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An Efficient LoRa-Enabled Smart Fault Detection and Monitoring Platform for the Power Distribution System Using Self-Powered IoT Devices

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ABSTRACT—

This project proposes a smart cable fault detection and monitoring system that accurately identifies and locates both open-circuit and short-circuit faults in electrical transmission lines using the ESP32 microcontroller as the central processing unit. The system is implemented with multiple switches placed at distances of 100 m, 200 m, 300 m, and 400 m from the test setup to simulate real-time cable fault conditions and enable precise fault localization. Through continuous monitoring of key electrical parameters, the system effectively detects abnormal variations in current and voltage levels that may indicate developing fault conditions, which could otherwise result in power interruption, equipment damage, or serious safety hazards. High-precision current and voltage sensors are employed to ensure accurate measurement of electrical parameters and to acquire real-time data from the connected lighting load. These real-time signals are processed by the ESP32, which continuously evaluates the operating condition of the system and determines whether the circuit is functioning normally or under faulty conditions. Upon fault detection, a relay-driven indicator system is activated to visually alert the presence of a fault, providing clear differentiation between fault and no-fault states, thereby enhancing operational awareness and significantly reducing maintenance response time. Furthermore, detailed fault information, including the type of fault and its exact distance from the source, is wirelessly transmitted to a laptop using the HC-12 communication module, enabling efficient remote monitoring and continuous data logging. This wireless communication feature allows operators to observe system status without physical inspection, thereby improving safety and reliability. The strong integration of sensing units, microcontroller- based processing, relay control, and wireless communication enhances industrial fault management by delivering reliable, real- time insights into system performance. Overall, the proposed system provides a cost-effective, scalable, and efficient solution for intelligent fault detection, remote monitoring, and preventive maintenance in modern electrical distribution networks, making it highly suitable for smart grid and industrial power applications.

1. Introduction

In modern electrical systems, the continuous supply of power and reliable network operation are vital. for industrial, commercial, and domestic applications. However, faults in electrical cables, such as open and short circuits are among the most common problems that disrupt system performance and cause equipment failures, energy losses, and safety risks. Early fault detection and accurate fault Location plays an important role in minimizing downtime, reducing maintenance costs, and ensuring uninterrupted operation of electrical distribution networks. The following project describes the development of an ESP32 microcontroller-based intelligent cable fault detection system that is capable of detecting and locating both open and short circuit faults across predefined distances. The proposed system will be effective and economical for fault detection by integrating It is equipped with various hardware components, including voltage and current sensors, switches for fault simulation, an LoRa wireless communication module and a relay-connected light indicator. The ESP32 is used as it is the central processing unit that monitors the electrical parameters in real time and performs logical analysis to detect abnormalities in the circuit. In industrial environments where wiring networks extend over long distances, it becomes inefficient and time-consuming for manual inspections to locate faults. consuming. Thus, the proposed system automates the process of fault detection and provides immediate Feedback regarding the nature and location of faults significantly improves system reliability and maintenance efficiency. Open circuit faults result when the continuity of the conductor is disrupted resulting in a complete interruption of current flow. On the other hand, short circuit faults arise when two points of different potential in a circuit are connected, resulting in excessive current flow that can damage components or trigger a hazardous situation. Accurate fault detection and classification are crucial to prevent electrical infrastructure damage while ensuring personnel safety. In the project, the system is designed detects both fault types by monitoring voltage and current level variations through sensors.

2. LITERATURE SURVEY

[1] R. S. Koley et al.: IoT-Based Smart Fault Detection in Power Distribution Systems (2023)

R. S. Koley et al. have proposed an IoT-based fault detection framework for electrical distribution networks using microcontrollers and wireless communication. The research study underlines the need for real-time monitoring of voltage and current parameters for the early identification of abnormal operating conditions. In this regard, the study outlines that integrating IoT into power systems enhances reliability while reducing system downtime and opening vistas for predictive maintenance. This study directly helps to validate the approach of the proposed project by using ESP32 and transmitting the data wirelessly for intelligent fault monitoring.

[2] V. Kumar et al.: Cable Fault Detection Using Microcontroller and Sensors (2022)

V. Kumar et al. presented in the year 2022 a microcontroller-based underground cable fault detection system which successfully detects open and short circuit faults by analyzing changes in voltage levels. The proposed system was able to successfully locate faults based on predefined distances using resistive network principles. This research forms the technical foundation for the distance-based fault identification used in the proposed model with switches configured at 100 m, 200 m, 300 m, and 400 m.

[3] A. D. Patel et al.: Wireless Sensor Networks for Power System Monitoring (2023).

The researchers Patel et al. have discussed the role of WSNs in modern power distribution systems in their 2023 work. Their work shows how real-time data transmission through low-power wireless modules enhances system supervision and increases fault response speed. Their results confirm that wireless communication minimizes human intervention and offers remote monitoring, thus directly supporting the use of the HC-12/LoRa module in the proposed system. [4] S. Mehta et al.: ESP32-Based Smart Energy Monitoring and Protection (2021) S. Mehta et al. 2021 explain the implementation of ESP32 in smart energy monitoring applications owing to its high processing capability, on-board communication features, and low power consumption. Their work demonstrates efficient sensor data acquisition, real-time processing, and automated fault indication using relays and indicators. This reference provides validity to the choice of ESP32 as the core controller for real-time fault detection and decision-making in the proposed system. [5] M. H. Rahman et al.: Current and Voltage Sensor-Based Fault Analysis (2022) Rahman et al (2022) target the application of voltage and current sensors for reliably detecting abnormal conditions during operation in electrical networks. The results of the study indicate that by continuously sensing and comparing parameters, early fault detection before reaching catastrophic failure is achievable. This research justifies the adopted sensor-based monitoring approach in the proposed system for real-time fault identification and the enhancement of safety.

[4] S. Mehta et al.: ESP32-Based Real-Time Fault Detection Using IoT (2021)

S. Mehta et al., 2021, proposed a real-time electrical fault detection system based on the ESP32 microcontroller and IoT technology. Their study focuses on continuous voltage and current monitoring for abnormal conditions in a power distribution network. The system makes use of sensor-based data acquisition and an intelligent processor to classify normal and faulty states with high accuracy. In this work, they have pointed out that the microcontroller-based methods will help to perform real-time fault detection along with automated alert mechanisms to meet the challenges of improved power system reliability. In this context, this reference directly supports the proposed project based on validation for the usage of ESP32 for real-time electrical parameter processing with fault decision-making.

[5] M. H. Rahman et al.: Secure Wireless Transmission of Power System Data Using IoT (2022)

M. H. Rahman et al. discuss the importance of secure and reliable wireless transmission of electrical fault data in power monitoring systems. Their work in this area has highlighted various challenges, such as data loss, interference in the signals, and unauthorized access to wireless power- monitoring networks. They go ahead to proffer an efficient data transmission framework with low-power wireless communication and encryption techniques. This reference provides a great basis for the wireless transmission of fault data in the proposed system using the HC-12 communication module, ensuring reliable remote monitoring and integrity of data. [6] Patel et al.: Smart Grid Fault Detection and Remote Monitoring Framework (2024) Patel et al. (2024) target the design of smart grid-based fault detection systems that employ real-time monitoring and visualization. Their work focuses on the shift from manually operated inspection techniques to intelligent, automated fault detection systems using IoT, wireless communication, and remote data logging. This paper identifies key integrations of sensing units, microcontroller processing, and a wireless network that can result in quicker response times with low maintenance costs. This work provides strong support for the proposed system's objectives of a scalable, real-time, remotely accessible fault detection platform for modern power distribution networks.

[6] Patel et al.: Intelligent Smart Grid Fault Detection and Remote Monitoring Framework (2024)

Recent research by Patel et al. (2024) focuses on enhancing the reliability and safety of power distribution systems through intelligent fault detection and real-time monitoring frameworks. Their work highlights a shift from conventional manual inspection methods to automated, multi- layered monitoring systems using IoT, embedded controllers, and wireless communication technologies. The authors propose a smart grid architecture that integrates voltage and current sensors, intelligent data processing units, and remote monitoring platforms to detect and localize faults with high accuracy. The system also emphasizes real-time visualization and automated alert mechanisms to enable quick maintenance response and reduce power outage durations Furthermore, the study discusses the role of wireless communication modules and cloud-based data logging for continuous supervision of electrical networks. This research strongly supports the proposed project by proving the definite need for a multi-layered, intelligent, remotely accessible fault detection system that ensures higher reliability, operational efficiency, and preventive maintenance in modern power distribution networks.

3. Proposed System Architecture / Methodology

1. Central Processing Unit and Data Manipulation The whole system is designed around the ESP32 microcontroller due to its low power consumption, high processing speed, dual-core architecture, and multiple hardware serial communication ports that support efficient parallel task execution. The ESP32 acquires real-time data through the current and voltage sensors and processes these electrical parameters to determine the operational condition of the transmission line. One serial interface is configured for communication with the HC-12 wireless module to transmit fault information, while other GPIO pins are used for sensor inputs and relay control. Internal memory and program storage log fault conditions and system status for stable operation, with accurate fault diagnosis even in continuous monitoring.
2. Fault Detection and Classification Module: This module acts as the core logic of the system; it constantly reads voltage and current values from the connected sensors. ESP32, therefore, compares the sensed data with the pre-set threshold limits for the detection of faults like open-circuit and short-circuit conditions. Further, for real-time cable fault simulation and precise fault localization, several switches are deployed at different distances of 100 m, 200 m, 300 m, and 400 m. Identification of a deviation then classifies the fault kind and locates its approximate location at the controller based on sensor readings and switch activation. The automatic identification of the fault reduces manual inspections significantly, thus enhancing reliability.
3. Alert, indication, and wireless monitoring module If a fault condition is encountered, the system triggers an indicator lamp via a relay for clear visual indication of the fault incidence. This serves to heighten awareness of the fault and quickens the pace of maintenance. Simultaneously, detailed fault information, including fault type, distance, and real-time voltage and current values, is transmitted wirelessly to a laptop with the use of the communication module HC-12. This allows for remote monitoring, real-time supervision, and continuous logging without the need for site inspection. The integration of local alert mechanisms with wireless communication ensures speed in fault reporting, heightened safety, and efficient preventive maintenance in power distribution systems.
4. Real-time fault data logging and wireless monitoring: The system continuously carries out real-time acquisition and logging of electrical parameters such as voltage and current using high-precision sensors interfaced with the ESP32 microcontroller. The detected values, along with the operational status of the transmission line, are processed and stored temporarily for analysis. In the event of any fault, the system instantly records critical fault information such as the fault type (open-circuit or short-circuit), the correct fault distance (100 m, 200 m, 300 m, or 400 m), and respective sensor measurements. This fault information will be transmitted wirelessly to a laptop through an HC-12 communication module for real-time visualization and continuous logging. Such a remote data logging feature facilitates an efficient digital audit trail of fault incidences, which is a key requirement for maintenance scheduling, performance analysis, and preventive maintenance in power distribution systems. With such an aspect, the utility operators will be capable of monitoring line conditions from their remote locations, analyzing the pattern of faults that have occurred, and quickly acting upon emerging issues to enhance the reliability of service and operational safety.

A. System Methodology

1. Integrated Development and Prototyping Phase The proposed system has been developed following the Rapid Prototyping Methodology, which is highly suitable for embedded system applications where hardware and software must operate in close coordination. Programming is done in the C++ environment using the Arduino Framework on either the Arduino IDE or Platform IO. In the initial development stage, interfacing and testing of hardware components were focused on, including the ESP32 microcontroller, current and voltage sensors, relay modules, fault simulation switches, and HC-12 wireless communication module. For all core operations like reading sensor data, triggering the relay, and sending data over the wireless module, separate helper functions have been developed. The idea is to abstract low- level hardware control so that the main program loop may remain focused on the high-level fault detection logics and system state management.
2. Two-Phase Fault Detection and Classification Process This is a continuous, two-phase monitoring and detection methodology. In Phase A (Parameter Monitoring), the ESP32 will continuously acquire real-time voltage and current data from connected sensors. After filtering, the readings obtained are compared with the already-defined threshold values representing normal conditions. In Phase B (Fault Identification and Localization), on the observation of abnormal deviations, the controller identifies that a condition exists for either an open-circuit or a short-circuit fault. The fault location is then determined by the activation of predefined switches placed at 100 m, 200 m, 300 m, and 400m. This staged approach will ensure correct classification of the fault type and concurrently provide accurate distance estimation.
3. Fault Management and System State Control If this fault is confirmed, the system will switch directly from the normal monitoring state to the fault handling state. The ESP32 turns on the relay-controlled indicator for clear visual indication. Meanwhile, it checks for the validity of sensor readings to prevent a false triggering, checks if the fault confirmation is stable, then proceeds with the transmission of data. The running status of the system is continuously updated as normal or faulty, and when the fault condition is cleared, the system automatically goes back into its mode of monitoring.

B. System Architecture / Block Diagram

Fig. 1. Block diagram of the proposed LoRa system

The architecture for the proposed smart cable fault detection and monitoring system revolves around the ESP32 microcontroller that will act as the main processing and control unit for the entire system. The ESP32 constantly monitors the electrical parameters, processes the sensor data, detects fault conditions, and controls the alert and communication modules. Thus, a complete system architecture integrates sensing, processing, indication, and wireless communication units. The power supply module delivers a regulated DC voltage to all system components: ESP32, current and voltage sensors, relay module, indicator lamp, fault simulation switches, and the HC-12 wireless communication module. In fact, a very stable and regulated power supply is quite necessary for accurate measurement and reliable operation of the system under continuous monitoring conditions. Current and voltage sensors constitute the chief sensing unit of this system. These sensors allow for continuous monitoring of the electrical parameters of the transmission line, forwarding real-time analog data to the ESP32. Further, this microcontroller has been programmed to determine abnormal deviations from predefined threshold values, indicating open-circuit or short-circuit fault conditions. Fault simulation switches at distances of 100 m, 200 m, 300 m, and 400 m, respectively, allow the exact determination and display of the fault location. The local alert mechanism consists of a relay module and an indicator lamp. In case of fault detection, ESP32 gives power to a relay that switches ON the indicator lamp, thus giving a clear visual alert about the fault condition. This, in turn, enables immediate awareness for the maintenance personnel on site. The HC-12 module is used for wireless communication, transmitting real-time fault information such as fault type, fault distance, and electrical parameter values to a laptop for remote monitoring and data recording. This allows for supervision of the power line in real time without having to physically inspect the line constantly. Overall, sensing modules integrated with an ESP32 processing unit, alert mechanisms, and wireless communication establish a robust, reliable, and intelligent architecture for real-time cable fault detection, remote monitoring, and preventive maintenance in modern power distribution systems.

I. RESULTS AND DISCUSSION

The proposed smart cable fault detection and monitoring system was implemented and tested successfully to validate the accuracy of fault detection, performance of sensors, reliability of wireless communication, and real-time monitoring capabilities. Experimental results obtained at various test conditions prove that the proposed system effectively and reliably identifies open-circuit and short-circuit faults that happen in electrical transmission lines. The system has been tested by simulating faults at distances of 100 m, 200 m, 300 m, and 400 m with the use of fault simulation switches; in all cases, the system correctly detected both the type and location of the fault.

Voltage and current sensors showed high precision during the test phase in measuring real-time electrical parameters. During normal operating conditions, the voltage and current values were found to be quite stable, and the system also showed its capability to identify abnormal deviations during the insertion of fault conditions. Open-circuit faults cause a sudden drop in current, while short-circuit faults create abnormal surges of current, both of which were correctly detected by the ESP32 within a very short time response. The average fault detection time was found to be below one second, ensuring rapid system response and improvement in safety.

The relay-controlled indicator lamp responded immediately to any detected faults, thereby giving clear visual indication of fault conditions. The 16×2 LCD display continuously showed the system status messages such as “System Normal,” “Open Circuit Fault,” “Short Circuit Fault,” and corresponding fault distance. Based on this, fault identification was easy on site. The wireless communication subsystem using the HC-12 module was tested for real-time data transmission, and fault information was received successfully on the laptop within 2–4 seconds on average. The system maintained reliable communication with minimum data loss; therefore, it was suitable for remote monitoring and continuous logging of data.

The overall performance of the proposed system suggests that the integration of ESP32, sensor-based monitoring, relay indication, LCD display, and wireless communication yields an efficient, reliable, and cost-effective solution for intelligent fault detection and preventive maintenance. The proposed system drastically cuts fault diagnosis time, reduces manual inspection efforts, and enhances general dependability and safety in modern electrical distribution systems.

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