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Original Article

Intelligent IoT-Cloud Integrated Wireless RF Framework for Transformer Fault Diagnosis and Predictive Maintenance

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Abstract - *Transformers play a significant role in the energy management aspect of distribution networks, particularly in the management of energy and voltage regulation. Defeated transformers result in an unsteady power supply, damaged equipment, and economic damage. Old-fashioned monitoring methods depend on excruciatingly slow manual checks that are only done on a reactive basis and are inefficient for advanced fault identification. The amplified need for dependable power highlights the necessity for real-time autonomous transformer efficiency monitoring. The incorporation of the IoT with cloud computing and wireless RF has changed the pace of industrial automation, allowing real-time data capture, monitoring, and maintenance from personnel geographically far away. IoT enables persistent tracking of crucial measurable figures like voltage, current, temperature, and humidity, while LoRa RF is the long-range, low-power radio ideal for electricity transformers situated in isolated regions. Data analytic tools hosted on the cloud easily visualize information, enabling faster maintenance and improved fault diagnosis accuracy. Traditional techniques like DGA, vibration monitoring, and thermal imaging used in fault diagnosis rest upon a feeble premise of slow detection of fault problems, expensive maintenance requirements, and poor flexibility. Our proposal seeks to address the aforementioned issues with an IoT-based Smart Transformer Monitoring System that utilizes machine learning for predictive maintenance, cloud analytics, and an almost limitless range achieved through LoRa RF. While traditional wireless technologies like ZigBee fail to work on transformers due to their range limitation, wired networks suffer from data loss and physical damage, offering no protection against these threats. Myriota will also implement a Transformer Health Monitoring Unit, which will be responsible for collecting real-time sensor data, and an Edge Gateway, which will process and transmit data to the ThingSpeak Cloud for visualization. An embedded Machine Learning model will analyze the data for early fault detection and maximize the reliability, cost, and scalability for optimal transformer monitoring. The goals of this framework are to reduce maintenance costs to improve grid stability and accomplish a higher level of power system management.*

Keywords - *Transformer Health Monitoring***,** *IoT-Based Fault Diagnosis, LoRa RF Communication, Edge Gateway, ThingSpeak.*

1. Introduction

Essential components of electric power systems are transformers, but accurate fault diagnosis is still a challenge. This paper describes a new transformer fault diagnostic method that is based on the use of an Internet of Things (IoT) monitoring system along with Ensemble Machine Learning (EML). The system has two parts, known as a data measuring subsystem and a data reception subsystem. The first part, the data measuring subsystem, captures vibrations from the transformer, which are then sent to a remote server through the data receipt subsystem [1]. Getting IoT engaged in research on IoT technology adoption or acceptance is of immense importance, and thus, the issue is being evaluated. The acceptance or adoption of IoT technology is an area of scholarly work that is not new, and many researchers have done it. Current and future generations of the internet are being dominated by the IoT. The primary focus of this survey, as opposed to earlier undertaken surveys, is to monitor the IoT technology and monitor the IoT acceptance level will enable researchers to do further. The Internet of Things brings to reality that nearly every appliance can now be monitored and controlled remotely via the internet [2].

The architecture in question offers a particularly efficient plan to address potential interruptions and faults in the power grid in the future. It does so using a reliable and cost-effective infrastructure that has the potential to predict and provide real-time health monitoring indices for the Iraqi grid network with very few interruptions to power supply.[3]. Electric power systems highly depend on transformers, although any faults within these devices are complicated to determine. This paper outlines a new IoT-based transformer defect diagnostic method implementing integrative ensemble machine learning. The IoT-based monitoring system is composed of two distinct components, which are the data measuring subsystem and the data reception subsystem. To start, the data measuring subsystem records vibration signals emitted by the transformer, which are sent to the remote server through the receipt of the data subsystem. After that, Deep Belief Networks (DBN), Stacked Denoising Auto Encoders (SDA), and Relevance Vector Machines (RVM) are integrated as an ensemble machine learning (EML) paradigm.[4]

This paper discusses the monitoring of transformers and the steps taken towards real-time transformer monitoring. It is obvious that any damage to the internal and external parts of the transformer can lead to a multitude of problems. All companies are finding the maintenance and replacement of transformers to be costly. Because of this, the IoT-based transformer monitoring system is developed to keep track of the 'health' conditions of transformers at set intervals. Any changes in voltage, current, temperature, or even loadability indicate that there is some change in the transformer. Various sensors measure several aspects of the device, and if only one of the values gets to a predefined critical point the information is transferred to an ESP8266 module and sent over HTTP protocol to a specific IP address, which displays the information in chart form in real-time on any mobile set or laptop [5].

The demand to build smart applications has made the Internet of Things (IoT) reach new heights. With a focus on increasing productivity, services that utilize IoT have been implemented by industries for the past few years. These services are now penetrating the wind energy sector, which is arguably the best renewable source of energy for electric power generation. This paper presents an automatic system designed to assist in diagnosing early defects in wind turbine electric generators in order to optimize maintenance procedures. Four Signal Features were extracted from the vibration signals, and different classifiers were applied to estimate the operating conditions of the wind turbine. [6].

A cost-effective ZigBee/GSM wireless security system architecture has been developed for the easy monitoring and control of dangerous situations like burglary at homes, cities, and even intrusion in other areas. Every cluster head of all sections talks to the main server of the city via GSM to extend the coverage area. It optimizes the communications that are necessary for efficient routing of the cluster node and cluster head by means of the PSO algorithm. Embedded Cluster node device with ZigBee modem and user switches is installed into each room [7]. Massive disasters often happen due to considerable alteration in the state's ecological and geographical conditions. Changes of such considerable magnitude are problematic as one's safety or life stands at risk. Along with these factors, taking relevant action as the time limit approaches is equally crucial. This can only be achieved through sufficient advanced technology. The home or the control room center is ultimately. The local control room aids in monitoring the situation by collecting data from the various sensor nodes. The local control room is only responsible for data monitoring and blazing discharge sensors that control the alteration of the appropriate gates up to particular parameters. Every single decision is made through an examination of all local areas from the center control room. Local control room node, along with a hooter, is also available in order to alert to a dangerous condition by means of a spear. A spear can warn of criticality or disparity if the warning threshold is exceeded [8].

The contributions of this study are as follows:

a) Creation of a Transformer Health Monitoring System featuring multiple IoT sensors for real-time detection of faults by measuring voltage, current, temperature, humidity, and oil levels.

b) Establishment of a LoRa RF-based wireless framework to support remote transmission of data from transformers that are installed in difficult-to-access locations.

c) Development of an Edge Gateway Unit for data collection, which locally processes the data and transmits it to the ThingSpeak platform for remote monitoring and analysis, utilizing an ATmega328 microcontroller and an ESP-01 WiFi module.

d) Application of machine learning-based fault scenario predictive models on maintenance of transformers using IoT for improving uptime, optimizing maintenance windows, and increasing reliability.

e) Implementation of a web-based interface on ThingSpeak Cloud for real-time access to health data from transformers, enabling proactive response to performance trends and failure prevention.

This is how the manual will be arranged. In Section 2, the literature review is given, which covers current transformer monitoring methods and their shortcomings. Section 3 covers the system architecture, including the block diagram as well as important parts of the Transformer Health Monitoring Unit and the Edge Gateway Unit. Details of the hardware development and implementation are addressed in Section 4, covering sensor interfacing, microcontroller selection, and wireless communication configuration. In Section 5, the implementation of the system and its components in real time is given; this includes data collection, cloud computation, and predictive maintenance. Lastly, in Section 6, the conclusion is drawn, detailing the important takeaways and recommendations for further research.

2. Review of Literature

Novel IoT technology can be successfully integrated into developing monitoring devices that will electronically supervise the number of entries of a person, as well as send an alert to the user's mobile phone once a certain threshold is met. As IoT-based smart peripherals are integrated into the rural areas, IoT can assist in monitoring the threshold value and critical values of indicator devices [9]. This paper aims to put forth a technique of fault diagnosis and prognosis of transformer windings by means of passive self-powered Radio Frequency Identification (RFID) tags. The novelty of the proposed tag is that it is equipped with an RFID tag, a power management unit, a microcontroller, and an accelerometer, enabling it to receive the vibration signals from the transformer windings inside the tank and send the signals to the RFID reader via the accelerometer wireless link.

The inductor for the passive sensor tag and the actuator is powered by the surrounding magnetic field. An energy harvest is integrated into the structure of the sensor tag with an accelerometer and a microcontroller. A dedicated AC-DC converter along with a low dropout regulator ensures that a stable voltage is supplied to the powered sensor tag [10]. The existing literature on complex rotating machinery systems that utilize multiple sensors poses the following challenges in employing attention models and transformer networks: i) absence of suitable fault specific embedding representation for a extensive period of vibration data, ii) inability to provide adaptive weightage to sensor segments based on its fault sensitivity during sensor fusion, and iii) omission of incorporating symptomatic fault features in fault decision making. Furthermore, the incorporation of AM and transformer networks in failure detection and predictive maintenance (FDPM) remains limited. Moving forward, we present an FDPM framework to solve the structural rotor faults (SRF) problems that lie within RM diagnostics [11].

The system allows an operator to remotely isolate the transformer from the distribution line when conditions exceed certain preset parameters. A transformer is thereby protected from any abnormal conditions. Therefore, this work develops algorithms for online monitoring, diagnostics, and control alerts for transformer faults. The IoT system is installed on the transformer base to which the transformer's considered parameters are timely transmitted for further analysis. In this manner, the data are used to monitor the transformer condition in real-time while the server saves them into a database for later analysis [12]. With the wind, as with many other renewable resources, there comes a different set of unique failures, such as excessive wear or physical damage. Unlike other resources, harnessed from nature, wind is unique in its utilization vertically (wind turbines). The energy generated from Turbines would in the larger scope fuel many machinery. Not only are the vertical turbines capable of generating power on a larger scale as compared to smaller turbines, but they also come with their own sets of issues that include minimal monitoring systems that currently don't utilize wireless technology or remote sensing. These smaller turbines also stand to benefit from innovative maintenance systems for the turbines, allowing them to track major faults and predict power generation with the aid of a proficient AI algorithm. [13]. Distributive Transformers are central to the functioning of the electrical power system. Monitoring of transformer condition and proper data collection are essential in averting transformer failures. For the operator to monitor the transformer, it is necessary for him to be on-site.

The main goal of the project is to monitor the transformer parameters, like temperature, current, voltage, and oil level, via IoT. Transformer's parameters are captured through sensor networks. This system can reduce the quantity of labor and also increase the accuracy, reliability, and efficiency of the system. Data obtained is forwarded to the Arduino UNO microcontroller. The collected information is transmitted via an ESP8266 Wifi module and can be accessed from any internet-enabled location in the world using IOT and the HTTP protocol. This enables identifying with no human interdependence [14].

This paper presents an IoT-based health monitoring system for the transformer that rationalizes the continuous monitoring of its operational condition to prevent disruption of distribution networks. As power systems change conditions, it becomes imperative to gather the real-time status of the transformer. At the core of this is the concept of a low-cost IoT-based remote health monitoring system with life span prediction for transformers. In this case, the output from the sensors is processed by the NodeMcu, which transmits the readings to the Thingspeak cloud platform for remote access. Transformers' IoT adoption can greatly boost power supply reliability. Such systems can easily be deployed on existing transformers [15]. Transformers of electrical distribution are one of the necessary apparatus in a power system. Considering the great number of transformers which are spread over a large region of the power electric system, data collection and system monitoring become a challenge. To perform this, an operator has to visit the site of the transformer.

The aim of this system is to use IOT in monitoring such parameters of distribution transformers as load current, voltage, oil level, and oil temperature. This aids in minimizing the work effort and improves the accuracy, stability, and efficiency of work. Sensing devices are meant for measuring the major parameters of equipment like voltage, current, temperature, oil, and so on. This data is transmitted to the ESP32 microcontroller. The ESP32 is a series of low-cost, low-power microcontroller chips with integrated Wi-Fi and Bluetooth. Therefore, there is no need to attach a Wi-Fi module separately. Thus, the size of the project is also small [16]. Combining the Internet of Things (IoT) with the monitoring systems of power transformers enhances the management of electrical grids. This paper describes the construction of an

IoT-based monitoring system for transformers built around the ESP-32 microcontroller. The main aim is to increase transformer reliability and efficiency using real-time operational and health information. The system also uses the wireless communication and data processing capacities of the ESP-32 to monitor temperature, load current, voltage, oil levels, and other critical parameters. The analyzed and visualized information for predictive maintenance and quick failure response is sent to a central cloud platform [17].

3. System Architecture

The proposed IoT-Cloud Integrated Wireless RF Framework makes use of the Transformer Health Monitoring Unit, which is a very important piece. Alongside that, this component is designed to monitor and manage the health parameters of the transformer. This data is then transmitted in real time to the Edge Gateway Unit, where it is processed further and integrated into the cloud. Alongside operation, the unit is equipped with a separate power supply for uninterrupted functionality. It consists of an ATmega328 microcontroller, condition monitoring sensors, and a LoRa RF module that enables long-range RF communication. The remote monitoring and predictive maintenance of the unit is consolidated by the wireless data transmission. The ATmega328 microcontroller extracts its name from the core Taurus Medical device, which offers sensors and holistic health care. It is widely regarded as the most reliable and effective device for Power Management - processing, acquiring, and formatting all modular data, and finally transferring through LoRa RF communications.

This microcontroller was selected because of the sensors of various types that are consistently available, and at lower energy and money. Alongside, higher levels of voltage, current, temperature, and humidity are consistently used in conjunction with diverse integration. This is why composite sensors fused into the device are so convenient. Simultaneously, as the remote communication of data is taking place from one source, the gateway is receiving the information as the LoRa RF module is transitioning signals over to Edge. LoRa RF is perfect for transformer monitoring as it consumes little energy, has a high capacity for penetration, and has the ability to operate in remote sites where traditional wireless networks like WiFi or Bluetooth are not possible. For all-inclusive monitoring, the Transformer Health Monitoring Unit has several sensors.

The voltage sensor has a constant reading of voltage across the terminals of the transformer, which can detect overload conditions and failures in insulation, which may range from minor to moderate. The current sensor oversees the electrical current that is passing through the transformer in conjunction with other machines, which help in recognizing excess load and other faults, which can either be short circuits or faults in the windings. Any sensor's parameters of measurement that fall outside the normal ranges could mean faulty connections, transformer losses, or even worse failures. These enable the sensing of the actual state of the transformer, which warrants corrective maintenance even before a critical state is reached.

Aside from the electrical components, the transformer's thermal conditions are well monitored by the DHT sensor and the temperature sensor. A transformer's excessive heating can result in the degradation of its insulation, which can lead to its failure. During this process, electrical resistance and energy conversion also take place. While the temperature sensor is responsible for tracking core and winding temperatures, the DHT sensor measures the levels of humidity that could lead to the deterioration of transformer performance. Breakdowns in insulation, degradation of oil, or failures within the cooling systems can often be indicated by high levels of temperature, prolonged overheating, or high levels of humidity.

These sensors provide real-time temperature and humidity data that help in being advantageous in averting failures. Precise timing for maintenance can also be determined by using data collected by these sensors. The ultrasonic sensor helps in tracking physical displacement and the levels of liquid in the transformer health monitoring unit. Oil level in the transformer tank can be measured using ultrasonic sensors, and smoke pouring down can be caused due to oil leakage, overheating, or oil aging, which can alter the performance of the transformer. These abnormalities can be avoided by constant monitoring of oil levels, along with tracking usage of the transformer and setting limits to avoid catastrophic failures. The monitored data flow under the Transformer Health Monitoring Unit is sequentially structured.

The parameters voltage, current, temperature, humidity, and oil levels are continuously monitored by the appropriate sensors. Unprocessed sensor data is fetched by the ATmega328 microcontroller, which works with the data by filtering noise and reformatting it. Processed information is sent over a long distance using the LoRa RF module to the Edge Gateway Unit. Communication zones allow for seamless transfer of information regardless of wires or ease of access to the site.

This method allows regions that have impaired regions to be monitored. In Figure 1, a block diagram of a Transformer Health Monitoring Unit is presented. Its components include a voltage and current sensor, a temperature sensor, a DHT sensor, an ultrasonic sensor, an ATmega328 microcontroller, a LoRa RF module, and a power supply for monitoring transformer conditions in real time. All of the sensors are attached to the ATmega328 microcontroller, which is the primary processing unit. The LoRa RF module functions as the interface for wired communication, which receives real-time data from the right transformer and sends it to the Edge Gateway Unit. The system works without interruptions because of a reliable power supply. Moreover, the system ensures that an ultrasonic sensor is used for safeguarding when detecting the level of oil and any structural damages or changes that may occur.

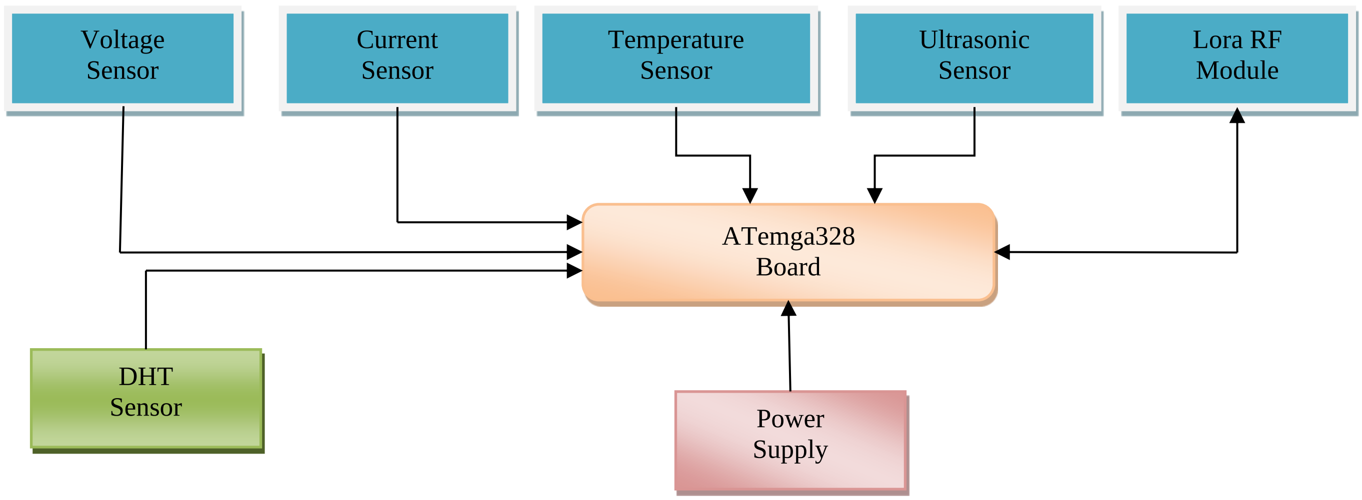

Fig. 1 Block diagram of the transformer health monitoring unit

With the adoption of this smart monitoring technology, the unit enables the early detection of faults, monitors conditions in real-time, and transmits data over long distances without wires. This information helps in optimizing the transformer's maintenance tasks, minimizing unanticipated failures, and increasing the productivity of the entire power distribution network. The combination of IoT sensors, LoRa RF communication, and advanced predictive analytics guarantees that the transformers operate at their optimal conditions, increasing the power system's reliability and decreasing expenses. This bottom unit of the Integrated IoT-Cloud Wireless RF Framework allows for efficient monitoring of transformers and implementation of data-driven fault detection and diagnosis. Enhanced transformer health assessment with reduced system downtime and increased power system reliability is achieved by employing cloud infrastructure, long-range wireless communication, and low-power microcontrollers.

The IoT-Cloud Integrated Wireless RF Framework has an Edge Gateway Unit, which is critical for cloud transmission, local processing, and data aggregation. The IoT-Cloud Integrated Wireless RF Framework has Enable Gateway Units for efficient health monitoring that act as an intermediate processing unit with the Transformer Health Monitoring Unit and the cloud server on ThingSpeak. Additionally, it takes care of proper transmission of data through wireless mediums while also visualizing the status of the transformer's health and processes it in real time. It is composed of an ATmega328 microcontroller and a LoRa RF module for long-range communication, and it also has an ESP-01 WiFi module for cloud communication. With these components integrated, the system comes alive in extreme remote areas where the energy consumption is minimal.

An ATmega328 microcontroller is at the heart of the Enable Gateway Unit; it supervises the process of reception, analysis, and transmission of data. During this process, the LoRa RF module picks health information from the transformer in real time and transfers it to the Transform Health Monitoring Unit, where the microcontroller analyzes it. The programmed function of the ESP-01 WiFi module is to facilitate cloud access, which allows the system to upload processed information to the ThingSpeak cloud portal for remote monitoring and analytics. The combination of local processing and cloud storage makes the Edge Gateway Unit an effective and scalable solution for transformer fault monitoring.

The LoRA RF module is responsible for the communication between the Transformer Health Monitoring Unit and the Edge Gateway Unit. LoRa technology best serves the purpose of long-distance communication, especially for the remote monitoring of transformers, because it is low-power and high-penetration. The ATmega328 microcontroller receives the sensor data sent from the Transformer Health Monitoring Unit, processes the information, removes noise, and produces accurate information, which is sent to the cloud. Afterwards, the ESP-01 WiFi module is used to communicate with the ThingSpeak cloud, after which the data is kept, processed, and displayed.

Because of the cloud integration through WiFi, the health data of the transformer is accessible in real-time, which permits maintenance personnel to address the most immediate situations effectively. Data Flow processes within an Edge Gateway Unit follow a repetitive methodology. First, the RF Front End LoRa module gets the sensor information from the Transformer Health Monitoring Unit. The information is then processed by the ATmega328 microcontroller, and only relevant information is sent to the cloud. At the same time, the ESP-01 WiFi module uses the ThingSpeak Cloud for storage, analysis, and graphical representation through dashboards. With this approach, transformer health data is processed so that it can be used on premises and in the cloud, augmenting the efficiency of the entire system.

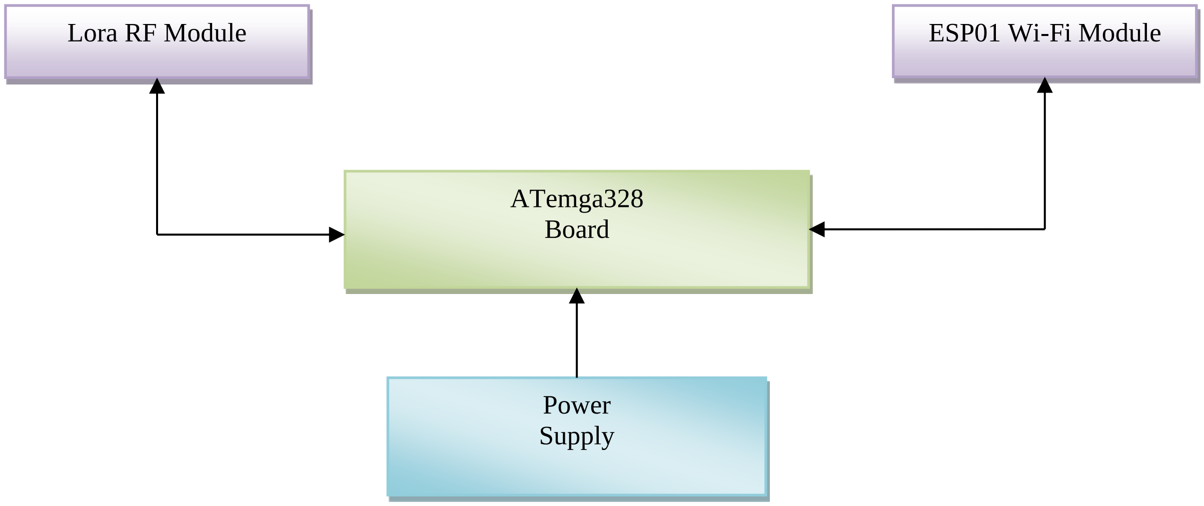

Fig. 2 Block diagram of edge gateway unit

Figure 2 depicts the block diagram of the Edge Gateway Unit, which contains an ATmega328 microcontroller, LoRa RF module for receiving transformer health data, and an ESP-01 WiFi module for transmitting information to the cloud. The LoRa RF module gets the information from the Transformer Health Monitoring Unit and sends it to the ATmega328 microcontroller. The ESP-01 WiFi Module provides cloud connectivity by sending the processed information to ThingSpeak. The Edge Gateway Unit enabled a stable operation for the transformer health monitoring system. Therefore, it has a guaranteed power supply unit. Thus, the unit behaves in a robust manner and is scalable. With this intelligent edge computing solution, the Edge Gateway Unit improves the monitoring of transformers by enabling real-time data representation, data processing, and storage in the cloud, as well as predictive analysis.

The amalgamation of LoRa RF for long-range communication, WiFi for cloud communication, and the cost-effective, energy-efficient scaling options guarantees an accurate assessment of the transformer's health. This method adds value to industrial IoT-backed power system monitoring by greatly augmenting the accuracy of fault diagnosis, decreasing maintenance expenses, and increasing power grid dependability.

4. Hardware and Implementation

The hardware connections of the Transformer Health Monitoring Unit have the following elements (Figure 3): The DHT11 sensor operates on, as well as records, the temperature and humidity values. The GND pin of the DHT11 is linked to the ground of the ATmega328 board, while the power pin is attached to the 5-volt supply. The data pin of the DHT11 is connected to one of the A2 pins of the ATmega328, which has the capability of reading the temperature and humidity values.

- The DS18B20 temperature sensor is used where higher accuracy of temperature measurement is necessary. The Vcc pin gets power from a 5V supply, the GND pin from ground, and the data pin from one of the ATmega328 A2 pins. In most cases, the data line must have a pull-up resistor for proper signal transmission.

- The Voltage Sensor measures the transformer's voltage. The sensor runs on two pins: Vcc, GND, and a signal output. Vcc is powered with 5 volts, GND is connected to ground, while the signal output is fed to the A1 analog pin of the ATmega328, through which voltage readings can be taken.

- The Current Sensor allows for measuring the transformer current. The Vcc pin is connected to a 5V supply, GND is connected to GND, and the analog output is connected to A0 analog input pin of ATmega328 for current measurement.

- SONAR 1 utilizes an HC-SR04 Ultrasonic Sensor to figure out distances, presumably to measure oil levels or the physical displacement of the transformer. The sensor's Vcc pin uses +5V while the GND connects to the GND of the ATmega328. A Trigger pin goes to a 3 no pin while Echo is attached to a 2 no pin of the ATmega328. Now, the microcontroller is able to send and receive ultrasonic signals to measure distances by calculating them.

- The Transformer Health Monitoring Unit utilizes SPI protocol to communicate with ATmega328 using the LoRa RF module. This allows long-distance data transfer. The ATmega328's 5V and GND power the module and address MISO (D12) and MOSI (D11) handle data. SCK (D13) will sync communications per standard. The LoRa module is selected with NSS (D10), DIO0 manages interrupts, and the RST pin allows resetting via the microcontroller. This allows for remote voltage, current, temperature, humidity, and oil-level monitoring of transformer health to be transmitted in real time.

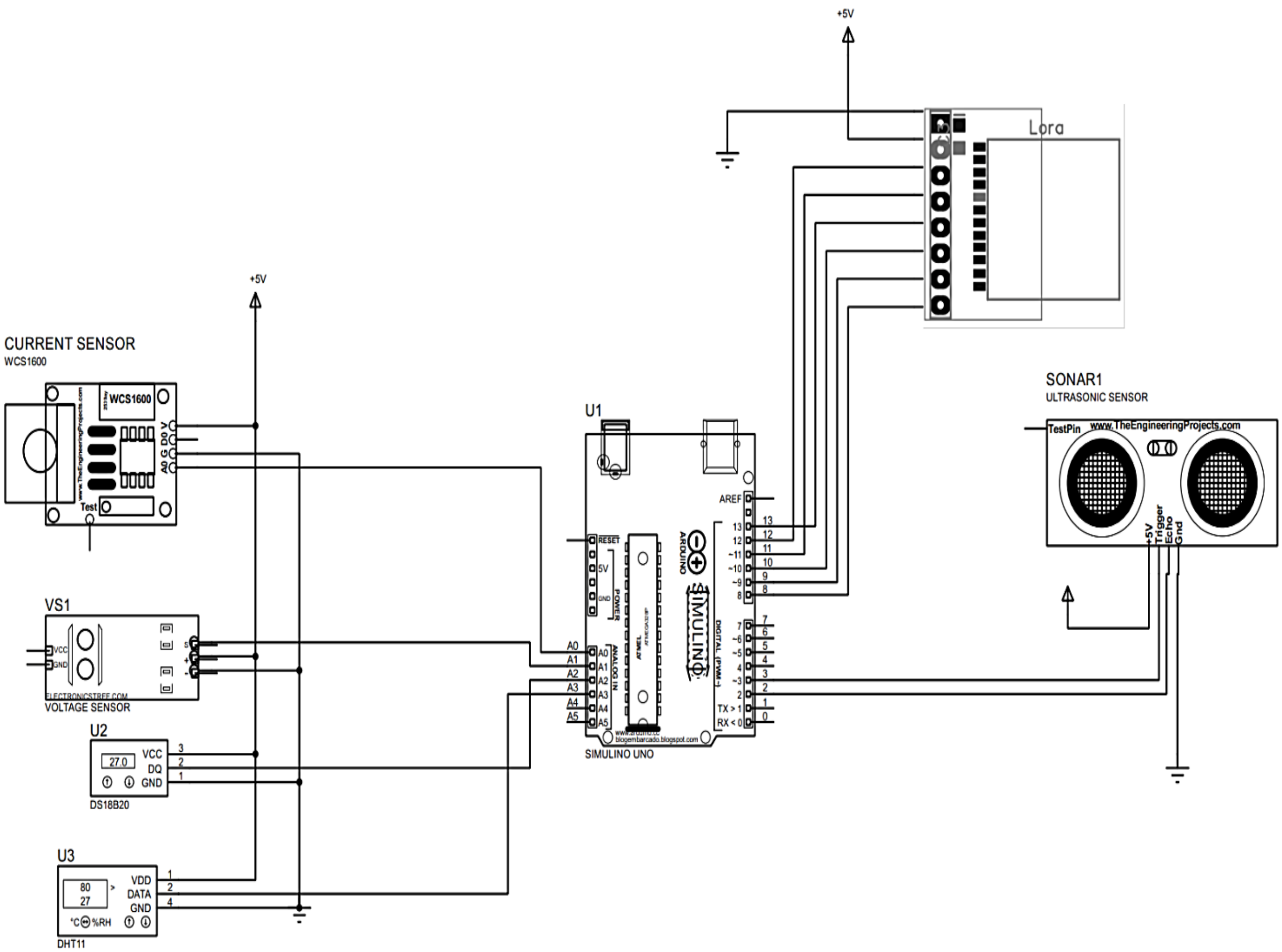

Fig. 3 Connection diagram of this transformer health monitoring unit

The hardware connections of the Edge Gateway Unit have the following elements (Figure 4):

- LoRa RF modules allow long-distance wireless communication by sending sensor data to a remote device. The LoRa module's Vcc and GND pins connect to the 5V supply and the ATmega328, respectively. LoRa module also connects to MISO of the ATmega328 on D12, MOSI on D11, and SCK on D13, working through SPI communication. The chip select pin NSS is connected to D10 to activate the module when needed. The DIO0 pin is linked to an ATmega328 digital pin to use for interrupts, and the RST pin allows the microcontroller to reset the LoRa module as required.
- The system incorporates the ESP-01 WiFi module for cloud access data transmission. The Vcc pin of the ESP-01 is connected to the 3.3V supply, whereas the GND pin is connected to the common GND of the ATmega328 system. The D7 pin of the ESP-01 that is programmed as the Transmitter using software serial communication is connected to the D6 of the ATmega328. Moreover, the D6 pin is connected to the D7 pin of the ATmega328 to allow UART Software serial communication. This arrangement enables the microcontroller to transmit information received from the sensors to the cloud for online monitoring.
- The LoRa RF module in the transformer health monitoring unit is able to communicate with the ATmega328 microcontroller through the SPI protocol for long-range communication. The Vcc and GND pins are connected to the 5V and GND lines on the ATmega328. MISO (D12) and MOSI (D11) pins are used for data transfer, while SCK (D13) is used for clock synchronization. The NSS (D10) pin selects the LoRa module, and DIO0 is responsible for handling interrupts. Additionally, the microcontroller can perform a reset through the RST pin. Because of this configuration, it is possible to transmit sensor data including voltage, current, temperature, humidity, and oil level in real time for transformer condition monitoring.

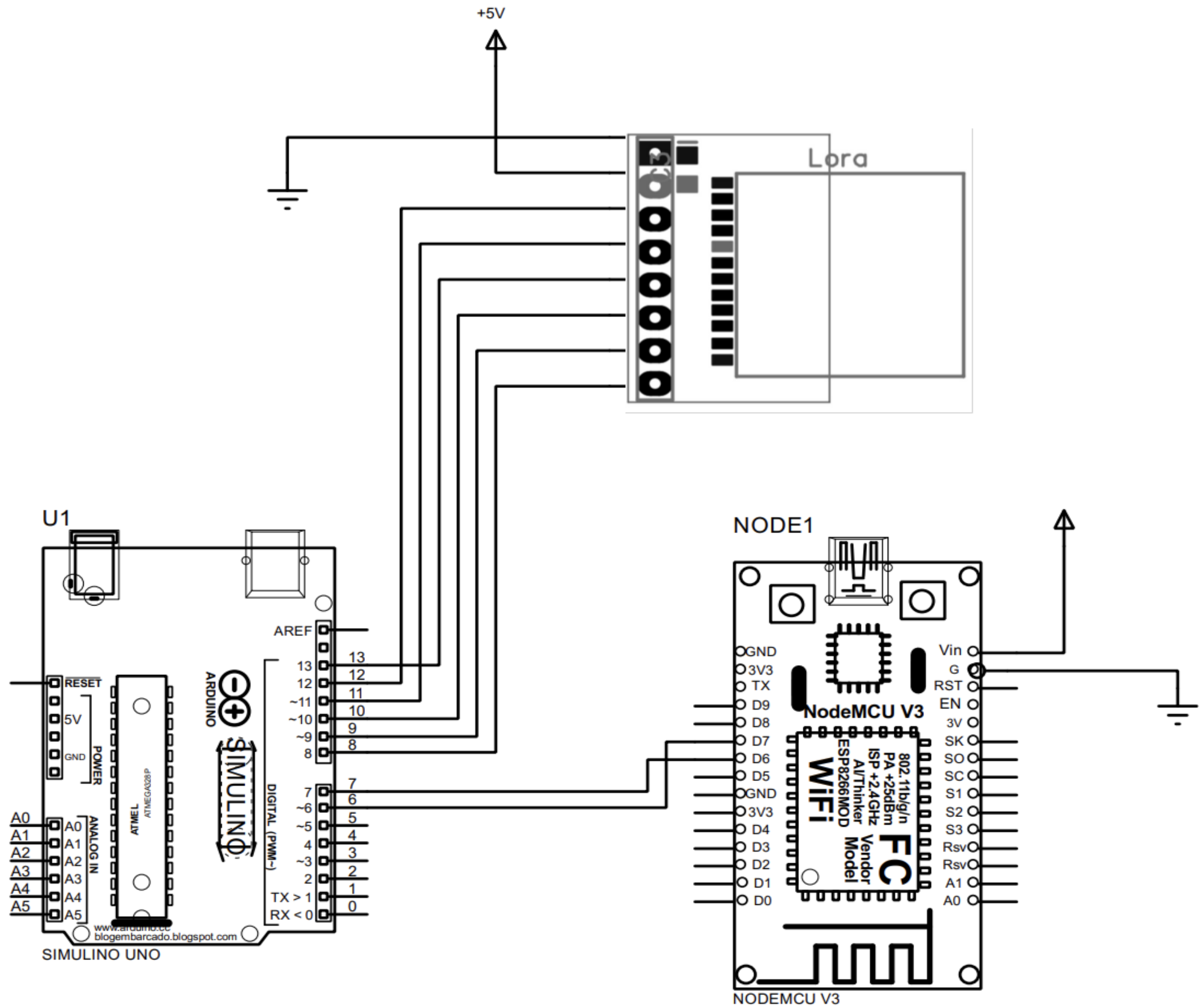

Fig. 4 Connection diagram of this edge gateway unit

5. Implementation of the System

The software and algorithm development for the unit goes far beyond employing technology for real-time data collection, processing, and wireless communication. The software manages sensor readings, noise filtering, data formatting, and LoRa RF communication transmission to the Edge Gateway Unit. Arduino IDE is used to develop embedded firmware in C/C++ to accommodate the ATmega328 microcontroller with the connected sensors. The entire system is optimized for low power consumption, minimized latencies, and dependable data transmission; these features render the system very effective for constant transformer health monitoring. Central to the software architecture of the transformer health monitoring unit is the module for sensor data acquisition, charged with the taking of periodic readings from multiple sensors mounted on the transformer. The sensors for voltage, current, and temperature, as well as the DHT (humidity) and ultrasonic sensor, offer real-time information about the transformer's condition. The ATmega328 microcontroller obtains data from these sensors through analog and digital pins and manipulates the data as necessary. To improve the accuracy of the data, the system uses calibration algorithms that account for sensor drift or changes in the environment. For example, temperature data from the temperature sensor goes through a temperature compensation algorithm so that the data can be trusted regardless of what the operating environment is like. The sensor data processes module is in charge of sanitizing and structuring the sensor data as it is sent out. Many sensor readings are subject to noise or fluctuations that cut the possibility of accurate fault diagnosis, which has caused the accurate reading to be of less use. The system utilizes a moving average and outlier detection filter to correct and smooth the readings. The filtered sensor data are formatted in the form of quanta containing the time of reading and enabling cloud analysis. Sensor ID and the sensor measured value, together with the unit of measurement, are encoded in each data packet before sending to the Edge Gateway Unit. To facilitate wireless communication, the LoRa RF module is integrated into the software stack of the Transformer Health Monitoring Unit. Owing to its low-power, long-range data transmission capabilities, the system can seamlessly function in harsh industrial settings. The firmware is engineered to transform the data collected from sensors into smaller LoRa packets, which helps to optimize the available bandwidth and lower the amount of packet loss. The environmental conditions dictate the frequency and power levels of the transmission, which allows for the improvement of signal strength and reduction of interference. The figure shows the developed Transformer Health Monitoring Unit, which is equipped with a variety of sensors and an LoRa RF module for real-time data acquisition and transmission. A transformation hand shaking mechanism is utilized between the Transformer Health Monitoring Unit and Edge Gateway Unit to guarantee the delivery of the packets as well as their retransmission in an instance where packet loss occurs. The data transmission unit is designed with efficiency in mind to enable the Transformer Health Monitoring Unit to be utilized for prolonged periods without high power usage. The firmware has low-power sleep modes where the microcontroller and sensors go into a standby mode when data transmission is idle, which reduces energy usage significantly.

This helps to achieve the feasibility of long-term system deployment. The intervals that facilitate waking up the units for data transmission are optimized against the operating conditions of the transformer, ensuring that critical faults are revealed in real-time, thus reducing unnecessary data transfers. A fault detection algorithm is integrated into the Transformer Health Monitoring Unit, which does preliminary analysis before sending information to the Edge Gateway Unit.

The algorithm continuously monitors sensor values for threshold values and abnormal parameters. Abnormal conditions such as voltage spikes, excessive current draw, overheating, or a low oil level get the systems to trigger alerts immediately and prioritize data transmission to the Edge Gateway Unit. Reducing the chances of major damage causes the late critical transformer failures that increase grid reliability while reducing maintenance costs. By ensuring that IoT-based sensor integration, fault detection algorithms, and LoRa RF communication are all working in tandem, proactive maintenance can easily be achieved without the risk of undetected unexpected failures.

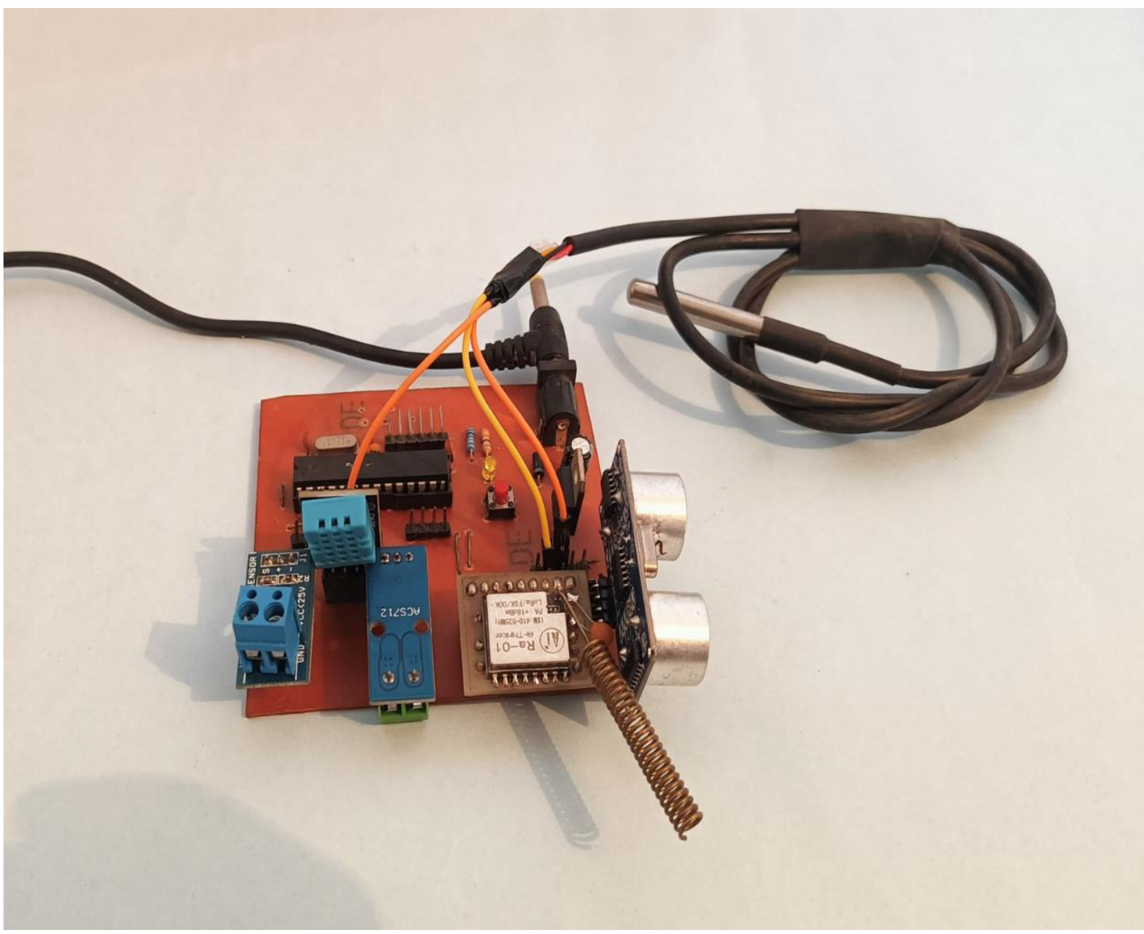

Fig. 5 Hardware node used for transformer health monitoring unit

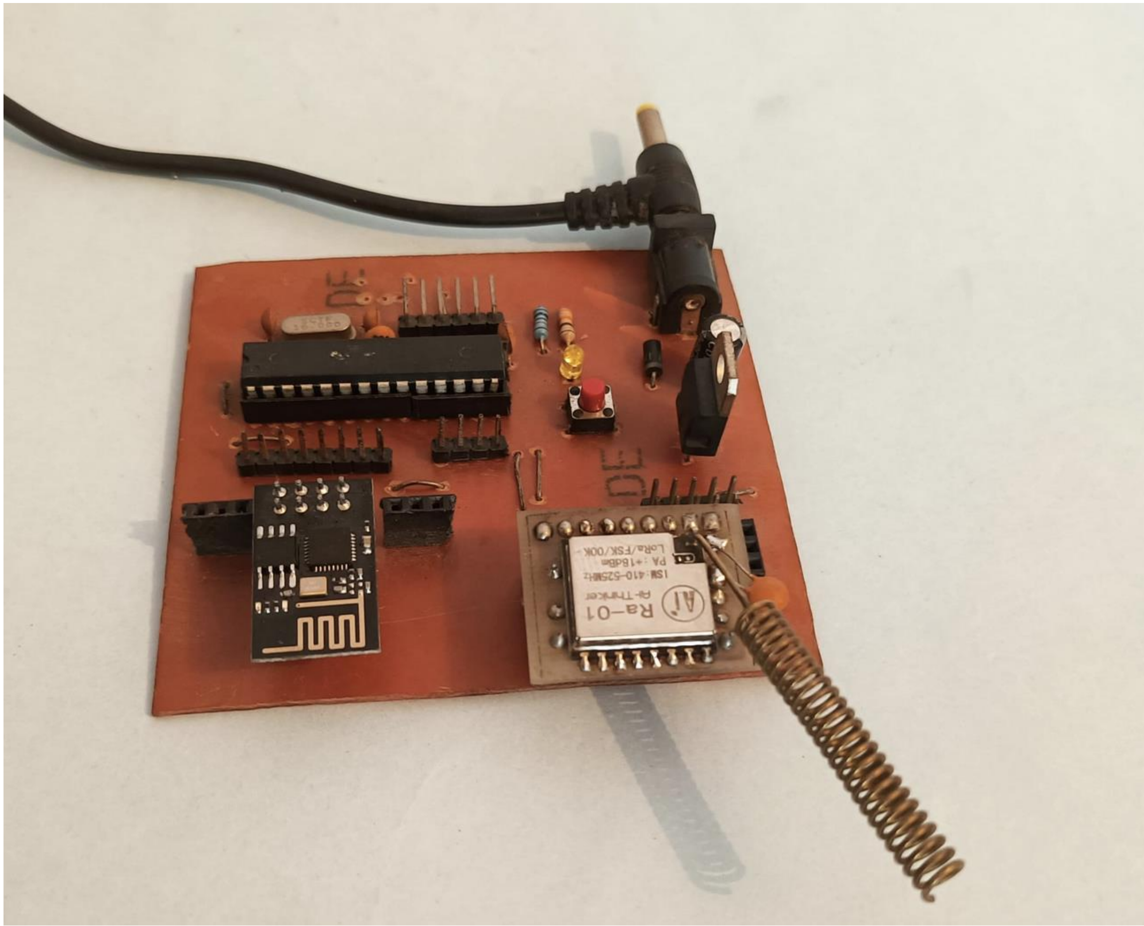

Fig. 6 Hardware node used for edge gateway unit

The Edge Gateway Unit is a significant part of the IoT–Cloud Integrated Wireless RF Framework, as it serves as a processing node in the RF framework between the Transformer Health Monitoring Unit and the cloud server. The Edge Gateway Unit software framework is developed with a focus on data reception, preprocessing, cloud uploading, as well as real-time monitoring and predictive analytics. The software part was implemented using C/C++ in Arduino IDE, and the firmware optimizing was done with low power usage, secure data passing, and high-speed processing for industrial-grade reliability. The wireless communication with the Transformer Health Monitoring Unit over LoRa RF is powered by the core of the Edge Gateway Unit, being the data reception module. An implemented Unit Edge Gateway is shown in Figure 6.

This unit integrates an ATmega328 microcontroller with a LoRa RF module, ESP-01 WiFi module for cloud data transmitting. The LoRa RF module gets sensor data packets from the Transformer Health Monitoring Unit. These packets include voltage, current, temperature, humidity, oil level reading, and timestamps with sensor IDs. Receiving data on the ATmega328 microcontroller is based on the integrity of the packets, which is validated through the checksum. If any data is damaged or incomplete, the system's the requests retransmission, ensuring the collected information is reliable and accurate. The data collected from the sensors is filtered and formatted by a data prepossessing module before being uploaded to the cloud. The raw readings taken from the sensors are usually distorted by environmental noise, erroneous transmission, or fluctuation. The firmware employs noise filtering techniques such as moving average filtering and outlier detection algorithms to solve this problem. The pre-processed data is then put into a JSON form so that it can be accessed through the ThingSpeak cloud API. Transmitting the data in JSON format allows for efficient and lightweight data transmission, minimizes latency, and ensures efficient network bandwidth utilization.

For cloud integration, the Edge Gateway Unit incorporates an ESP-01 WiFi module that establishes an HTTP connection with the ThingSpeak cloud server. The firmware is set up to perform HTTP POST requests on the cloud API periodically to ensure up-to-date logging and viewing of data. The system uses a data transmission schedule that maximizes efficiency by sending updates only on the significant changes in the parameters of the transformer. This strategy helps to reduce unnecessary calculations in the cloud and saves bandwidth. During WiFi disruptions, the firmware saves data on a buffer storage device and automatically transmits the data once the connection becomes stable. A predictive fault detection mechanism employing threshold-like anomaly detection was also included in the Edge Gateway Unit. The firmware also contains pre-programmed voltage, current, temperature, and humidity sensor thresholds that are above the defined safe operating ranges. When sensor readings are above the prescribed temperature range, the system sends immediate alerts to the cloud through ThingSpeak's MQTT-based messaging protocols. These alerts issue fault notifications to maintenance staff who will then take precautionary steps before the system suffers severe damage.

Fig. 7 Thingspeak web dashboard data visualization of the transformer health monitoring

The Edge Gateway Unit allows for the transfer of transformer health data to the ThingSpeak Cloud, where it is kept, processed, and monitored for maintenance purposes. When the data has been processed, the ESP-01 WiFi module connects to the internet and prepares to send information to ThingSpeak through a POST HTTP request. ThingSpeak is a visualization platform for real-time IoT. Using it, the parameters of the transformer can be shown on live graphs and dashboards. Maintenance teams are able to analyze trends and detect anomalies quickly since each transformer metric is graph separately and maintained voltage, current, temperature, humidity, and oil content.

Figure 7 is the ThingSpeak web dashboard, and it contains the real-time transformer health parameters for remote monitoring and predictive analysis. Like all IoT systems, users are constantly connected to the devices themselves and can thus monitor the actual condition of the transformer.

The system can also be configured to update every second, ensuring that the most recent transformer data is provided for inspection at all times. If any parameter exceeds predefined threshold limits, notifications and alerts can be triggered via ThingSpeak for the concerned personnel responsible for transformer maintenance.

6. Conclusion

The described system is a cloud-based ThingSpeak platform that allows for real-time remote monitoring of some critical transformer parameters like voltage, current, temperature, and humidity. With this information, proactive transformer maintenance is made possible, and unexpected failures can be reduced. This system incorporates multiple sensors, long-range LoRa RF communication, and cloud-based data logging to provide a comprehensive solution. A user-friendly interface alongside a cloud-based infrastructure enhances information accessibility from remote locations. Moreover, the wireless design allows for effective streamlining of operations alongside efficient deployment in areas where it is difficult to monitor the transformers. The power grid reliability is optimized alongside the operational cost when maintenance predictive techniques are employed. Future improvements may consist of the implementation of additional sensors for vibration analysis and oil monitoring, integration of edge computing for real-time, local processing, or more complex AI analytics for fault detection. Lastly, the futuristic implementation of data security through Blockchain Technology could be of assistance as well. From a broader perspective, these initiatives modernize IoT-based transformer monitoring systems and greatly enhance reliability, efficiency, and intelligence in the power distribution network.

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