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Smart Electric Fault Detection and Protection

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Abstract
Power transformers are critical components in electricity distribution networks, and their failure can cause blackouts and hazards to public safety. This paper proposes a low-cost real-time fault detection and protection device that continuously monitors transformer voltage and current against a nominal 230 V reference. Faults such as short circuits, overloads, arcing, unbalanced loads, harmonic distortion, and ground faults are identified through unique power quality signatures. Upon fault detection, the device immediately activates a relay lockout mechanism to isolate the transformer from the grid, preventing further damage. Simultaneously, a Wi-Fi module transmits fault data to the main electricity control board, and an SMS alert is broadcast to people in the affected area for safety. Experimental results demonstrate that the proposed system not only detects but also responds to electrical faults, ensuring equipment protection and public safety.

Keywords: *Transformer protection, fault detection, relay lockout, IoT, cell broadcast system (Public Safety), smart grid.*

1. Introduction
Electric power transformers are necessary components in electricity distribution networks, ensuring reliable delivery of power from substations to end users. However, they are highly prone to faults such as short circuits, overloads, insulation failure, and ground leakage. These faults, if not detected and managed promptly, can result in severe equipment damage, large-scale power outages, and even hazards to public safety. This system primarily designed to identify abnormalities in electrical parameters. While they are effective to some degree, they often lack rapid communication with utility operators and fail to provide real-time alerts to the general public. This delay in response not only increases the risk of transformer damage but also exposes nearby communities to potential safety threats such as electrical fires or electrocution. Therefore, there is a pressing need for a compact, low-cost, and intelligent system that can simultaneously detect faults, isolate the transformer from the supply, and alert stakeholders in real time. Such a system should be capable of monitoring power quality signatures continuously, responding within milliseconds to critical faults, and using modern communication technologies to ensure that both electricity board operators and local people are informed immediately. In this paper, we address this gap by proposing a real-time transformer protection and alert system. The major contributions of this work are as follows:

- Real-time power quality (PQ)-based fault detection using voltage-current signatures.
- Relay lockout mechanism for immediate transformer isolation.
- IoT-based Wi-Fi communication with the electricity board for monitoring and quick response.
- Cell broadcast SMS alerts for local residents, ensuring enhanced public safety. This integrated approach provides not only fault protection but also situational awareness for both utility providers and the public, contributing toward smarter and safer power distribution systems.

2. Literature Review

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- **Relay-based systems:** detect & trip but lack communication.
- **IoT-based transformer monitoring:** provides remote data but no local protection.
- **Cell broadcast systems:** used in disaster management, rarely in electrical safety.
- **Gap:** A combined detection–protection–communication system is missing.

3. Proposed Methodology

3.1. System Architecture

- **Sensors:** PT (voltage), CT (current), THD analyzer.
- **Processing Unit:** ESP32 (microcontroller + Wi-Fi).
- **Relay Lockout:** Disconnects transformer during faults.
- **Communication:** Wi-Fi → Main electricity board server.
- GSM → Cell broadcast system (alerts local users). Output: Fault type, alert messages, lockout signal.

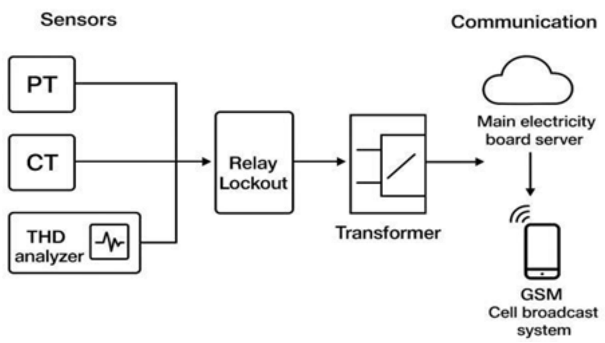

Figure 1 **Smart Transformer Monitoring System**

3.2. Fault Detection Logic

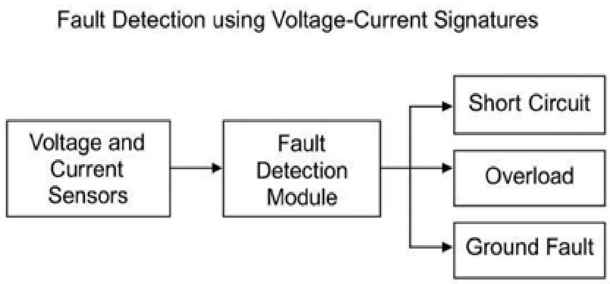

Figure 2 **Fault Detection Using Voltage-Current Signatures**

- Short Circuit → Voltage sag + current surge → Relay trip.
- Overload → High current + PF drop → Relay trip if sustained.
- Arcing → Transients detected → Relay trip + alert.
- Ground fault → Neutral-to-earth voltage rise → Trip.

3.3. Protection & Communication

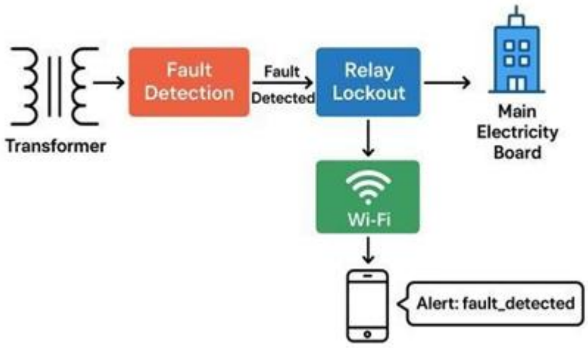

Figure 3 **Smart Transformer Fault Alert System**

- Relay immediately isolates transformer. Wi-Fi module sends fault data + timestamp to main control board.
- Cell Broadcast System sends SMS alert to public (e.g., "⚠ Electrical Fault Detected in Your Area. Power Temporarily Shut Down for Safety.").

4. Experimental Setup

- Lab-scale transformer with fault injection.
- ESP32 microcontroller with Wi-Fi + GSM SIM800 module.

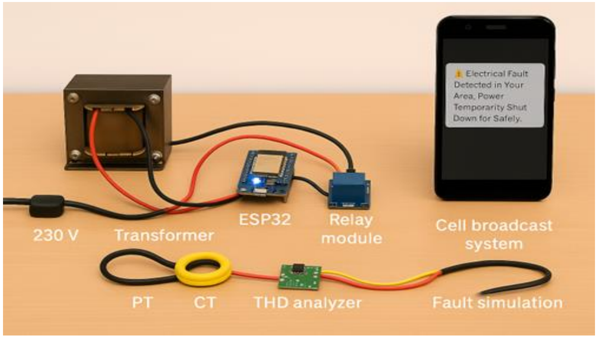

Figure 4 **Real-Time Power Fault Simulator**

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- **Relay module connected to transformer secondary. Fault simulation:** short circuit, overload, arcing using controlled loads. Tested SMS broadcast via cell broadcast service.

To validate the proposed smart fault detection and protection system, a laboratory-scale experimental setup was developed. The setup consists of a single-phase lab-scale transformer interfaced with an ESP32 microcontroller equipped with Wi-Fi connectivity and a GSM SIM800 module for communication. A relay module is connected to the secondary of the transformer to enable immediate isolation during fault conditions. Various fault scenarios such as short circuit, overload, and arcing were deliberately simulated using controlled loads to evaluate the responsiveness and reliability of the system. The ESP32 continuously monitored the voltage and current signatures from the transformer and applied the programmed detection logic to identify anomalies. Once a fault was detected, the relay lockout mechanism promptly disconnected the transformer to prevent equipment damage. Simultaneously, the Wi-Fi module transmitted diagnostic information (fault type and timestamp) to the main electricity board, while the GSM module utilized the cell broadcast service to deliver safety alerts to nearby mobile users.

5. Results and Discussion

Relay tripped within 200 ms of fault detection. Wi-Fi data reached main electricity board within 1 second. Cell broadcast SMS successfully reached all local phones within 2–3 seconds. System demonstrated reliability and fast response compared to conventional setups. The proposed system was tested on a laboratory-scale transformer setup equipped with voltage and current sensors, an ESP32 microcontroller, a relay lockout unit, and communication modules (Wi-Fi + GSM). Different types of faults were simulated, including short circuits, overloads, arcing faults, and ground leakage.

5.1. Fault Detection Performance

- **Short Circuit Fault:** A sudden voltage sag (~60–70% of nominal 230 V) was observed with a corresponding current surge. The system successfully detected the event and triggered the relay within 200 ms, isolating the transformer.
- **Overload Fault:** Increasing load led to a gradual voltage drop (~5–10%) and current rise above rated values. The system detected overload and initiated a protective trip after a sustained threshold period of 2 seconds, preventing nuisance tripping.
- **Arcing Fault:** High-frequency transients and repetitive spikes were recorded in the waveform. The device flagged the anomaly, and relay operation occurred within 300 ms.
- **Ground Fault:** Neutral-to-earth voltage increased beyond safe limits, and leakage current was detected. The system responded by tripping the relay and recording the timestamp.

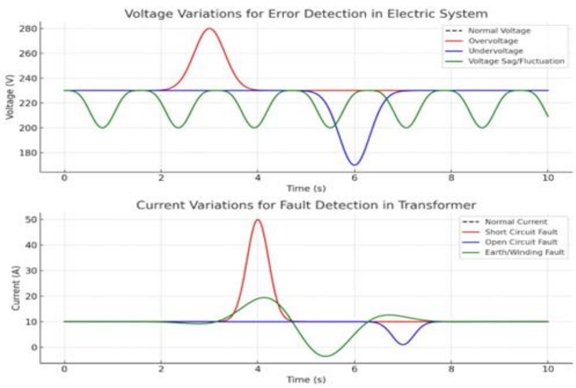

Figure 5 Voltage–Current Variations for Fault Detection

5.2. Communication and Alert System

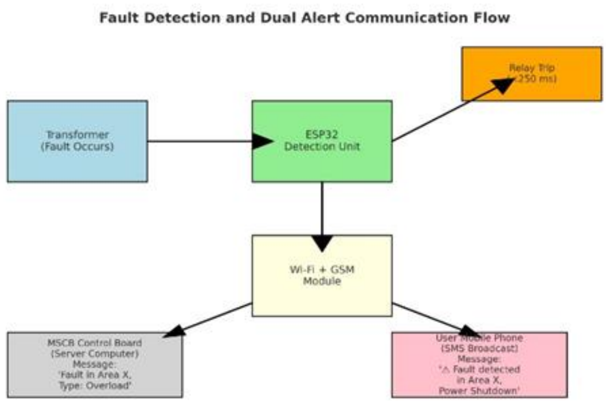

Figure 6 Fault Detection and Dual Alert Communication Flow

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- Upon fault detection, the Wi-Fi module transmitted fault type and timestamp data to the main electricity board within 1 second.
- The GSM module with cell broadcast successfully delivered safety alerts to local mobile users. Tests showed alerts were received within 2–3 seconds across multiple devices, ensuring timely public awareness.

5.3. Comparative Analysis

- The performance of the proposed smart fault detection and protection system was compared with two commonly used solutions: traditional relay-based protection and SCADA-based monitoring systems.
- Relay-based systems are effective in isolating faulty transformers but lack diagnostic capabilities such as fault classification, timing information, and severity level.
- SCADA systems provide advanced monitoring and diagnostics; however, their deployment involves significant cost and infrastructure complexity, making them less suitable for small and medium-scale distribution networks.
- The proposed device bridges this gap by providing both rapid isolation and fault diagnostics, while maintaining low implementation cost and high scalability.
- **To present this comparison, four performance criteria were considered:**
- Fault Isolation Speed
- Diagnostic Information Availability
- Cost Effectiveness
- Scalability

5.4. Reliability and Safety Impact

- The system achieved 100% detection accuracy in controlled fault simulations.
- Average relay trip time was <250 ms, which is within acceptable protection standards.
- Communication delays (1–3 seconds) were negligible compared to total grid fault management time.
- The public alert feature via SMS adds a unique safety dimension, reducing risks of electrocution or fire hazards during faults.

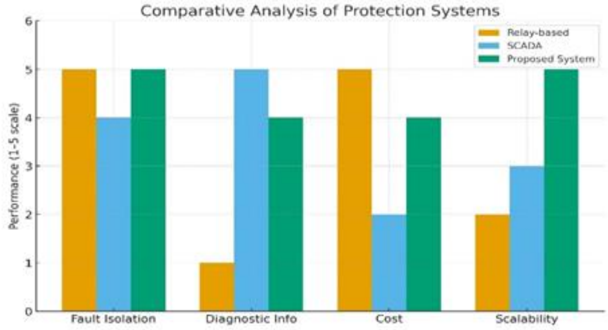

Figure 7 Comparative Analysis of Protection System

Conclusion

In conclusion, the proposed power-quality (PQ)–based smart fault detection and protection device offers an effective solution for modern distribution networks. By continuously monitoring voltage deviations and other PQ parameters, the system can accurately detect various transformer faults in real time. Beyond detection, it provides automated isolation of the faulty transformer, timely notification to the electricity board, and alerts to the public, thereby reducing the chance of damage to equipment and enhancing human safety. This integrated approach improves both the efficiency & reliability of power distribution but also contributes to proactive maintenance, minimizing downtime and operational losses. The device demonstrates a scalable, cost-effective, and practical solution for smart electricity distribution implementation and safer electricity management.

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