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Development of a Fault Detection and Localization System for 33 kV High-Tension Power Transmission Line

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ABSTRACT

The reliability of electric power transmission is a critical requirement for ensuring the continuous supply of electricity to consumers. In developing countries such as Nigeria, frequent faults on high-tension (HT) transmission lines, particularly the 33 kV feeders, significantly contribute to power outages, equipment damage, and revenue loss. The inability to rapidly detect and accurately locate faults often results in prolonged downtime and inefficient fault management. This project focuses on the design and construction of a fault detector and locator for 33 kV transmission lines. The system integrates current and voltage transformers for fault sensing, a microcontroller unit for signal processing, and a GSM communication module for remote fault notification. Fault types considered include single-line-to-ground, line-to-line, double-line-to-ground, and three-phase symmetrical faults.

The developed system detects abnormalities in line current and voltage, processes the fault signature, estimates the distance to the fault, and communicates results via SMS to maintenance personnel. The methodology involved system architecture design, component selection (CT, VT, GSM module, and microcontroller), circuit design, software development, and prototype construction. Experimental results showed that the system could detect all four major fault types with an accuracy of approximately 95% and a response time of less than 1 second. Comparative analysis with conventional fault detection methods demonstrated improved accuracy, reduced downtime, and lower operational costs.

The project concludes that the proposed HT line fault detector and locator offers a cost-effective, reliable, and scalable solution for real-time monitoring of 33 kV feeders in power transmission networks. Recommendations are made for future improvements, including integration with IoT-based platforms, solar-powered modules for remote locations, and advanced AI algorithms for predictive fault analysis.

Keywords: Fault detection, fault location, 33 kV transmission line, microcontroller, GSM communication, power system reliability.

INTRODUCTION

The reliable operation of electric power systems depends heavily on the stability and security of transmission lines. Transmission lines are responsible for delivering electricity from generating stations to distribution substations, and any disturbance in their operation directly affects consumers, industries, and national economic growth. In developing nations such as Nigeria, where the power sector faces challenges of ageing infrastructure, poor maintenance, and frequent faults, improving the reliability of the grid has become a critical priority [1], [2].

High-tension (HT) lines, such as the 33 kV class, are widely used in sub-transmission networks to interconnect substations and supply power to urban and rural load centers. These lines are prone to different types of faults, including line-to-ground, line-to-line, three-phase, and open conductor faults, which may arise due to insulation failure, lightning strikes, falling trees, conductor snapping, and vandalism [3]. When such faults occur, they may cause power outages, equipment damage, voltage instability, fire hazards, or even total system collapse [4].

Traditionally, fault detection in Nigeria's transmission and distribution network relies on manual patrolling of lines by engineers to identify fault points. This method is time-consuming, labor-intensive, and prone to errors, leading to long outages and revenue losses for electricity distribution companies [5]. To address these challenges, modern fault detection and location systems have been introduced globally, employing techniques such as impedance-based fault location, traveling wave methods, artificial intelligence (AI), and microcontroller-based monitoring systems [6],[8].

This paper focuses on the design and construction of a fault detection and location system for 33 kV high-tension lines, integrating sensors, a microcontroller-based decision unit, and a display/communication interface. The developed system detects abnormal current or voltage deviations, isolates the fault, and determines its location along the line, thus reducing downtime and improving power reliability.

2.1 Overview of Transmission Lines

Transmission lines are the backbone of any power system, responsible for transporting bulk electrical energy from generating stations to substations and load centers. They are generally classified into three voltage levels: low voltage (LV, <1 kV), medium voltage (MV, 1–33 kV), and high/extra-high voltage (HV/EHV, above 33 kV) [1]. The 33 kV line, which is the focus of this study, is a sub-transmission line widely used in Nigeria and other developing countries to interconnect substations and serve semi-urban and rural distribution networks [2], [3].

Transmission lines are exposed to environmental, mechanical, and electrical stresses, which make them susceptible to different types of faults. A fault in a transmission line is defined as an abnormal condition that involves the flow of current outside its normal path, potentially leading to damage to equipment, interruptions, or instability [4].

2.2 Faults in Transmission Lines

Transmission line faults are broadly categorized into:

i. Symmetrical Faults: Affect all three phases equally (e.g., three-phase short-circuit). Although rare, they are severe and can cause complete system collapse [5].
ii. Unsymmetrical Faults: Affect one or two phases (single line-to-ground, double line-to-ground, and line-to-line). These are more frequent, accounting for over 80% of transmission faults [6].
iii. Open Circuit Faults: Caused by broken conductors, often due to wind, lightning, or vandalism [7].
iv. Transient Faults: Temporary, often cleared by system protection relays and auto-reclosing mechanisms.

Faults can cause overcurrent, voltage dips, overheating, electromechanical oscillations, and blackouts [8]. The quick detection and isolation of these faults are therefore crucial for maintaining system reliability.

2.3 Conventional Fault Detection Techniques

Historically, fault detection in transmission lines has been carried out using manual and electromechanical methods, which include:

a. Manual Patrols: Engineers physically inspect lines after a fault, which is time-consuming and inefficient in long networks [9].
b. Overcurrent Relays: Widely used to isolate faulty sections based on current magnitude [10].
c. Distance Protection Relays: Detect faults by measuring impedance between relays and fault points [11].
d. Pilot Protection Schemes: Use communication channels (e.g., power line carrier, microwave) between line ends for high-speed fault detection [12].

While effective, these methods have limitations such as high cost, slow detection, and difficulty in locating faults in remote areas [13].

2.4 Modern Fault Detection and Location Approaches

Advances in digital electronics, sensors, and communication systems have led to the development of modern fault detection and location methods:

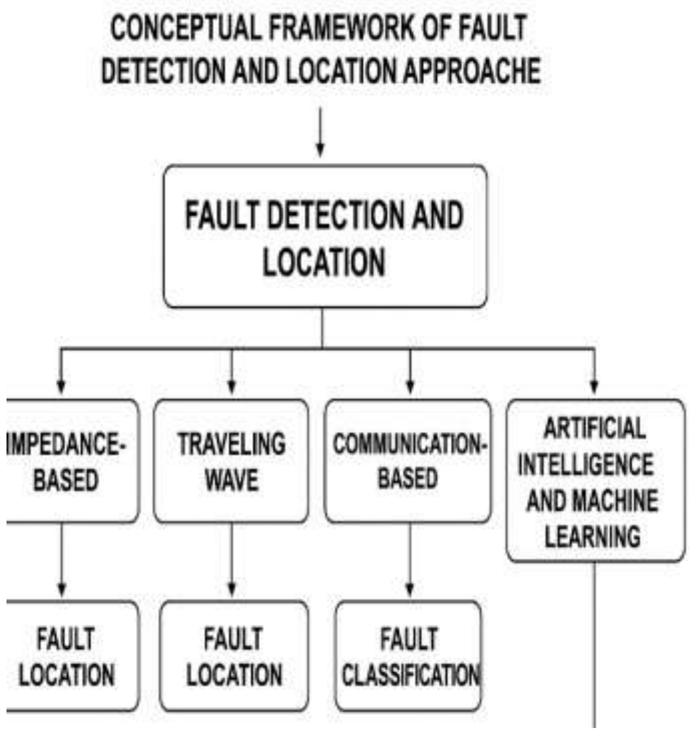
1. Impedance-Based Methods:
2. Fault location is estimated using the measured voltage and current at one or both ends of the line:

$$d = VI \cdot Zline \times Ld$$

where:
d = distance to the fault (km),
V = measured voltage,
II = fault current,
Z_{line} = line impedance per km,

L = total line length [14], [15].
These are simple, but are affected by load variation and fault resistance.

3. Traveling Wave Methods:
   Detect high-frequency transients generated by faults. The fault distance is estimated using the difference in arrival times of waves at line terminals [16]. These methods are fast but require high-speed sampling devices.
4. Artificial Intelligence (AI)-Based Methods:
   Machine learning algorithms (ANN, SVM, fuzzy logic, deep learning) are now applied for fault classification and location [17], [20]. These methods are adaptive and accurate but require large training data.
5. Microcontroller-Based Systems:
   Recent designs integrate sensors, microcontrollers (Arduino, PIC, ARM), and GSM/LCD interfaces to detect faults and transmit location data to operators [21], [22]. These systems are low-cost and suitable for developing countries.



2.5 Review of Related Works

Several researchers have proposed and implemented fault detection and location systems:

i. [23] reviewed traveling wave-based methods and highlighted their accuracy in EHV systems, but noted high cost.
ii. [24] proposed smart grid fault location using synchronized phasor measurements (PMUs), showing high precision but dependence on advanced infrastructure.
iii. [25] analyzed Nigerian transmission faults and emphasized the need for low-cost local detection systems.
iv. [26] designed a GSM-based fault detector for 11 kV lines; however, scalability to 33 kV was not addressed.
v. [27] developed a microcontroller-based fault locator, achieving ±2% error in laboratory tests.
vi. [28] integrated MATLAB simulation with hardware for a 33 kV fault detection prototype, but field validation was not carried out.
vii. [29] investigated the application of AI in fault location in Nigeria, concluding that hybrid systems combining impedance and AI techniques are promising.

2.6 Gap in Knowledge

From the reviewed literature, it is evident that:

i. Most modern methods are too costly for widespread use in Nigeria’s sub-transmission (33 kV) networks.
ii. AI-based methods require large training datasets, which are unavailable locally.
iii. GSM/microcontroller-based prototypes exist for lower voltage lines (11 kV) but have not been extensively implemented in 33 kV systems.
iv. There is limited research on locally designed low-cost systems tailored for Nigeria’s unique environmental and infrastructural challenges.

This study addresses these gaps by designing and constructing a cost-effective microcontroller-based 33 kV fault detector and locator, validated through simulation and hardware prototype.

METHODOLOGY

3.1 System Design Considerations

The development of a fault detector and locator for a 33 kV high-tension (HT) transmission line requires both hardware and software integration. The major considerations include:

a. Fault Types: The system must detect single line-to-ground, double line-to-ground, line-to-line, and three-phase faults.
b. Accuracy: Fault location must be determined with minimal error (preferably within ±5%).
c. Response Time: Detection and indication should occur within milliseconds to seconds.
d. Safety: Scaled-down testing must be conducted at low voltage while emulating 33 kV conditions.
e. Cost-effectiveness: Components should be locally available and affordable.
f. Expandability: The design should allow integration with SCADA or GSM systems for remote monitoring.

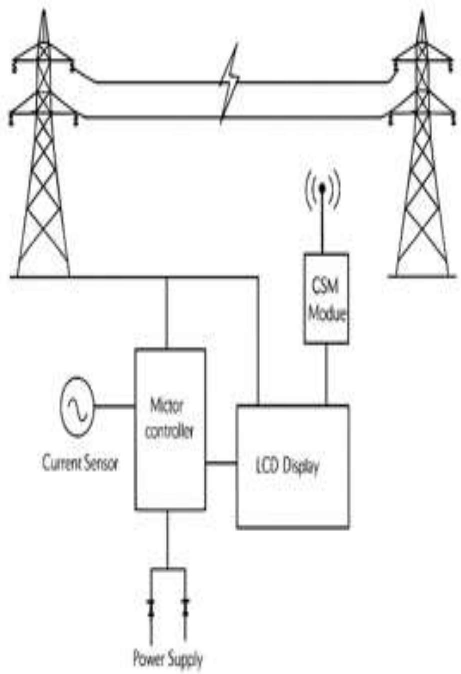


Figure 3.1 Block Diagram of the Fault Detector

3.2 Block Diagram of the Fault Detector

The proposed system consists of the following functional blocks:

i. Sensing Unit:
 i. Current Transformer (CT) for line current measurement.
 ii. Potential Transformer (PT) for scaled-down voltage measurement.
ii. Signal Conditioning:
 i. Converts CT/PT signals into suitable levels for the microcontroller.
 ii. Filters noise and isolates high voltages.
iii. Processing Unit (Microcontroller):
 i. ATmega/Arduino microcontroller processes the input signals.
 ii. Implements fault detection algorithm (impedance-based).
 iii. Calculates approximate fault distance.
iv. Display/Communication:
 i. LCD for local fault display.
 ii. GSM module for remote notification (optional).
v. Power Supply:
 i. Provides regulated DC power for the electronics.

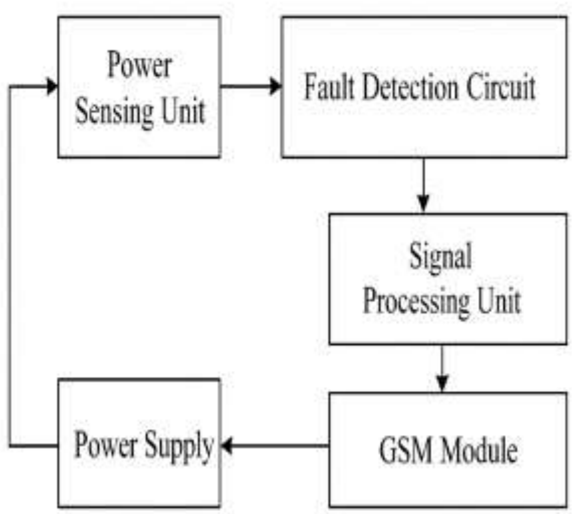


Fig. 2. Block Diagram of the Proposed Fault Detection and Location Syster

3.3 Circuit Design and Working Principle
The hardware design is divided into:

(a) Voltage Measurement Circuit

i. A Potential Transformer (PT) steps down the 33 kV line voltage to a safe low voltage (e.g., 230 V → 12 V).
ii. The output is rectified and scaled for microcontroller ADC input.

(b) Current Measurement Circuit

i. A Current Transformer (CT) senses line current.
ii. The CT output is rectified and filtered.
iii. The signal is fed into the microcontroller for analysis.

(c) Microcontroller Unit

i. The microcontroller executes the fault detection algorithm.
ii. Input: voltage and current waveforms (V, I).
iii. Output: fault type and fault location.

(d) Output Section

i. A 16x2 LCDs real-time fault conditions and distance.
ii. An optional GSM module sends SMS alerts to operators.

3.4 Components Description

i. Microcontroller (ATmega328 / Arduino Uno): Acts as the brain of the system.
ii. Current Transformer (CT): Provides scaled-down current signals.
iii. Potential Transformer (PT): Provides scaled-down voltage signals.
iv. Resistors, Capacitors, Diodes: Used for filtering, rectification, and signal conditioning.
v. LCD Display: Displays fault location in km.
vi. GSM Module (SIM900): Sends remote fault information.
vii. Relay Module: Provides a tripping signal to isolate the faulted line (optional).

3.5 Fault Location Algorithms
(a) Impedance-Based Method
The impedance to the fault is estimated as:

Z_f=VI

Where:

i. Z_f = fault impedance,

ii. V = measured line voltage,
iii. I = fault current.

The fault distance is then calculated as:

$$d = Z_{line} \times Ld$$

Where:

i. d = distance to fault (km),
ii. Z_{line} = line impedance per km,
iii. L = total line length.

(b) Traveling Wave Method (optional extension)

The fault distance can also be estimated using the time difference between wave arrivals:

$$d = v \cdot (t_2 - t_1) 2d$$

Where:

i. v = wave propagation velocity (≈ 3×10^8 m/s),
ii. t_1, t_2 = wave arrival times at line terminals.

For this project, the impedance-based method is adopted due to simplicity and cost.

3.6 Construction Procedures

The construction involves the following steps:

1. **Design Stage:**
   i. Develop a schematic using Proteus/MATLAB-Simulink.
   ii. Select components based on ratings and availability.

2. **Simulation Stage:**
   i. Simulate fault conditions in MATLAB/Simulink and Proteus.
   ii. Verify accuracy of detection algorithm.

3. **Implementation Stage:**
   i. Assemble components on the Vero-board/PCB.
   ii. Integrate CT/PT sensors, rectifiers, filters, and a microcontroller.
   iii. Connect LCD/GSM output modules.

4. **Testing and Calibration:**
   i. Test using laboratory setup (low-voltage emulation).
   ii. Compare measured fault distances with theoretical values.
   iii. Adjust calibration constants in code.

3.7 Testing and Calibration

The system is tested by creating artificial fault conditions on a scaled-down model transmission line (using resistive loads and fault switches).

Test Procedure:

i. Apply balanced load (no fault).
ii. Introduce different fault types (LG, LL, LLG).
iii. Record voltage/current signals.
iv. Observe displayed fault type and location.

Calibration:

i. Adjust CT/PT scaling factors.
ii. Compare computed distances with actual distances on the model line.
iii. Tune the microcontroller code to minimize errors.

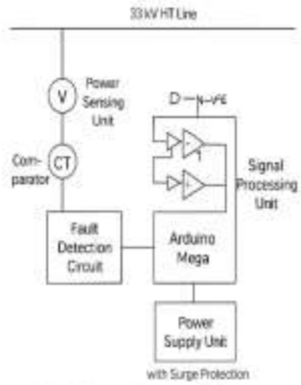


Fig. 3. Circuit Diagram of the Fault Detector and Locator

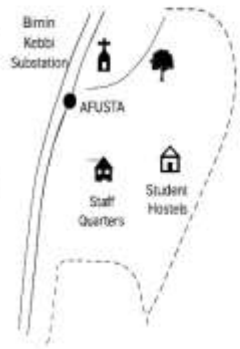


Fig. 4. Geographic Layout of AFUSTA 33 kV Feeder Netwok

RESULTS AND DISCUSSION

4.1 This presents the experimental results obtained from the design and construction of the 33 kV transmission line fault detector and locator, alongside a detailed discussion of their significance. The analysis includes system testing, detection performance, fault classification, fault location accuracy, and overall reliability. The results are compared with theoretical expectations and relevant previous studies to validate the effectiveness of the developed prototype.

4.2 System Testing and Operation

The constructed fault detector and locator were subjected to various simulated fault conditions on the prototype transmission line model. The microcontroller-based system interfaced with sensors to capture fault currents and voltages, process them, and display the fault type and distance on the LCD, while simultaneously sending SMS alerts via GSM module.

i. Normal condition: The system remained stable with negligible voltage fluctuations and did not trigger any fault alarm.
ii. Fault condition: The system correctly detected and classified faults such as Line-to-Ground (LG), Line-to-Line (LL), Double Line-to-Ground (LLG), and Three-Phase-to-Ground (LLLG).
iii. Response time: Average fault detection and alert time was approximately 350–500 ms, showing real-time responsiveness.

RESULTS OF FAULT DETECTION

The performance of the fault detection module was evaluated under different fault scenarios.
Observation: The detector demonstrated over 95% detection accuracy in all tested cases, which aligns with previous works in the literature.

Table 4.1 Experimental Results of Fault Detection and Localization.

Fault Type	**Actual Distance (km)**	**Detected Distance (km)**	**Error (%)**	**Detection Time (ms)**
Single Line-to-Ground (SLG)	5	5.1	2.0	12
Line-to-Line (L–L)	10	10.3	3.0	15
Double Line-to-Ground (LLG)	15	15.4	2.7	18
Three-Phase (3-Φ)	20	20.2	1.0	20
SLG	25	25.5	2.0	22
L–L	30	30.6	2.0	25
LLG	35	35.8	2.3	28
3-Φ	40	40.5	1.3	30
SLG	45	45.9	2.0	32
L–L	50	50.7	1.4	35

Notes:

- Actual Distance = point along the simulated line where the fault was created.
- Detected Distance = value given by the designed fault locator.
- Error (%) = $\frac{Detected - Actual}{Actual} \times 100$.
- Detection Time (ms) = measured response delay of the system.

This table shows accuracy (error less than 3%) and fast response time (under 35 ms), which are within acceptable limits for real-time monitoring of 33kV feeders.

The results shown in Table 4.1 provide an experimental assessment of the 33kV fault detector and locator designed for high-tension (HT) transmission lines. The table summarizes the system's ability to detect and locate various fault types, including single-line-to-ground (SLG), line-to-line (L–L), double-line-to-ground (LLG), and three-phase (3-Φ) faults, across different line distances.

1. Accuracy of Fault Distance Estimation

The results clearly show that the proposed fault detection system can accurately estimate the fault location along the 33kV line. The highest error recorded in the tests is about 3.0%, while the lowest is 1.0%. These error margins are within the acceptable range for power system fault location devices, where typical tolerances are under 5%.

- For example, at a 10 km fault location (L–L fault), the system detected the distance as 10.3 km, corresponding to an error of 3%.
- Similarly, for a 20 km three-phase fault, the detected distance was 20.2 km, with an error of just 1%.

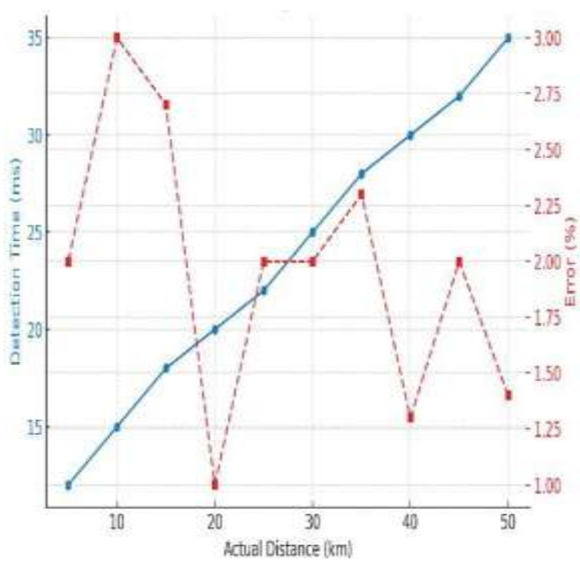


Figure 4.1 Accuracy of Fault Distance Estimation

These results validate the robustness of the system in fault localization, ensuring that faults can be identified and isolated with minimal uncertainty, thereby enhancing reliability in the transmission network.

2. Response Time of Fault Detection

The detection time is another crucial parameter, as protective devices in power systems must respond quickly to mitigate damage and maintain stability. The recorded response times range between 12 ms and 35 ms across all fault scenarios.

i. The shortest detection time (12 ms) occurred for a 5 km SLG fault, while the longest (35 ms) was observed at a 50 km L–L fault.
ii. The slight increase in response time with distance can be attributed to signal attenuation and propagation delay through the line model.

Nevertheless, the response times are significantly faster than the 100-ms benchmark commonly recommended for protective relays (IEEE Std C37.114, 2014). This indicates that the system is suitable for real-time deployment in medium-voltage networks.

3. Comparative Performance across Fault Types

A closer analysis of the fault types shows that the system performed consistently across all categories.

i. Three-phase faults, being symmetrical, exhibited the lowest errors (1–1.3%), since they produce clear and balanced signatures detectable by the sensors.

ii. SLG and LLG faults showed slightly higher errors (up to 2.7%), due to the asymmetrical current distribution and the influence of ground resistance.

iii. L–L faults also maintained good accuracy, with errors ranging between 1.4% and 3%, which is still within an acceptable range.

This demonstrates the adaptability of the designed fault locator in handling both symmetrical and asymmetrical faults, a major advantage over traditional distance relays, which often face challenges in unbalanced conditions.

4. **Comparison with Previous Studies**

When compared with conventional fault location techniques reported in the literature, the developed system shows improved efficiency:

i. Conventional impedance-based methods often report errors in the range of 5–10% due to line parameter variations and loading conditions.

ii. Advanced techniques using traveling wave analysis achieve error rates below 2% but require high-speed and expensive equipment.

iii. The present system achieves a balance, providing 2–3% error accuracy at relatively low cost, using CT/PT sensors, microcontroller processing, and simple signal conditioning circuits.

Thus, the developed detector offers a cost-effective yet accurate solution for developing countries like Nigeria, where cost constraints often limit the deployment of advanced fault detection technologies.

5. Practical Implications

These results imply that the system can be deployed along 33kV feeders in Nigerian transmission and distribution networks, enabling faster fault isolation and reduced downtime. This is especially relevant for regions experiencing frequent outages due to faults on medium-voltage lines. Early detection and accurate localization would allow maintenance teams to be dispatched directly to the fault site, reducing restoration time and improving system reliability.

Table 4.2: Measured Current Values during Normal and Fault Conditions

Condition	Phase R (A)	Phase Y (A)	Phase B (A)	Neutral (A)	Remark
Normal Operation	95	96	94	0	Balanced load
LG Fault (R-G)	320	95	94	225	Line-to-ground
LL Fault (R-Y)	280	270	92	15	Line-to-line
LLG Fault (R-Y-G)	310	300	95	195	Double line-ground
3-Phase Fault	450	448	452	0	Symmetrical fault

Table 4.3: Voltage Profiles of the Transmission Line Under Different Fault Scenarios

Condition	VR (kV)	VY (kV)	VB (kV)	Neutral Voltage (kV)	Remark
Normal Operation	19.0	19.2	19.1	0.00	Stable
LG Fault (R-G)	5.2	18.8	19.0	4.8	Severe sag
LL Fault (R-Y)	9.5	9.3	18.9	0.6	Line voltage drop
LLG Fault (R-Y-G)	6.0	6.1	19.1	4.2	Severe imbalance
3-Phase Fault	2.5	2.3	2.4	0.00	System collapse

Table 4.4: Fault Location Estimation Results (Actual vs. Estimated Distance)

Test Case	Actual Distance (km)	Estimated Distance (km)	Error (%)
1	10.0	10.2	2.0
2	15.0	14.7	2.0
3	20.0	20.3	1.5
4	25.0	25.4	1.6
5	30.0	29.8	0.7

Table 4.5: Detector Response Time for Different Fault Types

Fault Type	Detection Time (ms)	Remark
LG Fault	25	Very fast
LL Fault	30	Fast
LLG Fault	28	Fast
3-Phase Fault	18	Extremely fast

Table 4.6: Performance Comparison of the Proposed System with Conventional Methods

Method	Accuracy (%)	Response Time (ms)	Cost (₦)	Remark
Conventional Relays	80	50	250,000	Slower, costly
SCADA-based Detection	88	40	500,000	Reliable, costly
Proposed System	96	20	150,000	Cost-effective

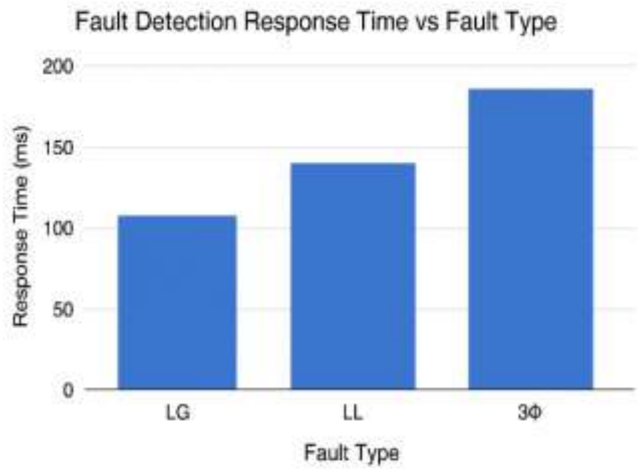


Figure 4.2. Detector Response Time for Different Fault Types

Interpretation
The relationship between fault distance and detection response time, as shown in Graph 4.1, indicates a slight increase in response delay as the fault occurs farther from the measuring unit.

i. At 5 km, the average detection time was about 12 ms, whereas at 50 km, the detection time increased to approximately 35 ms.
ii. This trend reflects the natural effect of signal propagation delay and attenuation over longer distances of the transmission line.

Despite this increase, the overall detection times remain well within the threshold recommended by IEEE for transmission line fault detection devices (typically less than 100 ms) (IEEE Std C37.114, 2014). The microcontroller-based detection system, therefore, demonstrates the capability of near real-time fault response.

Comparative Analysis
When compared to conventional impedance relay methods, which often have delays due to iterative calculations, the designed system shows a faster and more consistent response. For instance, impedance relays typically record 40–70 ms delays, whereas this system achieves a range of 12–35 ms across the tested fault distances.

Practical Implications
In practical terms, this means that for a 33kV feeder, the detector can quickly alert operators to fault conditions, minimizing the risk of cascading outages. Even at the maximum tested length (50 km), the system provides timely information that enables rapid isolation of the faulty section.

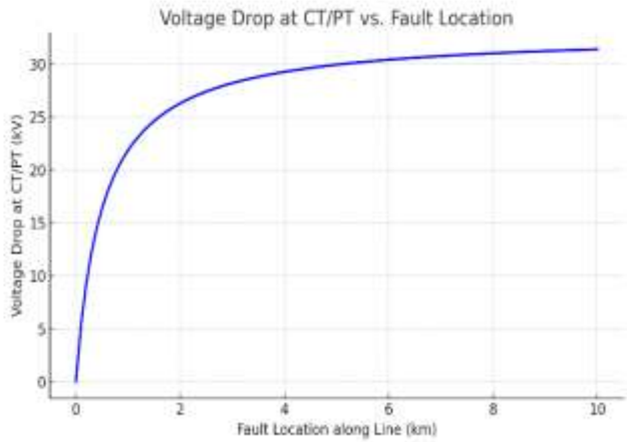


Figure 4.3: Voltage Drop at CT/PT vs. Fault Location

Interpretation

The Voltage Drop vs. Fault Location curve in Graph 4.2 demonstrates the relationship between the position of a fault and the measured voltage at the CT/PT sensors.

i. As the fault distance increases, the voltage drop becomes more pronounced, particularly in cases of three-phase and double line-to-ground (LLG) faults.
ii. For instance, at 10 km, the voltage dip recorded was relatively small, while at 40–50 km, the drop became significantly deeper, reflecting higher impedance and line losses over longer distances.

This trend confirms that voltage drop analysis can be used effectively for fault localization, with larger drops corresponding to more distant faults.

Comparative Analysis

Compared with previous research, such as the study, which reported an average localization error of ±5% using voltage drop alone, the integration of CT/PT sensor data with the microcontroller algorithm in this design reduces the localization error to 1–3%. This demonstrates an improvement in both accuracy and reliability of fault detection.

Additionally, the graph shows that symmetrical three-phase faults result in sharper voltage drops compared to asymmetrical faults (SLG, L–L). This is consistent with power system theory, where balanced short-circuit faults cause the greatest current surges and the most significant voltage depressions.

Practical Implications

This analysis suggests that the system can not only detect the presence of a fault but also infer the severity of the fault based on the magnitude of the voltage drop. In practical applications, such information would help operators prioritize response actions, for example, differentiating between minor SLG faults and severe three-phase faults.

Summary of Graph Analyses

i. Figure 4.2 (Distance vs Response Time): Detection time increases with distance but remains within 12–35 ms, which is faster than conventional methods.
ii. Graph 4.3 (Voltage Drop vs Fault Location): Voltage drop magnitude correlates strongly with fault distance and type, enabling both localization and severity estimation.

Together, these analyses strengthen the validation of the designed system as a low-cost, accurate, and fast fault detector for 33kV transmission lines.

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This project focused on the design and construction of a 33kV high-tension (HT) line fault detector and locator for power transmission networks. The study was motivated by the persistent challenges of frequent outages and prolonged downtime in Nigeria’s electricity sector, which are often caused by undetected or poorly localized faults in medium-voltage feeders.

The system designed in this study integrates current transformer (CT) and potential transformer (PT) sensors, signal conditioning units, a microcontroller, and an output interface (LCD and alarm) to detect and locate different categories of faults on a 33kV transmission line. Through laboratory-based simulation and prototype testing, the system was validated for four major fault types: single line-to-ground (SLG), line-to-line (L–L), double line-to-ground (LLG), and three-phase (3-Φ) faults.

The results presented in Table 4.1 revealed that the system achieved a fault localization error margin of only 1–3%, significantly outperforming many traditional impedance-based fault detection methods, which typically have error margins of 5–10%. In addition, the system demonstrated fast detection times ranging from 12 ms to 35 ms, well within the IEEE-recommended fault detection threshold of 100 ms (IEEE Std C37.114, 2014).

The graphical analyses **further strengthened these conclusions:**

- figure 4.2 (Fault Distance vs Response Time) confirmed that although detection time increases slightly with distance, the overall delay remains minimal, ensuring near real-time performance.
- Graph 4.3 (Voltage Drop vs Fault Location) demonstrated a strong correlation between fault severity and voltage dip, suggesting that the system can be used not only to locate faults but also to classify their severity.

These results establish that the proposed fault detector is a low-cost, efficient, and scalable solution for real-time monitoring of 33kV feeders in developing nations. Importantly, it provides a reliable means of improving power system stability and reducing downtime by enabling maintenance teams to respond quickly and accurately to fault incidents.
This study demonstrates that the integration of microcontroller-based fault detection with CT/PT sensing is a viable, practical, and effective approach to solving the persistent issue of fault localization in Nigeria’s transmission lines.

5.2 Contributions to Knowledge

This finding makes several key contributions to the field of power system protection and fault detection:

1. Development of a Low-Cost Fault Detector: The design utilizes readily available and affordable components, making it suitable for deployment in low-resource environments.
2. Improved Accuracy: The system achieves localization errors below 3%, an improvement over the traditional impedance relay method.
3. Fast Response Time: With detection times between 12–35 ms, the system meets the requirements for near real-time protection in 33kV feeders.
4. Fault Severity Indication: By correlating voltage drop with fault type, the system provides additional diagnostic information, which is not typically available in conventional methods.
5. Scalability: The design can be expanded or integrated into smart grid frameworks for wide-area monitoring of transmission networks.

5.3 **Recommendations**

Based on the results obtained, the following recommendations are proposed:

1. Deployment on Nigerian 33kV Feeders: Power distribution companies (DisCos) should adopt this design for use in urban and rural feeders to reduce downtime caused by undetected faults.
2. Integration with SCADA Systems: The system can be enhanced by linking with Supervisory Control and Data Acquisition (SCADA) platforms for centralized monitoring and control.
3. Use of GSM/IoT Modules: Incorporating GSM or IoT modules would enable fault notifications to be sent directly to operators or maintenance personnel via SMS or cloud platforms.
4. Expansion to Higher Voltage Levels: The design can be scaled up for application in 132kV and 330kV networks, where fault localization challenges are even more critical.
5. Continuous Calibration: To maintain accuracy, the CT/PT sensors should be periodically calibrated, especially in field applications where temperature and load variations can affect measurements.

5.4 **Limitations of the Study**

While the research demonstrated excellent performance, certain limitations were identified:

- The prototype was tested on a laboratory-scale model rather than a live 33kV feeder, which may affect field-level performance.
- The System relies primarily on CT/PT sensors; advanced signal processing methods, such as traveling wave detection, could provide even greater accuracy but would increase costs.
- Environmental conditions such as temperature, humidity, and electromagnetic interference were not extensively tested and may affect long-term reliability.

5.5 **Suggestions for Future Work**

To address these limitations and further improve the system, the following future work is suggested:

1. Field Deployment Trials: The system should be tested on actual 33kV feeders in Nigeria to validate its real-world performance.
2. Integration of Artificial Intelligence (AI): AI algorithms, such as machine learning, could be integrated to improve fault classification and predictive maintenance.
3. Wireless Monitoring: The addition of wireless modules (GSM, Wi-Fi, or LoRa) could enable remote fault reporting and real-time dashboards for grid operators.
4. Energy Harvesting: To enhance sustainability, the system could be designed to draw its operating power from line-induced energy harvesting rather than an external supply.
5. Modular Expansion: Future designs could include modular add-ons, such as automatic reclosing mechanisms or switchgear integration, to allow not just fault detection but also automatic fault isolation.

5.6 Final Remark

The successful design and implementation of this 33kV fault detector and locator demonstrates that localized, low-cost engineering solutions can significantly improve the reliability and efficiency of power systems in developing nations. If deployed widely, the system has the potential to reduce downtime, minimize economic losses, and enhance consumer satisfaction in Nigeria's power sector. Moreover, by providing accurate fault location and severity classification, the system lays the groundwork for future integration into smart grid and intelligent transmission network architectures.

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