SMART ELECTRIC POLE FAULT DETECTION USING IOT AND MACHINE LEARNING

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Abstract - Increasing complexity in modern electrical distribution networks demands intelligent, real-time fault monitoring mechanisms to enhance reliability and operational efficiency. Conventional protection systems predominantly rely on threshold-based relays, manual inspection, and delayed reporting procedures, resulting in extended outage duration and elevated maintenance costs. An IoT-enabled smart electric pole monitoring framework integrated with machine learning–based fault classification is presented to address these limitations. The system incorporates distributed sensors to continuously measure voltage, current, temperature, ambient light intensity, and conductor continuity at pole level. An ESP32-based embedded controller performs real-time data acquisition, preprocessing, and secure wireless transmission to a cloud platform for centralized analysis. Extracted electrical features are processed using supervised learning algorithms to accurately classify abnormal conditions including overvoltage, overcurrent, overheating, and line disconnection. Experimental evaluation demonstrates high classification accuracy, reduced false alarm rates, and significant improvement in response time compared with conventional monitoring approaches. Cloud-based visualization and historical data logging further enable predictive maintenance and scalable deployment across urban and rural infrastructures. The proposed architecture strengthens fault resilience, enhances safety, and supports intelligent smart grid transformation through data-driven decision-making.

Key Words: Intelligent Fault Diagnosis, Electrical Distribution Networks, Real-Time Monitoring, Supervised Learning.

1.INTRODUCTION

Electrical distribution networks constitute a critical component of modern infrastructure, ensuring uninterrupted power delivery to residential, commercial, and industrial sectors. Distribution poles are continuously exposed to environmental stress, fluctuating load conditions, insulation deterioration, and mechanical disturbances, which frequently result in faults such as overvoltage, overcurrent, conductor breakage, overheating, and lighting failures. Conventional fault detection mechanisms primarily rely on threshold-based relays, fuse protection, and manual inspection practices, which often lead to delayed identification and prolonged outage duration. Increasing penetration of distributed energy resources and bidirectional power flow has further complicated network protection coordination, reducing the effectiveness of traditional monitoring strategies. Recent advancements in Internet of Things (IoT) technologies and machine learning algorithms enable intelligent, real-time infrastructure supervision through continuous sensing and data-driven analysis. Embedded systems equipped with distributed sensors facilitate acquisition of critical electrical parameters and secure wireless transmission to centralized platforms. Supervised learning techniques enhance detection accuracy by identifying complex operational patterns beyond fixed threshold evaluation. Integration of cloud-based analytics and automated alert mechanisms improves maintenance response efficiency and supports scalable deployment across smart grid environments.

2. OBJECTIVE

The primary objective of the proposed Smart Electric Pole Fault Detection System is to design, develop, and deploy an intelligent real-time monitoring framework for electrical distribution poles in modern smart grid environments. The system focuses on continuous monitoring of critical electrical and environmental parameters including voltage, current, temperature, light intensity, and conductor continuity at the pole level. Continuous monitoring enables early detection of abnormal operating conditions before they escalate into severe failures. By integrating IoT-enabled sensing modules with an ESP32 microcontroller, the system ensures accurate data acquisition, efficient preprocessing, and secure wireless transmission to a centralized cloud platform.

Another major objective is to incorporate machine learning–based intelligent fault classification to overcome the limitations of conventional threshold-based protection systems. The framework is designed to automatically detect and classify overvoltage, overcurrent, overheating, and wire cut conditions with minimal false positives and reduced response delay. Real-time visualization through web and mobile applications enhances situational awareness for maintenance personnel. The overall objective is to improve operational reliability, reduce outage duration, enhance public safety, enable predictive maintenance strategies, and support scalable smart grid infrastructure development across both urban and rural environments.

3. EXISTING SYSTEM

Traditional power distribution systems rely on electromechanical relays, fuse protection mechanisms, and manual inspection procedures operating with predefined threshold limits. Although effective for basic fault interruption, these systems lack adaptive intelligence to handle dynamic load variations and fluctuating generation patterns.

In many practical scenarios, fault identification depends on customer complaints or periodic inspection schedules rather than continuous monitoring. This reactive approach results in delayed detection, prolonged service interruption, increased operational cost, and reduced overall reliability of the distribution network.

Modern distribution networks increasingly incorporate distributed energy resources such as solar and wind generation, which introduce bidirectional power flow and varying fault current levels. Conventional protection coordination strategies are not designed to accommodate such dynamic conditions, thereby reducing reliability. Advanced monitoring approaches including Phasor Measurement Unit (PMU)-based state estimation and traveling wave fault detection techniques provide improved accuracy and fast fault localization. However, these methods require high-speed sampling hardware, precise GPS-based synchronization, and significant investment in communication infrastructure.

3.1 DISADVANTAGES

Delayed fault identification and increased outage duration

Inability to efficiently handle bidirectional power flow

High capital and maintenance cost for advanced monitoring systems

Absence of intelligent multi-parameter fault classification

Limited scalability in geographically dispersed rural environments

Lack of centralized historical data storage and predictive analytics

4. PROPOSED SYSTEM

The proposed Smart Electric Pole Fault Detection System introduces an IoT-enabled intelligent monitoring architecture integrated with machine learning–based fault classification. Sensors deployed at each distribution pole continuously monitor electrical parameters and environmental conditions. Unlike traditional systems that rely solely on threshold comparison, the proposed framework analyzes multi-dimensional data patterns to detect abnormal behavior.

An ESP32 microcontroller acts as the core processing unit, performing signal conditioning, analog-to-digital conversion, and feature extraction. Processed data is securely transmitted to a cloud server for storage and advanced analysis. A Random Forest classifier evaluates extracted features and classifies fault types in real time. The monitoring layer includes a web-based dashboard and Flutter-based mobile application to provide graphical visualization, instant alerts, and historical trend analysis.

4.1 ADVANTAGES

Continuous real-time monitoring at individual distribution pole level for improved fault visibility

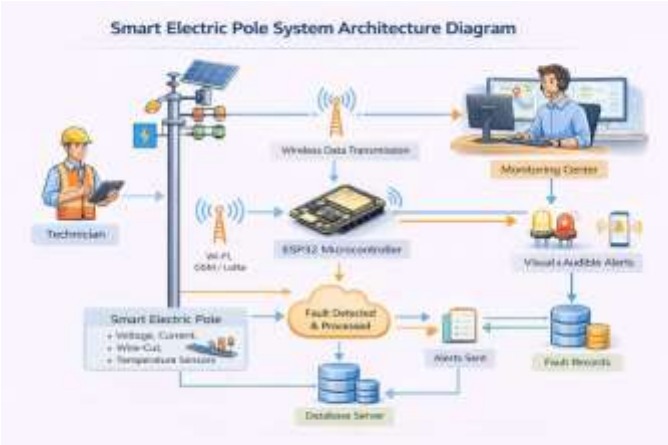
Intelligent multi-parameter fault classification using machine learning techniques

Significant reduction in manual inspection and faster fault restoration time

Cloud-based centralized supervision with secure data storage and historical logging

5. SYSTEM ARCHITECTURE

The proposed Smart Electric Pole Fault Detection System is designed using a multi-layered modular architecture to ensure scalability, reliability, and efficient data management. The architecture is divided into sensing, processing, communication, backend, database, and frontend layers. Each layer performs a dedicated function while maintaining synchronized data flow across the system.



5.1 ARCHITECTURE EXPLANATION

Sensing Layer: The sensing layer is deployed at the distribution pole and is responsible for continuous data acquisition. It consists of a ZMPT101B voltage sensor for AC voltage measurement, ACS712 Hall-effect current sensor for load current monitoring, DHT11 temperature sensor for thermal condition analysis, LM393 module for wire-cut detection, and an LDR module for ambient light supervision. Continuous monitoring enables early detection of abnormal electrical conditions.

Processing Layer: The processing layer is implemented using the ESP32 microcontroller. It performs analog-to-digital conversion, signal conditioning, noise filtering, and feature extraction. Preliminary fault detection logic is executed at this stage before transmitting structured data to the server.

Communication Layer: The communication layer enables wireless data transmission using the ESP32's built-in Wi-Fi module. Sensor data is securely transmitted to the backend server through HTTP or MQTT protocols. Encryption mechanisms ensure data integrity and confidentiality during transmission.

Backend and Database Layer: The backend server handles data validation, storage, and machine learning–based fault classification. A cloud-based MySQL database stores real-time sensor values, fault logs, timestamps, and pole identification details. Centralized storage supports historical analysis and predictive maintenance strategies.

Frontend Monitoring Layer: The frontend consists of a web dashboard and a Flutter-based mobile application. It provides real-time visualization of system parameters, fault alerts, and trend graphs. Automated push notifications and critical fault alerts enhance rapid response and remote supervision.

6. METHODOLOGY

The system operates through a structured workflow beginning with real-time data acquisition from sensors installed at the distribution pole. The collected signals undergo preprocessing and filtering to remove noise and improve measurement accuracy. Relevant features such as voltage deviation, current variation, and temperature thresholds are extracted for analysis. A machine learning model classifies the operating condition and identifies potential faults. The classified results are stored in the cloud database, and notifications are generated through the application, dashboard, and automated alert mechanisms for timely response. In case of critical faults, an automatic call alert is triggered to ensure immediate attention from maintenance personnel. Historical data is maintained for trend analysis and predictive maintenance planning. Overall system performance is evaluated using metrics such as accuracy, precision, recall, and response time.

6.1 SYSTEM DESIGN AND ARCHITECTURE

The system design integrates hardware sensing modules, embedded controllers, wireless communication networks, backend server infrastructure, and user interface platforms. Modular design ensures scalability and simplified maintenance.

6.2 DATABASE DESIGN

A structured MySQL relational database is implemented to store real-time sensor readings and fault detection records in a centralized manner. The database is designed to ensure data consistency, integrity, and efficient retrieval.

Key tables include:

Sensor Data: Stores voltage, current, temperature, light intensity, wire status, and corresponding timestamps for continuous monitoring.

Fault Logs: Maintains fault type, detection time, pole identification number, and severity level for event tracking and analysis.

User Management: Contains administrator credentials, user roles, and authentication logs to ensure secure access control.

A normalized schema design is adopted to eliminate redundancy, improve query performance, and support scalable deployment across multiple distribution poles.

6.3 NOTIFICATION SYSTEM

Upon detection of abnormal conditions, the backend server triggers automated push notifications through Firebase Cloud Messaging. Real-time alerts are displayed on the web dashboard to ensure centralized supervision. Optional SMS and email integration enhance redundancy in communication. For high-severity faults, the system initiates an automatic voice call alert to registered maintenance personnel to guarantee immediate response. Alert logs are recorded in the database along with timestamps and severity levels for traceability. This multi-channel notification mechanism improves response time, operational reliability, and fault management efficiency. Additionally, escalation protocols can be configured to notify higher-level authorities if the fault remains unresolved within a predefined time threshold.

6.4 USER INTERFACE

The web dashboard provides graphical representation of electrical parameters using line charts, real-time status indicators, and fault summary panels for centralized monitoring. The Flutter-based mobile application enables remote supervision, instant alert acknowledgment, and real-time system updates from any location. Users can view historical logs, analyze parameter trends, and monitor multiple poles simultaneously. Secure login authentication ensures controlled access to system data and administrative functions. The user-centric interface is designed for simplicity, responsiveness, and efficient navigation to support quick decision-making during fault conditions.

6.5 TESTING AND VALIDATION

Prototype validation is conducted under simulated conditions including overvoltage, overload, overheating, and conductor disconnection to evaluate system accuracy and responsiveness. Sensor calibration is performed to ensure measurement precision and minimize deviation errors.

Continuous operation testing assesses long-term system stability and communication reliability under varying network conditions. The response time between fault occurrence and alert generation is measured to verify real-time performance capability. Stress testing is also carried out to evaluate system behavior under high data transmission frequency and multiple fault scenarios. The experimental results confirm consistent operation, reliable fault detection, and minimal false alarm occurrence.

6.6 PERFORMANCE EVALUATION

Performance metrics include accuracy, precision, recall, F1-score, response time, and false positive rate to comprehensively evaluate system effectiveness. Experimental validation demonstrates approximately 95% classification accuracy with a significant reduction in false alarm occurrences under multiple simulated fault conditions. Confusion matrix analysis confirms reliable differentiation between normal and abnormal operating states. Comparative evaluation indicates faster detection and improved response speed when compared to conventional relay-based monitoring systems. The system also shows consistent performance under continuous operation and varying load conditions. Overall results validate the robustness, reliability, and scalability of the proposed intelligent fault detection framework for smart grid applications.

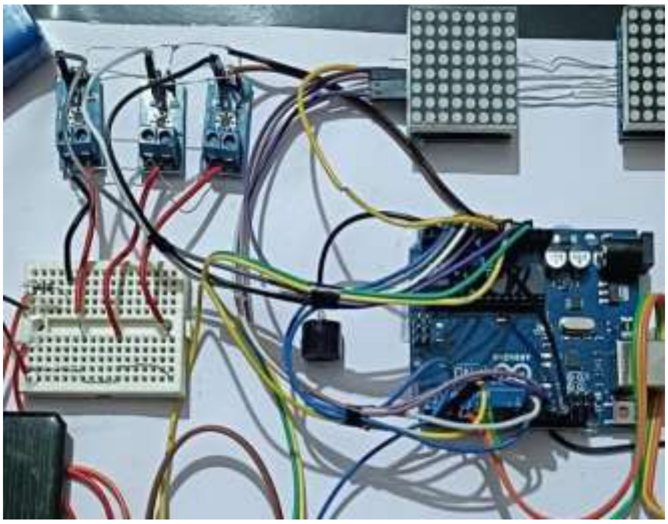
7. ALGORITHM USED

The Random Forest classification algorithm is selected due to its ensemble learning capability, high prediction accuracy, and robustness against overfitting. The algorithm constructs multiple decision trees using bootstrapped training samples and random feature selection to improve generalization performance. Each decision tree evaluates electrical features such as voltage deviation, RMS current variation, temperature threshold exceedance, and binary wire continuity status to identify abnormal patterns.

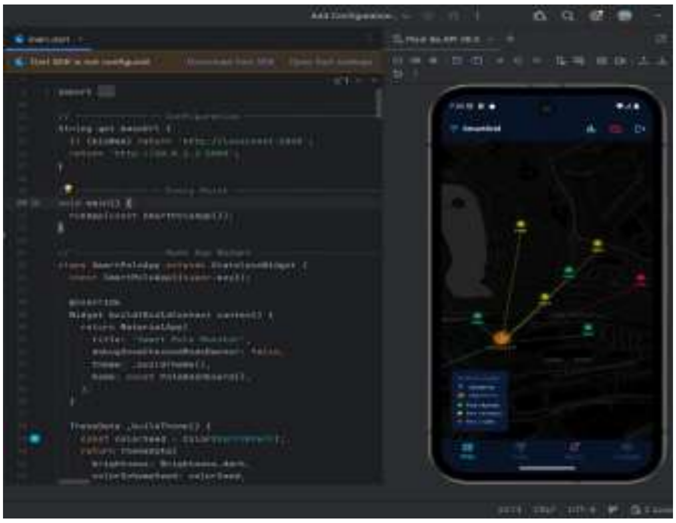
Final fault classification is determined through majority voting across all generated trees, ensuring reliable decision-making. Feature importance analysis is performed to determine the most influential parameters contributing to fault detection. Random Forest demonstrates strong stability under noisy sensor conditions and varying load patterns. Its ability to handle multi-dimensional data makes it highly suitable for intelligent multi-parameter electrical fault analysis in smart distribution networks. Additionally, the algorithm provides faster training and prediction time compared to complex deep learning models, making it computationally efficient for real-time embedded system applications.

8. IMPLEMENTATION AND RESULT

The hardware prototype is developed using the ESP32 Devkit V1 as the core microcontroller unit. It is integrated with ZMPT101B voltage sensor for AC voltage monitoring, ACS712 current sensor for load current measurement, DHT11 temperature sensor for thermal monitoring, LM393 module for wire-cut detection, and an LDR sensor for light intensity supervision. The ESP32 performs analog-to-digital conversion and preliminary signal processing. An LCD display module is connected to provide real-time parameter visualization at the pole level. Wireless communication is enabled using the built-in Wi-Fi module for data transmission to the cloud server.



The firmware for ESP32 is developed using Arduino IDE for embedded programming and sensor data handling. Backend services are implemented using the Python Flask framework with REST API integration to manage data communication and fault classification. A Random Forest machine learning model is deployed on the server to classify operating conditions. A MySQL database is used for structured storage of sensor data and fault logs. The frontend includes a web dashboard for centralized monitoring and a Flutter-based mobile application for real-time alerts and supervision. Push notifications and automated call alerts are integrated for critical fault conditions. Secure authentication and role-based access control mechanisms are implemented to ensure authorized system usage. The overall software architecture is designed to be modular, scalable, and compatible with future smart grid enhancements.



9. CONCLUSIONS

The proposed Smart Electric Pole Fault Detection System presents an intelligent and scalable solution for real-time monitoring of electrical distribution networks. By integrating IoT-enabled sensing modules with machine learning–based fault classification, the system overcomes the limitations of conventional relay-based protection mechanisms. Continuous monitoring of voltage, current, temperature, light intensity, and conductor continuity enables early detection of abnormal conditions and reduces outage duration. The implementation of the Random Forest algorithm enhances classification accuracy while minimizing false alarms. Cloud-based data storage, web dashboard visualization, mobile application support, and automated alert mechanisms improve operational efficiency and response time. Experimental validation demonstrates high accuracy, reliable performance, and practical feasibility under simulated fault conditions. The modular architecture ensures scalability and cost-effective deployment across urban and rural infrastructures. Overall, the system contributes toward intelligent fault management, predictive maintenance, and smart grid modernization.

Furthermore, the integration of automated call alerts ensures immediate human intervention during critical fault scenarios. The centralized database supports long-term analytical studies and condition-based maintenance planning. The system design also allows seamless integration with existing smart grid infrastructure without major hardware modification. Future enhancements can incorporate advanced deep learning models and edge computing for improved real-time decision-making.

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