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Design And Modeling of a Microcontroller-Based Fault Detector for Medium Voltage Distribultion

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ABSTRACT
Medium Voltage (MV) distribution networks are critical components of modern power systems, supplying electrical energy to industrial, commercial, and residential consumers. In developing countries, including Zambia, MV distribution feeders are highly prone to faults caused by lightning strikes, equipment ageing, conductor failures, vegetation encroachment, and environmental conditions. Conventional protection systems deployed in MV networks rely heavily on centralized relays and manual fault location methods, which often result in long outage durations, reduced reliability indices, and increased operational costs.
This research proposes the design and modelling of a microcontroller-based fault detection system for MV distribution networks. The system will continuously monitor electrical parameters such as current, voltage, and frequency, process them using signal conditioning and embedded algorithms, and identify fault types including single line-to-ground, line-to-line, double line-to-ground, and three-phase faults. Mathematical models of MV feeders and fault conditions will be developed to support algorithm design and validation. Simulation will be carried out using industry-standard software tools.
The expected outcome is a low-cost, reliable, and scalable fault detection solution capable of improving fault detection speed, accuracy, and overall distribution network reliability. The research contributes to smart distribution system protection and is particularly suited for application in resource-constrained power utilities.
Keywords: *Medium voltage; Microcontroller; Fault detection; Overcurrent relays; Distribution; Zambia*

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I. Introduction

The reliable supply of electrical energy is a cornerstone of modern economic development, industrial growth, and societal well-being. As electrical power systems continue to expand in scale and complexity, the need for efficient monitoring, protection, and control mechanisms has become increasingly critical. Among the various components of the power system, the distribution network plays a particularly vital role, as it represents the final stage in delivering electrical energy to consumers. Medium Voltage (MV) distribution systems, typically operating within the range of 11 kV to 33 kV, are especially significant due to their widespread use in both urban and rural electrification [1].

Despite their importance, MV distribution networks are inherently vulnerable to faults. These faults may arise from a variety of causes, including environmental factors such as lightning and vegetation, equipment ageing, insulation failure, and human interference. The occurrence of faults results in abnormal system conditions characterized by excessive currents, voltage drops, and system instability. If not detected and cleared promptly, such faults can lead to equipment damage, safety hazards, and prolonged power outages, thereby reducing system reliability and service quality [2], [3].

Conventional fault detection and protection methods in MV distribution systems are primarily based on centralized devices such as overcurrent relays, earth fault relays, and circuit breakers. While these systems are widely used due to their simplicity and reliability, they exhibit several limitations. In particular, they lack the ability to provide real-time monitoring along the entire feeder, resulting in delayed fault detection and location. Furthermore, traditional methods are often ineffective in detecting high-impedance faults, which produce relatively low fault currents that may not exceed relay thresholds but still pose significant safety risks [4], [5].

In recent years, advancements in embedded systems, digital signal processing, and communication technologies have led to the development of more sophisticated fault detection approaches. Techniques based on impedance measurement, traveling waves, and artificial intelligence have demonstrated improved performance in terms of fault detection accuracy and speed. However, these methods are often associated with high implementation costs, complex infrastructure requirements, and significant computational demands, which limit their applicability in resource-constrained environments [6]–[8].

The increasing integration of Distributed Generation (DG) sources, such as solar photovoltaic systems and wind energy, has further complicated fault detection in distribution networks. DG alters the conventional flow of power and affects fault current characteristics, making traditional protection schemes less reliable. This necessitates the development of adaptive and intelligent fault detection systems capable of operating effectively under varying network conditions [9].

Against this background, microcontroller-based systems have emerged as a promising solution for improving fault detection in MV distribution networks. Microcontrollers offer a cost-effective and flexible platform for implementing real-time monitoring and decision-making algorithms. By integrating voltage and current sensing with embedded processing, such systems can enable decentralized fault detection, rapid response, and improved system reliability [10].

II. PROBLEM FORMULATION AND RESEARCH OBJECTIVES

2.1 Fault detection challenges Medium Voltage (MV) distribution networks

While there has been great advancement in power system protection, most Medium Voltage (MV) distribution networks continue to suffer from extensive interruption periods resulting from insufficiently developed fault detection and localization methodologies. This situation is attributed to the following factors:

First, a centralized method of protection with restricted level visibility. Traditional protection schemes based at substations cannot observe conditions along the entire feeder length, leaving downstream faults invisible until customer calls are received [5], [9].

Second, manual procedures followed during location of faults that take plenty of time. Utility personnel rely on customer telephone calls and visual inspections to identify fault locations, a process that typically requires approximately 900 seconds (15 minutes) from fault occurrence to notification [7]. This delay translates directly into extended outage durations and reduced customer satisfaction.

Third, high costs associated with installing conventional Intelligent Electronic Devices (IEDs). SCADA systems and digital relays require substantial capital investment, making comprehensive distribution monitoring economically prohibitive for many utilities, particularly in developing regions [7], [10].

Fourth, the inability of typical circuit breakers to categorize faults properly, along with the limited flexibility they possess with respect to changes experienced by a network. The increasing penetration of distributed generation (DG) sources is fundamentally altering fault current characteristics, rendering traditional protection schemes less effective [11].

Fifth, high-impedance faults remain particularly problematic for existing detection methods. When a conductor breaks and falls onto a tree branch or dry soil, the resulting fault current may be only 10-50 amperes—insufficient to trigger conventional overcurrent protection but sufficient to maintain an electrical arc that can ignite surrounding vegetation [12], [13].

These reasons further contribute towards lower reliability indices like SAIDI and SAIFI. Therefore, what is needed at present is an intelligent fault detection system that can be deployed distributively, operates economically, and always maintains its operability within any type of environment in MV distribution systems.

2.2 Research Objectives

The specific objectives of this study are:

(i) Develop mathematical and simulation models of medium voltage distribution feeders under normal and faulted operating conditions in order to characterize voltage and current signatures associated with common distribution system faults.;

(ii) Design and simulate a microcontroller-based fault detection and classification algorithm using real-time voltage and current measurements for accurate identification of fault types in medium voltage distribution networks, including single line-to-ground, line-to-line, double line-to-ground, and three-phase faults;

(iii) Validate and evaluate the performance of the proposed fault detection system through simulation, assessing its accuracy, detection speed, reliability, and suitability for practical deployment in medium voltage distribution systems.

III. THEORETICAL FRAMEWORK AND MATHEMATICAL MODELLING

3.1 Theoretical Framework

The developed fault detection approach relies primarily on the analysis of RMS current values obtained from the monitored three-phase signals. RMS analysis is widely used in power system protection because it provides a

stable representation of the effective magnitude of alternating current signals under both normal and faulted conditions.
The RMS current value used in the proposed system is given by:

$$I_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} i^2(n)}$$

The calculated RMS current values are continuously compared with predefined threshold levels in order to determine whether abnormal operating conditions exist within the network. When the measured RMS current exceeds the specified threshold value, the system identifies the presence of a fault condition.

3.2 Mathematical Modelling

The mathematical modelling of the proposed fault detection system was developed using principles of three-phase power system analysis and fault theory. The MV distribution feeder was represented as a three-phase electrical network consisting of a power source, transmission line parameters, measurement units, and fault generation components.
Under balanced operating conditions, the three-phase voltages of the system can be represented as sinusoidal functions displaced by 120°:

$$V_a = V_m \sin(\omega t)$$
$$V_b = V_m \sin(\omega t - 120°)$$
$$V_c = V_m \sin(\omega t + 120°)$$

During fault conditions, the network impedance decreases significantly, causing fault currents to increase rapidly according to Ohm's Law:

$$I_f = \frac{V}{Z_f}$$

The reduction in fault impedance during abnormal operating conditions results in large current magnitudes, which are detected by the monitoring subsystem. The measured currents are processed using RMS calculation blocks and compared with predefined threshold values for fault identification.
The threshold-based detection principle implemented in the model can be expressed as:

If $I_{RMS} > I_{threshold}$, then a fault condition exists

where:

- $I_{threshold}$ represents the preset fault detection threshold current

The fault classification logic was mathematically represented according to the affected phase currents as follows:

- If only one phase current exceeds the threshold value:

$$I_A > I_{threshold}$$

then the system classifies the fault as a Single Line-to-Ground fault.

- If two phase currents exceed the threshold simultaneously:

$$I_A > I_{threshold} \text{ and } I_B > I_{threshold}$$

then the system classifies the condition as a Line-to-Line fault.

- If all three phase currents exceed the threshold values simultaneously:

$$I_A, I_B, I_C > I_{threshold}$$

then the system identifies a Three-Phase fault condition.
The mathematical model was implemented and validated within MATLAB/Simulink using subsystem blocks representing voltage measurement, current monitoring, RMS calculation, threshold comparison, and logical fault classification operations. The developed model enabled analysis of system behavior under both normal and faulted operating conditions within the MV distribution feeder.

IV. SYSTEM MODELLING AND SIMULATION METHODOLOGY

4.1 System Under Study

The system was modelled and simulated using MATLAB/Simulink in order to evaluate its performance under different fault conditions, including single line-to-ground (SLG), line-to-line (L-L), and three-phase faults. The simulation environment provides a safe and flexible platform for analyzing the behavior of the proposed fault detection algorithm before practical implementation.

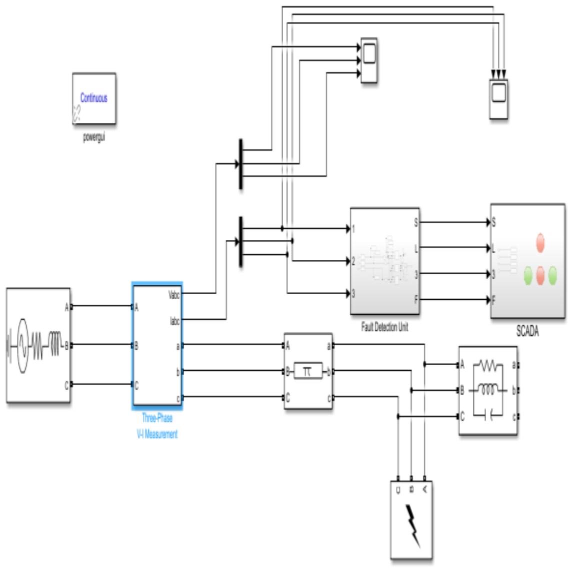

Figure 1: MATLAB/Simulink Model of the Proposed Fault Detection System

4.2 MATLAB/Simulink Subsystem Models

The simulation begins with the three-phase voltage source, which represents the MV power supply feeding the distribution network. The source provides balanced three-phase electrical power to the feeder model under normal operating conditions. The feeder section represents the transmission or distribution path through which electrical energy is delivered to the connected load.

Voltage and current measurement blocks are connected within the feeder in order to continuously monitor the electrical behavior of the system. These measurement units acquire real-time phase voltage and current signals required for fault analysis and system monitoring. The measured signals are then transmitted to the Fault Detection Unit for processing and evaluation.

The fault generation subsystem is used to introduce different fault conditions into the network during simulation. Various fault scenarios including Single Line-to-Ground (SLG), Line-to-Line (LL), and Three-Phase faults are simulated in order to evaluate the performance of the proposed fault detection approach under abnormal operating conditions. The fault block allows faults to be initiated at predetermined simulation times and locations within the feeder model.

The Fault Detection Unit serves as the central processing subsystem of the architecture. This unit analyses the measured voltage and current signals using RMS calculations, threshold comparison techniques, and logical decision-making operations. When abnormal current or voltage conditions exceed predefined limits, the subsystem identifies the presence of a fault and determines the corresponding fault category.

The outputs of the Fault Detection Unit are connected to the SCADA monitoring subsystem, which provides real-time visualization of system operating conditions and fault status indications. Indicator displays and monitoring signals are used to show whether the system is operating normally or under faulted conditions. This monitoring capability improves operator awareness and assists in rapid fault identification.

4.3 Simulation Parameters

Table 1 summarises the key MATLAB/Simulink simulation parameters, and Table 2 presents the Power World Simulator parameters.

Parameter	Value	Unit
RMS Voltage threshold	959.8	V
Grid Voltage	33	kV
System Frequency	50	Hz

RMS Current threshold	20	A
Simulation Time	2	s
Sampling Time	50×10^{-6}	s
Fault Resistance	0.05	Ω

Table 1. MATLAB/Simulink simulation parameters for the medium voltage fault detection system.

V. SIMULATION RESULTS AND DISCUSSION

5.1 Simulation results

The three-phase voltage and current waveforms were continuously monitored using a scope block connected to the SCADA system.

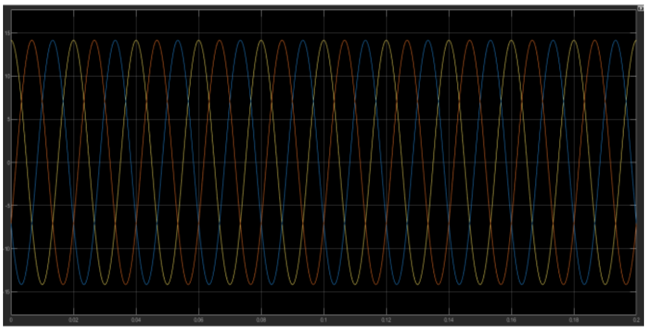

Figure 2: Voltage and current waveforms under normal operating conditions

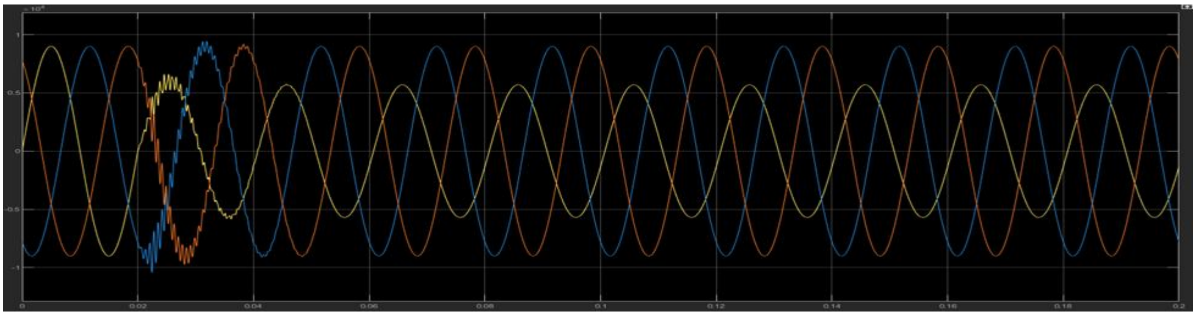

Figure 3: Voltage and current waveforms single line to ground fault conditions

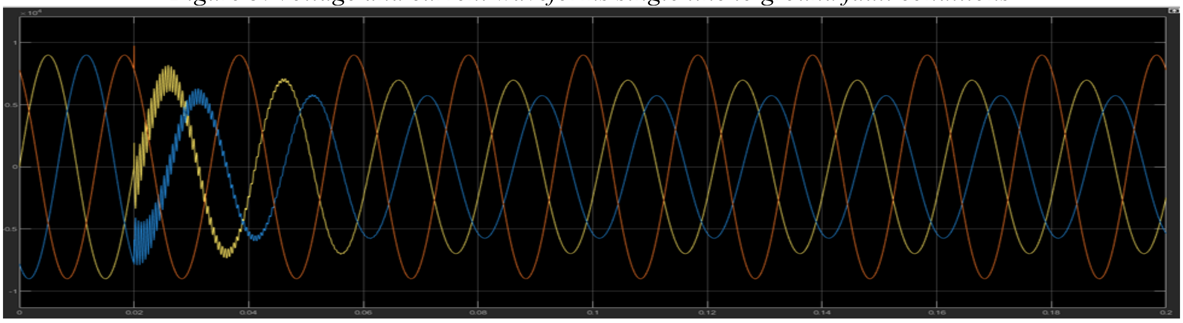

Figure 4: Voltage and current waveforms single line to ground fault conditions

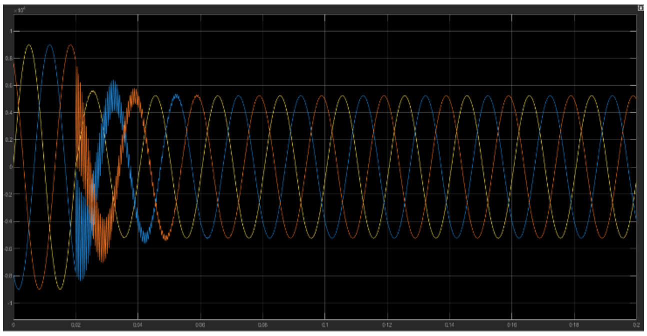

Figure 5: Voltage and current waveforms single line to ground fault conditions

5.2 Discussion

The simulation results validate the theoretical framework and mathematical modeling of the proposed microcontroller-based fault detection system. Under normal operating conditions, the system displays a balanced, steady-state three-phase sinusoidal waveform, adhering to the expected 120º phase displacement. During these periods, the calculated Root Mean Square (RMS) current remains safely below the designated 20 A threshold current, indicating a healthy network status.

When a fault is initiated via the fault generation subsystem at t = 0.02s, a sharp transient distortion and a rapid escalation in current magnitude are clearly observed across the waveforms.

The primary strength of the embedded algorithm lies in its decentralized fault classification logic:

- Single Line-to-Ground (SLG) Faults: The algorithm successfully flags an SLG fault when a single phase's RMS current surges past the 20 A threshold while the remaining phases stay within nominal parameters. This is seen in figure 3
- Line-to-Line (L-L) Faults: The simultaneous breach of the threshold by two phase currents activates the logical combination that classifies the event as an L-L fault. This is seen in figure 4
- Three-Phase Faults: A balanced, concurrent spike across all three phases triggers a comprehensive three-phase fault state identifier. This is seen in figure 5

By executing these threshold comparisons and logical operations using a tight sampling, the Fault Detection Unit achieves rapid, real-time processing. This processing speed addresses the critical 15-minute response delay typically associated with manual fault locations and customer-complaint-driven utility interventions.

Furthermore, because this architecture relies on fundamental processing blocks and localized threshold comparisons rather than highly complex, computationally heavy AI frameworks, it offers a highly scalable and low-cost alternative to expensive Intelligent Electronic Devices (IEDs) and comprehensive SCADA overhauls. This makes the system exceptionally viable for resource-constrained power utilities, such as those navigating the evolving landscape of medium-voltage distribution networks and solar-integrated feeders in Zambia.

VI. CONCLUSIONS

This research successfully designed and modeled a low-cost, decentralized, microcontroller-based fault detection and classification system tailored for Medium Voltage (MV) distribution networks. By utilizing a threshold-based Root Mean Square (RMS) current analysis operating at a high-resolution sampling time of 50×10^{-6} s, the system successfully characterized and identified critical network faults including Single Line-to-Ground (SLG), Line-to-Line (L-L), and Three-Phase faults —within a simulated MATLAB/Simulink environment

The evaluation of the system reveals three major conclusions:

- Enhanced Speed and Automation: The algorithm eliminates the traditional, time-consuming 15-minute delay associated with customer notifications and manual inspections, enabling instantaneous processing and classification at the moment a fault occurs.
- High Technical Fidelity: The proposed logical framework successfully bridges the visibility gaps of conventional substation relays, accurately matching severe fault current behaviors governed by Ohm's Law during low-impedance faults.
- Economic Viability: By relying on localized embedded processing instead of capital-intensive SCADA infrastructures and traditional Intelligent Electronic Devices (IEDs), this design provides a scalable, economically feasible protection layer.

Ultimately, this system proves highly suitable for resource-constrained power utilities, offering a robust foundational architecture to improve vital network reliability indices (such as SAIDI and SAIFI) in modern, solar-integrated distribution networks across Zambia.

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