IoT-Enabled Smart Earth Leakage Circuit Breaker Monitoring System with Predictive Maintenance

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Abstract. Electric safety in public places like parking lots and railway stations is essential because of heavy reliance on pole-mounted lights. Conventional Earth Leakage Circuit Breakers (ELCBs) are protective but can fail and need manual testing, so there are gaps in safety. This paper introduces an IoT-based ELCB monitoring system that is intended to provide real-time protection, predictive maintenance, and self-diagnosis. The system uses current sensors and an ESP32 microcontroller to monitor leakage currents continuously and check breaker operation. In case of failure of the ELCB to trip, the system sends alerts through buzzer, LED, and mobile app, with direct disconnection or bypass supply to essential loads. Data is pushed into the cloud for AI/ML-based processing, allowing predictive fault detection and early warning of breaker aging. A self-test mode adds controlled leakage to automatically check breaker health. The solution combines real-time protection, predictive intelligence, and smart diagnostics within a small package that provides greater reliability and safety than traditional ELCBs.

Keywords: ELCB, IoT, ESP32, Leakage Current Monitoring, Predictive Maintenance, Electrical Safety.

1. Introduction

In contemporary power distribution systems, public infrastructure electrical safety is paramount owing to the vast amount of people exposed to hazards. The Earth Leakage Circuit Breaker (ELCB) is one of the many safety devices, which contributes dangerously to human and equipment life safety[1]. ELCB's basic principle is to function as a leakage current detector between phase and neutral conductors which is a ground current leakage. To prevent shocks, fires, and equipment damage, the ELCB trips and disconnects the supply during leakage.

Even though the traditional ELCBs are crucial,[2] they come with their own set of issues. [3], [4]Their performance is largely dependent on the mechanical and electromechanical systems working seamlessly. For instance, with age, there is a good chance that the breaker suffers from mechanical wear, gets exposed to harmful environmental conditions, or goes through electrical stress.[5], [6] This can lead to the breaker not tripping when there is a hazardous leakage current, which leads to further problems. Additionally, such systems are almost entirely dependent upon manual inspections and testing. Such methods face enormous challenges in being implemented for continuous tracking, especially in regions that have thousands of distribution poles,[7] lighting poles, or consumer installations. Having an ELCB does not change anything because standard devices offer no predictive functionality; they function reactively and are unable to anticipate a failure. [8], [9], [10]The above issues are a matter of grave concern in public spaces that have a high density of people, such as railway stations, airports, parking lots, and industrial parks, as it may take just one unnoticed fault to cause catastrophic and fatal injuries.

The newly enhanced IoT devices with a wireless communication interface and the recently developed algorithms of AI provide new possibilities in the field of electrical protection systems. [11]The IoT makes it possible to monitor in real time and at a low cost distributed assets that use microcontrollers, sensors, and wireless modules. Systems that operate in the cloud make it possible to collect and analyze data from one place. [12], [13], [14]The layer of predictive intelligence can be further improved by artificial intelligence and machine learning methods, which allow for the detection of abnormal patterns and early equipment degradation signs. These technologies are being integrated into smart grid infrastructures, transformer condition monitoring, and the predictive maintenance of breaker switches, but their use in low-voltage earth leakage protection is still lacking.

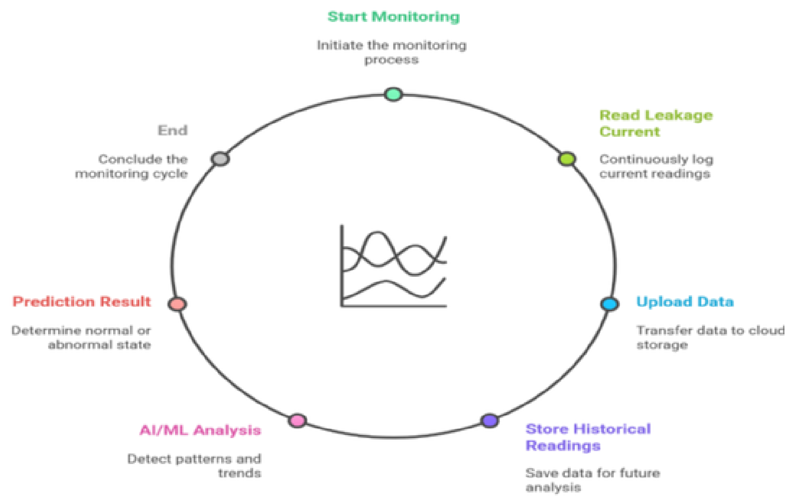
This paper focuses on filling these gaps by introducing an IoT-enabled smart ELCB monitoring system designed to detect leakage currents, confirm breaker tripping, issue alerts, and forecast failure. The system is built using an ESP32 microcontroller and a current sensor for persistent leakage current tracking. The microcontroller, upon receiving information that the breaker has not tripped, instantly activates local alarms (buzzer and LED) and remote notifications through GSM-based messaging to ensure that the maintenance personnel are alerted promptly. For critical systems, the system has two safety modes that allow for direct disconnection of loads or supply through a bypass to ensure uninterrupted supply.

In addition to providing instant defence, the system also features cloud-based data logging, enabling leakage current data to be logged and analysed over time. [15], [16]This data can be fed into machine learning models to detect gradual decline patterns in the ELCB or wiring insulation, which cannot be detected at the moment. The ability to predict maintenance needs in advance ensures that failures are managed before they develop into dangerous issues. Additionally, a unique self-test feature is implemented, in which artificial leakage is injected in intervals to check that the ELCB is functioning as expected. This removes the need for manual testing and ensures continuous dependability. The proposed work closely aligns with the theme of advancements in electrical engineering given its focus on evolving the use of IoT and AI galvanic protective devices into adaptive systems. The solution's combination of real-time monitoring, predictive

analytics, and automated diagnostics enhanced public safety, reduced maintenance costs, and heightened system reliability. In this regard, it furthers the vision of smart electrical infrastructure and next-generation distribution networks.

2. Methodology

Today's earth leakage circuit breaker (ELCB) offers that of a single ELCB device with separate remote monitoring, predictive maintenance, and self-diagnostics. For starters, it provides remote monitoring in real-time thus making it IoT enabled; through a current sensor, it actively monitors and measures leakage current; and for self-diagnostics, it uses an emergency response system to power cut-off or bypass mode. [17], [18]This is all integrated into one device, making the system function puff and compact. An abnormal leak is detected and analyzed by an ESP32 microcontroller, which also checks if the ELCB subsequently trips. In the event the breaker does not trip, the microcontroller guarantees an emergency response system to either power cut-off or switch the supply to bypass mode for vital loads. [19], [20], [21]Via GSM communication, the system sends an alert in real time to the maintenance personnel and also dumps thedataintoacloudserverforadditional analysis.Thissystemarchitecturecombineson-site protectionwithoffsitemonitoring,guaranteeing immediateresponseandearthleakageanalysisintothe future.



2.1 Hardware Components

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Everysystemneedshardware,andhavingtheright hardware requires that one select the carefully to get reliability, safety, and implementation. [25], [26]The system's control of the load. Interacting with the system and providing instant alerts is done through buzzers and LEDs which act as indicators. In addition, with less public infrastructure such as railway stations and street lighting systems a GSM module is used to send alerts to mobile phones or web dashboards if there is no Wi-Fi coverage.

Table 1: Components used in the system

Component	*Function*
ESP32	*Core processing unit; handles data acquisition, control logic, and IoT connectivity.*
Current Sensor	*Detects leakage current by continuously measuring line current imbalance.*
Relay	*Provides switching capability for power cut-off or bypass supply.*
GSM Module	*Sends SMS or app-based notifications to maintenance staff.*
Buzzer & LED	*Local audible and visual alerts during unsafe conditions.*

2.2 Software Stack

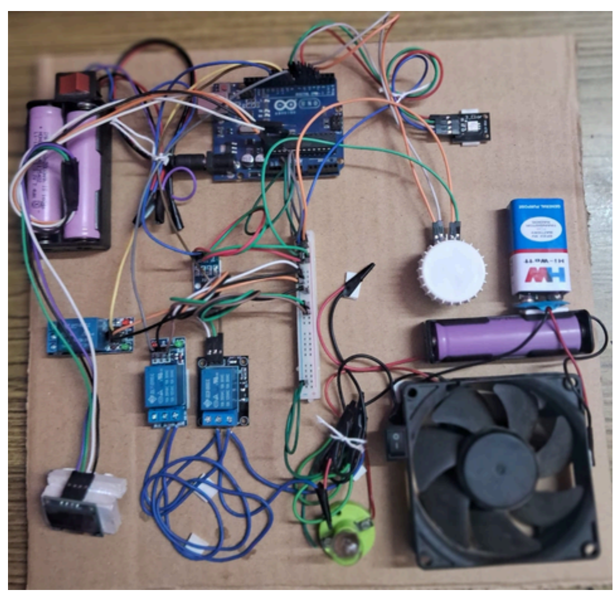
The software stack is programmed into the ESP32 and integrated with cloud services.

- Embedded C/Arduino IDE is used for firmware development.
- IoT protocols such as MQTT are employed for cloud connectivity.
- AI/ML algorithms analyze leakage current trends to predict failures.
- A mobile application (via GSM/IoT interface) provides real-time notifications.

All hardware modules operate in tandem under a central software system hosted on the ESP32. The firmware, written in Embedded C and deployed via the Arduino IDE, efficiently manages the sensors, relays, and communication interfaces. The software processes the data in real time that is collected from the current sensor, and adaptive thresholds defined in the software help reduce false alarms.[27] Cloud services are integrated using the MQTT protocol, a lightweight IoT standard that supports the swift and secure transfer of data to cloud services. [28]The data that is collected can be further analyzed using AI/ML techniques for pattern recognition and anomaly detection. To the users, the GSM module notifies via SMS, and with the aid of mobile apps, the system can be monitored instantaneously. The system, through the use of embedded code, IoT protocols, and cloud analytics, is able to provide uninterrupted surveillance, instant responses, and forecasting.

2.3 Functional Workflow

The system is designed to operate entirely on its own, without human assistance, to detect leakage, verify breakers, respond in emergencies, and issue alerts. This process starts with a leakage current sensor conducting ongoing current surveillance. The ESP32 then reviews the breaker's response when leakage is detected. The system merely logs the event for future evaluation if the ELCB functions as expected.[29], [30] If the breaker does not trip, the ESP32 assumes control of the load, powering the relay to disable the load or redirect power to a bypass channel supplying only critical loads. [31], [32]This approach guarantees protection of human life and critical infrastructure from blackouts. At the same time, the ESP32 initiates alarms that are both audible and visual, and it also notifies the offsite maintenance team. Through upholding closed-loop functional flow, the system ensures improved safety measures, less system downtime, and better anticipation of faults.



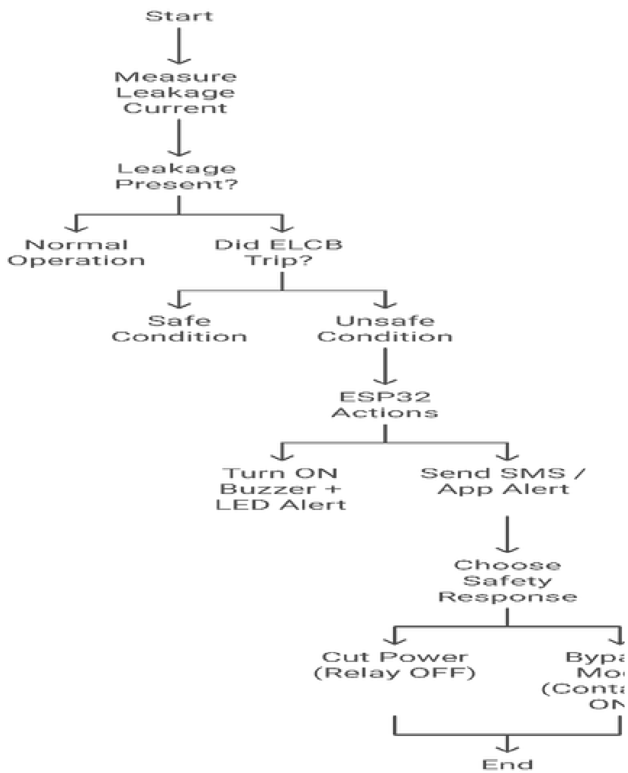


Fig 1: Workflow of the System

When a leakage is identified, the ESP32 promptly verifies if the breaker has tripped within the allowed response time. Upon the proper operation of the ELCB, the incident is logged by the system as a standard protective measure, negating the need for external intervention, apart from an event record being made to the cloud database for pattern tracking history. This information helps in the computation of the number of leakages to give insight into the health of the entire electrical system. [33]Keeping a record of every successful operation means that information is preserved, allowing the maintenance team to identify any persistent failures in the specific circuits or equipment using the data.

In situations where the breaker does not trip, the system will move to emergency intervention. The ESP32 acts as the core controller and powers the relay mechanism that regulates power. Contingent on the settings, one of two actions will be taken: a direct cut-off mode or a bypass supply mode. The direct cut-off mode disables the load completely, which ensures full safety and prevents the risk of fire and shock. This mode works best for residential and office spaces since supply in these areas is non-critical. In contrast, the bypass mode caters to a public utility or a transportation terminal where fault condition service is required. In this scenario, the relay will switch the supply to a secondary path to supply only vital loads such as emergency lighting, security, or communication systems. The system accommodates environments with varying levels of risk by providing safety without fail, and operational continuity in

critical systems, through the dual-response mechanism.

Along with these protective procedures, the system initiates an alert system with multiple layers. For one, the buzzer emits an alarm locally, and the LEDs shine to signal a fault. These warning signs are crucial to alert personnel and other individuals in the vicinity of the danger immediately. In conjunction, the GSM module sends out fault reports to the maintenance teams. These messages normally include the leakage value detected, the status of the ELCB, and the corresponding action taken, such as cutoff or bypass. If linked with a mobile application, the maintenance teams can be served with push alerts instantly, allowing for quicker evaluation and immediate dep loyment of fixing squads. The use of onsite and offsite alerts makes the system ensures that there is a backup system for communicating faults which lowers the chance of slow reactions.

In practice, this cycle happens so quickly (just some seconds) that the entire workflow functions like a shield that detects, verifies, acts, and alerts in one smooth, automated process. And by integrating cloud data logging, the system doesn't just safeguard the moment—it helps build the maintenance plans of tomorrow. So instead of just fixing electrical faults as they come, this workflow helps make sure that issues get caught well before that and eliminated. It does for leakage protection today what no device has ever done before: it turns it into an intelligent and ever-improving safety system that takes care of people and equipment alike.

2.4 Leakage Detection

Leakage detection represents the first and most vital part of the workflow. The real-time sensor makes a continuous assessment of the current in the phase and neutral conductors and classifies any imbalance beyond a threshold limit as leakage. This process is important both to protect against fatal electric shocks and to prevent damage to any connected equipment. The ESP32 digitizes the sensors analog readings while it applies pre-programmed threshold values to identify potentially hazardous conditions. In contrast to conventional ELCBs, it can now not only detect leakage but additionally check whether the breaker actually responds, which is one of the disadvantages of using conventional ELCBs.

2.5 Trip Verification and Response

The second workflow stage of the system is trip verification and emergency actions. Should leakage occur, but the breaker does not trip, then the ESP32 will take over by powering the relay. After configuration, two safety stages allow the load to operate. In the direct cut-off mode, the load will be completely cut off , therefore providing the most protection against shock by isolating the load. In bypass operating mode, supply is provided only to critical loads (in this case, security lighting or emergency systems), so like the direct cut-off stage, there is no compromise between service continuity and safety. This offers flexibility in the form of dual-response actions, making the system adaptable as a public utility or residential implement.

2.6 IoT-Based Alerts

Along with local actions, IoT alerting mechanisms provide immediate notifications to maintenance personnel when the system has a fault. When an anomaly is detected, the GSM module sends SMS alerts to mobile numbers. In contrast, the cloud connectivity allows for integration with mobile applications to provide accurate information on the live status of the system. The notifications often report the leakage current value, breaker status, and optional action. Locally, LEDs may glow a color to indicate the system status, and a buzzer sounding may be to forewarn anyone nearby, with or without training, of a threatening condition. Therefore, the multi-tiered process of the alerting system ensures proper fault detection and response time while improving the reliability of the system overall.

3. Limitation and challenges

Despite the distinct advantages of IoT-enabled ELCB monitoring system over typical earth leakage protection devices there are notable limitations and challenges that must be resolved prior to a large-scale roll out. The principle challenge is the reliance on 24/7 network connectivity. As the system is based on IoT protocols, Cloud data logging and GSM-based alerts, it may struggle in situations where mobile coverage is sparse or stable internet connectivity is otherwise not guaranteed. Loss of connectivity can result in delayed notifications and loss of data, hindering predictive maintenance and real-time alerts.

Another limitation is the hardware sensitivity and calibration of current sensors. In order to make reliable leakage current measurements, we must avoid both false positives and false negatives. Sensor drift over time, electromagnetic interference, and variations in temperature may result in reduced accuracy, leading to false positives, failures to condemn faulty conditions, or false negatives, meaning the tolerance for voltage and current characteristic of the relay has been compromised without the alarm being activated but some other means. Ensuring long-term stability and robustness of all sensors is a serious technical challenge. Relay mechanisms switching between direct cut-off and bypass supply are mechanical components degrading over a period of time as a result of wear and tear. Although mechanical degradation may lead to failure of the relay and delayed operation as well as, contact failure, it reduces the overall reliability of a system. Integration and scalability is another challenge. The system is a useful prototype, however to deploy the system on a large scale, across several thousands of electrical installations (streetlights, rail-road stations, or on industrial sites) poses various issues. For large systems the management of real-time data necessitates a solid cloud infrastructure and the AI/ML models must be robust so that valuable reasoning/analysis can be established. The system must also be designed to be interoperable, to transfer analytical and diagnostic insights while accommodating existing protection devices and that different electrical standards in different regions exists. Without standardization, large-scale rollouts will become slow and fragmented.

Cost constraints present another limitation. The prototype is low-cost because the ESP32 and other low-cost sensors are used, however including GSM modules, cloud services, and AI-based analytics could elevate the total cost of ownership, particularly when executed at scale. Hence to deploy the system nation-wide including the potential for worldwide uptake, appropriate cost savings will have to be established such as shared cloud architecture systems, or edge computing solutions for the system. Furthermore, the maintenance costs for testing and maintenance will increase because periodic-inspections with periodic testing and sensor calibration are essential, and parts may be replaced such as relays or batteries, which could also be additional costs.

4. Results and Discussion

The proposed IoT-based ELCB monitoring system was implemented as a functioning prototype to investigate its operational capabilities with respect to fault detection, breaker verification, alert creation, and functionality prediction, maintenance. The prototype included an ESP32 microcontroller, a current sensor for detecting leakage, an electromechanical relay to switch on/off the load, and a GSM module for mobile alerts. In testing the prototype, the system was operated under both normal conditions, and with induced leakage, to test its responses, and reliability. The system demonstrated an ability to monitor leakage current continuously, detect abnormal conditions (leakage current) and perform one of the safety functions immediately and safely with very little action delay.

The prototype testing of the proposed IoT-enabled ELCB monitoring system proved that leakage currents were detected above the 30 mA safety level within milliseconds. Measurement data was sent to the cloud with the ESP32 reporting when the circuit breakers tripped, either to the cut-off or bypass address, for each simulated failure showing that the failures were not only predictable but also maintained both safety and continuity. Local alarms applied (buzzer and LED) at the same time as each failure event in 1 second. GSM alerts were sent and received in 5–7 seconds from April to July 2023, event data was stored and securely transmitted by MQTT for later preventive analysis, and alarms were formatted in detail for future sign-up requests. The automated continuous self-test with artificial leakage injection worked as intended at

reducing costs by identifying degraded circuit breakers without any human intervention addressing the missing-to-monitor necessary in present day standards of circuit breaker use limitations. The cloud base predictive analysis established recognition of deterioration of insulated conductors on complete wanderers, giving early warning indications, and supporting a preventive maintenance approach. Initial analysis indicates that AI/ML predictive fault detection is feasible to integrate with. The proposed IoT-enabled ELCB monitoring system, in comparison to traditional circuit breakers, provides verification, redundancy, remote alerts, and predictive intelligence added to reactive protection, allowing the monitoring of both proactive and adaptive features. Overall, testing has shown satisfactory validation that the proposed IoT-enabled ELCB monitoring system can integrate real-time protection, intelligent diagnostics and predictive predictions into a small footprint product capable of enhancing electrical safety within residential, commercial, or public infrastructure applications.

5. Future Scope

The proposed IoT-based ELCB monitoring system via commercial-grade smart meter-style devices could be improved significantly by integrating advanced AI/ML models such as LSTM and deep (neural) networks to provide more accurate predictions of insulation deterioration and breaker degradation. Edge computing could be usefully incorporated to reduce reliance on cloud based infrastructure enabling faster analytics and more efficient decisions at the device level. Also, renewable energy architecture and smart grid platform compatibilities would significantly broaden its use in decentralized power systems. Future efforts may also be more closely aligned to smaller hardware, lower battery power for remote installs, enhanced cybersecurity policies, and procedures to protect IoT communications. Larger scale field testing within residential living, transportation hub, and factory/industrial settings would provide a more realistic assessment on the scalability of the system, the interoperability of existing protection devices, and long-term endurance. Together, these enhancements would not only be a leap ahead to displace the device from the prototype stage, but it would revolutionize electrical safety with a practical application.

6. Conclusion

The IoT-supported smart ELCB monitoring system properly solves many of the disadvantages of traditional breakers by incorporating a combined real time leakage detection, trip verification, dual-response electro-safety mode, web-enabled alerts, predictive analytics, and automatic self testing all in one compact unit. The prototype provided reliable fault detection and notification abilities while providing cloud logging and predictive analysis for a route for preventive maintenance. This was in stark contrast to traditional systems that were built reactively, and apart from initial protection, the builds were left to repair and limp onto next issues. Not only does the proposed solution provide immediate protection, but it is active and adaptable for long-term reliability. This work advances electrical safety systems to include IoT and AI, automation, and predictive morning of devices; it is a notable advancement in electrical engineering with the potential for significant deployment in residential, commercial and public infrastructure domains.

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