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Original Article

The Investigation of Circuit Tripping on Electric Distribution Network: A Case Study of a 2×7.5 MVA, 33/11 KV Distribution Substation in Delta State, Nigeria

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Abstract *- Reliable electric power supply is widely recognised as a prerequisite for economic growth, industrial productivity and social welfare, yet many power systems in developing countries remain characterised by chronic outages, voltage instability and poor service quality. This paper addresses this gap through a two-year case study of a 2×7.5 MVA, 33/11 kV injection substation and its three 11 kV feeders (Commercial, Town and Local) Distribution Substation in Delta State, Nigeria. Operational data from 2023–2024 substation logbooks were used to compute standard reliability indices using MATLAB and develop an ETAP model for load-flow and relay-coordination studies; expected post-mitigation reliability was then estimated from revised relay settings and targeted maintenance actions. Results show that total trippings increased from 574 in 2023 to 755 in 2024, with the Local feeder rising from 269 to 328 events and the Town feeder from 174 to 274. Town and Local feeders recorded low availability (0.56–0.57), and weak load–trip relationships ($|r| \leq 0.57$, $R^2 < 0.33$) indicate that overloading is not the primary driver of interruptions. ETAP simulations revealed severe relay miscoordination on Town and Local feeders, whereas the Commercial feeder was well protected. After relay re-coordination and targeted maintenance, SAIFI fell to 0.1079, 0.0233 and 0.0196, and availability rose to 0.998, 0.9995 and 0.9997 for Commercial, Town and Local feeders respectively. These results provide evidence that low-cost, data-driven improvements in protection coordination and asset management can yield substantial reliability benefits and provide a replicable model for Nigerian distribution utilities.*

Keywords *- Distribution system reliability, Relay coordination, Sympathetic tripping, Feeder outage analysis, Reliability Indices.*

1. Introduction

Reliable electricity supply underpins economic development, industrial production, healthcare, education, and virtually every aspect of modern society. Yet, maintaining reliable electricity delivery remains a major challenge across many developing countries, where consumers continue to experience frequent outages, voltage fluctuations, and poor service quality. In Nigeria, these problems have persisted despite several reforms within the electricity sector. Structural weaknesses across generation, transmission, and distribution have created a wide gap between installed generation capacity and the electricity ultimately delivered to consumers [1]. As a result, households, commercial establishments, and industries increasingly rely on alternative sources of power, leading to higher operating costs and reduced productivity [2]. The growing complexity of modern power systems has further increased the need for systematic reliability assessment, improved protection strategies, and smarter operational practices capable of minimizing service interruptions [3]. Recent work by Eyenubo et al. [4] demonstrated that intelligent load forecasting can support better transformer loading, energy dispatch, and operational planning, while the study conducted by Otuagoma [5] highlighted the persistent electricity supply challenges experienced within Oleh, Delta State. Together, these studies emphasize that improving electricity reliability requires more than expanding generation capacity; it also demands greater attention to how distribution networks are operated and protected.

Much of the existing reliability research has focused on power generation systems. Shopeju and Oyedepo [6] reviewed reliability assessment techniques for thermal power plants and showed how stochastic approaches provide more realistic estimates of equipment performance than conventional deterministic methods. Sultanov et al. [7] adopted a Monte Carlo framework to estimate equipment deterioration and remaining useful life, whereas Nasiriani et al. [8] extended reliability modelling to power systems incorporating Ocean Thermal Energy Conversion (OTEC) technology. Similar concerns have been reported in Nigeria, where Ogbah et al. [9]

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found that ageing equipment, inconsistent maintenance practices, and forced outages continue to limit the reliability of thermal power stations. These studies have improved understanding of generation reliability and the factors that influence plant availability. However, customers rarely experience generation failures directly. Most interruptions occur within distribution networks, where equipment condition, protection behaviour, maintenance practices, and local operating conditions collectively determine the quality of electricity supply.

For distribution utilities, reliability is commonly assessed using indices such as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Average Service Availability Index (ASAI), all of which provide quantitative measures of network performance [10]. Using these indices, Okorie et al. [11] evaluated the Kampala East distribution network and identified the major causes of feeder interruptions together with possible network improvements.

Joshua et al. [12] carried out a similar assessment on three 11 kV feeders in Benin City, while Onuigbo and Edokpia [13] analysed the reliability performance of the Ugbowo 33/11 kV distribution network using historical outage records. Although these studies were conducted on different networks, they reached similar conclusion: distribution reliability remains unsatisfactory, and systematic analysis of operational data is valuable for maintenance planning and investment decisions. Related studies have also examined distributed energy systems from techno-economic perspectives [14]. Nevertheless, the emphasis in most of these investigations remained on measuring reliability performance rather than explaining the operational mechanisms responsible for repeated feeder tripping.

Recent Nigerian studies have continued this trend by examining the reliability of individual substations. Onuigbo and Edokpia [13] analysed the tripping profile of the Ugbowo injection substation using annual outage records and standard reliability indices. Enobakhare and Oyonokpare [15] investigated the Etete 2 × 7.5 MVA, 33/11 kV Injection Substation and identified transformer and breaker failures as major contributors to poor network performance. Similarly, Eyenubo et al. [16] assessed the operational performance of the Oria Abraka 33/11 kV substation using multi-year operational data and reported persistent problems associated with transformer loading, voltage regulation, feeder congestion, prolonged restoration time, and poor power availability. While these studies provide valuable information on the operational condition of Nigerian distribution substations, they largely describe network performance after interruptions have occurred. Much less attention has been given to whether the protection system itself contributes to repeated circuit tripping and declining feeder reliability.

Outside Nigeria, several researchers have investigated the influence of protection coordination on distribution system performance. Atsever et al. [17] demonstrated that resistance-grounded systems with extensive underground cable networks are particularly susceptible to sympathetic tripping and proposed improved relay angle settings to enhance selectivity. Sabra et al. [18] documented field cases in which healthy feeders disconnected unnecessarily because of relay mal-operation during faults occurring elsewhere on the network. Firouzabadi et al. [19] later developed a protection strategy capable of reducing sympathetic tripping in active distribution systems containing distributed generation without requiring additional communication infrastructure. These contributions clearly establish that protection coordination has a direct impact on network reliability. However, the solutions were developed primarily for active distribution networks equipped with intelligent electronic devices, advanced automation, or distributed generation. Such network characteristics are still uncommon in most conventional Nigerian 33/11 kV radial distribution systems, where protection is predominantly based on overcurrent relays and relatively simple protection schemes.

When these studies are viewed together, an important gap becomes apparent. Nigerian investigations have successfully quantified feeder reliability using outage statistics, availability analysis, and standard reliability indices [13], [15], [16], while international studies have advanced relay coordination and sympathetic-tripping mitigation for highly automated distribution systems [17]–[19]. What remains largely unexplored is how these two areas can be brought together for conventional Nigerian distribution networks. In particular, there is limited evidence linking historical tripping records with statistical reliability assessment and detailed protection-coordination analysis to explain why certain feeders experience repeated interruptions despite routine maintenance activities. Without this understanding, utilities may continue to address the symptoms of poor reliability without identifying its underlying causes.

Existing studies have generally examined assessment, fault statistics, and protection coordination as separate problems. This study brings these elements together within a single analytical framework by combining two years of operational tripping records, reliability-index evaluation, statistical analysis of the relationship between feeder loading and tripping frequency, ETAP-based relay coordination studies, and an assessment of the expected reliability improvements achievable through optimized relay settings and targeted maintenance. Rather than simply reporting reliability indices, the study connects observed field behaviour with protection-system performance, providing a clearer explanation of the factors responsible for repeated feeder interruptions. The approach also offers a practical methodology that can support maintenance planning and protection improvement for conventional 33/11 kV

distribution substations operating under conditions similar to those found across many Nigerian electricity distribution networks.

Against this background, this study investigates the circuit tripping behaviour of a 2 × 7.5 MVA, 33/11 kV distribution substation and its associated 11 kV feeders in Delta State, Nigeria. The study evaluates feeder reliability using standard reliability indices, examines fault characteristics and tripping patterns from two years of operational records, analyses the relationship between loading conditions and fault occurrence, investigates protection coordination through ETAP simulations, and evaluates the expected improvement in reliability following optimized relay coordination and targeted maintenance interventions.

2. Materials and Methods

2.1. Study Area and Network Description

This study was carried out on a 2×7.5 MVA, 33/11 kV injection substation and its associated 11 kV distribution network of a distribution Substation, operated by the Benin Electricity Distribution Company (BEDC) in Sapele, Delta State, Nigeria. The substation steps down power from 33 kV to 11 kV and supplies three major feeders Amukpe Commercial, Amukpe Town, and Amukpe Local, which serve mixed commercial, urban, peri-urban, and rural loads.

The Amukpe Commercial feeder (17 km) predominantly supplies maximum-demand commercial customers and a few residential consumers with an average supply of 22–24 h/day. The Amukpe Town feeder (20 km) serves mainly residential customers with an average supply of 8 h/day, while the Amukpe Local feeder (28 km) supplies dispersed residential customers across rural and semi-urban areas with a similar average daily supply.

The feeders represent different loading and operating conditions and provide a good case study for assessing the causes and mitigation of circuit tripping in a typical Nigerian 33/11 kV distribution network.

2.2. Data Sources and Materials

A case study design was adopted, relying on both primary and secondary data. The main materials and data sources were: Substation logbooks and operation records:

- Detailed entries of the feeder tripping events, the duration of outages, the relay indications (earth faults and overcurrent) and load profiles in the years 2023 and 2024.
- Single Line Diagram (SLD): The 33/11 kV network diagram of Amukpe substation, showing the two 7.5 MVA power transformers, outgoing 11 kV feeders, and associated protective devices. The Single Line Diagram used is shown in Figure

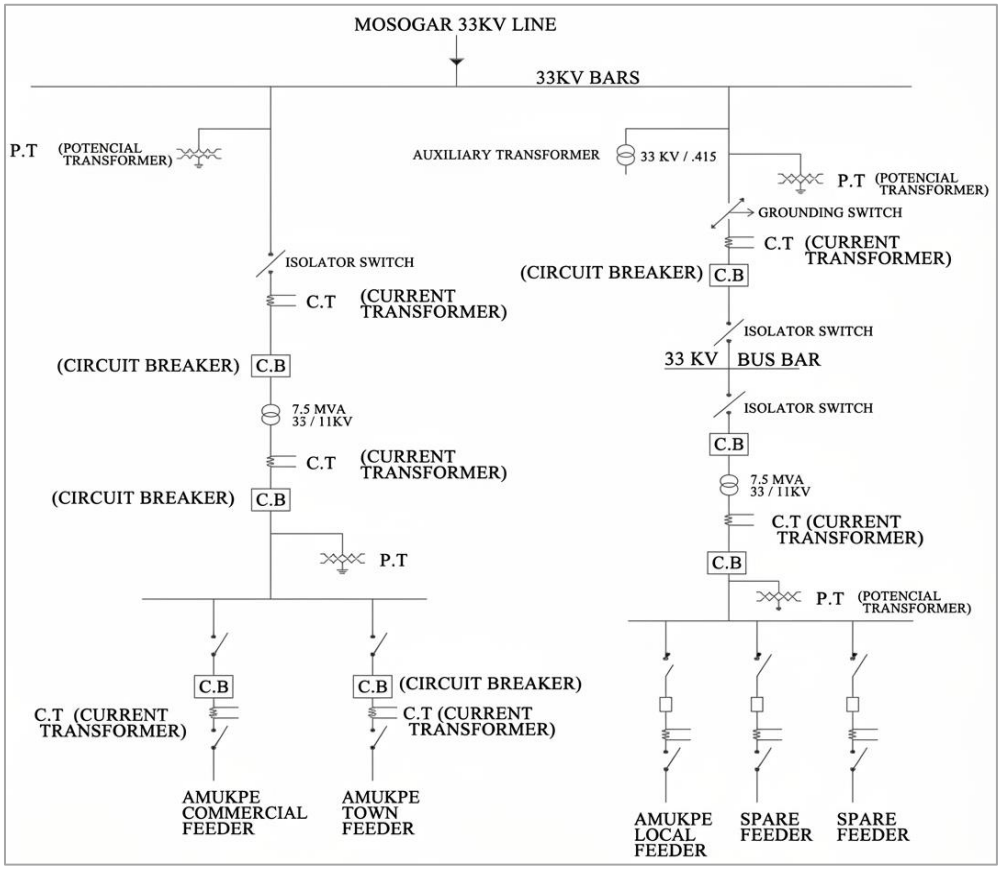

Fig. 1 Single Line Diagram (SLD) of the Amukpe 33/11 kV network

- Protection and relay records: Settings and event logs from overcurrent relays used to classify fault types and evaluate protection coordination.
- Software tools: MATLAB was used for computation and plotting of reliability indices, while Microsoft Excel was used for data entry, sorting, aggregation of monthly/annual statistics, and basic statistical analysis. ETAP was used to model the 33/11 kV network, perform load-flow studies, and assess relay coordination and operating times. Custom MATLAB scripts were developed to automate the computation of the reliability indices and to analyse the relationship between load, fault frequency, and feeder performance (see Appendix B and Appendix C), while the detailed relay-coordination outputs generated from the ETAP model are presented in Appendix D
- Field instruments: An earth resistance tester was used to check grounding conditions at the substation and along selected sections of the feeders, and a clamp meter was employed during field verification to observe current levels under typical loading.

2.3. Data Collection and Pre-Processing

Two years of operational data (January–December of 2023 & 2024) were extracted manually from the selected substation logbooks. For each month and for each 11kV feeder, the following variables were compiled:

- Monthly tripping frequency (number of trips).
- Total downtime (h) associated with all tripping events.
- Relay-indicated fault counts disaggregated into earth faults and overcurrent faults.
- Average monthly peak load (A) on each feeder. Traced physical causes of faults (e.g., transient/overload, animal interference, jumper cuts, broken poles, conductor snap, vehicle collision, vegetation interference, insulator damage). All of which are shown in Appendix A

Supplementary qualitative information was obtained through informal interviews with substation operators and protection engineers to verify logbook entries and clarify operational practices. Field inspections along selected sections of each feeder were also conducted to confirm reported physical fault causes (e.g., vegetation encroachment, damaged poles, jumper cuts).

The data were cleaned and validated by checking for missing or inconsistent entries and cross-referencing downtime, fault cause, and relay indication records. Monthly observations were then aggregated to obtain annual fault frequencies, annual downtime, and annual counts for each fault category per feeder.

2.4. Reliability Indices and Performance Metrics

The operational performance of the three 11 kV feeders was evaluated using standard distribution-system reliability indices. For each feeder and for each year, the following metrics were computed

Failure rate (λ): estimated from the total number of feeder interruptions and the corresponding operating hours.

$$\text{FailureRate } (\lambda) = \frac{1}{\text{MTBF}} \quad (1)$$

Where
MTBF: Mean Time before Failure (hours)

- Repair rate (μ): obtained as the reciprocal of the mean time to repair (MTTR).

$$\text{Repair Rate } (\mu) = \frac{1}{\text{MTTR}} \quad (2)$$

Where
MTTR: Mean Time to Repair (hours)

- Mean Time Before Failure (MTBF): calculated as the total operating hours divided by the number of recorded failures.

$$\text{Mean Time before Failure (MTBF)} = \frac{\text{Total operating hours}}{\text{Total failure}} \quad (3)$$

Where
Total Operating Hours: Cumulative hours of operation before failures occur
Total Failures: Number of recorded feeder or equipment trappings

- Mean Time to Repair (MTTR): computed as the total outage duration divided by the number of interruptions.

$$\text{Mean Time to Repair (MTTR)} = \frac{\text{Total Downtime hours}}{\text{Total failure}} \quad (4)$$

Where
Total Downtime Hours: Sum of hours lost due to repairs or fault clearance
Total Failures: Number of recorded tripping events

- System Average Interruption Frequency Index (SAIFI): representing the average number of interruptions experienced by a customer in a year.

$$SAIFI = \frac{\sum \lambda_s * N_i}{\sum N_i} \quad (5)$$

Where
$\sum \lambda_s * N_i$ = Total number of customer interruptions
$\sum N_i$=Total number of customers served

- System Average Interruption Duration Index (SAIDI): indicating the average duration of interruption per customer per year.

$$SAIDI = \frac{\sum U_s * N_i}{\sum N_i} \quad (6)$$

Where
$\sum U_s * N_i$ = Sum of customer interruption duration
$\sum N_i$=Total number of customers served

- Customer Average Interruption Duration Index (CAIDI): defined as the ratio of SAIDI to SAIFI, giving the average restoration time per interruption

$$CAIDI = \frac{\sum U_s * N_i}{\sum \lambda_s * N_i} \quad (7)$$

Where
$\sum U_s * N_i$ = Sum of customer interruption duration
$\sum \lambda_s * N_i$ = Total number of customer interruptions

- Average Service Availability Index (ASAI): representing the fraction of time the system was available, based on total service hours and total outage duration.

$$ASAI = \frac{8760 * \sum N_i - \sum N_i U_i}{8760 * \sum N_i} \quad (8)$$

Where
$\sum U_s * N_i$ = Sum of customer interruption duration
$\sum \lambda_s * N_i$ = Total number of customer interruptions

All indices were computed using standard expressions recommended for distribution networks, using the compiled interruption counts, outage durations, and customer population on each feeder. Results were obtained on a feeder-by-feeder basis to enable comparison of performance and identification of the weakest segments of the network.

2.5. Statistical Analysis of Load–Fault Relationship and Fault Composition

To quantify the contribution of different fault causes, the relative share of each fault type was evaluated as the percentage of total tripping events on each feeder and for each year. This allowed identification of predominant fault categories (e.g., animal contact, vegetation, conductor snap, transient/overload, equipment failure) contributing to poor reliability.

The relationship between load demand and fault occurrence was examined using the Pearson correlation coefficient. Average monthly peak load and corresponding monthly tripping frequency were paired to assess whether higher loading levels were statistically associated with increased fault frequency for each feeder. This analysis provided insight into the extent to which overloading or high loading conditions contributed to interruption patterns.

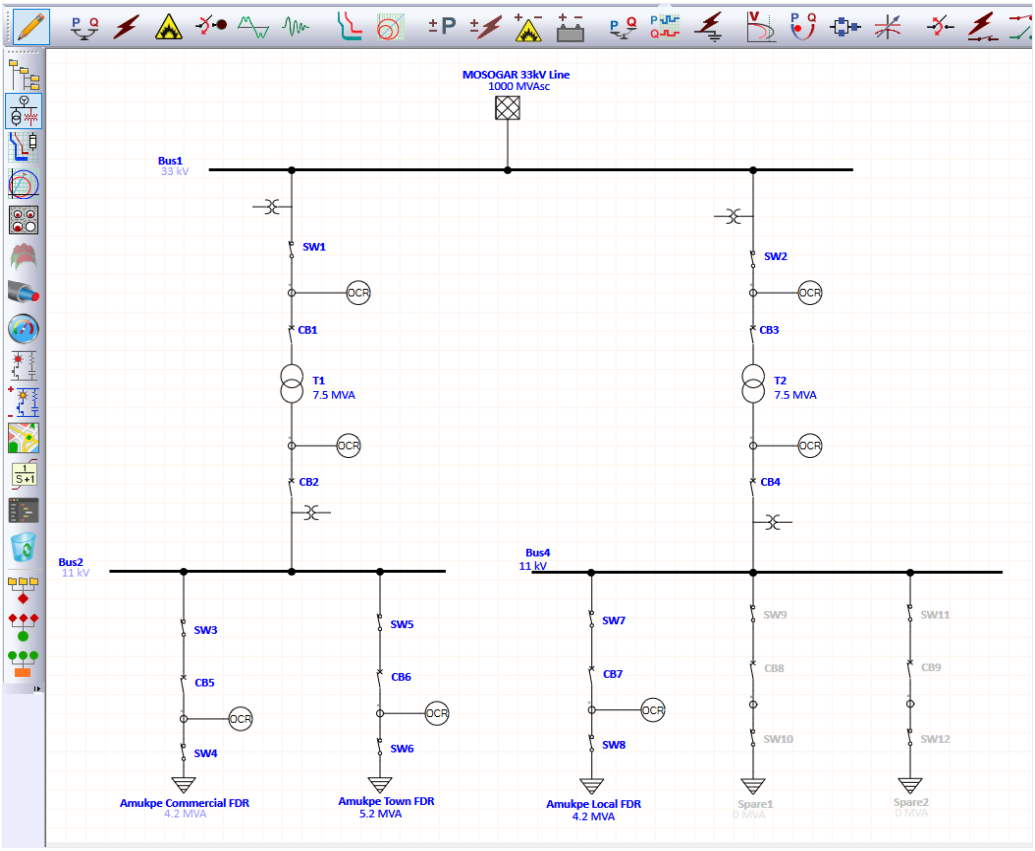

Fig. 2 ETAP Model of the Amukpe 33/11 kV Network Single Line Diagram (SLD)

2.6. Protection Coordination and Load-Flow Modelling

Protection coordination and relay performance were analysed using an ETAP model of the Amukpe 33/11 kV network, shown in Figure 2. The model consisted of the upstream 33 kV supply from MOSOGAR, the two 7.5 MVA 33/11 kV transformers, 11 kV buses, the three main feeders (Commercial, Town, Local), and associated circuit breakers and overcurrent relays. The network was represented as a radial 11 kV system with future expansion feeders modelled as spares.

A Newton–Raphson load-flow analysis was performed to obtain bus voltages, line currents, and loading conditions under normal operation.

Complex power at the *ith* node on the distribution line is given by

$$S_i = V_i I_i^* = P_i + jQ_i \tag{9}$$

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \tag{10}$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik}\, V_k \tag{11}$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik}\, V_k\right) \tag{12}$$

Let $V_i^* = V_{\mathrm{i}} \angle -\delta_i$, $V_k = V_{\mathrm{k}} \angle \delta_k$ and $Y_{ik} = Y_{\mathrm{ik}} \angle \theta_{ik}$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik}\, V_k \angle \delta_k + \theta_{ik} - \delta_i\right) \tag{13}$$

$$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \left[\cos(\delta_k + \theta_{ik} - \delta_i) + j \sin(\delta_k + \theta_{ik} - \delta_i)\right] \tag{14}$$

Separating (14) into real and imaginary parts, we have,

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \cos(\delta_k + \theta_{ik} - \delta_i) \tag{15}$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \sin(\delta_k + \theta_{ik} - \delta_i) \tag{16}$$

Where
Y_{ik} = the admittance matrix
P_i = the injected real power
Q_i= the injected reactive power
δ_i= phase angle
Expanding (3.24) and (3.35) in Taylor's series, neglecting higher-order terms, we have

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \frac{\Delta P_n^{(k)}}{\Delta Q_2^{(k)}} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \left|\begin{matrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{matrix}\right| & \left|\begin{matrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{matrix}\right| \\ \left|\begin{matrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{matrix}\right| & \left|\begin{matrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{matrix}\right| \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \frac{\Delta \delta_n^{(k)}}{\Delta |V_2^{(k)}|} \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix} \tag{17}$$

The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta_i^{(k)}$ and magnitude $\Delta|V_i^{(k)}|$ with a small change in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$ respectively.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{18}$$

Where
J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{19}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{20}$$

These results, together with the short-circuit capacity at the 33kV incoming bus, were used to estimate fault currents and to select appropriate relay settings. Overcurrent relay parameters, including continuous operating current, current setting (typically 120% of the relay operating current), plug setting multiplier (PSM), and time dial setting, were calculated using standard IEC/IEEE inverse-time characteristics (with constants A, B, C for very inverse curves).

Time-current coordination plots were then generated to verify selectivity between primary and backup relays along each feeder. Relay operating times were evaluated for different fault locations, and miscoordination (e.g., upstream relays operating before downstream devices) was identified. Based on these results, revised relay settings were proposed to ensure that the relay closest to the fault would operate first while maintaining adequate backup protection.

2.7. Estimation of Post-Mitigation Reliability

Finally, the potential impact of proposed mitigation strategies (e.g., improved relay coordination, vegetation management, replacement of weak components) on system reliability was assessed. Expected improvements in availability were estimated by applying the computed changes in interruption frequency and duration to the ASAI formulation, yielding a projected post-mitigation availability for each feeder. This provided a quantitative basis for comparing the "before" and "after" reliability performance of the Amukpe distribution network.

3. Results and Discussion

3.1. Predominant Causes of Circuit Tripping (2023–2024)

Tables 1 and 2, adapted from the 2023 and 2024 fault statistics for the Amukpe 33/11 kV network, show a clear imbalance in the spatial distribution of faults across the three feeders. The Local feeder consistently records the highest number of interruptions, with 269 tripping events in 2023 and 328 in 2024, compared with 174 and 274 on the Town feeder

and 131 and 153 on the Commercial feeder, respectively. This pattern indicates that consumers on the Local feeder are disproportionately exposed to supply interruptions, reflecting a combination of network length, exposure to external disturbances, and asset condition. Table 1 presents the classification and frequency distribution of the predominant causes of circuit tripping across the Commercial, Town, and Local feeders during 2023, providing a baseline assessment of the dominant fault mechanisms affecting network reliability.

Table 1. Classification of Predominant Causes of Circuit Tripping on Amukpe 33/11 kV Feeders in 2023

Cause of Circuit Tripping	Commercial Feeder		Town Feeder		Local Feeder	
	f	%	f	%	f	%
Transient/Overload	17	2.961672	28	4.878049	40	6.968641
Animal	30	5.226481	14	2.439024	30	5.226481
JumperCut	0	0	24	4.181185	43	7.491289
BrokenPole	18	3.135889	9	1.567944	42	7.317073
ConductorSnap	0	0	25	4.355401	26	4.529617
VehicleCollision	25	4.355401	8	1.393728	11	1.916376
JPFuseDrop	20	3.484321	28	4.878049	20	3.484321
Vegetation	11	1.916376	21	3.658537	33	5.749129
Insulator	10	1.74216	17	2.961672	24	4.181185
	131		174		269	

A closer look at the fault composition reveals that the tripping profile is shaped by both mechanical and environmental stresses. In 2023, jumper cuts and broken poles were predominant on the Local feeder, while the Town feeder was strongly affected by conductor snaps and JP fuse drops. On the Commercial feeder, animal contact and vehicle collisions accounted for the most significant shares of recorded faults. Vegetation interference contributed non-trivially on all feeders, but particularly on the Local feeder, where 33 cases (about 5.75%) were recorded. Table 2 summarizes the distribution of circuit tripping causes for 2024, enabling comparison with the 2023 fault profile and highlighting changes in the occurrence of different fault categories across the three feeders.

Table 2. Classification of Predominant Causes of Circuit Tripping on Amukpe 33/11 kV Feeders in 2024

Cause of Circuit Tripping	Commercial Feeder		Town Feeder		Local Feeder	
	f	%	f	%	f	%
Transient/Overload	23	3.046358	42	5.562914	48	6.357616
Animal	30	3.97351	28	3.708609	38	5.033113
JumperCut	18	2.384106	32	4.238411	35	4.635762
BrokenPole	10	1.324503	25	3.311258	38	5.033113
ConductorSnap	7	0.927152	32	4.238411	40	5.298013
VehicleCollision	14	1.854305	13	1.721854	25	3.311258
JPFuseDrop	21	2.781457	37	4.900662	30	3.97351
Vegetation	12	1.589404	34	4.503311	35	4.635762
Insulator	18	2.384106	31	4.10596	39	5.165563
	153		274		328	

The 2024 classification in Table 2 confirms that this pattern did not improve; instead, overall fault counts increased. The Local feeder again recorded the highest incidence with 328 events, followed by 274 on the Town feeder and 153 on the Commercial feeder. On the Local feeder, transient or overload faults, conductor snaps, and insulator failures became even more prominent, while the Town feeder remained dominated by JP fuse drops, conductor snaps, and vegetation interference. On the Commercial feeder, animal contact and JP fuse drops continued to be the main contributors.

The chi-square analysis comparing fault distributions between 2023 and 2024 yields a p-value slightly above the conventional 5% significance threshold, which implies that the change in the pattern of fault causes is not statistically significant at that level. However, from an operational point of view, the rise in total interruptions from 574 to 755 events

represents a substantial deterioration in service quality. This contrast between statistical and practical significance matters for the utility: even if the relative shares of different fault types have not changed dramatically, the absolute growth in event counts means more frequent outages, more switching operations, and more customer complaints. The persistence of jumper cuts, conductor snaps, and insulator failures, combined with widespread vegetation and animal interference, highlights the need for targeted investments in infrastructure resilience, rights-of-way maintenance, and predictive maintenance rather than reactive fault clearing alone.

3.2. Operational Performance and Reliability Indices

The reliability indices computed for the three 11 kV feeders provide a quantitative assessment of how these faults translate into customer-level performance. Table 3 summarises SAIFI, SAIDI, CAIDI, MTTR, failure rate, and availability for 2023 and 2024. The Commercial feeder, which mainly supplies maximum-demand commercial customers, maintains the best performance among the three. Its SAIFI values of 0.736 in 2023 and 0.803 in 2024 indicate that the average customer experienced fewer than one interruption per year. SAIDI values of around 4.3 hours in both years show that the cumulative interruption duration per customer remained relatively stable, and CAIDI values of about 5.4–5.8 hours suggest that restoration times per event were moderate. Availability for this feeder remained high at approximately 0.92, implying that it was in service for about 92% of the time on an annual basis. The reliability performance of the three feeders was evaluated using standard distribution reliability indices. Table 3 summarizes the computed reliability metrics for 2023 and 2024, providing a quantitative basis for comparing feeder performance.

Table 3. Comparative Operational Performance and Reliability Indices of Amukpe Distribution Feeders (2023-2024)

Feeder	Year	SAIFI	SAIDI	CAIDI	MTTR	MTTF	Failure Rate	Availability
Commercial	2023	0.736	4.281	5.817	5.817	66.870	131.0	0.920
Commercial	2024	0.803	4.304	5.358	5.358	61.259	143.0	0.920
Town	2023	0.104	3.918	37.764	37.764	50.345	174.0	0.571
Town	2024	0.144	4.055	28.097	28.097	36.198	242.0	0.563
Local	2023	0.114	2.903	25.382	25.382	32.565	269.0	0.562
Local	2024	0.142	2.843	20.078	20.078	26.306	333.0	0.567

By contrast, the Town and Local feeders exhibit significantly weaker reliability. In 2023, the Town feeder recorded a SAIFI of 0.104 and SAIDI of 3.918 hours, with a very high CAIDI of 37.764 hours, which indicates that when outages occur, they tend to be long and operationally demanding to clear.

The Local feeder showed SAIFI and SAIDI values of 0.114 and 2.903 hours, respectively, with CAIDI around 25.382 hours, again pointing to prolonged restoration per event. Availability for both feeders hovered around 0.56–0.57, meaning that customers effectively lost nearly half of their potential supply time when compared with an ideal, interruption-free operation.

In 2024, the trend for the Town and Local feeders is mixed but still unfavourable overall. SAIFI increased for both feeders, reflecting more frequent interruptions, while SAIDI changed only slightly. For many customers, this means more outages, even if each event is marginally shorter in duration. CAIDI values decreased for both feeders, which suggests that operational teams became somewhat more efficient in restoring supply after each trip. However, the improvement in restoration speed is insufficient to offset the increase in frequency, so the overall experience remains poor. Availability values remain trapped around 0.56–0.57, far below typical international benchmarks for distribution systems.

3.3. Relationship Between Load Demand and Fault Frequency

The relationship between load demand and fault frequency in Table 4 was explored using the average monthly peak load and the corresponding monthly tripping counts for each feeder.

Regression and correlation analysis reveal that the link between these two variables is relatively weak, with low coefficients of determination in all cases. For the Commercial feeder, the correlation in 2023 is close to zero and becomes moderately negative in 2024, indicating that variations in peak load explain only a small portion of the variation in trip counts.

The Town and Local feeders also exhibit moderate negative correlations, but with similarly low explanatory power. To investigate whether feeder loading contributes significantly to circuit tripping, correlation and regression analyses were performed between average monthly peak load and monthly tripping frequency. The corresponding statistical results are presented in Table 4.

Table 4. Load–Trip Correlation Analysis of Amukpe Distribution Feeders for 2023-2024

Feeder	Year	Intercept	Slope	Correlation	R2
Commercial	2023	-0.3069	0.0111	0.0881	0.0078
Town	2023	4.7054	-0.0272	-0.5365	0.2878
Local	2023	5.6292	-0.0354	-0.5287	0.2795
Commercial	2024	11.3472	-0.0395	-0.4606	0.2122
Town	2024	7.0793	-0.0370	-0.5688	0.3236
Local	2024	5.9936	-0.0321	-0.4903	0.2404

These results imply that increasing load on the feeders is not the primary driver of tripping events in the Amukpe network. If overloading were the dominant mechanism, one would expect a strong positive correlation between peak load and trip frequency; instead, the data suggest that many faults arise from structural weaknesses, environmental exposure, and protection behaviour rather than directly from thermal or voltage stress due to high demand.

From a planning and operational standpoint, this finding has important implications. It challenges the common assumption that load growth alone is responsible for deteriorating reliability in many Nigerian distribution systems. For Amukpe, the combination of a weak load–trip relationship with high fault rates and poor availability strongly suggests that the central problems are relay miscoordination, ageing line infrastructure, inadequate right-of-way clearance, and poor pole-top hardware condition. This means that investments in additional capacity or new transformers, while sometimes necessary, will not automatically resolve the reliability issues if protection and maintenance practices remain unchanged.

3.4. Protective Coordination and Operational Response Efficiency

The ETAP-based relay coordination studies provide a mechanistic explanation for the reliability patterns observed in the empirical data. The model of the Amukpe 33/11 kV network, which includes the upstream MOSOGAR 33 kV supply, two 7.5 MVA transformers, and the three 11 kV feeders, was used to simulate fault conditions and to assess whether the protection scheme operates selectively. Shown in Figures 3 to 6. For the Commercial feeder, the three-phase fault simulations show that the primary relay closest to the fault location operates within approximately 60 ms, while backup relays respond in a properly graded sequence. This correct selectivity limits the extent of outages to the minimum necessary section of the network and is consistent with the comparatively good reliability indices observed for this feeder.

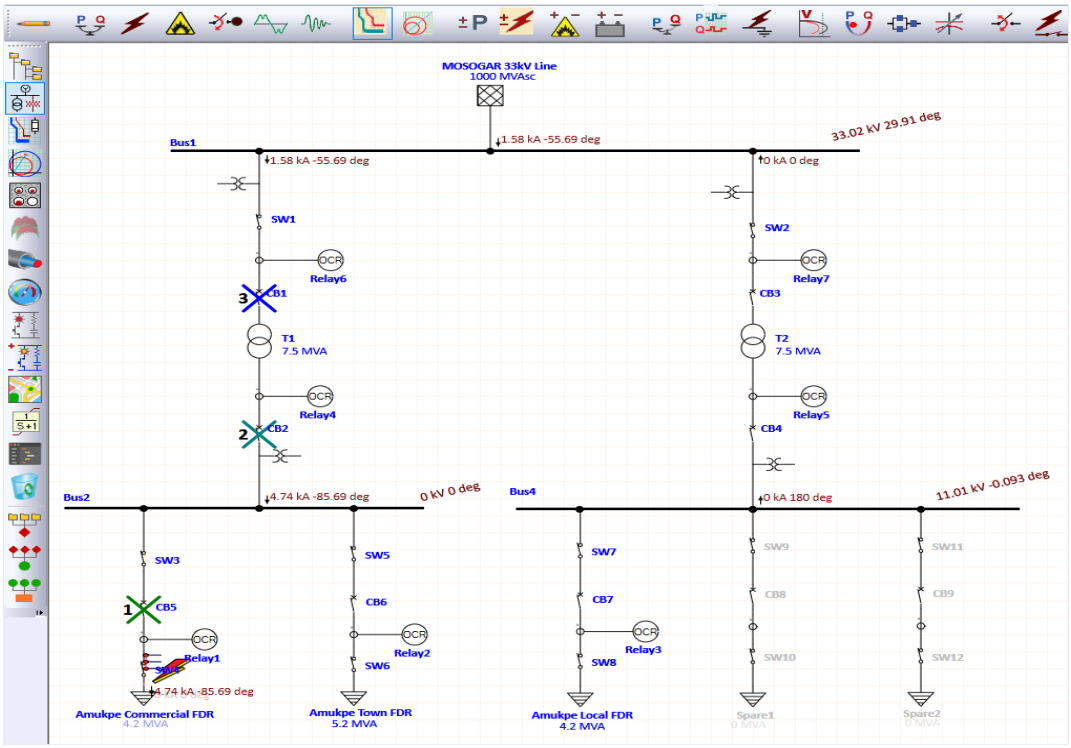

Fig. 3 Tripping Sequence of Relays for a Three-Phase Fault at Amukpe Commercial Feeder

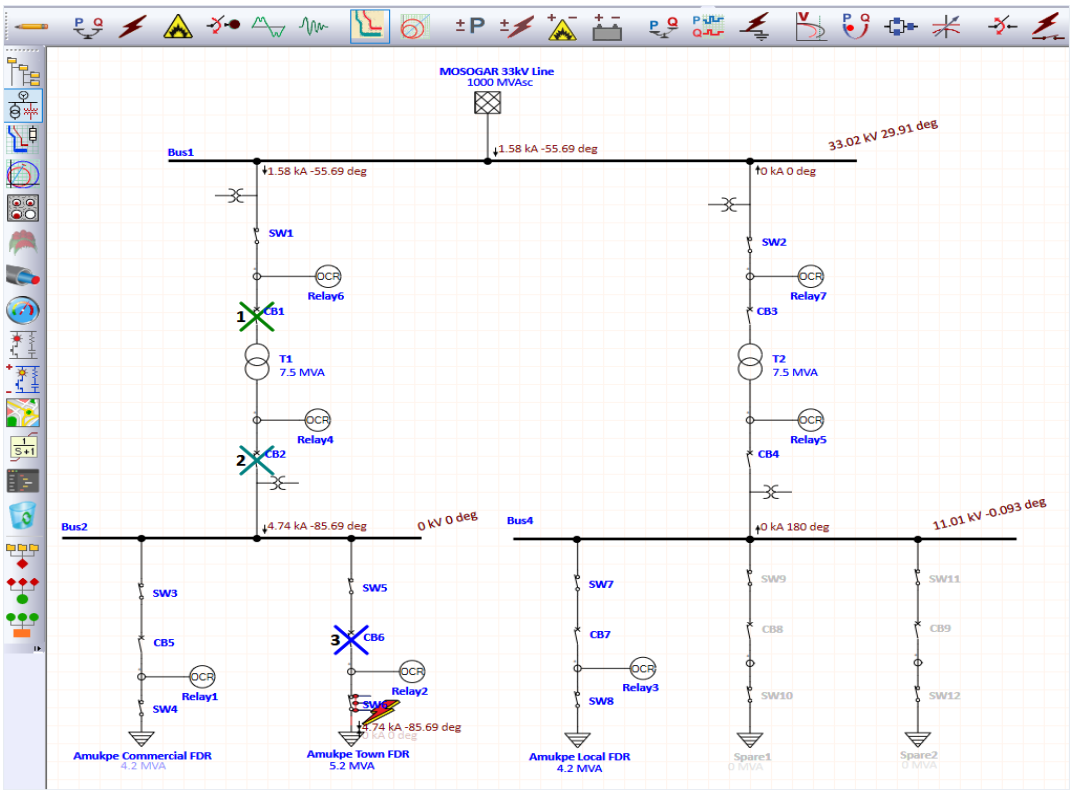

Fig. 4 Tripping Sequence of Relays for a Three-Phase Fault at Amukpe Town Feeder

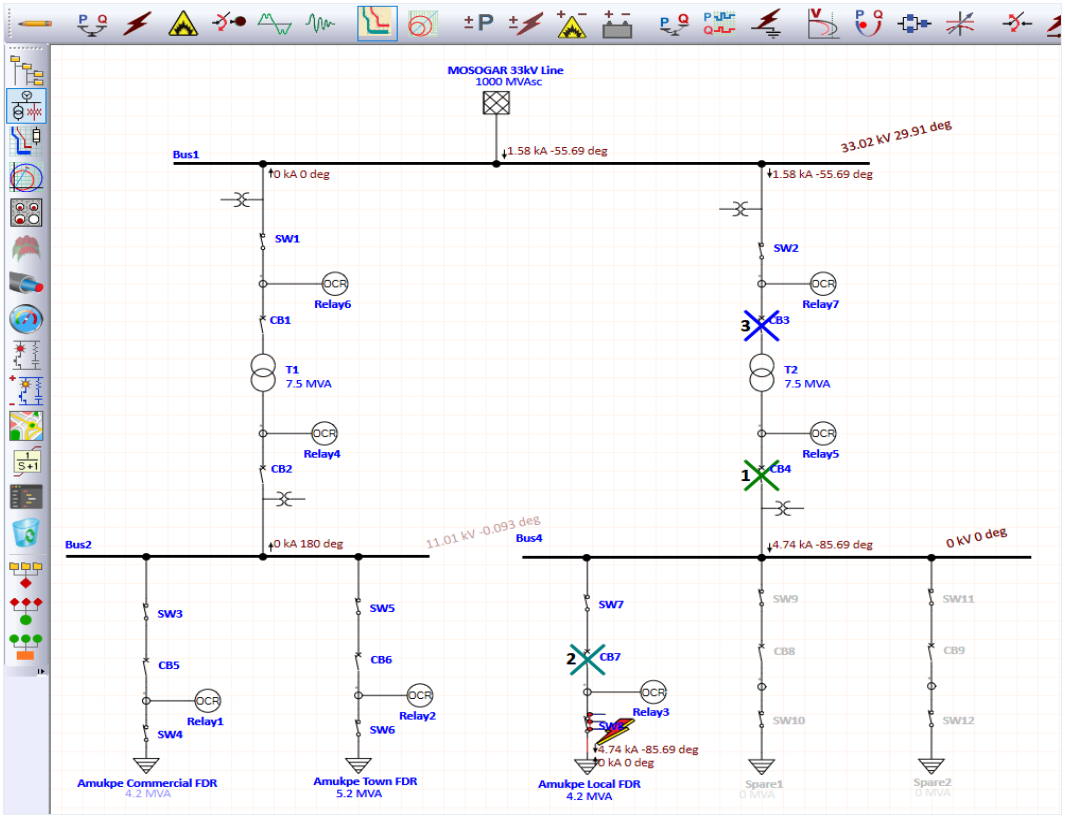

Fig. 5 Tripping Sequence of Relays for a Three-Phase Fault at Amukpe Local Feeder

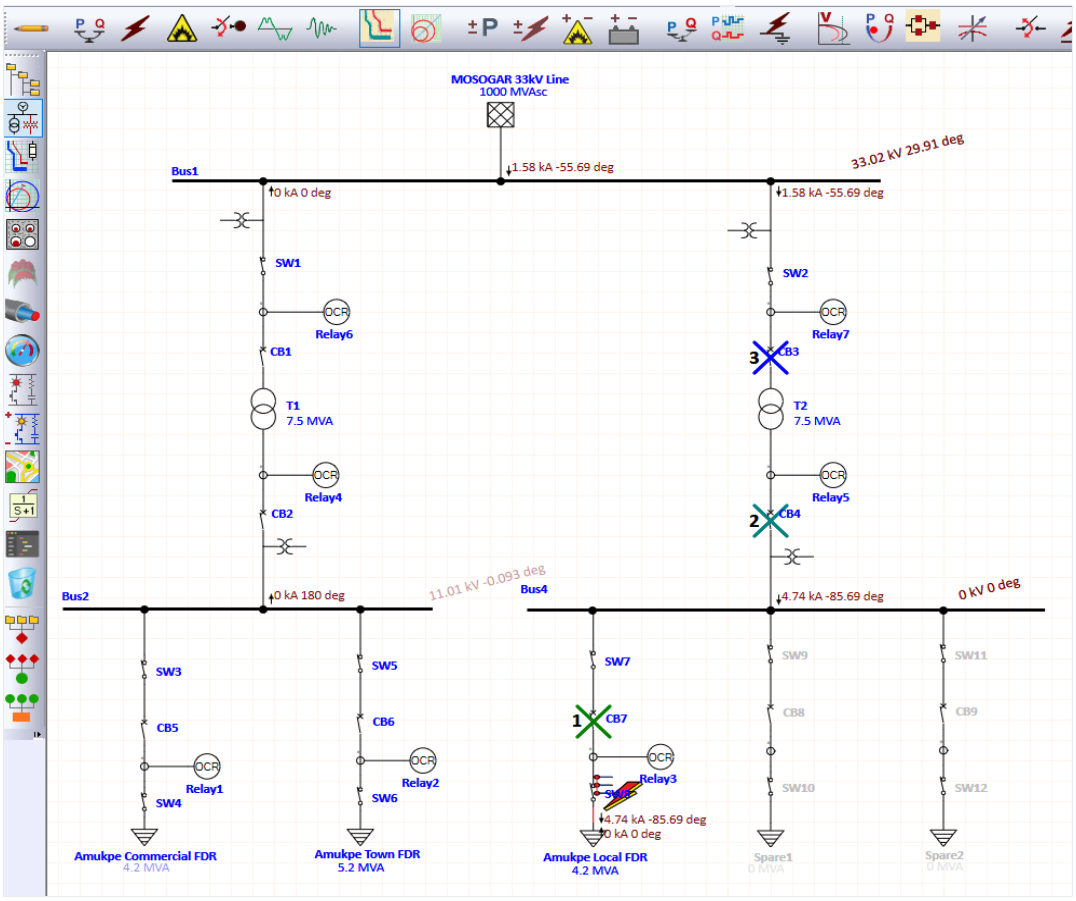

Fig. 6 Tripping Sequence of Relays for a Three-Phase Fault on Amukpe Local Feeder (Improved Coordination)

The situation is markedly different on the Town and Local feeders. Simulations indicate that upstream relays tend to operate before the primary relays that should be clearing faults at their respective locations. On the Town feeder, for example, Relay 6 trips ahead of Relay 2 under certain fault conditions, while on the Local feeder, a remote backup relay acts before the main protective device on the feeder.

Such miscoordination violates the principle of selectivity and leads to outages affecting larger portions of the network than necessary. It also explains the long CAIDI values observed in the field: when upstream devices trip first, operators must patrol and reconfigure more segments of the network before restoring supply, which extends restoration times.

These findings tie back directly to the reliability metrics. Feeders with miscoordinated protection, namely Town and Local, are those that show the poorest availability and the highest failure rates, despite only moderate load–trip correlation.

3.5. Post-Intervention Performance and Reliability Gains

Following the diagnosis of fault patterns and protection miscoordination, a set of technical interventions was implemented, including revised relay settings, improved vegetation management, and targeted maintenance on critical line components. The impact of these interventions is captured in the post-upgrade reliability indices presented in Tables 5 and 6, which compare the 2023–2024 baseline with post-intervention performance.

Table 5. Post-Improvement Operational Performance of Amukpe Distribution Feeders

Feeder	SAIFI	SAIDI	CAIDI	MTTR	MTTF	FailureRate	Availability
Amukpe Commercial	0.1079	1.4	12.95	1.4	438	20	0.998
Amukpe Town	0.0233	0.33	14.22	0.33	224.62	39	0.9995
Amukpe Local	0.0196	0.26	13.45	0.26	190.43	46	0.9997

Table 6. Comparative Reliability Indices of Amukpe Distribution Feeders (2023–2024 vs Post-Intervention)

Feeder	Year	SAIFI	SAIDI (hrs)	CAIDI (hrs)	MTTR (hrs)	MTTF (hrs)	Failure Rate	Availability
Commercial	2023	0.736	4.281	5.817	5.817	66.87	131	0.920
Commercial	2024	0.803	4.304	5.358	5.358	61.26	143	0.920
Commercial	Post-upgrade	0.1079	1.4	12.95	1.4	438	20	0.998
Town	2023	0.104	3.918	37.764	37.764	50.35	174	0.571
Town	2024	0.144	4.055	28.097	28.097	36.20	242	0.563
Town	Post-upgrade	0.0233	0.33	14.22	0.33	224.62	39	0.9995
Local	2023	0.114	2.903	25.382	25.382	32.57	269	0.562
Local	2024	0.142	2.843	20.078	20.078	26.31	333	0.567
Local	Post-upgrade	0.0196	0.26	13.45	0.26	190.43	46	0.9997

The improvements are striking across all feeders. On the Commercial feeder, SAIFI drops from 0.736–0.803 to 0.1079, and SAIDI falls to 1.4 hours per year, while availability climbs from 0.92 to 0.998. This shift indicates that customers on this feeder now experience very few interruptions and that outages, when they occur, are relatively short. For the Town feeder, SAIFI reduces to 0.0233 and SAIDI to 0.33 hours, with availability rising to 0.9995. The Local feeder, previously the worst performer, records SAIFI and SAIDI values of 0.0196 and 0.26 hours, respectively, and availability improves dramatically to 0.9997. These values are consistent with highly reliable distribution systems and represent a fundamental transformation in service quality.

One interesting nuance is that CAIDI increases slightly for the Town and Local feeders in the post-intervention scenario, reaching about 14.22 and 13.45 hours. This reflects a statistical effect: when outages become very rare, the average restoration time per event can appear higher even though customers experience far fewer interruptions overall. In practical terms, this trade-off is acceptable because consumers are more sensitive to how often supply is lost and the total annual hours of outage than to the exact duration of a small number of rare events.

3.6. Comparison with Similar Distribution Reliability Studies

To better understand the significance of the present findings, the reliability performance of the investigated substation was compared with results reported for similar 33/11 kV distribution substations and feeder reliability studies. Only studies that employed comparable reliability indices or analysed operational outage records for conventional distribution networks were considered. The comparison is presented in Table 7

Table 7. Comparison of the present study with similar distribution reliability studies.

Study	Distribution System	Reported Findings	Comparison with Present Study
[20]	Ekpoma 33/11 kV Injection Substation, Nigeria	Feeder availability ranged from 61.47% to 63.71%, while SAIFI varied between 0.1324 and 1.2418. Poor reliability was linked to ageing equipment, long feeder lengths, scheduled outages, and forced outages.	The Town and Local feeders in the present study recorded lower pre-intervention availability (56.2% and 57.1%, respectively), indicating poorer service continuity than that reported for the Ekpoma network. Following relay coordination and targeted maintenance, feeder availability improved to approximately 99.95–99.97%, representing a substantial improvement over the pre-intervention condition.
[15]	Etete 2 × 7.5 MVA, 33/11 kV Injection Substation, Nigeria	Average of 9 outages per year with an average interruption duration of 3.5 h. Approximately 70% of recorded outages were associated with transformer and circuit-breaker failures.	Both investigations considered identical 2 × 7.5 MVA, 33/11 kV substations. Similar equipment-related failures were observed; however, the present study further examined relay coordination and quantified the reliability improvement achievable after protection-system optimization.
[21]	Ugbowo 33/11 kV Distribution	Reliability was evaluated using SAIFI, SAIDI, CAIDI, ASAI, and failure rate. The study identified	Similar customer-oriented reliability indices were adopted in the present study. In addition, statistical load–trip analysis and ETAP-based relay coordination were

	Network, Nigeria	several poorly performing feeders requiring operational improvement.	used to explain the underlying causes of repeated feeder interruptions.
Present Study	Amukpe 2 × 7.5 MVA, 33/11 kV Injection Substation, Nigeria	Pre-intervention availability ranged from 56.2% to 92.0%, SAIFI from 0.104 to 0.803, and SAIDI from 2.843 to 4.304 h. Following relay coordination and targeted maintenance, feeder availability increased to approximately 99.95–99.97%.	Provides an integrated assessment combining historical outage records, reliability-index evaluation, statistical analysis of tripping behaviour, ETAP-based relay coordination, and post-intervention reliability assessment.

From Table 7, it is evident that the results of the current study largely corroborate the results of past reliability analyses of Nigerian 33/11 kV distribution substations. Issues such as lack of feeder reliability, equipment failure, and outages have been observed in Ekpoma, Etete, and Ugbowo distribution networks, which shows that these issues are still prevalent in conventional distribution substations. It should be noted that while earlier studies mainly focused on the quantification of reliability through standard reliability indices, the current study has gone a step further by conducting statistical load-trip analysis along with relay coordination through ETAP software.

In addition, the post-intervention analysis indicates that effective relay coordination and maintenance of the deteriorated network component(s) can help improve feeder reliability considerably. This is in agreement with the recommendation of IEEE Std. 1366-2022 [22] that stresses the importance of the use of standardized indices to assess performance and improve electric power distribution systems.

3.7. Engineering Implications

The results obtained from this study have significant engineering implications for the operation and maintenance of 33/11 kV distribution substations in Nigeria and in developing power systems in general. From the study, it is revealed that feeder unreliability in distribution substation is caused by the lack of proper protection system coordination, aged network elements, encroaching vegetation, and insufficient preventive maintenance. Therefore, besides the usual practice of reinforcing the network, utilities need to conduct relay coordination study periodically, practice condition-based maintenance, manage vegetation, and replace faulty network elements.

In addition, the study reveals that it is feasible to apply historical outage analysis and ETAP protection analysis of a distribution substation to identify the causes of repeated trips and also evaluate the corrective measures before its application. The approach can be useful for distribution companies in deciding on maintenance priority in order to reduce unnecessary outages in the network. This is an easy process that does not require any financial investments in order to achieve improvement in reliability.

4. Conclusion

This paper investigated the reliability performance and tripping behaviour of the 2×7.5 MVA, 33/11 kV injection substation and its three 11 kV feeders, Commercial, Town and Local, using two years of operational data, standard reliability indices and ETAP-based protection coordination studies. The analysis showed a high concentration of interruptions on the Town and Local feeders, with total trippings significantly increased from 2023 to 2024. The faults were mainly jumper cuts, conductor snaps, insulator failures, JP fuse drops, vegetation encroachment and animal interference, revealing significant structural and environmental weaknesses in those portions of the network.

The reliability indices demonstrated the seriousness of the problem. The Commercial feeder performed relatively well with a SAIFI of less than one interruption per customer per year and availability of around 0.92, while the Town and Local feeders had much lower availability (around 0.56–0.57) and high restoration times, indicating that customers on these feeders are subjected to frequent and operationally demanding outages. Correlation between the monthly peak load and the tripping frequency indicated no strong relationships, and thus, load growth is not the main reason for the interruptions. Instead, the dominant factors were poor asset condition, inadequate right-of-way maintenance and miscoordinated protection.

The ETAP simulations provided a mechanistic link between these observations and the protection scheme. For the Commercial feeder, relays operated selectively, with primary devices clearing faults quickly and backups responding in graded fashion. In contrast, Town and Local feeders suffered from clear miscoordination, with upstream relays operating before primary relays and unnecessarily de-energising large portions of the network. This behaviour explains the combination of high failure rates, poor availability and long customer interruption durations observed in the field.

After implementing revised relay settings and targeted maintenance measures, the post-intervention analysis demonstrated substantial improvements across all feeders. SAIFI and SAIDI dropped to very low values, particularly on the Town and Local feeders, and availability rose to about

0.998–0.9997, consistent with highly reliable distribution systems. These results show that relatively low-cost, data-driven interventions in protection coordination and asset management can deliver large reliability gains without immediate large capital expansion. The case study, therefore provides a practical framework for Nigerian distribution companies and regulators seeking to improve service quality: systematic use of operational data, reliability indices and protection studies can identify critical weaknesses, guide focused remedial actions and move existing networks significantly closer to international reliability standards.

Future work should extend this framework to multiple 33/11 kV substations and longer time horizons, integrating weather, asset-condition and advanced predictive analytics to validate the findings and support adaptive protection, risk-based maintenance and reliability-focused regulation in Nigerian distribution networks.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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