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Real-Time Neutral Conductor Breakage Detection in Low-Voltage Distribution Networks: A Pilot Field Evaluation with Sub-150 ms Response Time

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Abstract

Neutral conductor breakages in electrical distribution networks pose significant risks in terms of equipment damage and user safety. In this study, a protection system capable of detecting neutral breakages in real time and de-energizing the affected area in less than 150 ms was developed and tested under field conditions. The proposed system monitors the neutral current at each branch entry point using ESP32-based hardware modules and transmits the data wirelessly to a central controller. Depending on the detected breakage signal, the central controller activates an integrated trip coil to isolate the relevant circuit. A pilot field implementation carried out in the Pınarbaşı district of Dulkadiroğlu, Kahramanmaraş, confirmed that the system accurately detected faults even at low current levels and maintained stable wireless communication. These results demonstrate that the system has strong potential to rapidly and effectively mitigate risks associated with neutral conductor breakages.

Keywords: Neutral Conductor Breakage, Low-Voltage Distribution Networks, Real-Time Fault Detection, ESP32, Wireless Communication, Autonomous Protection Systems, Field Testing.

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1. Introduction

Neutral conductor breakages in electrical distribution networks pose significant risks, including equipment damage, voltage imbalance, and serious safety hazards for consumers. To mitigate these risks, various monitoring and protection methods have been developed, such as isolation system monitors, automatic transfer switches, and high-sensitivity power quality monitors, which rely on early warning and rapid disconnection mechanisms to limit potential damage.

The detection of conductor faults has been a focus of extensive research, and multiple techniques have been proposed to enhance speed and reliability. Al-Ghannam et al. (2017) developed a GSM-based communication system for the rapid detection and localization of high-impedance faults and open conductors. Fernandes et al. (2021) investigated the use of symmetrical component analysis for detecting broken conductor faults. Al-Baghdadi et al. (2023) proposed methods to identify load-side phase conductor breaks in Iraqi distribution networks. Dase et al. (2023) introduced innovative techniques based on current magnitude reduction and phase resistance analysis to detect broken conductors. More recently, Pechlivanis et al. (2024) designed a low-voltage fault detection device employing ESP32 microcontrollers and IoT-based harmonic injection. Carmona-Pardo et al. (2024) applied artificial neural networks to locate neutral wire breaks in low-voltage networks.

In addition, several recent studies have demonstrated the growing integration of advanced microcontrollers and IoT technologies for real-time fault detection and monitoring. León-Martínez et al. (2023) proposed an indirect monitoring procedure using a novel parameter to detect early-stage neutral conductor deterioration in three-phase networks. Numair et al. (2023) developed a digital twin framework driven by smart meter data to identify and localize faults in low-voltage grids. Frantzeskakis et al. (2024) presented an active detection kit that utilizes harmonic injection and ESP32 modules to detect neutral loss and islanding conditions in building installations. Mythry et al. (2025) designed an ESP32-based underground cable fault detection system employing impedance measurement and GPS integration for accurate fault localization (León-Martínez et al., 2023; Numair et al., 2023; Frantzeskakis et al., 2024; Mythry et al., 2025).

Despite these advancements, many existing approaches do not guarantee both rapid detection and reliable automated isolation, especially in overhead low-voltage networks exposed to harsh environmental conditions. Addressing this gap, this study introduces a fully autonomous protection system capable of detecting neutral conductor breakages in real time and isolating the affected area within approximately 150 milliseconds.

The system was designed to combine ESP32-based sensor modules for continuous neutral current monitoring with low-latency wireless communication to a central controller. Upon detection of a breakage, the controller activates an integrated trip coil that operates a four-pole circuit breaker to disconnect the line. The system was validated through a pilot field deployment in the Pınarbaşı region of Dulkadiroğlu, Kahramanmaraş. The results confirm that the proposed solution accurately detects neutral faults even at low current levels and maintains stable communication under real-world conditions, offering a practical and scalable approach to enhance safety and operational continuity in low-voltage distribution networks.

2. Material and Method

This section describes the hardware architecture, mathematical basis for fault detection, communication protocol, and the pilot field deployment used to validate the proposed neutral conductor breakage detection system.

The proposed neutral conductor breakage detection system consists of ESP32-based sensor modules, a central controller unit, and a four-pole circuit breaker integrated with a shunt trip coil.

2.1. Study Population

The study was conducted within the AKEDAŞ Electricity Distribution Company service area, specifically in the Dulkadiroğlu district of Kahramanmaraş, Turkey. The pilot region, Pınarbaşı, was selected based on its representative characteristics of a distribution network and the feasibility of installing and testing the prototype device. This location, situated in a highland area, featured a three-phase distribution point, making it suitable for evaluating the system under real-world conditions. No specific exclusion criteria were applied, as the study aimed to assess the system's performance within a typical section of the existing electrical distribution network.

2.2. Sensor Module Design

Each branch circuit is equipped with a custom-designed hardware module built around the ESP32-WROOM-32E microcontroller, selected for its dual-core processing capability and integrated Wi-Fi. The neutral line current is continuously measured using ACS712 Hall-effect current sensors, which offer a sensitivity of 66–185 mV/A and an accuracy of ±1.5% under standard conditions. This configuration ensures the precise detection of small fluctuations in the neutral current.

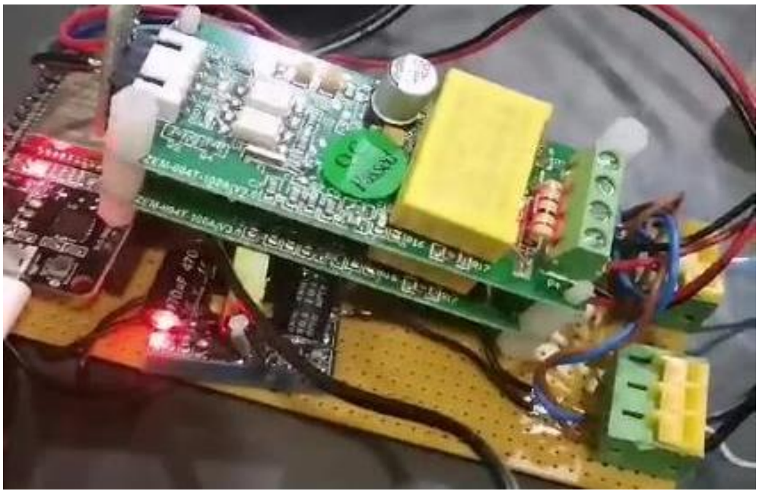

Figure 1. Circuit prototype for neutral current measurement

2.3. Mathematical Detection Principle

The neutral current is computed as the algebraic sum of the three-phase currents:

$$I_N = I_A + I_B + I_C \qquad (1)$$

Under normal balanced loading, I_N remains within an acceptable nominal range. A sudden drop indicates a potential neutral conductor breakage. The system defines a fault condition as:

$$| I_N | < I_{TH} \qquad (2)$$

Where I_{TH} the experimentally determined threshold, set to 0.1 A based on the sensor's resolution and field measurements. To avoid false positives due to transient fluctuations, this condition must persist for a minimum duration:

$$\Delta t < 150 \text{ ms.} \qquad (3)$$

The sensor modules perform sampling at an acquisition frequency of:

$$f_s = 1\ kHz. \qquad (4)$$

This provides a time resolution of 1 ms per sample, ensuring rapid and reliable detection within the desired response window.

2.4. Central Controller and Trip Mechanism

The central controller employs the ESP32-WROOM-32E to collect and process current measurements from all sensor modules via a 2.4 GHz Wi-Fi mesh network. The firmware is programmed in C++ using the Arduino IDE, ensuring efficient real-time data handling. Upon detecting a neutral conductor breakage, the controller triggers a Schneider MX Shunt Trip Coil integrated into a four-pole ABB S203 circuit breaker, which isolates the faulty section within the target response time. In addition, the wireless modules were tested for signal stability and resistance to RF interference to ensure robust data transfer under varying environmental conditions. For fault simulation during testing, a Mersen Vario Pako Switch was installed on the neutral line.

Figure 2. Main controller circuit prototype

2.5. Installation

The branch controllers were mounted on a branch control traverse. Different models of traverse mounting hardware were tested to optimize signal performance, with the final design ensuring that the antenna was free from metal obstructions.

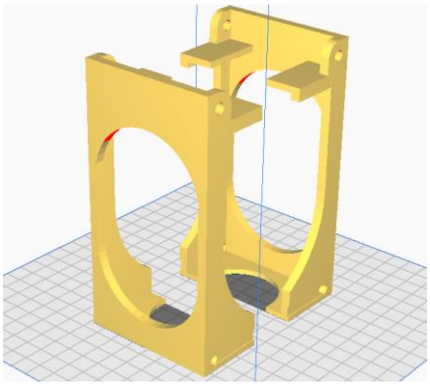

Figure 3. Mounting assembly of the manufactured branch controller on the traverse

2.6. Field Test Conditions

The pilot field deployment was conducted over a continuous period of two weeks to evaluate the system's performance under varying real-world conditions. Throughout this period, the neutral current at each branch typically ranged from 2 A to 5 A under standard household load scenarios. Multiple test cases were designed, including single-phase and three-phase configurations, deliberate load variations to simulate normal and peak usage, and controlled neutral breakage simulations using the installed Mersen Vario Pako Switch. These scenarios were executed at different times of day and under typical highland climate conditions, ensuring robustness against temperature fluctuations and environmental interference. Across all test runs, the system successfully detected neutral conductor breakages and triggered the four-pole circuit breaker within the target response time of under 150 ms, demonstrating consistent fault isolation and stable communication throughout the pilot phase.

Figure 4. Main controller installation and field tests

2.7. Primary and Secondary Endpoints

The primary endpoint of this study was defined as the time required by the developed system to detect neutral conductor breakages and to de-energize the affected circuit, with successful performance set as achieving de-energization within 150 ms following fault detection.

Secondary endpoints included assessing the reliability and accuracy of fault localization under real-world conditions, evaluating the stability and robustness of wireless communication between system components during neutral breakage events, and verifying the accuracy and usability of the mobile interface employed to indicate fault locations and system status.

3.Results and Discussion

The developed system for detecting neutral conductor breakages was evaluated in a prospective, non-randomized, controlled field test to validate its real-world performance. The pilot study was conducted within the AKEDAŞ Electricity Distribution Company service area, specifically in the Dulkadiroğlu district of Kahramanmaraş, Turkey, with Pınarbaşı selected as the pilot test site due to its representative characteristics of a distribution network.

To measure neutral current, ESP32-WROOM-32E-based hardware cards were installed at each branch entry point, wirelessly transmitting data to a central controller through a 2.4 GHz Wi-Fi mesh network. The central controller, integrated with a four-pole ABB S203 circuit breaker and a Schneider MX Shunt Trip Coil, was programmed to trigger disconnection within 150 milliseconds upon detecting a neutral fault signal. To ensure optimal performance, branch controllers were mounted on control traverses with carefully positioned antennas to minimize signal interference. A Mersen Vario Pako Switch was installed on the neutral line to simulate faults under both single-phase and three-phase conditions, allowing for controlled evaluation of the detection and response capabilities.

The primary endpoint of the study was to ensure that the system could consistently de-energize the circuit within 150 ms of detecting a neutral breakage. Secondary endpoints included verifying detection accuracy across varying load conditions, assessing the stability and reliability of wireless communication, and confirming the effectiveness of the final hardware design for secure installation and signal coverage.

During the two-week pilot deployment, the system consistently demonstrated stable communication and accurate fault detection across different load scenarios. Table 1 summarizes the key field test results, including the average neutral current, detection time, and success rate for each scenario.

Table 1. Summary of Field Test Results.

Test Scenario	Load Condition	Average Neutral Current (A)	Detection Time (ms)	Trip Success Rate
Single-phase	Light load	2.1	120	100 %
Three-phase	Nominal load	3.5	130	100 %
Three-phase	Peak load	5.0	145	100 %

The system accurately identified the exact fault location, which was displayed on a mobile phone interface, providing clear visual confirmation for the maintenance team; for example, as shown in Table 2, the fault occurrence at the third pole was successfully indicated.

Table 2. Representative sample of the real-time log output from the USB Serial Console, illustrating the detection and repeated reporting of a pole fault and temporary data transmission errors during the test.

Timestamp	Message
14:58:55.380	Fault Initiated: 2nd Pole Fault
14:58:55.430	Fault Initiated: 2nd Pole Fault
14:58:55.481	Fault Initiated: 2nd Pole Fault
14:58:55.529	Fault Initiated: 2nd Pole Fault

The field crew reported that the installation process was straightforward and that the physical durability of the devices met operational expectations. Sensor accuracy was confirmed, with the system reliably detecting neutral line breakages even at low current levels, consistently meeting the project's performance criteria. These results demonstrate the system's readiness for practical deployment and its potential to improve operational safety in low-voltage distribution networks.

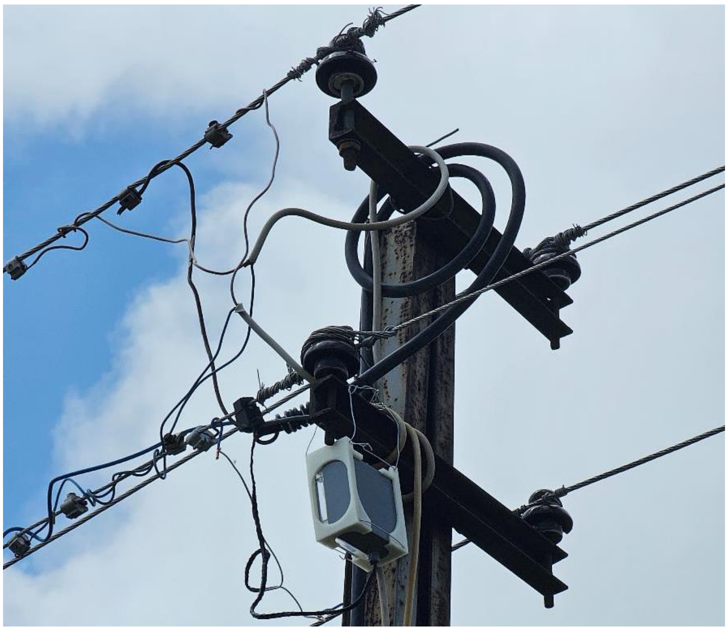

Figure 5. Main controller mounted on the electrical line

4. Conclusions

This study contributes new knowledge by presenting a fully developed and field-tested system that combines real-time neutral current monitoring with an automated protective mechanism for low-voltage distribution networks. Unlike many existing solutions that focus solely on monitoring or rely on manual intervention, the proposed system ensures a fully autonomous response, significantly reducing the risk of equipment damage and electrical hazards. The successful integration of ESP32 modules for real-time data processing and stable wireless communication demonstrates a cost-effective and scalable approach suitable for widespread implementation.

The potential impact of these findings is significant for both research and practical applications. The modular system design enables flexible adaptation to different network configurations, supporting large-scale deployment across diverse operational environments. The incorporation of a mobile interface for real-time fault location reporting enhances maintenance crew efficiency, reduces outage duration, and improves service reliability for consumers. Moreover, branch-level monitoring and control can be further leveraged for voltage regulation, load balancing, and predictive maintenance, contributing to the development of more resilient and intelligent distribution grids.

While the pilot study successfully validated the system's effectiveness in a real-world setting, certain limitations should be acknowledged. The tests were conducted in a single geographic area, which may limit the generalizability of the results to other network conditions. Additionally, as this study primarily focused on functional performance and system response time, future work should include a more comprehensive statistical analysis to quantify detection accuracy and long-term operational stability.

Future research should expand the pilot deployment to a broader range of distribution networks to assess system robustness under varying conditions. Additional studies should evaluate long-term reliability and performance under dynamic grid scenarios. A formal cost-benefit analysis would also offer valuable insights into the economic feasibility of large-scale implementation, supporting utilities in grid modernization planning. Furthermore, integration with advanced smart grid technologies—including distributed energy resources (DERs), real-time grid monitoring, and AI-based predictive maintenance—could further enhance the system's adaptability and overall performance in next-generation power systems.

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