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MONITORING AND CONTROL OF IOT-BASED TRANSFORMER SUBSTATION FOR SMART GRID APPLICATIONS

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The concept of the Internet of Things has become increasingly intriguing in recent years. It is foreseeable that in the coming years, systems used in various fields, such as healthcare, agriculture, transportation, and energy, will transition to IoT-based systems. The transition of transformer substations, which hold a crucial position in the power distribution network, to IoT-based applications forms the foundation of this study. In many systems currently in operation, transformer substations are monitored and controlled via SCADA. However, SCADA systems require devices that perform central control and data monitoring functions to use the same communication protocol. In contrast, IoT-based systems enable the use of various devices and do not require additional storage capacity for data. In this study, a model has been developed to monitor and control an IoT-based transformer substation for smart grid applications. The identified transformer parameters were tracked through an IoT-based monitoring system. The obtained data demonstrated the system's successful operation.

1. INTRODUCTION

The transformer is one of the most crucial components in the power transmission network, playing a significant role throughout the entire energy system [1]. The electrical energy system is an instantaneous power transmission system; it generates power, facilitates transmission, and provides power when demanded [2]. Distribution transformers operate continuously in the power distribution network, ensuring uninterrupted service 24 hours a day. Therefore, any malfunction in such transformers can cause significant inconvenience to numerous consumers and lead to financial losses for service providers. Consequently, preventing transformer failures and operating distribution transformers under specified conditions are imperative [3,4].

Transformers can experience premature aging during operation due to factors such as overheating, excessive loading, and other malfunctions [5 6]. Therefore, regular monitoring and control of transformers during operation are crucial. Monitoring involves collecting and analyzing data from nearby sensors using various measurement methods. The fundamental purpose of monitoring systems is to detect adverse conditions instantly and enable intervention [7].

Rapid technological changes have brought about fundamental shifts in monitoring systems. Costly, complex, and manpower-intensive SCADA systems are giving way to IoT-based systems. IoT-based monitoring systems have become increasingly prevalent as the number of devices connected to the Internet worldwide approaches billions [8]. IoT equipment, such as sensors and processors, is cost-effective, open-source software, and easily adaptable to various applications [9–12].

Monitoring systems, previously predominantly used for smart buildings and environments, have been adopted in recent years for electrical equipment and transformer substations [10,13].

The study outlined in [14] introduces a monitoring system aimed at instantaneously tracking the aging level of transformer insulation and predicting service requirements. In this context, measurements are taken not only for winding, oil, and ambient temperatures but also for current values. External temperature threshold values are established during operation, and a message alert system is activated to protect transformers.

In [15], when IoT is investigated under the topic of smart environments, smart grids come into prominence. In particular, the key solutions for improving power quality will be IoT-based. Continuous control of the health status of power and distribution transformers ensures an uninterrupted power supply. 19% reduction in transformer outages and a 36% increase in average life can be observed by monitoring the health status of transformers and performing interventions at the correct time and with the correct methods.

In [16], a study on the health status analysis of power transformers within the scope of smart grids in power transformers; winding incipient fault model, aging assessment model, transformer loading management model, voltage regulation model, transformer connection monitoring model, and insulating oil condition model are investigated.

In [17], an IoT-based approach is proposed for monitoring and controlling many distribution transformers in power distribution networks. The vibration analysis method is used, and the results show that the improved diagnosis algorithm achieves 99.01%, 100%, and 100% accuracy for normal, aging, and faulty transformers, respectively.

In [18], the conventional electricity distribution principle will be replaced by smart grids powered by renewable energy, and control and remote monitoring systems are of great importance as the key enablers here. The importance of information and communication technologies has increased, especially with the introduction of distributed energy from centralized energy. At this point, IoT's ability to collect data, to understand data, to simulate data, and to reveal the system allows data mining.

In [19], IoT was used to monitor transformer parameters. In the experiment, a one-phase 230 / 110V transformer and Intel Galileo (2nd Generation) were used. Temperature, primary, and secondary voltage values were obtained from the transformer.

In [20], research was conducted to analyze the transformer status. For the test, a 3-phase 3 kVA 230/400V transformer with a star/delta connection scheme was used. As a microcontroller, an Arduino Uno, temperature, and spark sensors were used to generate data. It is thought that abnormalities in the transformer core will be detected by the temperature sensor, and abnormalities in the inner windings will be detected by the spark sensor. The data obtained were interpreted with IoT-based solutions.

In [21], the Italian electrical system operator Terna continued

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to expand its online monitoring system from 2005 to 2017. While the system was being built, it was based on the criteria of the list of priorities, key parameters to be followed, the IEC standards, the creation of algorithms that will work with information from the company and equipment manufacturers' experience, the architectural structure of the monitoring system, and the human-machine interface (operator machines).

In [22], to support the Industry 4.0 concept for online monitoring and diagnosis of transformer operating conditions, transformer operating conditions have been developed from vibration signals. The developed model aims to detect faults in transformer vibration signals at the early stages of a significant fault, such as a short circuit.

In [23], an IoT-based system is proposed for real-time monitoring and fault detection of distribution transformers. It uses a low-cost gateway and sensors to measure three-phase load current, oil level, and temperature. Data is sent to the cloud via a publish/subscribe model, processed, and stored for real-time visualization and abnormality detection.

In this study, an IoT system has been designed to perform the same functions as traditional systems, monitoring and controlling transformer substations, but at a lower cost and with a more scalable structure. Various sensors were used with a 50 VA power transformer to monitor and record the transformer's winding temperatures, current values, and humidity conditions in real time under different load conditions. Instant interventions were possible when transformer parameters reached abnormal values.

2. **CONCEPT AND COMPONENTS OF IOT**

2.1 DEFINITION OF CONCEPT OF IOT

Various definitions are available for IoT. But there are slight differences between the definitions. This can also be seen as differences in interpretation for a newly developing field. Some describe IoT as an interconnection that enables integrated data-processing devices within the existing Internet infrastructure to be uniquely identified; others view it as electronic devices connected to the Internet [24]. But the most comprehensive definition is: IoT is a scenario in which objects, animals, or humans can automatically transmit unique tokens and data over a network without the need for human-human or human-computer interaction [25].

2.2 BASIC COMPONENTS

The basic components of IoT include a sensor, cloud computing, information/data transfer technology, and a microcontroller that processes, transmits, receives, and executes commands.

2.2.1 SENSORS

Sensors convert physical signals into electrical signals. In an IoT application for health care. It is expected that the patient will have a heart rhythm sensor that continuously measures and records the pulse. In addition, in the event of a heart attack, the GPS sensor records the patient's position, which is expected to be reachable. In an IoT application for an agricultural field, it is expected that sensors can measure the temperature and humidity information that plants need.

2.2.2 CLOUD COMPUTING

Cloud technology is a system that allows you to sync files and share them across many devices. It is a technology we use actively in our daily life. The images and videos uploaded to platforms such as Facebook and Twitter that we use on our phones are uploaded to the cloud servers of these platforms. Beyond cloud backup/virtual hard disk usage, the cloud has broader implications for IoT. In an IoT application for the cloud, data/information storage and the creation of the decision mechanism and/or meaningful information by making this stored data/information meaningful. This decision mechanism provides either by issuing commands to actuators directly or by informing the person who controls the system via the user interface about the data meaning in the cloud.

2.2.3 MICROCONTROLLER

A microcontroller, an electronic microcomputer that receives data from the outside, processes it through the programs written for it, and then outputs it, has different characteristics and brands. Microcontroller cards can be purchased according to the requirements. When we commonly use the microcontroller for IoT:

- Arduino (Some models may require some plugins for IoT. The cloud service must be purchased externally.)
- Intel Galileo/Edison (IoT compatible, internal Intel cloud service)
- Raspberry Pi 3 (IoT compatible, internal Microsoft Azure cloud service)
- Particle Photon (IoT compatible, internal Amazon-Google cloud service)

3. **MATERIAL AND METHODS**

In this study, a model has been developed for the monitoring and control of an IoT-based transformer substation for smart grid applications.

The proposed model comprises various components, including a temperature and humidity sensor, current sensors for primary and secondary windings, temperature sensors for primary and secondary windings, a transformer, a microcontroller, a relay, and a load. Additionally, it incorporates Wi-Fi communication and cloud software. Fig.1 illustrates the block diagram of the proposed model.

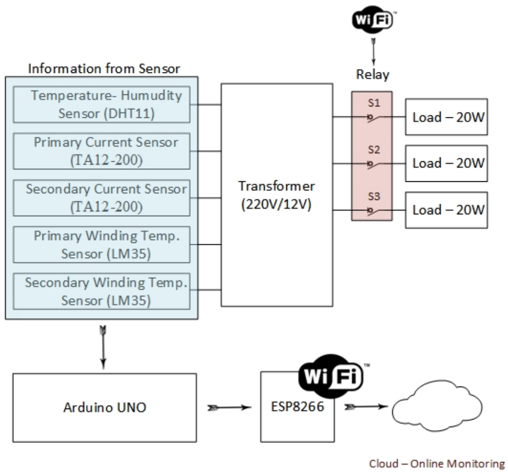

Fig. 1 – Block diagram of the proposed model.

3.1 MICROCONTROLLER SELECTION

The microcontroller, the Arduino Uno, was selected. Arduino Uno has gained the ability to connect to the Internet with the ESP 8266 Wi-Fi module. NodeMCU, which controls the relay, is connected to the internet without needing any module because of its internal Wi-Fi module. Temperature, humidity, and current sensors were used in the prototype. With the DHT11 sensor, temperature and humidity information in the environment has been monitored. This data was used to monitor the values permitted by the regulations at the transformer substation. The primary and secondary winding temperature control of the transformer is monitored by the sensor probes created. The transformer used has 50 VA power and a 220/12 V turns ratio. With the current sensor located at the 12V end, the current drawn from the transformer is measured based on the load. The relay, which represents switchgear, has a 5 V electrical characteristic that the microcontroller can control.

3.2 SENSOR AND EQUIPMENT SELECTION

3.2.1 TEMPERATURE AND HUMIDITY SENSOR

The DHT11 temperature and humidity sensor has been employed to acquire ambient temperature and humidity information. The chosen sensor possesses a high-performance 8-bit microcontroller. Its rapid data reading response, data reading stability during prolonged usage, and cost-effectiveness make it the preferred choice.

3.2.2 TEMPERATURE SENSOR

Four LM35 sensors have been employed to measure the primary and secondary temperatures of the transformer. Two of them are used for actual measurements, while the other two serve as backups and verify the accuracy of the acquired data. The sensors are of the 3-pin type and come in a TO-92 package. To facilitate the placement of the sensors within the transformer windings, the pin outputs have been extended, allowing measurements to be taken in the control box. During the wiring process, yellow is used for the signal cable, red for the power cable, and black for the ground line.

3.2.3 CURRENT SENSOR

To measure the primary and secondary currents of the transformer, 2 Seeed Studio TA12-200 current transformers were employed. Their compact size, high precision, and successful performance in measuring alternating currents make them the preferred choice.

3.2.4 RELAY SELECTION

A single-channel relay compatible with NodeMCU, capable of driving a 12 V load, was chosen to represent the OG breakers.

3.2.5 TRANSFORMER SELECTION

The transformer is of standard power, with a rating of 50 VA and a voltage of 220/12V. Inside the primary windings, two temperature sensors are placed, and within the secondary windings, there are two additional sensors, making a total of four temperature sensors incorporated.

3.2.6 LOAD SELECTION

To enable loading the transformer at 40%, 80%, and 120% capacity, an inductive load with a power factor of 0.9 was chosen. As the load, three G4 socket lamps with a power of 20 W, operating at 12 V, and belonging to energy efficiency class C have been used.

3.3 COMMUNICATION TECHNOLOGY

One of the most important components for IoT, after cloud computing, is communication technology. In our system, wireless network (Wi-Fi) technology has been utilized. The obtained data is sent to the cloud software via Wi-Fi, establishing a monitoring and tracking system.

3.4 CLOUD COMPUTING

Cloud computing services, which are a crucial component of IoT, have numerous application areas such as visualization of data obtained from objects, development of monitoring systems, advanced management services, mathematical analysis processes, data management, management of different data from a single information pool, holistic system management, device management, and application development layers (25).

In this study, Ubidots, a user-friendly, straightforward cloud platform, was developed and utilized. The obtained data was sent to Wi-Fi via the cloud, and a follow-up/monitoring system was established. https://ubidots.com is used for cloud computing. Figure 2 shows the phases of IoT-based application development. From the transformer temperature information, temperature and humidity information from the environment where the transformer operates, current and voltage information obtained from transformer-connected loads, and the transformer load value are collected by means of instantaneous cloud computing.

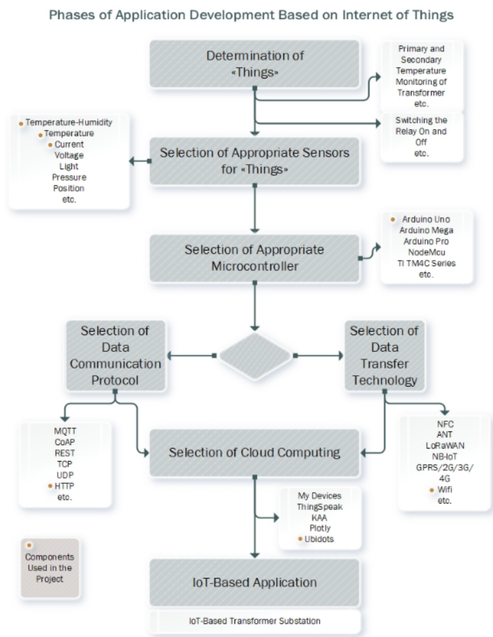

Fig. 2 – IoT-based application development scheme.

The circuit of the IoT-based system, whose design and implementation have been completed, is shown in Fig. 3.

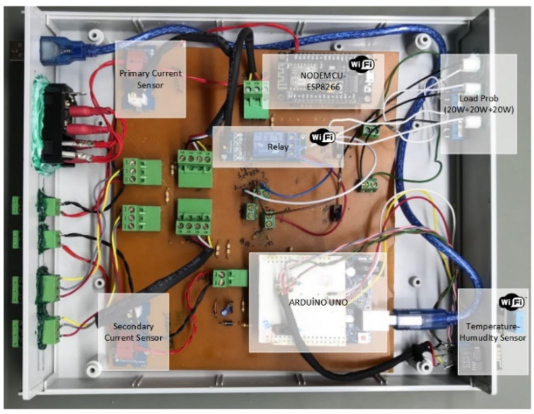

Fig. 3 – The diagram of the proposed system.

4. EXPERIMENT RESULTS

By utilizing a transformer model, a test setup was created to monitor and control the relationship between the transformer's load and temperature. Tests were carried out at 24-25° C and 50% relative humidity. The transformer was initially operated without a load, and subsequently with loads of 40%, 80%, and 120%, respectively. Primary/secondary winding temperatures, primary/secondary current, and ambient temperature-humidity data from the transformer were saved to the local computer in the form of cloud computing (Ubidots) CSV format. Each saved file has an average of 1000-2000 rows of data, and a total of 198,000 rows of data has been created. The obtained data are plotted using the Python software language and the Pandas and Matplotlib libraries.

4.1 DATA OF TRANSFORMER NO-LOAD

220V mains voltage is applied to the primary part of the designed transformer. No load connected to the secondary side. When the transformer is no-load, iron loss caused by the core, dielectric losses caused by the insulating material (oil, resin), and copper losses caused by the current circulating on the primary side cause the transformer to overheat. Figure 4 shows the primary winding temperature of the transformer.

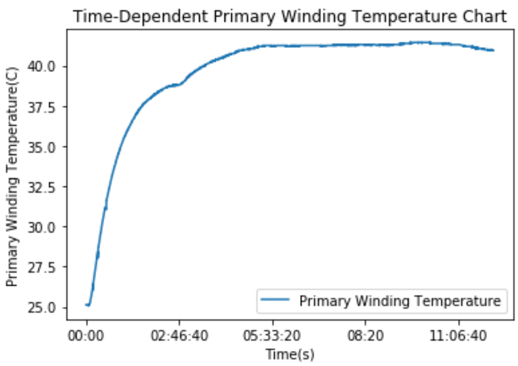

Fig. 4 – Time-dependent primary winding temperature chart.

The sensors that are connected to the Arduino Uno microcontroller in the No-Load Test Set, the DHT11 sensor, the ESP8266 module, and the primary and secondary winding temperature measurement are active. Data from sensors is sent to the user interface via Wi-Fi, and the values are monitored. Switch 1 is the key that activates the ESP8266 module and is open if the control box is running. The Arduino Uno program is set to the off position during the update. Figure 5 shows the system's operating diagram.

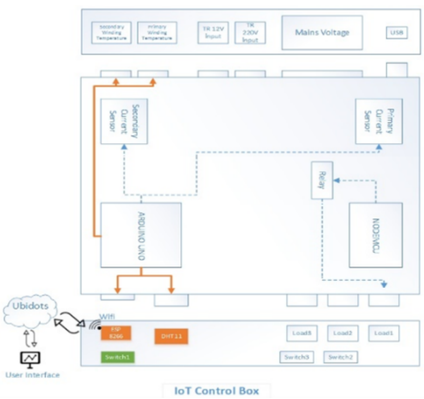

Fig. 5 – No load block diagram.

4.2 DATA OF TRANSFORMER %40 LOAD (20W)

220V mains voltage is applied to the primary part of the designed transformer. A 20 W lamp load is connected to the secondary side. The lamp load was activated by the command of the relay button in the online user portal. In addition to losses during no-load operation, there is copper loss on the secondary side. The sum of these losses causes the transformer to heat up. With the start of the load, the average current values of 0.1 A in the primary windings and 1.75 A in the secondary windings were reached. Figure 6 shows the average primary current, and Fig. 7 shows the average secondary and Fig. 8 shows the average secondary winding temperature of the transformer.

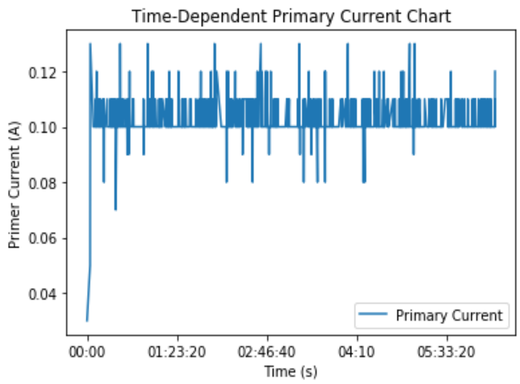

Fig. 6 – Time-dependent primary current chart.

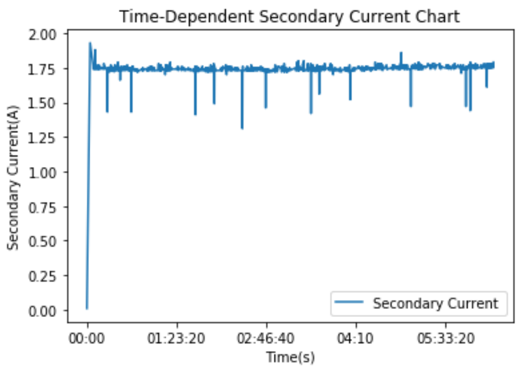

Fig. 7 – Time-dependent secondary current chart.

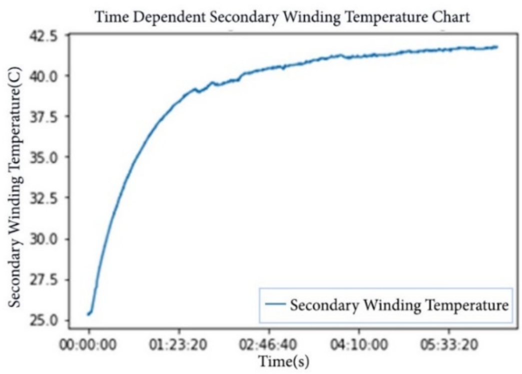

Fig. 8 – Time-dependent secondary winding temperature chart.

4.3 DATA OF TRANSFORMER %80 LOAD (40W)

220 V mains voltage is applied to the primary part of the designed transformer. A 40 W lamp load is connected to the secondary side. The Lamp-1 load was activated by the command of the relay button in the online user portal. The

Lamp-2 load was activated with the control button. With the start of the load, the average current values of 0.2 A in the primary windings and 3.25 A in the secondary windings were reached. Figure 9 shows the average primary current, Fig. 10 shows the average secondary current, and Fig. 11 shows the average secondary winding temperature of the transformer.

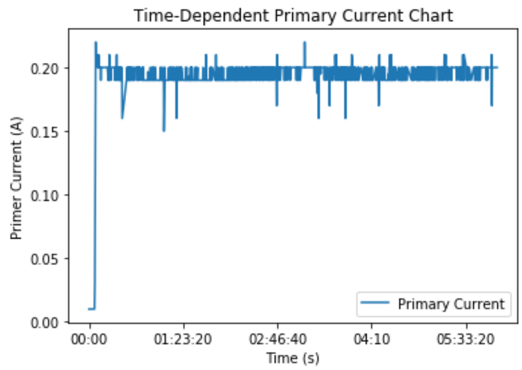

Fig. 9 – Time-dependent primary current chart.

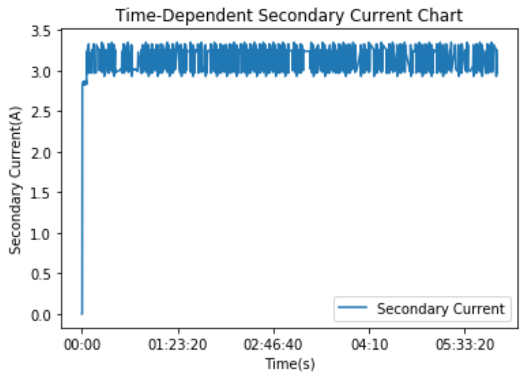

Fig. 10 – Time-dependent secondary current chart.

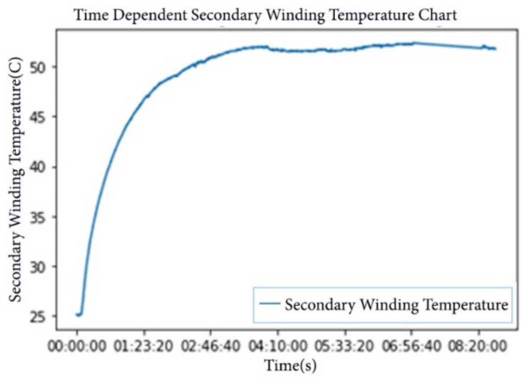

Fig. 11 – Time-dependent secondary winding temperature chart.

In the 80% load (40 W) working experiment set, sensors are connected to the Arduino Uno microcontroller and the ESP8266 module, and the primary and secondary current and winding temperature measurements are active. The command given from the user interface is transmitted to NodeMCU via Wi-Fi, and the connected relay activates the Lamp-1 load. The Lamp-2 load was activated manually with the Switch2 control button.

4.4 DATA OF TRANSFORMER %120 LOAD (60 W)

220 V mains voltage is applied to the primary of the designed transformer. A 60 W lamp load is connected to the secondary side. The Lamp-1 load was activated via the relay button in the online user portal. Lamp-2 and Lamp-3 loads were activated with the control button. With the start of the load, the average current values of 0.3 A in the primary windings and 4.75 A in the secondary windings were reached. Figure 12 shows the average primary current, Fig.13 shows the average secondary current, and Fig. 14 shows the average secondary winding temperature of the transformer.

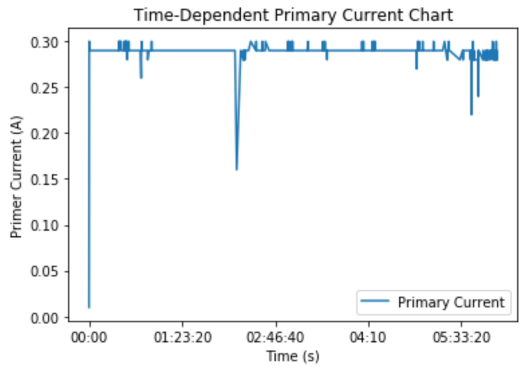

Fig. 12 – Time-dependent primary current chart.

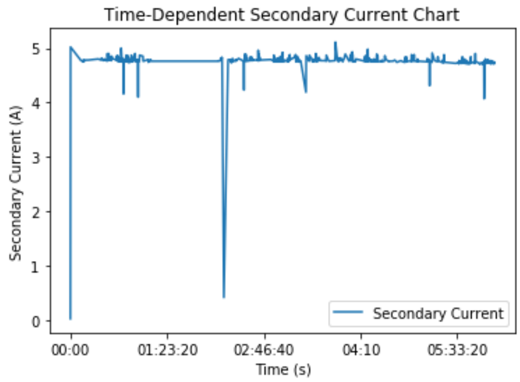

Fig. 13 – Time-dependent secondary current chart.

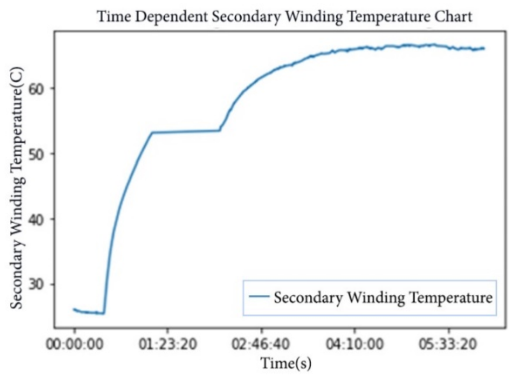

Fig. 14 – Time-dependent secondary winding temperature chart.

In the 120% loading scenario, the transformer was operated for 6 hours. Under this load, the secondary current reached 4.8 A. After 6 hours of operation, the temperature of the secondary winding increased from 26.13°C to 66.06°C. Due to the secondary current exceeding the permissible current level (4 A), the S1, S2, and S3 switches were activated, opening the relay and shedding the load. Thus, the transformer was put into no-load operation and taken under protection.

All the provided graphs were generated using data obtained from the IoT system prototype.

In the developed system, the relationship between the load and winding temperatures of a single-phase transformer was investigated using IoT. The impact of different loads on winding temperature affects transformer efficiency. Under a 40% load condition, with an ambient temperature of 25°C, the primary winding temperature was fixed at 45.81°C, and no efficiency loss was observed in the transformer. However, under a 120% load condition with an ambient temperature of 25°C, the primary winding temperature was fixed at 75.75°C, resulting in a 6% efficiency loss in the transformer.

5. CONCLUSIONS

In this study, an IoT-based, highly reliable, cost-effective, and high-capacity data storage, remote control, and data monitoring system has been developed for transformer substations, surpassing traditional systems. Monitoring a transformer substation with IoT ensures that temperatures and load conditions remain within acceptable limits. Additionally, nominal operating conditions can be adjusted online in unexpected situations, making the overall system more efficient and flexible.

Data from the transformer's load ratios, hourly temperatures, and the latest temperature measurement will provide information on the transformer's aging rate. Additionally, tracking the relay's opening and closing events is crucial for monitoring its mechanical lifespan.

This system, developed for transformer substations, can efficiently perform all functions of traditional systems while incurring lower maintenance and operational costs.

In terms of feasibility and scalability, the initial steps to establish an IoT-based system in transformer substations using existing infrastructure involve using wireless sensors, revising measurements for existing devices, and establishing thermal and image processing infrastructure. This hardware revision will be sufficient on its own. However, to mature the system software, it is highly important to create a database by conducting measurements over at least a few years and to generate predictive maintenance tables using machine learning and deep learning methods.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

MUSTAFA YAĞCI: theory, computations.
SALIH BERKAN ATEŞ: simulations, results.
SERTAÇ GÖRGÜLÜ: formal analysis, editing.

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