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Original Article

Energy-Efficient IoT and RF-Driven Smart Gateway for Transformer Health Monitoring in Cloud-Connected Power Systems

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Abstract - *Transformers are pivotal components in power distribution for electrical grids as they directly affect the reliability and efficiency of energy delivery. Effective maintenance of transformers decreases energy losses, improves the grid's reliability, and contributes to sustainable energy management aligned with the United Nations Sustainable Development Goal (SDG) 7: Affordable and Clean Energy. Conventional methods focus on onsite guarantee inspections, showing blind or gut-feeling maintenance, rather than well-defined maintenance management systems. These limitations have triggered the use and development of IoT and wireless technologies for the remote health monitoring of transformers. The authors designed a smart gateway based on LoRa technology that monitors transformers' health in real-time. The system integrates two hardware nodes. The first one is the Transformer Health Data Collection Node, which collects operational data that include, but are not limited to, voltage, current, temperature, humidity, and vibration through various sensors. The second one is the LoRa Gateway Node, which processes and uploads the information collected to Blynk Cloud. The Blynk Cloud application allows grid operators to visualize the data in real-time, thus enabling prompt attention to maintenance actions and diagnosing faults within the grid. The system was designed to consume low power and transmit data over long distances while providing reliable remote control using LoRa RF and ESP-01 WiFi. This approach resolves issues related to low energy consumption and access limitations while improving the power systems' monitoring methods. Moreover, with the aid of cloud computing, it is no longer necessary for workers to supervise the site constantly, which improves efficiency and scalability while also lowering costs. This document describes the specifics of system architecture, the design of devices, the communication protocols used for data exchange, and the interface for monitoring the cloud system. These changes in IoT allow for improving the maintenance of transformers, shortening the downtime needed for repairs, and increasing the reliability of the power distribution arteries with thorough data analysis and real-time monitoring.*

Keywords - *Transformer Health Monitoring, LoRa RF, Internet of Things, Sustainable Energy Management*, *Affordable and Clean Energy*.

1. Introduction

The top causes of blackouts include failing transformers in the power systems. The goal of this project is to create a low-cost monitoring system for power grid transformers that uses the Internet of Things (IoT) for real-time tracking capabilities. The system will capture temperature, humidity, oil level, voltage, vibration, and pressure, which are critical parameters for status tracking. These parameters will be captured using multiple sensors connected to a microcontroller with an embedded Wi-Fi module (DOIT Esp32 DevKit v1). The information will be uploaded to a cloud interface for constant checking and processing [1]. Achieving equitable distribution of healthcare services in rural and socio-economically challenged areas is difficult due to cost issues and the availability of services. The need for IoT-based remote health monitoring has also risen. This project presents an IoT-based smart edge system that aids in remote health monitoring using a wearable sensor.

The sensor data is sent to two software engines: Rapid Active Summarization for Effective Prognosis (RASPRO) and Criticality Measure Index (CMI) alerts. RASPRO transforms sensor data into Personalized Health Motifs (PHMs) for effective clinical interpretation, and CMI computes an aggregate criticality measure index score. The system is based on a risk protocol: acute unsolicited alerts and PHMs are sent directly to the physician, and the complete health data is accessible through the cloud for further queries. The system has undergone clinical validation and has been evaluated to assess its performance. These results determined the effectiveness of the proposed solution [2].

This initiative seeks to implement IoT to help understand and improve maintenance strategies for transformers. The IoT technology will be integrated with breather components for real-time monitoring and control of humidity, temperature, silica gel color, and gas concentration. This approach makes it possible to perform reliable maintenance, improving the transformer's reliability while expanding its operational lifespan [3]. The core aim of the proposal is an IoT system to oversee transformer parameters: temperature, current, voltage, and oil level. A constellation of sensors captures these parameters and sends them to an Arduino UNO microcontroller. The collected data is transmitted over a Wi-Fi network using ESP8266, providing remote access to global information using the IoT and the HTTP protocol [4].

Since transformers play a pivotal part in the operation and maintenance of power distribution systems, monitoring them at all times is important to ensure the system does not go down. This paper proposes an IoT-based health monitoring solution using the NodeMCU microcontroller for data collection and the ThingSpeak platform for data visualization. Incorporating IoT applications into electrical transformers improves the reliability of the power supply by allowing fault location and taking corrective action in advance [5]. This work focuses on providing an IoT-based medical monitoring system that is cloud-centric and enables public verifiability. The proposed system employs an EF-IDASC scheme to achieve reliable data transmission without an escrow. Medical data is collected from a wearable sensor, encrypted, aggregated with other data by the IDASC scheme, and securely transmitted to a medical cloud server through a smartphone [6].

In tandem with the rise of automation, the Internet of Things has proven incredibly useful in managing large-spanning transformer networks. Manual inspection of transformers is poorly efficient, and alongside automated data acquisition and monitoring systems are crucial. This project incorporates transformer condition monitoring with a mobile-embedded device to track load currents, overvoltage incidents, oil levels, and temperature changes. It relies on a GSM modem, microcontroller, and sensors for realtime data collection and analysis in the field [7]. Transformers are basic electrical machines that perform the task of voltage-level conversions. High-generated temperature and noise symptoms can show potential failures. This project develops the IoT-based system for evaluating the transformer's performance based on measured current, current audibility, and temperature. Data is collected using ESP32 microcontrollers, processed and sent to the Blynk application on the internet. The system measures and evaluates conditions of transformers under load and no load using an ammeter, ACS712 current sensor, and MLX90614 temperature sensor [8].

The key contributions of this study are as follows:

- Sensor Integration and Wireless Communication – Selection and integration of appropriate sensors to monitor transformer health parameters such as voltage, current, temperature, humidity, and vibration while establishing energy-efficient wireless communication using LoRa RF and ESP-01 WiFi for real-time data transmission.
- Development of a real-time monitoring System – Implement an IoT-enabled smart gateway with ATmega328 microcontrollers, LoRa RF modules, and ESP-01 WiFi, ensuring continuous data collection, fault detection, and predictive maintenance for enhanced power grid reliability.
- Cloud-Based Data Visualization and Remote Accessibility – Deployment of a Blynk IoT dashboard for real-time transformer health monitoring, enabling interactive data visualization, remote accessibility, and timely anomaly detection to improve decision-making and grid management.

The manuscript's structure is as follows: Section 2 presents the literature review, discussing existing transformer monitoring methods and identifying research gaps. Section 3 describes the system architecture, including the block diagram and sensor integration. Section 4 details the hardware implementation, covering the Transformer Health Data Collection Node and LoRa Gateway Node. The real-time system implementation and data transmission process are discussed in Section 5. Finally, Section 6 provides the conclusion and future research directions.

2. Review of Literature

In order to monitor and control security threats such as unauthorized access and dangerous environments, a wireless security system that operates on ZigBee and GSM modems has been proposed. The system consists of several cluster nodes communicating to a central control room using GSM, which provides great coverage. A Particle Swarm Optimization (PSO) algorithm is used to optimize communication between embedded devices with ZigBee modems to improve it further. To mitigate risks, there needs to be sufficient observation and interference because changes in the environment and geographic areas may result in calamities. This project designs a sensor node system that cooperates with local control rooms and a master control salon. Sensor nodes store information from the environment. Such discharge sensors will control the gates to eliminate danger by opening them to the appropriate angles. The office or department of the Central Control Room issues local control units, which then make contact with them. An integrated hooter system is able to transcend normal operating parameters and emit critical safety signals.

Smart monitoring systems using IoT can greatly improve their functionality. As part of the innovation, an IoT device was created that monitors the occupancy level within a certain restricted space, generating alerts if the level is exceeded. The application of such smart monitoring solutions in the hinterlands is useful because they enable tracking in real-time and sending mobile alerts for critical notifications [9]. The dependability of transformers within power systems is essential, but diagnosing faults accurately remains a problem. This work deals with an IoT-assisted EML system for transformer fault diagnosis. The supervising system comprises a data acquisition block, which records captured vibration signals and sends them to the remote server for processing and analysis [10].

This study focuses on the power consumption analysis of six wireless health monitoring units built with GPRS/UMTS, Wi-Fi, and Bluetooth technologies. Results reveal that Bluetooth-based systems have the highest energy efficiency compared to systems using GPRS/UMTS or Wi-Fi [11]. Although distribution transformers are of enormous importance in power networks, their extensive usage poses problems regarding manual supervision. This project proposes an IoT-based system for effective remote supervision of crucial parameters of transformer units, e.g., load current, current voltage, oil level, and temperature. It effectively supersedes other microcontrollers with its simple architecture, and increased accuracy, stability, and efficiency are achieved because data collection and transmission are performed with the aid of integrated Wi-Fi and Bluetooth [12].

With the growth of smart cities, proactive transformer maintenance has become mandatory due to the commitment to constant power supply availability. IoT-based transformer health monitoring facilitates predictive maintenance to reduce outages and optimize grid performance. With an IoT-integrated AI system, the data is analyzed, and alerts are produced without the need for human interference, subsequently enhancing the effectiveness of decision-making [13]. Predictive and corrective measures to combat the faults of a power grid require a reliable and easy-for-all access infrastructure. This report conducts continuous real-time monitoring of the Iraqi power grid along with building health indices and preventative power interruption controls through predictive analytics to increase the power grid's resiliency [14].

3. System Architecture

The Health Data Collection Node for Transformers is a mechanism tasked with receiving operational data from transformers in real time and sending it to a central monitoring station through wireless connections. This node incorporates an ATmega328 microcontroller that serves as the main processing unit, which collects the data from the sensors and then relays it using LoRa RF communication. Incorporating numerous sensors guarantees thorough tracking of voltages, currents, temperatures, humidity, and even vibrations to ensure the transformer is in optimal condition. The block diagram in Figure 1 depicts the assembly of ATmega328 board, LoRa RF Module, Voltage Sensor, Current Sensor, Temperature Sensor, Ultrasonic Sensor, DHT Sensor and Power Supply, from which the Health Data Collection Node is constructed. The voltage and current sensors are responsible for the monitoring and electrics load control, as well as abnormal power flow detection. Such sensors are primarily employed to capture fluctuations that would indicate some inefficiencies or possible failures on the transformer. The working temperature of the transformer is being monitored by the temperature sensor to see whether it exceeds the allowed levels. Its critical overheating detection feature helps sustain the operating temperature that the transformer was designed for, avoiding any damage to the insulation and thus increasing the transformer's life. There is also a DHT sensor that measures temperature and humidity in the area in order to monitor how these environmental factors affect the transformer's efficiency. An ultrasonic sensor that measures distance has also been incorporated, which may be useful for monitoring the height of oil in the transformer or for measuring any changes that take place on the housing of the transformer.

The LoRa gateway receives data sent from the remote transformers using a LoRa RF module because it supports wireless communication over long ranges. The LoRa system's low power usage and its long-distance communication make it an excellent solution for implementing transformer monitoring systems at remote or difficult-to-access locations.

The power supply unit ensures proper operation of the system components by providing the required voltage levels for the ATmega328 board and the sensors. After processing data, the LoRa RF module wirelessly sends the information to the LoRa gateway for additional processing and integration to the cloud. With this architecture, modern power grids can ensure real-time health checks on transformers, thereby ensuring early detection and predictive maintenance of possible faults. Loosely coupling several sensors, wireless communication, and the internet to a single device greatly improves the efficiency and reliability of transformer monitoring systems.

The LoRa Gateway Node is the basic component that integrates the transformer health data from the Transformer Health Data Collection Node, processes it, and forwards it to the cloud for remote monitoring. Unlike other nodes, this is built on an ATmega328 microcontroller, which acts as a core processor. It has the basic ability to receive, display, and communicate the data to the cloud. The LoRa Gateway Node comprises an ATmega328 Board, LoRa RF Module, ESP01 Wifi Module, 20x4 LCD Display and Power Supply, as shown in Figure 2.

This node has an important component, which is the LoRa RF module. It provides low-power wireless communication over long ranges with the Transformer Health Data Collection Node. The node collects and remembers the real-time voltage, current, temperature, humidity, and other important parameters of the transformer and ensures that data transmission over distances is done reliably and securely. After the data is received, it is processed and stored in a format that can be used for local display or upload to the cloud.

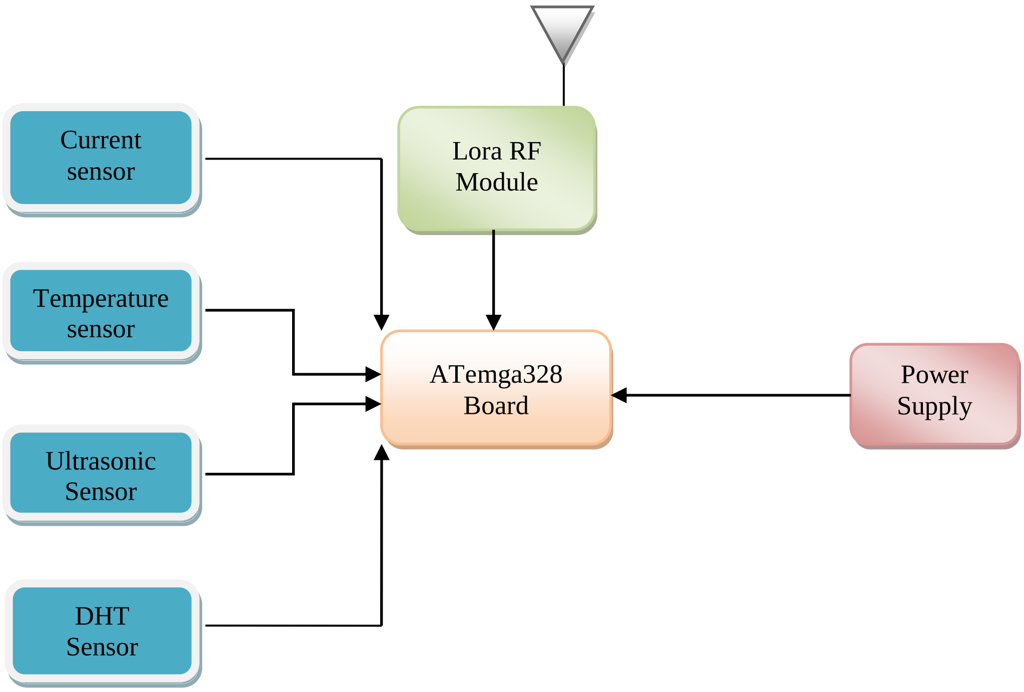

Fig. 1 Block diagram of the transformer health data collection node

An onsite 20x4 LCD display is incorporated to show assignable parameters for the transformer's health. This allows the engineers or technicians to view and monitor key readings in real time without constantly interacting with external devices. The LCD display updates in real-time when new sensor information is sent from the remote node, thus providing real time local feedback on the transformer's status. The processed information is sent to the Blynk Cloud platform through the ESP-01 WiFi module, which enables cloud connectivity. With this module, information about the transformer's health is made available on the web dashboards and mobile apps for remote monitoring and timely decisions. The module connects to the existing network, and the data is transmitted securely to the cloud, where the users have access to real-time updates of the transformer's conditions. The power supply unit provides proper levels of voltage and current to guarantee the stable functioning of the ATmega328 board, LoRa RF module, ESP-01 WiFi module, and LCD display. Due to the importance of this gateway node for monitoring the transformer's health, power saving and reliable operation are essential for constant data collection and transmission.

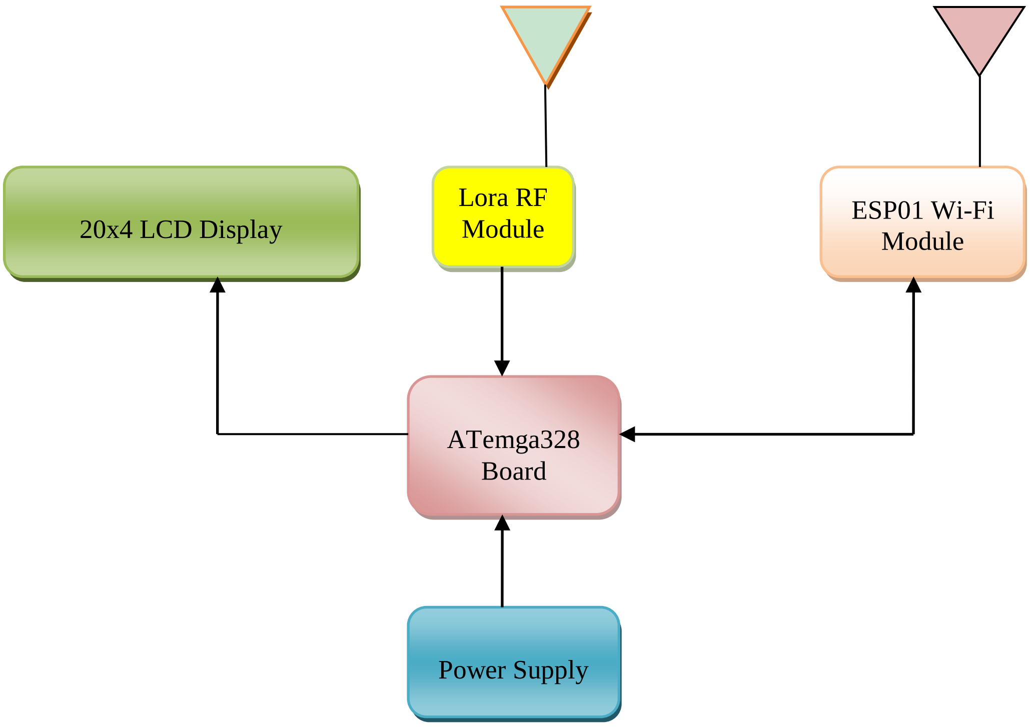

Fig. 2 Block diagram of LoRa gateway node

This LoRa Gateway Node functions as an interface between remotely acquired data and cloud analytics by employing LoRa RF for long-distance communication, ESP-01 WiFi for the cloud and a local LCD screen for local monitoring. The result is remote supervision, real-time health monitoring, proactive fault detection, predictive maintenance, and greater operational efficiency within power distribution networks.

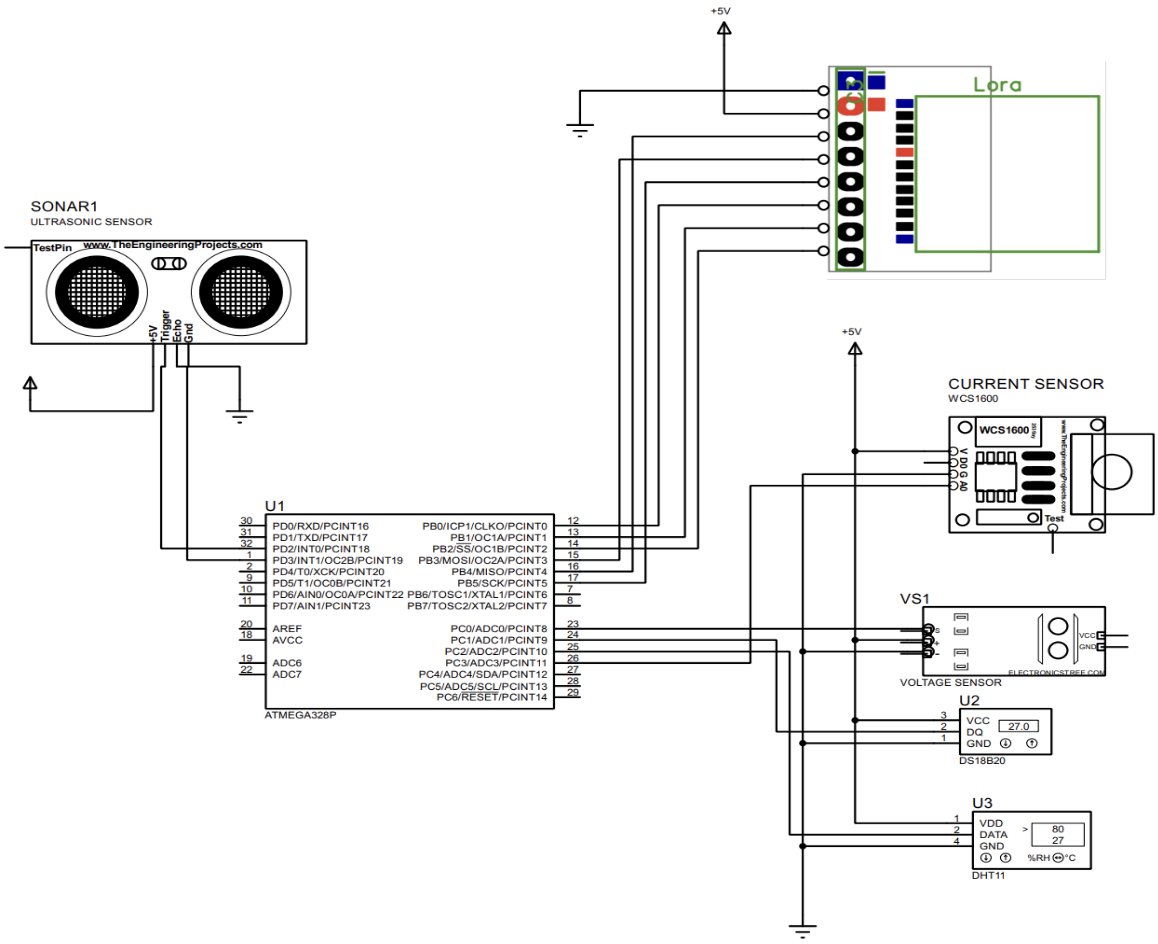

Fig. 3 Connection diagram of this transformer health data collection node

4. Hardware and Implementation

The hardware connections of the Transformer Health Data Collection Node have the following elements (Figure 3):

- The DHT11 sensor attached to the ATmega328 microcontroller measures the humidity and temperature. The GND terminal of the DHT11 pins connects to the GND terminal of the ATmega328 so that common ground is established. The VCC terminal is connected to the 5V terminal of the ATmega328 to allow it to power on. The Data pin of the DHT11 is also connected to the ADC2 pin of the ATmega328. This allows the microcontroller to have omnipresent access to the environment surrounding the transformer and ensures that every change in humidity and temperature is captured within the system.

- For accurate temperature measurement of the transformer system, the DS18B20 temperature sensor is utilized. The GND pin of the DS18B20 is connected to the GND pin of the ATmega328, and the VCC terminal is wired to the 5V line to apply the power. The Data pin of DS18B20 is wired to a PC1 pin of the ATmega328 to communicate through the 1-Wire protocol. This way, the temperature can be measured more accurately and sent to the microcontroller to assess transformer health.

- The Voltage Sensor VS1 allows for the measurement of transformer voltage. The GND pin of the voltage sensor is wired to the GND of the ATmega328, while the VCC pin is supplied with 5V to power the module. The voltage sensor's analog output is fed to the ADC0 input of the ATmega328. Thus, the microcontroller can read and compute the voltage values. This makes it possible to monitor voltage levels constantly, which assists in fault diagnosis at an early stage of the transformer.

- The WCS1600 current sensor monitors the current flowing through the transformer. The GND pin of the current sensor is wired to the GND of the ATmega328. Both devices use the same reference level. The VCC pin is connected to the 5V pin of the microcontroller to supply power to the sensor. The sensor's analog output is connected to the A3 input of ATmega328. The microcontroller captures the voltage from the sensor and processes it into amperes, facilitating observing load changes on the transformer.

- An oil level ultrasonic sensor HC-SR04 monitors the transformer's oil level. The ultrasonic sensor's GND pin connects to the GND of the ATmega328, while the VCC pin connects to the 5V pin. The Trigger pin connects to D2, and the Echo pin connects to D3 of the ATmega328. ATmega328 microcontroller triggers the sensor, and in return, the sensor sends an echo signal based on the oil level detected. This process enables oil level monitoring, which is vital for maintaining the transformer and avoiding damage.

- The transformer health data is transmitted wirelessly using the LoRa RF Module. The GND pin of the LoRa module is connected to the GND pin of the ATmega328, and the VCC pin is connected to the 5V power supply. The LoRa module is wired to the MISO, MOSI, SCK, and CS pins on the ATmega328 for serial communication. With this configuration, the microcontroller can send real-time voltage, current, temperature, humidity, and oil level readings to a monitor station.

The hardware connections of the LoRa Gateway Node have the following elements (Figure 4):

- LoRa Gateway Node is controlled by an ATmega328 microcontroller, which acts as the main processing unit. It is responsible for transmitting data between the LoRa RF module, the ESP-01 WiFi module and the LCD display. The microcontroller also receives power from the 5V supply, and the GND pin is connected to the circuit's common ground. He interacts with some peripherals to control the data collection and data communication processes.

- LoRa RF module serves the purpose of long-distance wireless communication. The GND pin of the LoRa Module is connected to the GND of the ATmega328. Both modules can be powered since the VCC pin is connected to the 5V supply.

The module features MISO, MOSI, SCK, and CS pins, which support the SPI interface of the ATmega328, thus permitting high-speed serial exchange of information. This arrangement enables the microcontroller to receive sensor data from remote nodes via LoRa and process it before sending it with the ESP-01 module for cloud communication.

- The ESP-01 WiFi module sends all collected data either to a cloud server or to the local network. In this case, the GND pin of the ESP-01 is connected to the GND of the ATmega328. The VCC pin is connected to the 3.3V supply, which ensures stable operation.

  Additionally, the TX pin of the ESP-01 is connected to the RX pin PD0 of the ATmega328, and the RX pin of ESP-01 is connected to the TX pin PD1 of ATmega328. These pins provide a UART communication link so the microcontroller can send the processed data from the LoRa module through the ESP-01, which uploads it to the internet.

- The 20x4 LCD Display (JHD-20416-02) will use the received data from the LoRa module sent using the ESP-01 module as a real-time data display. The VCC pin of the LCD is connected to the 5V supply, and GND is connected to common ground. The SDA and SCL pins of the LCD are connected to the corresponding I2C pins of the ATmega328 so that the I2C protocol is used for communication. This display serves as a basic visualization of the sensor data undergoing wireless transmission.

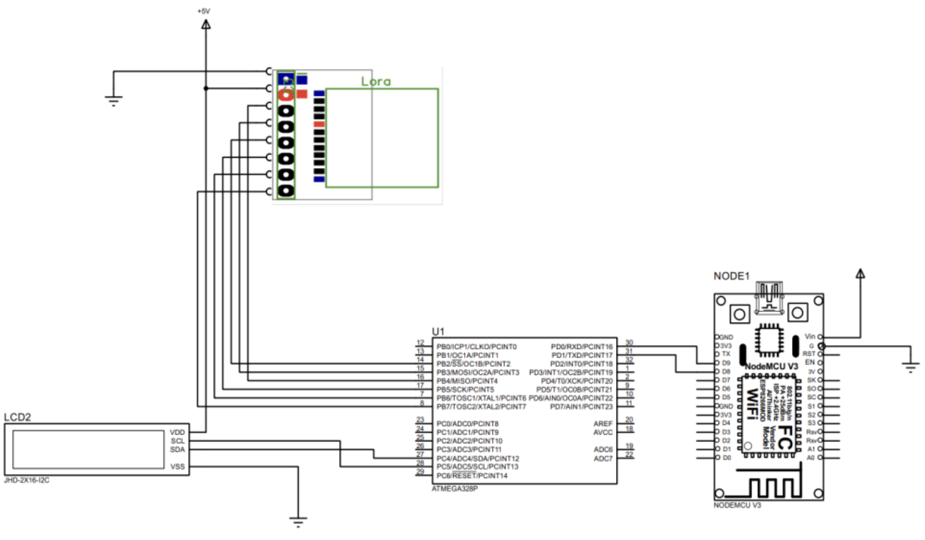

Fig. 4 Connection diagram of this LoRa gateway node

5. Implementation of the System

The monitoring unit pertaining to transformer health has been developed in a fashion that guarantees continuous collection, processing, and transmission of sensor data for health monitoring. At the core of this system is the ATmega328 microcontroller, which controls the communication of various sensors with the LoRa RF module responsible for sending data over long distances. The system ensures low power consumption, reliable data capture, and connectivity to the IoT cloud application. The process starts by turning on all hardware elements, including the voltage, current, temperature, humidity, ultrasonic sensors, and communication modules. The ATmega328 microcontroller collects real-time data from these sensors at set intervals and adds compensation for calibration to enhance accuracy if needed. The data captured is placed into formatted and structured packets for transmission to reduce the amount of data that could potentially get lost. After processing, the information is sent wirelessly through the LoRa RF module to the LoRa Gateway Node, which relays the data to the cloud. Due to LoRa's long-range and low-power requirements, transformer health parameters can be transmitted from remote sites with little maintenance and energy. The gateway node receives and processes the data and then sends it via the ESP-01 WiFi module to the cloud, which can be visualized on the Blynk IoT dashboard for real-time monitoring.

For off-site monitoring purposes, the LoRa Gateway Node features a 20x4 LCD screen that displays the received health data of the transformer. This ensures that service and maintenance staff can check the operational state of the transformer instantly without needing to do so on any outside networks. If voltages, overheating, or unusual current flow are detected, the system is capable of sending alerts through the Blynk platform. This enables users to take quick corrective actions. The algorithm used for monitoring the transformer's health works sequentially to guarantee the reliability of the information received and effective wireless data transmission. The procedure starts with the initialization of the sensors and then data collection, where the ATmega328 microcontroller gathers sensor readings at predetermined intervals. Figure 5 portrays the integrated transformer health data collection node with multiple sensors and communication elements. Thereafter, the information is compared to benchmarks to spot significant critical failures like overvoltage, excess heating and sudden changes in humidity. If all parameters appear at normal and acceptable values, the sensor outputs are aggregated and sent via LoRa RF. First, the data is received by the LoRa Gateway Node. Then, it is processed and sent to Blynk Cloud through the ESP-01 WiFi module for active monitoring. The system saves and serves as a reminders in case any disruptions occur so that they may be further examined. These measures guarantee efficient, accurate and timely perpetual transformer monitoring, prevention of failures and performance maintenance using low power. By using power wireless communication and integrating services to the cloud, the system ameliorates the efficiency and reliability of the power distribution networks by ensuring perpetual monitoring and management of the transformer's health.

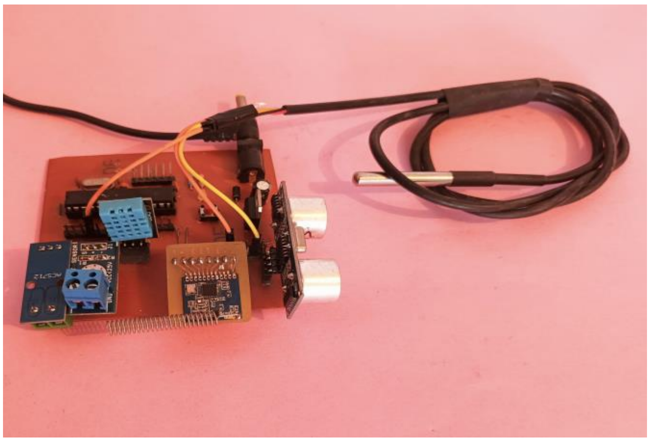

Fig. 5 Hardware node used for transformer health data collection node

The Edge Gateway Unit is the interface that connects the transformer health data collection node to the cloud for monitoring and processing cloud resources. The unit is constructed with an ATmega328 microcontroller, which gathers data from the LoRa RF module, processes it, and uploads it to the Blynk Cloud via an ESP-01 Wi-Fi module. Since the Edge Gateway Unit is the interface that connects the transformers to the IT environment, it creates optimal conditions for the data fusion of the margins, eliminating delays, reducing bandwidth consumption, and making it possible to see real-time data of the transformer's operating conditions. The process of deploying the Edge Gateway Unit begins with the setting up of the LoRa RF module, which has the function of receiving information packets produced by the data collection node. Following the reception of information, the ATmega328 microcontroller is supplied with the relevant information, which includes voltage, current, temperature, humidity, and vibration. This step helps filter the data anomalies, remove duplicates, and format the information before sending it to the cloud. The logic behind this is to provide edge monitoring capability for transformer health metrics. The Edge Gateway Unit contains a 20x4 LCD, which provides onsite operational metrics at any time. This enables maintenance staff to view critical parameters instantly without cloud dependency. New sensor measurements are used to update the LCD, so the latest status of the transformer is always available.

The ESP-01 Wifi module connects to the existing network and uploads processed data to the Blynk Cloud platform. It shows the implanted LorRa Gateway node with different communication modules and a display setup. This allows users to check transformer health metrics from a web dashboard or a mobile app. Cloud storage provides options to retain the collected data, send alerts in case of critical conditions, and forecast maintenance needs using trend analysis. The Edge Gateway Unit logically operates by a specific algorithm to guarantee that data is correctly captured, processed, and sent out. First, the Transformer Health Data Collection Node is activated, and the LoRa RF module is configured to receive data packets. As soon as the data is received, the ATmega328 microcontroller will first threshold and filter the data, removing every erroneous reading and, in essence, parsing the data. Then, the processed data is displayed on an LCD screen for immediate onsite assessment. At the same time, the formatted data from the ESP 01 WiFi module is being sent to the Blynk Cloud to establish a connection that enables real-time remote viewing. The cloud dashboard will get triggered if there is overheating, voltage surges, or another form of abnormal current flow. An alert will be sent to the users for immediate action. With the help of edge processing, cloud monitoring, and wireless transmission, the Edge Gateway Unit boosts reliability, energy efficiency, and transformative health maintenance systems. It permits wireless data capture and distribution during active monitoring of the power distribution systems. Such a system enables remote and local functionalities, making it smart grid-ready ready, which translates the unit to minimize downtime while improving the overall management of the transformer.

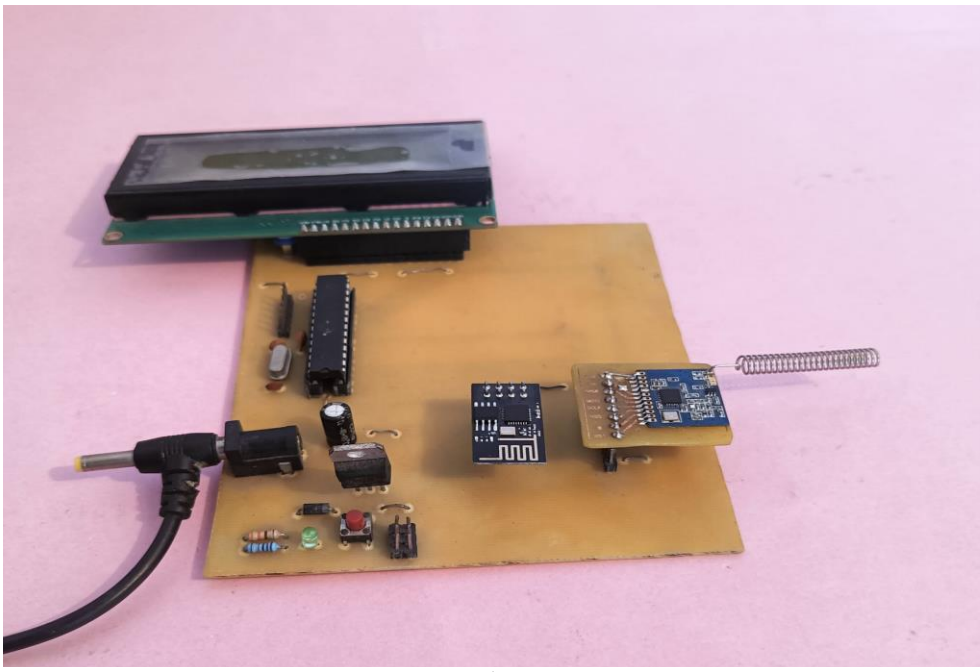

Fig. 6 Hardware node used for LoRa gateway node

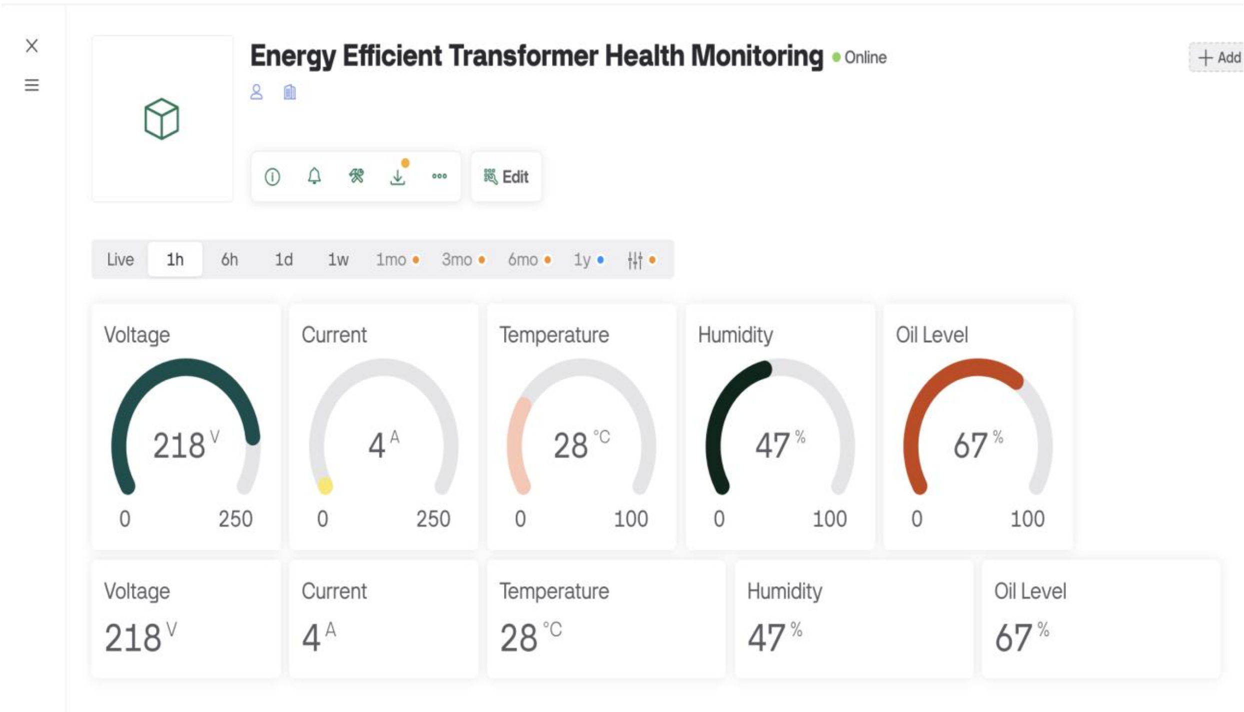

Fig. 7 Web dashboard data visualization of the health monitoring of transformer in blynk web dashboard

Users can continuously monitor the health of transformers using the Blynk Web Dashboard, which features an interactive interface that displays real-time data. The Edge Gateway Unit data is transmitted through the ESP-01 WiFi module, then organized and displayed through the Dashboard. As shown in Figure 7, critical transformer metrics such as voltage, temperature, humidity, and vibration levels are presented by widget gauges, graphs, and labels and displayed in an easy-to-read manner. Parameters are updated in real-time, accompanied by the necessary charts for historical data and constant alerts for abnormal conditions. The Blynk platform also sends notifications as alerts if any overvoltage, overheating or irregular current flow is detected, empowering users to take corrective measures immediately.

6. Results and Conclusion

The monophasic prototype presented is an energy-efficient IoT gateway built for remote monitoring of transformer health with the integration of several sensors using LoRa RF communication and real-time visualization of data on the Blynk dashboard. This system can improve predictive maintenance and fault detection and stabilize the grid, increasing its effectiveness in the health assessment of transformers in power distribution systems. Its architecture enables cloud computing, allowing remote monitoring to be conducted without requiring manual inspection to enhance operational efficiency. The absence of wires improves the design's flexibility and ease of deployment, making it suitable for urban and remote power infrastructures. Further developments can focus on integrating advanced AI-driven predictive analytics to permit real-time anomaly detection and automated fault diagnosis. Also, edge computing can be incorporated to minimize the cost of latency and bandwidth by processing data locally. Further enhancement towards the diagnostics of transformers would be done by incorporating improved sensors for oil quality evaluation and monitoring of insulation deterioration. This research represents an important step towards modernizing power systems monitoring and providing a scalable, economical, and environmentally friendly means of managing smart grids.

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