

ESP32-Based Transformer Health Monitoring System Using IoT: Design, Implementation, and Validation

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Abstract:

Electrical power transformers are critical and expensive assets in power distribution networks, vulnerable to failures from electrical, thermal, and mechanical stresses. Unplanned outages result in significant financial losses and safety hazards. This research presents the design and implementation of a comprehensive, low-cost transformer health monitoring system utilizing an ESP32 microcontroller and Internet of Things (IoT) technology. The system continuously monitors five key parameters—voltage, current, temperature, humidity, and vibration—using dedicated sensors: ZMPT101B, ACS712, DHT22, and SW-420. Data is processed by the ESP32 and transmitted in real-time to the Blynk cloud platform via Wi-Fi. The system implements a robust fault detection algorithm with configurable thresholds and software debounce logic. Upon detecting an anomaly (e.g., overvoltage, overload, overheating), it triggers a local buzzer, displays the fault on a 16x2 LCD, and sends an instant push notification to a remote operator. Hardware validation confirmed accurate sensor readings and a 100% success rate in detecting six simulated fault conditions within 3–10 seconds. With a total hardware cost, this system offers a scalable, cost-effective solution for proactive transformer maintenance, enabling a shift from reactive, periodic inspections to continuous, real-time monitoring.

I. INTRODUCTION

Transformers are fundamental components in electrical power systems, responsible for efficient voltage transformation across generation, transmission, and distribution networks. Their continuous operation under dynamic loads exposes them to cumulative stresses—electrical (overvoltage, transients), thermal (winding overheating), and environmental (moisture ingress, mechanical vibration). These factors progressively degrade insulation materials and dielectric oil, leading to premature aging and catastrophic failure. According to industry analyses, transformer failures account for a substantial portion of unplanned power outages, causing extensive economic disruption and safety risks [1].

Traditional maintenance relies on periodic manual inspections and techniques like Dissolved Gas Analysis (DGA) and thermal imaging. While valuable, these methods are inherently reactive, offering only snapshots of transformer health and leaving extended windows where developing faults can escalate undetected [2]. The economic

further limits their deployment to only critical high-capacity transformers, leaving the vast majority of distribution transformers unmonitored.

The convergence of affordable microcontroller units (MCUs), low-cost sensors, and ubiquitous cloud connectivity through IoT presents a paradigm shift. This research leverages the ESP32 System-on-Chip (SoC)—known for its integrated Wi-Fi, dual-core processor, and versatile analog/digital interfaces—to develop a comprehensive, yet economically viable, online monitoring system [3]. The proposed system aims to bridge the gap between costly commercial solutions and the unmet need for continuous health assessment of distribution transformers, particularly in rural and semi-urban networks. This document is a template. An electronic copy can be downloaded from the conference website. For questions on paper guidelines, please contact the conference publications committee as indicated on the conference website. Information about final paper submission is available from the conference website.

II. BACKGROUND AND LITERATURE

A. Conventional Transformer Monitoring Techniques

Transformer health monitoring has evolved over decades. Dissolved Gas Analysis (DGA) is a well-established diagnostic technique that analyzes gases dissolved in transformer oil (e.g., H₂, CH₄, C₂H₂, C₂H₄) to identify incipient faults like arcing, overheating, and partial discharge. Methods like the Duval Triangle and IEC 60599 provide diagnostic interpretation [3]. While highly sensitive, DGA requires oil sampling, laboratory analysis, and skilled personnel, making it unsuitable for continuous monitoring. Infrared thermography is another widely used offline technique for detecting hot spots on bushings, connections, and tank walls caused by overloads or degraded cooling [4]. Commercial online monitoring systems (e.g., ABB TEC, Siemens SITRANS) integrate multiple sensors for parameters like load current, winding temperature, and gas concentrations but are cost-prohibitive (₹5–50 lakhs), limiting their use to critical transmission-level transformers [5].

B. IoT-Based Monitoring Systems

The application of IoT technology represents a transformative approach. A systematic review in *MDPI Applied Sciences* (2024) concluded that IoT significantly enhances predictive maintenance and fault detection accuracy by enabling continuous, multi-parameter condition monitoring [1]. Common architectures include direct cloud-connected microcontrollers, gateway-aggregated sensor networks, and fog computing models. Research by IJRASET demonstrated an ESP32-based system for monitoring voltage, current, temperature, and oil level, achieving data upload latency under two seconds and push notification delivery within 3–5 seconds using the Blynk platform [2]. Studies indicate that a five-parameter monitoring approach (covering electrical, thermal, and mechanical aspects) provides superior fault detection accuracy compared to simpler systems [3].

C. The ESP32 in Industrial IoT

The ESP32 SoC has become ubiquitous in edge IoT applications. Its features—dual-core Xtensa LX6 processor up to 240 MHz, integrated 802.11 b/g/n Wi-Fi, Bluetooth, 12-bit SAR ADC, and low

power consumption—are packaged at a unit cost below ₹400, making it ideal for cost-sensitive deployments [6]. For analog sensing, a critical constraint is that ADC2 channels cannot be used concurrently with active Wi-Fi, necessitating the use of ADC1 channels (GPIO32-39) for uninterrupted sensor readings [7]. Its robustness and extensive library support have been validated in various industrial monitoring applications, from motor diagnostics to environmental sensing.

D. IoT Cloud Platforms and Sensor Technologies

Cloud platforms form the backbone of IoT systems. Blynk is popular for prototyping due to its free tier, intuitive drag-and-drop dashboard, real-time widgets, and event-triggered notifications [8]. ThingSpeak, integrated with MATLAB, is favored for data analysis but has slower update rates on its free tier [9]. Sensor selection is crucial for accuracy and cost. The ZMPT101B voltage sensor provides galvanic isolation and ±1% accuracy for AC mains measurement [10]. The ACS712 Hall-effect current sensor offers non-contact measurement, with the 30A variant having a sensitivity of 66 mV/A [10]. The DHT22 digital sensor provides calibrated temperature (±0.5°C) and humidity (±2%) readings via a single-wire interface [3]. The SW-420 vibration module offers a simple digital output for detecting abnormal mechanical shocks [11].

III. METHODOLOGY

E. System Architecture Overview

The proposed system employs a layered architecture comprising the Sensor Layer, Processing Layer, Output Layer, and Cloud/User Layer. The Sensor Layer consists of the ZMPT101B (voltage), ACS712 (current), DHT22 (temperature & humidity), and SW-420 (vibration) modules. The Processing Layer is built around the ESP32 DevKit V1 microcontroller, which acquires sensor data, executes the fault detection algorithm, and manages communications. The Output Layer includes a 16x2 LCD for local display, a piezoelectric buzzer for audible alarms, and a relay module for potential load tripping. The Cloud/User Layer leverages the Blynk IoT platform for remote dashboard visualization, data logging, and push notification alerts to an operator's smartphone.

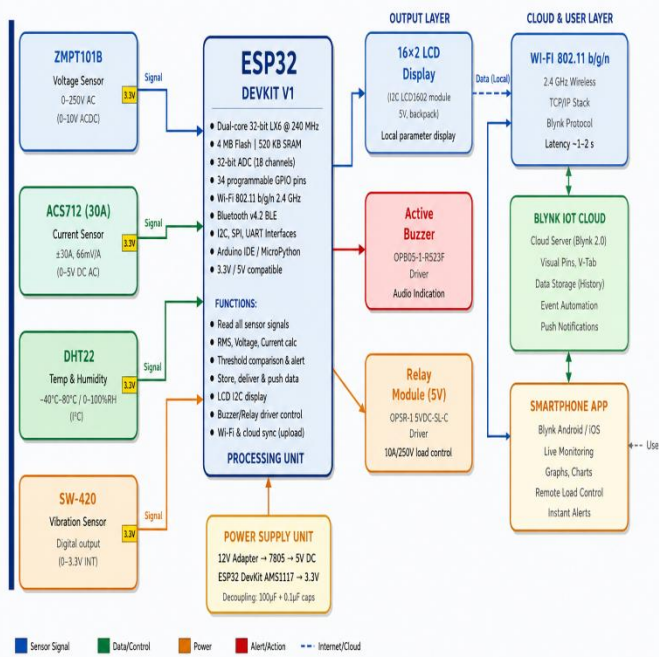


Fig. 1 Block Diagram of the Proposed System

F. Hardware Components and Specifications

- 1) **ESP32 DevKit V1 Microcontroller:** The core processing unit. Key specs: Dual-core Xtensa LX6 @ 240 MHz, 4 MB Flash, 520 KB SRAM, Integrated 802.11 b/g/n Wi-Fi, 34 GPIOs, 12-bit ADC (18 channels). Powered via 5V USB/VIN, with an onboard AMS1117-3.3V LDO regulator [6], [7].
- 2) **ZMPT101B AC Voltage Sensor Module:** A transformer-based isolated sensor. Input: 0–250V AC; Output: 0–5V analog (corresponding to 0–250V RMS); Accuracy: ±1%. Connected to ESP32 GPIO34 (ADC1_CH6) [10].
- 3) **ACS712-30A Current Sensor Module:** A Hall-effect based linear current sensor. Range: ±30A; Sensitivity: 66 mV/A; Zero-current output: VCC/2 (2.5V). Connected to ESP32 GPIO35 (ADC1_CH7) [10].
- 4) **DHT22 Digital Temperature & Humidity Sensor:** Provides calibrated digital output. Temperature Range: -40°C to +80°C (±0.5°C). Humidity Range: 0–100% RH (±2%). Uses a single-wire protocol on GPIO4 with a 10 kΩ pull-up resistor [3].
- 5) **SW-420 Vibration Sensor Module:** Contains a spring-type normally-closed vibration switch and an LM393 comparator. Outputs a digital LOW upon vibration detection. Connected to GPIO13 configured as a falling-edge interrupt
- 6) **16x2 LCD with I2C Interface:** HD44780-based display with a PCF8574 I²C backpack (address 0x27). Reduces connection wires to two (SDA →GPIO21, SCL →GPIO22).
- 7) **Output Actuators:** A 5V active buzzer (GPIO26) for audible alarms and a single-channel 5V relay module (10A/250V AC contact, GPIO25) for optional load disconnection

8) **Power Supply:** A 12V/1A DC adapter feeds a 7805 linear regulator to provide a stable 5V rail for sensors, LCD, and relay. The ESP32 derives its 3.3V supply internally from the 5V input.

G. Software and Firmware Design

The firmware was developed using the Arduino IDE with the ESP32 board support package. The code is modularly structured into managers

- 1) **SensorManager:** Handles periodic reading and RMS calculation for analog sensors, and digital polling of DHT22
- 2) **FaultDetector:** Compares readings with configurable thresholds and implements a 3-second debounce logic to confirm faults.
- 3) **DisplayManager:** Controls the LCD state machine (Normal, Fault, Connecting modes).
- 4) **AlertManager:** Generates non-blocking buzzer patterns and controls the relay.
- 5) **IoTManager:** Manages Wi-Fi connection, Blynk communication (Blynk.run()), and virtual pin updates.

The main loop executes a 1-second timer-based cycle: read sensors → check thresholds → update LCD → send data to Blynk → check/trigger alerts. Persistent configuration (thresholds, calibration factors) is stored in the ESP32's Non-Volatile Storage (NVS) using the Preferences library.

H. Cloud Integration and Dashboard

The Blynk 2.0 platform was configured with a device template defining six data streams: V0 (Voltage), V1 (Current), V2 (Temperature), V3 (Humidity), V4 (Vibration Status), and V5 (System Status String). A mobile dashboard was created with gauge widgets for V0-V3, an LED for V4, and a button for manual relay control. Blynk Automations were set to trigger instant push notifications to a smartphone when any data stream exceeds its predefined threshold (e.g., V2 > 85 for over temperature) [8].

I. Fault Detection and Control Strategy

The system monitors five independent parameters against the thresholds derived from standards like IEC 60076 and IS 2026 [12], [13]. The fault detection algorithm employs a two-tier, debounced approach to ensure reliability:

Fault Detection Algorithm Flowchart:

Threshold Parameters:

- Voltage: Safe range: 180V – 260V AC.

- Current: Overload threshold: 120% of rated current ($I_{rated} \times 1.2$).
- Temperature: Overtemperature threshold: 85°C.
- Humidity: High humidity threshold: 80% RH.
- Vibration: Fault confirmed if ≥ 5 events are detected within any rolling 10-second window.

Upon fault confirmation, a three-tier alert is triggered:

- Local Audible Alert: Buzzer activates with a distinct pattern.
- Local Visual Alert: LCD display alternates between the fault message and live readings.
- Remote Notification: Instant push notification is sent via Blynk to the operator's smartphone.

IV. RESULTS AND DISCUSSION

A. Experimental Setup

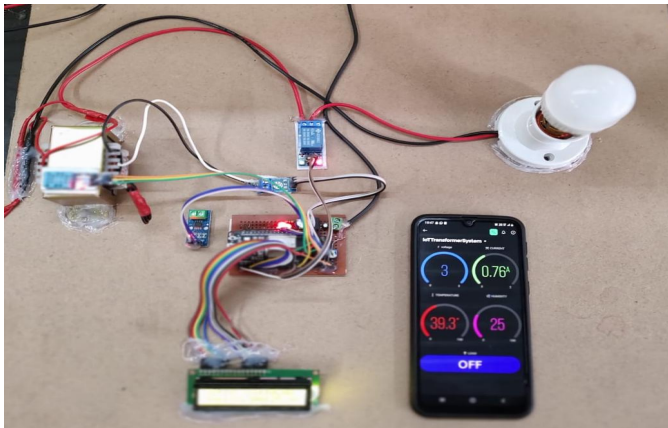


Fig. 2 Assembled hardware prototype during testing, showing the ESP32, sensor modules, LCD, and connected test transformer.

The prototype was tested in a laboratory environment. The test setup included the assembled prototype PCB, a 50VA step-down test transformer (230V/12V), a 25W incandescent bulb as a load, and reference instruments: a Fluke 117 True-RMS multimeter for voltage/current, an HTC MT-6 non-contact thermometer, and a Fluke 971 humidity meter. Faults were simulated using a variac (for voltage), additional load bulbs (for current), a heat

gun (temperature), a steam humidifier (humidity), and mechanical tapping (vibration).

B. Live Sensor Readings and Accuracy

The system successfully acquired and displayed live sensor data. The table below compares ESP32 readings with reference instrument values under normal operating conditions

TABLE I Live Sensor Readings — ESP32 vs. Reference Instrument Comparison

Sr	Parameter	ESP32 Value	Reference Instrument	Error	Threshold	Status
1	Voltage (V AC)	3.0 V	3.1 V (DMM)	-0.1V (3.2%)	180–260V	NORMAL
2	Current (A)	0.76 A	0.78 A (Clamp)	-0.02A (2.6%)	$< 1 \times 1.2$	NORMAL
3	Temperature (°C)	39.3°C	39.8°C (Therm.)	-0.5°C (1.3%)	$< 85^\circ\text{C}$	NORMAL
4	Humidity (%RH)	25% RH	26% (Meter)	-1% (3.8%)	$< 80\%$	NORMAL
5	Vibration	Not detected	None applied	N/A	$< 5/10\text{s}$	NORMAL
6	Relay / Load	OFF	Bulb OFF (visual)	N/A	Controlled	NORMAL

All measurement errors were within the manufacturers' specified accuracy ranges, validating the sensor interfacing and calibration routines. The slightly higher percentage error for voltage at 3V is attributed to reduced linearity of the ZMPT101B at very low voltages compared to its 250V rated range.

C. IoT Dashboard Performance

The Blynk mobile dashboard successfully displayed all parameters in real-time. Data update latency from sensor read to dashboard refresh was consistently below 2 seconds under stable Wi-Fi (RSSI ≈ -55 dBm). The dashboard provided clear visualization through gauges and status LEDs, confirming effective cloud integration.

D. IoT Dashboard Performance

All six programmed fault conditions were successfully simulated and detected. The results are summarized in the table below.

The system achieved a 100% detection rate. The 5-second detection time for overheat (vs. 3 seconds

for others) is attributed to the thermal response time of the DHT22 sensor itself. Push notifications were delivered to the test smartphone within 2–4 seconds of fault confirmation.



Fig. 3 Blynk IoT mobile dashboard showing live readings (V=3V, I=0.76A, T=39.3°C, H=25%) during testing

TABLE 2 Fault Detection Test Results — All 6/6 Tests: PASS

Fault Type	Test Method	Threshold	Measured	Detect Time	LED	Buzz.	Notif.
Overvoltage	Variac → 270V	260V upper	271.2V	3.0 s	Y	Y	Y
Undervoltage	Variac → 160V	180V lower	158.7V	3.0 s	Y	Y	Y
Overload	Extra load bulbs	I × 1.2	I=6.4A	3.0 s	Y	Y	Y
Overheat	Heat gun near DHT22	85°C	91.4°C	5.0 s	Y	Y	Y
High Humidity	Steam humidifier	80% RH	86.2% RH	3.0 s	Y	Y	Y
Vibration	Mechanical tapping	5/10s	7 events/10s	< 10 s	Y	Y	Y

The results validate the system's core proposition: it transforms transformer maintenance from a reactive, periodic task into a proactive, continuous process. The dramatic reduction in fault detection time—from days to seconds—can prevent the escalation of incipient faults into catastrophic failures. The low cost addresses the primary barrier to large-scale deployment, making it viable for utilities to monitor thousands of distribution transformers

TABLE 3 Comparison — Proposed IoT System vs. Conventional Manual Inspection

Parameter	Manual Inspection	Proposed IoT System
Monitoring Frequency	Weekly / fortnightly rounds	Continuous — 1-second intervals 24/7
Fault Detection Delay	Up to 7–14 days	3–10 seconds from fault onset
Parameters Monitored	2–3 (limited by instruments)	5 simultaneously: V, I, T, H, Vibration
Remote Access	Not available — site visit required	Worldwide via Blynk smartphone app
Data Logging	Manual paper logbook (monthly)	Automatic cloud — 30-day history, 1-s resolution
Fault Alert	None — detected at next visit only	Instant push notification in 2–4 seconds
Night/Off-Hours	No monitoring outside working hours	Full monitoring 24 hours/day, 7 days/week
Cost	Rs 500–2000 per inspection visit	One-time Rs 1,420 hardware per transformer

V. CONCLUSIONS

This paper presented the successful design, implementation, and validation of a low-cost, ESP32-based IoT system for comprehensive transformer health monitoring. The system simultaneously tracks five critical parameters—voltage, current, temperature, humidity, and vibration—enabling a holistic assessment of transformer condition. The implemented fault detection algorithm with software debouncing ensures reliable alerting without false positives. Integration with the Blynk cloud platform provides real-time remote visualization and instant push notification to field engineers, irrespective of their location. Laboratory testing confirmed the system's functionality, with accurate live readings and 100% detection of all simulated fault conditions within 3–10 seconds. With a total hardware cost of approximately ₹1,500 per unit, the proposed system offers a transformative, economically viable solution for enabling predictive maintenance of distribution transformers. It effectively bridges the gap between the need for continuous monitoring and the cost constraints of large-scale deployment, particularly in rural and semi-urban power networks.

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