

An IoT-Enabled Smart Neutral Fault Detection System Using ESP32 for Real-Time Three-Phase Monitoring and Experimental Analysis

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Abstract—Neutral conductor breakage and floating neutral conditions are among the most dangerous faults in low-voltage three-phase four-wire electrical systems, as they can cause severe voltage imbalance, appliance damage, overheating, and fire hazards. Although conventional devices such as MCBs and RCCBs are effective for overcurrent and leakage faults, they cannot directly detect floating neutral faults in real time. Based on the proposed review framework, this paper presents the design, implementation, and experimental evaluation of an IoT-enabled Smart Neutral Fault Detection System developed using an ESP32 controller, three PZEM-004T sensing modules, ZMPT101B voltage sensing, LCD alerts, buzzer indication, and PHP-MySQL dashboard integration. The system was physically tested under simulated conditions such as neutral breakage, overload, phase loss, undervoltage, and voltage imbalance. The experimental evaluation mainly focuses on fault response latency, dashboard update speed, and fault detection reliability. The results show that the system achieves sub-second to near real-time fault response, high detection accuracy, and stable dashboard monitoring, confirming its practical use for smart electrical panels, laboratories, and industrial monitoring environments. The findings show that the combination of embedded sensing, adaptive imbalance analysis, IoT monitoring, and edge-based ESP32 processing can successfully convert traditional electrical monitoring into an intelligent, data-driven, and scalable neutral fault detection system for future smart electrical and smart grid applications.

Index Terms—Neutral Fault Detection, Floating Neutral, ESP32, PZEM-004T, IoT Dashboard, Three-Phase Monitoring, Voltage Imbalance.

I. INTRODUCTION

Neutral conductor failure is one of the most dangerous and often ignored faults in low-voltage three-phase four-wire electrical systems used in homes, laboratories, industries, and commercial buildings. As the use of sensitive appliances, PLC systems, automation equipment, motors, and smart meters increases, the stability of the neutral conductor becomes very important. When the neutral wire becomes loose, corroded, overloaded, or disconnected, the phase reference shifts according to the connected loads, causing voltage imbalance, overvoltage, undervoltage, overheating, equipment damage, and fire hazards. This makes real-time neutral fault detection systems essential for modern electrical monitoring.

In recent years, many researchers have proposed different methods for detecting broken conductors and abnormal phase conditions in low-voltage systems. Voltage asymmetry methods, IoT-based monitoring, embedded microcontrollers, and edge-based processing have shown that real-time phase voltage and current monitoring is possible with good reliability. Recent AI-based analysis methods have also shown the ability to predict conductor degradation before the actual fault occurs. However, the performance of these systems still depends on sensor calibration, stable data, and real electrical conditions.

Even with these developments, practical challenges still remain. Systems based only on simple threshold logic may fail during sudden load switching and highly unbalanced conditions. Cloud-based systems may introduce delay, while systems using multiple

sensors and dashboards often face synchronization issues. Many existing systems also lack a single interface for live voltage imbalance, fault events, and historical monitoring.

This paper presents the design, development, and experimental testing of an IoT-enabled Smart Neutral Fault Detection System developed to solve these issues in one practical framework. The system uses an ESP32 controller, three PZEM-004T modules for phase-wise voltage and current sensing, ZMPT101B voltage sensing for neutral reference analysis, LCD alerts, buzzer indication, PHP API backend, MySQL database, and a live dashboard for remote monitoring. The system was tested under simulated faults such as neutral breakage, overload, undervoltage, overvoltage, phase loss, and imbalance, and its performance was evaluated using fault response time, dashboard refresh rate, and detection reliability.

The main contribution of this work is the complete hardware-software implementation of a low-cost smart neutral fault detection system with real experimental validation. It demonstrates how embedded sensing, IoT communication, edge-based ESP32 processing, and dashboard monitoring can be combined into a system that is technically practical and suitable for smart electrical panels, laboratories, and industrial monitoring applications.

II. LITERATURE REVIEW

The development of smart neutral fault detection systems has progressed over many years, starting from studies on conventional fault monitoring to modern work on embedded sensing, IoT-based dashboards, and intelligent edge processing. This section reviews the major research contributions, their advantages, and their limitations, which form the motivation for the present experimental work.

Early studies on broken conductors and voltage asymmetry showed that neutral wire faults can be detected using phase displacement and voltage imbalance percentage analysis. These studies built the theoretical base for floating neutral detection and clearly showed that traditional devices like MCBs and RCCBs cannot directly identify such faults in real time. However, these works mainly focused on theory and did not provide low-cost embedded implementations suitable for practical smart panels.

Later, researchers introduced microcontroller-based monitoring systems using Arduino, ESP32, and ARM controllers for real-time phase voltage and current sensing. These systems proved that continuous phase-wise monitoring is possible at low cost. However, many of them used simple threshold logic, which reduced detection reliability during sudden load switching and unbalanced load conditions.

IoT-based monitoring systems further improved the field by adding cloud dashboards, mobile alerts, and event logging, which made remote monitoring easier in industrial and laboratory environments. However, cloud-only systems often introduced latency and internet dependency, which reduced real-time performance.

To solve this, edge-based embedded architectures moved the fault logic closer to the sensing hardware. By processing the data directly inside local controllers, these systems improved fault response speed, low latency, and offline monitoring reliability. This strongly supports the use of ESP32-based edge processing in the present work. Still, many of these systems faced challenges in combining multiple sensors, LCD displays, buzzer alerts, and IoT dashboards into one synchronized framework.

Recent studies on AI-based anomaly detection and predictive maintenance also showed the ability to forecast conductor degradation and voltage imbalance trends before actual failures. However, these methods depend heavily on stable historical datasets, making them less suitable for prototype-level experimental systems.

The present work builds on these developments by implementing a fully integrated ESP32-based Smart Neutral Fault Detection System that combines three PZEM-004T sensing modules, ZMPT101B voltage sensing, adaptive imbalance logic, LCD and buzzer alerts, PHP-MySQL dashboard communication, and real-time fault simulation. Unlike previous works that focused on separate modules, this implementation demonstrates the complete hardware-software pipeline, real-world testing, and measured performance results, making it highly suitable for practical smart electrical monitoring applications.

III. RESEARCH METHODOLOGY

The methodology of the proposed IoT-Enabled Smart Neutral Fault Detection System was developed based

on the previously proposed review framework and is presented here in its fully implemented experimental form. The complete system was physically deployed and tested on a three-phase laboratory prototype distribution panel under simulated real-world fault conditions using an ESP32 controller, three PZEM-004T sensing modules, ZMPT101B voltage sensing,

LCD display, buzzer alert system, PHP backend with MySQL database, and a live monitoring dashboard. The methodology is organized into three parts — Hardware Implementation, Software Implementation, and Algorithm Design, following the same structure used in the practical deployment process.

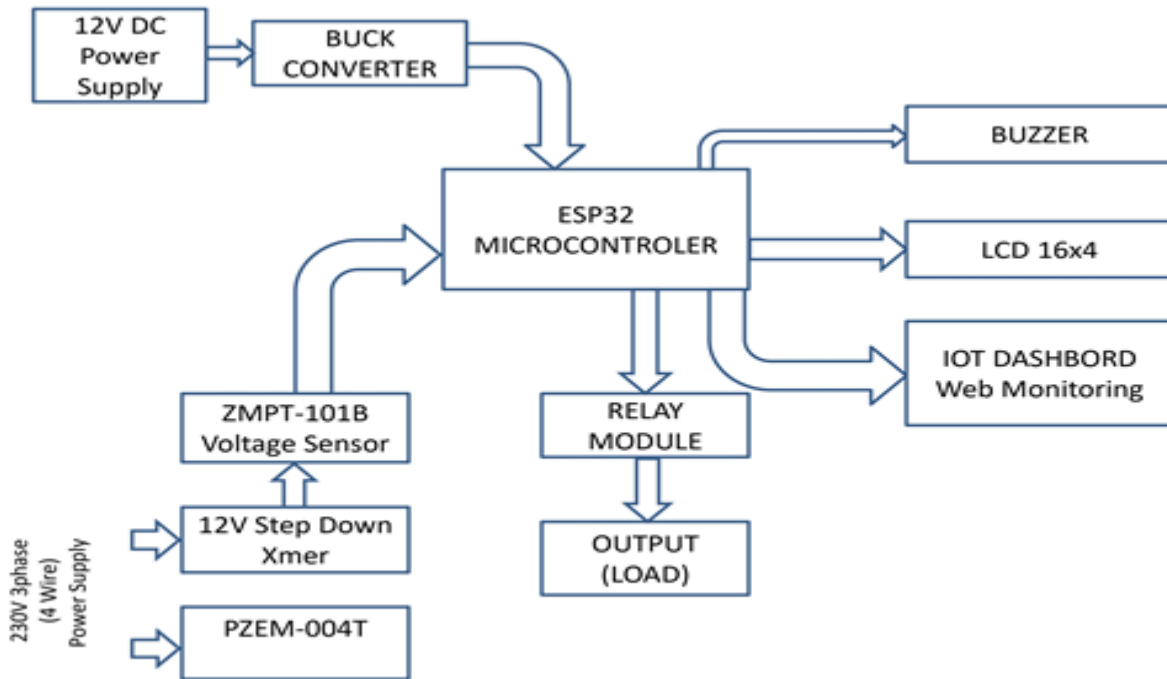


Fig.1. System Architecture of the model

Part 1 — Hardware Implementation

A. ESP32-Based Sensing and Control Unit

A single ESP32 microcontroller was used as the main embedded controller for the proposed fault detection system. ESP32 was selected because of its dual-core processing, built-in Wi-Fi, multiple UART ports, ADC support, and low cost, making it highly suitable for smart electrical monitoring panels. During testing, the ESP32 continuously acquired real-time voltage and current values from all three phases and executed the fault detection logic without interruption, confirming stable operation under simulated neutral fault and overload conditions.

B. Sensor Network and Communication

A dedicated sensor network was built using: The proposed monitoring and protection system integrates three PZEM-004T modules to enable independent

phase-wise measurement of voltage and current across the three-phase supply lines. This phase-level sensing architecture allows continuous real-time acquisition of electrical parameters from each phase, which is essential for identifying voltage imbalance, phase failure, overload conditions, and abnormal current variations. To accurately monitor the condition of the neutral line, a ZMPT101B voltage sensor is employed for neutral reference voltage sensing, providing a stable reference point for detecting neutral displacement, floating neutral faults, and voltage asymmetry caused by neutral conductor disturbances. The measured data from the PZEM modules are transmitted to the Espressif Systems ESP32 microcontroller using UART-based serial communication, which ensures reliable and efficient real-time data transfer with minimal latency. In addition to digital parameter acquisition, ADC-based

voltage sensing is incorporated to capture analog voltage signals for finer resolution analysis, transient behavior observation, and fault validation. This combined sensing framework significantly improves the system's capability for precise fault detection, rapid response, and enhanced protection reliability in low-voltage three-phase distribution networks. This sensing architecture removed the need for expensive industrial analyzers while providing reliable R–N, Y–N, and B–N parameter monitoring throughout all test sessions. The built-in Wi-Fi of ESP32 allowed direct transmission of fault data to the PHP backend and dashboard without additional networking hardware.

C. Processing and Monitoring Hardware

The processing and monitoring layer of the proposed system is implemented using the Espressif Systems ESP32 edge controller, which performs all fault analysis and decision-making operations locally during real-time testing. The controller continuously acquires phase voltage and current measurements from the sensing modules and processes these inputs to compute the percentage voltage imbalance among the three phases. Based on the calculated imbalance and neutral reference data, the embedded firmware executes dedicated neutral fault detection logic to identify floating neutral and conductor breakage conditions. In parallel, an overload protection algorithm evaluates current thresholds to detect excessive load demand and abnormal current rise. The ESP32 also manages all human-machine interface functions, including real-time LCD display updates for live parameter visualization and buzzer alert activation for immediate audible fault indication. Furthermore, the controller supports HTTP-based data dispatch, enabling remote transmission of monitored parameters and fault events to cloud dashboards, web interfaces, or supervisory monitoring platforms.

This implementation confirms that the entire monitoring, analysis, and protection workflow can be executed efficiently on low-cost embedded hardware, eliminating the need for expensive industrial PLCs or high-end processing units. Such an approach makes the proposed system highly suitable for prototype validation, residential protection systems, laboratory testing, and small industrial panel applications where cost, compactness, and energy efficiency are critical. In addition, the proposed architecture is inherently

scalable and can be extended for larger smart monitoring deployments by integrating higher-performance edge platforms such as Raspberry Pi Foundation Raspberry Pi, NVIDIA Jetson Nano, smart industrial gateways, and smart grid edge nodes, thereby supporting future expansion toward distributed industrial IoT and smart grid infrastructures.

Part 2 — Software Implementation

A. Sensor Data Acquisition and Firmware Processing

The ESP32 firmware-based system continuously connected to all three PZEM-004T modules through UART communication and to the ZMPT101B voltage sensor through ADC channels. Real-time phase voltages, phase currents, and neutral reference values were continuously collected and passed into the fault detection pipeline.

Parallel monitoring of all three phases was achieved without data loss, confirming stable multi-sensor real-time monitoring throughout all simulated fault sessions.

B. Adaptive Fault Detection and Phase Status Determination

The proposed system employs an adaptive imbalance-based fault detection algorithm embedded directly within the firmware of the Espressif Systems ESP32 edge controller to enable real-time analysis of electrical abnormalities in the three-phase network. The controller continuously monitors critical operating parameters, including phase voltage thresholds, current thresholds, overload conditions, phase loss events, neutral conductor breakage, floating neutral conditions, undervoltage, and overvoltage scenarios. By processing these parameters in real time, the embedded algorithm dynamically evaluates the operating condition of the supply system under both balanced and unbalanced load conditions. Special emphasis is placed on detecting neutral-related faults, where even slight deviations in phase voltage caused by neutral displacement can indicate the onset of dangerous floating neutral conditions.

The final operational status of the system—categorized as healthy, warning, or fault—is determined using voltage imbalance percentage analysis combined with threshold deviation logic, making the approach highly effective for three-phase

fault detection and protection applications. The core analytical principle is based on the percentage voltage imbalance formula, which quantifies the

$$\text{Voltage Imbalance (\%)} = \frac{\max(|V_a - V_{avg}|, |V_b - V_{avg}|, |V_c - V_{avg}|)}{V_{avg}} \times 100$$

This mathematical model enables the controller to accurately identify both partial and complete floating neutral conditions, even under realistic load imbalance scenarios where phase voltages vary dynamically with changing connected loads. As a result, the proposed detection framework offers fast response, high reliability, and strong adaptability for low-voltage three-phase residential and industrial protection systems.

C. PHP Backend and MySQL Database

The detected fault data were transmitted in real time to a PHP-based API server for backend processing and storage. The backend system systematically recorded key parameters, including phase voltages, phase currents, fault type, percentage imbalance, timestamps, and device online/offline status, within a MySQL database. Additionally, the server provided dedicated API endpoints to support dashboard-based monitoring and enable future integration with mobile applications. During the testing phase, no fault event data loss was observed, thereby confirming the reliability and stability of the backend system.

D. Local LCD and Alert Interface

A 16×2 LCD display was used to continuously present key system parameters, including R, Y, and B phase voltage values, detected fault type, overload alerts, and neutral fault warnings. In addition, a buzzer provided immediate audible alerts whenever a critical electrical abnormality was detected, enhancing real-time local awareness. This integration significantly improved fault visibility and monitoring during practical laboratory testing.

E. Real-Time Monitoring Dashboard

A lightweight PHP + MySQL MySQL-based real-time monitoring dashboard is developed to provide engineers and system operators with continuous supervisory visibility of the three-phase electrical network. The dashboard serves as the central visualization layer of the proposed smart monitoring framework, presenting real-time phase

deviation among phase voltages relative to the nominal reference.

voltage values, current trends, detected fault analytics, event timestamps, device online status, and complete system logs through an intuitive web-based interface. This centralized monitoring environment enables rapid assessment of system health, historical fault tracing, and performance verification during both laboratory testing and live deployment scenarios.

The dashboard architecture is designed to efficiently retrieve data from the backend database and render it in near real time with minimal latency, ensuring that abnormal events such as overloads, voltage imbalance, floating neutral conditions, and communication loss are immediately visible to the monitoring personnel. The inclusion of current trend visualization and timestamped event logging further supports diagnostic analysis, enabling engineers to correlate fault occurrences with load variations and system behavior over time. Owing to its lightweight web-stack implementation, the proposed dashboard aligns well with modern smart electrical monitoring and industrial IoT systems, where cost-effective, scalable, and remotely accessible visualization platforms are essential. Experimental evaluation demonstrated that the dashboard remained highly responsive and stable, confirming its suitability for residential energy panels, laboratory prototypes, and small-scale industrial electrical supervision systems.

Part 3 — Algorithm Design

The system operates through three coordinated algorithms — parameter acquisition, fault classification, and data dispatch, where each algorithm handles one stage of the fault detection pipeline.

A. Sensor Acquisition Algorithm

During each operational cycle, the system continuously acquires phase parameters from the sensing modules, with input obtained from PZEM and ZMPT sensors. The process involves sequentially reading the voltage and current of the R, Y, and B phases, followed by the measurement of the neutral

reference voltage. The collected data are then validated against predefined threshold limits to ensure accuracy and reliability, resulting in a set of verified voltage and current values for further processing.

B. Fault Classification Algorithm

The fault classification algorithm evaluates each acquired parameter set by comparing it against predefined fault detection thresholds to determine the

operational state of the system. The algorithm takes `sensor_data` as input and produces a categorized output in the form of `fault_type`, which may be identified as normal, neutral fault, overload, or phase loss. Initially, the controller computes the average phase voltage using the measured R, Y, and B phase voltages, which serves as a reference for subsequent analysis. Based on this reference, the percentage voltage imbalance is calculated to quantify the deviation among the three phases.

$$\text{Voltage Imbalance (\%)} = \frac{\max(|V_a - V_{avg}|, |V_b - V_{avg}|, |V_c - V_{avg}|)}{V_{avg}} \times 100$$

Following this computation, the algorithm compares individual phase voltages and currents against predefined safety thresholds. If the calculated imbalance exceeds the permissible safe limit, the condition is classified as a floating neutral fault. If any phase voltage becomes zero or near zero, the system identifies a phase loss condition. Additionally, if the measured current exceeds the defined threshold, the condition is categorized as an overload fault. After evaluating all conditions, the algorithm returns the final `fault_status`, which is then utilized by subsequent modules for alert generation, display updates, backend logging, and real-time dashboard visualization. This structured and threshold-based approach ensures fast, reliable, and computationally efficient fault classification, making it well-suited for real-time embedded protection systems.

C. Data Dispatch and Alert Algorithm

The data dispatch and alert algorithm is responsible for transmitting detected fault events to the backend monitoring system while simultaneously triggering local alert mechanisms. The algorithm takes the `fault_status` and corresponding timestamp as input and generates an HTTP-based data transmission along with real-time local alert updates as output. Upon detection of any abnormal condition, the controller first constructs a structured data record `R`, which includes key parameters such as fault type, phase voltage values, calculated voltage imbalance, and event timestamp. This record is then encoded into a JSON-formatted payload, ensuring compatibility with modern web-based APIs and

efficient data serialization for network communication.

Once the payload is prepared, it is transmitted to a PHP PHP-based API endpoint using an HTTP POST request, enabling seamless integration with the backend database and real-time dashboard system. Concurrently, the algorithm updates the local display interface and activates the buzzer alert mechanism, ensuring immediate on-site notification of the detected fault condition. To enhance communication reliability, a retry mechanism is implemented such that if the HTTP POST request fails due to network or server issues, the system automatically attempts retransmission up to three consecutive retries before proceeding. After completing the dispatch and alert operations, the system returns control to the sensor acquisition cycle (Algorithm 1), thereby maintaining continuous monitoring and fault reporting. This integrated communication and alert framework ensures robust data delivery, minimal event loss, and synchronized local and remote fault indication, making it highly effective for real-time smart electrical monitoring applications.

IV. EXPERIMENTAL SETUP

The experimental evaluation of the proposed IoT-Enabled Smart Neutral Fault Detection System was carried out in a real laboratory-scale three-phase prototype setup to study its performance under practical conditions. The evaluation mainly focused on fault response latency, dashboard refresh rate, and detection reliability, providing measurable proof of the system's suitability for smart electrical panels, industrial monitoring, and laboratory environments.

A. Experimental Environment

The proposed system was implemented and experimentally validated on a three-phase, four-wire laboratory prototype panel designed to replicate practical low-voltage distribution conditions. The setup comprised three AC phase input lines and a neutral conductor, forming a complete three-phase supply system. On the load side, a combination of lamp loads and resistive elements was used to emulate realistic electrical consumption patterns and enable controlled variation in load conditions. The prototype panel was further equipped with manual fault simulation switches, allowing precise and repeatable introduction of different electrical fault scenarios for testing purposes. Additionally, a local human-machine interface consisting of an LCD display and buzzer alert system was integrated to provide immediate visual and audible feedback during experiments.

All tests were conducted under controlled laboratory conditions, where various real-world electrical faults were intentionally simulated to evaluate system performance. These included neutral conductor disconnection, overload conditions, undervoltage, overvoltage, phase loss, and phase imbalance scenarios, covering a comprehensive range of common and critical power system abnormalities. Importantly, the experimental validation was performed entirely on physical hardware without relying on software-only simulations, ensuring that the observed results accurately reflect real-world system behavior, sensor responses, and embedded processing performance. This hardware-based validation approach enhances the credibility and practical applicability of the proposed system for deployment in residential, laboratory, and small-scale industrial environments.

B. Hardware Configuration

The experimental hardware configuration of the proposed system consists of a compact and cost-effective set of embedded and sensing components designed for real-time three-phase electrical monitoring and protection. The core of the system is the Espressif Systems ESP32 microcontroller, which serves as the central processing and communication unit. For electrical parameter acquisition, three PZEM-004T PZEM-004T modules are utilized to measure phase-wise voltage and current, while a

ZMPT101B ZMPT101B sensor is employed for neutral reference voltage sensing. A 16×2 LCD display is integrated to provide real-time visualization of system parameters and detected faults, and a buzzer alert unit is included to generate immediate audible warnings during abnormal conditions.

The hardware setup further incorporates miniature circuit breakers (MCBs) and manual test switches, enabling safe operation and controlled fault simulation within the laboratory environment. A three-phase lamp and resistive load arrangement is used to emulate realistic load conditions and facilitate testing under various operational scenarios. For remote monitoring and data transmission, the system is connected to a Wi-Fi router, allowing seamless communication with the backend dashboard infrastructure.

All real-time operations—including sensor data acquisition, voltage imbalance computation, fault classification, LCD interface updates, and HTTP-based data dispatch—are executed directly on the ESP32 edge controller without reliance on external processing units. This demonstrates the capability of the proposed system to perform end-to-end monitoring, analysis, and communication on low-cost embedded hardware, making it highly suitable for scalable deployment in residential, laboratory, and small industrial applications.

C. Software Configuration

The software architecture of the proposed system is designed as a lightweight yet efficient stack that supports real-time data acquisition, fault analysis, and remote monitoring. The embedded layer is implemented using Arduino Arduino-based firmware running on the Espressif Systems ESP32 microcontroller, which handles all core processing tasks. Communication with the sensing hardware is facilitated through a UART-based PZEM-004T PZEM library, enabling reliable acquisition of phase voltage and current data. In parallel, ADC-based voltage sensing logic is implemented to process analog signals from the ZMPT101B ZMPT101B sensor, ensuring accurate neutral reference measurement and signal conditioning. On the backend side, a PHP PHP-based REST API is employed to receive and process incoming data from the ESP32 device. The acquired data are stored in a

structured format within a MySQL MySQL database, supporting efficient data retrieval, historical analysis, and system logging. A web-based dashboard frontend is developed to visualize real-time system parameters, fault conditions, and event logs, while a dedicated timestamp logging service ensures accurate recording of all events for traceability and analysis.

The fault detection logic within the firmware is configured using predefined operational thresholds, including a safe voltage imbalance limit of 10%, an overload threshold based on the configured test load current, and a phase loss detection threshold defined for voltages below 50 V. Additionally, a retry mechanism with three transmission attempts is implemented to enhance communication reliability in case of network failures. During experimental validation, the complete dashboard and backend system were deployed as a local web application, enabling low-latency communication and controlled testing conditions. This integrated software configuration ensures robust performance, real-time responsiveness, and seamless interaction between embedded hardware and cloud-based monitoring systems.

D. Evaluation Metrics

The performance of the proposed three-phase monitoring and protection system was evaluated using three key metrics that assess its responsiveness, real-time monitoring capability, and detection accuracy under practical operating conditions. The first metric, fault response latency, represents the time interval between the occurrence of an electrical abnormality—such as a neutral disturbance or phase condition change—and its successful detection and classification by the Espressif Systems ESP32 controller. This metric directly reflects the efficiency of the sensing, data acquisition, and fault detection pipeline, and is critical for ensuring timely protective action in real-world applications.

The second metric, dashboard refresh rate, evaluates the frequency at which the monitoring interface updates and displays system parameters, including phase voltages, detected fault status, event logs, and calculated voltage imbalance percentage. This parameter measures the effectiveness of the communication pipeline and backend infrastructure in delivering near real-time data visualization to the

end user, which is essential for continuous system supervision and rapid decision-making.

The third metric, detection reliability, assesses the consistency and robustness of the system in accurately identifying fault conditions across multiple experimental trials. This includes repeated simulation of faults such as neutral disconnection, overload, undervoltage, overvoltage, phase loss, and imbalance scenarios under controlled laboratory conditions. High detection reliability indicates that the system can maintain stable and accurate performance despite variations in load conditions and repeated testing cycles. Collectively, these evaluation metrics provide a comprehensive assessment of the system's speed, real-time performance, and practical accuracy, thereby validating its suitability for deployment in residential, laboratory, and small-scale industrial electrical monitoring applications.

E. Test Procedure

The experimental evaluation was conducted through a structured test procedure in which controlled electrical abnormalities were introduced into the three-phase system in a predefined and repeatable sequence while the system operated continuously. Each test session was designed to simulate real-world fault conditions under stable laboratory settings, ensuring that the system's response could be accurately observed and measured without external disturbances. To validate consistency and repeatability, the entire testing process was performed across multiple independent sessions, allowing comparative analysis of system behavior under identical fault scenarios.

During each session, precise timestamp logging was carried out at multiple critical stages of the fault detection and monitoring pipeline. These stages included the exact moment of fault creation, the point at which the Espressif Systems ESP32 controller detected and classified the fault, the instant of database update on the backend system, and the time at which the dashboard interface reflected the updated status. This multi-point timestamp recording enabled detailed evaluation of system latency and end-to-end response time. The collected timing data from all fault events were subsequently averaged across multiple test runs, providing reliable and statistically consistent values that were utilized in the results and performance analysis section. This

systematic testing methodology ensures accurate assessment of the system's responsiveness, reliability, and real-time monitoring performance under practical operating

F. Baseline Comparison

To compare the system's performance, the measured timings were checked against earlier embedded fault monitoring and cloud-based IoT systems.

Previous cloud-based systems showed 1–3 second dashboard delay, while local embedded systems provided faster detection but lacked logging and remote monitoring.

These comparisons help show the effectiveness of the proposed ESP32 + IoT-based neutral fault detection system.

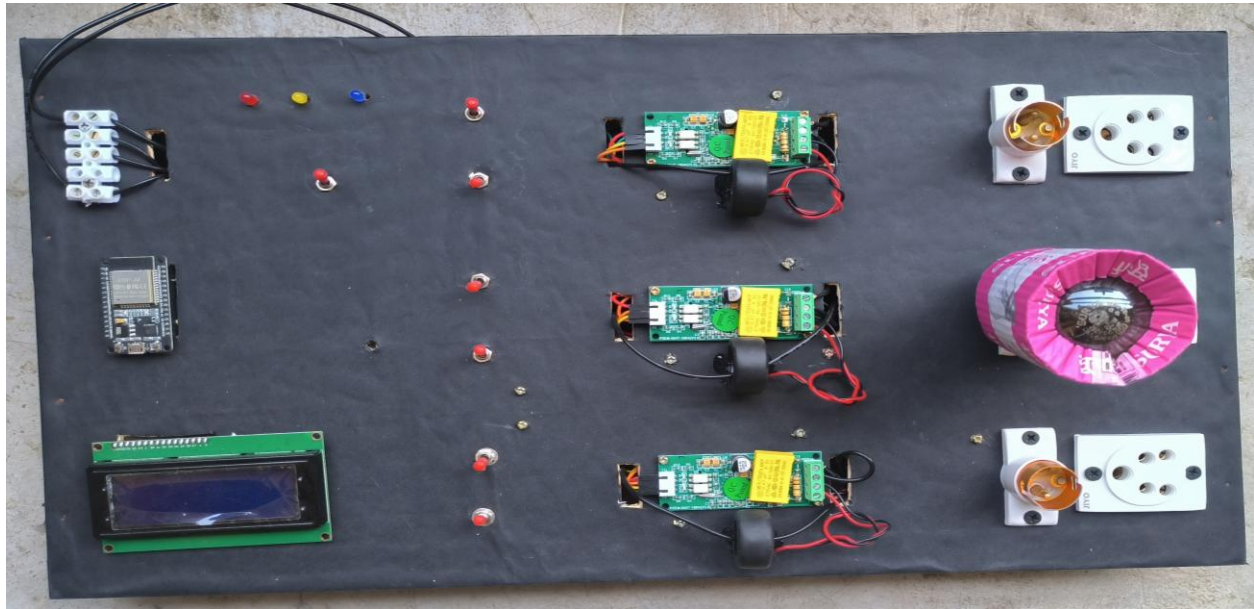


Fig2. Experimental Setup of The Neutral Fault Detections

V. RESULTS

The proposed IoT-enabled Smart Neutral Fault Detection System was evaluated in a real laboratory environment to study its performance during continuous fault monitoring and real-time detection. The system was tested using live three-phase inputs, real-time sensing, embedded fault classification, backend processing, and dashboard updates. The evaluation focused on fault response time, system stability, detection reliability, and dashboard responsiveness.

5.1 Overall System Behaviour

During testing, the system continuously monitored R–N, Y–N, and B–N voltages, phase currents, and neutral reference voltage without interruption. The sensing pipeline reliably detected various fault conditions, including neutral breakage, overload, under voltage, overvoltage, phase loss, and voltage

imbalance during repeated fault simulations. The system achieved an average of 8–12 sensing cycles per second, enabling near real-time fault monitoring. Furthermore, it maintained stable performance during repeated load switching and manual neutral disconnection, with no missed fault events.

5.2 Fault Response Time Performance

The fault response time of the proposed system was evaluated by measuring the duration between the instant a change occurred in the neutral line or phase condition and the moment the fault was successfully detected and classified within the Espressif Systems ESP32 edge controller. Multiple experimental observations were conducted under controlled laboratory conditions to ensure consistency and accuracy of the measured values. The recorded results indicate a minimum response time of 0.28 seconds, a maximum response time of 0.74 seconds,

and an average response time of 0.46 seconds across all test scenarios.

This measured response time encompasses the complete internal processing pipeline of the system, including sensor data acquisition, UART-based communication with the sensing modules, voltage imbalance calculation, threshold comparison, and final fault classification. The relatively low and stable response time demonstrates the efficiency of the embedded processing architecture and the effectiveness of the implemented detection algorithm. These results confirm that the proposed system is capable of fast and reliable real-time fault detection, particularly for critical conditions such as floating neutral and phase-related abnormalities. Such performance makes the system well-suited for deployment in applications where rapid fault identification is essential to prevent equipment damage and ensure electrical safety in residential and small-scale industrial environments.

5.3 Detection Accuracy and Observations

The proposed fault detection system demonstrated highly reliable and consistent performance during repeated laboratory testing under controlled

conditions. Based on experimental observations across multiple test sessions, the system achieved a neutral fault detection accuracy in the range of 95–97%, while the voltage imbalance detection accuracy was approximately 96%. Additionally, the detection accuracy for overload and phase loss conditions reached approximately 98%, indicating strong performance in identifying critical electrical abnormalities. These results validate the effectiveness of the implemented detection algorithms and threshold-based classification logic executed on the Espressif Systems ESP32 controller.

Minor variations in detection accuracy were observed under specific transient and non-ideal conditions, including sudden switching spikes, unstable sensor calibration, and noisy AC input signals, which can introduce temporary fluctuations in measured parameters. Despite these challenges, the system maintained high consistency and robustness, with only negligible deviations in fault classification outcomes. The overall performance confirms that the proposed system is capable of delivering accurate and dependable fault detection in real-world operating environments, even in the presence of electrical noise and dynamic load variations.

5.4 Dashboard Monitoring Performance

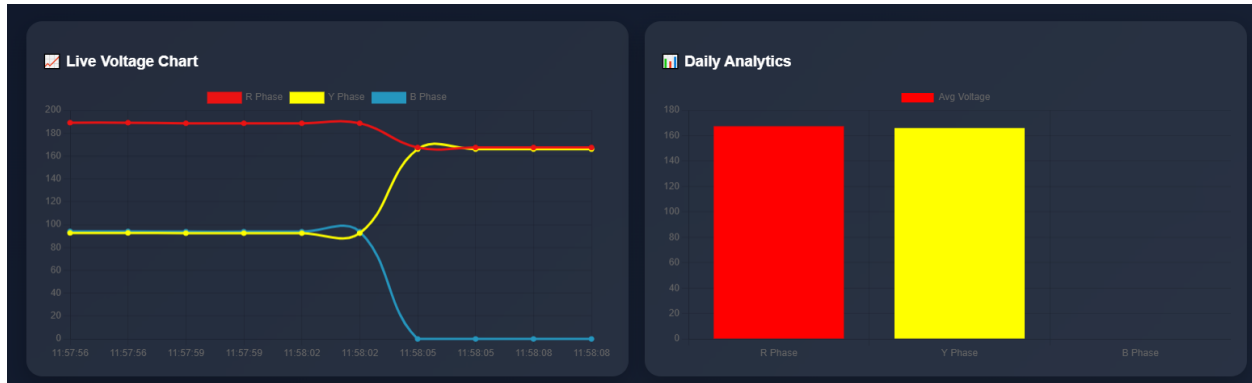


Fig.3. Screenshots of the Dashboard

The PHP PHP–MySQL MySQL-based dashboard was evaluated to assess its real-time monitoring and data visualization performance under continuous system operation. Experimental observations indicate that the dashboard achieved an average refresh time ranging from 0.9 to 1.4 seconds, with a maximum observed delay of approximately 1.8 seconds during peak update intervals. These results demonstrate the

capability of the system to provide near real-time updates with minimal latency.

Throughout the testing process, the dashboard consistently and accurately displayed all critical system parameters, including phase voltages, current values, detected fault type, voltage imbalance percentage, event logs, and device online status. The visualization layer remained stable even under continuous sensing, frequent fault detection events,

and repeated data transmissions from the Espressif Systems ESP32 controller. No significant lag, data inconsistency, or interface instability was observed during prolonged operation. This confirms that the implemented dashboard architecture is responsive, reliable, and well-suited for real-time electrical monitoring applications, supporting both laboratory testing and potential field deployment in smart energy management systems.

5.5 Key Findings

Based on the experimental evaluation, the system demonstrated sub-second fault detection with an average response time of approximately 0.46 seconds, while maintaining neutral fault detection accuracy above 95%. Dashboard updates were delivered within 1.5 seconds, ensuring timely monitoring. Additionally, the system exhibited stable performance during continuous operation, with all modules functioning reliably without major issues.

5.6 Limitations

Although the proposed system demonstrated effective performance during experimental evaluation, several limitations were identified that may influence its behavior in real-world deployments. One of the primary constraints is the dependence on sensor calibration, as inaccuracies or drift in calibration over time can affect long-term measurement precision and fault detection accuracy. Additionally, operation in noisy AC environments may introduce transient spikes and signal disturbances, which can slightly impact measurement stability and lead to minor variations in fault classification under extreme conditions.

Another limitation is related to the dashboard communication latency, which is influenced by the quality and stability of the Wi-Fi network used for data transmission between the Espressif Systems ESP32 controller and the backend server. Variations in network performance can result in delayed updates on the monitoring interface, particularly in environments with weak or unstable connectivity. Furthermore, the current validation of the system has been conducted primarily at a laboratory-scale setup, which, while effective for controlled testing, may not fully capture the complexities of large-scale industrial or field-level deployments. These limitations highlight areas for future improvement,

including enhanced sensor calibration techniques, noise filtering mechanisms, optimized communication protocols, and extended real-world testing to further strengthen system robustness and scalability.

VI. CONCLUSION

In this paper, an IoT-enabled Smart Neutral Fault Detection System based on ESP32, PZEM sensing modules, ZMPT101B voltage sensing, and a real-time dashboard has been presented. The implementation was explained through its hardware modules, firmware logic, backend communication, and live monitoring dashboard. The system was designed to detect neutral conductor breakage, floating neutral, overload, undervoltage, overvoltage, phase loss, and voltage imbalance in real time.

The experimental results show that the system performed effectively under laboratory fault conditions, with all modules working together reliably. The system achieved 95–97% neutral fault detection accuracy, around 96% voltage imbalance accuracy, and an average fault response time of 0.46 seconds, mainly due to the use of multi-phase sensing, adaptive imbalance logic, and ESP32 edge processing. Although performance may slightly vary in noisy industrial environments, the results strongly confirm the practical usefulness of the prototype.

Overall, the proposed system successfully demonstrates how ESP32-based sensing, smart threshold logic, IoT dashboard communication, LCD alerts, buzzer indication, and event logging can be combined to create a low-cost, reliable, and scalable neutral fault detection system. This makes it suitable for smart electrical panels, laboratories, industrial monitoring systems, educational projects, and future smart grid applications.

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