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IOT-Powered Substation Surveillance System

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ABSTRACT: An IoT-based substation monitoring system provides an intelligent and efficient means for the continuous, real-time observation of critical parameters in power substations, overcoming the shortcomings of conventional monitoring that predominantly depends on manual inspection. This system incorporates IoT sensors to continually monitor voltage, current, temperature, humidity, and gas levels (including SF6), hence evaluating the operational integrity of substations. The gathered data is conveyed across secure networks to a central server or cloud platform for processing and analysis. The system use predictive analytics to detect early indicators of equipment failure or performance irregularities, activating warnings for prompt intervention. This reduces downtime, averts expensive repairs, and prolongs the lifespan of essential substation components by facilitating condition-based maintenance instead of conventional, time-based inspections. Operators can obtain real-time data and alarms via an intuitive online or mobile interface, enabling remote monitoring of substations and facilitating timely, data-informed choices. The IoT-based monitoring system improves operational safety, efficiency, and reliability in energy distribution through remote oversight and rapid response capabilities. This technology-centric strategy not only diminishes maintenance expenses and enhances asset management but also fortifies the power grid's resilience, allowing it to satisfy escalating demands for stability, automation, and efficiency.

KEYWORDS: IoT-based monitoring, substation automation, predictive maintenance, real-time data analysis, power grid resilience.

INTRODUCTION

The increasing demand for continuous, dependable, and efficient power distribution has exerted considerable pressure on contemporary electrical grid systems. Substations, essential elements of power distribution systems, are crucial for efficiently transmitting electricity from power plants to customers[12]. Historically, substations have been overseen and serviced via manual inspections, scheduled testing, and regular maintenance. Although these systems have fulfilled their function, they frequently exhibit sluggishness, reactivity, and susceptibility to human error, resulting in postponed fault detection, unwarranted downtime, and elevated operational expenses. Recent Internet of Things (IoT) technology improvements have created a transformative potential to enhance substation management. IoT-based systems employ sensors, communication networks, and data analytics to monitor substation conditions in real-time. These systems perpetually gather data on essential factors, including voltage, current, temperature, humidity, gas concentrations (e.g., SF6), and vibration. These are vital for evaluating the operational integrity of substation apparatus such as transformers, circuit breakers, and bus bars[13].

The incorporation of IoT facilitates predictive maintenance, enabling operators to detect possible problems before they escalate into expensive breakdowns. Utilizing machine learning and artificial intelligence, IoT systems may examine historical and real-time data, identify patterns, and forecast component deterioration[14]. This enables prompt maintenance interventions, minimizing unanticipated outages and prolonging the lifespan of essential equipment. The IoT-enabled substation monitoring system improves safety and operational efficiency through remote monitoring. Operators can receive warnings and notifications regarding anomalies directly on their mobile devices or laptops, facilitating prompt responses without requiring on-site visits. This skill facilitates expedited decision-making and minimizes human exposure to perilous settings, essential for worker safety. The transition to IoT-based monitoring systems signifies a fundamental transformation in substation management.

These solutions improve the power grid's reliability, efficiency, and resilience by delivering precise, real-time insights into the status of substation assets. Moreover, they establish the groundwork for smart grids, wherein substations serve as crucial nodes within an extensive network of interconnected, intelligent devices that can self-monitor, self-heal, and optimize energy distribution. This change is essential for addressing the changing requirements of contemporary energy systems and securing a sustainable, resilient energy future[15].

LITERATURE SURVEY

The implementation of the Internet of Things (IoT) in the energy industry, especially for the monitoring and management of substations, has garnered considerable attention in recent years. The Internet of Things facilitates real-time surveillance, enhanced asset management, and predictive maintenance, revolutionizing the operation and upkeep of substations. Conventional substation monitoring systems have depended significantly on manual inspections, which are labor-intensive, expensive, and susceptible to human mistake. Research conducted by Wang et al. [1] and Garcia et al. [2] demonstrates that IoT-enabled substation monitoring can diminish human intervention through the automation of data gathering and processing. IoT systems use diverse sensors, including those for temperature, humidity, gas, voltage, and current, within substations, delivering continuous real-time data to evaluate the condition and efficiency of electrical equipment. Kumar et al. [3] shown that the implementation of wireless sensor networks in substations improves the precision and promptness of fault detection, hence reducing the likelihood of equipment failure.

A key benefit of IoT-based systems in substations is their capacity to transition from reactive to predictive maintenance. Through the continuous monitoring of critical metrics, IoT systems can anticipate potential equipment problems prior to their occurrence. Research conducted by Zhang et al. [4] and Singh et al. [5] has illustrated the capability of IoT-based systems to identify early indicators of equipment degradation, including transformer overheating and SF6 gas leakage in circuit breakers. Predictive algorithms examine sensor data to detect patterns linked to equipment breakdown, facilitating proactive maintenance strategies that minimise expensive emergency repairs and unanticipated downtime.

IoT-based substation monitoring systems provide remote oversight, markedly improving operational efficiency and safety. Meena et al. [6] highlighted that real-time data transfer using cloud-based platforms enables operators to make educated decisions remotely. This functionality is especially advantageous in rural areas where substations are challenging to reach. Mobile applications and dashboards furnish operators with immediate information and alerts about anomalous conditions, enabling prompt actions and diminishing the necessity for manual checks.

Moreover, IoT systems enhance energy efficiency and grid optimization through the continuous monitoring of power flow and load distribution, the identification of inefficiencies, and the optimization of substation operations. Zhang et al. [4] emphasised that IoT-enabled substations offer insights into power losses, voltage variations, and energy consumption trends. Resolving these difficulties enhances grid stability, minimizes energy waste, and fits with the objectives of smart grid advancement, rendering power networks more flexible and self-repairing.

Notwithstanding these evident benefits, numerous problems must yet be resolved as IoT-based substation monitoring systems gain widespread adoption. A primary problem is the security and privacy of data sent from sensors to centralised platforms. Given that substations constitute essential infrastructure, stringent cybersecurity protocols are required to avert hacking or data breaches. Sharma et al. [7] underscored the need of secure communication protocols and encryption techniques for safeguarding sensitive data. Moreover, the integration of IoT with legacy substation systems presents technical obstacles, as older equipment may lack compatibility with contemporary IoT technology. Future research tackles these difficulties by creating solutions for seamless integration, improved data security, and scalable IoT-based systems inside extensive, varied substation networks.

The literature indicates that IoT-based substation monitoring systems provide substantial benefits compared to conventional monitoring techniques, such as real-time data collecting, predictive maintenance, and remote operation. These innovations minimise downtime, save expenses, and improve operational efficiency[9]. Despite enduring problems including cybersecurity and legacy system integration, continuous research and technology advancements are anticipated to surmount these obstacles, rendering IoT-based monitoring systems essential for smart and resilient energy grids.

PROPOSED MODAL

The IoT-based substation monitoring system integrates multiple sensors, an ESP32 microcontroller, and cloud communication to continuously monitor key parameters such as current, voltage, humidity, and fault detection. The system operates on a systematic flow involving real-time data acquisition, local data processing, fault detection, and remote monitoring to ensure the substation's operational safety and efficiency[16].

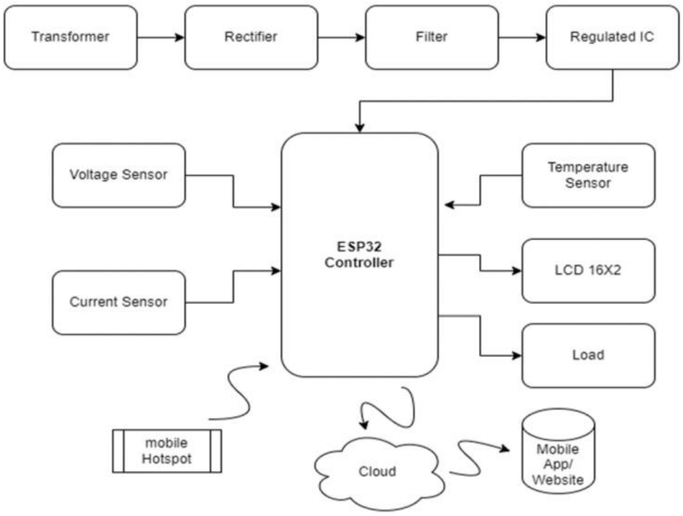


Fig.1.IOT-Powered Substation Surveillance System

Data Collection (Sensing and Measurement):

The IoT-enabled substation monitoring system continuously gathers data from many sensors located throughout the substation. These sensors track essential electrical and environmental metrics to guarantee efficient and secure operations. For example, the ACS712 current sensor quantifies the electrical current traversing components such as transformers, circuit breakers, and bus bars. This data aids in identifying overloads or short-circuit conditions, crucial for preventing equipment damage. Similar to the ZMPT101B, the voltage sensor assesses voltage levels at multiple locations within the substation. Voltage variations, whether excessive or insufficient, may signify defects such transformer failures or grid instability, rendering continual voltage monitoring essential for ensuring system reliability.[8]

Moreover, environmental variables like as humidity, which can affect the integrity of electrical components, are assessed using sensors like the DHT22. This sensor monitors ambient temperature and humidity, which, if excessive, may induce corrosion or compromise the insulation of electrical equipment, resulting in probable failures. The sensors are connected to the ESP32 microcontroller, which serves as the system's central processing unit[17]. The microprocessor converts analogue inputs, including current and voltage data, using its integrated Analog-to-Digital Converter (ADC), and processes digital signals, such as temperature and humidity, over I2C or GPIO interfaces. This configuration guarantees the comprehensive capture, processing, and transmission of sensor data for subsequent analysis and monitoring.

Data Preprocessing and Threshold Analysis:

The IoT-enabled substation monitoring system continuously gathers data from many sensors located throughout the substation. These sensors track essential electrical and environmental metrics to guarantee efficient and secure operations. The ACS712, a contemporary sensor, quantifies the electrical current traversing components such as transformers, circuit breakers, and bus bars. This data aids in identifying overloads or short-circuit conditions, crucial for preventing equipment damage[10]. Similar to the ZMPT101B, the voltage sensor assesses voltage levels at multiple locations within the substation[18]. Voltage variations, whether excessive or insufficient, may signify defects such as transformer failures or grid instability, rendering continual voltage monitoring essential for ensuring system reliability.

Upon data collection by the sensors, the ESP32 microcontroller executes critical preprocessing to guarantee data accuracy. The system initially employs data filtering techniques to eliminate noise from the raw sensor data, utilizing methods such as averaging or moving averages to stabilize the values[19]. Subsequent to filtration, the system juxtaposes the measured values with established safe operational thresholds. The thresholds are established according to the nominal operating conditions for substation apparatus. Should any sensor values surpass certain thresholds, the system detects a malfunction. If the current beyond its safe threshold, it may suggest a short circuit or overload, whilst irregular voltage measurements could indicate overvoltage or under voltage issues. Furthermore, if humidity exceeds permissible levels, it may indicate excessive moisture, perhaps resulting in corrosion or insulation deterioration. The ESP32 analyses these comparisons and records departures from standard parameters as fault conditions.

Fault Detection and Alarm Triggering

Fault detection is an essential component of the IoT-based substation monitoring system, intended to discover defects that may compromise the substation's performance and safety. The system detects prevalent defects like overcurrent, overvoltage, under voltage, and high humidity. When the current surpasses a predetermined threshold, signifying an overload or short circuit, the device activates an alarm and alerts operators. Voltage fluctuations over the permissible range may indicate overvoltage or under voltage, resulting in potential equipment damage[20]. Elevated humidity levels beyond the threshold may signify moisture-related problems such as corrosion or insulation failure. The technology guarantees prompt identification of dangers, activating alerts and enabling operators to implement preventive measures, thus reducing the likelihood of equipment damage.

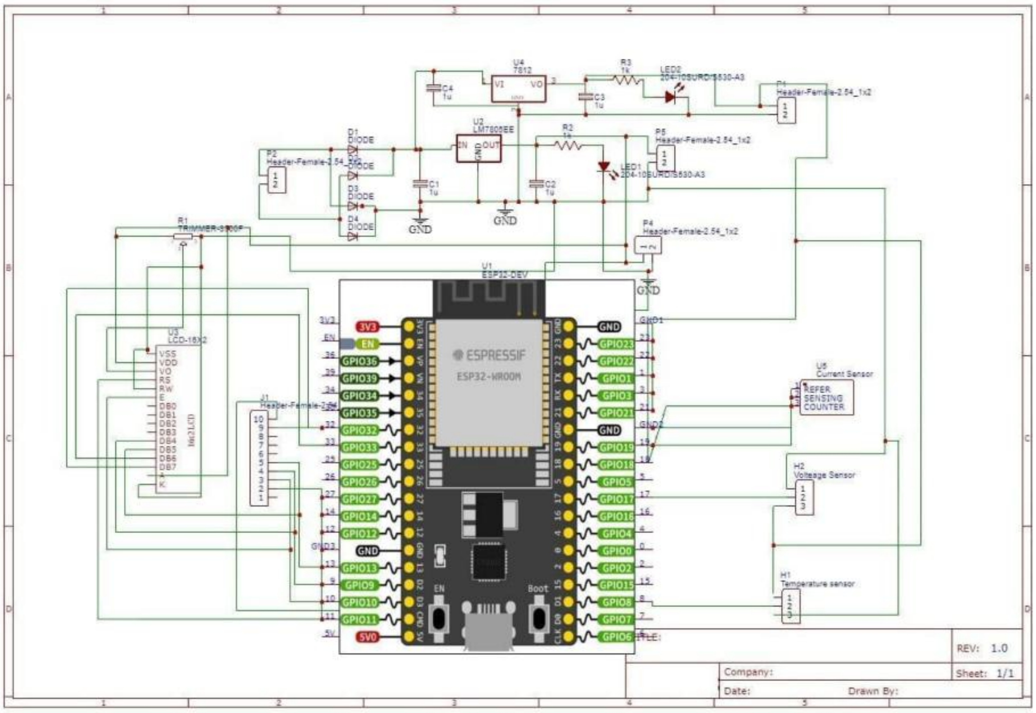


Fig.2.Circuit Diagram of IoT Based Monitoring System

Communication and Data Transmission

The ESP32 microcontroller relays the pertinent information to a cloud-based server or a centralized database upon processing the data and identifying anomalies. Communication occurs over Wi-Fi, facilitating wireless data transmission. This phase entails. Immediate Surveillance Real-time data, encompassing current, voltage, and humidity measurements and defect notifications, is transmitted to a central cloud platform or a remote server. This enables operators to monitor the health of substations from any place continuously[21]. Data recording the system facilitates real-time communication and records past data for subsequent study. This historical data can facilitate pattern detection, trend analysis, and evaluation of substation equipment performance over time[11]. Upon detecting a fault, the system activates an alarm transmitted in real-time to the operators through several channels (email, SMS, or push notifications). These notifications encompass essential details regarding the fault, including its classification, geographical position, and intensity.

Remote Monitoring and Control

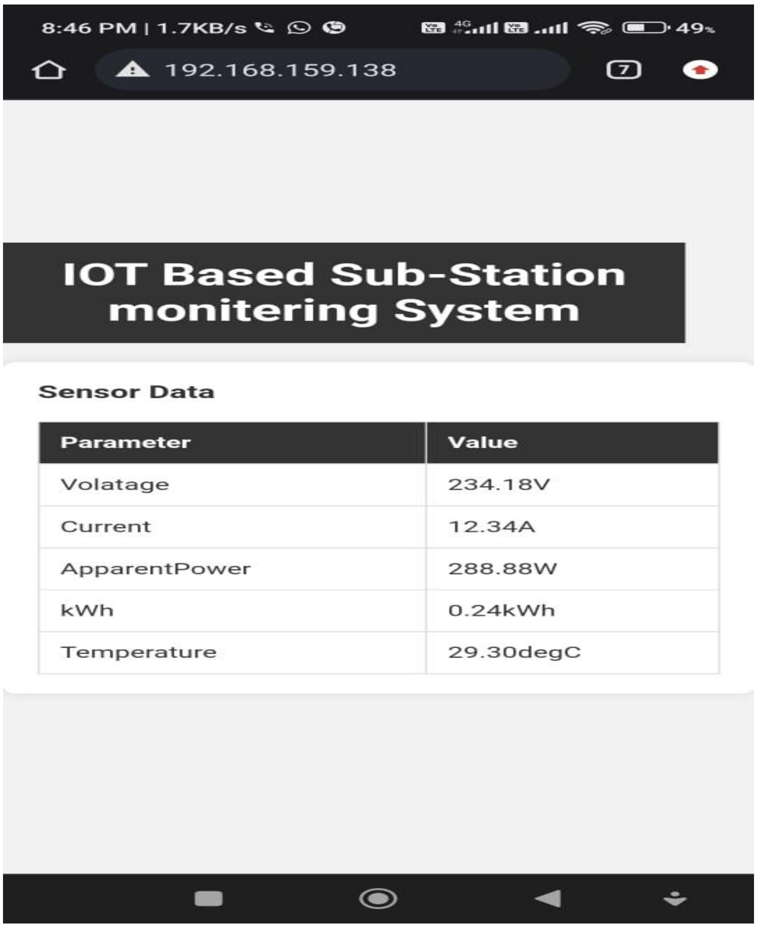
One of the primary advantages of the IoT-based substation monitoring system is its ability to offer remote monitoring and control capabilities[22]. The operators can access the cloud Monitor Parameters. Through the cloud platform, operators can view the real-time status of key parameters such as current, voltage, humidity, and fault alerts. The dashboard visually represents these parameters, often in graphs or charts, making it easy to interpret the data. Analyze Trends The system’s logging and storage capabilities allow operators to access historical data and analyze trends. For example, the system might display trends of increasing current over time, indicating that maintenance may be needed before a failure occurs. Receive Alerts In the event of a fault; the system alerts the operators in real-time[23]. The alerts typically include the type of fault, the equipment involved, and the location of the fault, enabling quick decision-making. Control Equipment Remotely In some configurations, operators may be able to take corrective actions remotely. For example, if a circuit breaker is in danger of tripping, operators can initiate the necessary action, such as remotely disconnecting the equipment or sending a shutdown command.

Predictive Maintenance

Predictive maintenance is made possible by the IoT-based substation monitoring system's analysis of past sensor data that is saved in the cloud. It continuously tracks variables like humidity, voltage, and current[24]. A slow rise in current, for instance, can be a sign that a transformer is nearing the end of its useful life. By comparing trends in sensor data to established failure models, the system may also anticipate possible problems. For example, increasing humidity can indicate corrosion is about to occur. By using this predictive capacity, operators can plan repairs ahead of time, reducing downtime and enhancing substation dependability.

Scalability and Integration

The solution is designed to be scalable and easy to integrate with current infrastructure. Additional sensors can be added to monitor new parameters, and the system can be scaled to monitor several substations[25]. It can also be connected with existing SCADA systems to improve overall power grid management. Scalability ensures that the system may grow to meet the needs of the power grid, ensuring future adaptation.



IOT Based Sub-Station monitering System

Sensor Data

Parameter	Value
Volatage	234.18V
Current	12.34A
ApparentPower	288.88W
kWh	0.24kWh
Temperature	29.30degC

RESULT AND ANALYSIS

a) Temperature.

The DHT22 sensor offers real-time temperature and humidity data for the substation environment.

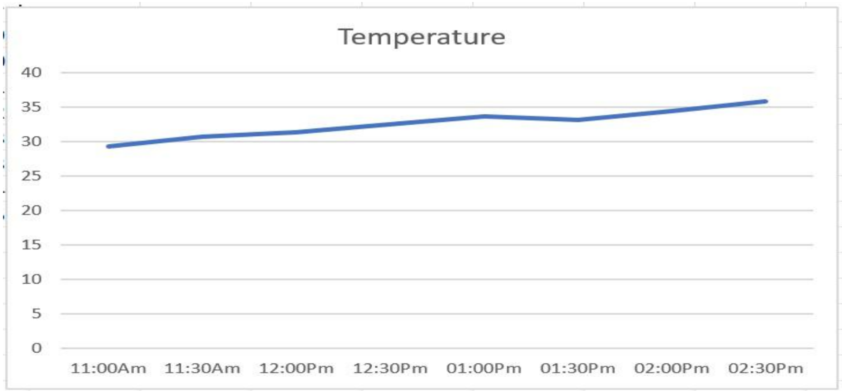


Fig 3.Temperature Monitoring Line Graph

Expected Output: The sensor produces a digital output that shows the temperature (in °C) and humidity (in %). This information is crucial because high humidity levels can cause equipment corrosion and malfunction, and extreme temperatures can impair equipment operation[26].

Example Result: If the temperature exceeds a safe working limit (for example, 40°C) or the humidity climbs beyond 85%, the system will sound an alarm, encouraging the maintenance crew to examine and correct the environmental conditions.

b) Current Measurement

The ACS712 current sensor is used to measure the current flowing through the substation equipment. The results from this sensor are monitored continuously by the ESP32.

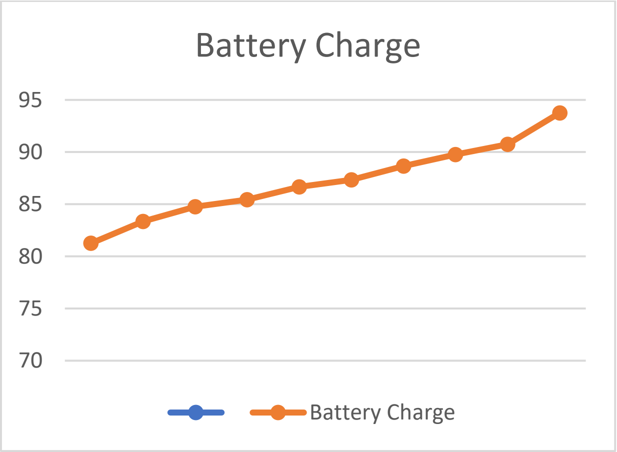


Fig 4.Current Monitroing Line Graph

Expected Output: The current sensor produces an analog voltage output that is linearly proportional to the measured current. For example, the output voltage increases as the current flowing through the conductor increases[27]. The ESP32 reads this analog signal and converts it into a digital value.

Example Result: If the current exceeds a preset threshold, say 10A, the system will detect this and trigger a fault alarm. The threshold values can be adjusted based on the type of equipment being monitored. For instance, an overload condition may trigger a relay to disconnect the affected circuit.

c) Voltage Measurement (ZMPT101B Sensor)

The ZMPT101B voltage sensor measures the AC voltage in the substation.

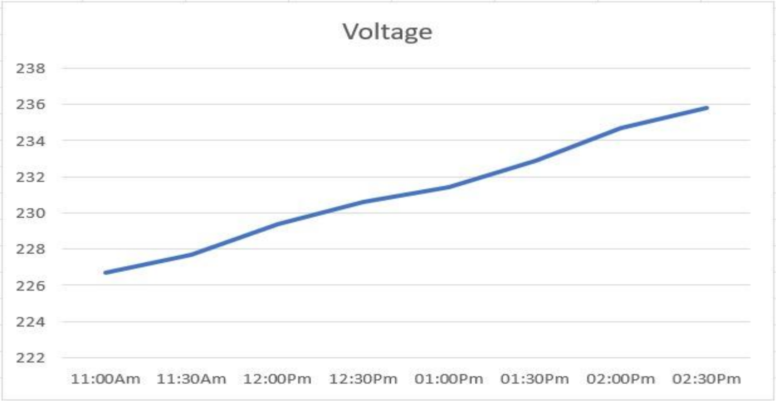
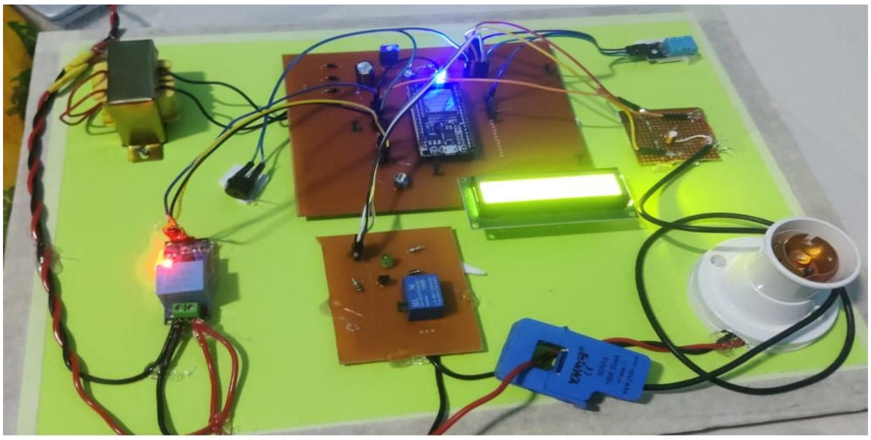


Fig.5Voltage Measurement Line Graph

Expected Output: The voltage sensor outputs an analog signal that corresponds to the AC voltage being measured. The ESP32 converts this analog value into a digital format using its ADC (Analog-to-Digital Converter).

Example Result: If the voltage exceeds a predefined value (e.g., 240V for a standard 230V line), the system will detect this and trigger a fault notification to alert the operator. Similarly, under voltage conditions (e.g., dropping below 200V) can also be monitored and generate an alert monitored and generate an alert.



CONCLUSION

In conclusion, the incorporation of Internet of Things technology into the management of substations represents a significant step forward in the field of power distribution technologies[29]. In order to achieve the requirements for dependability and efficiency that are present in modern electrical grids, the traditional techniques of monitoring and maintenance, which depended mainly on human inspections and reactive interventions, need to be updated. Substations' operational integrity can be considerably improved by utilising technologies that are based on the Internet of Things (IoT), which provide real-time monitoring, predictive maintenance, and data-driven insights[28]. These systems help in the prevention of costly breakdowns, the reduction of downtime, and the extension of the life of important equipment by utilising machine learning and artificial intelligence to forecast component failure and permit prompt interventions[30]. In addition, remote monitoring that is possible by the Internet of Things brings about improvements in safety and operational efficiency, and it provides the framework for the creation of smart grids. In order to fulfil the ever-changing requirements of energy systems and to guarantee a sustainable and resilient future for global power distribution, it is vital to make this shift to systems that are more intelligent, networked, and capable of optimising themselves at the same time.

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