

5 Future Improvements

- Use advanced sensors with auto-calibration for accurate measurements, and incorporate prototype sensors for Vacuum Circuit Breakers (VCB) and Air Circuit Breakers (ACB) to enhance monitoring and protection capabilities.
- Add backup communication options like GSM or LoRa for reliable connectivity.
- Store data in the cloud and use advanced analytics for monitoring and maintenance.
- Use durable industrial microcontrollers instead of Arduino for tough environments.
- Design the system to easily handle bigger or multiple transformers.
- Include battery backup to keep the system running during power cuts.
- Use special sensors to better check oil quality and contamination.
- Create a user-friendly mobile app or web dashboard with alerts and reports.
- Protect the system with weatherproof cases against dust, humidity, and heat.

6 Discussion

The Arduino-based transformer monitoring system enables real-time tracking, proactive maintenance, overload protection, and remote access, improving reliability, efficiency, and safety. Key limitations include sensor accuracy, reliance on stable Wi-Fi and power, environmental impacts, limited industrial scalability, and integration challenges. Despite this, it is well-suited for low-cost, small to medium-scale systems. Future enhancements like better sensors, GSM/LoRa communication, cloud analytics, rugged enclosures, industrial-grade microcontrollers, and power backup can expand its performance and industrial applicability. Overall, it is a promising step toward smarter, more resilient transformer management.

7 Conclusions

The project developed a real-time monitoring and protection system for three-phase transformers using Arduino and various sensors to track phase voltages, current, oil level, temperature, and quality. It included safety features like phase failure detection, load sharing, and abnormal condition alerts. The system offered local display and remote access via ESP32 and Blynk IoT for timely maintenance, enhancing reliability, safety, and energy efficiency. Despite sensor accuracy and power dependence limitations, it lays a foundation for future industrial scalability, data logging, and AI-based fault prediction, advancing smart grid modernization.

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