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Smart Distribution Transformer Health Monitoring Using LoRa

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BSc. in
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Declaration

We hereby declare that this thesis is based on the results found by ourselves. Materials of work found by other researchers are mentioned by reference. This thesis, neither in whole nor in part, has been previously submitted for any degree.

Signature of Authors Signature of Supervisor

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ACKNOWLEDGEMENT

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ABSTRACT

Distribution transformers play a crucial role in the distribution of electrical power. Their surprise breakdown causes not only power cuts but also monetary loss and decreased reliability of the system. Traditionally, transformer monitoring methods are mainly done manually and periodically, and these cannot guarantee real-time fault detection.The project intends to develop a health monitoring system for smart distribution transformers which will utilize LoRa technology. The transformers will be equipped with sensors that would monitor their parameters—temperature, oil level, voltage, and current—on a continuous basis. A microcontroller will handle the sensor data and then use the low-power long-range communication technology called LoRa for wireless transmission. The system proposed opens up the possibilities of real-time monitoring, early fault detection, reduced maintenance cost, and a conquering of the transformer’s lifespan.

CHAPTER 1

INTRODUCTION

Electrical power distribution systems are essential components of modern life. Distribution transformers lower the voltage from power lines to a level that is usable by consumers. Given factors such as escalating load requirement, ageing assets and environmental issues that apply severe stress on transformer systems, the possibility of failing increases.

Conventional transformer monitoring approaches are based on the visual inspection and periodic maintenance. These techniques are expensive, slow and do not supply online information. Hence, there are many faults that are discovered late after substantial failures and disasters have happened.

Recently, IoT and wireless communication technology enables smart monitoring system. The object of this paper is divided into a smart- transformer health monitoring system, which is using LoRa and real- time data to decrease the maintenance cost and increase the reliability of distribution line.

1.1 Background

Electrical energy is essential for modern society. An efficient power distribution system is vital for ensuring a reliable electricity supply. Distribution transformers are crucial in the power distribution network. They lower high voltage to a level that end users can safely use. These transformers run continuously under different load conditions and environmental pressures. Over time, these factors can impact their performance and reliability. Because they operate continuously, distribution transformers face thermal stress, electrical stress, and aging insulation. Common issues like overheating, oil leaks, voltage changes, and overloading can cause transformers to degrade and fail unexpectedly if not caught early. When transformers fail, it leads to power outages and costly repairs. It also decreases the system's reliability. In many traditional power systems, transformer monitoring and maintenance happen through regular manual inspections. This method does not allow for real-time monitoring and often misses early warning signs of faults. Therefore, maintenance tends to be reactive instead of preventive. Recent improvements in embedded systems, sensors, and wireless communication have enabled the creation of smart monitoring solutions for power equipment. Keeping a close watch on key transformer metrics such as temperature, oil level, voltage, and load current helps detect faults early and allows for condition-based maintenance. Among the various wireless communication options, LoRa (Long Range) has become a great choice for long-distance and low-power data transmission. LoRa technology offers broad coverage, low energy use, and dependable communication. This makes it especially useful for monitoring distribution transformers in remote and rural areas. This project focuses on developing a smart health monitoring system for distribution transformers using LoRa technology. The goal is to improve transformer reliability, lower maintenance costs, and support the growth of smart power distribution systems.

Figure1:Conventional Distribution transformer

1.2 Importance of Transformer Health Monitoring

Transformer health monitoring is crucial for ensuring the reliable and continuous operation of electrical power distribution systems. Distribution transformers work under different load conditions and face environmental stress, which can lead to gradual insulation degradation, overheating, oil leakage, and overloading. Without proper monitoring, these problems can cause sudden transformer failure. Constant health monitoring helps detect abnormal operating conditions early, such as excessive temperature increases, unusual voltage changes, and drops in oil levels. Early fault detection allows for preventive maintenance, which greatly reduces the risk of a catastrophic transformer failure and extends the lifespan of the transformer. Transformer health monitoring also boosts power system reliability by reducing unexpected outages. It cuts maintenance costs by shifting from time-based maintenance to condition-based maintenance. Additionally, real-time monitoring improves operational safety and aids in efficient asset management for power utilities. With modern sensors, microcontrollers, and wireless communication technologies, smart transformer health monitoring systems are key to developing intelligent power distribution networks and smart grid applications.

1.3 Limitations of Conventional Methods

Conventional transformer monitoring and maintenance mostly rely on manual inspections and periodic testing. These methods have several limitations that reduce their effectiveness in today's power distribution systems. One major issue is the absence of real-time monitoring. Manual inspections happen at set intervals, making it hard to spot sudden or fast-developing faults. Consequently, transformer failures can happen without any warning. Another problem is the high cost and labor involved in maintenance. Regular field visits need skilled workers, transportation, and time, which makes the process inefficient and costly. Moreover, manual monitoring can lead to human error, resulting in inaccurate assessments of transformer health. Standard systems also lack the ability for remote monitoring, particularly for transformers located in rural or isolated areas. In many instances, communication infrastructure is weak, making continuous monitoring difficult. Because of these limitations, traditional transformer monitoring methods are not suitable for modern power systems that need reliable, efficient, and real-time monitoring solutions. These challenges show a clear need for smart, automated, and wireless transformer health monitoring systems.

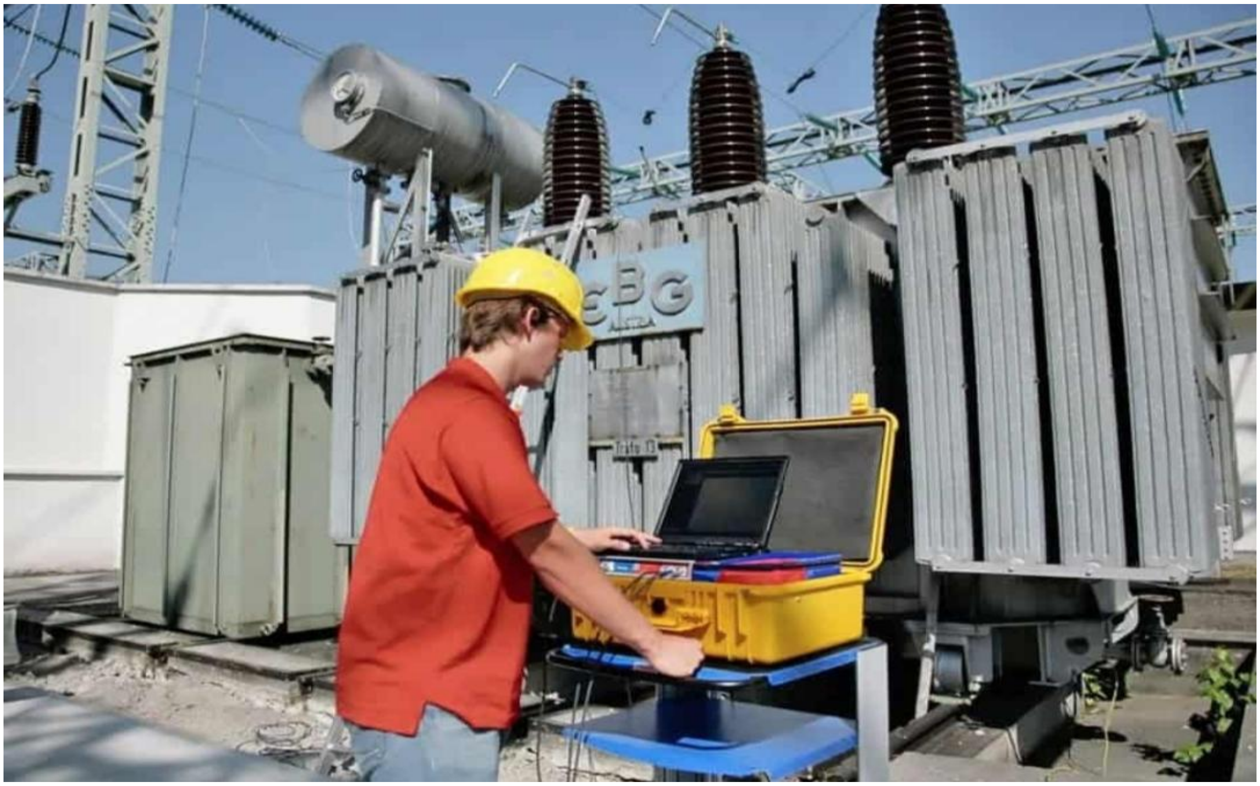

Figure 1.1 Conventional Transformer monitoring Techniques

1.4 Motivation

The creation of smart grids and IoT tech has driven the need for transformer monitoring systems that work in real time. Figure 1.2 shows how smart transformer monitoring can work with IoT and LoRa tech by allowing data to be gathered and watched remotely in real time.

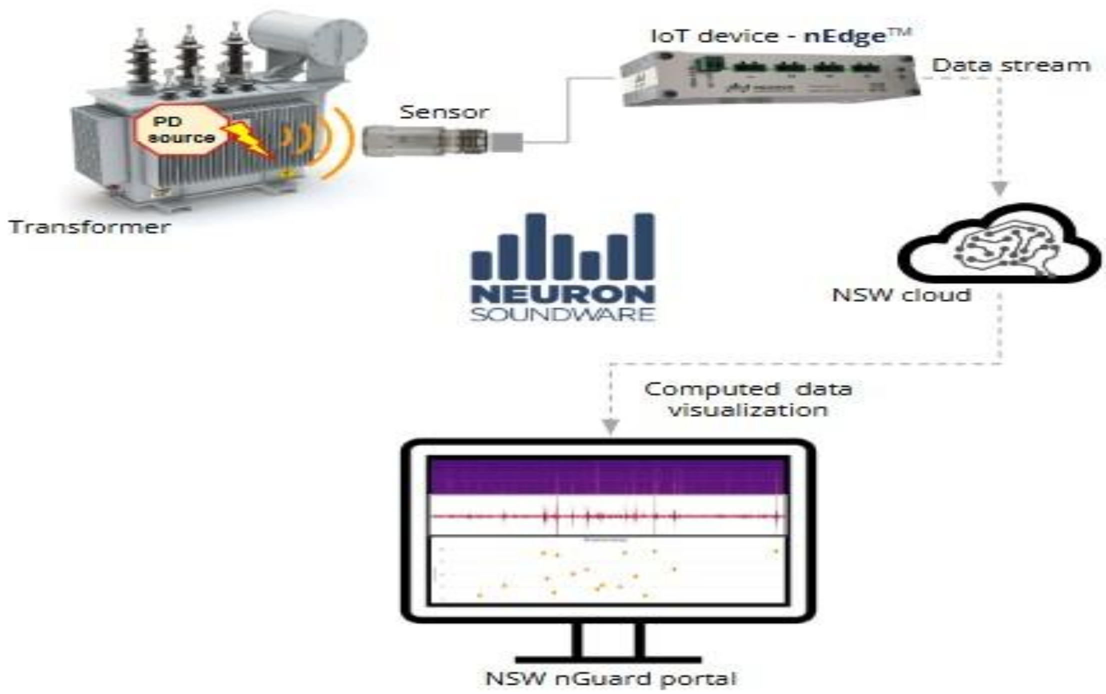

Figure 1.2 Real time monitoring IoT

1.5 LITERATURE REVIEW

Checking how transformers are doing has become a hot topic lately because everyone wants power grids that don't fail. Keeping an eye on things like temperature, oil, voltage, and current is super important to stop breakdowns, cut down on repairs, and keep the power on.

Sidhu and Singh [1] came up with a cool system that uses sensors to spot weird stuff with temperature and voltage. Their work showed why watching things in real-time is key to stopping transformers from breaking down. But, the system used wires, which means it can't be used everywhere, especially in far-off places.

Rahman et al. [3] built a system that uses the internet to find transformer problems, mixing sensor info with cloud computing. This system lets you watch things from far away and get alerts, but it needs a good internet connection, which isn't always possible in the sticks.

LoRa is known as a good way to watch things from far away without using much power. Adelantado et al. [4] talked about what's good and bad about using LoRaWAN for keeping an eye on industrial stuff, pointing out that it's good for watching energy use. Raza et al. [5] said that networks like LoRa are great for smart grids and the internet of things because they cover a lot of ground and don't need much power.

l-Ali et al. [6] created a smart system with embedded microcontrollers to keep tabs on transformer stations. Their work showed that keeping a constant watch and catching problems early can really make transformers more reliable. Semtech Corporation [7] also put out some helpful info on LoRa modulation, which is great for figuring out how to build wireless transformer monitoring setups.

Looking at what's already out there, most systems seem to focus on either using sensors to monitor things or using IoT for communication. But not many put together low-power, long-range communication (LoRa) with actually watching transformers as they work. Our system tries to fix this by mixing sensor connections, microcontroller processing, and LoRa communication. This should give us a reliable and cheap way to keep an eye on how transformers are doing.

So, the key things from the research are:

* Watching transformer stats live.

* Spotting problems early.

* Using wireless that doesn't hog power and reaches far.

* Being able to grow the system and check it from anywhere.

All of this gives us a base to build a cool system that keeps tabs on how distribution transformers are doing, using LoRa technology.

1.6 Objectives

- Transformer supervision in real-time.
- To Communication over a long distance by means of wireless.
- To Designing a system that is both low in power consumption and cost-effective.

CHAPTER 2

SYSTEM OVERVIEW AND ARCHITECTURE

2.1 Overall System Description

This LoRa-based system keeps an eye on how distribution transformers are doing by constantly checking key info and sending updates to the monitoring station. The goal is to spot any issues early, so we can stop the transformer from breaking down and save on repairs.

Basically, we put sensors on the transformer to keep track of things like temp, oil level, how much power it's using, and the voltage coming in. These things tell us how the transformer is doing. A small computer then looks at the sensor data and compares it to what's expected. If anything seems off, it raises a flag.

After the info is processed, it's sent wirelessly using a LoRa module. LoRa is great because it can communicate over long distances and doesn't use much power, so it's a solid fit for rural spots. The data is picked up by a LoRa gateway, which sends the info to a monitoring platform or a cloud server. Then, people can check out what's happening in real-time, see past trends, and get alerts if something goes wrong.

By keeping an eye on things and catching problems early, this system helps utilities do maintenance when it's actually needed. This boosts reliability and helps transformers last longer. Plus, the design is easy to expand and can be added to smart grid tech later on.

2.2 System Block Diagram

The overall system architecture is illustrated in Figure 2.1

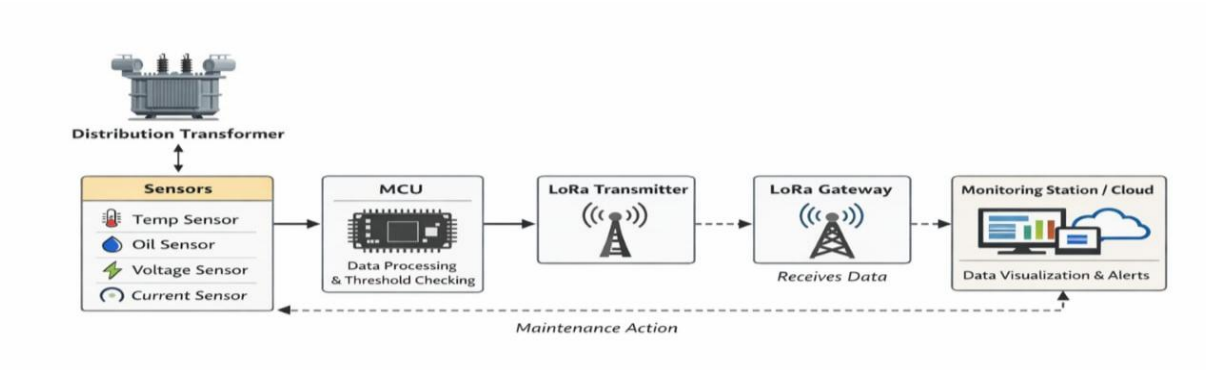

Figure 2.1: Block Diagram of Smart Distribution Transformer Health Monitoring System using LoRa.

The block scheme illustrates the transformer fitted with sensors linked to a microcontroller. The microcontroller unit (MCU) gathers sensor data, processes it, and sends it through the LoRa module to the LoRa gateway. The gateway then transfers the data to the monitoring station, which visualizes and evaluates it.

2.3 Data Flow in the System

- Here proposed system's data flow is carried out in the following sequence:
- Temperature, oil level, voltage, and current are monitored by sensors.
- Microcontroller gathers the sensor data and verifies it against the threshold values.
- If something's not right, it sends out a warning.
- Once processed, it is sent back through the LoRa module, arriving at the gateway.
- The gateway sends the data to a place where people can watch it, like a computer or cloud..
- People look at the data, spot patterns, and fix any problems.

2.4 Communication Flow

The transformer node and the monitoring station talk to each other wirelessly over a long distance. LoRa lets data go several kilometers without using much power.

Lots of transformer nodes can send data to one gateway. This allows a single place to keep tabs on many distribution transformers.

CHAPTER 3
SYSTEM DESIGN AND IMPLEMENTATION

3.1 System Architecture

A Distribution Transformer, sensors, a Microcontroller Unit (MCU), a LoRa thingy for talking to other devices, a LoRa gateway, and a place to watch everything – either a Monitoring Station or the Cloud. The general framework is depicted in Figure 3.1. The sensors provide the data, the MCU processes it, the LoRa communication carries it to the gateway, and the monitoring platform shows it.

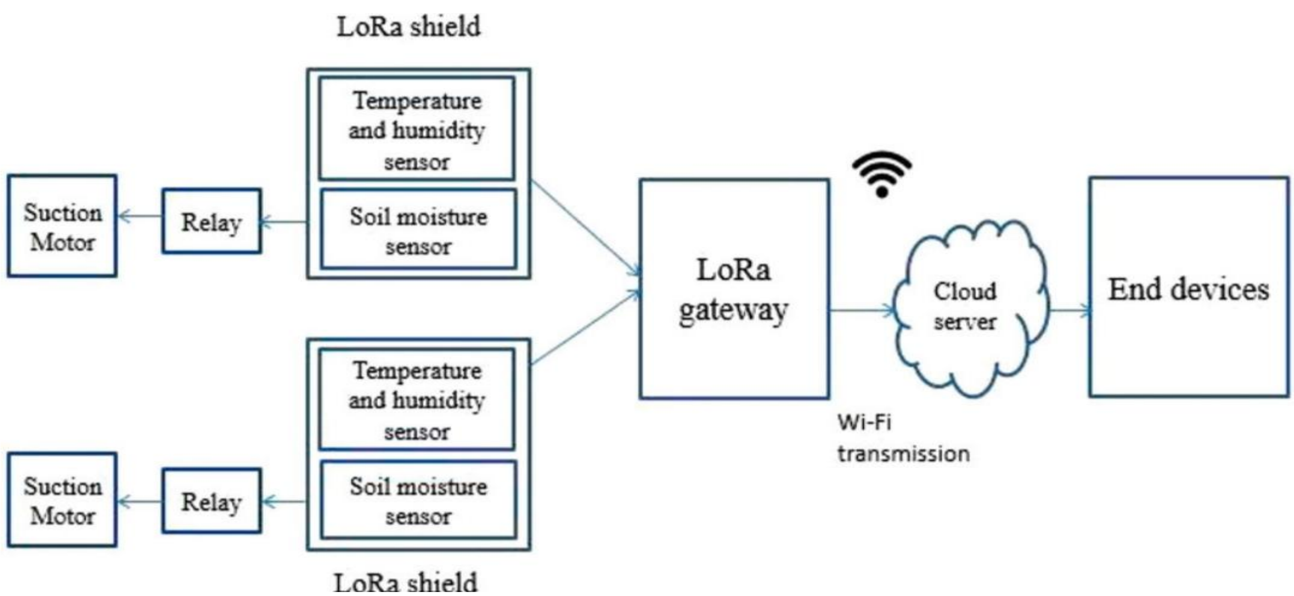

Figure 3: Block Diagram of Smart Distribution Transformer Health monitoring System Using LoRa

3.2 Hardware Design

The Smart Distribution Transformer Health Monitoring System's hardware, made with LoRa, is all about grabbing data reliably, not using much power, and sending info wirelessly without issues. We built the hardware like building blocks. This way, swapping out parts or making upgrades later on is a cinch.

This system keeps an eye on how a distribution transformer is doing by using several sensors. For example, a temperature sensor checks the temperature of the oil or windings. This is important because it tells us if the transformer is getting too hot or being overworked. There's also an oil level sensor that looks for leaks or low oil, which can mess with how well the transformer is insulated and cooled. And to top it off, voltage and current sensors track the electrical load on the transformer.

The sensors all feed into a Microcontroller Unit (MCU), basically the system's brain. This MCU constantly grabs both analog and digital signals from the sensors and turns them into useful numbers using its built-in converter. The microcontroller also does some simple number crunching, comparing what it measures to set limits to spot anything weird going on.

We're using a LoRa thingy with the microcontroller for wireless stuff. We picked LoRa because it can reach far, doesn't eat up much power, and works pretty well outside. The LoRa module sends the sensor info to a LoRa gateway far away, so we can communicate over long distances without needing a complicated setup.

A regulated power supply is applied to maintain stable voltage for all the hardware such as sensor, microcontroller and LoRa module. Good power regulation provides stable system stability and protects hardware from high voltage.

In summary, the hardware design provides precise data sensing, high-performance processing capabilities and robust long-distance communication ability for the proposed system to be applied in real-time transformer health monitoring.

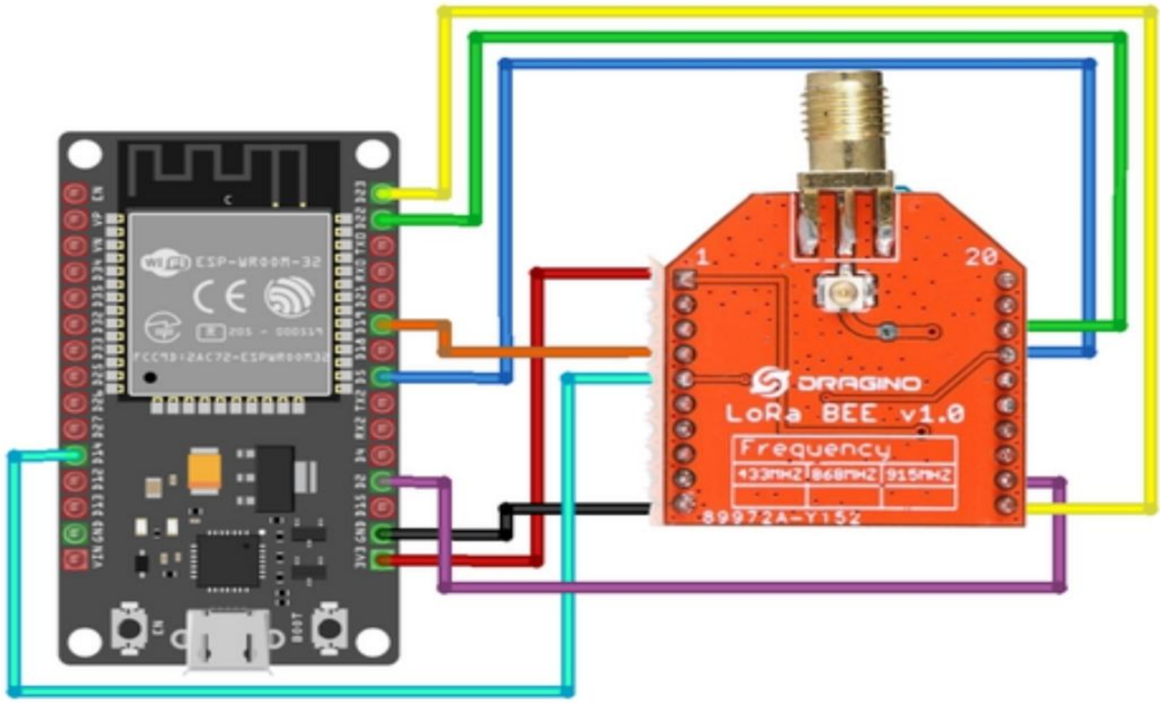

Figure 3.1 : Hardware connections.

- Sensors: Temperature, Current, Voltage , Oil Level
- Microcontroller: ESP32-based MCU
- LPWAN module: One which is SX1278 compatible
- Power supply: Regulated form of 5V

3.3 Sensor Interfacing

Sensor interfacing is one of the main parts in proposed smart transformer health monitoring system, which guarantees credible obtaining of transformer operated parameters. This system involves the use of various sensors which are connected to the microcontroller for sensing oil level, load current, voltage and temperature.

The temperature transducer is connected to an analog input pin of the microcontroller for tracking the transformer oil or winding temperature. This parameter is critical in the monitoring of overheating conditions due to overload or deterioration insulation. Similarly the oil level sensor is attached to an analog input pin and is used for sensing the fall in transformer oil level either on account of leakage or aging of transformer.

Voltage and current sensors are coupled to the microcontroller for sensing an electrical condition of the transformer. The voltage sensor sensing the input or output voltage of the transformer and the current sensor detecting a load current are included. These sensors are used to sense overloading and unusual working conditions.

The microcontroller gets the sensor signals via its internal analog-to-digital converter (ADC). After this, the raw sensor data gets transformed into real-world units by means of appropriate scaling and calibration methods. Proper sensor interfacing guarantees that data collection will be reliable, measurements will be accurate, and the system will have stable performance. After interfacing, the sensor data is processed and sent out via the LoRa communication module. Interfacing between various sensors and the microcontroller unit is depicted in Figure 3.2. All the sensors are connected to the MCU's analog/digital pins.

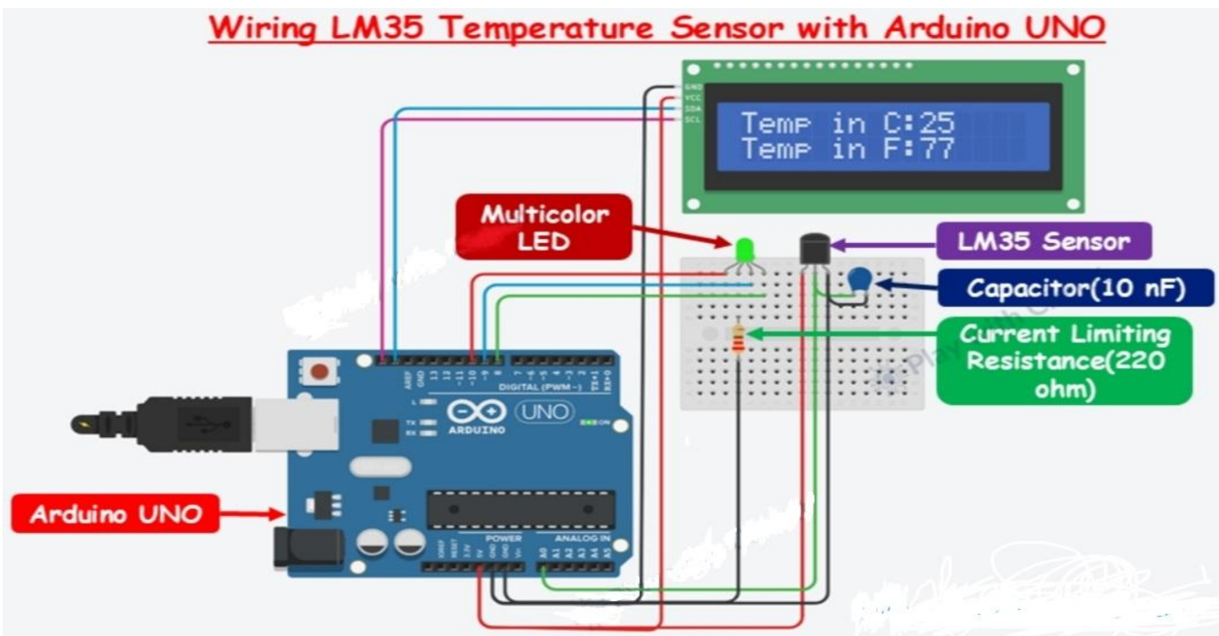

Fig. 3.2: Sensor Interfacing Diagram

- The temperature → A0
- The oil level → A1
- The voltage → A2
- The current → A3

3.4 LoRa Communication

Wireless communication is one of the principal elements of the designed system, and the LoRa (Long Range) technology is the medium for data transfer between the unit for checking the transformer and the remote monitoring station. LoRa is one of the LPWAN (Low-Power Wide-Area Network) technologies, which allows communicating over long distances using very little power.

In the proposed system, the LoRa module is connected to the microcontroller via SPI communication. After analyzing the sensor data, the microcontroller sends the information to the LoRa module, which transmits the data wirelessly to a LoRa gateway. The gateway plays the role of an intermediate device that collects data from one or more transformer monitoring units and sends the data to a centralized monitoring station or cloud server.

The main benefit of LoRa communication is its coverage area of great distances, even in rural or remote locations, without the need for cellular or wired communication infrastructure. Furthermore, LoRa ensures reliable data transmission and uses very little energy, hence making it fit for continuous monitoring applications.

With the help of LoRa communication, remote access is provided to real-time transformer health data and alerts are sent out when abnormal operating conditions are detected. The LoRa communication flow between the transformer unit and the gateway is depicted in Figure 3.3.

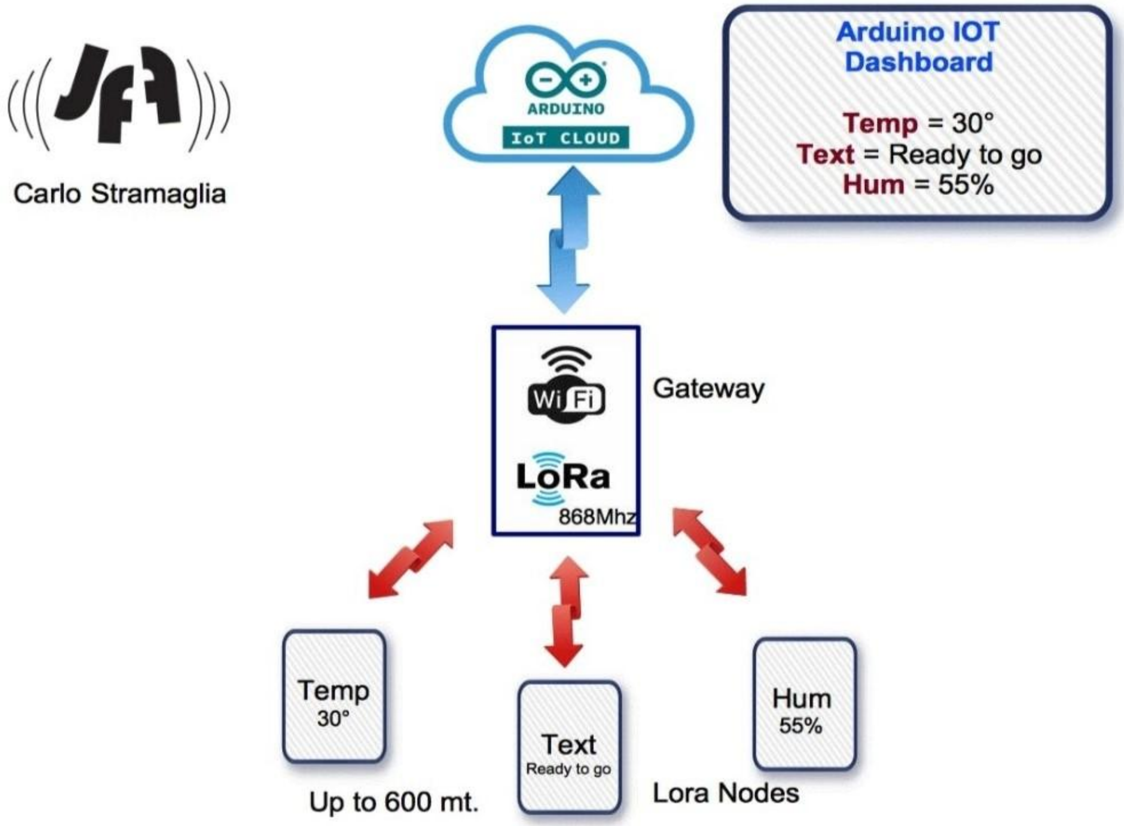

Fig. 3.3: LoRa Communication Flow

- MCU → LoRa Transmitter → Gateway → Cloud/Monitoring Station
- Frequency: 915 MHz (region-specific)

3.5 Software Flowchart

The software flowchart indicates comprehensively the logical operation of the smart distribution transformer health monitoring system. It gives a complete account of the system's operation as it initializes itself, captures data from the sensors, processes the data and finally transmits it through the LoRa communication module.

The very first step in the program is the initialization of the microcontroller, sensors and the LoRa module, which are the system's hardware components, in that order. Some parameters, including baud rate, sensor configuration and communication settings, are set during the initialization stage. Thus, all system components come up and wired ready for operation.

Then, the microcontroller continues to read data, after the initialization, from the sensors that are connected. The temperature sensor is responsible for getting the oil or winding temperature of the transformer, while the oil level sensor indicates the status of the oil level. Current and voltage sensors continuously check the electrical operating conditions of the transformer. The sensors are arranged in such a way that every reading is taken at regular intervals so that monitoring is done uninterruptedly. The sensor data that was acquired is the first thing that is received by the microcontroller, which then makes the next move. The sensor readings which were taken in their raw states are made to be actually physical through the application of predetermined calibration factors. In turn, those values are subjected to comparison with sets of predefined limits and grouped as normal or abnormal depending on which group the values from the transformer fall under. If wrong limits are crossed in the case of any parameter, the system classifies the event as a fault.

The last step in the data processing is when the microcontroller sends the already processed data of the sensor to the LoRa module. Then, the LoRa module passes the data on wirelessly to the LoRa gateway from where it reaches the remote monitoring station. This provision allows instantaneous monitoring of the health of the transformer even if one is at a far-off place.

The process is repeated by the system continuously in a loop to make sure that the monitoring is done without any break. The software flowchart of the proposed system in Figure 3.4 indicates the operational sequence step by step.

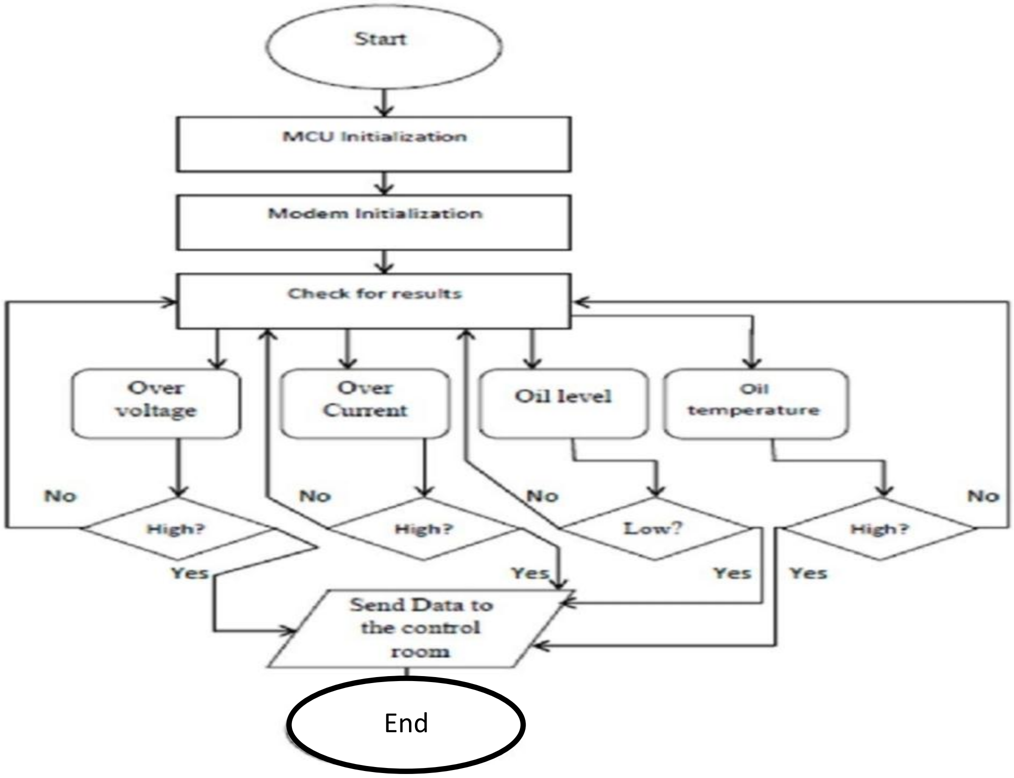

Fig. 3.4: System Operation Flowchart

❖ Steps:

- Reading of the sensor's values
- Comparison with the preset limits
- Generation of an alert if the condition is abnormal
- Transmission via LoRa network
- Showing it on the control panel

3.6 Experimental Setup

The development of the prototype for the proposed smart distribution transformer health monitoring system is intended to confirm the practicality and performance of the designed hardware and software in real-world applications. The experimental arrangement includes sensors, a microcontroller unit, a LoRa communication module, and a regulated power supply all set up in a laboratory environment.

In the prototype model, either a low-voltage transformer or an equivalent transformer setup is used to mimic actual operating conditions. Suitable points on the transformer model are where temperature, oil level, voltage, and current sensors are deployed to get real-time data about the operating conditions. The sensors feed into a microcontroller that constantly receives and handles the measured values.The programmer has set up the microcontroller so that it will keep an eye on the sensor data and by checking the measured characteristics against the set threshold values, it will know if the conditions are abnormal or not. During the normal operation of the system, the sensor data is sent out at regular intervals through the LoRa module. If the conditions are abnormal such as a high temperature, low oil level, or the equipment being overloaded, then the system will raise an alarm and pass on the information at once to the remote monitoring station.

The LoRa module set up in such a way that it can communicate with the nearest LoRa gateway which picks up the data and then sends it to the monitoring interface. This configuration highlights the use of long-range and low-power wireless communication in transformer monitoring applications as an effective one.To provide reliable operation during the experiments, the entire prototype is fed with a stable power supply. The prototype's experimental results validated that the system could perform real-time monitoring, fault detection, and long-distance data transmission. The prototype developed and the experimental setup of the proposed system are illustrated in Figure 3.5.

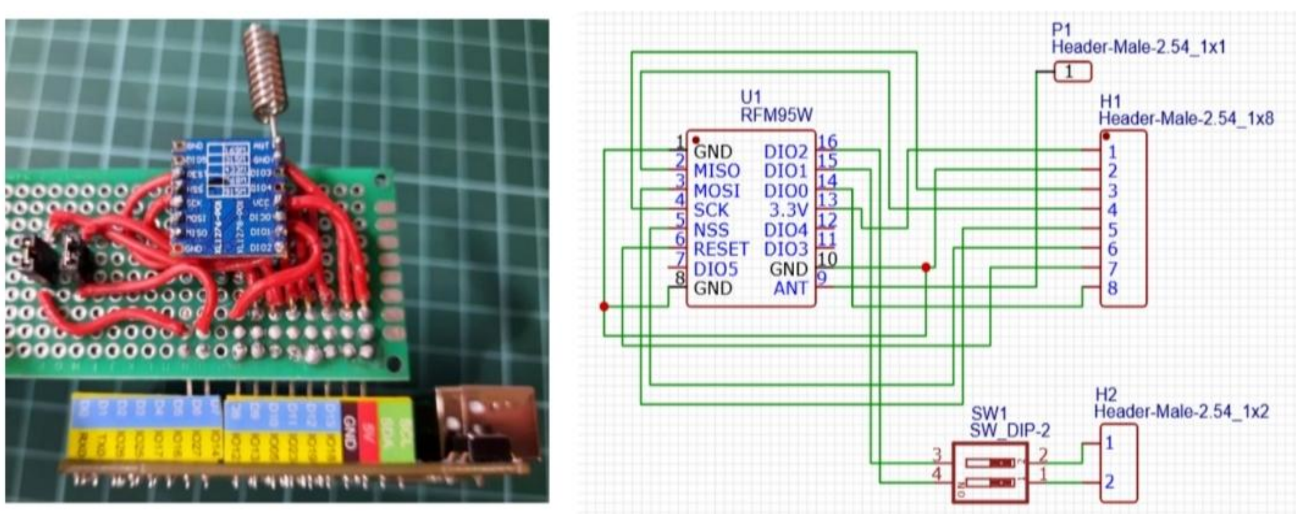

Fig. 3.5: Hardware Prototype

- Sensors installed on transformers.
- MCU and LoRa module interfaced.
- Data is transmitted to the control room.

3.7 Cost Analysis

Here's a breakdown of what it actually costs to build this smart distribution transformer health monitoring system with LoRa technology. The main goal here is simple: figure out the total hardware cost, and show that this setup isn't just affordable—it actually makes sense if you want to use it in the real world.Most of the expenses come from the basics: sensors, a microcontroller, the LoRa module, and power supply parts. There are a few other odds and ends, but nothing fancy. Every piece in the prototype is easy to find on the market and doesn't break the bank. So, if you're thinking about rolling this out on a big scale, the price won't hold you back.

Table: Cost Analysis of the Proposed System

SI.No	Component Name	Total Cost (BDT)
1	Arduino Uno (2 pice)	1100 TK
2	LoRa Module (2 pice)	2800 TK
3	Temp Sensor	200 TK
4	Oil level sensor	250 TK
5	Voltage Sensor	200 TK
6	Current sensor	300 TK
7	Rectifier Diode	15 TK
8	Filter Capacitor	50 TK
9	Voltage regulator	30 TK
10	Transformer	300 TK
11	Buck Converter	400 TK
12	LCD Display	200 TK
13	LED,Switch,Resistor	100 TK
14	PCB,WIRE,OTHERS	1500 TK
	Total	7,445 TK

Looking at the cost analysis table, you can see the total hardware cost for this system stays pretty low. That's thanks to the choice of cheap sensors, an Arduino microcontroller, and a LoRa module—all of which help cut the price down.If you line this up against the usual transformer monitoring setups, which often depend on expensive infrastructure or just plain old manual checks, this new system stands out. It's not just easier on the wallet—it also gives you real-time monitoring. That low price tag means you can actually roll it out across big distribution networks, even in rural or out-of-the-way places. smart transformer monitoring system isn't just affordable—it actually works for real-world use.

CHAPTER 4

SOFTWARE DESIGN AND IMPLEMENTATION

4.1 Introduction

In this chapter, the integration of the suggested smart distribution transformer health monitoring system with LoRa technology is described. It illuminates the way the hardware components are put together with the software and how the system functions in a real-time fashion to track the health parameters of transformers.

4.2 System Implementation

The full-fledged system that has been proposed to be built employs combining sensors, a microcontroller unit, and a LoRa communication module, which would all work together on one platform. The hardware parts have been linked up as per the designed circuit layout that was explained in the previous chapter. Sensors for temperature, oil level, voltage, and current have all been connected to the microcontroller for real-time monitoring of the transformer operating conditions. The microcontroller plays the role of acquiring the sensor's data, processing it, and determining if the conditions are abnormal or not based on the preset threshold values.The communication between the LoRa module and the microcontroller can be either serial or SPI. Once the sensor data is processed, the microcontroller sends the information via the LoRa gateway to a distant monitoring station. This allows for very long-range and low-power data transmission via wireless technology.

4.3 Software Implementation

The system software is created with a microcontroller's embedded programming platform which is its suitability for. The program gives the impression of being a rather enclosed entity since it has labelled parts for easy reading and modification.

The software performs first the initialization of all hardware peripherals no matter what kind: sensor pins, ADC modules, or communication interfaces. After initialization, the system gets into a loop that runs continuously and meters the sensor data at regular intervals.

The sensor values that are collected are subjected to processing and conversion into physical parameters that can be expressed in numbers through the application of calibration factors. These numbers are then subjected to comparison with the previously set threshold limits. If any parameter breaks the safe limit, the system interprets it as an abnormal condition.

4.4 Microcontroller Code

(Arduino Code)

```
 #include
#include
 const int tempPin = A0;
 const int oilLevelPin = A1;
 const int voltagePin = A2;
 const int currentPin = A3;
const float tempThreshold = 80;
 const float oilThreshold = 90;
const float currentThreshold = 5.5;
 const long frequency = 915E6;
 void setup()
 {
Serial.begin(9600);
while(!Serial);
if(!LoRa.begin(frequency))
{
```

```
while(1);
}
}
void loop()
 {
 float temperature = map(analogRead(tempPin),0,1023,0,100);
 float oilLevel = map(analogRead(oilLevelPin),0,1023,0,100);
 float voltage = map(analogRead(voltagePin),0,1023,210,250);


 float current = map(analogRead(currentPin),0,1023,0,10);
String status="Normal";
 if(temperature>tempThreshold) status="Overheat!";
 if(oilLevel<oilThreshold) status=" Oil Low";
 if(current>currentThreshold) status=" Overload";
 String(oilLevel)+ "%, Volt:"+String(voltage)+"V, Current:"+String(current)+ "A,
Status:"+status;
 LoRa.beginPacket();
LoRa.print(msg);
 LoRa.endPacket();
 Serial.println(msg);
delay(2000);
}
```

4.5 Coding Explanation

The embedded program is responsible for a handful of vital functions that contribute to the overall reliability of the system. Specifically, the functions for reading sensors facilitate the gathering of real-time information from the temperature, oil level, voltage, and current sensors. Furthermore, conditional statements are utilized to ascertain if the recorded values are above the maximum allowable limits.

As soon as the system figures out that everything is running smoothly, the sensor data is sent out via the LoRa module at regular intervals. The opposite scenario will trigger the generation of alert messages that will be sent to the monitoring station right away.

The structure of the program consists of initialization, data acquisition, processing, decision-making, and data transmission. Such a structured coding manner has not only improved the efficiency of the system but also made troubleshooting easier.

4.6 Summary

The implementation and coding details of the smart transformer health monitoring system were provided in this chapter. The combination of hardware and software parts guarantees precise monitoring, efficient data processing, and reliable wireless communication with the help of LoRa technology. The successful application of the system confirms the feasibility of the proposed system for real-time transformer health monitoring.

- Sensors → MCU → LoRa → Gateway → Cloud

CHAPTER 5

Results

5.1 Data Tables

Table 5.1: Transformer Parameter Monitoring Results

Time	Temperature	Voltage	Current	Oil level
10:00	25	4	3.2	High
10:15	27	5	3.5	High
10:30	29	6	3.7	Low
10:45	30	5	3.3	Low
11:00	31	4	3.1	Low

Description of Result Data Table

The data table of results illustrates the transformer operating parameter values that were obtained through measurements in the experimental setup. Items such as temperature, oil level, voltage, and load current are the parameters shown in the table, recorded at different time intervals. These values depict both the normal and the abnormal operating conditions of the transformer.

From the data table, it is evident that the transformer is operated safely under normal load conditions as the temperature and oil levels are in the safe range. The voltage is almost equal to the rated voltage, and the load current is below the maximum limit. This indicates the transformer is operating stably and healthily The rise in temperature and current values as the load increases is gradual and this is very clear from the data table. When the temperature and current measured are more than the preset threshold values, the system correctly identifies the abnormal condition. Similarly, any significant drop in oil level is precisely detected and recorded in the data table.

Moreover, through the data table, the LoRa communication system's reliability is assured since no data loss occurred during the transmission of all the measured data values to the remote monitoring station. In conclusion, the result data table proves the proposed system's efficiency in monitoring the health parameters of transformers and in real-time fault detection.

5.2 Graphical Representation

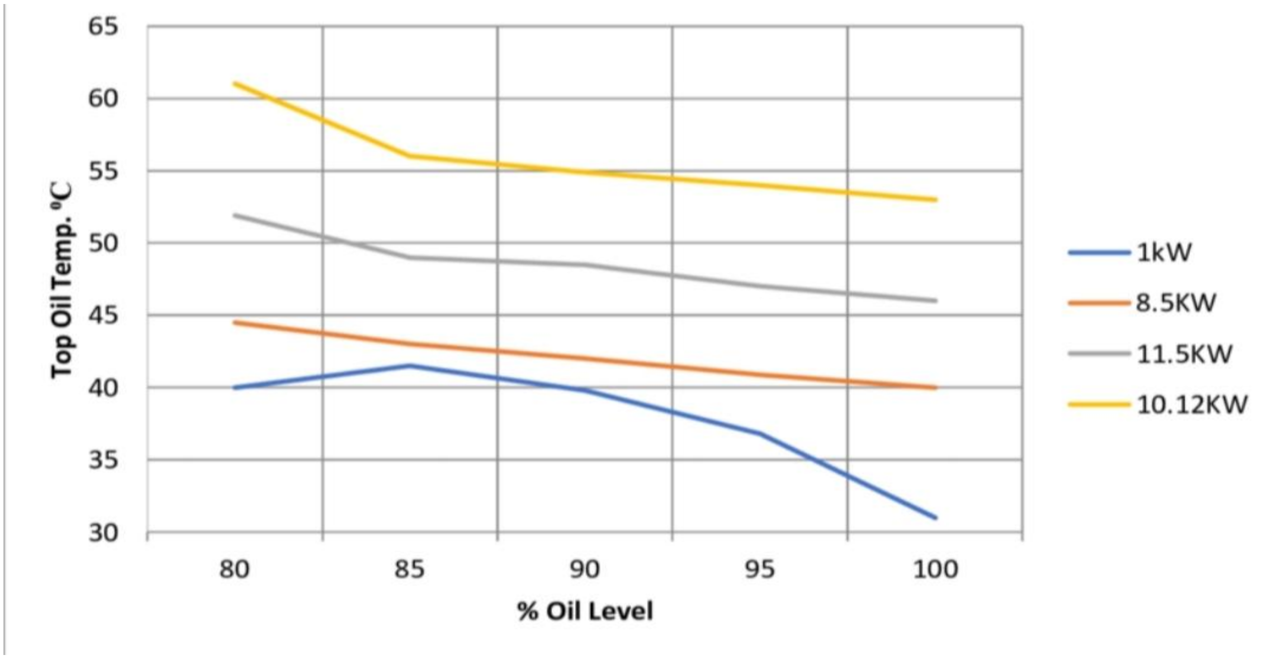

Figure 5.1: Line graph of Temperature, Oil Level, and Load Current vs Time

❖ Temperature Level Graph

The plot in Figure 5.1 depicts the temperature fluctuation of the transformer over a period of time. The graphical representation suggests that the temperature levels are always within the safe limits during regular operation. A slow but certain rise in temperature is noticed with the increase in load on the transformer. Upon crossing the set limit for temperature, the abnormal condition is detected by the system and an alert is sent via the LoRa communication module. This outcome validates the temperature monitoring capability of the proposed system as a great one.

❖ Oil Level Monitoring Graph

The visual representation indicates that the oil level is constant all the time that the system is working correctly. Conversely, a quick drop of the oil level can be a symptom of a leakage of oil or a failure of the insulation. The system right away identifies the oil level drop and communicates the unusual situation to the remote monitoring station. Thus, early fault detection and preventive maintenance are guaranteed.

- **Voltage Monitoring Graph**

The graph shows that voltage is always monitored and goes up and down and the system immediately detects any voltage Unacceptable range. The graph really proves the efficiency of the installed system in fluctuations monitoring and hence, transformer protection from bad operation.

- **Load Current Monitoring Graph**

The load and the current always go together; one if the load increases, the current also increases and vice versa. The graph suggests that if and when the current goes beyond the limit, the system will identify it as an overloaded condition and consequently send out an alarm. This will be an important step in protecting the transformer from thermal stress and damage.

- **LoRa Communication Performance Graph**

The graph portrays the correlation between the distance of transmission and the signal strength received from the module of LoRa communication. The graph illustrates that data can be transferred and received over long-distance with only a small amount of signal loss, hence confirming that the use of LoRa communication for monitoring transformers in areas that are isolated and are not served by public utilities is indeed very appropriate.

- **System Response Time Graph**

This indicates how long the system took to detect and report the fault conditions. The graph shows that the response time is incredibly fast, thus making it possible to monitor almost in real-time. Such a performance of the proposed system in giving timely alerts and thus increasing transformer reliability has been displayed. Temperature (Red), Oil Level (Blue), Current (Green)Shows trends and abnormal conditions.

5.3 DISCUSSION

The results obtained from the experimental setup demonstrate the effectiveness and reliability of the proposed smart distribution transformer health monitoring system using LoRa technology. The system successfully monitored critical transformer parameters such as temperature, oil level, voltage, and load current in real time

The results of temperature monitoring demonstrate that the system is able to accurately and reliably detect gradual increases in temperature due to the increase in loading conditions. When the temperature goes beyond the threshold, the system will immediately recognize the abnormality and send out an alert. This gives support to the argument that the devised system can do high dielectric breakdown and insulation failure effectively.

The outputs of oil level monitoring also support that even tiny cuts off in oil level can be detected by the system. The early detection of oil leakage is very important for the insulation and cooling efficiency of the transformer. Thus, the results validate the oil level sensor as being the one that provides accurate and consistent data.

The results from voltage and current monitoring show that the system can correctly and precisely track the electrical operating conditions within the transformer. The conditions of overvoltage, under voltage, and overloading have been detected and, as a result, the transformer is protected from electrical stress and possible failure.

Results of LoRa communication demonstrate that long-range data transmission can be done reliably and with low power consumption at the same time. The experiment data reveal that the signal from the sensor reaches the remote monitoring station almost instantly and with no important data loss whatsoever. This characteristic of the system qualifies it for the monitoring of transformers placed in inaccessible and countryside areas.

In sum, the experimental findings back the claim that the proposed system is able to offer accurate monitoring, early fault detection, and effective wireless communication. The system increases the reliability of transformers, cuts down on maintenance costs, and has a positive impact on the performance of the power system.

5.4 Advantages of the Proposed System

The smart distribution transformer health monitoring system based on LoRa is the one that offers numerous benefits compared to traditional transformer monitoring methods.

- **Real-time monitoring**

The system has a feature of continuous and real-time monitoring of critical transformer parameters such as temperature, oil level, voltage, and load current. Therefore, abnormal conditions can be detected at an early stage.

- **Early detection of the fault**

Overheating, oil leakage, and overloading are some of the issues that can be detected by the continuous monitoring of transformer health parameters thus preventing the sudden failure of the transformer.

- **Long-Range Communication**

LoRa technology is utilized to enable the transmission of data across large areas while consuming almost no power, and that makes the system ideal for rural and remote locations.

- **Low Power Consumption**

The communication via LoRa requires much less power than the one via GSM or Wi-Fi, and that guarantees the operation to be highly energy-efficient.

- **Reduced Maintenance Cost**

The system is capable of maintenance based on the condition rather than the manual inspection performed periodically, thus cutting down the maintenance cost and the need for manpower.

- ### Improved Reliability of Power Distribution

The power transformers are monitored continuously thus their reliability is improved and the number of unexpected outages is reduced, which results in a good quality of power supply.

- ### Scalability and Flexibility

A single LoRa gateway can monitor several transformers at once, which makes the system scalable and easy to grow.

- ### Remote Monitoring Capability

Transformer health data can be accessed easily and quickly through a centralized monitoring station or cloud platform, thus enhancing the efficiency of operations.

5.5 Applications of the Proposed System

The suggested system can be utilized in numerous domains of the electrical grid and smart grid infrastructure.

- ### Distribution Transformer Monitoring

The system is applicable for the observation of distribution transformers in the electricity distribution systems of both cities and the countryside.

- ### Smart Grid Systems

Real-time monitoring and proactive maintenance of distribution assets are, thus, among the important functions that the smart grid technology can provide through this system.

- ### Rural Electrification Projects

The system's capability for long-range and low-power communication makes it the perfect fit for transformer monitoring in isolated and rural electrification projects.

- **Industrial Power Distribution**

The system can be adopted by manufacturing units possessing their own distribution transformers, to ensure that operations remain within the limits of safety and reliability.

- **Utility Maintenance Management**

Power utilities can leverage the system for predictive maintenance planning and consequently lowering the transformer's failure rate.

- **Substation Monitoring Systems**

The system that is suggested could be merged with existing substation monitoring systems thereby resulting in one central control and supervision.

- **Research and Educational Purposes**

The system will have a place in academic institutions to provide research and practical learning in smart grid and IoT-based power system.

5.6 Conclusion

The paper provided a smart distribution transformer health monitoring system design using LoRa technology and its implementation. The developed system was aimed at monitoring the transformer parameters such as temperature, oil level, voltage, and load current over the entire life of the transformer in real-time.

The results obtained from the experiment proved that the system is capable of correctly identifying the operating conditions of the transformer and consequently, the detection of abnormal situations such as overheating etc. The use of a microcontroller plays an important role in effective data acquisition and processing, plus, limits that are set beforehand ensure that errors are detected early.

LoRa communication was employed to its full potential in sending the sensor data over long distances using negligible power. The outcome of the experiment shows that the wireless communication was very good with very little delay thus making the system applicable for monitoring transformers located in far-off areas as it does not require a complex communication set-up.

The system not only assists in the detection of faults at a very early stage thus allowing the maintenance to be planned but also increases the reliability of the transformer. It also leads to a reduction in maintenance and unexpected transformer failures. All in all, the project is a successful demonstration of a cost-effective, reliable, and efficient solution for smart distribution transformer health monitoring.

5.7 Future Scope

There are numerous ways in which the proposed health monitoring system of a smart distribution transformer with LoRa technology can be improved. The next step could be to add humidity, vibration, and dissolved gas sensors in addition to the already existing ones to give a more complete view of the condition of the transformer.

One way to enhance the system is through the use of cloud-based platforms for the collection and visualization of data. This would enable the utility staff to not only access the data of the past but also understand and control the present and future aspects of the transformers by using data analytics techniques to perform predictive maintenance. There can also be mobile and web applications developed for the purpose of monitoring in real-time and alert notifications. Future advancements may involve the implementation of sophisticated fault diagnosis algorithms and machine learning to be able to detect transformer failures before they actually happen.

Thus, the system will be more dependable and the costs for maintenance will be lower. With the installation of multiple LoRa gateways along with the use of adaptive data rate techniques, the communication range and data reliability can be increased. On top of that, renewable energy sources like solar power can be used to power the system thus making it more energy-efficient and suitable for installation in remote locations.

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