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IoT-Based Monitoring and Control of Substation Equipment

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Abstract: *The reliability and efficiency of electrical power systems are critical for modern industrial and domestic applications. Substations play a vital role in power transmission and distribution, where continuous monitoring and control are essential to avoid failures and ensure system stability. This paper presents an Internet of Things (IoT)-based system for real-time monitoring and control of substation equipment. The proposed system uses sensors to measure parameters such as voltage, current, temperature, and transformer oil level. These parameters are continuously monitored using a microcontroller (ESP32), and the data is transmitted to a cloud server for remote access via a web or mobile application. In case of abnormal conditions, the system automatically triggers protective mechanisms such as relays and circuit breakers while generating alerts. The proposed system improves reliability, reduces maintenance costs, and enhances operational efficiency.*

Keywords*:* IoT, Substation Automation, ESP32, Real-Time Monitoring, Smart Grid, Sensors, Relay Protection

I. INTRODUCTION

Electrical power systems are among the most critical infrastructures in modern society, ensuring the continuous supply of electricity for industrial, commercial, and domestic applications. Due to their large-scale, interconnected, and non-linear nature, these systems require reliable monitoring and control mechanisms to maintain stability, efficiency, and safety. Substations play a vital role within the power system, acting as key nodes responsible for voltage transformation, switching operations, protection, and power distribution.Conventional substation monitoring systems primarily depend on manual inspection and periodic maintenance practices. While these methods have been widely used, they often result in delayed fault detection, increased operational downtime, and higher maintenance costs. Furthermore, the growing demand for uninterrupted power supply and improved power quality has highlighted the limitations of traditional approaches.With the rapid advancement of Internet of Things (IoT) technology, modern power systems are transitioning towards intelligent and automated monitoring solutions. IoT enables real-time data acquisition, remote accessibility, and automated decision-making, significantly enhancing the efficiency and reliability of substation operations. By integrating sensors, microcontrollers, and communication networks, it becomes possible to continuously monitor critical parameters such as voltage, current, temperature, and transformer oil level.

In this context, the present research proposes an IoT-based monitoring and control system for substation equipment. The primary objectives of the proposed system are to:

- Continuously monitor key substation parameters in real time
- Detect faults and abnormal conditions promptly
- Automatically activate protection mechanisms such as relays and circuit breakers
- Enable remote monitoring and control through web and mobile applications

The implementation of such a system aims to improve operational reliability, reduce human intervention, minimize maintenance costs, and enhance the overall efficiency of power distribution networks.

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1.1 Conceptual Framework: Traditional vs. IoT Monitoring

The transition from conventional manual monitoring to advanced IoT-based systems is a key theme of your research. This image visually compares these two approaches, highlighting the limitations of the traditional method and the advantages of your proposed solution.

Left side (Traditional): Illustrates a technician manually inspecting equipment with notes and a multimeter, representing periodic maintenance, delayed fault detection, and higher downtime.

Right side (IoT-Based): Shows sensors and microcontrollers integrated with substation equipment, feeding data to a central cloud server for real-time monitoring on dashboards and mobile devices. This highlights automated data acquisition, remote accessibility, and prompt fault detection. (Refer figure 1)

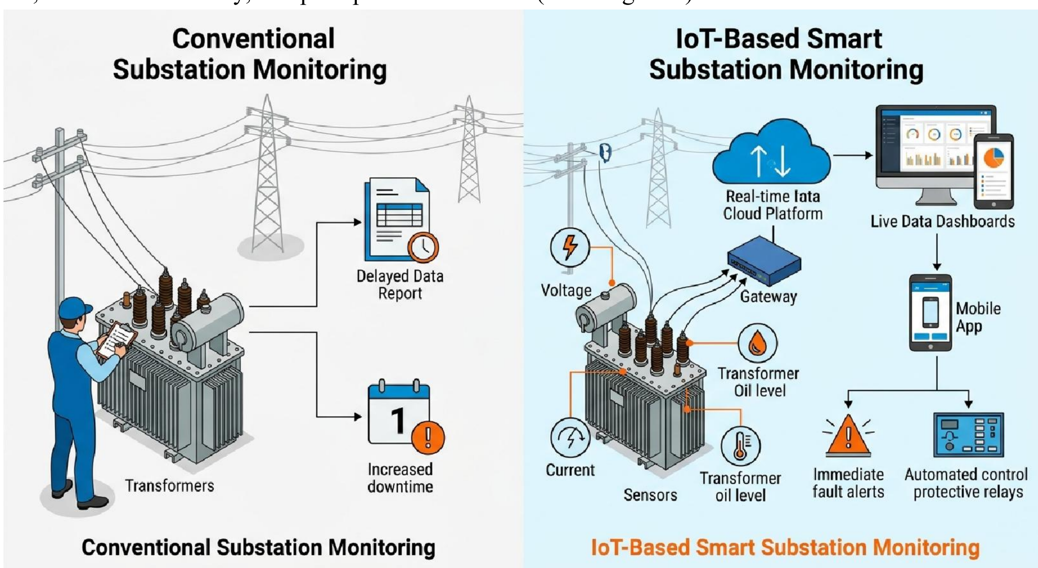

Figure 1 Traditional vs. IoT Monitoring

1.2 Architecture Diagram of the Proposed System

This diagram is crucial for the methodology section of your paper. It provides a structured, multi-layer overview of how your proposed system is built and how data flows from the physical substation to the end-user application.

Layer 1: Perception Layer (Sensors): Shows the instruments installed on transformers and switchgear (voltage, current, temperature sensors).

Layer 2: Network/Control Layer (IoT Gateway): Displays the microcontrollers and gateways collecting data and managing automated protection (relays and circuit breakers).

Layer 3: Application Layer (Cloud & Users): Illustrates the cloud infrastructure, data analytics, and the remote monitoring applications (web and mobile dashboards).

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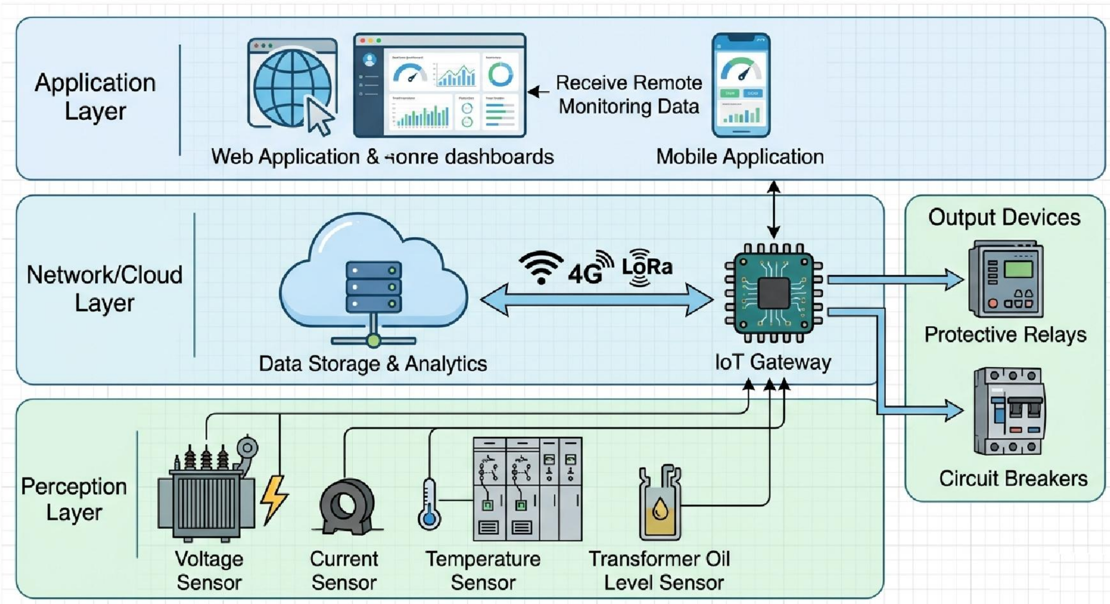

Figure 2 Architecture Diagram of the Proposed System

II. LITERATURE REVIEW

The increasing complexity of electrical power systems and the growing demand for reliable power supply have led to significant research in substation monitoring and automation. Various technologies such as IoT, GSM communication, microcontrollers, and SCADA systems have been explored to improve the efficiency, reliability, and safety of substations.A study by Kate et al. (2018) proposed an IoT-based substation monitoring system that utilizes sensors to measure key electrical parameters such as voltage, current, temperature, and frequency. The collected data is transmitted to a web server for real-time monitoring. The system also incorporates relay protection to disconnect the load during abnormal conditions. The authors demonstrated that IoT technology can significantly enhance the monitoring capabilities and operational efficiency of substations.Dhimar et al. (2017) developed a microcontroller-based substation monitoring and control system using GSM communication. In this system, real-time electrical parameters are transmitted via SMS to operators. Additionally, users can request system data remotely by sending SMS commands. The study highlights the advantage of GSM technology in remote areas where internet connectivity is limited, although it lacks real-time continuous monitoring compared to IoT-based systems.

Similarly, Narejo et al. (2015) proposed a remote monitoring system using a GSM modem integrated with a microcontroller. The system continuously compares real-time electrical parameters with predefined threshold values and triggers protective actions when abnormalities occur. The use of GSM ensures timely fault notification; however, the system is limited in scalability and data visualization capabilities.Sacerdoțianu et al. (2019) focused on condition-based monitoring of substations and emphasized the importance of predictive maintenance strategies. Their research highlights that continuous monitoring of equipment condition can reduce maintenance costs, extend equipment life, and improve system reliability. The study also discusses the integration of monitoring systems with SCADA for enhanced performance and decision-making.Hanafi et al. (2011) presented a simulation-based integrated monitoring system using LabVIEW for high-voltage substations. The system provides a graphical user interface (GUI) to monitor parameters such as voltage, frequency, temperature, and load conditions. The study demonstrates the effectiveness of centralized monitoring systems but also indicates higher implementation costs and complexity.From the reviewed literature, it is evident that significant advancements have been made in substation monitoring technologies. However, limitations such as high implementation cost, lack of real-time data accessibility, and limited automation still exist in many traditional and GSM-based systems. Therefore, there is a need for a cost-effective, scalable, and real-time monitoring solution. The proposed IoT-based system addresses these challenges by providing continuous monitoring, automated fault detection, and remote accessibility, thereby enhancing the overall efficiency and reliability of substation operations.

III. PROPOSED SYSTEM

3.1 System Overview

The proposed system is an Internet of Things (IoT)-based solution designed for real-time monitoring and control of substation equipment. The primary objective of this system is to enhance the reliability, safety, and efficiency of electrical substations by continuously monitoring critical operational parameters and enabling automated fault response.
The system focuses on monitoring key substation parameters, including:

Voltage – to ensure stable power supply and detect overvoltage or undervoltage conditions

Current – to identify overload or short-circuit conditions

Temperature – to monitor the thermal condition of equipment and prevent overheating

Transformer Oil Level – to ensure proper insulation and cooling of transformers

These parameters are measured using appropriate sensors and are interfaced with an **ESP32 microcontroller**, which serves as the central processing unit of the system. The ESP32 is selected due to its built-in Wi-Fi capability, low power consumption, and efficient real-time data processing features.

The collected sensor data is continuously processed and transmitted to a cloud server through the ESP32's wireless communication module. This enables remote monitoring of substation conditions via a web-based or mobile application. Additionally, a local LCD display is used to show real-time parameter values for on-site monitoring.

3.2 Working Principle

The working of the proposed system is based on real-time data acquisition, processing, and automated control. The overall operation can be described in the following steps:

Data Acquisition:

Sensors installed in the substation continuously measure parameters such as voltage, current, temperature, and oil level. These sensors convert physical quantities into electrical signals, which are then fed into the ESP32 microcontroller.

Data Processing and Analysis:

The ESP32 processes the incoming sensor data and compares it with predefined threshold values stored in the system. These threshold values represent safe operating limits for the substation equipment.

Fault Detection:

If any parameter exceeds or falls below the predefined limits, the system identifies it as an abnormal condition or fault. Examples include:

- Overheating of transformer
- Overcurrent or short circuit
- Low transformer oil level

Protection and Control Action:

Upon detection of a fault, the system automatically initiates protective actions:

The **relay is activated**

The **circuit breaker is triggered (trip condition)**

The affected section of the system is isolated to prevent further damage

Alert Generation:

Simultaneously, the system generates alerts and notifications, which are sent to the operator through the connected IoT platform. This ensures immediate awareness and quick response.

Data Visualization:
The real-time and fault data are displayed on:
LCD Display for local monitoring
Mobile/Web Application for remote monitoring
This integrated approach ensures continuous supervision of substation operations, rapid fault detection, and automatic response, thereby minimizing downtime, reducing maintenance costs, and improving overall system reliability.

IV. METHODOLOGY

4.1 Power Supply Design

The proposed system requires a stable and regulated DC power supply for reliable operation of electronic components. A transformer-based power supply circuit is designed to convert AC mains voltage into a regulated **+5V DC output**.
The design parameters are as follows:
Secondary Voltage = 9V
Output Power = 4.5 W

$$A_i = \sqrt{\frac{W_p}{0.87}} = 2.673\,\mathrm{cm}^2$$

4.2 Transformer Design

Based on the design calculations, the number of turns required for the transformer windings are determined as:
Primary Turns = 4302
Secondary Turns = 168
These values ensure the required voltage transformation from the input AC supply to the desired output level.

4.3 Rectifier and Filter Design

A rectifier circuit is used to convert the AC output of the transformer into DC voltage. A full-wave rectifier configuration is employed for improved efficiency.
Output DC Voltage ≈ 5V
Diode Used: **1N4007**
Filter Capacitor: **1000 µF**
The filter capacitor is used to reduce ripple and provide a smooth DC output suitable for microcontroller and sensor operation.

V. HARDWARE IMPLEMENTATION

5.1 ESP32 Microcontroller

The ESP32 microcontroller serves as the central processing unit of the system. It offers the following features:
Built-in Wi-Fi and Bluetooth connectivity
Low power consumption
High processing capability for real-time data handling

5.2 Sensors Used

Various sensors are integrated into the system to monitor substation parameters:
DHT11 Sensor: Used for temperature monitoring
Ultrasonic Sensor: Used to measure transformer oil level
LDR Sensor: Used to detect oil quality based on light intensity

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5.3 Relay Module

The relay module acts as a switching device to control external electrical components. It plays a critical role in system protection by:

Controlling connected loads

Automatically tripping the circuit during fault conditions

5.4 LCD Display

A 16×2 LCD display is used for local monitoring. It provides real-time visualization of system parameters such as temperature, voltage status, and oil level.

VI. RESULTS AND DISCUSSION

The developed IoT-based substation monitoring and control system was successfully implemented and tested under various operating conditions. The system demonstrated reliable performance in continuously monitoring critical substation parameters and executing automated control actions during abnormal conditions.The experimental results confirm that the system is capable of real-time acquisition and processing of electrical and environmental parameters, including voltage, current, temperature, and transformer oil level. The integration of sensors with the ESP32 microcontroller ensures accurate data collection and efficient communication with the cloud platform.One of the key achievements of the system is its ability to automatically detect faults and initiate protective actions. Whenever any parameter exceeds the predefined threshold limits, the system promptly activates the relay mechanism, leading to the tripping of the circuit breaker. This rapid response helps in preventing equipment damage and ensures system safety.Furthermore, the system enables remote monitoring and data visualization through IoT-based web and mobile applications. Operators can access real-time data and system status from any location, which significantly enhances operational convenience and decision-making capabilities.

The implementation of the proposed system offers several advantages in terms of performance and operational efficiency:

Reduced System Downtime: Continuous monitoring and instant fault detection minimize unexpected failures and downtime.

Faster Fault Detection and Response: Automated alerts and control actions ensure quick identification and isolation of faults.

Improved Operational Safety: Reduced human intervention in high-voltage environments enhances safety for personnel.

Lower Maintenance and Operational Costs: Predictive monitoring reduces the need for frequent manual inspections and maintenance activities.

Overall, the results indicate that the proposed IoT-based system significantly improves the reliability, efficiency, and safety of substation operations, making it a suitable solution for modern power system automation.

VII. ADVANTAGES AND LIMITATIONS

Advantages

- Real-time monitoring of substation parameters
- Remote accessibility through mobile and web applications
- Enhanced safety by minimizing human intervention
- Reduction in labor and maintenance costs

Limitations

- High initial implementation cost
- Dependence on stable network connectivity
- Potential cybersecurity risks in IoT-based systems

VIII. CONCLUSION

This study presents a reliable and cost-effective IoT-based monitoring and control system for substation equipment. The proposed system enhances operational efficiency by enabling real-time monitoring, automated fault detection, and remote accessibility. It significantly reduces the need for manual supervision while improving system reliability and safety.

The integration of IoT technology in substations represents a major step toward smart grid development and intelligent power management systems

IX. FUTURE SCOPE

The proposed system can be further enhanced by incorporating advanced technologies such as:

- Integration of Artificial Intelligence (AI) and Machine Learning (ML) for predictive maintenance
- Integration with SCADA systems for centralized monitoring and control
- Implementation of advanced cybersecurity mechanisms
- Expansion toward smart grid and smart energy management applications

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