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Smart IoT-Enabled Condition Monitoring and Predictive Maintenance Framework for Distribution Transformers

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Abstract

Distribution transformers play a very important role in ensuring that power is not interrupted in the modern electrical grids. In this paper, the author suggests a smart Internet of Things (IoT)-based condition-based monitoring system that will be used to monitor distribution transformers in real-time and for predictive maintenance. The system combines the functions of multi-parameter sensing, embedded processing, and cloud-based analytics to constantly check voltage, current, temperature, and oil level. An MQTT-based communication module based on Node MCU makes it possible to transmit data to the IoT platform easily via the MQTT protocol. The suggested framework will help the early identification of faults with the help of threshold-based analysis and real-time alerts. Experimental validation has proven to be more responsive, accurate, and reliable in the system as compared to the traditional monitoring methods. The system provides a low-cost and scalable system in accordance with smart grid and digital substation requirements.

Keywords: Condition Monitoring, Distribution Transformer, Internet of Things (IoT), Predictive Maintenance, Smart grid, Embedded Systems, Cloud Analytics.

1. Introduction

Distribution transformers are essential resources in the electrical power systems, which work under different load and environmental conditions. Their inability may cause major service disruptions and loss of money. Conventional maintenance approaches are mostly reactive or time-based, which do not provide real-time insight into transformer health. The current developments in the fields of IoT and embedded systems have allowed switching to condition-based and predictive maintenance models. With the help of real-time sensor data and cloud analytics, the incipient faults can be detected prior to the catastrophic failures[1]. This article proposes a low-budget, scalable IoT-based transformer monitoring system that provides the capability to carry out real-time monitoring, remote diagnostics, and intelligent decision-making. The most important contribution is that of combining the multi- sensors data acquisition with the cloud-based monitoring to improve operational reliability.

2. Literature Review

The proposed IoT-based transformer monitoring system will be useful in filling these gaps in research since it will offer a multi-parameter and real-time monitoring framework with cloud connectivity and notifications. The system will provide a viable and effective solution to the contemporary power distribution network with low-cost and scalable IoT architecture, which is in line with the changing needs of smart grids and smart management of assets. Distribution transformers and their monitoring and protection has been a research topic because of its significance in the reliability and stability of power systems. Historically, the evaluation of the state of transformers was based on the methods of manual inspection and offline tests, including thermal measurements, insulation resistance testing, and oil analysis. These techniques are useful in diagnosis, but will always be limited by their periodicity and failure to identify abnormalities in real-time, which can lead to a delay in the detection of faults and the possibility of a disastrous failure.

As communication technologies were developed, the initial work on the monitoring system of the transformer was proposed using GSM. It was suggested that a system should be used that makes use of GSM modules to send transformer parameters like load current and temperature through SMS alerts. Although this solution enhanced remote accessibility, it had a number of disadvantages such as limited scalability, expensive communication and unlimited data streaming. Likewise, other articles had investigated GSM-based condition monitoring, but was limited in that it lacked real-time visualization and data analytics [2].

In order to address these shortcomings, scholars started incorporating wireless sensor networks (WSNs) and embedded systems into transformer systems to monitor them. Local monitoring using less power was made possible by ZigBee and other short-range communication protocol-based systems. As an example, a transformer monitoring system based on ZigBee was developed in order to improve communication efficiency in local networks. These systems, however, had problems to do with limited range of the transmission, reliability of the network as well as the difficulty in large scale application in geographically dispersed power networks [3].

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Simultaneously, much research has been done on improved diagnostic methods, including Dissolved Gas Analysis (DGA), partial discharge and vibration study. These methods offer profound information on the condition of internal transformers and mechanisms of faults. Transformer fault detection using diagnostic signals has also been applied in the neural network-based methods, which demonstrates the prospect of artificial intelligence in predictive maintenance. Nonetheless, these systems can be costly to implement, expensive to acquire specialized sensors, and intricate to interpret data so they can not be easily deployed on the low-cost distribution networks [4].

The advent of the Internet of Things (IoT) has disrupted transformer monitoring by making it possible to access the data in real-time, store it in the cloud, and be able to access it remotely. IoT systems are designed using sensors, microcontrollers and wireless communication unit to develop scalable intelligent monitoring systems. The recent research has shown that IoT platforms like Thing Speak and Adafruit IO are effective in terms of offering real-time visualization, data logging, and remote diagnostics. Such systems prove to be of great value in terms of efficiency because of the possibility to constantly monitor the systems and detect faults in time [5].

Although there are such developments, there are still several challenges. Numerous current IoT systems are dedicated to the parameter monitoring of narrow parameters, do not have sophisticated fault detection algorithms, and fail to utilize predictive analytics to the full potential. Moreover, network dependency, cyber threat, and sensor precision remain the problems that influence the reliability of the system.

In this regard, the proposed IoT-based transformer monitoring system will fill these research gaps by offering a multi-parameter and real-time monitoring system with cloud connectivity and alert systems. The system can be used in the current power distribution network by integrating affordable hardware with scalable IoT architecture to provide an effective and viable solution to the current demands of the smart grid infrastructure and intelligent asset management.

The Smart IoT-Enabled Condition Monitoring and Predictive Maintenance Framework that is proposed is targeted at offering a complete, real-time-based monitoring solution to distribution transformers through the combination of sensing, embedded processing, and cloud-based analytics in a unified framework [6].

The system is oriented towards a constant learning of the crucial parameters of health of the transformer such as voltage, current, temperature, and oil level. All these parameters are chosen depending on the direct effect they have on the performance of transformers, life of insulation, and the probability of failure. Measures of voltages and currents allow identifying the state of load and indicating an overloading situation, and measures of temperatures allow the understanding of thermal stress and insulation degradation. Monitoring of the level of oil is to provide integrity in cooling and insulation, which are critical towards safe operation of the transformers.

The sensing subsystem includes the voltage divider circuit, which is used to measure the voltage, ACS712 Hall-effect current sensor, which is used to detect the load current, LM35 precision temperature sensor, and ultrasonic sensor, which is used to estimate the oil level. These sensors are connected to a microcontroller which does signal conditioning, analog to digital conversion and initial data validation.

The IoT gateway is the data that is sent over a NodeMCU (ESP8266) module. The module is able to support a wireless connection through Wi-Fi, as well as MQTT protocol to provide efficient and lightweight data transfer. MQTT is very appropriate in the use of IoT because it has low bandwidth and ensures the reliability of the message delivery.

On the cloud platform, ThingSpeak or Adafruit IO are used to perform real-time data visualization, storage, and analytics. These platforms offer dashboards where the parameter trends can be seen and the operators can check the health of the transformer remotely[7].

One of the aspects that the proposed system has is the use of fault detection that is based on threshold. All the parameters are constantly contrasted with established safe operating limits. Deviations are sent to the system that will provide immediate alerts, which can be used to intervene in good time. This method shifts between reactive and predictive maintenance strategy which decreases the risk of failures to a significant degree.

The diagram 1 represents the general design of the proposed transformer monitoring system based on IoT. The transformer will be linked to several sensors which will record load voltage, load current, temperature and oil level. The data sent by these sensors is processed instantly into the Arduino Nano (microcontroller) where the first processing and validation are performed.

The data is then processed and sent to the NodeMCU module that serves as a communication gateway and transmits the information to the cloud platforms using Wi-Fi. Cloud interface makes it possible to visualize, store, and analyze parameters of transformers in real-time. Notifications and insights created by cloud analytics are used to help operators make informed decisions when it comes to making decisions on maintenance[8].

The system is designed in a modular manner, which provides it with scalability such that it is easy to add more sensors or sophisticated analytics capabilities. In general, the architecture has shown a smooth transition between data collection and smart decision-making, which is a strong base of smart grid utilization.

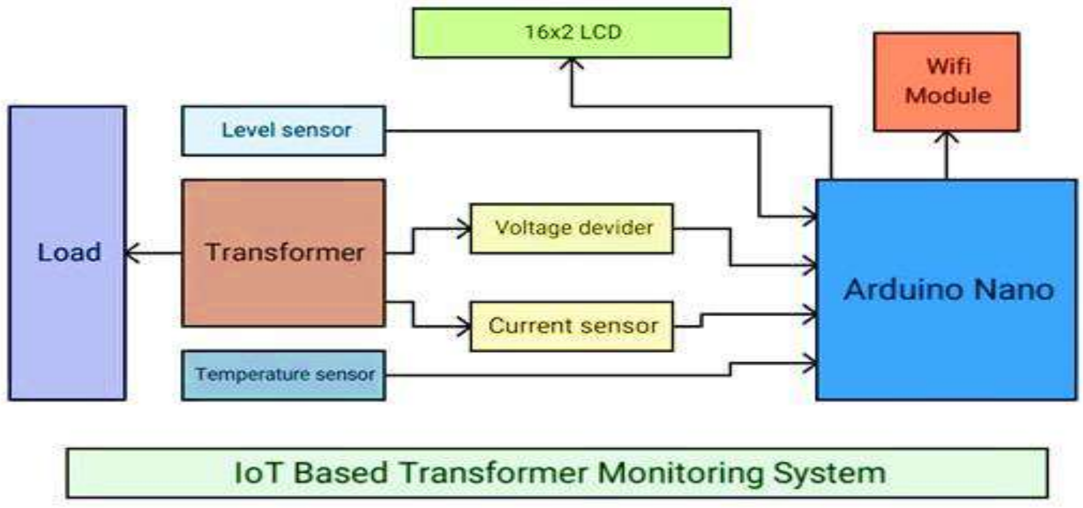

Figure 1. IoT-Based Transformer Monitoring System Architecture

3. Methodology

The proposed system has a methodology that consists of four key steps; data acquisition, data processing, communication, and data analysis. The system is systematic and closed loop as demonstrated in Figures 2 and 3 whereby it will guarantee continuous monitoring, efficient data management and timely fault detection.

3.1 Data Acquisition

As Figure 2 shows, the data acquisition phase consists of constant monitoring of the vital parameters in the transformer with the help of several sensors. The voltage divider circuit is used to attenuate high voltages to an attainable level that can be measured by the microcontroller. ACS712 current sensor is the load current sensor that operates on the principle of Hall-effect so that it provides the correct and non-invasive sensing. LM35 temperature sensor offers accurate thermal readings with a linear output which depend on the temperature and the ultrasonic sensor detects the oil level through distance between the sensor and the oil surface.

The sensor outputs, as depicted in the figure, are all connected to the Arduino Nano which is the major data acquisition unit. It is important to appropriately calibrate and locate sensors in order to get reliable measurements that are accurate under the different operating conditions.

3.2 Data Processing (Edge Processing Layer)

The analog signals that are received through the sensors are digitized by the inbuilt ADC of the microcontroller as shown in Figure 2. The microcontroller is used to do the preliminary data processing which includes filtering, normalization and formatting. This layer of edge processing decreases the computing workload on the cloud by performing initial processing on one computer.

Moreover, noise reduction methods are also used as presented in the system architecture to enhance the quality of signals that will guarantee that the environment will not interfere with sensor readings. This phase also improves responsiveness of the system because providing quick local decisions regarding critical state of affairs is possible.

3.3 Communication Layer

The communication stage is deployed with the help of the NodeMCU (ESP8266) module, as demonstrated in Figure 2, that is a connector between the hardware system and the cloud platform. The data that is processed by the Arduino Nano is relayed to the NodeMCU which transmits the data to the cloud via Wi-Fi.

MQTT protocol will be employed in transmitting data because it is lightweight and effective in transmitting real-time data streams. This provides a reliable low-latency communication as shown in the figure and therefore the system would be applicable in continuous remote monitoring applications [9].

3.4 Data Analysis and Visualization based on the cloud.

On the cloud, platforms like ThingSpeak or Adafruit IO are employed in the storage, visualization, and processing of incoming data as depicted in the figure. These systems offer easy to use dashboards which show real time and past trends of transformer parameters [10].

The historical data logging and alert generation is also supported by the cloud layer. At sensor values that are above the set thresholds, the sensor raises an alarm and notifies the operators by sending an alert or warning. This allows for proactive maintenance and decreases the chances of unwarranted failures.

As Figure 2 below indicates, the layout depicts the hardware design of the transformer monitoring system. It contains sensor connections with the Arduino Nano, signal flow routes, and connections with the NodeMCU module. The diagram shows well the process of gathering real-time data, processing and sending the same to the cloud.

3.5 System Workflow

The process of the system operation has a well-organized flow as shown in Figure 3 (Flowchart):

- The process starts with system initiation, in which all the sensors, communication modules, and display units are set.
- The system then goes into an endless monitoring process, as illustrated by the flowchart, sensor data is obtained, summarized, and transformed into useful values.
- The processed information is shown locally (through LCD, in case of usage) and at the same time sent to the NodeMCU to upload to the cloud.
- The system, as shown in the decision block of the flowchart, checks real time values with predetermined threshold limits.
- On one hand, in case any parameter surpasses safe values, an alert is created and sent to the user through the cloud platform.

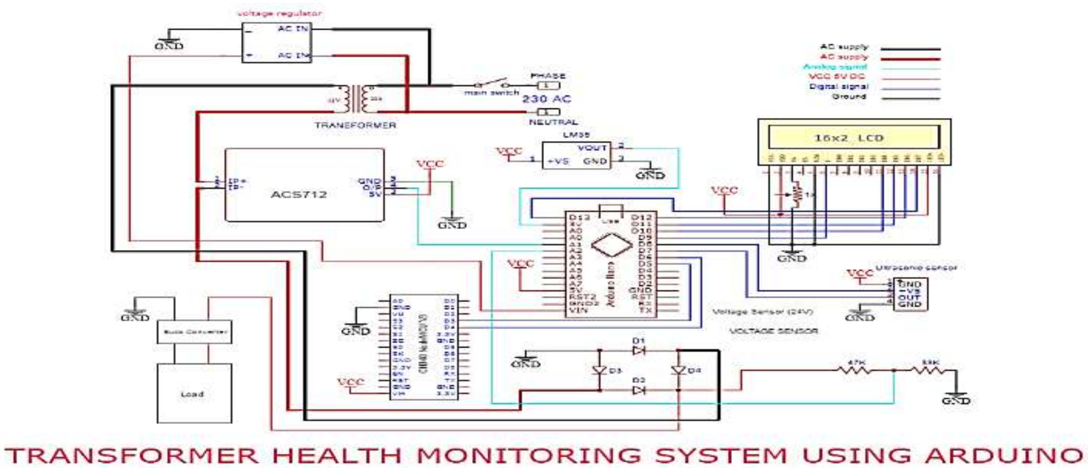

Figure 2. Layout

- In the case of no abnormal condition detected, then the system remains in real time monitoring.If no abnormal condition is detected, the system continues monitoring in real time.

Thus, as shown in Figure 3, the system operates as a closed-loop process involving sensing, processing, transmission, analysis, and alert generation.

3.6 System Architecture Overview

As shown in Figure 2, the overall architecture is designed as a multi-layered framework consisting of sensing, edge processing, communication, and cloud layers. Each layer performs a specific function while maintaining seamless data flow across the system.

The sensing layer forms the foundation by collecting real-time operational data. The edge layer (Arduino Nano) ensures efficient preprocessing, while the communication layer (NodeMCU) enables reliable data transfer. Finally, the cloud layer provides intelligent monitoring, visualization, and decision support.

This layered architecture enhances system flexibility and scalability, allowing easy integration of additional sensors or advanced analytics features in the future.

As shown in Figure 3, the flowchart represents the step-by-step operation of the system, starting from initialization to continuous monitoring, decision-making, and alert generation. It highlights the logical flow and closed-loop nature of the system.

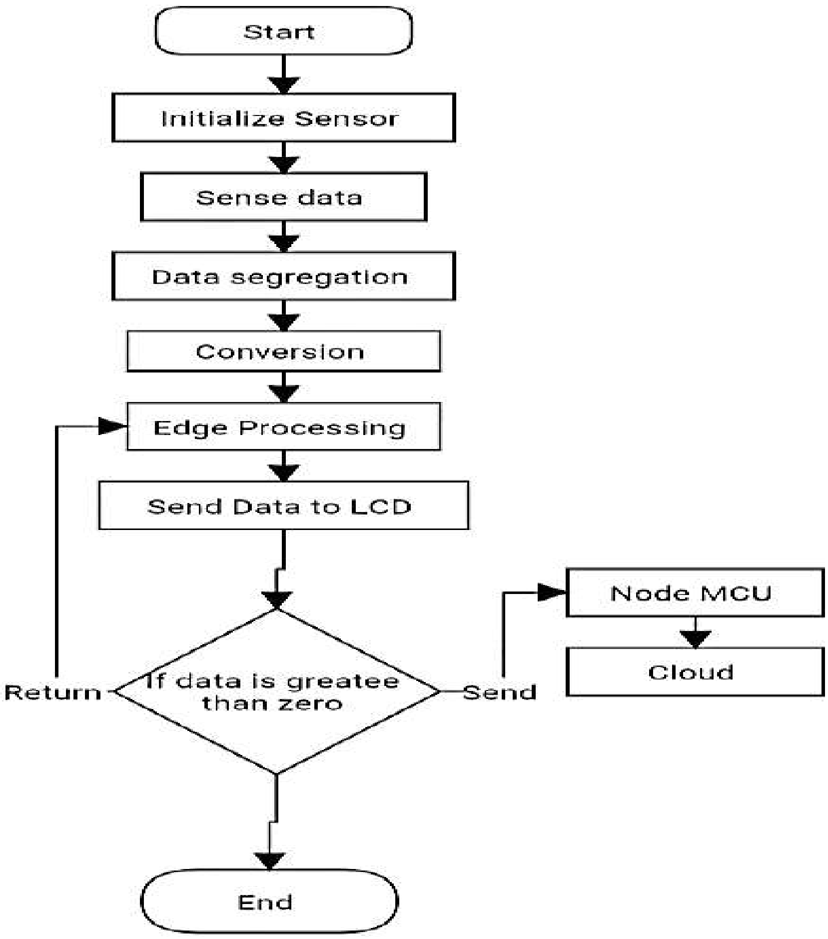

Figure 3. System Flowchart

4. Results and Discussion

The suggested system was deployed and experimented under different working conditions to measure its use in real time transformer monitoring.

When applied in an experiment, it was shown that the system has been able to capture and transmit transformer parameters with high accuracy. Voltage and current readings were observed to be in agreement with the standard measuring tools which showed good performance of the sensor. There was also little deviation in temperature readings, thus the LM35 sensor was proven to be effective.

The system showed effective real time data transmission with MQTT protocol and the latency was insignificant. The information was uploaded to the cloud platform successfully and could be viewed in forms of dashboards to monitor the information remotely.

Among the most important observations was that the system would identify the abnormal conditions like overloading and overheating. Upon exceeding parameter thresholds, alerts were created in real time and corrective measures were taken in good time. This greatly eliminates chances of transformer failure.

The proposed system can also provide better reliability, continuous monitoring and faster response time as compared to traditional methods of monitoring. It is also cost-effective to use in large-scale use due to the use of low-cost components.

Nonetheless, dependency on network connection and the accuracy of sensor calibration was also noted to have certain limitations. These aspects need to be tackled in order to be applied in practice.

In general, the findings confirm the usefulness of the offered system in improving the monitoring of transformers and making them predictably maintained.

5. Conclusion

The Smart IoT-ENABLED Condition monitoring and predictive maintenance Framework offers an effective and powerful solution to the contemporary transformer monitoring problems. The system will allow real-time tracking, early warning of failures, and making decisions based on facts through the implementation of IoT technologies, embedded systems, and cloud computing.

The suggested scheme overcomes the drawbacks of the traditional monitoring methods by offering uninterrupted insight into the functioning of the transformers. Multi-parameter sensing and cloud integration make the device be able to provide end-to-end health assessment and be accessed remotely and scaled.

The system provides a major boost in reliability through the ability to implement predictive maintenance plans, minimise unplanned outages and increase the life of the transformers. It is cheap in design and can find massive application in the distribution networks especially in the developing areas.

Future upgrades can involve the incorporation of machine learning algorithms to predict faults more advanced, the implementation of cybersecurity measures, and the extension to large-scale smart grid systems.

To sum up, the suggested system is a milestone in the intelligent distribution of power and development of smart grids as a practical and scalable solution to the next-generation monitoring of transformers.

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