IJARSCT
ISSN: 2581-9429
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Volume 5, Issue 10, April 2025
Impact Factor: 7.67

Real-Time Detection and Classification of Three-Phase Transmission Line Faults Using an IoT-Enabled Arduino and ESP32 Embedded System

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Abstract: *This paper presents the design and implementation of an embedded system for the detection and classification of faults in a three-phase transmission line. The proposed system uses an Arduino UNO microcontroller and ESP32 IoT module to detect four types of faults: line-to-line (L-L), line-to-ground (L-G), open-circuit, and over/under voltage. The system utilizes sensing circuits to monitor phase voltages and currents, with an LCD display for real-time fault information, a buzzer for audible alerts, and SMS notifications sent to a mobile device using the Twilio API. Additionally, the system incorporates a relay mechanism for phase isolation in case of voltage anomalies. Testing results indicate the system's accuracy in detecting faults, fast response time, and efficient alerting mechanism, making it a reliable and cost-effective solution for improving the safety and reliability of power transmission systems. The integration of IoT-based notifications enables remote monitoring, while the system's modularity allows for scalability in larger networks..*

Keywords: embedded system

I. INTRODUCTION

The growing demand for efficient and reliable monitoring systems in power transmission infrastructure has driven the development of advanced fault detection mechanisms[1]. This research introduces a microcontroller-based system utilizing the Arduino platform to detect and classify multiple faults in a three-phase transmission line[2]. The system is designed to identify four types of electrical faults: line-to-line faults, line-to-ground faults, over-voltage and under-voltage conditions, and open-circuit faults[3].

The detection mechanism relies on the principles of Ohm's law, offering a simple and effective way to identify abnormalities within the transmission system. The system is both cost-effective and rapid in its response, making it ideal for real-time monitoring. A key component of the system is the integration of an ESP32 module with built-in Wi-Fi, which enables real-time fault notifications via SMS alerts using the Twilio API[4].

A potentiometer is included to simulate various voltage levels, enabling controlled testing for voltage-related faults. When a fault is detected, the system triggers an audible alarm through a buzzer and displays the fault type on an LCD screen. For voltage anomalies, such as over- or under-voltage conditions, a relay mechanism trips the circuit, and the affected phase is indicated by a corresponding light bulb.

Current sensing is achieved through a combination of resistors and switches interfaced with the Arduino's analog-to-digital conversion (ADC) port[5]. These sensors are calibrated to represent cable lengths in kilometers, and fault induction is manually initiated at specific points. The Arduino UNO, powered by a rectified supply, serves as the control unit. This model not only enhances transmission line safety but also offers scalability for smart grid applications[6].

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II. OBJECTIVES

The primary objective of this research is to design and implement a microcontroller-based three-phase transmission line fault detection system capable of identifying and responding to various electrical faults. The specific objectives of the proposed system are as follows:

- To develop a fault detection system for three-phase transmission lines that can accurately identify:
  - Line-to-line (L-L) faults
  - Line-to-ground (L-G) faults
  - Open-circuit faults
  - Over-voltage and under-voltage conditions
- To integrate an Internet of Things (IoT) module for real-time fault notification, enabling remote alert delivery to the user via mobile communication platforms.
- To implement over-voltage and under-voltage protection mechanisms that ensure safe operation by automatically tripping the system when abnormal voltage levels are detected.
- To provide immediate audible fault indication using a buzzer to enhance system responsiveness and local awareness of the fault condition.
- To display the type and nature of the detected fault on an LCD screen, ensuring clear and accessible visual information for system operators or technicians.

III. OVERVIEW

Embedded systems combine hardware and software to perform specific tasks within a larger system[7]. These systems often use microprocessors or microcontrollers as the core processing units. Microprocessors are general-purpose processors that require external components for functions like data storage and I/O interfacing. In contrast, microcontrollers are self-contained units with processing cores, memory, and peripheral interfaces, allowing them to process data and control connected devices effectively.

The proposed project uses an embedded system to detect and classify faults in a three-phase transmission line in real-time[8]. It identifies line-to-line (L-L), line-to-ground (L-G), open-circuit faults, and over-voltage and under-voltage conditions. The system integrates with the Internet of Things (IoT) via the ESP32 microcontroller, enabling fault notifications through mobile alerts using the Twilio API.

Additionally, the system provides visual feedback via an LCD display, indicating the fault type and affected phase (R, Y, or B). Over-voltage and under-voltage conditions trigger a protective relay that disconnects the circuit and activates indicator bulbs for the corresponding phase. A buzzer also provides an audible alert, ensuring quick response and fault resolution. This system enhances the safety and reliability of three-phase power networks[9].

IV. METHODOLOGY

The proposed three-phase fault detection system is developed using an embedded platform centered around the Arduino UNO microcontroller[10]. This system combines hardware and software components to detect, classify, and alert users about faults, providing both visual and audible notifications.

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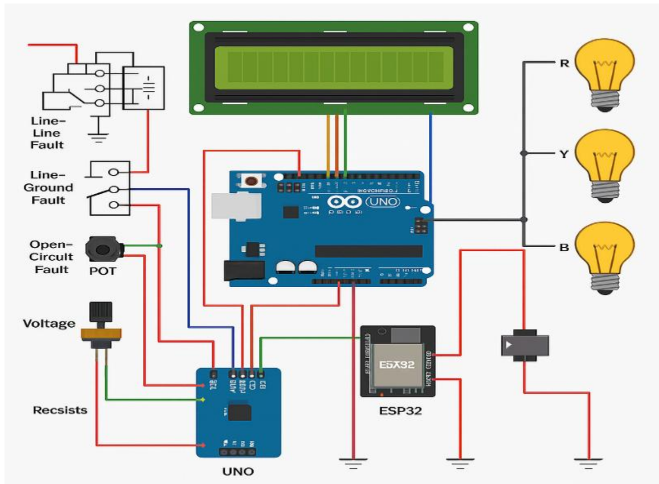

Figure 1. Methodology of the project

System Architecture

The architecture consists of several key modules:

Fault Detection Circuitry: A set of resistors and switches is used to simulate various faults, including line-to-line (L-L), line-to-ground (L-G), open-circuit, and over/under voltage. These faults are manually triggered at predefined points for testing purposes.

Voltage Variation Unit: A potentiometer adjusts voltage levels to simulate over-voltage and under-voltage conditions.

Microcontroller Unit: The Arduino UNO processes analog inputs from the sensing circuitry, compares them to programmed thresholds, and makes decisions to classify faults.

Figure 2. Arduino UNO

IoT Notification Module: The ESP32, with built-in Wi-Fi, sends real-time fault notifications to the user via the Twilio platform[11]. It relays fault data from the Arduino to the cloud.

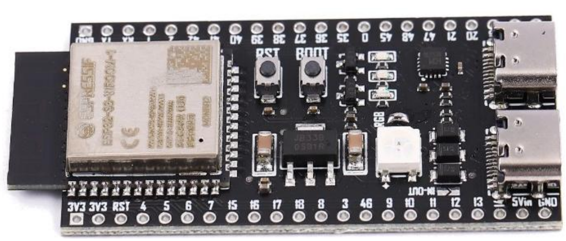
Figure 3. ESP32

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Relay and Load Circuit: A relay circuit is connected to indicator bulbs for the three phases (R, Y, B), demonstrating the tripping mechanism during voltage anomalies.

Figure 4. Relays

Alert and Display Unit: A buzzer sounds an audible alert, and a 16x2 LCD module displays the fault type and the affected phase.

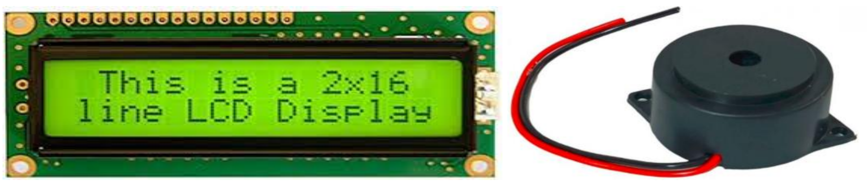

Figure 5. 16 x2 LCD and Buzzer

Software Development

The firmware, developed using Embedded C and uploaded through the Arduino IDE[12], performs tasks such as analog-to-digital conversion, fault classification, LCD interfacing, and relay control for tripping faulty phases.

Fault Simulation and Testing

Faults are manually simulated using switches, and the system determines if the input voltage/current is within safe limits, classifies the fault, and initiates responses like activating the buzzer, displaying the fault on the LCD, tripping the relay, and sending SMS alerts via Twilio.

Communication and Alerts

The Twilio API, integrated with the ESP32, sends SMS notifications about fault types and affected phases, ensuring remote fault monitoring.

V. CIRCUIT DIAGRAM EXPLANATION

The circuit diagram of the proposed three-phase fault detection system is designed to replicate real-world transmission line conditions and demonstrate fault detection and classification using embedded components[13]. The system integrates fault simulation switches, voltage variation modules, sensing units, and output indicators, all connected to a central microcontroller (Arduino UNO) and an IoT module (ESP32).

Power Supply Section

The system is powered by a regulated DC supply. An AC source is stepped down by a transformer, rectified using a bridge rectifier, and regulated by voltage regulators to provide a stable 5V DC output to the Arduino UNO, ESP32, and other components.

Fault Simulation Network

The system uses manually operated switches to simulate various faults:

- **Line-to-Line Fault (L-L):** Shorting two phase lines using a switch.
- **Line-to-Ground Fault (L-G):** Connecting a phase line to the ground terminal.
- **Open Circuit Fault:** Breaking the path of any line to stop current flow.
- **Over/Under Voltage Faults:** Adjusting voltage levels with a potentiometer to simulate voltage fluctuations.

These switches are placed to represent distances (in kilometers) along a transmission line, allowing for scalable fault localization.

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Sensing and Input Section

Voltage and current variations are monitored using voltage dividers and resistor networks. These signals are fed to the Arduino UNO's analog-to-digital converter (ADC) pins, which separately monitor each phase (R, Y, B) for anomalies[14].

Microcontroller Interface

The Arduino processes these analog inputs and classifies the faults based on predefined thresholds. It then activates the LCD display, buzzer, and sends a fault signal to the ESP32 for mobile notifications.

Output Display and Alert Section

The system provides feedback through an LCD display, buzzer, and phase indicators. The LCD shows the fault type and affected phase, while the buzzer gives an audible alert. Relays trip the corresponding phase bulb during over/under voltage events.

IoT and Notification Module

The ESP32, connected to the Arduino via serial communication, processes the fault data and sends SMS alerts using the Twilio API, providing remote notifications about the fault and the affected line.

This system offers a comprehensive approach for detecting, displaying, and notifying faults in a three-phase transmission line, ensuring rapid response and maintenance.

VI. WORKING PRINCIPLE

The operation of the proposed three-phase fault detection system is based on continuous monitoring of voltage and current parameters in each phase of the transmission line using an embedded microcontroller. The central processing unit, Arduino UNO, analyzes these parameters in real-time to detect and classify electrical faults.

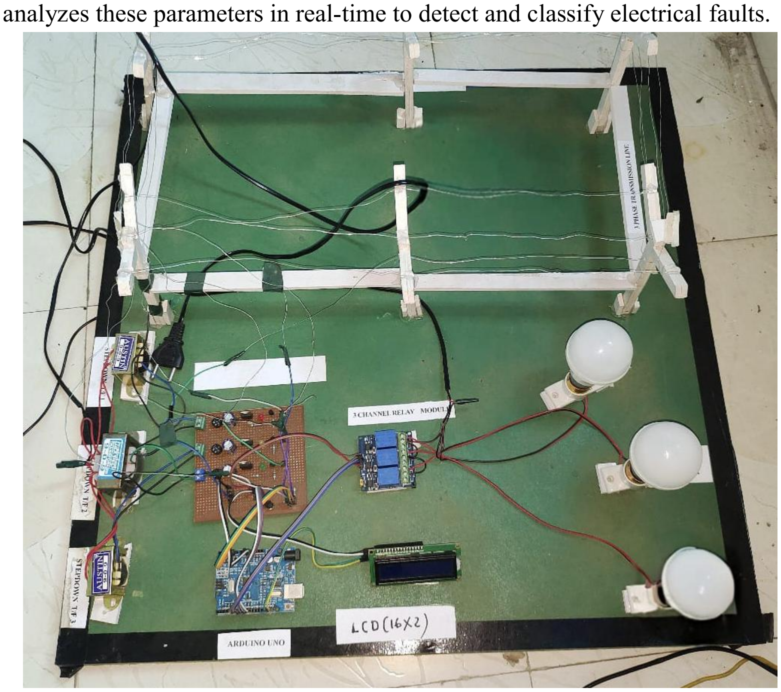

Figure 6. Project Image

Fault Detection Mechanism

The system is designed to detect four primary fault types:

- **Line-to-Line Fault (L-L):** Occurs when two phase lines come into contact, causing a drop in resistance and an increase in current. The system detects this fault through abnormal current readings and voltage deviations.
- **Line-to-Ground Fault (L-G):** Happens when a phase line is connected to the ground, leading to a surge in current. The system identifies this fault through a current spike.
- **Open-Circuit Fault:** Occurs when current flow is interrupted in one or more phases. The system uses Ohm's Law to detect the absence of current or voltage, indicating an open circuit.
- **Over-Voltage/Under-Voltage Fault:** Voltage levels are adjusted using a potentiometer to simulate abnormal conditions. If voltage exceeds or falls below predefined thresholds, the system detects it as over-voltage or under-voltage.

System Operation

- **Monitoring:** The Arduino reads analog voltage values from each phase's sensing circuit, converting them into digital values via ADC ports.
- **Comparison and Decision Making:** These values are compared to predefined thresholds, and logical conditions determine whether the line is normal or faulty.
- **Fault Classification:** If a fault occurs, the type and affected phase are identified based on the voltage or current deviations.
- **System Response:** The LCD displays the fault and phase, the buzzer sounds, a relay isolates the faulty line, and an SMS alert is sent to the user via the ESP32 module and Twilio API.
- **Reset and Recovery:** The system resets after the fault is resolved, resuming monitoring.

VII. RESULTS

The fault detection system was successfully implemented and tested under various conditions. The system accurately identified and classified faults[15], including line-to-line (L-L), line-to-ground (L-G), open-circuit, and over/under voltage faults. When a fault was detected, the LCD display showed the fault type and affected phase. The system also activated the buzzer for immediate audible alerts and sent mobile notifications using the Twilio API for real-time updates.

For voltage-related faults, such as over-voltage and under-voltage, the relay mechanism quickly disconnected the circuit, and corresponding phase indicator bulbs were lit. The system's response time was fast, ensuring timely detection and mitigation of faults. Manual fault induction at specific distances allowed for the testing of fault localization, and the system reliably identified the fault type and location.

Overall, the system demonstrated high accuracy, fast response time, and effective fault notification and protection, proving to be a reliable solution for enhancing power transmission safety.

VIII. ADVANTAGES

The fault detection system offers several key benefits:

- **Real-time detection**: Quickly identifies faults and displays the fault type and phase.
- **Cost-effective**: Uses affordable components, making it an economical solution.
- **Remote notifications**: Sends real-time alerts to users via mobile using the Twilio API.
- **Enhanced safety**: Automatically isolates faults using a relay mechanism and provides audible and visual alerts.
- **Scalable**: The system can be expanded for larger networks or integrated into smart grid applications.
- **User-friendly**: LCD display and buzzer provide clear local alerts.

These advantages make the system an efficient and reliable tool for enhancing the safety and reliability of power transmission networks.

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IX. CONCLUSION

This research presents a microcontroller-based system for real-time detection and classification of faults in a three-phase transmission line[16]. The system effectively identifies line-to-line, line-to-ground, open-circuit, and voltage-related faults. It features IoT-based mobile notifications, local fault indication on an LCD display, and automatic fault isolation via a relay mechanism. The system demonstrated high accuracy, fast response, and reliability, offering a cost-effective and scalable solution for improving power transmission safety. Future work may focus on enhancing fault localization and integrating advanced communication protocols for larger networks.

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DOI: 10.48175/IJARSCT-25664

ISSN 2581-9429 IJARSCT