

AI-Based Fault Detection and Health Monitoring System for Transformers

Akash Sawant, Nishant Pudale, Mayuresh Patil, Kirti Jadhav

U.G. Student, Department of Electrical Engineering, Nanasaheb Mahadik College of Engineering, Sangli, MH, India

U.G. Student, Department of Electrical Engineering, Nanasaheb Mahadik College of Engineering, Sangli, MH, India

U.G. Student, Department of Electrical Engineering, Nanasaheb Mahadik College of Engineering, Sangli, MH, India

Associate Professor, Department of Electrical Engineering, Nanasaheb Mahadik College of Engineering, Sangli,
MH, India

ABSTRACT: Transformers are critical components in electrical power systems, and their failure can result in significant economic losses, safety risks, and power interruptions. Conventional maintenance methods are primarily reactive and rely on periodic inspections, which lack real-time monitoring and early fault detection capability. To address these limitations, this paper presents an AI-based fault detection and health monitoring system integrating Internet of Things (IoT) and Artificial Intelligence (AI) techniques. The proposed system employs a dual-layer architecture. The first layer consists of an IoT-based hardware module that continuously monitors essential parameters such as voltage, current, oil level, and temperature using sensors interfaced with a microcontroller and Wi-Fi module. The collected data is transmitted to a cloud platform for real-time monitoring and anomaly detection. The second layer focuses on internal fault analysis using AI techniques. Various transformer fault conditions are simulated in a MATLAB/Simulink environment, and the resulting electrical data is processed using a Python-based model to detect and classify faults accurately. The integrated approach provides a cost-effective, reliable, and proactive solution for transformer health management. It enhances operational safety, reduces downtime, and improves system reliability, contributing to the development of smart and resilient power systems.

KEYWORDS: Transformer Health Monitoring, Fault Detection, Internet of Things (IoT), Artificial Intelligence (AI), Predictive Maintenance, Smart Power Grid

I. INTRODUCTION

The electrical power system forms the backbone of modern infrastructure, enabling industrial operations, commercial activities, and domestic usage. Among its key components, transformers play a crucial role in ensuring efficient transmission and distribution of electrical energy. The reliability of the entire power grid is highly dependent on the operational health of transformers, as their failure can lead to power outages, economic losses, and safety hazards. In practical conditions, transformers are subjected to continuous electrical and environmental stresses such as load variations, voltage fluctuations, and temperature changes. Over time, these factors degrade internal components including insulation oil and winding structures. Undetected faults, such as insulation failure or inter-turn winding faults, can escalate into severe failures, resulting in equipment damage, fire hazards, and system instability.

Conventional maintenance strategies for transformers are largely reactive or based on periodic inspections. These methods involve manual monitoring of parameters such as temperature and oil level, which are time-consuming and do not provide continuous real-time data. Consequently, sudden faults that develop between inspection intervals often remain undetected, leading to unexpected failures and increased downtime. To overcome these limitations, this paper proposes an AI-based fault detection and health monitoring system for transformers. The system integrates Internet of Things (IoT) technology for real-time monitoring of physical parameters, including voltage, current, oil level, and temperature, using sensor-based hardware modules connected to a microcontroller. The collected data is transmitted to a cloud platform for remote monitoring and analysis. In addition, an Artificial Intelligence (AI)-based module is incorporated to detect internal electrical faults that are not directly observable through physical sensors. Fault conditions are simulated using MATLAB/Simulink, and the resulting electrical data is processed using a Python-based

model to classify and identify faults accurately. The proposed system provides a proactive, reliable, and cost-effective solution for transformer health management, enhancing system safety, reducing downtime, and improving overall grid reliability.

II. LITERATURE SURVEY

Conventional transformer protection techniques such as overcurrent, earth fault, and differential relays have been widely used due to their simplicity and reliability, but they fail to detect low-level internal faults like inter-turn short circuits at an early stage, leading to severe damage [1]. To address these limitations, Artificial Neural Networks (ANN) were introduced, enabling data-driven fault detection and identification of non-linear fault patterns, although early implementations were limited by computational constraints [2]. Wavelet transform combined with pattern recognition techniques further improved fault diagnosis by providing better time-frequency analysis of non-stationary signals and detecting transient disturbances accurately [3]. Hybrid approaches integrating wavelet transforms with ANN enhanced fault classification accuracy while reducing noise and improving efficiency [4]. GSM-based monitoring systems enabled remote tracking of parameters such as oil level and temperature but remained reactive in nature [5]. Arduino-based embedded systems provided low-cost monitoring solutions, though they lacked advanced analytical capabilities [6]. Machine learning techniques such as Support Vector Machines and Decision Trees improved fault detection accuracy and enabled precise fault location [7]. Recent IoT-based systems using NodeMCU and platforms like Blynk allow real-time monitoring and cloud-based visualization [8]. Deep learning methods, such as CNN with wavelet scalograms, further enhanced the detection of internal faults [9]. Modern systems integrate IoT with AI to enable predictive maintenance, improving reliability and supporting smart grid development [10].

III. METHODOLOGY

The proposed system is designed as a hybrid architecture integrating Internet of Things (IoT)-based real-time monitoring with Artificial Intelligence (AI)-based fault detection. The methodology consists of four main stages: system architecture design, data acquisition, fault analysis, and system integration.

3.1 System Architecture

The overall system is divided into two main modules: (i) IoT-based hardware monitoring and (ii) AI-based fault detection.

In the hardware module, sensors are deployed on the transformer to continuously monitor key parameters such as oil level, temperature, voltage, and load current. An Arduino Nano is used as the central processing unit to collect sensor data, while a NodeMCU (ESP8266) module transmits the data to a cloud platform via Wi-Fi. This enables real-time remote monitoring through a graphical dashboard.

3.2 Data Generation and Acquisition

To analyze internal electrical faults, a three-phase transformer model is developed using MATLAB/Simulink. The model simulates normal and faulty operating conditions, including line-to-ground faults and inter-turn winding faults. The system captures three-phase voltage and current signals (V_a , V_b , V_c and I_a , I_b , I_c), which are exported as CSV files for further analysis.

3.3 AI-Based Fault Detection

A Python-based algorithm is developed to process the exported electrical data. The algorithm analyzes current waveforms and compares them with predefined threshold values to identify abnormal conditions. Based on variations in magnitude and pattern, the system detects and classifies faults such as phase faults and inter-turn faults. This approach enables accurate identification of internal faults that cannot be detected using external sensors.

3.4 System Integration

The IoT monitoring module and AI-based analysis module are integrated to form a unified system. The hardware module provides real-time physical condition monitoring, while the AI module performs detailed fault analysis using simulated data. The combined system generates alerts and diagnostic outputs, enabling predictive maintenance and improving transformer reliability.

3.5 Testing and Evaluation

The system is tested under various conditions to validate its performance. Hardware sensors are evaluated using controlled inputs, while multiple fault scenarios are simulated in MATLAB to generate datasets. The Python algorithm is tested for accuracy in fault detection and classification. Additionally, the reliability of data transmission and system response time are analyzed to ensure effective real-time operation

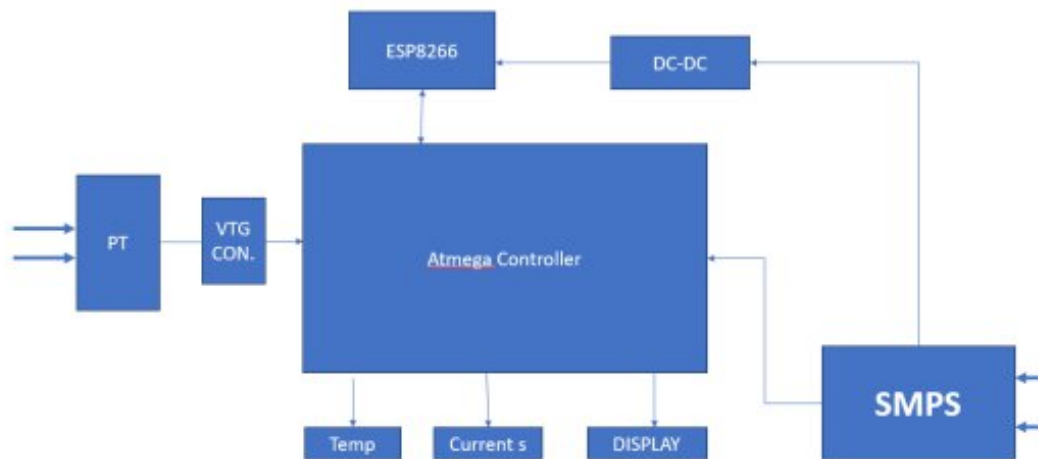


Figure 3.1: Block Diagram of System

Working Principle

A. The proposed AI-based transformer monitoring system operates through a hybrid architecture consisting of two parallel modules: an IoT-based hardware monitoring unit and an AI-based fault analysis module.

B. The hardware module is installed on the transformer to continuously monitor physical parameters such as oil level, temperature, voltage, and load current. An Arduino Nano acts as the central controller, acquiring data from sensors including an ultrasonic sensor for oil level measurement and a temperature sensor for thermal monitoring. The collected data is processed and transmitted to a NodeMCU (ESP8266) module via serial communication. The NodeMCU connects to a Wi-Fi network and uploads the data to a cloud-based IoT platform such as Blynk or ThingSpeak. This enables real-time visualization of transformer parameters and triggers alerts when predefined safety thresholds are exceeded.

C. In parallel, internal fault detection is performed using a simulation-based AI approach. A three-phase transformer model is developed in MATLAB/Simulink to simulate various operating conditions, including normal operation, line-to-ground faults, and inter-turn winding faults. The model generates three-phase voltage and current signals (V_a , V_b , V_c and I_a , I_b , I_c), which are exported as CSV files for analysis.

D. A Python-based algorithm processes the exported data to identify abnormal patterns in current waveforms. The algorithm compares real-time values with predefined thresholds and detects anomalies such as sudden current spikes in specific phases. Based on this analysis, the system classifies faults and generates diagnostic outputs, enabling accurate identification of internal transformer faults.

E. By integrating real-time IoT monitoring with AI-based fault analysis, the system provides comprehensive protection by detecting both external physical abnormalities and internal electrical faults, thereby improving transformer reliability and enabling predictive maintenance.

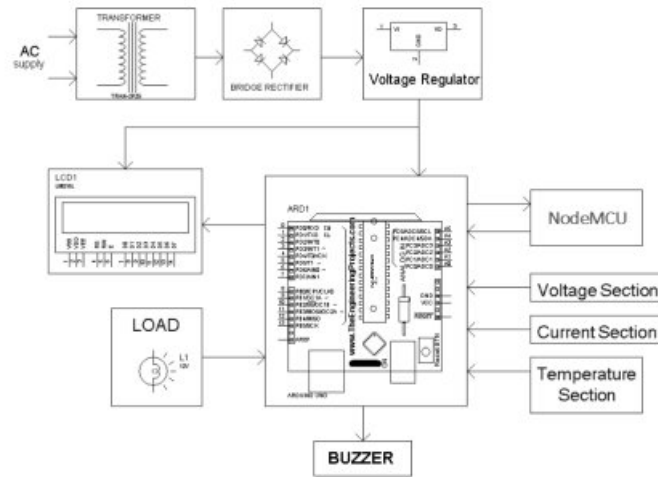
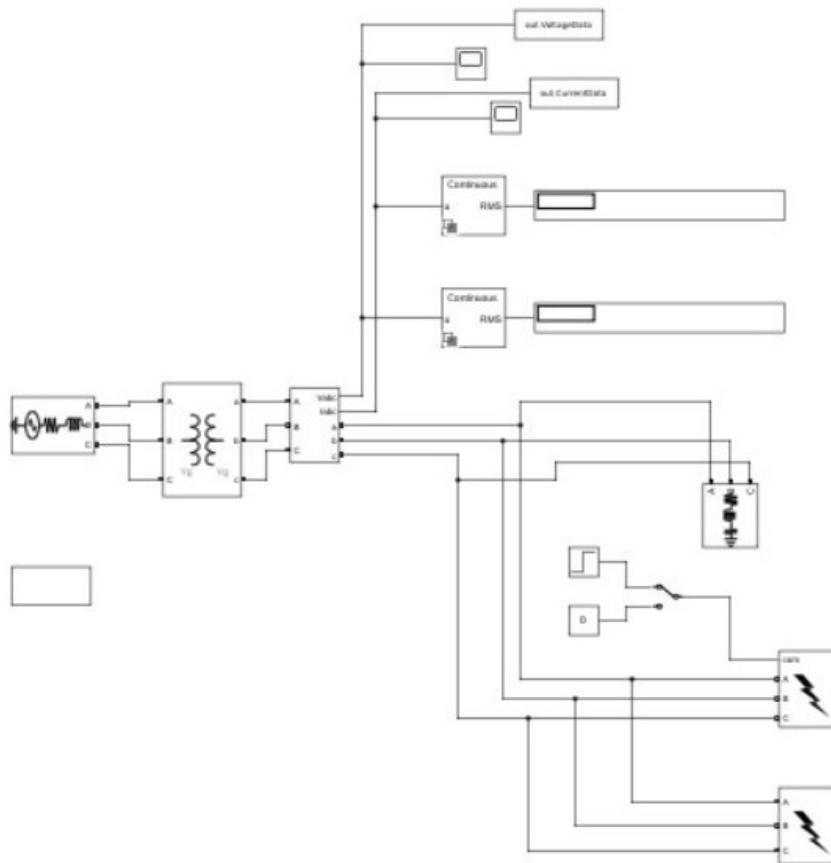


Figure 3.2: Circuit Diagram of the System

MATLAB Simulation



IV. EXPERIMENTAL RESULTS

A. AI-Based Analysis under Normal Condition

Fig. 1(a) represents the system behavior under normal operating conditions using simulation data. The ai-based analysis processes three-phase voltage and current values and verifies that all parameters remain within predefined safety limits. The observed results indicate that the voltage across all three phases (phase a, phase b, and phase c) is approximately equal (≈ 359 v), and the current values remain stable (≈ 3.59 a). This confirms balanced load conditions and proper transformer operation. The ai model analyzes the incoming data and classifies the system state as healthy, ensuring that no abnormality is present. This validates the reliability of the system in correctly identifying normal operating conditions without generating false alarms.

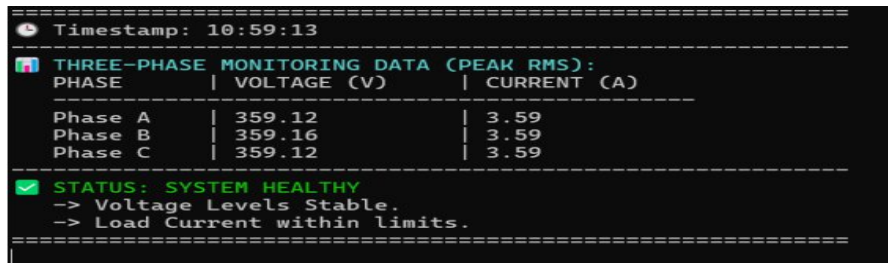


Fig. 1(a)

B. AI-Based Fault Detection (Abnormal Condition)

Fig. 1(b) shows the system response under abnormal conditions when a fault (such as inter-turn or three-phase symmetrical fault) is introduced in the simulation. In this case, the current magnitude increases drastically in the affected phase(s), indicating severe electrical stress within the transformer.

The AI model continuously monitors the current waveform and detects this sudden spike as an anomaly. It accurately identifies the fault type and the affected phases (e.g., A-B-C fault) and classifies it as a critical fault condition. Additionally, the system generates diagnostic output and suggests protective actions such as circuit breaker tripping. This demonstrates the effectiveness of the AI algorithm in detecting internal faults that are not visible through conventional monitoring systems.

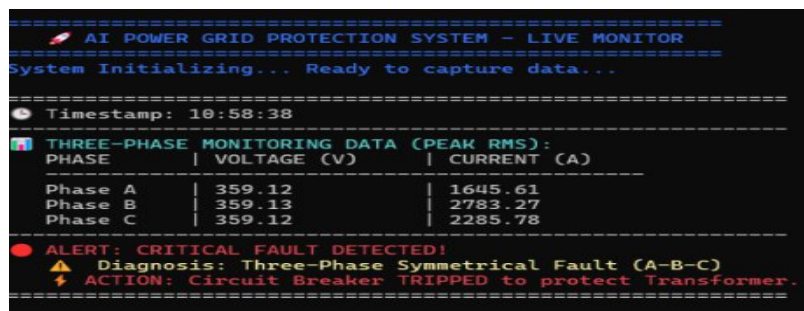


Fig. 1(B)

C. IoT-Based Hardware Monitoring Results

The IoT-based monitoring system provides real-time visualization of key transformer parameters, including current, voltage, oil level, and temperature, as shown in Fig. 1(c). The current graph (Field 1) indicates a gradual increase in load current over time, reflecting changes in load conditions. The voltage graph (Field 2) shows relatively stable voltage levels with minor fluctuations, confirming proper voltage regulation under operating conditions. The oil level graph (Field 4) exhibits a significant variation, which can be interpreted as a simulated change in oil level condition, useful for testing alert mechanisms in case of leakage or abnormal drop. The temperature graph (Field 3) remains

nearly constant throughout the observation period, indicating stable thermal performance of the transformer. Overall, the results demonstrate that the IoT module effectively captures, transmits, and visualizes real-time transformer parameters, enabling continuous monitoring and early detection of abnormal conditions.

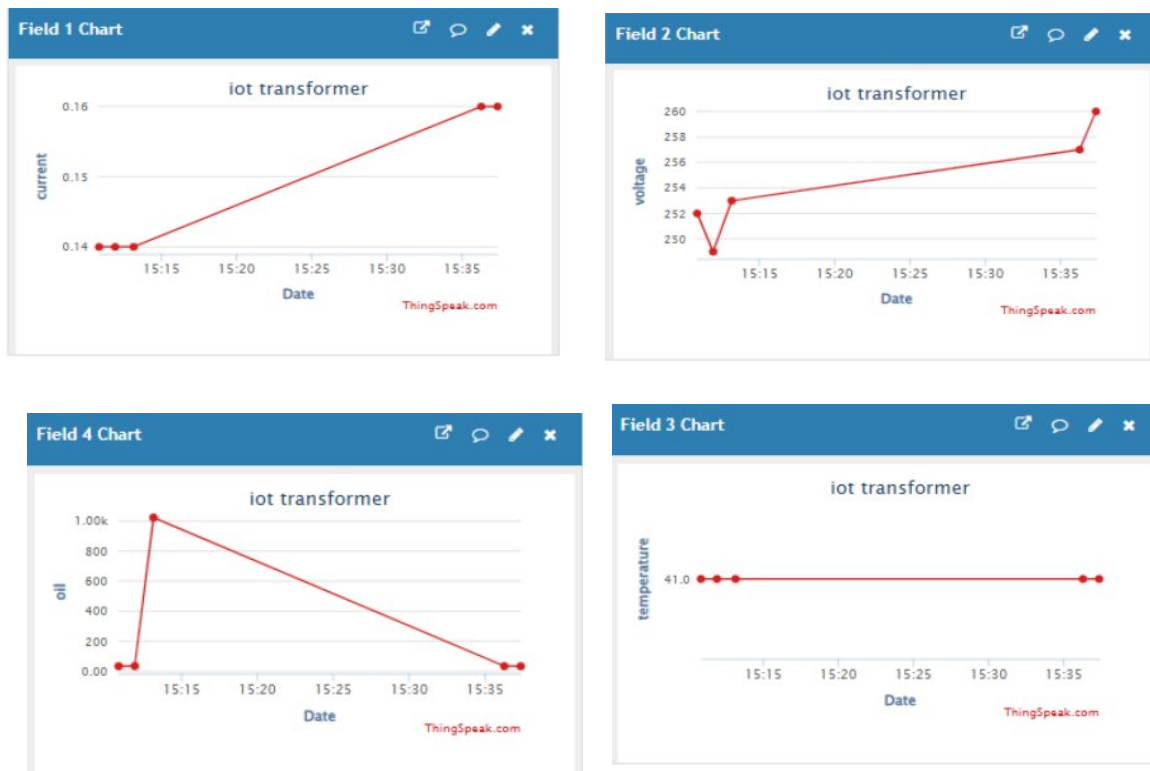


Fig. 2(a,b,c,d)

V. CONCLUSION

We have implemented a hybrid IoT and AI-based system for transformer monitoring, enabling real-time tracking of parameters like temperature and oil level while detecting internal faults using AI analysis. It improves reliability, reduces maintenance costs, enhances safety, and supports predictive maintenance for efficient and uninterrupted power system operation.

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Volume 15, Issue 4, April 2026**|DOI: 10.15680/IJRSET.2026.1504225|**

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