DESIGN OF THREE-PHASE AUTO-RECLOSURE RELAY FOR 33 KV TRANSMISSION NETWORK USING A FUZZY LOGIC APPROACH

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ABSTRACT

This paper investigates the limitations of conventional fixed dead-time auto-reclosing schemes and proposes a fuzzy logic–based auto-reclosure relay (FL-ARR) for 33 kV transmission networks to improve system reliability and operational continuity. Conventional auto-reclosure employs a single fixed dead time irrespective of fault type and location, resulting in suboptimal reclosing decisions, unnecessary delays in service restoration, and increased customer interruption—particularly for transient faults that could be swiftly cleared. Moreover, the inability to distinguish between transient and permanent faults leads to repeated supply disruptions and elevated circuit-breaker maintenance costs. The study aim is to design and simulate 3phase intelligent autoreclosure relay capable of determining optimal reclosing dead time based on fault type and location. A Mamdani fuzzy logic–based auto-reclosing scheme with an intelligent decision mechanism was developed and modelled in MATLAB/Simulink. The fuzzy logic controller dynamically determines the optimal reclosing dead time by intelligently classifying fault types under four scenarios—Line-to-Ground (L-G), Line-to-Line (L-L), Double Line-to-Ground (2L-G), and Three-Line-to-Ground (3L-G)—at multiple feeder locations. Simulation results demonstrate that the proposed scheme reduces dead time for transient faults from 230 ms to 100 ms, a reduction of approximately 52–56%. These results confirm that the FL-ARR enhances reclosing success rates, minimizes unnecessary breaker operations, and reduces equipment stress—offering a practical and validated solution for improving reliability in medium-voltage transmission networks. It is recommended that additional research should be extended to larger transmission network such as 330kv double circuit voltage level that is close to generating station.

Keywords: 3Phase Auto-reclosure, fuzzy logic controller, 33 kV transmission, dead time optimization, MATLAB/Simulink

1 INTRODUCTION

Electricity is a cornerstone of modern socioeconomic development. In power networks, energy reaches consumers through a chain of generation, transmission, and distribution infrastructure. Transient faults—caused predominantly by lightning strikes, wind-induced conductor contact, vegetation encroachment, and animal interference—account for approximately 80–90% of all incidents on overhead transmission lines. Such faults naturally extinguish after arc de-ionization; however, conventional fixed-time protection schemes cannot restore supply promptly or adapt to varying fault conditions without human intervention. Auto-Reclosure Relays (ARRs) were introduced to automatically re-energies faulted lines after transient events, significantly reducing downtime and improving reliability indices such as SAIDI and

SAIFI. However, conventional ARRs apply a single fixed dead time for all fault types and locations—an approach that is inherently suboptimal for the diverse and dynamic fault conditions encountered on real feeders [1, 2]. For the Jambutu 33 kV transmission feeder studied in this paper, incessant transient tripping under fixed-time reclosure leads to excessive breaker operations, prolonged outages, and significant customer inconvenience. Three-phase auto-reclosure is particularly suited to industrial and critical infrastructure loads because it handles multi-phase faults more effectively than single-phase pole tripping, where only the faulted phase is isolated. Disconnecting all three poles simultaneously prevents the risk of unbalanced energization under multi-phase conditions [3]. This paper proposes a three-phase Fuzzy Logic–Based 3Phase Auto-Reclosure Relay (FL-ARR) capable of intelligently distinguishing permanent from transient faults and dynamically selecting the optimal reclosing dead time. The system is modelled and validated on Jambutu 33kv feeder from transmission down to Jambutu 33/11 kV injection substation feeder using MATLAB/Simulink.

2. RELATED WORK

Conventional auto-reclosure schemes reclose the faulted phase after a constant predefined dead time, irrespective of the fault condition. As illustrated in Figure 1 below for a 33 kV system, based on the relay theory and application at frequency of 50HZ the minimum dead time is calculated as the following equation [4].

$$T = 10.5 + \frac{kV}{34.5}\ cycles \tag{1}$$

For 230kv transmission line,T = 10.5+230kv/34.5 [=17.166 cycle =343ms. For 132kv transmission line, T = 10.5+132kv/34.5 =14.32 cycle =286.5 ms. For 33kv transmission line,T = 10.5+33kv/34= 11.45 cycles = 230 ms for a 33 kV. A fixed value applied regardless of fault nature or location [4]. While this provides a safe arc de-ionization margin, it fails to adapt to variable system conditions, resulting in unnecessary breaker operations and the risk of energizing permanent faults [5, 6].

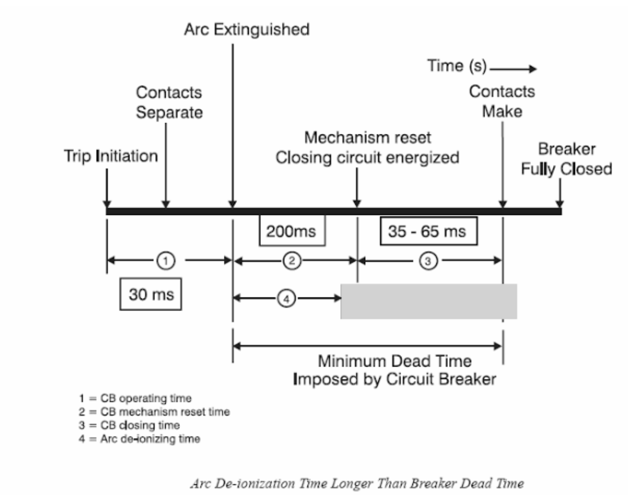

Figure 1. Arc De-ionization and Minimum Dead Time for Conventional Auto-Reclosure

2.1 Communication-Based Adaptive Schemes

Communication-based schemes synchronize electrical parameters from both line terminals through dedicated channels. PMU-based adaptive schemes at the distribution level discriminate between permanent and temporary single-phase faults using phasor data. Power-line carrier (PLC)–based schemes detect secondary arc extinction by comparing PLC signals before and after fault occurrence. While accurate, these methods are costly, require noise-free infrastructure, and face reliability challenges due to nonlinear network disturbances [6, 7, 8].

2.2 Non-Communication-Based Schemes

Non-communication schemes rely solely on local signal analysis. The Hilbert–Huang Transform (HHT) has been employed to detect arc extinction during transient faults on overhead lines, effectively differentiating fault types. Wavelet-based and frequency-domain analysis methods have also been applied, though high computational complexity and limited three-phase fault handling remain key limitations of existing approaches [9].

3 METHODOLOGY

The methodological framework that was employed to create a 33kv transmission network 3phase ARR using fuzzy logic approach.

3.1 System under Study

The Jambutu 33 kV transmission outgoing feeder supplying the Jambutu 33/11 kV injection substation in Yola North, Nigeria, was selected as the case study. This radial overhead feeder spans 9km and is operated by the Yola Electricity Distribution Company (YEDC). It frequently experiences transient faults caused by vegetation contact, animal interference, rainstorms, and lightning.

3.2 Problem Formulation

The objective is to minimise a composite cost function that accounts for unnecessary breaker operations, total outage duration, and erroneous reclosing into permanent faults: [10].

$$Minimize\, J = \alpha \cdot O + \beta \cdot Tout + \gamma \cdot Fperm \tag{2}$$

Where O is the number of breaker operations, Tout is total outage duration per event, Fperm is the number of reclosing attempts into permanent faults, and α, β, γ are weighting factors. System constraints include the following.

$$Voltage\ recovery\ (Vpost \geq Vmin) \tag{3}$$

Where Vpost is the phase voltage at relay location and $Vmin$ is set between. (0.8–0.9 p.u.), for 33kv system.

$$Fault\ current\ decay\ (Ifault \leq Ipickup) \tag{4}$$

Where Ipickup is the minimum operating current for phase or earth fault protection.

$$(Tdead, min \leq Tdead \leq Tdead, max) \tag{5}$$

Where $Tdead, min$ is the minimum dead time, while $Tdead, max$ is the maximum dead time. Transient stability index (Stability ≥ Critical), and a maximum of two to three reclosure attempts [8, 10, 11].

3.3 Fuzzy Logic–Based ARR Design

The FL-ARR uses a Mamdani fuzzy inference system to evaluate real-time fault characteristics and determine the appropriate reclosing action. Fuzzification converts three crisp input variables into fuzzy sets using membership functions (MFs) as described in Table 1 The Mamdani inference engine evaluates rules using the min operator for firing strength and the max operator for aggregation. Defuzzification uses the centroid method to yield a crisp reclosing command [12].

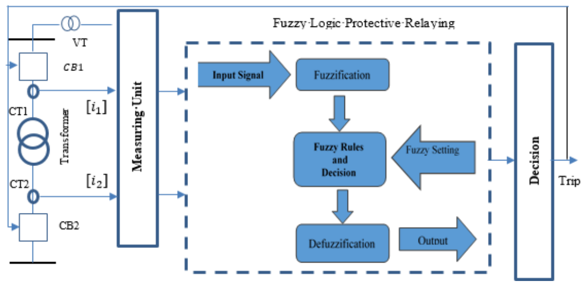

Figure 2. Fuzzy Logic Protective Relaying – Fuzzification, Inference, and Defuzzification Block Diagram [13]

Table 1. Fuzzy Input Variables, Linguistic Labels, and Membership Function Details

Input Variable	Range	Linguistic Label	MF Type
Fault Current (If)	0–10 kA	Low	Triangular
		Medium	Triangular
		High	Triangular
Voltage Dip (ΔV)	0–1 p.u.	Shallow	Trapezoidal
		Moderate	Trapezoidal
		Severe	Trapezoidal
Fault Duration (tf)	0–3 s	Short	Gaussian
		Medium	Gaussian
		Long	Gaussian
Output: Reclose Action	0–1	Fast Reclose	Triangular
		Delayed Reclose	Triangular
		Block	Triangular

MATLAB Fuzzy Logic Designer – Mamdani FIS Configuration for FL-ARR. The rule base, derived from the protection engineering principles, is summarized in table 2 Rules encode the protection heuristics that transient faults should be reclosed quickly, permanent faults should never be reclosed into, and ambiguous conditions require cautious, moderated responses [12, 14].

Table 2. Fuzzy Rule Base Summary

Fault Behaviour	Fault Current	Voltage Dip	Fault Duration	Fuzzy Decision
Clear transient	Low or High	Shallow	Short	Fast Reclose
Mildly severe	Medium	Moderate	Medium	Delayed Reclose
Highly ambiguous	Medium	Moderate–Severe	Medium	Multi-Attempt Reclose
Clearly permanent	High	Severe	Long	Block

3.4 Simulation Procedure and Fault Scenarios

Simulations were conducted using MATLAB/Simulink with discrete-time solvers to capture transient effects with high fidelity and the fuzzy inference system is shown in Figure 3. The flowchart in Figure.4 outlines the simulation procedure from data collection through system model initialization, fault scenario construction, execution of the reclosing process, recording of outputs, and post-simulation analysis.

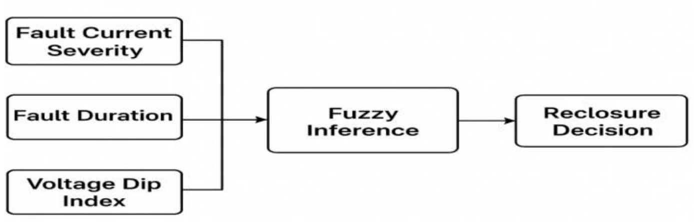

Figure 3. Fuzzy Inference System

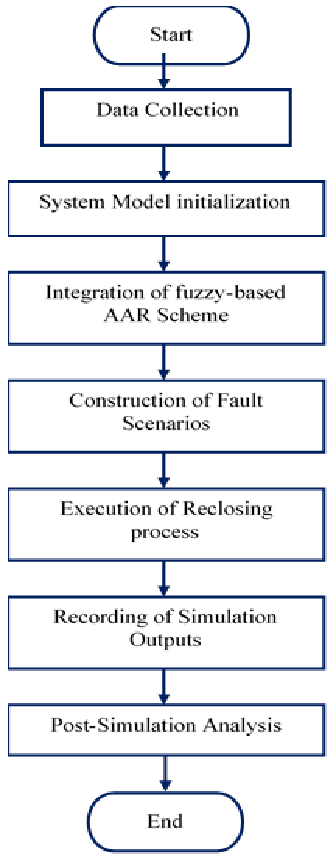

Figure 4. Simulation Flowchart

Four fault types—L-G, L-L, L-L-G, and L-L-L-G—were applied at five feeder locations (2, 3, 3.5, 7, and 9 km from the substation). Fault resistance ranged from 0.1 to 40 Ω with fault durations of 100–110 ms to simulate transient disturbances. A programmable fault block was connected to the 33 kV transmission line with voltage and current measurement blocks at both feeder ends feeding the MHO distance relay logic. The fault programming interface for each scenario is illustrated in Figure 4.

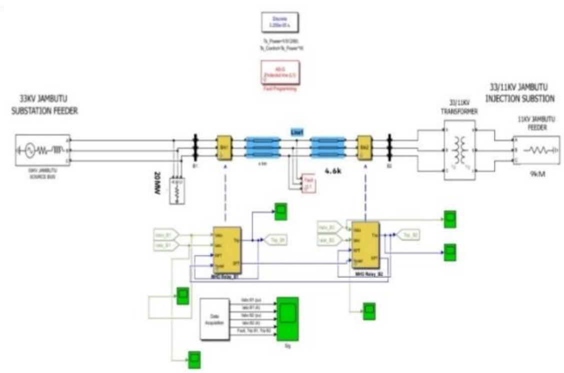

Figure 5. Fault Programming Block Parameters for Different Fault Scenarios (a) No Fault (b) L-G (c) L-L-G (d) L-L-L-G

4.0 RESULTS AND DISCUSSION

4.1 Pre-Fault Baseline

Under normal pre-fault conditions, the feeder voltage was maintained at approximately 33 kV line-to-line RMS with balanced phase currents at 400 A RMS. Voltage and current waveforms were symmetrical sinusoids confirming stable, balanced operation. These baselines served as references for evaluating transient disturbances.

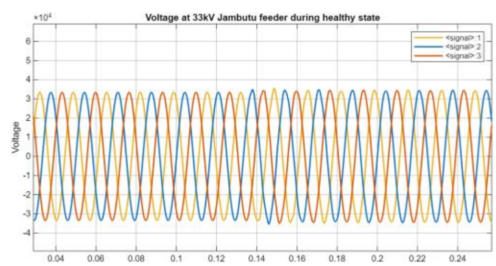

Figure 6. Voltage Waveform During Healthy (Pre-Fault) State

Figure 7. Current Waveform during Healthy (Pre-Fault) State

4.2 Line-to-Ground (L-G) Fault Response

When an L-G fault was applied at 2 km, (Figure 8) the faulted phase voltage collapsed sharply to near zero at $t \approx 0.10$ s due to the low fault loop impedance, while healthy phases exhibited significant overvoltage and high-frequency oscillations. Peak fault current exceeded 9,000 A. At 7 km, (Figure 9) higher feeder impedance attenuated the fault current to approximately 3,000 A and reduced transient severity. The FL-ARR selected a 0.20 s reclosing delay in both cases, successfully restoring balanced sinusoidal currents after reclosure.

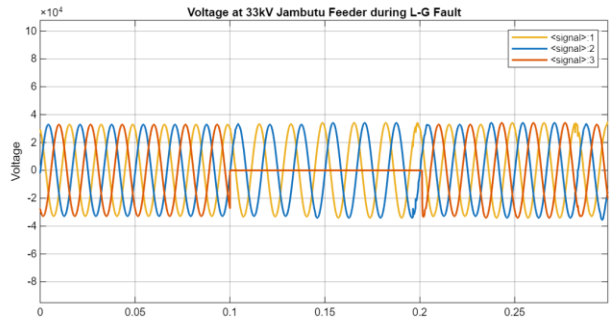

Figure 8. Voltage Waveform – L-G Fault at 2 km

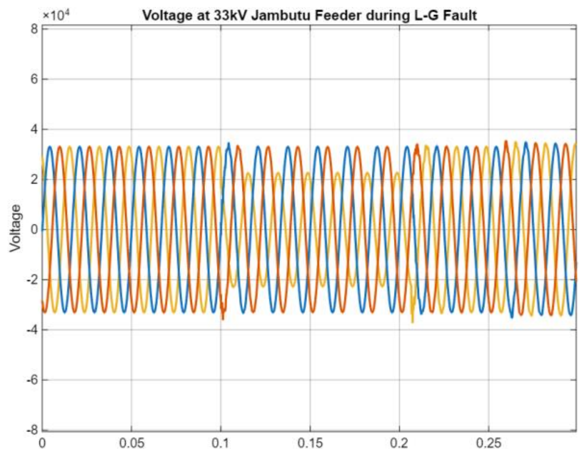

Figure 9. Current Waveform – L-G Fault at 2 km

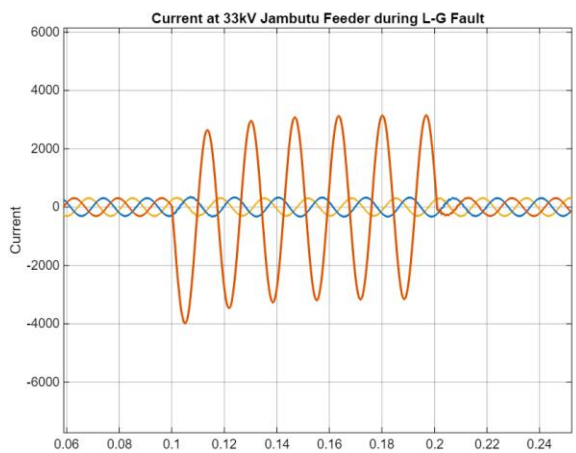

Figure 10. Current Waveform – L-G Fault at 7 km

4.3 Line-to-Line (L-L) Fault Response

An L-L fault at 3 km caused abrupt voltage depression in both faulted phases at t ≈ 0.10 s, accompanied by strong high-frequency oscillations. At 3.5 km, the depth of voltage sag was reduced by higher feeder impedance with more damped oscillations. Both faulted phase currents rose steeply to approximately 6,000 A at 3 km (Figure 11), while the 3.5 km fault exhibited lower peak magnitudes (~4,000 A) with better-damped transients (Figure 12). The FL-ARR correctly identified both as transient and initiated fast reclosure, restoring normal voltage in both cases.

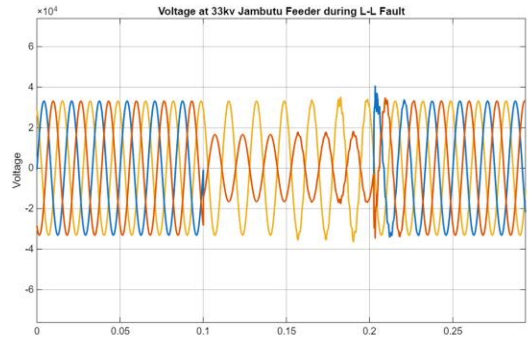

Figure 11. Voltage Waveform – L-L Fault at 3 km

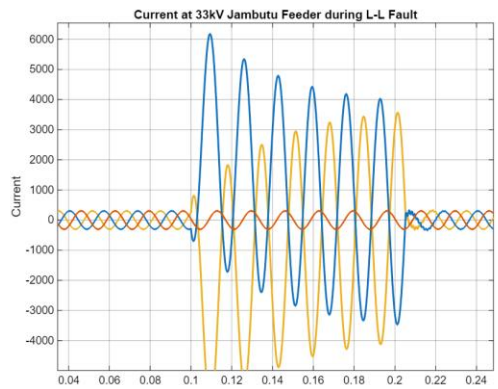

Figure 12. Current Waveform – L-L Fault at 3 km

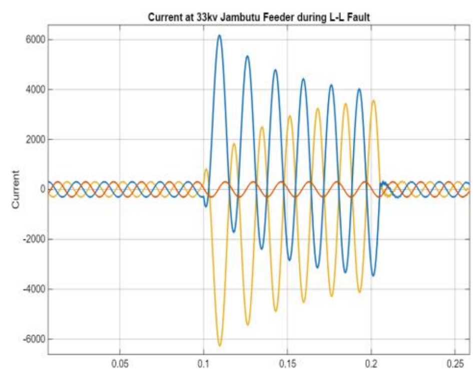

Figure 13. Current Waveform – L-L Fault at 3.5 km

4.4 Double Line-to-Ground (2L-G) Fault Response

The L-L-G fault at 2 km caused near-instantaneous collapse of two-phase voltages to zero with intense electromagnetic transients. Faulted phase currents rose to approximately 9,000 A peak (Figure 14). At 7 km, the pattern was similar but less severe, with the higher feeder impedance limiting fault energy. The 7 km current peaks reached approximately 5,500 A with better-damped oscillations (Figure 15). The FL-ARR blocked or delayed reclosure appropriately based on fault severity in both cases.

Figure 14. Voltage Waveform – L-L-G Fault at 2 km

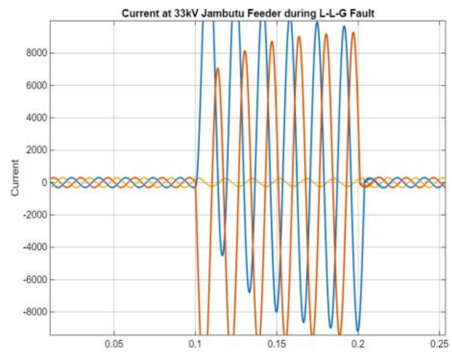

Figure 15. Current Waveform – L-L-G Fault at 2 km

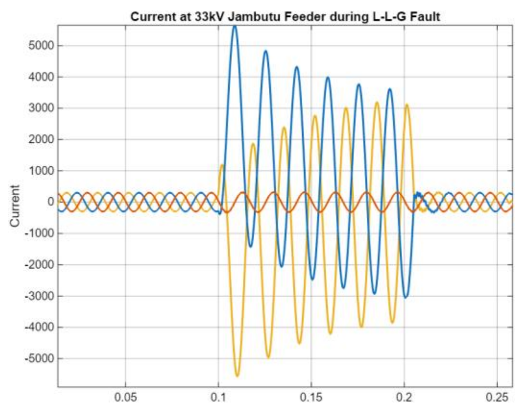

Figure 16. Current Waveform – L-L-G Fault at 7 km

4.5 Three-Line-to-Ground (L-L-L-G) Fault Response

The L-L-L-G fault at (Figure 17) caused simultaneous collapse of all three-phase voltages at t ≈ 0.10 s with a severe, low-impedance symmetric short circuit. High-frequency oscillations dominated the voltage waveform during the fault. After relay isolation, voltages gradually recovered with visible distortion. Upon auto reclosure, voltages stabilized to normal sinusoidal patterns, verifying successful fault clearance.

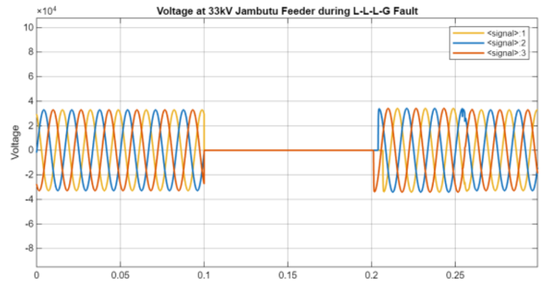

Figure 17. Voltage Waveform – L-L-L-G Fault

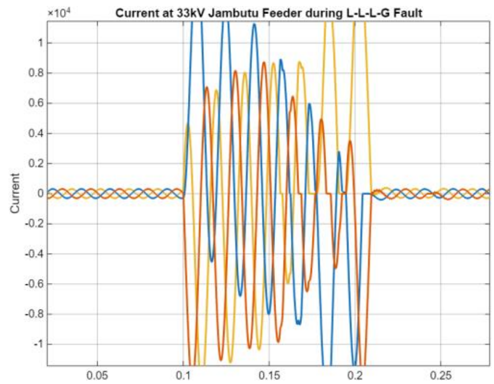

Figure. 18. Current Waveform – L-L-L-G Fault

4.6 Fault Clearance and Outage Duration

Table 3 compares outage durations for the conventional fixed-time ARR (230 ms dead time for all scenarios) against the proposed FL-ARR. The fuzzy logic controller reduces outage duration by 52–56% consistently across all tested scenarios. Near-substation faults (2–3 km) are cleared faster than far-end faults (7–9 km), as the FL-ARR accounts for line impedance and fault current magnitude in its reclosing decision [6].

Table 3. Outage Duration Comparison – Conventional ARR vs. Proposed FL-ARR

Fault Type	Location (km)	Conventional ARR (ms)	FL-ARR (ms)	Improvement (%)
L-G	2	230	100	56
L-G	7	230	110	52
L-L	3	230	100	56
L-L	3.5	230	100	52
L-L-G	2	230	100	56
L-L-G	7	230	110	52
L-L-L-G	9	230	100	56

5 CONCLUSIONS

This paper presented the design, modelling, and simulation-based performance assessment of a three-phase fuzzy logic–based Auto-reclosure relay (FL-ARR) for the Jambutu 33 kV transmission feeder in Yola, Nigeria. The proposed system addresses the fundamental limitation of conventional fixed dead-time relays by dynamically evaluating fault current magnitude, voltage dip severity, and fault duration through a Mamdani fuzzy inference system to classify faults and optimize reclosing timing. Simulation results across seven fault scenarios (L-G, L-L, 2L-G, and 3L-G at multiple feeder locations) demonstrate an average dead-time reduction of 52–56%, with outage duration decreasing from 230 ms to 100–110ms. Confirming substantially enhanced service continuity. The FL-ARR also exhibited improved selectivity, faster voltage recovery, and fewer unnecessary breaker operations, directly reducing equipment stress and extending component lifespan. Future work should explore integration with distributed generation and renewable energy sources, neurofuzzy (ANFIS) inference for self-learning capability, Hardware-in-the-Loop (HIL) validation using platforms such as OPAL-RT, and extension of the methodology to higher voltage levels (132 kV and 330 kV) proximal to generating plants.

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