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IoT-Based Smart Circuit Breaker Control System for Lineman Safety Using MQTT Protocol

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Abstract: Maintenance and repair operations on electrical power distribution networks present significant life-threatening risks to linemen, primarily caused by miscommunication and the lack of reliable power isolation mechanisms. Traditional safety practices often depend on manual coordination between field staff and substation operators, a process highly susceptible to human error and accidental re-energization while work is in progress. Simultaneously, utility providers face increasing challenges in maintaining grid integrity and identifying technical losses resulting from unauthorized consumption or electricity theft.

To address these critical safety and monitoring gaps, this project presents an integrated IoT-Based Lineman Safety System designed to provide secure, remote control of distribution feeders. The system architecture utilizes an ESP32 microcontroller that communicates via the MQTT protocol with a cloud-hosted broker to enable a dedicated mobile application interface. This framework allows authorized linemen to remotely trigger a relay module for load isolation and restoration after verifying their identity. Furthermore, the system incorporates current and voltage sensors to continuously analyze load profiles, enabling the real-time detection of discrepancies indicative of electricity theft or unauthorized tapping.

Experimental results from the implemented prototype demonstrate a highly responsive and reliable solution for modern smart grid management. The system effectively eliminates human dependency in the switching process, providing immediate "Line ON/OFF" feedback to both the field personnel and a central monitoring dashboard. By combining secure remote access with automated fault and theft alerts, the proposed design minimizes operational risks, reduces technical losses, and offers a scalable, low-cost platform for enhancing workplace safety in the electrical distribution sector.

Keywords: IoT, Lineman Safety, Circuit Breaker, ESP32, MQTT

I. INTRODUCTION

Electrical power distribution systems are fundamental to modern infrastructure, yet the maintenance of these lines involves extreme risks for linemen working near live equipment. A significant number of industrial accidents occur due to miscommunication between substation operators and field staff, often leading to the accidental restoration of power while repairs are still in progress. Consequently, there is a critical need for an automated safety mechanism that minimizes human dependency and ensures the protection of personnel during hazardous maintenance operations.

In traditional utility frameworks, linemen lack a reliable method to directly verify or control line status, relying instead on manual procedures and verbal confirmations.

This systemic gap not only increases the likelihood of fatal errors but also hinders the efficient monitoring of grid integrity and unauthorized electricity consumption. The absence of real-time feedback and remote accessibility makes conventional systems increasingly inadequate for the demands of modern electrical distribution and workplace safety standards. The emergence of Internet of Things (IoT) technology offers a transformative solution by enabling real-time, wireless communication between electrical hardware and remote users. By integrating microcontrollers with cloud platforms, the operation of circuit breakers can be shifted from manual switching to secure, remote-controlled commands. This project proposes a system that allows linemen to isolate power lines independently via a mobile interface, ensuring that the electrical supply remains de-energized until maintenance is safely completed.

This research introduces an integrated safety and monitoring framework utilizing an ESP32 microcontroller, an MQTT broker, and high-precision sensors to detect faults and electricity theft.

Beyond providing remote control, the system continuously analyzes load profiles to identify discrepancies indicative of unauthorized tapping or technical losses. The resulting design offers a low-cost, scalable solution that enhances operational transparency, reduces technical risks, and effectively modernizes safety protocols within the smart grid environment.

II. LITERATURE SURVEY

[1] IoT-Based Lineman Security System Using Controlled Switchover with Transmission Line Fault dentification

This survey examines systems that utilize controlled switchover mechanisms to protect linemen during maintenance. The primary focus is on integrating fault identification directly with the security protocols used by field staff. By identifying the exact nature and location of a transmission line fault through IoT, the system ensures that power is not restored until the fault is cleared and the lineman is safe.

[2] Password Base Circuit Breaker Using GSM Modem

This study examines a remote-control system for circuit breakers that utilizes GSM communication for operation. The primary objective of such a system is to provide a password-protected mechanism that allows maintenance staff to switch power lines via a mobile device, thereby reducing the risks associated with manual operation.

While these systems introduced basic remote functionality and status updates, they are noted for several limitations compared to modern IoT solutions, including a restricted communication range and higher operational costs. Furthermore, GSM-based models often lack real-time data visualization and continuous monitoring of electrical parameters, which are essential for comprehensive lineman safety and grid management.

[3] Operation of Circuit Breaker with Authentication

This survey discusses a research paper presented at the 2nd International Conference on Power, Control and Computing Technologies (ICPC2T) in 2022. The study focuses on the critical role of user authentication in the operation of circuit breakers to prevent accidents caused by unauthorized or accidental switching. By implementing a secure control mechanism, the system ensures that only verified personnel can manipulate the state of the power distribution lines during maintenance. This research addresses a vital safety gap by moving away from traditional systems that lack restricted access, thereby reducing the probability of human error leading to fatal injuries.

The integration of authentication serves as a fail-safe isolation mechanism, ensuring that power remains disconnected until a deliberate, authorized command is issued to restore the supply.

[4] IoT-Based Fault Detection of Underground Cables through NodeMCU Module

This literature survey, authored by L. Goswami and colleagues, examines the application of the NodeMCU module for diagnosing faults specifically in underground cable systems. Unlike overhead lines, underground cables present significant challenges for physical inspection and manual fault location.

The research demonstrates how a low-cost, Wi-Fi-enabled microcontroller can be used to continuously monitor cable integrity and identify the specific location of faults remotely. By leveraging the IoT framework, the system provides a more efficient alternative to traditional diagnostic methods, enabling faster repair times and reducing the technical complexities involved in underground power distribution maintenance.

[5] A Technical Review on Self-Healing Control Strategy for Smart Grid Power Systems

This literature survey, authored by D. Sarathkumar and colleagues, provides a comprehensive technical overview of self-healing control strategies within modern smart grid infrastructures. The research explores the transition from traditional, reactive maintenance models to intelligent systems capable of autonomously detecting, isolating, and responding to network disruptions. By analyzing various protection approaches, the study highlights how automated control logic can minimize downtime and enhance the overall reliability of the power system.

For the scope of this project, this review provides a critical theoretical foundation for integrating IoT-based safety modules into a larger, automated grid environment where the system can proactively manage faults and ensure the continuous safety of the distribution network.

III. DESIGN AND COMPONENT SELECTION

A. System Architecture

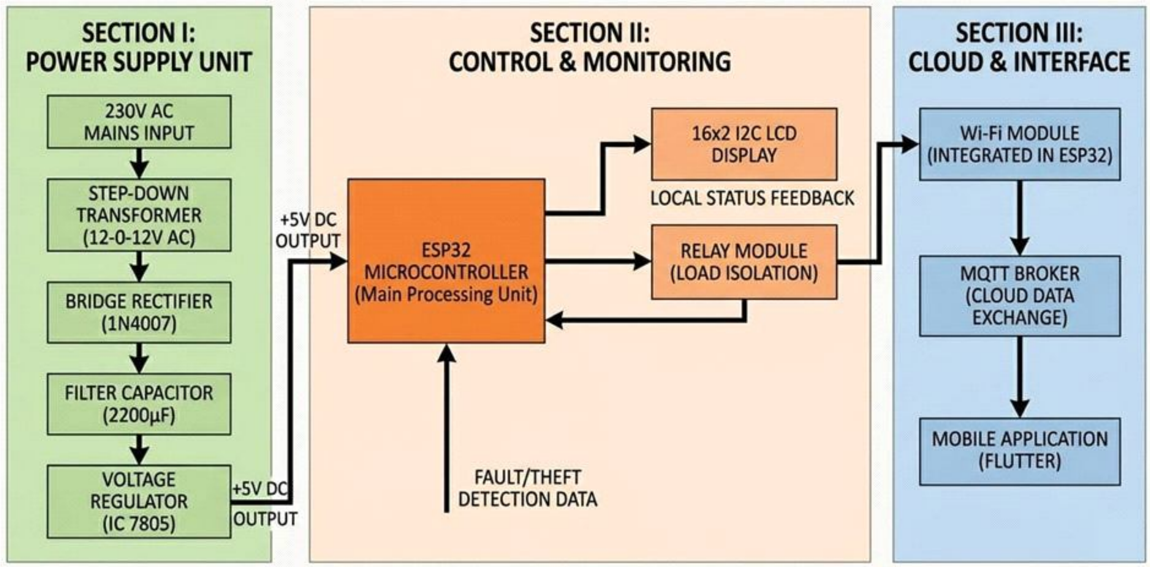

Fig 3.1: System Architecture

The overall system architecture for the IoT-based circuit breaker is organized into a modular framework consisting of three primary sections designed to ensure a secure and intelligent interface for power line maintenance. This design focuses on providing remote switching and real-time monitoring while maintaining a safe distance between the lineman and high-voltage equipment. The integration of these sections allows for a seamless flow of data and control signals from the user interface down to the physical hardware installed on the distribution line.

The first functional block is the Power Supply Unit, which is responsible for converting the high-voltage 230V AC mains input into a stable DC voltage required by the electronic components. This process involves a step-down transformer to reduce the voltage, followed by a bridge rectifier and filter capacitor to convert and smooth the signal into DC. Finally, a voltage regulator ensures a constant 5V DC output, protecting the microcontroller and relay modules from electrical noise and fluctuations.

The second block is the Control and Monitoring Section, which acts as the central processing hub of the system. At its core is the ESP32 microcontroller, which processes incoming control commands and manages the switching logic for the relay module. This section also handles local feedback through an LCD display, providing field technicians with immediate visual confirmation of the line's ON or OFF status. Additionally, sensors are integrated into this block to continuously monitor electrical parameters such as current and voltage for fault and theft detection.

The third block is the Cloud and Interface Section, which facilitates wireless connectivity and remote accessibility. The system utilizes the ESP32's integrated Wi-Fi module to communicate with an MQTT broker, serving as the bridge for data exchange between the field hardware and the cloud platform. Authorized personnel can then access a Flutter-based mobile application to send isolation commands or view real-time status updates and alerts from any location with internet access. This architecture ensures that power remains safely isolated until an authenticated command is issued by the lineman.

B. Hardware Component Selection

The selection of hardware components is a critical phase of the design process, as each part must meet specific requirements for reliability, power efficiency, and compatibility with the IoT framework. The system is built around a low-cost, modular design that ensures maximum safety and functionality with minimal expenditure.

The central processing unit chosen for the system is the NodeMCU (ESP32), which is selected for its integrated Wi-Fi capabilities and dual-core processing power. This microcontroller handles all major tasks, including receiving remote control commands from the cloud, managing data from sensors, and updating the local display. Its ability to connect directly to the internet simplifies the hardware setup by eliminating the need for separate communication modules.

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For the switching operation, a JQC-3F(T73) Relay Module is utilized to act as the electronic circuit breaker. The relay is essential because it allows the low-power signals from the ESP32 to safely control high-voltage loads while providing electrical isolation between the sensitive control logic and the 230V power line. This physical separation is a primary safety feature that prevents accidental energization during maintenance work.

The power management system relies on a Power Supply Unit designed to convert 230V AC mains into a stable 5V DC output. This unit incorporates a step-down transformer, a 1N4007 bridge rectifier, a 1000µF/25V filter capacitor, and a 7805 voltage regulator . Providing a regulated supply is necessary to protect the electronic components from voltage fluctuations and electrical noise.

Visual feedback is provided by a 16x2 I2C LCD Display, which offers real-time status updates such as "LINE ON" or "LINE OFF" directly at the work site. This immediate local indication reduces uncertainty for the lineman and enhances workplace transparency.

To add a layer of intelligent monitoring, current and voltage sensors are integrated into the hardware setup. These sensors, specifically the ACS712 for current monitoring, allow the system to detect overloads, faults, and load discrepancies that suggest electricity theft.

C. Control Logic and Software

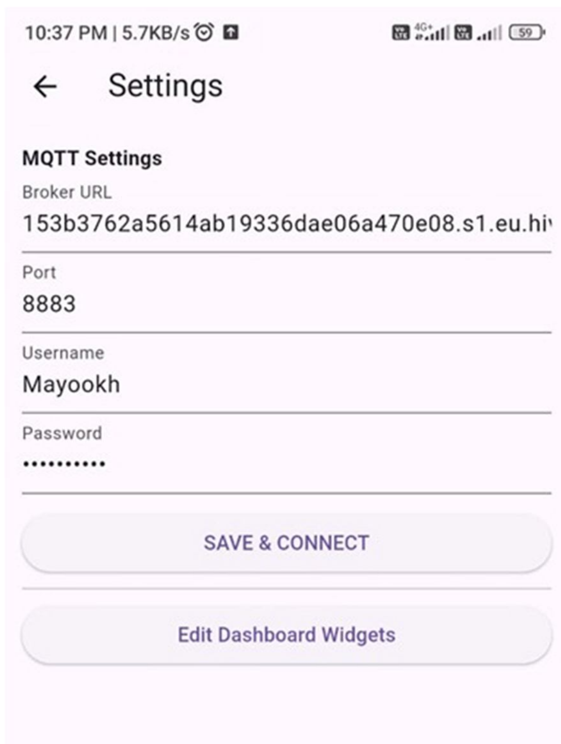

Fig 3.2: MQTT setting

The software framework for the IoT-based circuit breaker is designed to manage hardware operations, facilitate cloud communication, and prioritize lineman safety through a strict logical sequence. The system's intelligence resides in the firmware developed for the ESP32 microcontroller using the Arduino Integrated Development Environment (IDE). Upon system startup, the control logic initializes all digital and analog input/output pins, configures the Wi-Fi credentials, and establishes a secure connection with the HiveMQ MQTT cloud broker.

The primary operation of the software is based on a request-response model where the controller enters a continuous monitoring state, waiting for authenticated commands from the mobile application. When a lineman issues an "OFF" command to isolate a line, the ESP32 processes the packet through the MQTT callback function and triggers the relay module to physically disconnect the load. Simultaneously, the software updates the local LCD display and the remote mobile dashboard to confirm the "LINE OFF" status, ensuring the user has direct verification before beginning maintenance.

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To enhance grid security and provide a fail-safe environment, the software incorporates a continuous monitoring loop for electrical parameters. Using data from the current and voltage sensors, the algorithm calculates real-time consumption and compares these values against predefined safety thresholds. If the software detects an abnormal current surge or a discrepancy indicative of electricity theft, it is programmed to automatically isolate the power supply as a protective measure and transmit an immediate fault alert through the cloud platform. This integrated logic ensures that the system remains responsive to both manual safety commands and automated hazardous conditions.

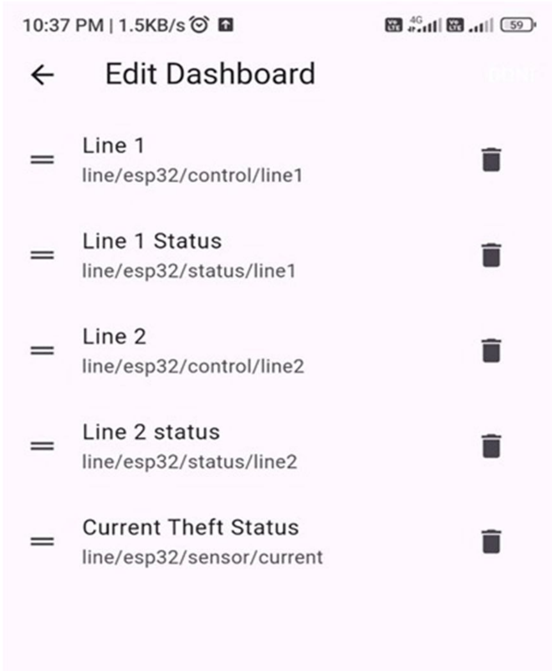

Fig 3.3: Adding commands

D. Circuit Diagram

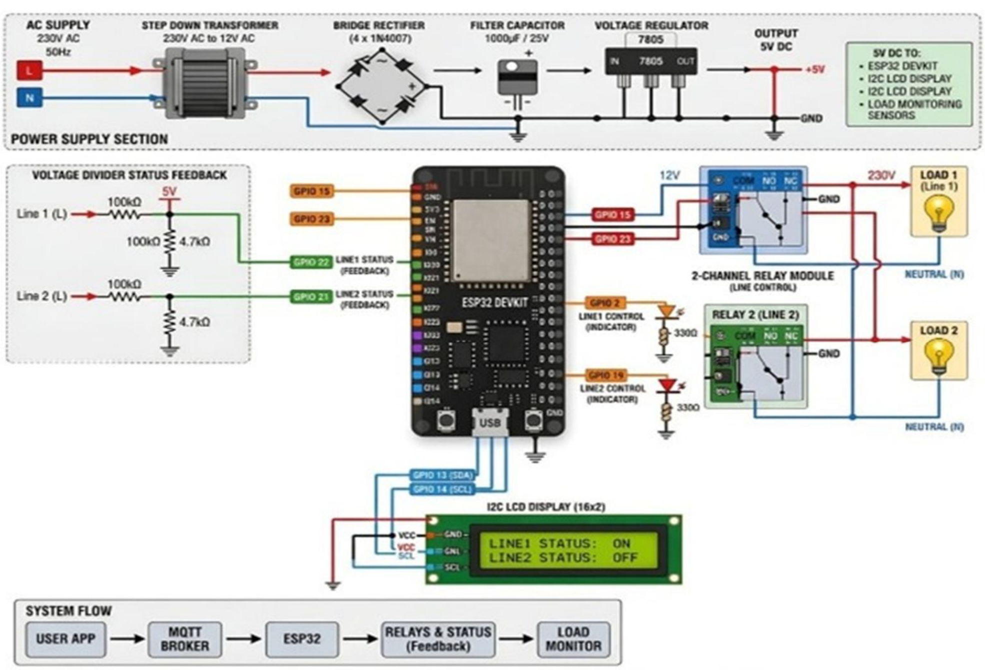

Fig 3.4: Circuit Diagram of IoT-Based Lineman Safety System Using ESP32

The circuit diagram represents the complete hardware implementation of the IoT-based lineman safety system, integrating power supply, control, and load management sections. The system is powered from a 230V AC mains source, which is stepped down to 12V AC using a transformer. This is then converted into DC using a bridge rectifier and filtered using a capacitor to remove ripples. A 7805 voltage regulator is used to provide a stable 5V DC output, ensuring safe and reliable operation of the ESP32 microcontroller, relay module, and display unit. At the core of the system is the ESP32 microcontroller, which acts as the main control unit. It receives commands from the cloud via the MQTT protocol and processes them to control the relay module. The 2-channel relay acts as an electronic switch that allows the ESP32 to safely control high-voltage AC loads. Based on the received command, the relay turns the connected loads ON or OFF, effectively functioning as a circuit breaker. Additionally, a voltage divider circuit is used to monitor the status of the electrical lines by stepping down the voltage to a level suitable for the ESP32 inputs. The system also includes a 16x2 I2C LCD display that provides real-time status information such as whether the lines are ON or OFF. When a command is issued from the mobile application, the ESP32 activates the corresponding relay and updates both the load condition and display status simultaneously. The feedback mechanism ensures that the system can detect faults or abnormal conditions and respond accordingly. Overall, the circuit enables safe, remote, and automated control of electrical lines, significantly improving lineman safety during maintenance operations.

IV. WORKING PRINCIPLE

The working principle of the IoT-based circuit breaker is centered on shifting the authority of electrical isolation directly to the lineman through a secured, digital framework. By utilizing an internet-enabled control mechanism, the system removes the traditional dependency on manual switching and verbal coordination with substation operators, which are primary causes of industrial accidents. The operational cycle begins with a secure command generated through the Flutter-based mobile interface. When a lineman initiates a maintenance task, they issue an isolation command that is transmitted as a data packet to the cloud-hosted MQTT broker. The broker then publishes this command to the ESP32 microcontroller at the field site. Upon receiving and verifying the command, the microcontroller executes a switching action by activating the relay module, which physically disconnects the power supply to the distribution line. Once the line is isolated, the system provides immediate feedback to ensure a safe working environment. The ESP32 updates the local 16x2 LCD display and sends a status confirmation back to the mobile app, confirming that the line is de-energized. To maintain safety, the relay acts as a protective switching element that keeps the line disconnected until the lineman explicitly restores the supply through the same authenticated interface after completing the work.

Beyond manual control, the system operates on a supervision principle to detect grid abnormalities. Sensors continuously measure current and voltage, feeding real-time data to the microcontroller for analysis. If the algorithm identifies a fault or a discrepancy indicating electricity theft, the system is programmed to immediately isolate the line and transmit an emergency alert to both the field staff and the central monitoring station.

V. RESULTS AND ANALYSIS

The performance and reliability of the IoT-Based Circuit Breaker Controlling System were evaluated using a test setup that replicated a basic electrical distribution environment. The experimental results demonstrate that the system successfully fulfills its primary objectives of providing secure remote control and real-time monitoring of electrical lines.

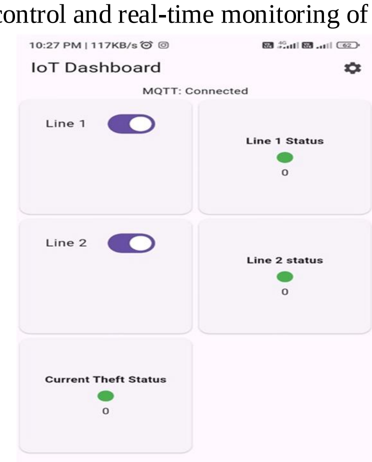

Fig 5.1: App Interface

A. *System Performance and Response Time*

Testing confirmed that the communication between the Flutter-based mobile application and the ESP32 microcontroller remains stable with minimal latency. Upon issuing an "ON" or "OFF" command through the interface, the relay module performed accurate switching of the simulated electrical load almost instantaneously. This quick response time is a critical performance parameter, as it ensures that isolation commands are executed without dangerous delays in a field environment.

B. *Fault and Theft Detection Analysis*

The integration of current and voltage sensors allowed the system to effectively supervise the operating condition of the line. During fault simulation test cases, the system identified abnormal sensor readings and automatically triggered the protective relay to disconnect the power supply. The control algorithm successfully detected load discrepancies indicative of electricity theft, transmitting immediate alert notifications to the user interface. This dual functionality of manual control and automated fault response highlights the system's reliability in managing grid integrity.

C. *Reliability and Safety Evaluation*

The system maintained consistent performance over repeated operations, indicating a high level of hardware and software stability. Local feedback through the 16x2 LCD display consistently matched the remote dashboard status, ensuring that linemen have synchronized information at the field site. Furthermore, the implementation of authentication mechanisms successfully restricted control access to authorized users only, effectively mitigating the risk of accidental re-energization during maintenance. Overall, the analysis validates that the proposed design is an efficient, low-cost solution for enhancing workplace safety in the power distribution sector.

VI. CONCLUSION

The design and implementation of the IoT-Based Circuit Breaker Controlling System successfully address the critical safety challenges inherent in traditional electrical distribution networks. By leveraging the ESP32 microcontroller and MQTT communication protocol, the project provides a secure, decentralized method for linemen to manage power isolation independently. This approach effectively minimizes the risk of fatal accidents caused by miscommunication or accidental re-energization during hazardous maintenance operations.

Experimental testing of the prototype confirmed that the system is highly responsive, with isolation and restoration commands executed with minimal latency through the dedicated mobile application. Beyond its primary safety functions, the system demonstrated reliable monitoring capabilities by accurately detecting abnormal load profiles and identifying discrepancies indicative of electricity theft. These integrated features provide utility providers with enhanced grid transparency and a robust tool for reducing technical losses.

While the prototype establishes a strong foundation for smart grid safety, it remains subject to certain limitations such as dependency on stable internet connectivity and the need for industrial-grade components in high-voltage environments. However, the successful integration of low-cost hardware with cloud-based control validates that IoT technology is a viable and scalable solution for modernizing power system safety mechanisms. Future enhancements, such as GPS integration and advanced predictive maintenance analytics, will further improve the system's effectiveness in real-world utility operations.

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