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Real-Time Monitoring of Oil Temperature in Distribution Power Transformer by Using Internet of Things

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ABSTRACT

In Malaysia, on-site technical personnel manually inspect power transformers. Some vital condition indicators, such as oil and winding temperatures, are not monitored in real-time. This condition can be hazardous if the transformer gets overheated. Overheating can cause mechanical deformation and insulation degradation if not monitored regularly. Thus, an online monitoring system that meets industry standards is needed to enhance power transformer monitoring and troubleshooting. In this research, the Internet of Things (IoT) based data acquisition (DAQ) system was deployed for real-time oil temperature monitoring and inspection to detect incipient faults in power transformers early. This IoT-based DAQ system was connected to the substation remote terminal unit (RTU) to update real-time data on each power transformer. The long-range (LoRa) technology is proposed for the system to transmit temperature, current, and voltage from the power transformers. The data transmission from the oil temperature indicator (OTI), network server, and database was monitored and compared. It is observed that the temperature data was transferred from the network server to the database without any transmission delay. The average deviation from the two experiments was 0.006 and 0.003, respectively, compared to the manual reading from the OTI scale meter with a digital reading by the proposed DAQ system. For testing purposes, the alert

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module in this system would notify technical personnel if the temperature exceeded +40°C in the power transformers. The proposed system can be used to assist with the upgrade and maintenance of the existing power transformer.

Keywords: Data acquisition (DAQ) system, Internet of Things (IoT), LoRa technology, oil temperature indicator (OTI), power transformers, real-time monitoring

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INTRODUCTION

Power transformers are vital to enable electrical energy transmission, distribution, and generation in electrical network circuits. Transformers are designed to operate for 20 to 30 years; if properly used, their lifespan may exceed 40 years. Damages or ageing of a power transformer's external or internal part can adversely reduce its efficiency and lifespan (Hernández-Callejo, 2019; Martin et al., 2017). Area blackout may happen if the power transformer fails in its operation. Besides, any faulty is hazardous due to a large amount of oil in direct contact with high voltage (HV) elements (Christian & Gläser, 2017). A higher risk of explosion and fire is deleterious to human safety and surroundings. Such a hazardous event lowers the reliability of the power system and incurs financial damages. Hence, it is crucial to enhance power transformer monitoring and troubleshooting (Wani et al., 2021; Xie et al., 2020).

There are internal and external faults in power transformers. Internal faults, for example, high current flow, can deteriorate the insulation. Mechanical damage can also occur when the cooling mechanism fails to function properly. It may gradually turn into a serious fault, such as overheating, winding failure, and oil contamination (Chandran et al., 2021; Murugan & Ramasamy, 2019). Most of these faults can be prevented through testing and maintenance. An external fault is a damage that cannot be prevented or predicted, such as lightning, earthquakes, or an abnormal tension causing a direct failure. These hazards stress the transformer, which may be of concern and may shorten the transformer's life. In Malaysia, technical personnel manually inspect power transformers on-site. Routine preventative maintenance and testing are executed on a regular basis. However, some vital condition indicators, e.g., oil and winding temperatures, are left unmonitored on a real-time basis (Ghazali et al., 2009). This condition can be hazardous if the transformer's temperature fluctuates and gets overheated. Overheating can occur when temperatures exceed the rating for the insulation system. The insulation will deteriorate and lose its mechanical, electrical, and chemical strength, thereby reducing the lifespan of the transformer or causing early failure (Singh et al., 2020). It can cause more significant damage if it is not monitored regularly. Other methods, such as oil sample quality, dissolved gas, and furfural analyses, are used to check the condition of the power transformer, which requires costly field visits and laboratory sample testing. Thus, a crucial need is emerging for an online monitoring system in accordance with the industry standards to enhance power transformer monitoring and troubleshooting.

The shifting dynamics in the global power market seek cutting-edge transformer technology. The use of grid sensors contributes to the digital transformation of electrical substations (Liu et al., 2020; Butt et al., 2021; Pong et al., 2021; Raghavan et al., 2021). Smart monitoring via the Internet of Things (IoT) technology offers asset owners access to real-time power transformer conditions regardless of location. Thus, transformer conditions may be assessed without on-site technical personnel, saving precious resources and time. Integrating IoT into transformer technology enhances the basic network of power transmission and its stability (Gajenthiran et al., 2022; Wang et al., 2020). The IoT technology connects node sensors and network devices with power transformers in a flexible, secure, and cost-effective manner. It minimises operational overheads in condition-based maintenance, thus initiating evolvement in the energy segment in this digital era.

Several methods have been proposed for power transformer smart monitoring systems. Wireless communication via the ZigBee network was introduced to monitor the frequency of all loads, energy, power, current and voltage in a distribution transformer (Guardarrama et al., 2016). Such real-time monitoring system applies ADE7753 IC and BeagleBone Black with ZigBee Pro S2 as the primary monitoring device. Zigbee covers short-range wireless communication with low energy consumption, thus suitable for urban distribution electric networks. A mobile embedded system for monitoring temperature, oil level, current, humidity, and vibration of a distribution transformer is proposed by Pawar et al. (2017). The PIC18F4550 microcontroller and the Global System for Mobile (GSM) - General Packet Radio Service (GPRS) communication module were used to collect and transmit data. Alert messages were sent via Short Message Service (SMS) when the parameters exceeded predetermined thresholds. However, this monitoring system lacks the server and database modules. The long-range (LoRa) technology implemented with Arduino Uno and selected sensors was used to monitor and diagnose voltage, current, oil and winding temperatures, as well as silica gel status in the breather of distribution transformers (Kumar & Ajitha, 2018). The system displayed continuous monitoring and alerted abnormality. Nonetheless, the database environment was also omitted in this paper.

The field-programmable gate arrays (often shortened to FPGA) embedded controller is introduced for a high-speed IoT-based power transformer monitoring system with a recording function (Zhao et al., 2019). Parameters such as transformer temperatures, circuit breaker status, power, frequency, and voltage are monitored, recorded and stored at network-attached storage (NAS) through the Local Area Network (LAN). The LAN network only covers a small geographical area. A data acquisition (DAQ) system using GPRS and communication with SCADA by DNP3 protocol was initiated for online temperature monitoring systems in power transformers (Kunicki et al., 2020). The system used Raspberry PI 3B/B+ combined with converters as the basic hardware component. Temperature gradient and ambient temperature were measured in the study. The incorporation of GPRS in the system was limited to power transformers in remote regions. Using satellite communication to monitor power transformers in remote areas without network coverage will be costly. The online monitoring system for distribution transformer based on cloud side end collaboration of IoT is proposed by Zu et al. (2021). The GSM is used as a communication module and the PIC18F458 microcontroller as a core processing chip for hardware. This system can shorten the response time for information status when compared with the existing system. However, GSM technology can only operate in areas with the mobile network coverage. Most cellular operators are retiring GPRS and GSM to make room for Long Term Evolution (LTE) and 5G technologies.

These reviews summarise the identified research gap in the existing power transformer smart monitoring system; the usage of short-range wireless communication, wired network, limited coverage for rural areas and unavailability of the database management system. Based on these findings, a reliable IoT-based DAQ system with LoRa technology for real-time oil temperature monitoring for power transformers is proposed. LoRa is a centralised network that provides a broad range of coverage in urban, rural, and indoor environments with low power consumption.

METHODOLOGY

The proposed IoT-based DAQ system consists of hardware and software parts in this research. The hardware includes the measurement unit, which is the sensor node, wireless communication, and data transmission modules. The software part is comprised of the diagnostic unit, which is the data processing, communication protocol, and data monitoring modules. This IoT-based DAQ system was designed to enable smart grid initiatives in urban and rural areas or indoor environments in accordance with the industry standards with a reliable database module. The following section discusses the proposed IoT-based DAQ system architecture with LoRa technology.

System Architecture

Figure 1 presents the block diagram of the proposed IoT-based DAQ system to monitor real-time oil temperature in the power transformer. The system denotes the integration of the LoRa sensor node with a multi-channel LoRaWAN gateway as a measurement unit. This unit will be installed in the selected Remote Terminal Unit (RTU) in Regional Control Centre (RCC) at the substation to gather input and output (I/O) signals from the existing power transformer. First, real-time data such as oil and winding temperature reading were retrieved from the power transformer temperature indicator at RTU. Next, the data were transmitted to the network server, which served as the central data repository. It also functioned as routing IoT data between devices and applications.

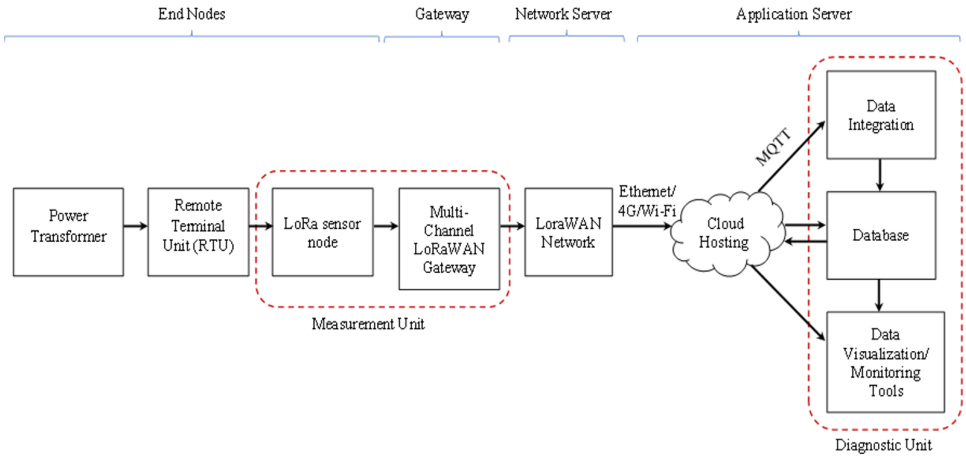


Figure 1. Block diagram of the DAQ system for oil temperature online monitoring in power transformer

The network server was connected to cloud hosting as a storage resource and outsourced data for integration via IoT communication protocol, Message Queuing Telemetry Transport (MQTT). Data were added to the time series database, which could manage massive volumes of data points per second. The time series data may be visualised using analytics platform tools as a diagnostic unit. Such a tool aids technical personnel in analysing and monitoring the pattern of oil temperature data in a power transformer over a certain duration by indicating its location, time, and severity level. This tool can be viewed on any mobile device, tablet, and computer for convenient usage anytime and anywhere.

The alert system module will notify technical personnel if any abnormality is detected in the power transformer. Hence, the technical personnel may take apt measures to hinder failures and power transformer outages. The transformer reliability is also enhanced upon determining the transformer condition in real-time compared to conventional monitoring. Furthermore, immediate corrective/preventive maintenance that increases the lifespan of a power transformer can slash operational costs and resources. Therefore, the proposed system fills the gap in terms of long-range wireless communication and a reliable IoT-based DAQ for the power transformer smart monitoring system. The following section describes the specific equipment and methods utilised in the proposed system.

Power Transformer Temperature Indicator

Oil and winding temperatures are the critical parameters determined in power transformers. Proper monitoring of these parameters is crucial for electrical asset managers, maintenance teams, and electrical system operators. Two temperature indicators are the oil temperature indicator (OTI) and the winding temperature indicator (WTI). These indicators measure the instantaneous temperature based on the principle of thermal imaging (Askari et al., 2021).

They record the maximum temperature rise of windings and oil in the power transformer. OTI and WTI give alarm and control signals that activate the cooling control systems in a power transformer when the temperature hits a predetermined maximum limit. It can extend the lifespan of a transformer (Patel & Chothani, 2020). Failure or incorrect indication of these devices may have an important impact on transformer ageing. It may also affect the transformer's reliability. Utility experience shows that most transformer maintenance is devoted to OTI/WTI (Sparling, 2017).

Figure 2 illustrates a MESSKO BeTech thermometer—the OTI used in this study to directly display oil temperature measurement from the power transformer. This OTI consisted of a TT version temperature sensor (Figure 3) connected to a measurement unit via a capillary tube. The sensor converted the temperature value to the electrical signal of 4-20 mA and/or 0-5 V DC. Its required power supply was 24V. The OTI/WTI was equipped with a pointer that could turn to display the temperature on a scale. The measuring range for this OTI was 0-150°C. It was also used to measure low voltage (LV) and high voltage (HV) winding temperatures.

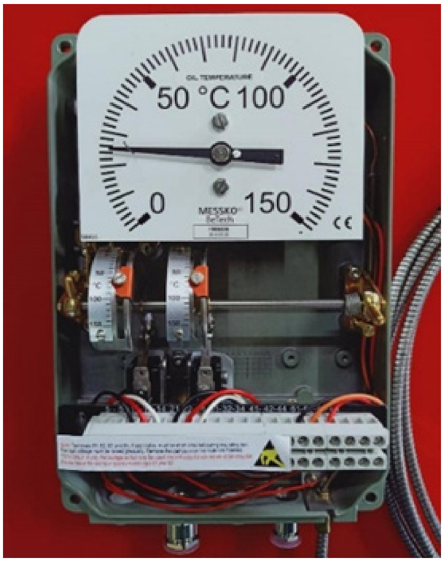


Figure 2. MESSKO BeTech thermometer

Figure 3. TT version sensor

LoRa Technology

The LoRa radio technology denotes a wireless protocol for long-range transmission with low-power communication (Faber et al., 2020). It is used for Machine-to-Machine (M2M) and IoT applications. The LoRa operates 865-867 MHz and 920-923 MHz bands in Asia. Wirelessly connects sensors, machines, gateways, and devices to the cloud. LoRa communication protocol uses the unlicensed radio spectrum in the Industrial, Scientific and Medical (ISM) band (Polak & Milos, 2020). The LoRa signal efficiently provides enough coverage for urban, rural and indoor environments with low development costs.

In this paper, LoRaWAN Gateway (Multi-Channel with 4G) was deployed to transmit and receive data from the TT version sensor to the LoRaWAN network. It has a built-in GPS module connected to the SX1308 chip directly for ultra-low power or indoor solution. It is connected concurrently with the LoRa board using 4G, Ethernet or Wi-Fi. This gateway can serve multiple devices simultaneously. It can detect LoRa board input and output (I/O) signals as far as 10 km apart. Thus, this technology can monitor several power transformers within the range.

Messaging and Data Exchange for IoT

MQTT refers to a lightweight messaging protocol with rapid response time (Mishra & Kertesz, 2020; Shanmugapriya et al., 2021). It is based on the subscribe-and-publish model. This protocol can translate messages among devices, servers, and applications. The MQTT can transfer data even with unstable connections. It is an excellent option for sending high volumes of sensor data to cloud solutions and analytics platforms. This protocol is suitable for any small device with low power consumption. It is primarily used for low-bandwidth connections to remote locations. It is also ideal for small devices that require efficient battery usage and bandwidth. Turning to this study, the MQTT was deployed as a light and energy-efficient communication protocol to monitor real-time oil temperature in a power transformer.

Measurement Unit

Figure 4 illustrates a schematic diagram of the measurement unit to retrieve the input and output (I/O) signal from the TT version sensor on the MESSKO BeTech-OTI meter. This study applied the Talk^2 Whisper Node AVR LoRa board, a low-power version of Atmel AVR ATMega328p. It has a built-in LoRa Wireless communication of RFM95/96 sub-GHz module radio (Semtech SX1276). The board can be powered with a minimum of 0.9 V (alkaline battery) or connected to a 5 V power supply. In addition, the W25X40CL 4MBit SPI Flash is attached to the board, suitable to store more data from the power transformer and capable of running for over a year.

The IoT technology used to monitor the condition of real-time power transformer at substation requires continual power. Figure 5 displays the experimental power consumption data for the proposed circuit diagram in its measurement unit. The power consumption is calculated as given in Equation 1 (Patel, 2012):

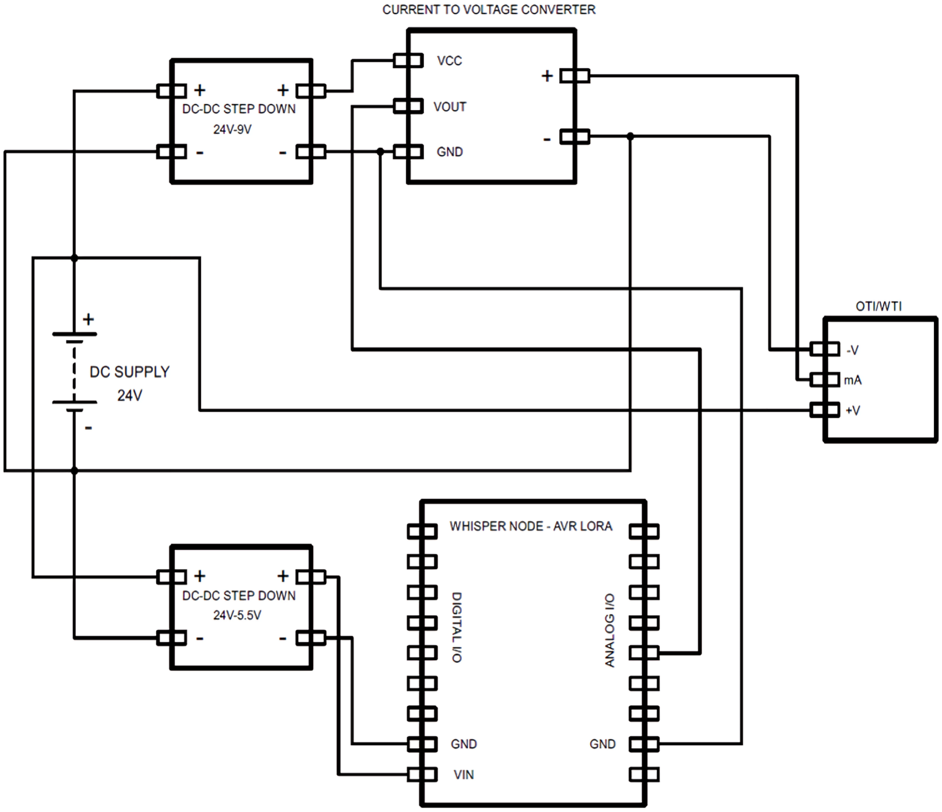


Figure 4. Schematic diagram

$$P_{offset} = V_{cc} \times I_{offset} \quad (1)$$

The power consumption increased to 0.126 watts upon load addition. More power was required as the circuit was connected to the LoRaWAN network, and data were continuously retrieved from the OTI TT version sensor. The proposed system is only suitable for operation in cyclic sleep mode if a battery is used. Battery power limits the system's capacity and dismisses its viability for emerging IoT devices and sensors with the LoRaWAN network. The use of new or rechargeable batteries and their servicing and replacement has been proven costly (Al Shaqsi et al., 2020).

This research applied two units of DC-DC step-down power converter (24V-9V and 24V-5.5V). They were connected to the Whisper node and OTI/WTI, which demanded a 24V power supply for operation. In actual practice, this measurement unit is installed at the RTU. The temperature data collected by the measurement unit were transferred to the network server via a multi-channel LoraWAN gateway connected to 4G, Ethernet or Wi-Fi.

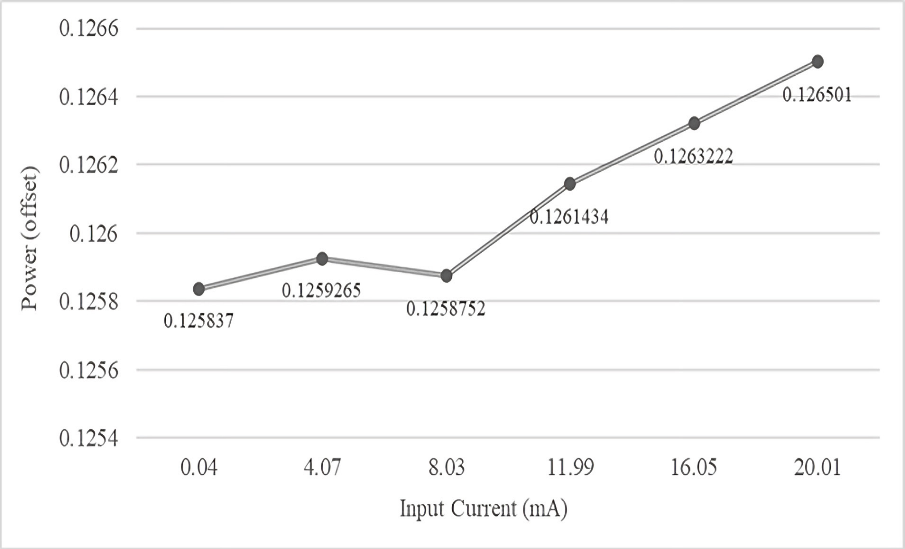


Figure 5. Power consumption

Diagnostic Unit

Figure 6 portrays the IoT block diagram for oil temperature online monitoring of the power transformer. The data flow from and to the IoT platform using the MQTT protocol. First, data retrieved from the OTI sensor in the measurement unit (Figure 4) were transmitted to the network server; The Things Network (TTN) served as the central repository of data. It also functioned as the routing of IoT data between devices and applications. The TTN was connected to the cloud hosting by Digital Ocean as a storage resource and outsourced the data for integration via the MQTT broker. Node-RED was deployed in this study to wire together the measurement unit, Application Programming Interfaces (APIs), and diagnostic unit to create a smooth data flow in the editor dashboard (Ahmadpanah et al., 2021; Ferencz et al., 2020). Node-RED refers to a JavaScript-based tool built with the Node.js platform. The created flows in Node-RED were stored using JavaScript Object Notation (JSON) format. Next, the data were stored in the InfluxDB database that can manage massive volumes of data points per second. The OTI data stored in InfluxDB can be visualised by using Grafana. This tool indicates a diagnostic unit and can be viewed on all mobile devices, tablets, and computers for convenient usage anytime and anywhere.

Figure 7 illustrates the installation setup in accordance with the schematic and block diagrams. Due to safety concerns, conducting high current experiments on-site with an in-service power transformer is prohibited. In order to make the testing close to the field situation, an electric hot air blower was applied to heat the OTI TT version sensor during the experiment. The electric hot air blower acts as a heat source and is used to emulate the hot temperature of transformer oil in the range of +25°C to +140°C. This situation is practically identical when the sensor is placed inside the transformer. This laboratory testing is conducted prior to the device being installed on-site.

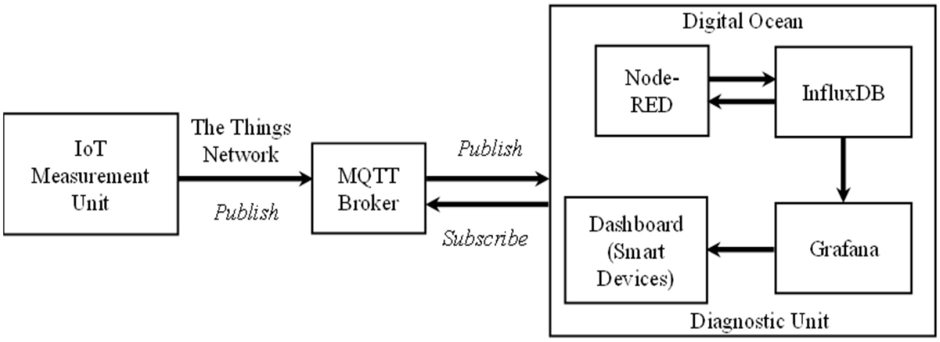


Figure 6. Power transformer oil temperature online monitoring system architecture

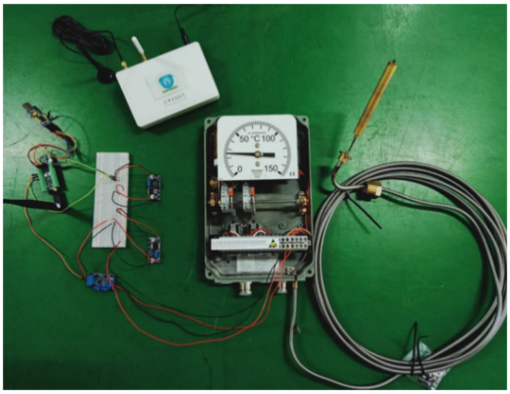


Figure 7. IoT-based DAQ system installation setup

RESULTS AND DISCUSSIONS

Temperature Monitoring and Assessment of OTI for Power Transformer

The data transmission from the OTI scale meter, network server TTN and database InfluxDB was monitored and compared. Two cycle readings were taken during the experiment for the temperature ranging between +25°C and +140°C. Table 1 and Table 2 list the readings.

Notably, the temperature data reading was transferred from the TTN network server to the database InfluxDB without transmission delay. The deviation was measured from the manual reading on the OTI scale meter with a digital reading by the proposed DAQ system. The average deviation from the two experiments was found to be 0.006 and 0.003, respectively. The deviation is caused by the capillary tube's response to changes in its surrounding environment by the hot air blower. It is observed that the digital reading by the IoT-based DAQ system is more precise than the analogue OTI scale meter. Figure 8 presented the OTI temperature reading when the system was tested on Grafana at *http://iotsmart.host*. The data recorded and stored in the database could be monitored continuously. Here, the data is stored on a 25GB SSD in Ubuntu 20.04 (LTS) 64bit server.

Table 1

OTI TT 1st cycle sensor reading

OTI Meter (°C)	TTN (°C)	InfluxDB (°C)	Deviation
26	24.63	24.63	0.0527
30	29.03	29.03	0.0323
40	39.15	39.15	0.0213
50	49.71	49.71	0.0058
60	60.55	60.55	-0.0092
70	70.23	70.23	-0.0033
80	79.32	79.32	0.0085
90	90.76	90.76	-0.0084
100	99.4	99.4	0.0060
110	110.85	110.85	-0.0077
120	119.94	119.94	0.0005
130	132.11	132.11	-0.0162
140	139.29	139.29	0.0051

Table 2

OTI TT 2nd cycle sensor reading

OTI Meter (°C)	TTN (°C)	InfluxDB (°C)	Deviation
25	24.83	24.83	0.0068
30	29.02	29.02	0.0327
40	39.85	39.85	0.0037
51	49.7	49.7	0.0255
60	60.85	60.85	-0.0142
70	70.03	70.03	-0.0004
80	80.01	80.01	-0.0001
91	90.8	90.8	0.0022
100	99.4	99.4	0.0060
110	110.15	110.15	-0.0014
119	120.14	120.14	-0.0096
130	130.11	130.11	-0.0008
140	140.02	140.02	-0.0001

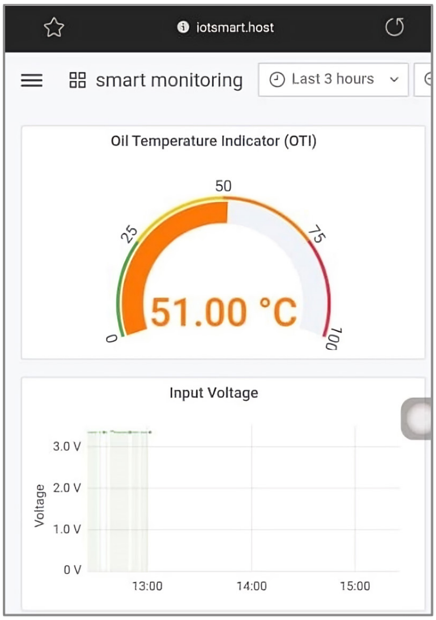


Figure 8. Grafana view for OTI temperature reading

The range of oil temperatures should typically vary between +40°C and +60°C, depending on the operating conditions. These values are based on a maximum ambient temperature of +40°C according to IEEE C57.12.00-2000 standard (IEEE, 2000). The maximum allowable temperature rise for the transformer is usually specified on the transformer nameplate. In this experiment, the notification alert system was set when the temperature exceeded +40°C for testing purposes. In practice, the temperature limit for the on-site alert system will vary based on the requirements of the energy suppliers, as indicated on the transformer's nameplate. The temperature limit can be determined using the following Equation 2 (Ghosh, 2016):

$$\theta_{top} = \theta_{op} - \theta_{amb} \qquad (2)$$

where θ_{top} is the top oil temperature rise, θ_{op} is the operating temperature, and θ_{amb} is the ambient temperature. The notification system is set by using Node-RED as in Figure 9. The alert function would do the operation by sending an e-mail to the person in charge to notify them about the status of the OTI/WTI sensor. The sample for notification alert e-mail is given in Figure 10. Essentially, the proposed IoT-based DAQ system offers a viable solution for real-time online power transformer monitoring.

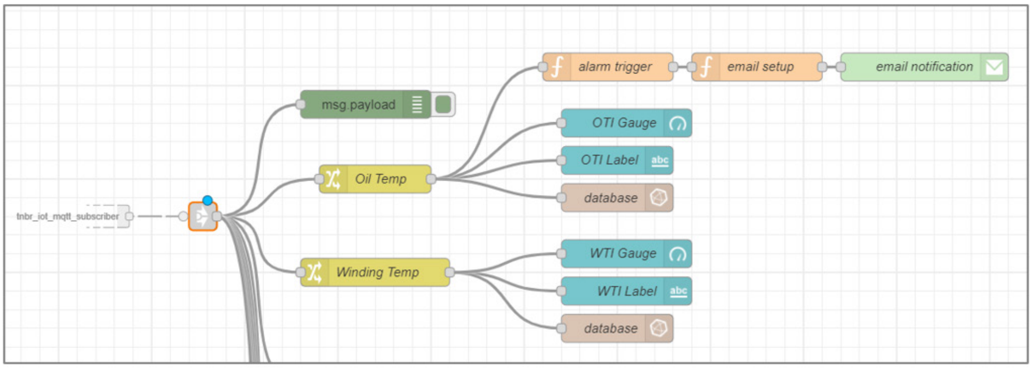
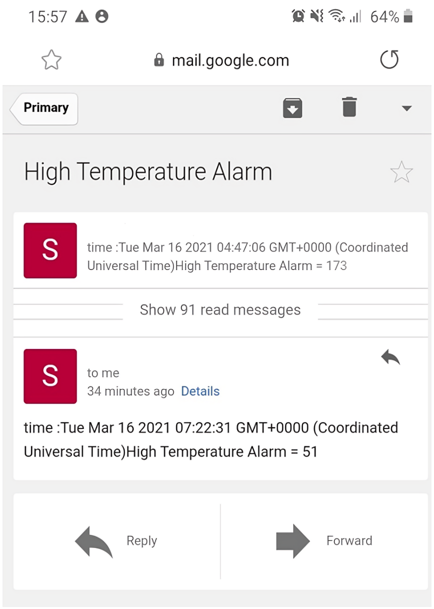


Figure 9. Node-RED flow for alarm trigger and notification



High Temperature Alarm

time :Tue Mar 16 2021 04:47:06 GMT+0000 (Coordinated Universal Time)High Temperature Alarm = 173

Show 91 read messages

to me
34 minutes ago Details

time :Tue Mar 16 2021 07:22:31 GMT+0000 (Coordinated Universal Time)High Temperature Alarm = 51

Figure 10. Notification system

CONCLUSION

This study presents the development and application of an IoT-based DAQ system with LoRa technology for real-time oil temperature monitoring of power transformers. The research was conducted to demonstrate the efficacy of the proposed IoT-based DAQ system. The experimental findings indicate that the temperature data reading was transferred from the network server to the database without any transmission delay. The average deviation from the two experiments was found to be 0.006 and 0.003, respectively, compared to the manual reading from the OTI scale meter with a digital reading by the proposed DAQ system. Thus, it can be used to assist and would give better performance to monitoring oil temperature as compared to the manual monitoring method. Furthermore, the alert system would notify technical personnel if any abnormality is detected in the distribution power transformer. This system effectively enables asset owners to use the transformers and detect faulty ones prior to catastrophic failure.

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