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Full Length Article

Wireless Power Line Monitoring Node With Fault Prediction

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Abstract
Reliable and uninterrupted electric power distribution is one of the most important requirements of modern society. Residential homes, commercial establishments, hospitals, educational institutions, and industrial sectors depend on continuous electricity supply for their daily operations. Any interruption in the distribution network may cause financial losses, operational delays, equipment malfunction, and inconvenience to consumers. Power distribution lines are often exposed to several risks such as voltage fluctuations, overload current conditions, short circuits, conductor heating, smoke generation, and accidental fire incidents. If these abnormalities are not detected at an early stage, they may lead to serious equipment damage, transformer failures, line breakdown, and public safety hazards. Therefore, continuous monitoring of distribution lines has become an essential requirement for modern power systems.
Traditional monitoring methods such as manual inspection, wired supervisory systems, and SCADA-based infrastructure are expensive and usually concentrated only at substations or major control points. These methods are not suitable for real-time monitoring at the distribution pole level where many faults begin. To overcome these limitations, this paper presents a Wireless Power Line Monitoring Node with Fault Prediction using ESP32 microcontrollers and ESP-NOW communication technology. The proposed system continuously monitors voltage, current, smoke, and flame conditions through distributed wireless sensor nodes. The collected information is transmitted to a central server node for real-time analysis and alert generation.
Whenever abnormal parameters are detected, the system activates a buzzer, displays warning messages on an LCD screen, and sends Telegram notifications to maintenance personnel. The use of wireless communication eliminates complex cabling, reduces installation cost, and enables deployment of multiple monitoring nodes across wide areas. Experimental observations show that the system offers quick fault indication, reliable communication, and effective preventive maintenance support. The proposed solution is economical, scalable, and highly suitable for smart grid monitoring applications.
Keywords
Power Line Monitoring, Fault Prediction, ESP32, ESP-NOW, Wireless Sensor Networks, Smart Grid, Voltage Monitoring, Current Monitoring, Real-Time Alerts.

Introduction

Electrical power distribution systems form the final and most critical stage of the power delivery process. After generation and transmission, electricity reaches consumers through distribution feeders, transformers, poles, and service lines. Since every consumer directly depends on this stage, any failure in the distribution system immediately affects daily life and industrial productivity. Reliable operation of power lines is therefore essential to ensure uninterrupted power supply.
However, distribution lines are constantly subjected to dynamic loading conditions and environmental stress. Sudden increase in demand may create overcurrent conditions. Loose connections may cause sparking and heating. Aging conductors may result in voltage drops. External factors such as weather, dust, fire, or nearby combustible materials may create additional risks. If these issues remain unnoticed, they may lead to major outages or dangerous accidents.
To maintain operational safety, utilities require continuous monitoring systems capable of detecting abnormalities in real time. Advances in embedded systems and wireless communication now make it possible to install compact sensor nodes directly near power poles for intelligent monitoring.

Need for the System

Conventional power monitoring methods have several drawbacks. In many locations, faults are detected only after consumers report outages. Utility personnel then inspect the lines manually to locate the problem. This process consumes time and increases downtime.

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Existing SCADA systems are effective for centralized control but mainly monitor substations rather than individual poles or feeders. They require expensive hardware, communication infrastructure, and dedicated maintenance. Wired sensor systems also involve trenching, cable laying, insulation, and regular maintenance, making them costly for distributed deployment.

Hence, there is a strong need for a low-cost wireless system that can continuously monitor important parameters and instantly report abnormal conditions before failures become severe.

Literature Survey

Fig 1: A modern example of wireless communication

SCADA-Based Monitoring Systems

Several researchers have discussed supervisory monitoring systems for power utilities. SCADA platforms are widely used to observe voltage, current, breaker status, and transformer operation from centralized control centers. Although these systems are effective for large installations, they are expensive and mostly limited to substations. They do not provide economical pole-level deployment.

Single Parameter Monitoring Approaches

Some earlier studies proposed overload detection systems based only on current sensing. These systems can identify excessive load but cannot detect voltage abnormalities or environmental hazards. Other works focused only on voltage drop or phase imbalance detection. Such limited approaches fail to capture complete fault conditions.

Wireless Sensor Networks

Wireless sensor networks have been introduced for industrial monitoring applications. ZigBee-based systems reduce wiring requirements but may face interference and range limitations. Wi-Fi based systems offer internet connectivity but consume more power and often require routers.

GSM and LoRa Systems

GSM-based systems can send SMS alerts over long distances but depend on telecom networks and recurring charges. LoRa technology provides long-range communication with low power consumption, but its data rate may not be ideal for rapid continuous monitoring.

Research Gap

Most existing solutions either monitor limited parameters or use communication technologies with practical limitations. Very few systems combine electrical and environmental monitoring with fast wireless communication and instant local plus remote alerting. This project addresses that gap.

Wireless Power Line Monitoring Node with Fault Prediction

The growing demand for reliable and uninterrupted electricity supply has increased the need for intelligent monitoring systems in power distribution networks. Distribution lines are exposed to electrical stress, changing load conditions, weather effects, conductor aging, overheating, and environmental hazards such as smoke or fire. These conditions may gradually develop into serious faults if they are not identified at an early stage. Conventional monitoring systems often detect problems only after service interruption has already occurred, leading to power outages, equipment damage, and higher maintenance costs.

To overcome these challenges, this project proposes a **Wireless Power Line Monitoring Node with Fault Prediction**, which is a low-cost, scalable, and smart monitoring solution designed for distribution pole-level deployment. The system uses ESP32-based wireless sensor nodes capable of continuously observing important parameters such as voltage, current, temperature, vibration, smoke, and flame conditions. These parameters provide complete awareness of both electrical and environmental conditions around the power line.

The collected data is processed locally at each node using embedded intelligence techniques. Edge processing methods such as threshold comparison, RMS calculation, anomaly detection, and machine learning-based fault prediction help in identifying abnormal conditions before severe failures occur. Once any dangerous situation is detected, the node transmits alerts wirelessly to a central server unit through ESP-NOW, Wi-Fi, or LoRa communication.

The proposed system is suitable for smart grid applications because it enables continuous real-time monitoring, localized fault detection, quick maintenance response, reduced downtime, and predictive maintenance planning. Its modular design allows utilities to deploy multiple nodes across long distribution feeders in a cost-effective manner.

Existing System

Existing power line monitoring systems have several technical and practical limitations that reduce their efficiency in modern electrical networks. Many traditional systems are reactive in nature and respond only after a fault has already caused interruption or damage.

Most conventional monitoring systems observe only a single parameter such as voltage or current. While these values are important, they are not sufficient to detect early warning conditions such as conductor heating, vibration, insulation stress, smoke formation, or harmonic distortion. As a result, several developing faults remain unnoticed.

SCADA-based systems are commonly used in substations and major control centers. These systems offer centralized supervision but require expensive infrastructure, dedicated communication channels, and regular maintenance. They are generally not suitable for deployment on every distribution pole or local feeder section due to cost and complexity.

Earlier wireless monitoring methods based on ZigBee or Wi-Fi introduced some flexibility by reducing wiring requirements. However, these systems often suffer from limited communication range, higher power consumption, signal interference, and poor reliability in outdoor environments. This makes them less suitable for long-distance distribution line monitoring.

Some modern systems use GSM or LoRa communication to transmit alerts. Although they improve communication distance, many such systems are focused only on fault reporting after the fault occurs. They do not provide predictive analysis or advanced signal processing methods such as Fast Fourier Transform (FFT), Total Harmonic Distortion (THD), or anomaly-based learning models.

Another major limitation is the lack of instant local alerting. In many existing systems, abnormal data is sent only to a remote control room. This delays response time because field staff may not be informed immediately at the fault location.

Therefore, existing systems require significant improvement in the areas of multi-parameter sensing, predictive intelligence, pole-level deployment, communication reliability, and fast localized warning capability.

Key Features of the Proposed System

Multi-Sensor Monitoring

Unlike traditional systems that monitor only voltage or current, the proposed node integrates multiple sensors including voltage, current, temperature, vibration, smoke, and flame sensors. This enables complete monitoring of power line health and surrounding environmental safety.

Edge Processing at Node Level

Each ESP32 node performs local computation such as RMS calculation, peak analysis, threshold comparison, FFT analysis, THD estimation, and anomaly detection. This reduces communication traffic and enables faster decision making.

Efficient Wireless Communication

The system uses ESP-NOW, Wi-Fi, or LoRa protocols depending on deployment needs. These communication methods support low-latency, low-power, and reliable outdoor wireless data transfer.

Fault Prediction Capability

Machine learning and anomaly detection techniques are used to predict possible faults such as overload conditions, insulation deterioration, conductor heating, and abnormal operating behavior before failure occurs.

Real-Time Alerts

Whenever abnormal values are detected, the node immediately activates alerts through buzzer alarms, LCD messages, and mobile notifications. This allows quick maintenance response.

Historical Data Logging

All sensor readings and fault records are stored in the server memory or cloud database. Historical trends help utilities plan preventive maintenance schedules.

Scalable Design

Multiple nodes can be deployed over large areas. Each node has a unique ID, making the system highly scalable for city-wide or rural distribution networks.

Pole-Level Monitoring

Since nodes are installed directly on poles, localized conditions can be observed accurately instead of depending only on substation-level measurements.

Fast Fault Localization

Using node identification numbers, the server can immediately determine the exact pole or feeder section where abnormality has occurred.

Hybrid Detection Logic

The system combines fixed threshold rules with intelligent anomaly detection. This increases fault detection accuracy and reduces false alarms.

Modular Sensor Expansion

Additional sensors such as humidity, power factor, pressure, GPS, or weather sensors can be added without redesigning the complete system.

Multi-Node Synchronization

Simultaneous monitoring of adjacent poles allows comparative analysis and improved fault diagnosis.

Independent Node Operation

Basic decisions are taken locally at the node, so even if communication is interrupted temporarily, the node can still generate local warnings.

Block Diagram

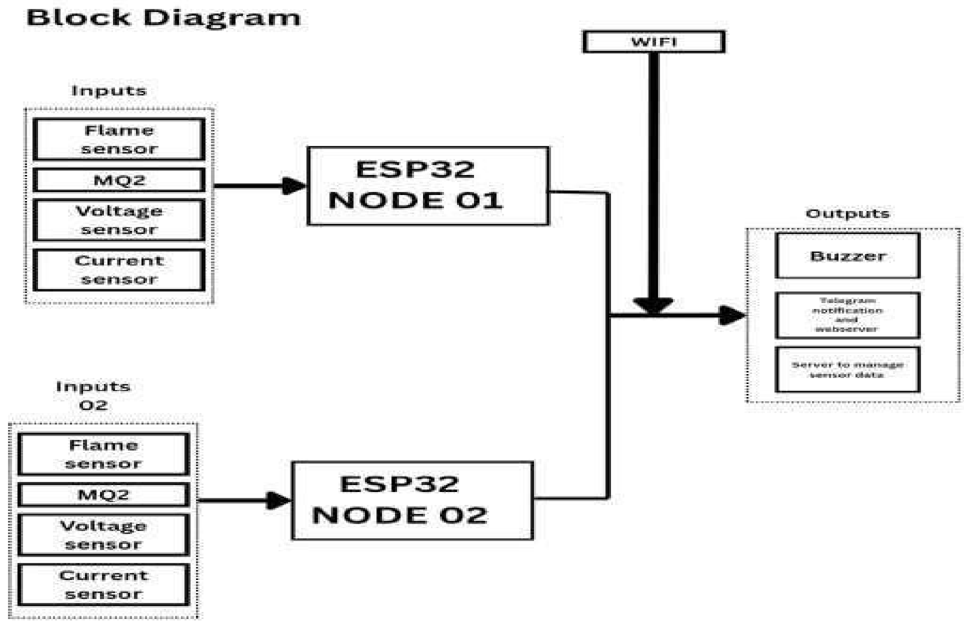

Fig 2: Block Diagram of Multi-Node Wireless Power Line Monitoring System

The block diagram of the proposed system consists of two sensor nodes (Node 01 and Node 02), wireless communication links, and a central server or gateway unit. Each node includes identical sensing and processing sections. The nodes continuously monitor field conditions and send processed information to the server.

Hardware Requirements

ESP32 Microcontroller

ESP32 is the main controller used in both node and server units. It offers analog input channels, digital I/O pins, wireless communication, sufficient memory, and efficient power operation.

Voltage Sensor

The voltage sensor safely scales line voltage into a measurable signal suitable for the ESP32 analog input.

Current Sensor

Current sensors such as ACS712 or current transformer modules measure line current and help detect overload conditions.

MQ-2 Smoke Sensor

The MQ-2 sensor detects smoke and combustible gases that may indicate heating, sparking, or fire risk.

Flame Sensor

The flame sensor identifies infrared radiation emitted by fire and supports immediate hazard detection.

LCD Display and Buzzer

The server unit uses an LCD to display node status and fault messages. A buzzer provides audible emergency alerts.

Software Requirements

The system firmware is developed using Arduino IDE with embedded C/C++ programming. The software periodically reads sensors, filters noise, compares readings with thresholds, transmits packets through ESP-NOW, and handles alerts at the receiver side.

Telegram bot integration is implemented for remote notifications. This enables maintenance staff to receive alerts instantly on mobile devices.

Working Procedure

Initially, all sensor nodes start continuous monitoring mode. Voltage, current, smoke, and flame data are sampled at regular intervals. The ESP32 processes sensor values locally and checks whether they are within safe operating ranges.

Under normal conditions, the node transmits regular status updates to the server. If abnormal values are found, the node sends a high-priority warning message. The server then activates the buzzer, updates the LCD, and sends a Telegram message indicating the affected node and fault type.

This real-time sequence significantly reduces response delay.

Results and Discussion

Prototype testing shows that the proposed system successfully detects multiple abnormal conditions. Overcurrent tests triggered rapid warning messages. Voltage fluctuation scenarios were correctly identified. Smoke and flame sensors responded effectively during hazard simulation tests.

ESP-NOW communication demonstrated reliable short-range transmission with low delay. Compared with wired systems, installation complexity was greatly reduced. Compared with internet-dependent systems, node-to-node communication remained simple and efficient.

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The multi-sensor approach provides better fault awareness than systems based on a single parameter. For example, conductor heating may first appear as increased current followed by smoke, enabling earlier intervention.

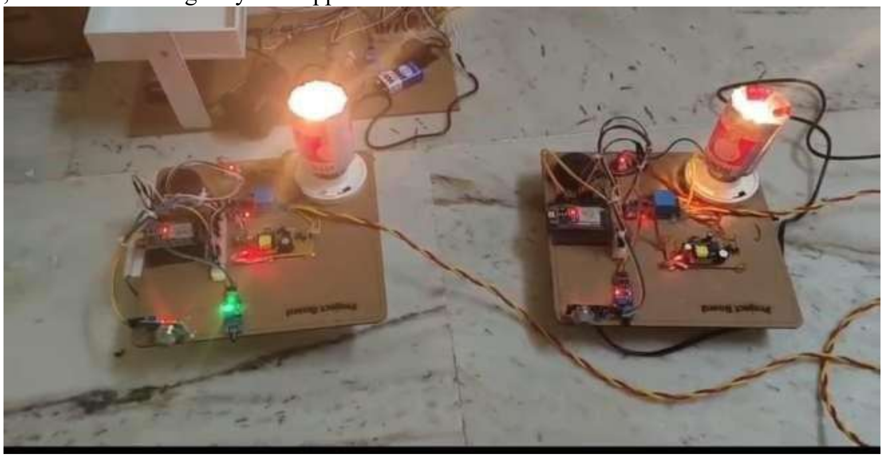

Fig 3: Real-Time Voltage and Current Monitoring Setup

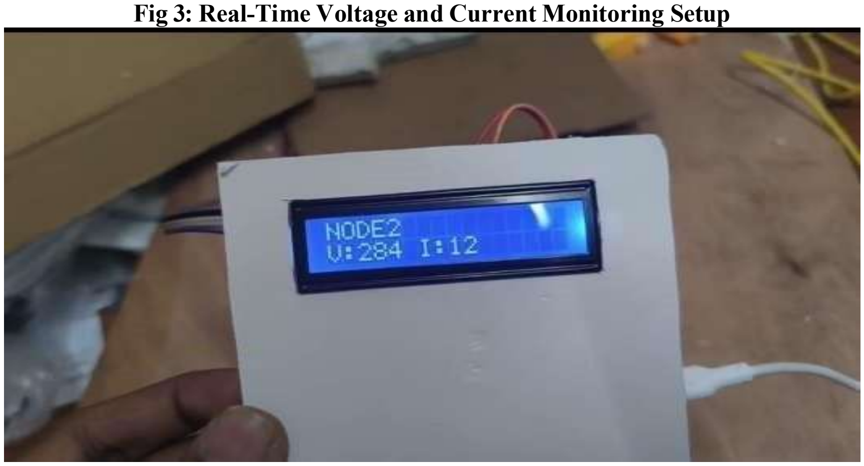

Fig 4: LCD-Based Monitoring Output of Voltage (284 V) and Current (12 Amp)

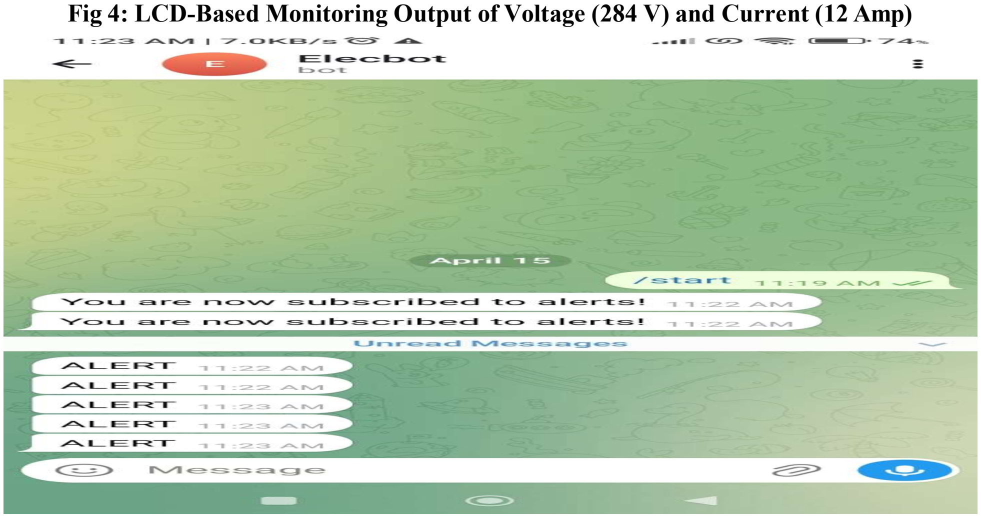

Fig 5: Alert on telegram bot for fault detection

Fig 6: Hardware setup of Monitoring node

Fig 7: LCD Display of server

Conclusion

In conclusion, the development of the **Wireless Power Line Monitoring Node with Fault Prediction** represents an important step toward improving the reliability, safety, and intelligence of modern power distribution systems. Conventional monitoring approaches are often limited by high installation cost, delayed fault detection, dependence on manual inspection, and lack of localized real-time monitoring. These limitations create operational challenges for utilities and increase the risk of outages, equipment damage, and maintenance delays. The proposed system successfully addresses these issues by introducing a distributed wireless monitoring architecture based on ESP32 sensor nodes and intelligent fault prediction techniques.

The implemented system continuously monitors essential electrical and environmental parameters such as voltage, current, temperature, vibration, smoke, and flame conditions. By collecting these parameters in real time, the system provides complete visibility into the health of power distribution lines. Unlike traditional systems that react only after faults occur, the proposed model supports predictive monitoring by identifying abnormal trends and warning signs before they develop into severe failures. This proactive approach helps utilities perform timely maintenance, reduce service interruptions, and improve operational efficiency.

The use of wireless communication technologies such as ESP-NOW, Wi-Fi, or LoRa enables reliable transmission of sensor data to a central monitoring station without requiring expensive wired infrastructure. This significantly reduces installation complexity and allows easy deployment across multiple poles or feeder sections. Since each node is uniquely identified, the system can quickly determine the exact location of a fault, reducing troubleshooting time and accelerating repair operations.

Another major advantage of the system is the integration of local and remote alert mechanisms. Whenever abnormal conditions are detected, the system activates buzzers, LCD displays, and mobile notifications to inform maintenance personnel immediately. This fast response capability enhances public safety and prevents fault escalation. Historical data storage and analysis further support long-term maintenance planning and performance optimization.

The modular and scalable nature of the proposed design makes it suitable for both rural and urban distribution networks. Additional sensors and advanced analytics can be integrated easily without redesigning the entire architecture. The system aligns strongly with the goals of modern smart grids by combining sensing, communication, automation, and intelligent decision making.

Overall, the project demonstrates that combining wireless sensor networks with predictive fault analysis can transform traditional power line supervision into an efficient, data-driven, and preventive maintenance model. The proposed solution ensures safer operation, lower downtime, reduced maintenance cost, and improved continuity of power supply. It provides a practical and economical pathway toward smarter and more resilient electrical infrastructure.

Future Scope

The proposed wireless power line monitoring system offers wide opportunities for future enhancement and large-scale deployment. As power systems continue to evolve toward digital and smart grid environments, the integration of advanced technologies can further improve the intelligence, efficiency, and reliability of the system.

One major area of future development is the use of advanced machine learning and artificial intelligence algorithms. More sophisticated predictive models can be trained using historical sensor data to improve fault classification accuracy, identify hidden patterns, and estimate the remaining useful life of electrical components. Deep learning techniques may also be used for detecting complex faults that are difficult to identify using conventional threshold methods.

Another promising direction is the development of energy-harvesting sensor nodes powered by solar panels, vibration energy, or ambient electromagnetic sources. Such self-sustaining nodes can operate for long periods with minimal maintenance, making them ideal for remote and inaccessible locations. This would significantly reduce battery replacement costs and improve long-term deployment feasibility.

Integration with Internet of Things platforms and cloud computing systems can provide centralized dashboards, real-time analytics, automated maintenance scheduling, and large-scale data management. Utility operators could monitor thousands of nodes simultaneously through web or mobile applications. Cloud storage would also support trend analysis, fault history management, and predictive maintenance planning.

Future systems may incorporate additional sensing capabilities such as humidity, pressure, conductor sag, wind speed, power factor, harmonic distortion, and weather conditions. Multi-parameter sensing would provide a more complete understanding of line health and surrounding environmental stress factors.

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