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Overhead Line Faults Detector with Auto Trip Protection

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Abstract: Overhead electrical distribution lines constitute a major portion of power delivery infrastructure in developing as well as developed regions due to their economic feasibility and ease of installation. Despite their advantages, these systems are continuously exposed to environmental and mechanical stresses, making them highly susceptible to electrical faults. Fault conditions such as open conductor faults, line-to-line short circuits, and line-to-ground faults can result in serious hazards including electric shock incidents, fire accidents, equipment damage, and prolonged power outages. Rapid detection and isolation of such faults are therefore essential for ensuring safety and maintaining system reliability. This paper presents the design, simulation, and hardware implementation of a three-phase overhead line fault detection and automatic trip protection system using embedded controllers. The proposed system integrates an ESP32 microcontroller for generating balanced three-phase sinusoidal pulse width modulation signals and an Arduino Mega microcontroller for continuous monitoring of voltage and current parameters. A relay-based isolation mechanism disconnects the faulty phase upon detection of abnormal electrical conditions. Additionally, a GSM communication module is incorporated to transmit real-time fault alerts to authorized personnel. The system was validated through simulation and experimental testing, demonstrating reliable fault detection performance and rapid protective action. The proposed prototype provides a scalable and cost-effective solution for enhancing safety in overhead distribution networks.
Keywords: Three-phase fault detection, ESP32, Arduino Mega, SPWM generation, GSM alert system, Overhead line protection, Automatic trip system.

I. INTRODUCTION

Electrical power distribution networks are the final stage in the power delivery chain, transferring electrical energy from substations to residential, commercial, and industrial consumers. In many regions, overhead lines are extensively used due to their comparatively low installation cost and simplified maintenance requirements. However, the exposed nature of overhead conductors makes them vulnerable to climatic disturbances such as storms, heavy rainfall, lightning, and strong winds. Mechanical damage caused by falling trees, vehicular accidents, or aging conductors further increases the probability of faults.

Faults in overhead distribution lines may be categorized into open-circuit faults, line-to-line faults, line-to-ground faults, and three-phase faults. Open-circuit faults generally occur due to conductor breakage or loose connections, resulting in interrupted current flow. Line-to-line faults arise when two conductors come into contact due to insulation failure or external interference. Line-to-ground faults occur when a conductor accidentally touches the earth or grounded objects. Each of these fault conditions alters the electrical parameters of the system and can cause hazardous situations.

Traditional protection systems installed at substations, such as overcurrent relays and circuit breakers, primarily protect large feeder sections and may not detect localized distribution-level faults promptly. Delays in fault identification increase downtime and pose significant safety risks. Therefore, there is a need for intelligent, decentralized monitoring systems capable of real-time fault detection and immediate isolation at the distribution level.

The objective of this project is to develop a smart embedded-based protection system that continuously monitors three-phase voltage and current values, detects abnormal conditions using predefined thresholds, isolates faulty phases using relay mechanisms, and communicates fault information remotely through GSM technology. The system is designed as a laboratory-scale prototype demonstrating the feasibility of implementing smart protection techniques in real-world overhead distribution systems.

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II. PROBLEM STATEMENT

Overhead distribution lines frequently experience fault conditions that may remain undetected until significant damage occurs. In rural areas, broken conductors may fall on roads or agricultural fields while remaining energized, creating severe risks to human life and animals.

Conventional protection mechanisms may fail to identify such faults immediately if fault currents are below relay pickup thresholds. Moreover, manual inspection of long distribution lines consumes time and resources.

Another major challenge is the lack of real-time communication between distribution points and maintenance personnel. In many cases, field workers are informed about faults only after consumer complaints are registered. This delay in response increases outage duration and negatively impacts reliability indices.

Hence, there exists a need for a compact, intelligent system capable of detecting various fault conditions at the distribution level, isolating faulty phases automatically, and notifying authorized personnel instantly.

III. SYSTEM ARCHITECTURE

Fig1 shows the circuit diagram of the prototype. The proposed system is divided into two primary subsystems: the three-phase AC generation unit and the monitoring and protection unit. The three-phase AC generation unit is implemented using an ESP32 microcontroller programmed to generate six sinusoidal pulse width modulation signals with precise 120-degree phase displacement. SPWM is chosen because it provides better harmonic performance and closely approximates sinusoidal waveforms when filtered properly.

The generated SPWM signals are fed into L298N dual H-bridge driver modules. These drivers amplify the low-voltage control signals and produce alternating positive and negative half cycles for each phase. To obtain smooth sinusoidal waveforms, LC low-pass filters are employed to remove high-frequency switching components. The filtered output provides approximately 12 V AC per phase, suitable for laboratory-scale simulation of three-phase distribution lines.

The monitoring and protection subsystem is centered around an Arduino Mega microcontroller. Voltage sensors and current sensors are connected to each phase to continuously measure electrical parameters. The sensed analog signals are converted to digital values using the built-in analog-to-digital converter of the microcontroller. A 20×4 LCD display is used to provide real-time visualization of voltage and current readings for all three phases.

When abnormal operating conditions are detected, the Arduino triggers a relay module to disconnect the faulty phase. Simultaneously, a GSM module sends SMS notifications to predefined mobile numbers, enabling remote awareness of fault conditions.

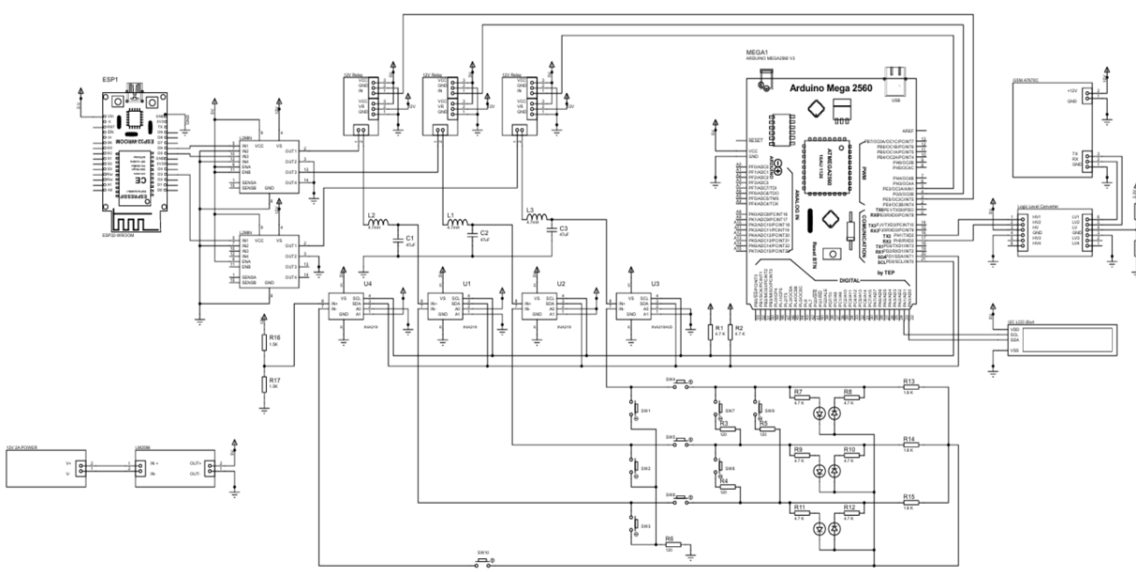

Fig. 1 Circuit diagram

IV. METHODOLOGY

The methodology begins with the generation of balanced three-phase SPWM signals using the ESP32 microcontroller. The duty cycle of the PWM signals is modulated according to sinusoidal reference signals, ensuring a 120-degree phase difference between phases. These PWM signals are amplified through H-bridge drivers and filtered to produce sinusoidal AC outputs.

The Arduino Mega continuously samples voltage and current signals from sensors connected to each phase. The sampling is performed at regular intervals to ensure accurate monitoring of electrical conditions. The effective RMS values of voltage and current are calculated using standard mathematical relations.

Fault detection logic is implemented using threshold-based comparison. An open-circuit fault is identified when the current in a particular phase approaches zero while voltage remains present. This condition indicates a possible conductor breakage. A short-circuit or line-to-ground fault is identified when the current exceeds a predefined maximum threshold. Line-to-line faults are detected by observing abnormal current increases in two phases simultaneously. Fig2 shows the block diagram. Upon detecting a fault, the microcontroller sends a digital signal to the relay driver circuit, causing the relay to open and disconnect the affected phase. At the same time, the GSM module is activated to transmit an SMS containing fault details. This dual action ensures both immediate isolation and remote notification.

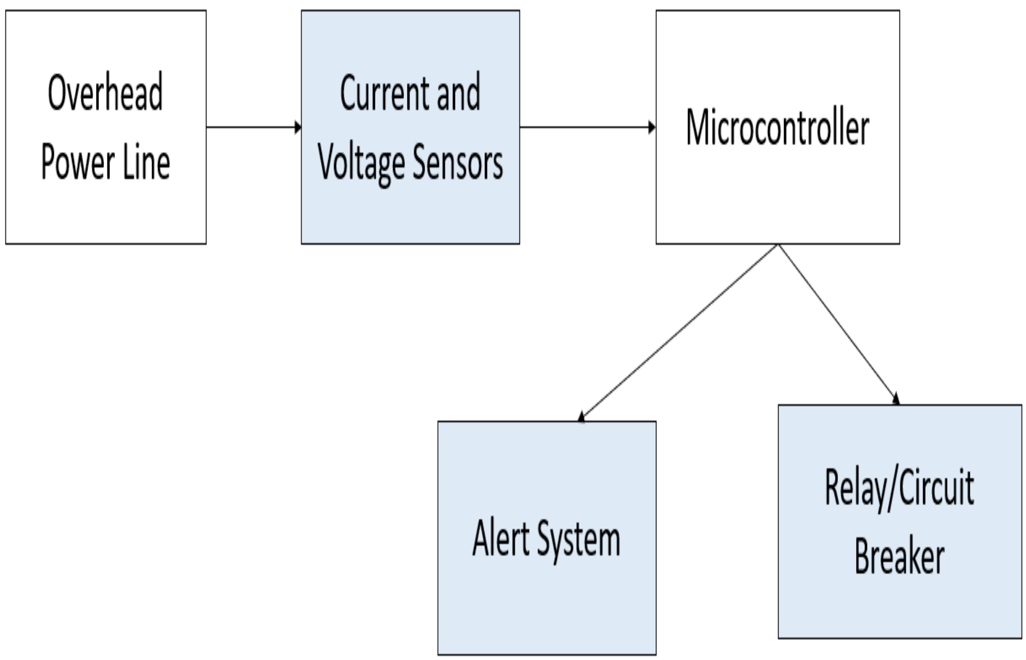

Fig2: Block diagram

V. WORKING PRINCIPLE

During normal operation, the ESP32 generates balanced three-phase SPWM signals, and the monitoring unit continuously measures voltage and current values. The microcontroller compares the measured values with predefined threshold limits stored in the program memory.

When a fault occurs, electrical parameters deviate from their normal operating range. For example, in an open-circuit condition, the current in the affected phase drops significantly while voltage remains present. In contrast, during a short-circuit or line-to-ground fault, the current increases rapidly beyond the safe operating limit. The microcontroller identifies these deviations and classifies the type of fault based on the pattern of parameter changes.

Upon detection of abnormal conditions, the microcontroller activates the relay corresponding to the faulty phase. The relay contacts open, thereby disconnecting the affected phase from the load. Simultaneously, the GSM module sends a text message indicating the type of fault and the affected phase. This dual action ensures immediate protection and rapid communication

VI. MATHEMATICAL ANALYSIS

The effectiveness of the fault detection mechanism depends on accurate calculation of RMS values of voltage and current. RMS values provide a measure of the equivalent DC value of an AC waveform in terms of power delivery capability.

The RMS voltage is mathematically defined as the square root of the mean of the squared instantaneous voltage over one complete cycle. Similarly, RMS current is calculated as the square root of the mean of the squared instantaneous current over a cycle. These calculations enable precise comparison with safety thresholds.

Let V(t) represent instantaneous voltage and I(t) represent instantaneous current over a time period T. The RMS values are obtained by integrating the squared waveform over one cycle and dividing by the period before taking the square root. These values are computed numerically within the microcontroller using discrete sampling methods.

Threshold limits are determined based on rated system parameters. If the measured RMS current exceeds the upper threshold, the system classifies the condition as a short circuit. If the current drops below a minimum threshold while voltage persists, an open-circuit fault is detected. This analytical approach ensures reliable and consistent fault identification.

VII. SIMULATION RESULTS

Simulation of the proposed overhead line fault detection system was conducted in Proteus software to evaluate its functional accuracy and reliability prior to hardware implementation. The simulation model consisted of a three-phase AC supply generated using sinusoidal pulse width modulation techniques with precise 120-degree phase displacement between the phases. Voltage and current sensing elements were incorporated into each phase, along with relay switching components and programmable fault insertion points. This configuration allowed systematic testing of normal and abnormal operating conditions within a controlled environment.

Under normal operating conditions, the simulated three-phase output exhibited balanced sinusoidal waveforms with uniform amplitude across all phases. The voltage magnitude remained within the predefined rated limits, and the load current drawn from each phase was symmetrical and stable. The monitoring algorithm continuously sampled the electrical parameters and calculated RMS values to verify system stability. No relay activation occurred during this period, indicating that the system correctly identified normal operating conditions without producing false fault detections.

To analyze open-circuit fault behavior, one phase was intentionally disconnected from the load during simulation. In this condition, the current in the affected phase dropped to nearly zero while the voltage waveform remained present due to the absence of current flow through the load. The system identified the discrepancy between voltage presence and negligible current as an open-circuit fault. Immediately upon detection, the control logic triggered the corresponding relay, isolating the affected phase and preventing further abnormal operation.

Short-circuit and line-to-ground faults were simulated by introducing a low-resistance path between the conductor and ground. This resulted in a sudden and significant rise in current magnitude beyond the permissible threshold. The voltage waveform in the affected phase showed noticeable distortion due to excessive current flow. The microcontroller-based detection algorithm rapidly compared the measured RMS current with preset limits and identified the condition as a short-circuit fault. The relay mechanism was activated almost instantaneously to disconnect the faulty phase, thereby limiting the duration of fault current flow.

Line-to-line fault conditions were also examined by creating an electrical short between two phases. In this scenario, abnormal current increases were simultaneously observed in both affected phases, while the remaining phase continued normal operation. The monitoring system successfully distinguished this condition from single-phase faults by analyzing current variations across all three phases. The protection unit responded by isolating the impacted phases, demonstrating effective multi-phase fault identification capability.

Fig3 shows the simulation circuit. The response time of the detection and isolation mechanism was observed to be minimal, occurring within a few electrical cycles after fault initiation. Additionally, GSM communication functionality was tested in the simulated environment. Upon fault detection and relay activation, a fault notification message was generated and transmitted to a predefined mobile number. The successful transmission of alert messages confirmed the reliability of the remote communication subsystem. Overall, the simulation results validate that the proposed system performs accurate fault detection, rapid isolation, and dependable remote notification under various fault scenarios.

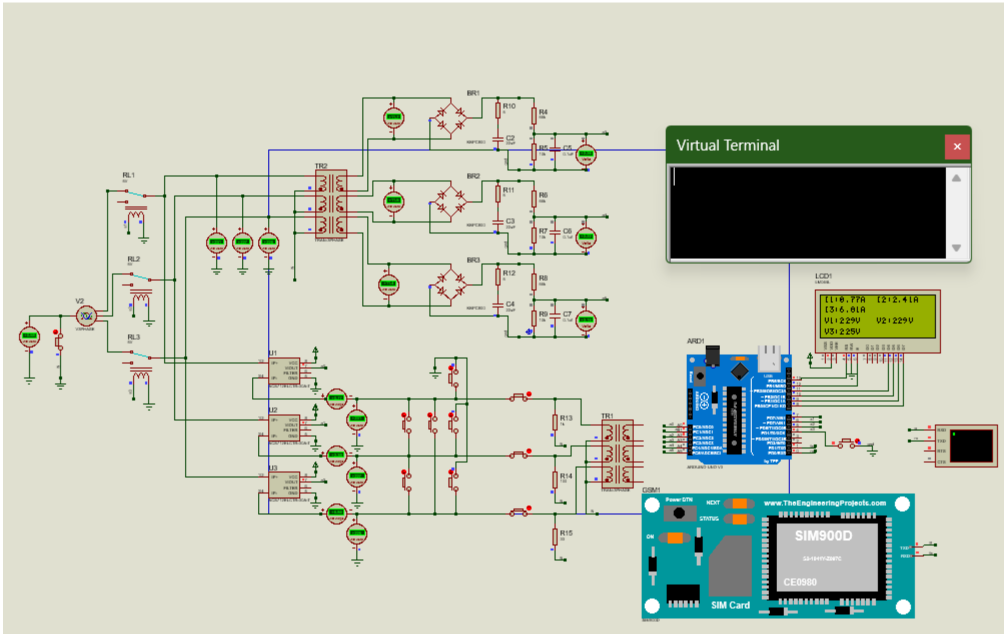

Fig3: Simulation circuit

VIII. HARDWARE IMPLEMENTATION

Fig 4 shows hardware of the prototype. A hardware prototype of the proposed overhead line fault detection and automatic trip protection system was developed to validate the practical feasibility of the design under real operating conditions. The prototype was assembled using modular components including the ESP32 microcontroller, Arduino Mega, L298N dual H-bridge driver modules, LC filter networks, voltage and current sensing units, relay modules, GSM communication module, and a 20×4 LCD display. The system was powered using a regulated DC supply, and careful grounding and isolation techniques were implemented to ensure stable and noise-free operation during testing.

The ESP32 microcontroller was programmed to generate six sinusoidal pulse width modulation signals required for three-phase AC generation. The SPWM signals were configured with precise 120-degree phase displacement to emulate a balanced three-phase system. These low-voltage control signals were fed into the L298N H-bridge driver modules, which amplified them to produce alternating positive and negative half cycles for each phase. The output of the H-bridge modules was passed through LC low-pass filters designed to attenuate high-frequency switching harmonics. The filtered output waveforms closely approximated sinusoidal AC signals with an amplitude of approximately 12 V per phase, suitable for laboratory-scale testing.

The monitoring subsystem was implemented using the Arduino Mega microcontroller, selected for its multiple analog input channels and higher memory capacity. Voltage sensors and current sensors were connected to each phase to measure electrical parameters continuously. The analog signals obtained from the sensors were converted into digital values using the built-in analog-to-digital converter of the Arduino. The measured RMS voltage and current values were calculated within the microcontroller and displayed on a 20×4 LCD screen in real time. The display provided clear visibility of phase-wise electrical conditions, enabling easy observation during experimental testing.

Fault conditions were manually introduced to evaluate the protective performance of the system. Open-circuit faults were created by disconnecting one of the phase conductors, while short-circuit conditions were simulated by introducing a low-resistance path between phase and ground. During open-circuit testing, the affected phase exhibited negligible current flow while maintaining voltage presence. The control algorithm successfully detected this condition and triggered the corresponding relay to isolate the phase. In short-circuit scenarios, a sudden increase in current was observed, and the relay responded immediately to disconnect the faulty phase, thereby preventing sustained fault currents.

The GSM communication module was interfaced with the Arduino Mega through serial communication to enable remote fault notification. Upon detection of any abnormal condition, the microcontroller transmitted a predefined SMS message containing details of the fault type and affected phase. The message was successfully received on the designated mobile number without noticeable delay.

The overall hardware performance closely matched the simulation results, demonstrating accurate fault detection, rapid protective response, and reliable communication. The experimental validation confirms the robustness and practical applicability of the proposed system for overhead distribution fault protection must be numbered using uppercase Roman numerals.

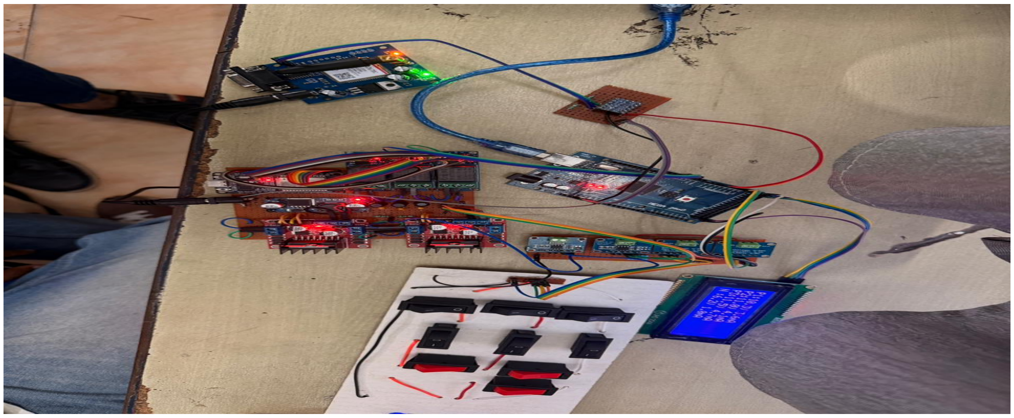

Fig: 4 Hardware

IX. ADVANTAGES AND APPLICATIONS

The proposed overhead line fault detection and automatic trip protection system offers significant advantages in terms of operational safety, reliability, and response time. One of the primary benefits of the system is its real-time monitoring capability, which continuously measures voltage and current parameters of all three phases. This ensures early identification of abnormal operating conditions before they escalate into severe damage. The automatic relay-based isolation mechanism minimizes fault duration by disconnecting the affected phase immediately upon detection. This rapid protective action reduces the risk of equipment damage, fire hazards, and electric shock incidents. Furthermore, the integration of GSM-based remote notification enhances situational awareness by instantly informing authorized personnel about the fault condition, thereby reducing maintenance response time.

Another major advantage of the proposed system is its cost-effectiveness and simplicity of implementation. The use of widely available embedded controllers such as ESP32 and Arduino Mega makes the system economically feasible for small-scale and medium-scale distribution applications. The modular design allows easy installation and maintenance without requiring complex infrastructure modifications. The threshold-based detection algorithm is computationally efficient and does not require high-end processors or advanced signal processing hardware, making the system energy-efficient and reliable for long-term operation. Additionally, the scalable architecture enables expansion to monitor additional feeders or higher voltage levels with suitable sensor and isolation arrangements.

The system has wide-ranging applications in power distribution and safety management. It can be deployed in rural overhead line networks where conductor breakage and environmental disturbances are common. The design can be extended for distribution transformer protection by monitoring secondary output parameters and isolating faults before transformer damage occurs. Integration with smart grid frameworks would enable automated power management, remote supervision, and predictive maintenance. Moreover, the system can be adapted for industrial environments where real-time electrical safety monitoring is critical for preventing accidents and ensuring uninterrupted production. With further development and integration of IoT-based cloud platforms, the proposed solution can serve as a foundational element in modern intelligent power distribution systems.

X. FUTURE ENHANCEMENTS

Future improvements to the proposed overhead line fault detection system can focus on integrating cloud-based data logging and remote analytics platforms. By incorporating IoT connectivity, real-time electrical parameters and fault history can be uploaded to a centralized cloud server for continuous monitoring and long-term performance analysis. Such data storage would enable predictive maintenance by identifying recurring fault patterns and trending abnormalities before they lead to system failures. Advanced signal processing techniques, including harmonic analysis and digital filtering algorithms, can be implemented within the embedded controller to improve fault classification accuracy and reduce the possibility of false triggering. The inclusion of machine learning–based anomaly detection models could further enhance the system's capability to distinguish between transient disturbances and genuine fault conditions.

In addition, the communication subsystem can be upgraded by incorporating long-range wireless technologies such as LoRa or NB-IoT, particularly for deployment in rural and geographically dispersed distribution networks where GSM coverage may be limited. These technologies provide extended communication range with low power consumption, making them suitable for remote installations. For practical large-scale implementation, the system can be adapted to operate at higher voltage levels by incorporating appropriate isolation transformers, high-voltage sensors, and protective insulation techniques. With enhanced scalability, improved communication infrastructure, and advanced analytical capabilities, the proposed system can evolve into a comprehensive smart distribution protection solution suitable for real-world power networks and smart grid environments.

XI. CONCLUSION

This paper presented the design and implementation of a smart overhead line fault detection and automatic trip protection system aimed at improving safety and reliability in power distribution networks. The proposed system integrates ESP32-based three-phase sinusoidal pulse width modulation generation with Arduino Mega–based real-time monitoring of voltage and current parameters. By continuously analyzing electrical quantities and comparing them with predefined safety thresholds, the system effectively identifies open-circuit faults, line-to-line faults, and line-to-ground faults. The coordinated operation of sensing units, embedded controllers, relay mechanisms, and communication modules ensures accurate detection and immediate protective action under abnormal conditions.

The automatic relay-based isolation mechanism significantly reduces fault duration and minimizes the risk of equipment damage, electric shock incidents, and fire hazards. The inclusion of GSM-based remote alerting further enhances operational efficiency by enabling instant communication of fault details to authorized personnel. Simulation and hardware validation confirm that the system performs reliably under both normal and fault conditions. The developed prototype demonstrates the practical feasibility of implementing intelligent, decentralized protection systems at the distribution level. With further enhancement and scalability, the proposed design can serve as a foundational framework for advanced smart grid applications and modern power system automation.

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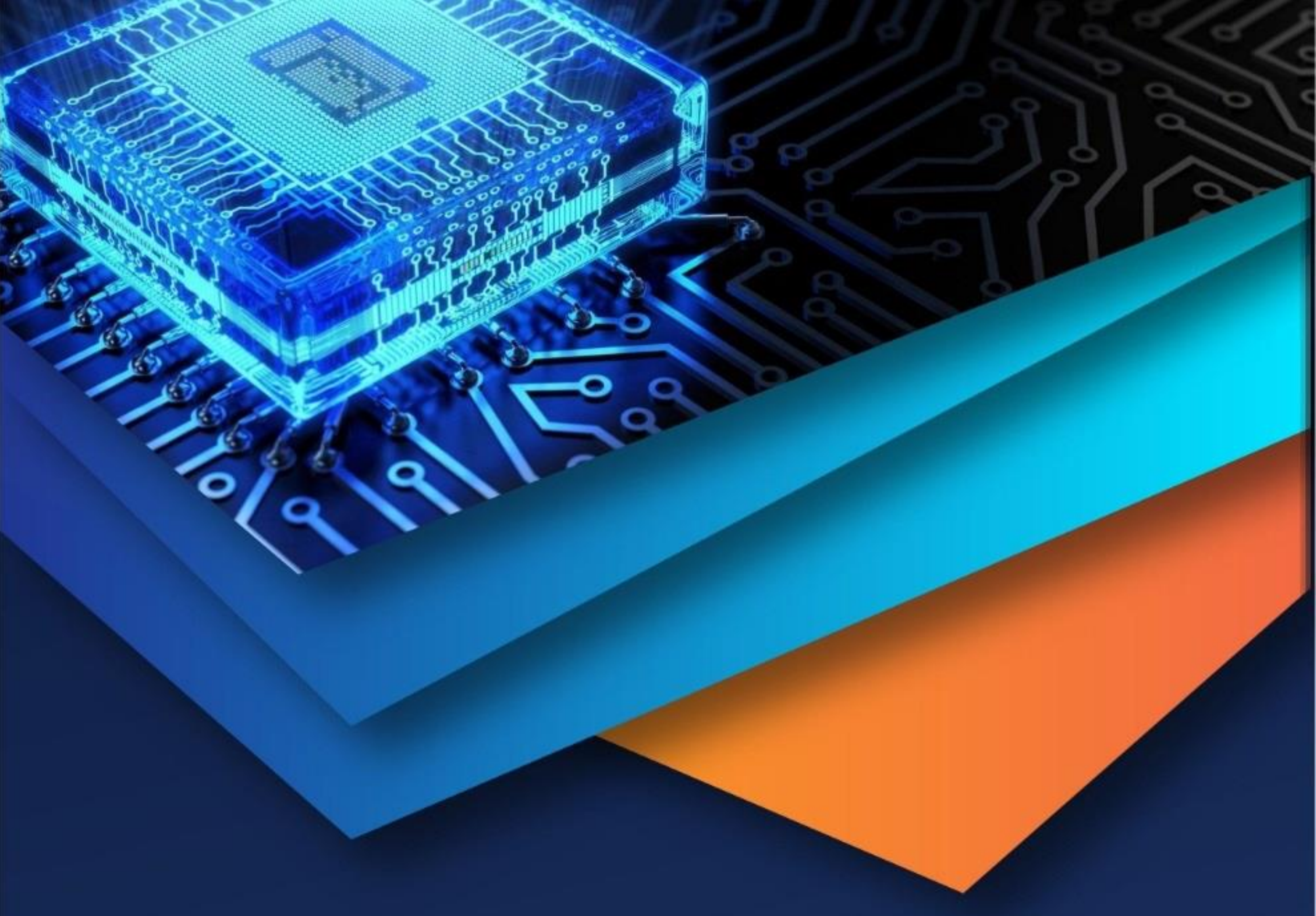

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