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# Development of an IoT-Based Smart Distribution Transformer Monitoring System for Reliable Rural Electrification

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***Abstract***
*Distribution transformers are essential components of electric power distribution networks, and their reliable operation depends on continuous monitoring of critical operating parameters. However, conventional inspection techniques are periodic, labour-intensive, and incapable of providing the real-time information required for proactive maintenance. This study presents the design, implementation, and experimental validation of an Internet of Things (IoT)-based smart distribution transformer monitoring system for real-time acquisition and remote visualisation of transformer operating parameters. The developed system integrates isolated voltage and current sensing circuits, an Arduino Uno microcontroller, an ESP8266 Wi-Fi communication module, a 16 × 2 liquid crystal display (LCD), and the Blynk cloud platform for simultaneous local and remote monitoring. The sensing circuits were calibrated using polynomial and exponential regression models to improve measurement accuracy, while the complete hardware was designed, simulated, and verified using the PROTEUS Design Suite before fabrication. Experimental evaluation was conducted over a voltage range of 181–249 V and load currents up to 9 A. The developed system exhibited excellent agreement with calibrated reference instruments, recording a maximum voltage deviation of approximately 1 V (less than 0.5%) and a maximum current deviation of 0.1 A (approximately 1.1%). In addition, the estimated apparent power, real power, and power factor closely matched the reference values. The communication subsystem maintained stable Wi-Fi connectivity, achieving a data transmission success rate exceeding 99% with dashboard refresh times below 2.1 s, thereby enabling reliable real-time cloud monitoring. The proposed monitoring system provides a low-cost, accurate, and scalable solution for continuous condition monitoring of distribution transformers and offers significant potential for predictive maintenance and intelligent asset management in modern smart grid applications.*

***Keywords:*** *Condition monitoring, Distribution transformer, Internet of Things (IoT), Remote monitoring, Rural electrification.*

## 1.0 Introduction

Access to reliable electricity remains a prerequisite for sustainable socio-economic development, industrial growth, healthcare delivery, education, and improved living standards. Reliable electricity is also fundamental to achieving the United Nations Sustainable Development Goals (SDGs), particularly Goal 7, which advocates affordable, reliable, sustainable, and modern energy for all [1], [2]. Although many developing countries have invested significantly in expanding electricity access, the reliability of distribution networks remains a major challenge, particularly in rural communities where infrastructure is sparse and maintenance resources are limited [3], 4]. Distribution transformers constitute one of the most critical assets in these networks, serving as the final voltage transformation stage between medium-voltage feeders and consumers. Their operational condition directly influences power quality, supply continuity, and overall network reliability. Consequently, transformer failures often result in prolonged outages, increased maintenance costs, equipment replacement, and significant economic losses for both utility companies and electricity consumers [3], [5],[6].

In many developing nations, including Nigeria, distribution transformers operate under increasingly demanding conditions driven by rapid urbanisation, population growth, uncontrolled load expansion, illegal connections, voltage fluctuations, and inadequate preventive maintenance. As shown in Figure 1, distribution transformers deployed in rural electrification systems are often geographically dispersed across vast areas, which makes routine inspection both expensive and time-consuming. This spatial distribution further compounds the vulnerability of rural networks, where utilities still rely heavily on periodic manual inspections. Such inspections provide only limited operational information and cannot capture transient overloads or progressive deterioration occurring between inspection intervals. Consequently, maintenance strategies remain largely reactive, leading to higher operational costs and reduced network availability [3], [5], [7].

Distribution transformer failures are commonly associated with prolonged overloading, insulation degradation, excessive operating temperatures, voltage imbalance, abnormal current flow, and poor cooling conditions. Continuous exposure to these conditions accelerates insulation ageing, reduces transformer lifespan, and eventually results in catastrophic failures if corrective actions are not implemented promptly. Traditional maintenance practices therefore struggle to provide the situational awareness required for modern electricity distribution systems. As electricity demand continues to rise, intelligent monitoring systems that continuously

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supervise transformer operating conditions and support predictive maintenance have become indispensable [5],[6], [8].

Figure 1. Typical distribution transformer used for rural electricity distribution

Recent advances in digital technologies have significantly transformed electrical power infrastructure. Among these technologies, the Internet of Things (IoT) has emerged as one of the most promising paradigms for intelligent asset monitoring by enabling sensors, embedded processors, communication modules, and cloud platforms to exchange operational data in real time [9,10,11]. IoT architectures support continuous data acquisition, remote accessibility, real-time visualisation, automated decision-making, and predictive maintenance, thereby providing a technological foundation for smart grid applications [9], [10], [12].

Unlike conventional supervisory methods based on periodic inspections, IoT-enabled monitoring systems continuously acquire transformer operating data, process the information locally through embedded controllers, and transmit it wirelessly to cloud servers for storage, visualisation, and analysis. This enables utility engineers to remotely supervise transformer conditions, receive early fault notifications, and schedule maintenance before minor abnormalities evolve into catastrophic failures, thereby reducing downtime and improving network reliability [7], [13], [14].

Several studies have demonstrated the effectiveness of IoT-based transformer monitoring. Early systems primarily employed GSM communication for transmitting voltage, current, oil temperature, oil level, and load information. Although GSM-based solutions represented a significant improvement over manual inspection, they incurred higher communication costs and depended heavily on cellular network availability. More recent developments have shifted towards Wi-Fi-enabled IoT platforms, Message Queuing Telemetry Transport (MQTT) communication protocols, cloud databases, and web-based dashboards that provide continuous monitoring with lower operating costs and improved accessibility [7], [13], [15].

A comprehensive survey by [7] reviewed over one hundred IoT-based transformer monitoring studies and found that Arduino emerged as the most widely adopted embedded platform, primarily due to its affordability, ease of programming, and strong community support. In parallel, [5] underscored the increasing role of artificial intelligence, machine learning, and real-time sensing in transformer health monitoring. These technologies enable continuous monitoring, which not only enhances fault prediction accuracy but also supports the shift from traditional time-based maintenance toward more efficient condition-based maintenance strategies [5], [7], [16].

Cloud computing has further strengthened IoT-enabled monitoring systems by providing scalable infrastructure for storing, processing, and visualising transformer operating data. Cloud platforms enable historical trend analysis, real-time dashboards, alarm management, and remote accessibility while facilitating integration with predictive maintenance algorithms and artificial intelligence-based fault diagnosis [9,10], [17].

Despite these advances, many reported transformer monitoring systems remain relatively complex because they employ numerous sensing devices, including dissolved gas analysers, vibration sensors, humidity sensors, infrared cameras, and sophisticated protection relays. Although these systems provide detailed diagnostic information, their complexity substantially increases implementation cost, maintenance requirements, and energy consumption, limiting their suitability for resource-constrained rural electrification projects. Furthermore, many existing studies emphasise communication architecture while providing limited attention to practical hardware integration, isolated sensing circuits, embedded signal conditioning, local fault indication, cloud visualisation, and low-cost implementation. Consequently, there remains a need for practical, reliable, and scalable monitoring platforms capable of continuously supervising essential transformer operating parameters [7], [11], [18].

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This study addresses this research gap through the development of an IoT-based smart distribution transformer monitoring system for reliable rural electrification. The proposed system continuously monitors four critical electrical parameters—voltage, current, real power, and apparent power—using isolated sensing circuits and an Arduino Uno microcontroller. An ESP32 Wi-Fi module provides wireless communication with a cloud-based IoT platform for real-time visualisation through mobile devices, while a 16 × 2 liquid crystal display (LCD) and an audible alarm provide local monitoring and fault indication. The resulting modular architecture integrates embedded sensing, IoT communication, cloud computing, local visualisation, and fault notification into a single low-cost platform suitable for practical deployment within electricity distribution networks [4], [7], [13], [16].

The principal contribution of this work is the development and experimental validation of a modular, scalable, and economically viable IoT-based transformer monitoring system that supports continuous condition monitoring to improve distribution network reliability.

## 2. Methodology

### 2.1 System Architecture

The proposed Internet of Things (IoT)-based smart distribution transformer monitoring system was developed using a modular embedded architecture for continuous monitoring, processing, and remote visualisation of transformer operating parameters. Before hardware implementation, the complete circuit was designed and simulated in the PROTEUS Design Suite to verify functionality, optimise component selection, and minimise implementation errors. The validated design was subsequently fabricated, programmed, calibrated, and experimentally evaluated.

The system consists of two integrated subsystems: the hardware subsystem, which performs signal acquisition, conditioning, embedded processing, local display, and wireless communication; and the software subsystem, which manages data acquisition, parameter estimation, fault detection, and cloud communication.

As shown in Figure 2, the monitoring system comprises six functional modules: the regulated power supply, voltage measurement, current measurement, signal conditioning and fault detection, embedded processing, and IoT communication and visualisation units.

The voltage and current sensing modules acquire transformer operating parameters through isolated sensing transformers. The conditioned analogue signals are digitised by the ATmega328P analogue-to-digital converter (ADC) and processed in real time. The processed data are transmitted through an ESP32 Wi-Fi module to the Blynk cloud platform for remote monitoring while simultaneously being displayed on a 16 × 2 LCD. An active buzzer provides an audible alarm whenever abnormal operating conditions are detected.

The modular architecture enhances system reliability, electrical safety through galvanic isolation, and scalability, while providing a suitable framework for future integration of predictive maintenance and intelligent fault diagnosis techniques.

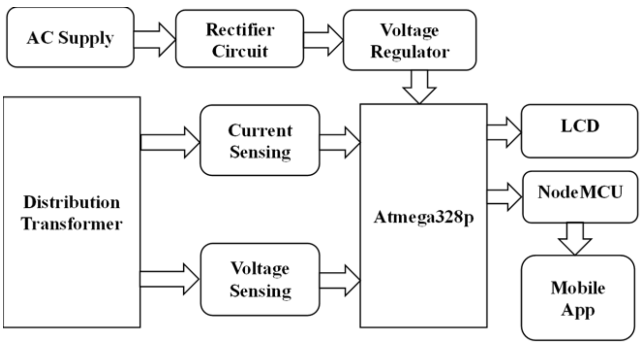


Figure 2: Block Diagram of IoT-based smart distribution transformer monitoring system

### 2.2 Regulated Power Supply Unit

The hardware was developed using a modular design approach, where each functional unit was designed, tested, and validated before integration. The system comprises a regulated power supply, voltage and current sensing circuits, signal-conditioning unit, Arduino Uno, ESP8266 Wi-Fi module, LCD, and audible alarm. Electrical isolation between the transformer and the monitoring circuitry is achieved using voltage and current transformers to ensure safe operation.

A regulated +5 V DC supply was designed to power the embedded components. As shown in Figure 3, the power supply consists of a 230/12 V step-down transformer, a full-wave bridge rectifier, a smoothing capacitor, an LM7805 voltage regulator, and bypass capacitors. The transformer reduces the mains voltage while providing electrical isolation, and the bridge rectifier converts the AC voltage to DC.

The transformer secondary voltage is given by Equation (1):

$$v_s(t) = V_m \sin(\omega t) \tag{1}$$

where $V_m$ is the peak voltage and $\omega = 2\pi f$. The peak voltage is defined in Equation (2):

$$V_m = \sqrt{2}V_{\text{rms}} \quad (2)$$

The rectified DC voltage can be approximated using Equation (3):

$$V_{DC} \approx \sqrt{2}V_{\text{rms}} - 2V_D \quad (3)$$

which yields approximately 15.6 V for a 12 V secondary, providing sufficient input for the LM7805 regulator. The ripple voltage after filtering is estimated by Equation (4):

$$V_r = \frac{I_L}{2fC} \quad (4)$$

where $I_L$ is the load current, $f$ is the supply frequency, and $C$ is the filter capacitance. Finally, the LM7805 regulator suppresses the residual ripple and maintains a stable output voltage as expressed in Equation (5):

$$V_o = 5.0 \pm 0.1 \text{ V} \quad (5)$$

provided that the input voltage exceeds the regulator dropout requirement. The regulated supply therefore provides a stable and low-noise DC source for the sensing, processing, communication, display, and protection circuits.

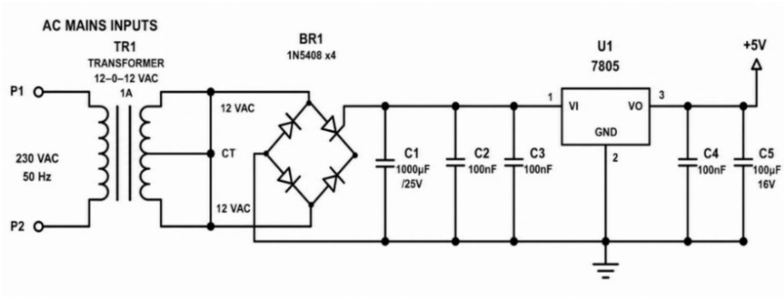


Figure 3. Regulated +5 V DC power supply circuit

## 2.3 Voltage Measurement Unit

The voltage measurement unit was designed to safely measure the distribution transformer voltage while ensuring compatibility with the 0–5 V input range of the Arduino Uno analogue-to-digital converter (ADC). As shown in Figure 4, the circuit consists of an isolated voltage transformer (TR2), a full-wave bridge rectifier (BR2), a smoothing capacitor (C6), and a resistive voltage divider comprising a resistor $R_1$ and a calibration potentiometer $RV_2$.

The voltage transformer provides galvanic isolation and steps down the mains voltage from 230 V to 12 V AC. The reduced AC voltage is subsequently rectified using a full-wave bridge rectifier and filtered by a capacitor $C_6$ to obtain a stable DC signal. The voltage divider network scales the filtered voltage to within the ADC input range, while the potentiometer enables calibration to compensate for component tolerances and measurement deviations.

The 10-bit ADC converts the analogue input voltage into a digital value according to Equation (6):

$$ADC = \frac{V_{in}}{V_{ref}} \times 1023 \quad (6)$$

where $V_{ref} = 5\text{V}$.

To improve measurement stability and minimise random noise, 1000 consecutive ADC samples were acquired and averaged using Equation (7):

$$ADC_{avg} = \frac{1}{1000}\sum_{i=1}^{1000} ADC_i \quad (7)$$

The corresponding analogue voltage is obtained from $V_{ADC} = \frac{ADC_{avg}}{1023} \times V_{ref}$

## 2.4 Current Measurement Unit

The transformer load current was measured using an isolated current transformer (CT), as shown in Figure 5. A conventional step-down transformer was modified to function as a current transformer by rewinding its secondary winding with seven turns of high-gauge conductor. This configuration enabled the device to operate as a current step-up transformer, producing a secondary signal proportional to the primary load current.

The CT output was converted into a measurable DC voltage using a full-wave bridge rectifier (BR3) and smoothing capacitor (C9). A resistive voltage divider comprising $R_7$ and a calibration potentiometer $RV_5$ subsequently scaled the voltage to the 0–5 V input range of the Arduino Uno analogue-to-digital converter (ADC).

The current transformation ratio is given by Equation (8):

$$\frac{I_p}{I_s} = N \quad (8)$$

where $I_p$ is the primary current, $I_s$ is the secondary current, and $N$ is the current transformation ratio.

To reduce the measurement noise, the Arduino acquired 1000 consecutive ADC samples and computed their average using Equation (9),

$$ADC_{avg} = \frac{1}{1000}\sum_{i=1}^{1000} ADC_i \quad (9)$$

The corresponding analogue voltage is determined based on Equation (10):

$$V_{\text{Read}} = \frac{ADC_{avg}}{1024} \times 5 \quad (10)$$

An empirical calibration was performed using a calibrated clamp meter under varying load conditions. The measured ADC voltage was correlated with the reference current using the exponential regression model of Equation (11):

$$I = 0.148e^{1.9439V_{\text{Read}}} \quad (11)$$

where $I$ is the transformer load current (A) and $V_{\text{Read}}$ is the measured ADC voltage (V). The calibration model effectively compensates for the nonlinear characteristics of the modified current transformer, thereby improving current measurement accuracy over the operating range.

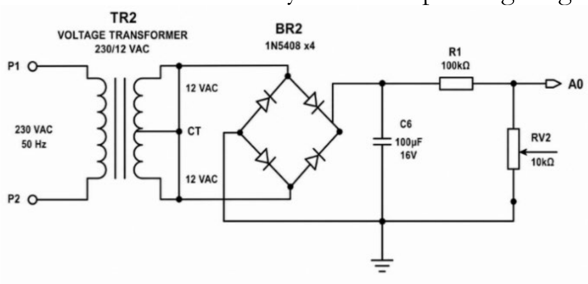


Figure 4. Voltage sensing circuit.

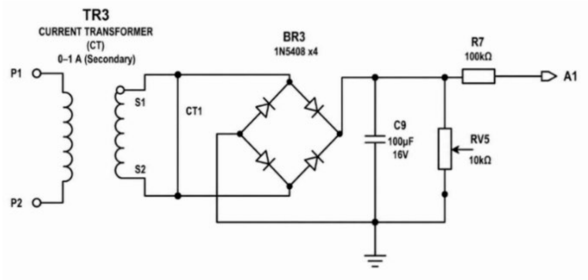


Figure 5. Current sensing circuit.

## 2.5 Signal Conditioning and Fault Detection Unit

The conditioned voltage and current signals were subsequently processed through an LM358 dual operational amplifier, configured as voltage comparators, to enable reliable threshold-based fault detection. The corresponding subcircuit is presented in Figure 6.

The comparator continuously compares the measured analogue signals against predetermined reference voltages corresponding to acceptable transformer operating conditions. The comparator output is governed by Equation (12):

$$V_o = \begin{cases} V_{OH}, & V_+ > V_- \\ V_{OL}, & V_+ < V_- \end{cases} \quad (12)$$

where $V_+$ and $V_-$ denote the non-inverting and inverting inputs of the comparator, respectively.

Whenever the measured voltage exceeds the permissible operating limit, or the measured current surpasses the overload threshold, the comparator output changes logic state, generating a digital fault signal that is supplied to the Arduino controller for further processing. Fast-switching 1N4148 diodes were incorporated to provide signal isolation and prevent reverse current flow between comparator outputs, while precision resistors established stable reference voltages.

The signal conditioning stage enhances measurement reliability by reducing susceptibility to electrical noise, ensuring stable comparator switching, and improving the accuracy of subsequent digital processing.

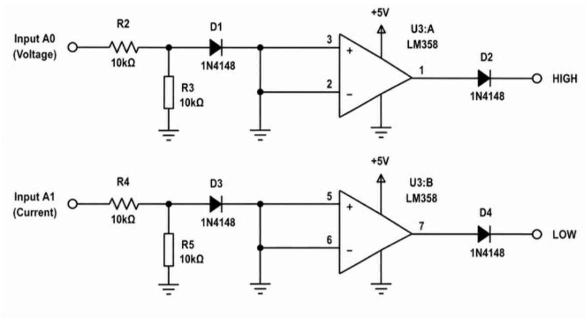


Figure 6. Signal conditioning and fault detection circuit

## 2.6 Embedded Processing Unit

The Arduino Uno, built around the ATmega328P microcontroller, served as the central processing unit of the proposed monitoring system, as illustrated in Figure 7(a). The microcontroller was chosen for its low power consumption, 10-bit analogue-to-digital converter (ADC), adequate computational capability, extensive

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community support, and ease of integration with IoT communication modules. Operating at 16 MHz with a 5 V supply, the ATmega328P provides six analogue input channels suitable for multi-sensor data acquisition.

The controller continuously sampled the voltage and current sensing circuits through analogue channels A0 and A1. To minimise fluctuations caused by electrical noise and switching transients, 1000 ADC samples were acquired before computing the average measurement value. IoT connectivity was achieved using the NodeMCU ESP8266 module, shown in Figure 7(b), which enabled real-time transmission of transformer parameters to the cloud platform.

The average ADC value is expressed as Equation (13):

$$ADC_{avg} = \frac{1}{N}\sum_{i=1}^{N} ADC_i \quad (13)$$

Where $N = 1000$samples.

The averaged ADC values were subsequently converted into calibrated voltage and current values using the empirical calibration equations developed in Sections 2.4 and 2.5.

The controller then calculated the transformer apparent power, real power, and power factor according to Equation (14)

$$S = VI \quad (14)$$

Where $S$is the apparent power (VA), $V$is the RMS voltage, $I$is the RMS current.

The real power delivered by the transformer is governed by Equation (15):

$$P = VI\cos\phi \quad (15)$$

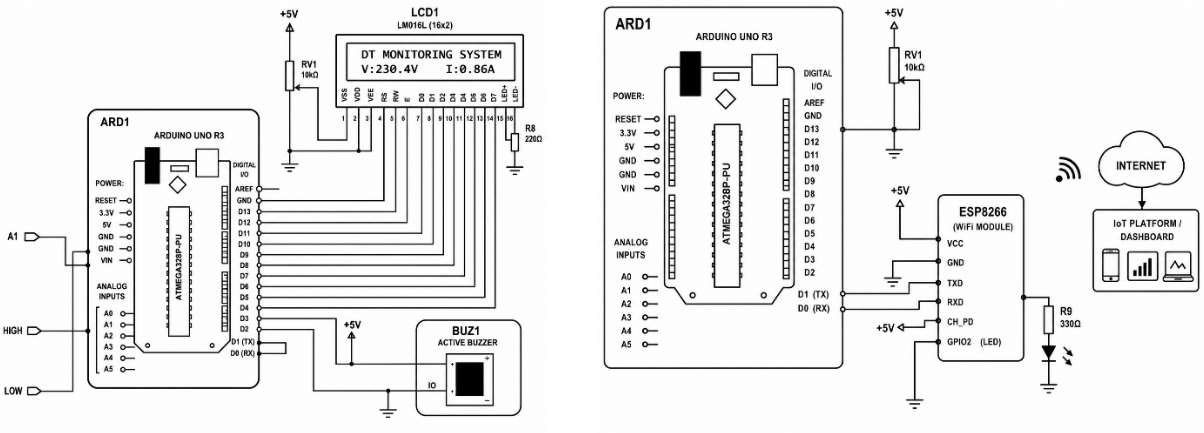
where $P$is the real power (W), $\phi$ is the phase angle between voltage and current.

The transformer power factor is therefore

$$PF = \cos\phi = \frac{P}{S} \quad (16)$$

The calculated parameters were continuously compared with predefined operating thresholds. Whenever abnormal operating conditions were detected, the controller activated the audible alarm and updated both the local LCD and the cloud dashboard.

The embedded firmware was developed using the Arduino Integrated Development Environment (IDE) and implemented in C/C++.




(a) (b)

Figure 7. (a)Arduino Uno processing subsystem. (b)NodeMCU ESP8266-based IoT communication architecture

### 2.7 IoT Communication and Cloud Monitoring Unit

Remote monitoring was implemented using a NodeMCU ESP8266 Wi-Fi module interfaced with the Arduino Uno via Universal Asynchronous Receiver–Transmitter (UART) serial communication. The ESP8266 was selected because it integrates a 32-bit processor, Wi-Fi capability, adequate memory, and low power consumption, making it suitable for IoT applications.

The Arduino transmitted processed transformer parameters, including voltage, current, apparent power, real power, and power factor, to the ESP8266 through the serial interface. The ESP8266 then connected to the local Wi-Fi network and uploaded the data to the Blynk cloud server for remote access. The communication pathway follows: Arduino → ESP8266 → Wi-Fi → Cloud → Mobile Dashboard

This architecture enables real-time remote monitoring of transformer operating conditions through smartphones or web browsers. The cloud platform also archives measurement data and provides graphical trends, facilitating early detection of abnormal operating conditions and improving preventive maintenance.

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### 2.8 Transformer Monitoring and IoT Communication Algorithm

The following algorithm outlines the process for transformer monitoring and IoT communication, from signal acquisition to real-time data transmission.

**Algorithm 1. Transformer Monitoring and IoT Communication Algorithm**

*Input: Voltage and current analogue signals from the sensing circuits.*

*Output: Real-time transformer parameters displayed locally and transmitted to the IoT cloud platform.*

1. *Begin*
2. *Initialize the Arduino controller, LCD, ESP8266 communication module, ADC, and system variables.*
3. *Set the sampling counter,* $n = 1000$.
4. *Repeat*
   - i. *Set* $V_{sum} = 0$ *and* $I_{sum} = 0$.
   - ii. *For* $i = 1$ *to* $n$ *do*
     - *Acquire voltage ADC sample.*
     - *Acquire current ADC sample.*
     - *Accumulate voltage reading:* $V_{sum} \leftarrow V_{sum} + ADC_V$
     - *Accumulate current reading:* $I_{sum} \leftarrow I_{sum} + ADC_I$
   - iii. *End For*
   - iv. *Compute the average ADC values:*

     $$ADC_{V,avg} = \frac{V_{sum}}{n}$$

     $$ADC_{I,avg} = \frac{I_{sum}}{n}$$
   - v. *Convert the averaged ADC values into calibrated voltage and current using the experimentally derived calibration models.*
   - vi. *Compute the transformer apparent power:* $S = VI$
   - vii. *Compute the real power:* $P = VI\cos\phi$
   - viii. *Determine the power factor:* $PF = \frac{P}{S}$
   - ix. *Update the LCD with the measured and computed parameters.*
   - x. *Transmit the measured data to the IoT cloud platform through the ESP32 Wi-Fi module.*
   - xi. *If any measured parameter exceeds its predefined operating threshold then*
     - *Activate the audible alarm. Else*
     - *Deactivate the alarm. End If*
5. *Until the system is powered OFF.*
6. *End*

### 2.9 Complete Circuit Diagram and IoT Monitoring Platform

The complete circuit diagram of the developed IoT-based distribution transformer monitoring system is presented in Figure 9. The hardware integrates the regulated power supply, voltage and current sensing circuits, signal-conditioning unit, Arduino Uno microcontroller, ESP8266 Wi-Fi communication module, liquid crystal display (LCD), and the associated interfacing components required for signal acquisition, processing, display, and wireless data transmission. The sensing circuits continuously acquire transformer electrical parameters, while the Arduino Uno performs data acquisition, signal processing, and computation of the transformer operating variables. The processed data are displayed locally on the LCD and simultaneously transmitted to the ESP8266 through Universal Asynchronous Receiver–Transmitter (UART) serial communication for cloud-based monitoring.

To enable remote supervision, the ESP8266 connects to a local Wi-Fi network and uploads the measured transformer parameters, including voltage, current, apparent power, real power, and power factor, to the Blynk cloud server. The Blynk mobile application provides an intuitive human–machine interface (HMI) through which these parameters are displayed in real time using configurable dashboard widgets. The platform also archives historical measurements and supports alarm notifications whenever predefined operating thresholds are exceeded, thereby facilitating early fault detection and preventive maintenance of distribution transformers.

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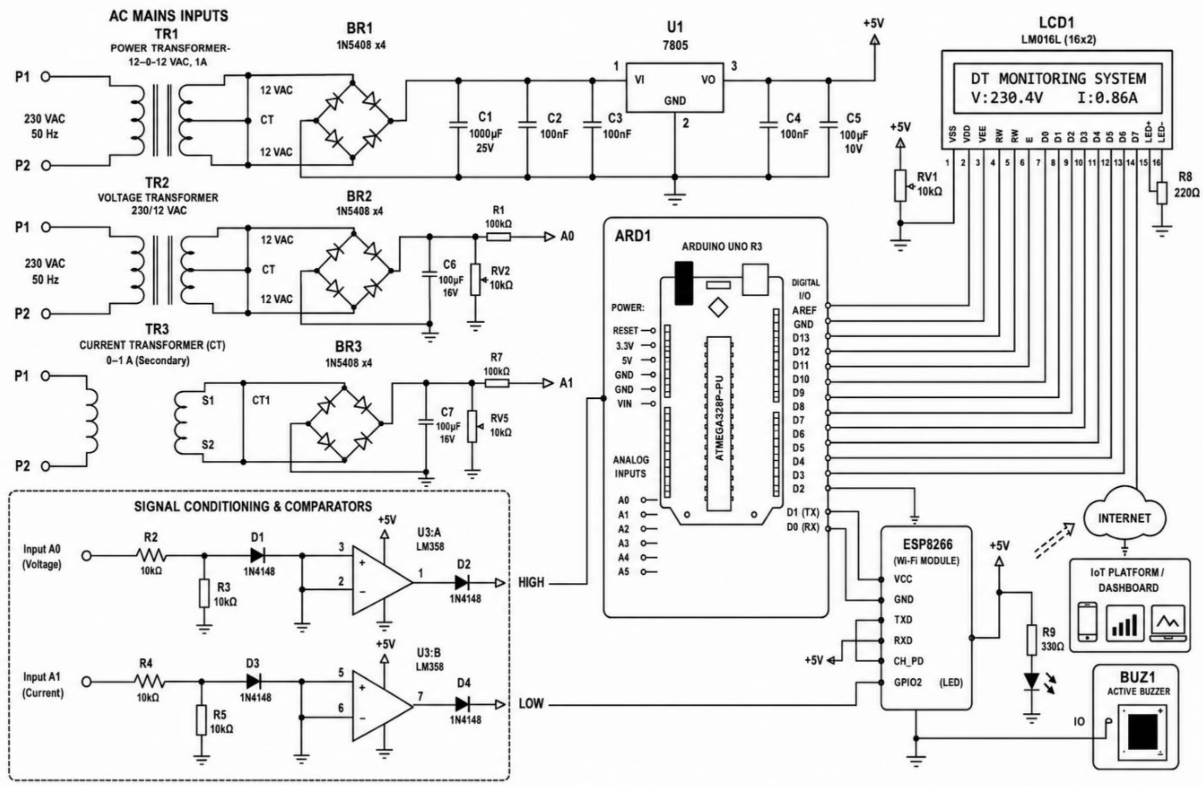


Figure 9: Complete circuit diagram of the developed IoT-based smart distribution transformer monitoring system

## 3. Results and Discussion

### 3.1 Developed Monitoring System

The proposed IoT-based distribution transformer monitoring system was successfully designed, implemented, and experimentally validated. The developed prototype integrates four major functional units: the sensing subsystem, embedded processing subsystem, communication subsystem, and visualisation subsystem. The sensing unit comprises the regulated power supply and voltage/current sensing circuits, while the Arduino Uno performs data acquisition, signal processing, electrical parameter computation, and fault monitoring. The ESP8266 Wi-Fi module enables wireless communication with the Blynk cloud platform, whereas local and remote visualisation is provided through a 16 × 2 LCD and the Blynk mobile application, respectively.

The prototype was developed through circuit simulation, hardware implementation, firmware programming, calibration, and experimental testing. The successful operation of the developed system demonstrates its capability for continuous acquisition, processing, and wireless transmission of transformer operating parameters in real time.

### 3.2 Hardware Implementation

The hardware prototype was initially assembled on a solderless breadboard to verify circuit functionality, calibrate the sensing circuits, and validate the embedded software. As shown in Figure 10(a), the breadboard implementation facilitated rapid testing and debugging while providing real-time display of the measured parameters through the LCD module. The successful prototype operation confirmed the proper integration of the sensing circuits, Arduino controller, ESP8266 communication module, and display unit.

Following successful validation, the prototype was migrated to a fabricated printed circuit board (PCB) for a more compact and reliable implementation. The completed PCB, shown in Figure 10(b), integrates the power supply, sensing circuits, microcontroller, and communication module into a single hardware platform suitable for continuous operation. Compared with the breadboard prototype, the PCB implementation reduced wiring complexity, improved mechanical stability, minimised electrical noise, and enhanced the overall robustness of the monitoring system.

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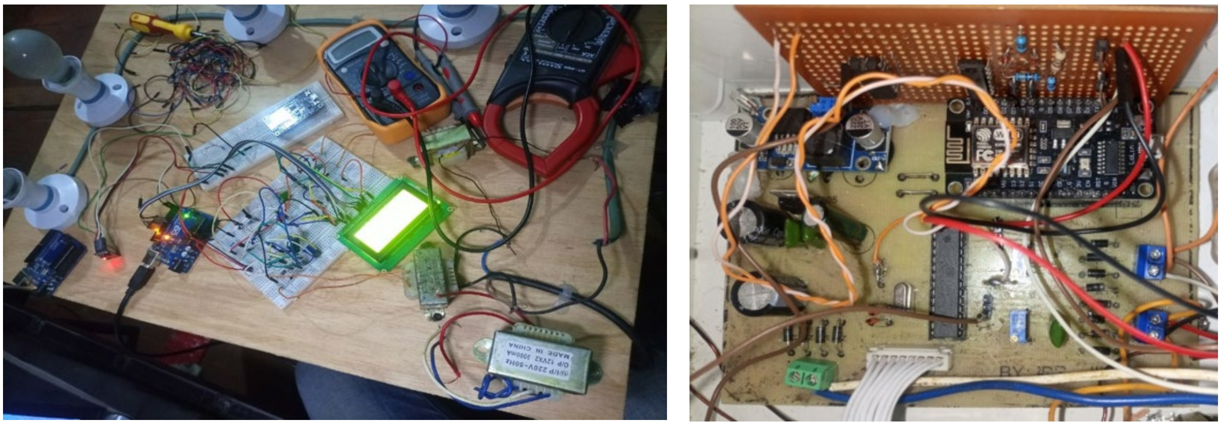


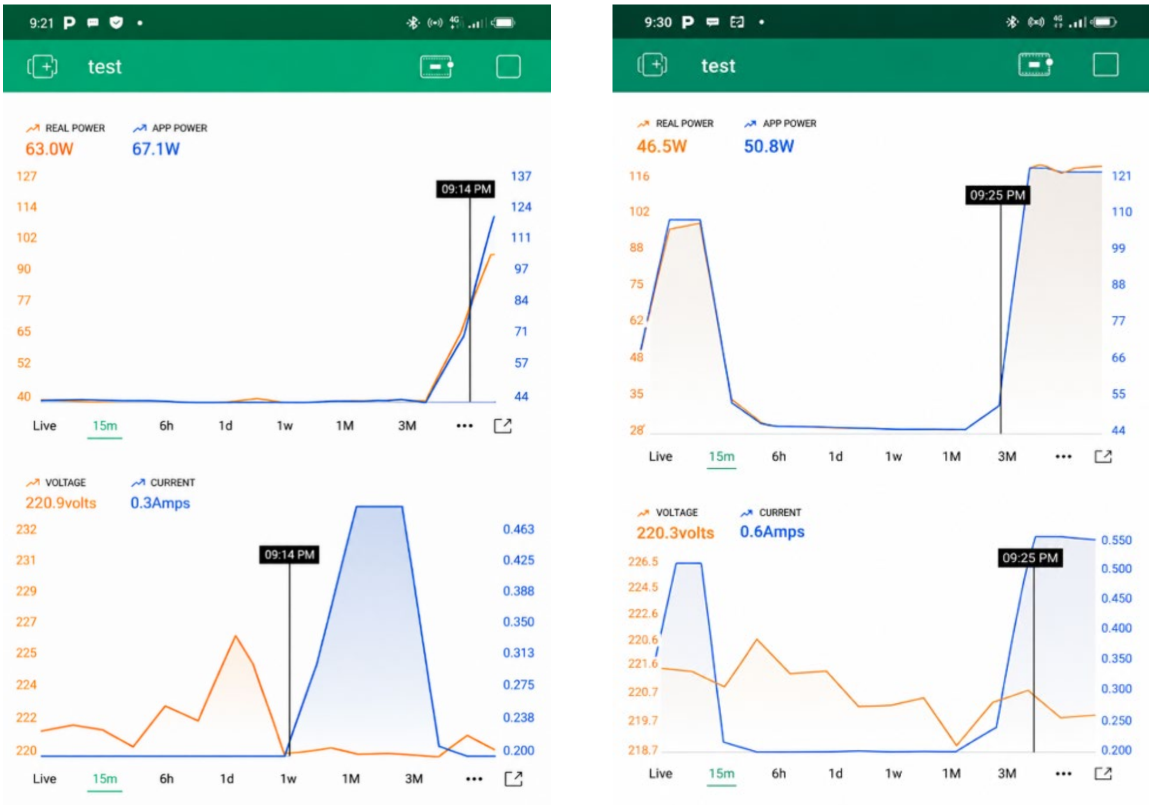
(a) (b)

Figure 10: (a) Breadboard implementation of the proposed IoT-based distribution transformer monitoring system. (b) Fabricated printed circuit board of the developed monitoring system

### 3.3 IoT Monitoring Interface

The developed monitoring system successfully transmitted transformer operating parameters to the Blynk cloud platform via the ESP8266 Wi-Fi module, enabling continuous real-time remote monitoring. The measured voltage, current, real power, and apparent power were simultaneously displayed on both the local LCD and the mobile dashboard, providing users with instant access to transformer operating conditions.

Representative screenshots of the Blynk dashboard are shown in Figures 11(a) and 11(b). Under one operating condition, the system recorded 220.9 V, 0.30 A, 63.0 W real power, and 67.1 VA apparent power. Under another loading condition, the measured values were 220.3 V, 0.60 A, 46.5 W real power, and 50.8 VA apparent power. The dashboard also provides real-time graphical trends of the measured parameters, allowing changes in transformer operating conditions to be monitored continuously. The successful synchronisation between the measured values and the cloud dashboard confirms the reliability of the wireless communication subsystem and the effectiveness of the developed IoT platform for continuous remote monitoring.




(a) (b)

Figure 11: (a) Blynk cloud dashboard showing real-time monitoring of transformer voltage, current, real power, and apparent power under one operating condition. (b) Remote monitoring interface illustrating successful wireless transmission and visualisation of transformer electrical parameters under a different loading condition

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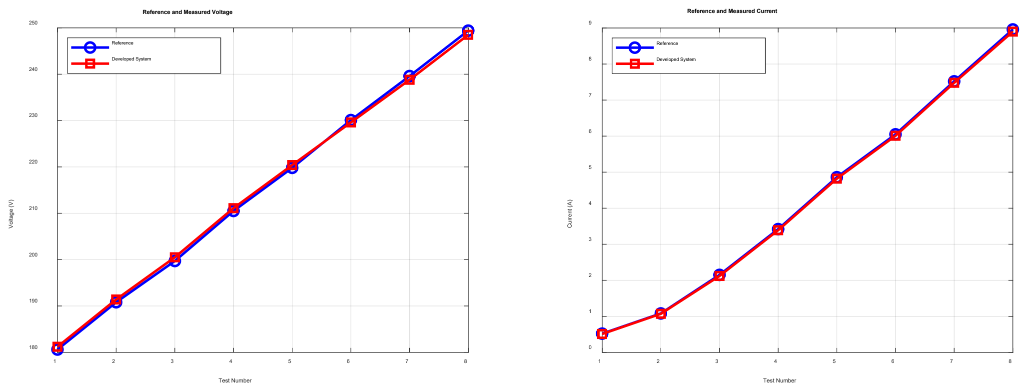
### 3.4 Performance Evaluation

The performance of the developed IoT-based distribution transformer monitoring system was evaluated by comparing the measured voltage and current with readings obtained from calibrated reference instruments under different operating conditions. The results were used to assess the measurement accuracy of the sensing circuits and the effectiveness of the adopted calibration models.

#### 3.4.1 Voltage and Current Measurement Performance

The voltage measurement performance of the developed system was evaluated by comparing its readings with those of a calibrated reference instrument over the operating range of 181–249 V, as shown in Figure 12(a). The measured values closely follow the reference measurements, with both curves exhibiting nearly identical trends across all eight test points. The maximum deviation observed was approximately 1.0 V, corresponding to a maximum percentage error of 0.40%, while the average error remained below 0.25%. This close agreement demonstrates the voltage-sensing circuit's high accuracy and the effectiveness of the adopted calibration model.

Similarly, Figure 12(b) presents the comparison between the reference and measured load current over a test range of 0.5–9.0 A. The developed system accurately tracked the reference current throughout the experiment, with the maximum deviation not exceeding 0.1 A, corresponding to a maximum error of approximately 1.1% at full load. The measured and reference curves almost overlap, confirming that the modified current transformer and signal conditioning circuit provide reliable current measurement under varying loading conditions. The experimental results indicate that the developed monitoring system achieved high measurement accuracy for both voltage and current, with excellent agreement between the measured and reference values. The small deviations observed are within acceptable limits for distribution transformer monitoring, thereby validating the suitability of the proposed sensing and calibration approach.




(a) (b)

Figure 12: (a) Comparison of reference and measured transformer voltage. (b) Comparison of reference and measured transformer load current

#### 3.4.2 Apparent Power and Real Power Estimation

Figure 13(a) compares the apparent power measured by the developed system with the reference values. The close overlap between both curves across the entire operating range indicates that the proposed system provides accurate apparent power estimation.

Similarly, Figure 13(b) presents the comparison of the measured and reference real power. The developed system closely follows the reference measurements, with only slight deviations observed at higher loading conditions due to cumulative measurement uncertainties. These results demonstrate the reliability of the proposed system for real-time power monitoring.

#### 3.4.3 Power Factor Estimation and Communication Performance

Figure 14(a) compares the estimated power factor with the reference values. The developed system closely follows the reference measurements across all test conditions, with only negligible deviations, demonstrating the accuracy of the implemented power factor estimation algorithm.

The communication performance of the IoT subsystem is presented in Figure 14(b). The system maintained stable Wi-Fi connectivity with an average connection time of approximately 3 s, dashboard refresh times below 2.1 s, and a data transmission success rate exceeding 99% throughout the experimental evaluation. These results confirm the reliability of the ESP8266-based communication module for continuous real-time transformer monitoring.

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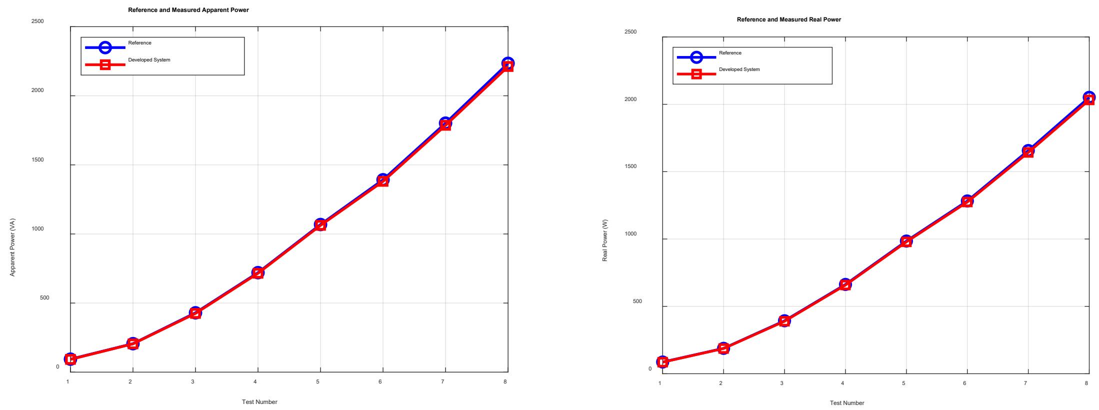
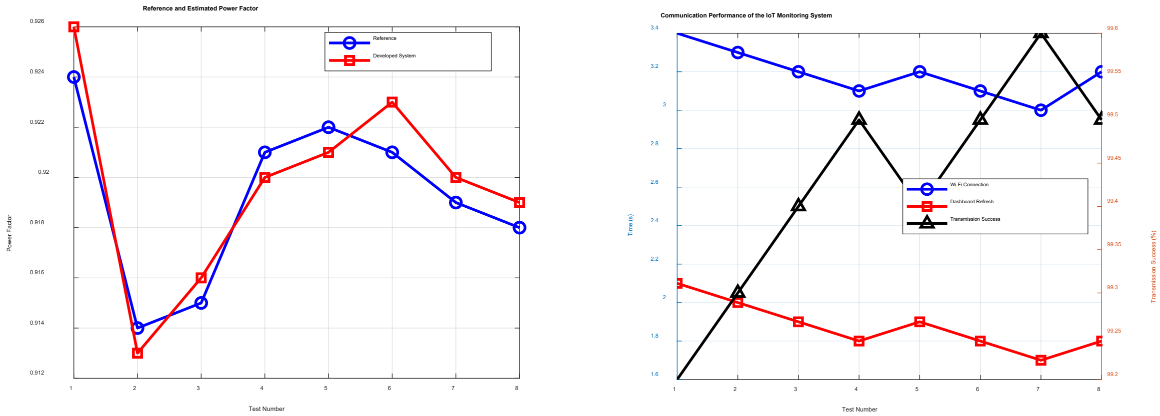
The developed system demonstrated accurate estimation of electrical parameters and reliable cloud-based data transmission, validating its suitability for remote condition monitoring of distribution transformers.




(a) (b)

Figure 13: (a) Comparison of reference and measured apparent power. (b) Comparison of reference and measured real power




(a) (b)

Figure 14: (a) Comparison of reference and estimated power factor. (b) Communication performance of the developed IoT-based distribution transformer monitoring system

## 5. Conclusion

This study presented the design, implementation, and experimental validation of an IoT-based distribution transformer monitoring system for continuous real-time monitoring of transformer operating parameters. The developed system integrates voltage and current sensing circuits, an Arduino Uno microcontroller, an ESP8266 Wi-Fi communication module, and a Blynk cloud platform to provide both local and remote visualisation of transformer operating conditions.

Experimental evaluation demonstrated the satisfactory performance of the developed system. The measured voltage closely matched the reference instrument over the operating range of 181–249 V, with a maximum deviation of approximately 1 V (less than 0.5% error). Similarly, current measurements exhibited a maximum deviation of about 0.1 A across the 0.5–9.0 A test range. The estimated apparent power, real power, and power factor also showed excellent agreement with the reference measurements, confirming the effectiveness of the sensing circuits and calibration algorithms. Furthermore, the communication subsystem maintained stable Wi-Fi connectivity, with dashboard refresh times below 2.1s and a data transmission success rate exceeding 99%, enabling reliable real-time cloud-based monitoring.

The developed monitoring system provides an accurate, low-cost, and reliable solution for continuous condition monitoring of distribution transformers. By enabling real-time acquisition, visualisation, and remote access to transformer operating data, the proposed system has the potential to improve maintenance planning, facilitate early fault detection, and enhance the operational reliability of electrical distribution networks. Future work will focus on incorporating additional condition-monitoring parameters, including transformer oil temperature, oil level, dissolved gas concentration, and vibration, as well as integrating artificial intelligence and machine learning techniques for predictive fault diagnosis and remaining useful life estimation, thereby supporting intelligent asset management in smart grid environments.

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