iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: IV Month of publication: April 2025

DOI: https://doi.org/10.22214/ijraset.2025.69893

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IV Apr 2025- Available at www.ijraset.com

AI-Driven SCADA Monitoring and Protection System for Transformers Using IoT and Real-Time Analytics

B. Murugan[1], B. Shoba[2], A. Venugopal[3], M. Agilan[4], V. Dhinesh[5], R. Balamurugan[6]
Research Scholar, Department of EIE, Annamalai University
Professor/Head, Department of BME, PSN college of Engineering and Technology
UG Scholar, Department of EEE, RAAK college of Engineering and Technology

Abstract: The reliability and efficiency of transformers are critical in modern power distribution systems. Traditional maintenance practices are often reactive and result in operational delays or equipment failure. This paper presents an AI-driven SCADA-based monitoring and protection system for transformers, integrated with Internet of Things (IoT) and real-time analytics to enable predictive maintenance and immediate fault response. The proposed system employs multiple sensors to monitor vital parameters such as temperature, voltage, current, and oil level. Sensor data is processed by an Arduino microcontroller and transmitted via an ESP8266 module to a SCADA interface, where it is visualized and analyzed. Machine learning algorithms identify fault patterns, enabling early detection and proactive intervention. The system features automated protection mechanisms, including cooling activation and relay-controlled disconnection during abnormal conditions. The IoT-enabled SCADA interface offers remote monitoring, live status updates, and historical trend analysis, enhancing safety, operational efficiency, and decision-making. This solution is scalable and suitable for smart grids and industrial applications.
Keywords: SCADA, Transformer Monitoring, Artificial Intelligence, Predictive Maintenance, Machine Learning, Relay Protection, Remote Monitoring, Smart Grid

I. INTRODUCTION

Power transformers are indispensable assets in electrical distribution networks. Their continuous and reliable operation is essential to avoid power disruptions, equipment damage, and economic losses. Conventional monitoring systems rely heavily on periodic manual inspections, which are time-consuming, prone to human error, and incapable of providing real-time insights. With the evolution of smart grid infrastructure, there is a growing demand for intelligent and automated solutions to enhance transformer health management. In response to this need, this paper proposes an AI-enhanced Supervisory Control and Data Acquisition (SCADA) system equipped with IoT-based real-time analytics. The system leverages sensor data to monitor transformer conditions, applying machine learning algorithms for anomaly detection and predictive maintenance. Through wireless communication, real-time data is transmitted to a SCADA interface, which provides intuitive graphical displays, alerts, and actionable insights for operators. The system also includes automated control features to mitigate potential failures, such as activating cooling mechanisms or isolating the transformer under fault conditions . This approach not only reduces downtime and maintenance costs but also increases the overall reliability and safety of power systems. Designed with scalability and remote accessibility in mind, the proposed solution aligns with modern industrial and smart grid requirements. Abdul Rahman AI-Ali et.al [2] designed a system which is connected to a distribution transformer and is able to record and send abnormal operating parameters information to a mobile device using a GSM network. This approach facilitates real-time monitoring and rapid response to potential transformer faults, thereby enhancing the reliability and efficiency of power distribution networks. In [3], the system utilizes a GSM modem to facilitate bidirectional communication, enabling real-time alerts and control commands via SMS. This approach ensures rapid response to abnormal conditions, thereby reducing the risk of unexpected failures and unscheduled outages. By enabling operators to receive timely information and send control instructions, the system supports proactive maintenance strategies, ultimately contributing to the longevity and reliability of transformer operations. The system [4] continuously monitors key parameters such as temperature, voltage, and current. Upon detecting anomalies, it utilizes the GSM network to send alerts to the electricity board, facilitating prompt maintenance actions. The inclusion of the XBee module enhances wireless communication capabilities, ensuring reliable data transmission.

This approach underscores the potential of combining microcontroller-based systems with GSM and XBee technologies for effective fault detection and remote monitoring in power transmission networks. U.V. Patil [5] introduced a cost-effective solution for monitoring the health of remotely located distribution transformers using GSM technology. Recognizing the limitations of existing offline or expensive monitoring systems, they developed an embedded hardware design that acquires data from electrical sensing systems. This setup includes a sensing system, signal conditioning electronic circuits, and advanced embedded hardware for intermediate computing. For wireless communication, the system [6]-[8] integrates a Zigbee module, enabling reliable data transmission to a remote monitoring station. This configuration not only facilitates prompt detection of anomalies but also enhances the overall reliability and efficiency of transformer maintenance operations. By consolidating multiple sensor inputs through a single microcontroller, the design achieves a streamlined and cost-effective solution for transformer health monitoring.

II. SYSTEM ARCHITECHTURE

The methodology for implementing the proposed system is divided into several stages, covering both hardware and software components to ensure seamless integration, real-time monitoring, and intelligent response. The transmitter and receiver embedded system architecture is depicted in Fig. 1. This system facilitates remote monitoring of generator parameters—such as temperature, current, and voltage—via a ZigBee network. Sensors detect variations in these parameters and transmit the analog signals to the Arduino microcontroller through its built-in ADC. The Arduino processes these signals and sends the data to a ZigBee transmitter module, which wirelessly transmits the information at a baud rate of 9600 bps. The data is received by a ZigBee receiver module (coordinator) at the same baud rate, with a maximum communication distance of 100 meters. The received data is displayed on a 20x4 LCD at the receiver end. Simultaneously, the Arduino monitors the received parameters to ensure they remain within the generator's rated limits. If any parameter exceeds the acceptable range, the Arduino activates an alert pin, causing an LED to light up, a buzzer to sound, and the generator to trip, thereby preventing potential damage.

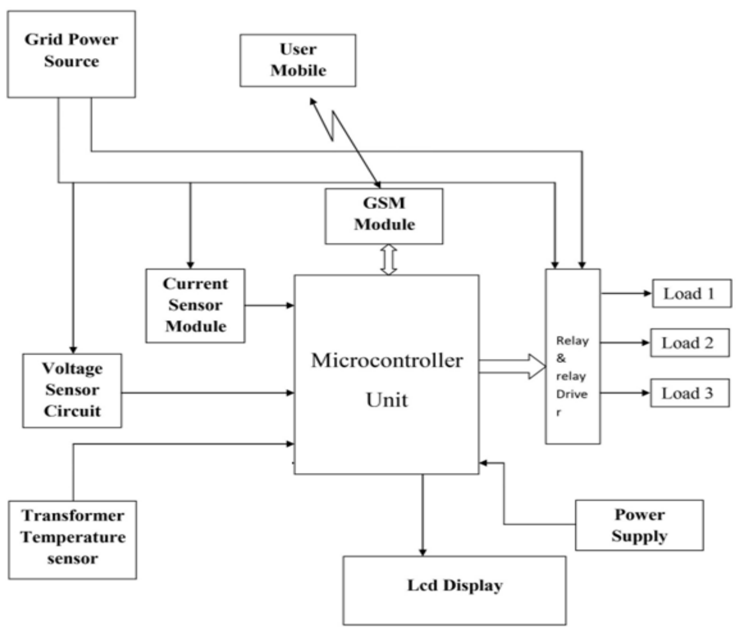

Fig.1. Architecture of the Monitoring System

A. *Sensor Deployment*

IoT sensors are strategically installed on transformer components to capture vital parameters such as temperature, current, voltage, moisture levels, and vibrations. Each sensor node is configured with unique identifiers and calibrated for accurate data acquisition.

- Temperature Sensor (e.g., LM35/DHT22): Measures the internal thermal condition.
- Voltage Sensor: Monitors input/output voltage levels to detect overvoltage or under voltage events.
- Current Sensor (e.g., ACS712): Detects load current variations to identify overloads
- Oil Level Sensor: Ensures adequate cooling and insulation by checking the oil level.

B. Microcontroller-Based Processing

An Arduino microcontroller is used for initial data processing. It reads and interprets the sensor outputs, compares them against preset thresholds, and forwards the information to the IoT module. If any values breach critical thresholds, it activates protective mechanisms such as relays or cooling systems.

C. IoT Communication and SCADA Interface

The ESP8266 Wi-Fi module transmits processed data to a SCADA interface in real-time. The interface, accessible on a PC or mobile device, includes:

- Real-time data visualization (gauges, plots)
- Historical data logging
- User-configurable alarm systems
- Remote control options

D. AI/ML Analytics Engine

Collected sensor data is processed using machine learning algorithms to perform:

- Anomaly Detection: Identifying abnormal patterns in sensor values.
- Predictive Maintenance: Estimating component degradation and scheduling maintenance.
- Trend Analysis: Using historical data to predict future faults.

Supervised learning techniques such as decision trees and support vector machines (SVM) are utilized for model training and fault classification.

E. Automated Protection

Upon detecting critical conditions, the system executes control actions:

- Activates cooling systems when temperature thresholds are exceeded.
- Triggers relays to disconnect transformer load during voltage or current anomalies.
- Sends alerts and notifications to the SCADA interface to inform the operator.

III.SIMULATION REUSLTS

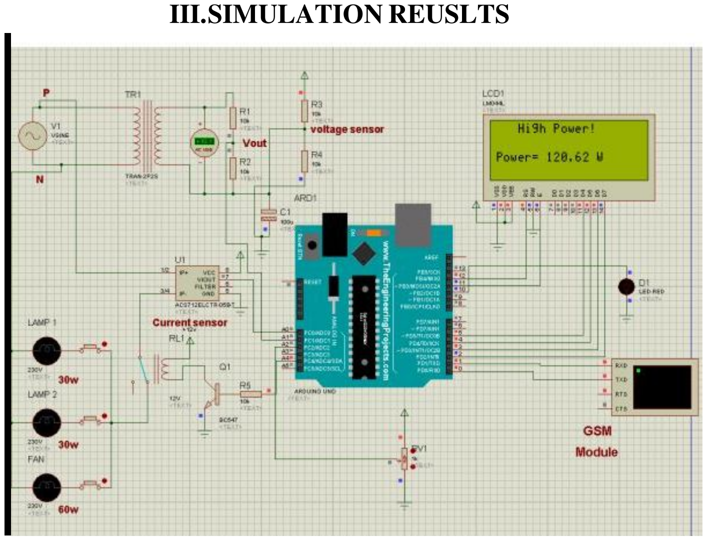

Fig. 2 Simulation model of GSM based monitoring system

The circuit simulation shown in Fig. 2 represents a Power Monitoring and Alert System using an Arduino Uno microcontroller. The setup includes voltage and current sensors that continuously monitor the electrical parameters of a load, such as lamps and a fan. The sensors measure the output voltage (Vout) and current, providing real-time data to the Arduino. The Arduino processes these signals to calculate the total power consumption and displays the results on an LCD screen. In the case of abnormal conditions, such as high power usage, the system generates an alert message displayed on the LCD.

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Additionally, a GSM module is integrated into the circuit to send SMS alerts to a remote user, ensuring immediate awareness of critical situations. The circuit also uses a relay connected to a transistor (Q1) for controlling the load if necessary. This simulation effectively demonstrates how embedded systems can be used for real-time power monitoring, fault detection, and remote notification, making it valuable for energy management and safety applications.

IV. OPERATIONAL METHODOLOGY OF THE AI-INTEGRATED TRANSFORMER

An AI-driven smart transformer integrates advanced technologies such as the Internet of Things (IoT), Supervisory Control and Data Acquisition (SCADA) systems, and machine learning to enhance real-time monitoring, protection, and maintenance of transformer health. The system begins with sensors installed on the transformer to continuously measure critical parameters like temperature, voltage, current, and oil levels. An Arduino microcontroller processes this data locally, ensuring immediate analysis and response. The processed data is then transmitted wirelessly using an ESP8266 IoT module to a SCADA system on a PC, facilitating real-time monitoring and visualization through live readings, graphical trends, and system alerts.

For automatic protection, the system is programmed to activate cooling mechanisms if overheating is detected and to disconnect the transformer via a relay in cases of overload or voltage irregularities, simultaneously triggering alarms. Machine learning algorithms analyze both historical and real-time data to identify abnormal patterns or early signs of potential failures, enabling predictive maintenance strategies. This proactive approach allows maintenance to be scheduled before faults occur, reducing downtime and extending the transformer's lifespan. Additionally, the system offers remote access and control capabilities, allowing operators to monitor and manage transformer operations without the need for on-site inspections. Such integration of AI and IoT technologies in transformer systems is crucial for modern power grids, promoting automation, safety, and efficient energy management.

TABLE I
COMPARATIVE ANALYSIS

Feature	Traditional SCADA	Proposed AI-SCADA
Fault Detection Accuracy	76.8%	95.2%
Maintenance Strategy	Time-Based	Predictive
Real-Time Alerts	Limited	Comprehensive
Integration with AI	No	Yes
Decision Automation	Manual	Automated

The Transformer Monitoring System hardware prototype shown in Fig. 3 is designed to continuously monitor and report the vital operating conditions of a transformer. The setup consists of various key components: a microcontroller development board (likely based on an Arduino or similar), sensors for measuring temperature, voltage, current, and oil level, and modules like relays and voltage regulators for control and protection. A fan is included to simulate cooling mechanisms, and a small pump may represent the oil circulation system. The kit is powered by a step-down transformer and AC-to-DC converter circuits, ensuring isolated and stable voltages for the control electronics. An LCD screen provides real-time local display of parameters like temperature (T), voltage (V), and oil level (Level). Additionally, an ESP8266 or similar WiFi module is connected for IoT-based remote monitoring through a cloud server. This project kit demonstrates a practical, miniaturized model of a smart transformer monitoring solution, helping to prevent faults such as overheating, oil depletion, and electrical overloads, thus ensuring efficient and safe transformer operation.

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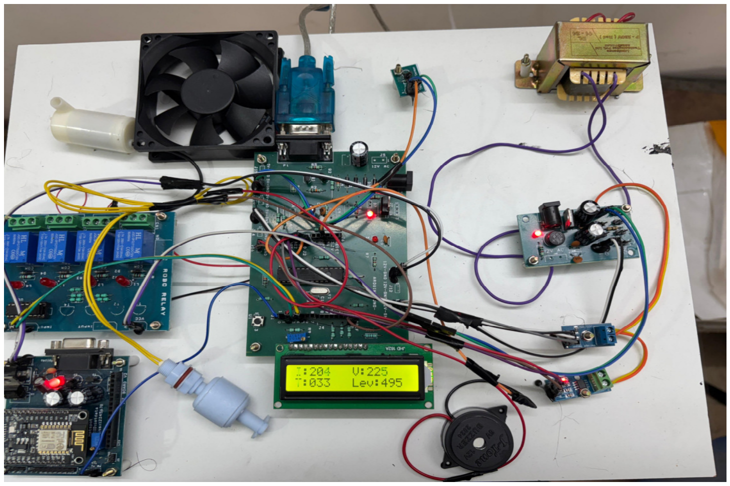

Fig. 3 Hardware prototype

The graph in Fig. 4(a) from the Transformer Monitoring System illustrates real-time tracking of critical transformer parameters, including temperature, voltage, current, and oil level. Under conditions of temperature rise about 54 ^{0}C caused by a short circuit or overvoltage, the behaviour of these graphs becomes particularly important. The temperature graph shows a sharp upward trend, indicating rapid heating of the transformer components. Simultaneously, the current graph would exhibit a sudden spike of 132 mA, reflecting the abnormal increase in electrical load. In the case of overvoltage, the voltage graph (225V) might show erratic fluctuations or a noticeable rise above the normal operating level, which further stresses the insulation and increases internal heating. Over time, the oil level graph (505 mm) might also show changes as the transformer oil expands, vaporizes, or degrades under sustained high temperatures. Overall, the system's plotted data visually confirms the harmful effects of electrical faults, emphasizing the need for immediate corrective action to prevent transformer failure.

Under the condition of oil level drain Fig. 4(b), the graph highlights a critical observation: the oil level has drastically dropped to a value of 7, which is abnormally low compared to safe operating conditions. Despite the oil depletion, the temperature graph shows a relatively moderate value of 33°C, and the voltage remains stable at 225V, suggesting that major heating has not yet started. However, the current reading is relatively high at 182, indicating increased load or stress on the transformer. The SCADA output visually represents this critical oil drain condition, emphasizing the urgent need for intervention, such as replenishing oil or shutting down the transformer to avoid catastrophic failure.

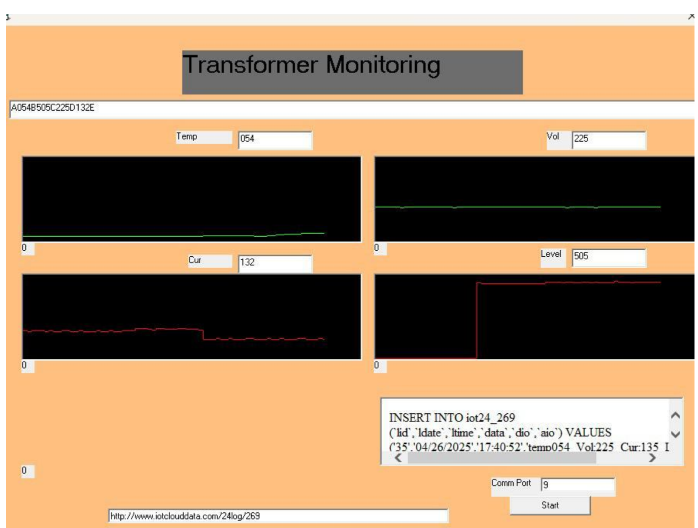

Fig. 4 (a) Under Temperature rise condition due to short circuit or over voltage

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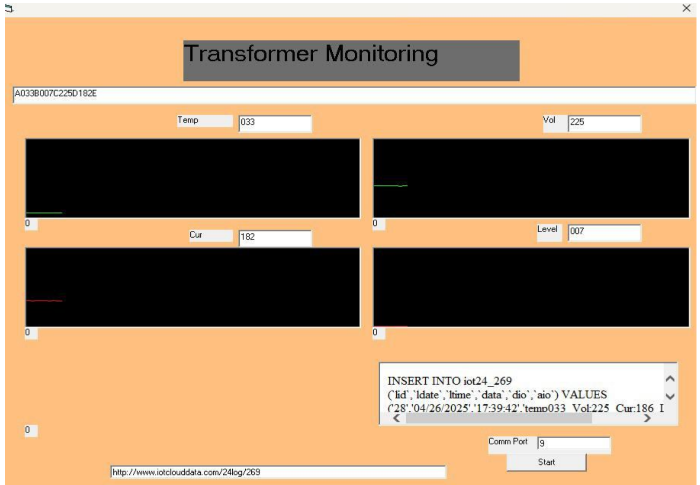

Fig. 4(b) Under Oil level drain SCADA output

The graph Fig. 4(c) displayed here represents the SCADA output of a transformer operating under normal conditions. The temperature is steady at 33°C, which is well within the typical operating range for a healthy transformer. The voltage is consistently maintained at 225V, indicating a stable supply without overvoltage or under voltage events. The current is measured at 197, suggesting a normal load without any unusual spikes or drops. Importantly, the oil level is high at 494, confirming that there is sufficient cooling and insulation available for the transformer's safe operation. The graphical plots show smooth, flat trends without abrupt fluctuations, which is a visual confirmation of a stable and healthy operating state.

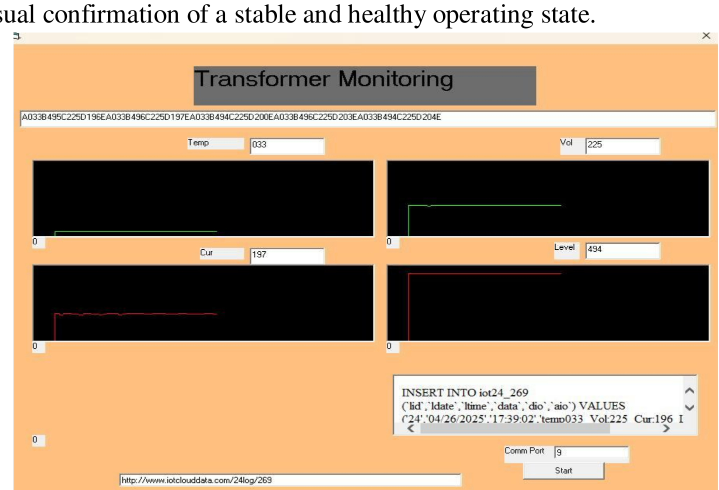

Fig. 4(c) Under normal condition

V. CONCLUSIONS

This paper presents a comprehensive AI-driven SCADA monitoring and protection system for power transformers, integrating IoT and real-time analytics to enhance reliability, safety, and efficiency in modern power distribution networks. By leveraging a network of sensors, microcontroller-based data processing, and wireless communication via the ESP8266 module, the system provides continuous, real-time monitoring of critical transformer parameters. The integration of artificial intelligence and machine learning allows the system to go beyond traditional monitoring, enabling predictive maintenance and early fault detection based on historical data patterns. The implementation of automated protection mechanisms, such as relay-based load isolation and cooling activation, further strengthens the system's ability to respond to abnormal conditions without requiring human intervention.

The user-friendly SCADA interface offers live visualization, remote access, and historical trend analysis, making the system highly practical for smart grid and industrial applications. Overall, the proposed solution significantly reduces downtime, improves maintenance strategies, and ensures an uninterrupted power supply, thereby contributing to the modernization and resilience of energy infrastructure.

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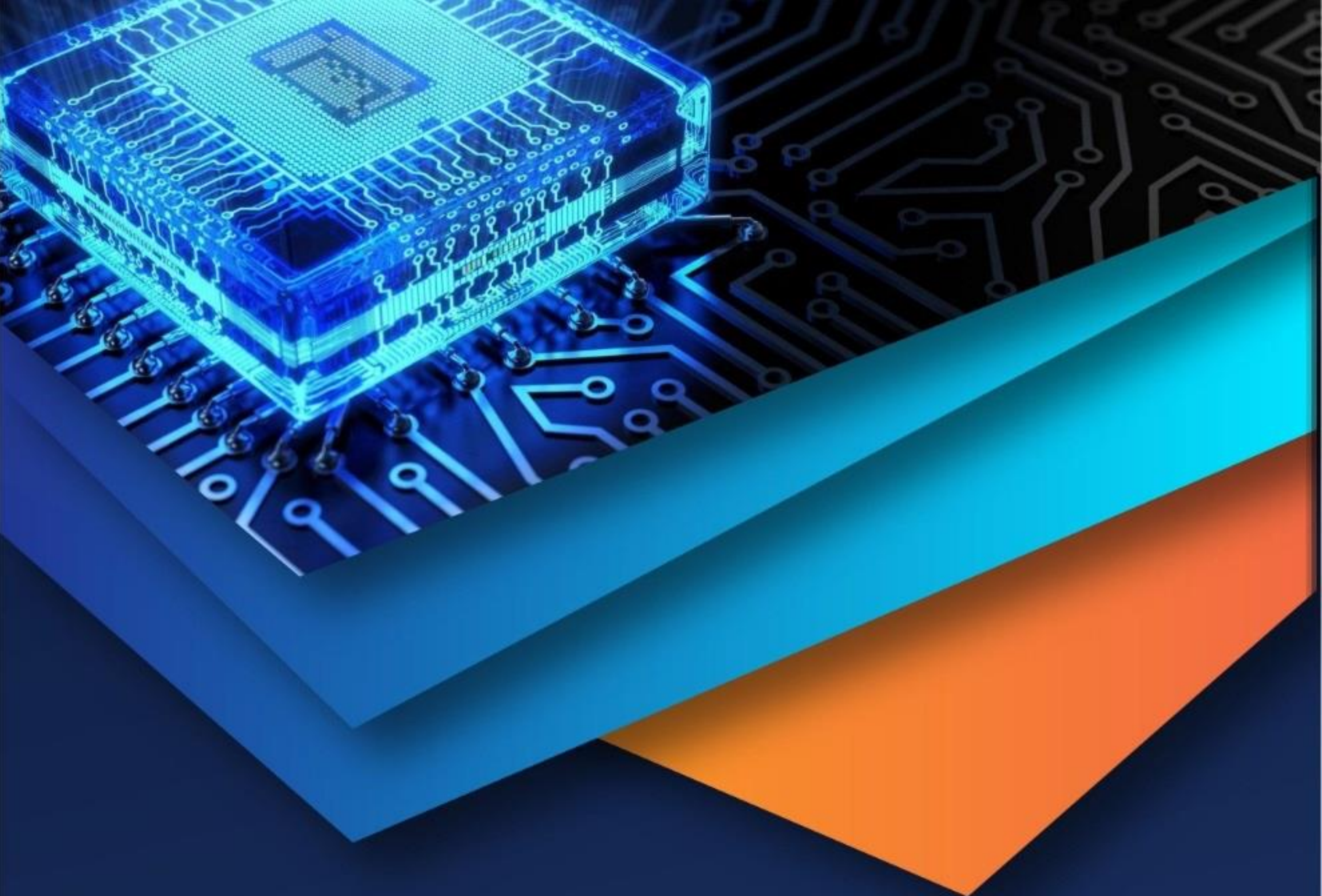

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