

Pole-Mounted Distribution Transformers in Rural Areas During Disaster Times Using Wireless Communication

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Abstract

The pole-mounted transformer is very important when distributing electricity to rural areas since these transformers are exposed to unfavorable environmental conditions. In case of disasters such as cyclones, floods, and earthquakes, the transformer can easily be affected by problems such as oil leakage, overload of electricity, fire danger, and pole failure. Conventional monitoring of these transformers is conducted manually and the process is inefficient in terms of cost and time in remote and disaster-ridden environments. This research describes the development of an Internet of Things (IoT)-based system for monitoring the health status of pole-mounted transformers using wireless technology. This system comprises various types of sensors such as MQ sensors for oil leakages, voltage and current sensors for the flow of electricity, flame sensors to detect fire, and MEMS sensors to measure pole tilt and vibration. The data obtained from the sensors is transmitted by ESP32 microcontroller through the HC-12 wireless transmitter module to the remote monitoring center.

Keywords: IoT, Transformer Monitoring, ESP32, Wireless Communication, HC-12, Fault Detection, Rural Power Systems, Disaster Management.

1. Introduction

The transmission of electric power in rural settings mainly revolves around the installation of distribution transformers mounted on poles. These are very important in the

distribution of power to scattered populations in rural settings. Distribution transformers tend to be located in exposed conditions where there is little physical protection, hence being very prone to environmental pressures. In times of natural calamities like cyclones, floods, earthquakes, and stormy weather, there tends to be a high level of vulnerability in these transformers. This results in many problems like faulty insulation, overheating, oil spillage, and even mechanical problems.

The impact of transformer failure is even higher in the countryside because of the unavailability of sufficient infrastructure, slower maintenance reaction time, and restricted access. The failure of transformers in the countryside can affect numerous things in people's lives, ranging from simple things like cooking and illumination at night to important ones like healthcare facilities, communication systems, and disaster management efforts. Therefore, it becomes essential to ensure that transformers in the countryside run continuously without experiencing any faults and give reliable data regarding their present state. Traditional transformer maintenance and monitoring processes in the countryside involve routine inspection. Although it is ineffective and expensive, this approach is the most prevalent one adopted when monitoring transformers. This traditional process is ineffective in times of disasters due to restricted accessibility, which makes it impossible to collect real-time data. Thus, the problems go unnoticed, resulting in fires and equipment damages.

The above-mentioned limitations stress the importance of intelligent automation in the monitoring process so that it functions continuously even in difficult environments. Recent innovations in the fields of Internet of Things, wireless communication, and embedded system technology make it possible to incorporate intelligent monitoring methods into power system operation. IoT-enabled equipment makes it easy to gather data and monitor processes remotely, and make intelligent decisions by integrating various sensors, microcontrollers, and communication technology. Such methods facilitate continuous monitoring of key transformer parameters, which include voltage, current, temperature, gas leakage, and mechanical integrity of the equipment. In addition, wireless communication technology allows us to transfer data to the monitoring centers even if there is no good wired communication link.

Under these circumstances, the current study introduces the design of a smart monitoring system based on Internet of Things for pole-mounted distribution transformers in rural areas and disaster-prone regions. This system is capable of identifying various types of

electrical faults, any possible leakages of oil from transformers, potential risks of fire, and mechanical problems using multiple sensors. Information obtained by the sensor devices will be processed by the microcontroller and then sent via wireless communication in order to provide effective monitoring of the systems.

2. Literature Review

Reliability and robustness of pole mounted distribution transformers during natural calamities in rural areas are emerging as crucial issues for current power systems. Fault diagnosis of transformers using artificial intelligence techniques is one of the new technologies which has recently been used in transformers. A novel deep transformer architecture named TranAD has been introduced for fault diagnosis in lithium batteries. This technique proves that transformers have effective applications in fault detection of complex electrical systems [1].

Hybrid SMOTE and Random Forest technique has also been applied in fault diagnosis of transformers to increase efficiency using data analysis and machine learning approaches [2]. Another important issue regarding transformer's performance in adverse conditions like disaster is the performance and insulation of transformers. Thermal performance of transformers has been studied using thermal hydraulic network to determine oil temperature variations in transformers [3]. As a complement to this, ester oil has been explored as an alternate material for use as an insulator due to its higher degree of sustainability and better insulation properties than mineral oils [4]. Overall, all these researches stress the significance of effective thermal management and insulation practices in order to ensure optimal functioning of transformers when used in rural settings. Intelligent systems have played their role in improving transformer health management as well [5].

Moreover, IoT-based techniques for health monitoring and fault identification showcase the utility of networked systems in monitoring the status of transformers [6]. These techniques have great significance especially in rural regions where physical inspections are difficult, and prompt fault identification is important for disaster scenarios. However, these techniques require the underlying technology base which is the development of the IoT and wireless communications. Various surveys on enabling technologies for IoT, protocols, and applications in smart grids and energy management systems have been presented [7].

Moreover, the application of IoT technology in industrial processes, especially in the improvement of efficiency and automation, has been discussed extensively [8]. It is evident from the above-reviewed articles that implementation of an IoT-based monitoring system in rural areas prone to disasters is feasible. The wireless sensor network (WSN) plays a vital role in data acquisition and communication in such environments. An architectural design of WSN for environmental monitoring has been proposed, which could be used for transformer monitoring in rural environments [9].

Similarly, IoT-enabled power monitoring using current and potential transformers supports the idea that IoT is feasible in energy infrastructure monitoring [10]. It is clear from the above literature review that there is a high degree of integration between machine learning, IoT, and wireless technologies in transformer monitoring and diagnosing faults. This development provides a robust base for designing pole-mounted distribution transformers in rural areas prone to disasters.

3. Proposed System

The present work describes a proposed smart monitoring system using Internet of Things technology to provide a more reliable and safe performance of distribution transformers mounted on poles. Such locations often experience poor supervision, as well as high exposure to environmental factors. Real-time monitoring becomes necessary in such locations. The monitoring system described here is developed in order to ensure continuous acquisition of electrical, environmental, and mechanical parameters related to transformer functioning. Using multiple sensors, a built-in processor, and wireless connection, the proposed system aims at timely detection of possible problems and sending corresponding information to the control station.

3.1 System Architecture

The architecture of the suggested model (see Figure 1) comprises three major layers, namely sensing, processing, and communication. Together, they are aimed at monitoring and diagnosing faults in the pole-mounted transformer. The role of the sensing layer includes monitoring and sensing using the variety of sensors like voltage sensor, current sensor, MQ gas sensor, flame sensor, and MEMS sensor. They monitor different aspects of performance and

status, including the measurement of electrical parameters, environmental conditions, and the structure of the transformer pole. All obtained data are passed through the processing layer, where the analysis and filtration take place under the control of the ESP32 microcontroller. Specifically, the obtained measurements are digitized, filtered, and then compared to the pre-defined threshold values. In case of abnormal situations, the information goes to the communication layer, where the HC-12 module transmits it to the receiving unit. Further, at the monitoring station, all gathered information is displayed, and notifications about the presence of faults, such as overload, gas, fire or tilt are provided.

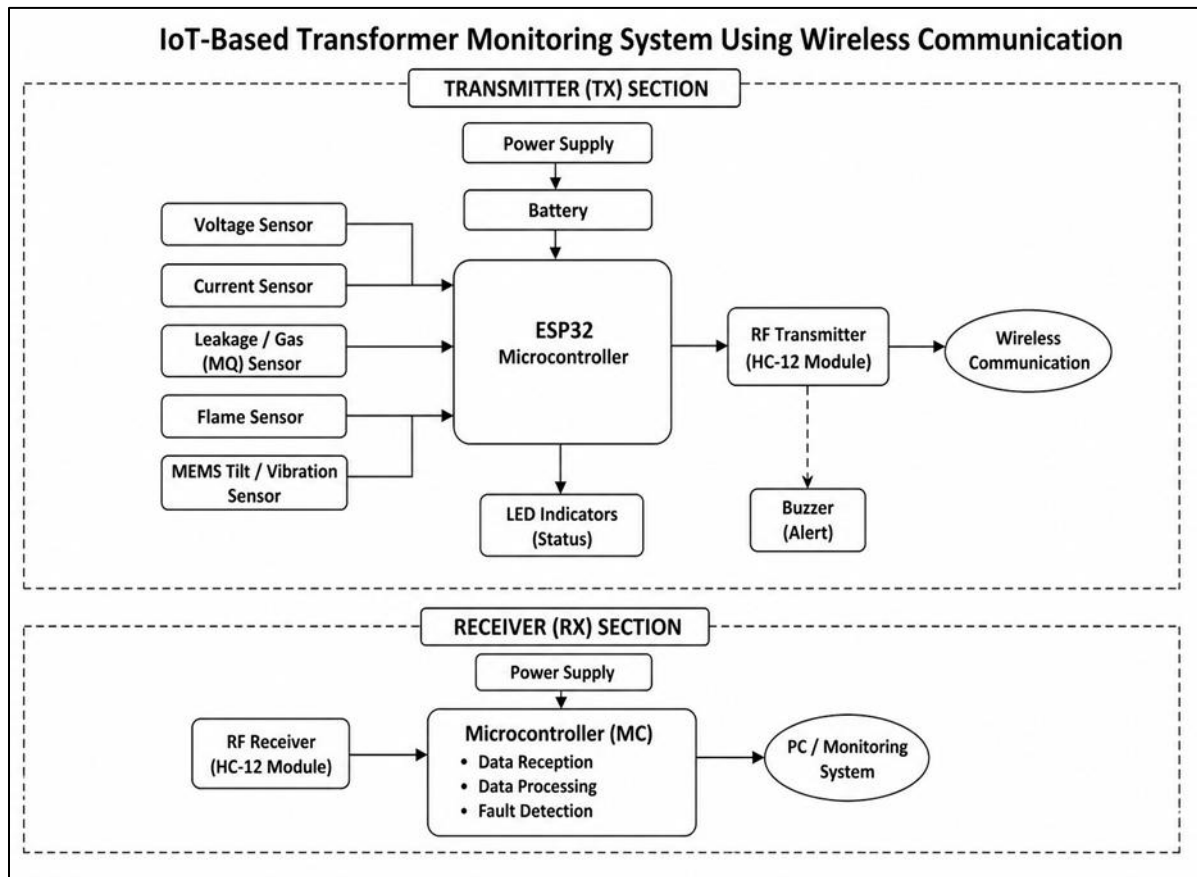


Figure 1. Architecture of the Proposed IoT-based Transformer Monitoring System

The proposed system functions based on the continuous process of sensing, processing of data, and wireless communication for monitoring the condition of pole mounted distribution transformers. A variety of sensors such as voltage, current, MQ gas, flame, and MEMS sensors are placed in the transformer to continuously sense parameters related to voltage and current, gas leakage, presence of any fire, and vibration of poles.

The analog signals from the sensors are supplied to the ESP32 microcontroller, which converts analog input signals to digital signals through the use of an analog-to-digital converter (ADC) circuit built inside the controller. Processing of data in the microcontroller is followed by filtering of the data as well as comparing its value against the set thresholds to find out whether the system is functioning normally or abnormally. Abnormalities in the system indicate any fault that could be either overload of transformers, leakage of oils, fire hazards, and/or pole vibration and tilting. In case of exceeding of thresholds for any parameter, the system immediately issues warning messages. Finally, the data that was analyzed by the system is transferred wirelessly to the receiving end using the HC-12 communication module.

3.2 System Workflow

The process flow diagram (Figure 2) explains how the proposed system operates in the sequential manner from data acquisition to alert creation. In the first place, all the sensors including voltage, current, MQ gas, flame, and MEMS sensors constantly monitor all the characteristics of the transformer together with its surroundings. The information about the electrical characteristics, gas leak, fire condition, and pole stability is acquired by these sensors in the form of analog signals.

This microcontroller analyzes the values obtained from sensors in comparison to pre-established threshold values in order to find out whether the system is running properly or whether any fault condition has arisen. In case all parameters are found to be safe, the system will keep running normally. But in case of any problem like overload, gas leakages, fire hazards, or pole tilt, the fault conditions are recognized by the system. If any fault is detected in the system, the data is prepared by the ESP32 controller to be sent wirelessly via the HC-12 module to the receiving module. The data is then shown on the monitor at the receiving station in order to alert operators about any fault that might have occurred.

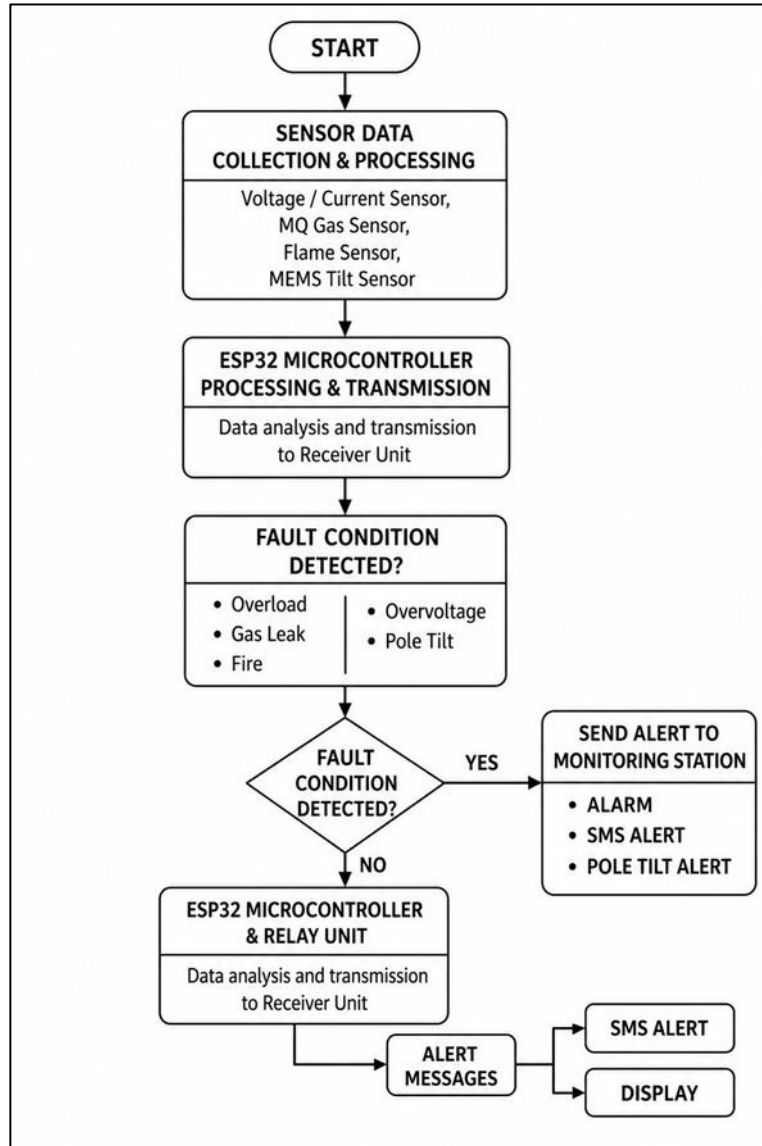


Figure 2. Workflow Diagram of the Proposed System

3.3 Proposed Algorithm

Algorithm 1: IoT-Based Transformer Fault Monitoring and Alert System

Input: Sensor data (Voltage V, Current I, Gas level G, Flame status F, Tilt angle T)

Output: Fault detection status and alert notification

Step 1: Initialize ESP32 microcontroller and communication module (HC-12)

Step 2: Initialize all sensors (Voltage, Current, MQ Gas, Flame, MEMS)

Step 3: Define threshold values:

V_{th} → Voltage limit

I_{th} → Current limit

G_{th} → Gas leakage limit

T_{th} → Tilt angle limit

Step 4: Start continuous monitoring loop

Step 5: Read sensor values:

Measure voltage V

Measure current I

Measure gas concentration G

Detect flame status F

Measure tilt angle T

Step 6: Convert analog signals to digital values using ADC

Step 7: Apply filtering to remove noise from sensor data

Step 8: Compare sensor values with threshold limits

Step 9: Fault Detection Logic:

If $V > V_{th}$ → Overvoltage fault

If $I > I_{th}$ → Overload fault

If $G > G_{th}$ → Oil leakage fault

If $F = TRUE$ → Fire hazard detected

If $T > T_{th}$ → Pole tilt fault

Step 10: If any fault is detected:

Generate alert message

Send data via HC-12 module to monitoring station

Step 11: If no fault detected:

Continue monitoring

Step 12: Repeat Steps 5-11 continuously

3.4 Working Principle

The working of the suggested system revolves around real-time sensing, processing, and communication in order to ensure continuous monitoring of the pole-mounted distribution transformers. Initially, different types of sensors like voltage sensor, current sensor, MQ gas sensor, flame sensor, and MEMS sensor are attached to the transformer to monitor electrical parameters, check oil leakage, fire hazards, and also pole tilt or vibration. Different types of sensors continually sense the parameter values in the form of analog signals, which are then sent to the ESP32 microcontroller. ESP32 converts the analog signals to digital data and

processes the information received from sensors through filtering and comparison with predetermined threshold values. Depending upon the result of this comparison, the system can determine whether there is any fault in the transformer or not. If any fault occurs in the transformer, the system detects the problem immediately, which could be anything from overloading, gas leakage, fire hazard, or instability. After identifying any faults, the data that is processed will be transferred through wireless transmission to the receiver using the HC-12 communication module. The receiver then displays the information and produces an alert signal, making it easier for the operator to react and act accordingly. Therefore, the system helps to monitor the process efficiently and detect faults early enough.

4. Results and Discussion

4.1 Experimental Setup

This experiment is performed on the proposed design of the system as shown in Figure 3. It includes a variety of electronic components. The hardware configuration includes ESP32 microcontroller, voltage and current sensors, MQ gas sensor, flame sensor, MEMS sensor, HC-12 wireless communication modules, and regulated power supply module. The sensors are integrated correctly into the ESP32 to receive the readings from the transformer model. The transmitter part is made to create various faults in the transformer model like overload, gas leakage, fire detection, and pole tilting.

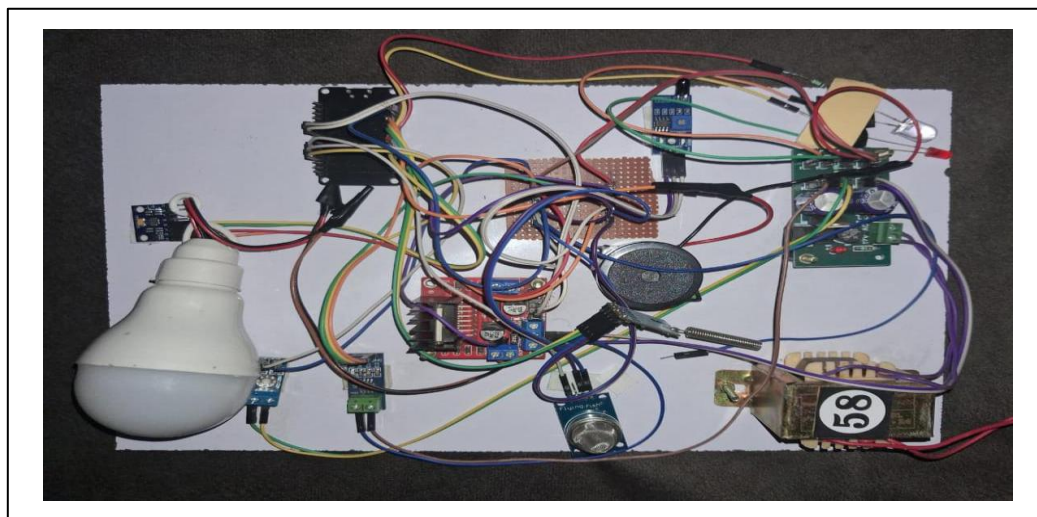


Figure 3. Experimental Setup of the IoT-Based Transformer Monitoring System

The receiver setup consisted of an HC-12 module, which was interfaced to a system monitoring unit where the data sent was received and shown on display. The link between the transmitter and receiver modules was established at a specific distance to test for reliable data transfer using wireless communication. During the testing process, sensor data was continuously monitored while observing the behavior of the system both in normal and faulty states. Faulty states led to the generation of alerts successfully, proving the capability of the system to detect faults and monitor conditions in real time. It is evident that the suggested system can be implemented in practice.

4.2 Fault Detection Results

This system contains different kinds of sensors like voltage sensors, current sensors, MQ gas sensors, flame sensors, and MEMS sensors. In addition, this system has ESP32, HC-12 communication module, and monitoring unit in it. This system is used for various purposes including electrical fault detection, fire hazards, detection of gas/oil leakages, and detection of pole tilting/vibration. Voltage and current sensors detect overload, overvoltage, and short circuit in the system respectively. The MQ gas sensors detect the leakage of transformer oil and harmful gases in the transformer system, while the flame sensor detects fire hazards around the transformer. MEMS sensor is used to detect any kind of tilt or vibrations of poles particularly in disastrous circumstances like storms and earthquakes. All the detected signals are processed by ESP32, and then these signals are sent through HC-12 wireless communication modules to the receiver unit. This system shows real-time values, and also alerts (as shown in Figure 4) for any kind of abnormal situation.

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Arduino Serial Monitor - COM3
Voltage: 13.55 V
Fire Sensor: 1
Tilt Angle: 96
System Status:
----- Raw Data: -----
449, 2.42, 13.02, 1, 96.00, NORMAL

----- RECEIVED DATA -----
MQ135 Gas Value: 449
Current: 2.42 A
Voltage: 13.02 V
Fire Sensor: 1
Tilt Angle: 96
System Status: NORMAL

 Autoscroll  Show timestamp 115200 baud Clear out

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Figure 4. Real-Time Fault Detection Results

4.3 Discussion

The design of the proposed model shows a robust and efficient method of pole-mounted distribution transformer monitoring in remote areas that experience disasters regularly. The combination of voltage, current, MQ gas, flame, and MEMS sensors enables the system to monitor faults in the form of electrical problems, leaking of oil, fire risks, and stability of the pole. The ESP32 microcontroller enables efficient data analysis, whereas HC-12 wireless module allows long-range wireless communication.

In addition to this, the system had a fast response time, as well as the capacity to detect any errors within the electrical system, which is important in avoiding transformer failures, and ensuring continuous flow of power. Unlike conventional approaches involving physical inspections, which are not only tedious but also costly, this system can monitor the electrical circuitry continuously, without the need for any human intervention. This makes it safer than other approaches. Nevertheless, some limitations may occur due to reliance on sensors' accuracy and the environment. For example, future advancements could include integrating this technology with cloud computing platforms for more reliable data storage and processing, developing applications to remotely access data, as well as deploying technologies such as machine learning to analyze the data and predict errors in advance. This system offers a cost-effective way of improving reliability.

5. Conclusion

The IoT-based monitoring system for pole-mounted distribution transformers is an ideal method of achieving fault detection and analysis in rural and disaster-prone areas through efficient and reliable processes. Through the use of various sensors like voltage, current, MQ gas, flame, and MEMS sensors, it is able to detect problems such as overloaded, leaking oil, fire risk, and poles tilting. This process is achieved by the use of an ESP32 microcontroller in processing data efficiently as well as the HC-12 wireless communication technology which enables data transfer over long distances to the monitoring center. With its ability to reduce labor work as well as saving money on maintenance, this system makes power transmission more secure and reliable. In addition, any problem is detected quickly and dealt with hence ensuring no failure and down time. From the results obtained from this study, there are numerous ways of improving transformer monitoring systems.

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