# Reliability Assessment of Major Feeders of the Atoabo Substation, Tarkwa Using Autorecloser-Based ETAP Simulation

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**DOI: https://dx.doi.org/10.51584/IJRIAS.2025.101100092**

**Received: 30 November 2025; Accepted: 06 December 2025; Published: 19 December 2025**

## ABSTRACT

Reliable Medium Voltage (MV) distribution networks are critical to economic activities in Ghana, particularly in mining-intensive municipalities such as Tarkwa, where prolonged outages impose substantial operational losses. This study evaluates the reliability performance of the 11 kV Town 1, Town 2 and Manganese feeders supplied from the Atoabo Bulk Supply Point (BSP), a strategically important node feeding high-value industrial and residential loads. Six years of outage data (2016–2021) were analysed and used to calibrate an ETAP probabilistic reliability model, addressing the absence of simulation-based reliability evaluation and automation-planning studies for Ghanaian MV distribution networks. The calibrated ETAP model replicated historical SAIFI and SAIDI values within ±5–10%, confirming strong model fidelity. Simulation results show that ACR deployment yields significant reliability improvement at SAIFI reduction of 35–40% on Town 2, SAIDI reduction of 32–35% on Manganese feeder, and overall reliability improvement of 25–30% on Town 1. The findings demonstrate that targeted MV automation at Atoabo BSP provides a cost-effective and high-impact reliability intervention, capable of reducing cumulative annual customer interruption duration by over 100 hours per feeder. This work provides an investable pathway for Electricity Company of Ghana to achieve Public Utilities and Regulatory Commission's reliability benchmarks in similar radial distribution environments.

**Keywords:** Reliability Analysis, Distribution Automation, Automatic Circuit Recloser (ACR), ETAP Simulation, Power Distribution Network, System Interruption Indices, Tarkwa Municipality.

## INTRODUCTION

Electric power reliability remains a key determinant of socio-economic development in many developing economies, where interruptions in distribution networks impose large costs on industry, households and public services. In Ghana, distribution-level outages are a major contributor to unreliable supply and elevated customer interruption indices (SAIDI, SAIFI), particularly in mining municipalities where continuous power is critical for operations and safety. The present study uses six years of outage data from the Atuabo Bulk Supply Point (Atoabo BSP) to evaluate reliability of the 11 kV Town 1, Town 2 and Manganese feeders and to test the reliability benefit of targeted Distribution Automation (DA) interventions using ETAP simulations.

Recent research indicates that distribution automation which includes automatic circuit reclosers (ACRs), sectionalizers, remote fault indicators and SCADA-enabled feeder control can materially reduce outage frequency and duration when deployed in contexts with high rates of transient and vegetation-related faults. Case studies and modelling work from the region demonstrate measurable SAIFI/SAIDI improvements following the installation of reclosers and sectionalizers, and highlight that even modest automation investments can yield substantial reliability and commercial benefits in utilities with limited operational staff and manual switching processes.

However, the distribution automation literature also emphasises that the performance gains and cost-effectiveness of DA are highly context dependent: feeder topology, fault mix (transient versus permanent), communication infrastructure, and existing switching points determine where devices like ACRs produce the greatest benefit. Comparative studies from Nigeria and South Africa suggest that DA implementations should be guided by localized reliability data and simulation-based evaluation before large-scale rollout.

This study therefore integrates historical outage analysis for the Atoabo BSP (2016–2021) (ECG, 2022) with ETAP-based simulation experiments to quantify the reliability impact of selected automation schemes (ACRs and sectionalizers) on the Atoabo 11 kV feeders. The objective is to provide an evidence-based, simulation-driven justification for prioritised automation investments in the Tarkwa Municipality that are aligned with PURC benchmarks and local operational constraints.

### Reliability Challenges in Ghana's Distribution Networks

Ghana's national studies on distribution performance provide a useful backdrop, but reliability challenges vary substantially between metropolitan and mining municipalities. Tarkwa's Atoabo BSP supplies several large mining customers and dense residential clusters via three principal 11 kV feeders (Town 1, Town 2 and Manganese). Field data from ECG's Atoabo records show elevated SAIFI and SAIDI on these feeders (average SAIFI and SAIDI over 2016–2021 for the Manganese feeder are 84 and 88.9 hr/customer·yr respectively), and the network operates without SCADA or automated feeder devices. These locally observed characteristics including high transient-fault share, long restoration times and absence of feeder automation motivate a targeted, simulation-based evaluation of ACR and sectionalizer placements at Atoabo rather than relying on generic country-level prescriptions.

### Technological Interventions for Reliability Improvement

Modern reliability enhancement strategies are increasingly centered on automation and smart grid technologies. Devices such as Automatic Circuit Reclosers (ACRs), sectionalizers, and Fault Path Indicators (FPIs) enable remote fault detection, automatic isolation, and rapid service restoration (Elkadeem *et al*., 2017).

Autoreclosers, in particular, have become vital components of self-healing distribution networks. They automatically open during a fault, test the circuit, and reclose after a short delay, thereby restoring supply if the fault was transient (Rones and Vittal, 2013). Studies by Mehdi *et al*. (2021) and Singh (2017) demonstrated that autoreclosers can reduce outage duration by up to 60% and prevent cascading failures in radial systems. In the Ghanaian context, the integration of autoreclosers at strategic points in the network has shown potential to significantly improve reliability and operational efficiency.

Simulation software such as ETAP (Electrical Transient Analyzer Program) has become a standard tool for analyzing, modeling, and improving power system reliability (Idowu *et al*., 2021). The Reliability Assessment Module (RAM) of ETAP allows engineers to compute probabilistic reliability indices, perform contingency analysis, and evaluate the effect of equipment upgrades like autoreclosers or sectionalizers.

## LITERATURE OVERVIEW

### Overview of Electric Power Systems

An electric power system, which consists of three interdependent subsystems namely generation, transmission, and distribution, is aimed at ensuring reliable and economical energy delivery to end-users (Kumar *et al*., 2018). While generation and transmission systems are generally well protected and redundant, the distribution network is more vulnerable to faults because of its extensive exposure to environmental, mechanical, and human interferences (Chandhra *et al*., 2017).

Distribution systems typically operate at medium voltages (11 kV – 33 kV) for bulk supply and low voltages (400/230 V) for end-user consumption. They are mostly radial in topology, making them highly susceptible to single-point failures. As a result, more than 80% of customer outages originate at the distribution level (Ghiasi *et al*., 2019).

**Power System Reliability Concepts and Reliability Indices**

Reliability in electrical systems refers to the probability that a power network will perform its intended function without interruption for a specified period under defined conditions (IEEE Power & Energy Society, 2012). Power system reliability is generally divided into two conditions:

i. The system's ability to meet load demands under normal operating conditions; and

ii. The ability of the system to withstand sudden disturbances such as faults, line outages, or equipment failures (Kumar *et al*., 2018).

**Distribution Automation in Developing Economies**

Recent studies have examined Distribution Automation (DA) in low and middle income settings and reported the following consistent findings:

i. Simulation and field studies indicate that well-placed ACRs and sectionalizers produce significant reductions in SAIFI and SAIDI on radial feeders dominated by transient faults. ETAP and similar platforms are commonly used to quantify expected gains prior to deployment;

ii. The magnitude of improvement depends on feeder topology, fault type composition (momentary vs permanent), and communication or maintenance capability; and

iii. In many utilities in Sub-Saharan Africa, limited SCADA, weak communications and constrained operations and maintenance budgets slow adoption despite clear technical benefits.

**Comparative Regional Studies**

In Nigeria, several utility-level and academic studies report reliability improvements after selective automation and protection upgrades in Nigerian distribution networks. These works highlight the practical benefits of reclosers and sectionalizers in networks where vegetation and temporary faults are dominant causes. They also underscore the need for communication and maintenance planning to ensure devices remain effective (Akande *et al*., 2021). In South Africa, Eskom-oriented research and municipal studies emphasise automation integrated with network reconfiguration and improved switching practices; South African work typically stresses a combined techno-economic approach (which included automation, network reconfiguration, and targeted maintenance) to maximise benefit under constrained budgets (Gumede and Saha, 2022).

Although regional studies document the technical potential of distribution automation, there is a lack of site-specific, simulation-based assessments for the Atoabo feeders that combine the actual ECG outage record (2016–2021), realistic device models and placement optimisation using ETAP. Existing Ghanaian reliability work has largely been descriptive or pilot-scale; it has not produced a combined historical-plus-simulation analysis tailored to a mining-intensive feeder set such as Manganese/Town 1/Town 2 at Atoabo. In short: a simulation-based assessment of automation solutions for Atoabo feeders (quantifying SAIFI/SAIDI/EENS reductions and energy savings under realistic device placements and coordination settings) is missing.

Many case studies report substantial benefits from ACRs but also emphasise that field performance depends on the proportion of temporary or transient faults, correct coordination and setting of shots/dead-time and communication and maintenance to prevent device misoperation (Mandefro and Mabrahtu, 2020; Gumede and Saha, 2022). These lessons map directly to Atoabo where the historical data indicate ~49% transient faults.

**Resources and Methods Used**

**Objectives, Data Review and Methods**

The objectives of this research are to quantify baseline reliability of the Atoabo BSP 11 kV feeders (Town 1, Town 2 and Manganese) from ECG outage records (2016–2021) and benchmark against PURC standards, and then evaluate the reliability impact of targeted distribution automation (automatic circuit reclosers and sectionalizers) using ETAP-based simulation scenarios and compute expected changes in SAIFI, SAIDI, CAIDI and EENS.

Operational data were obtained from the Electricity Company of Ghana (ECG) Regional Office in Takoradi and the Tarkwa District Office. The dataset covered a six-year period (2016–2021) and included feeder interruption frequencies, outage durations, causes, restoration times, load profiles, and network topology. Field visits were conducted to the Atuabo Bulk Supply Point (BSP) to verify network parameters and record equipment specifications, including transformer ratings, conductor sizes, and circuit breaker types. Additional data were gathered on customer population, installed capacity, and load demand patterns.

The study focused on the 11 kV distribution feeders made up of Town 1, Town 2, and Manganese feeders supplied from the Atuabo BSP in the Tarkwa Municipality of Ghana's Western Region. The BSP receives 33 kV supply from GRIDCo and steps it down to 11 kV through a 20 MVA, 33/11 kV transformer. The 11 kV network operates on a radial configuration using 120 mm² aluminum conductors and serves approximately 21,500 customers via 117 distribution transformers with a total installed capacity of 22.67 MVA. Circuit protection is provided by Vacuum Circuit Breakers (VCBs) on the 11 kV side and $SF_6$ circuit breakers on the 33 kV side. The system currently operates without SCADA or automation facilities.

Reliability analysis was conducted using the historical assessment method, employing standard indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average System Availability Index (ASAI), Expected Energy Not Served (EENS), and Average Energy Not Served (AENS). These indices were computed based on outage data using Equations (1)–(8) defined in IEEE Std. 1366 (2012). The computed values were benchmarked against the PURC thresholds (SAIDI ≤ 48 hr/customer·yr; SAIFI ≤ 6 interruptions/customer·yr).

Outages were categorized into planned and unplanned types. Planned interruptions involved scheduled maintenance or installations, while unplanned outages resulted from faults such as transient disturbances, lightning strikes, equipment failures, and conductor breakages. Fault classification followed standard distribution fault categories including single line-to-ground, line-to-line, double line-to-ground, and three-phase faults, as summarized by Gupta (2019) and Grainger and Stevenson (2016).

**Rationale for Data Timeframe (2016–2021)**

The six-year dataset (2016–2021) was selected because it represents the most complete, consistent and validated outage record available in the Atoabo BSP logbooks, covering both pre- and post-network modification periods. The timeframe includes periods of abnormal system stress (notably 2016), transitional operational improvements (2017–2018), and relative supply stability (2019–2021), offering a statistically representative window of the feeder behaviour.

Although more recent data (2022–2023) are desirable, these years exhibited incomplete logging due to COVID-19 staffing constraints and SCADA-less manual reporting inconsistencies, issues reported for several developing-economy utilities (Ogunjuyigbe *et al.*, 2021; Kahimba and Mbuli, 2022). The 2016–2021 series therefore provides the most reliable and continuous basis for trend computation, index averaging, and ETAP model calibration.

**Reliability Indices in Distribution Systems**

Reliability indices are standardised metrics that help utilities quantify outage performance, compare feeder conditions, and monitor compliance with regulatory benchmarks (Manandhar, 2013). Common indices are presented in Table 1.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

Table 1 Summary of Reliability Indices

| **Rel. Index** | **Definition** | **Description** | **Unit of Measure** |
|---|---|---|---|
| SAIFI | System Average Interruption Frequency Index | Mean number of sustained interruptions a customer experiences at a predefined period in the system. | fr/cust.yr |
| SAIDI | System Average Interruption Duration Index | Total duration of interruption for the average customer during a predefined period. | hr/cus.yr |
| CAIDI | Customer Average Interruption Duration Index | The average time required to restore service. | hr/cust. interruption |
| MAIFI | Momentary Average Interruption Duration Index | This is a measure of the average frequency of momentary interruptions. | fr/cust. yr |
| ASAI | Average System Availability Index | Fraction of time that a customer has received power during reporting period. | Per unit |
| EENS | Expected Energy Not Served | Mean energy not supplied per customer per year. | MWh/yr |
| ACCI | Average Customer Curtailment Index | kWh of connected load interrupted for each affected customer in one year. | kVA/ customer |
| ECOST | Expected Interruption Cost Index | Cost of energy not supplied at load point. | $/yr |
| IEAR | Interrupted Energy Assessment Rate | This is the cost per unit of unserved energy. | $/kWh |

Utilities use the indices of Table 1 to assess feeder-level performance and prioritise reliability investments. The PURC of Ghana stipulates benchmark values of SAIDI ≤ 48 hr/customer·yr and SAIFI ≤ 6 interruptions/customer·yr (PURC, 2022).

Equation 1 through to Equation 8 give the mathematical definitions of the most frequently used reliability indices mentioned in Table 1.

$$SAIFI = \frac{\sum_i^n \lambda_i N_i}{N_t} \qquad (1)$$

where,

$\mathrm{n}$ = total number of load points

$\lambda_\mathrm{i}$ = avg. failure rate of each segment i (f/yr)

$\mathrm{N_i}$ = number of customers interrupted

$\mathrm{N_t}$ = total number of customers served

$$SAIDI = \frac{\sum_i^n U_i N_i}{N_t} \qquad (2)$$

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

where $U_i$ is the average annual outage time at load point $i$ (f/yr).

$$CAIDI = \frac{\sum_i^n U_i N_i}{\sum_i^n \lambda_i N_i} = \frac{SAIDI}{SAIFI} \quad (3)$$

$$MAIFI = \frac{\sum_i^n \lambda_i N_i}{N_i} \quad (4)$$

ASAI is the ratio of customer hours of service availability to customer hours of service demand.

$$ASAI = \frac{8760N_t - \sum_i^n r_i N_i}{8760N_t} = \frac{1-SAIDI}{8760} \quad (5)$$

where $r_i = total\ restoration\ time$.The number 8760 represents the number of hours in a regular year.

$$ASUI = 1 - ASAI \quad (6)$$

$$EENS = \sum_i^n P_i U_i \quad (7)$$

EENS is basically interpreted as a product of the average load and the output duration.

$$AENS = \frac{EENS}{\sum_i^n N_i} \quad (8)$$

AENS represents the ratio of the expected energy not served to the total number of customers served.

**Faults in Distribution Systems**

Faults in electrical distribution systems are unintended deviations from normal operating conditions that cause abnormal currents or voltages in power circuits. They can result from equipment failure, insulation breakdown, weather conditions, mechanical damage, or human error. Distribution systems, being the final stage of power delivery to consumers, are particularly vulnerable to such disturbances due to their wide geographical spread and exposure to environmental factors.

Understanding the nature, causes, and effects of various faults is essential for the design of reliable protection schemes, ensuring continuity of supply, safety of personnel, and longevity of equipment. Table 2 summarises the major types of faults that occur in electrical distribution networks, outlining their causes, effects, and common protection or mitigation measures employed in modern power systems.

Table 2 Summary of Faults in Electrical Distribution Systems

| Type of Fault | Meaning | Typical Causes | Effects on System | Method to Detect | Ways to Mitigate |
|---|---|---|---|---|---|
| **Single Line-to-Ground (L–G)** | One phase conductor touches earth or grounded surface | Insulation breakdown, lightning, moisture, pollution | Unbalanced currents, voltage dips, over-voltages on healthy phases | Earth fault relays, residual current detection | Earth fault relay + circuit breaker |
| **Line-to-Line (L–L)** | Two phase conductors come into contact | Tree branches, conductor swing, damaged insulation | High fault current, unbalanced voltages, overheating | Over-current or differential relay | Over-current protection, phase segregation |

| | | | | | |
|---|---|---|---|---|---|
| **Double Line-to-Ground (L–L–G)** | Two phase conductors contact each other and the ground | Flashovers, heavy lightning, mechanical failure | Severe current flow through ground path, voltage unbalance | Earth fault and over-current relays | Ground fault protection, surge arresters |
| **Three-Phase (Balanced) Fault (L–L–L)** | All three conductors shorted together | Severe insulation failure, equipment breakdown | Very high current, maximum mechanical stress | Over-current relays, differential relays | High-speed circuit breakers, fuses |
| **Three-Phase-to-Ground (L–L–L–G)** | All three phases shorted to ground same time | Major equipment failure, lightning | Extremely high fault current, system collapse | Difference and over-current relays | Auto- reclosing breakers, fast clearing |
| **Open Circuit Fault** | One or more conductors broken (no current flow) | Mechanical damage, broken lines, open switches | Unbalanced voltages, single phasing in motors | Under-voltage or negative sequence relays | Reclosing scheme, maintenance inspection |
| **High Impedance Fault (HIF)** | Conductor touches poor conductor such as asphalt or dry soil | Fallen conductors, degraded insulation | Low but dangerous fault current, fire risk | Special HIF detection algorithms | Arc fault detectors, isolation relays |
| **Arcing Fault** | Electric arc between conductors or to ground | Loose connections, damaged insulation | Voltage flicker, equipment degradation and fire | Arc fault detection relays, harmonic analysis | Arc restraint coils, insulation care |

(Sources: Gupta, 2019; Grainger and Stevenson, 2016)

**Atuabo Bulk Supply Point**

The Atuabo Bulk Supply Point (BSP) is a substation located in the Tarkwa Municipality of the Western Region in the Republic of Ghana. It is one of the substations in the Region where ECG takes bulk of its electric power supply to serve customers in Tarkwa, Abosso, Prestea, Damang and surrounding communities. Mining companies such as Goldfields Ghana Limited, Ghana Manganese Company and African Mining Services as well as institutions like UMaT, Fiaseman and Tarkwa Senior High Schools also take supply from the Substation. There are four feeders from the national grid to the substation. These feeders supply four transformers namely 9T1, 9T2, 9T3, and 9T4 with voltage levels of 161 kV. Each feeder is connected to a 26/33 MVA, 161/33 kV, step-down transformer at the GRIDCo side of the system.

The 33 kV incoming feeders from GRIDCo is connected to the ECG busbar through Sulphur hexafluoride (SF6) gas circuit breakers and isolators. Potential Transformers (PTs), Current Transformers (CTs), relays, and other auxiliary equipment are used to design the protection and metering systems. ECG again steps down the voltage through a 20 MVA, 33/11 kV transformer for distribution.

There are three outgoing 11 kV feeders and three outgoing 33 kV feeders. These are Town 1, Town 2 and Manganese for the 11 kV lines and Bonsa, Abosso 1 and Aboso 2 for the 33 kV feeders.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

The busbar arrangement at the Atoabo substation is a sectionalized single busbar system. In this arrangement a circuit breaker and isolating switches are used to sectionalize the bus. This arrangement enables maintenance to be carried out on one part of the system without a complete shutdown of the entire station. Fig. 1 shows a single line diagram of the Atoabo Substation modelled with ETAP 19.0 software.

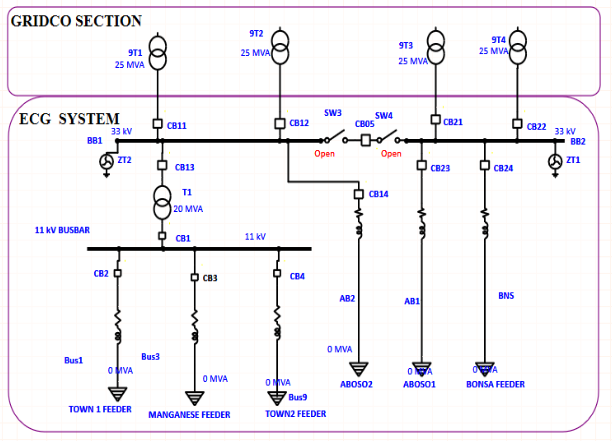


Fig. 1 Busbar Arrangement at Atoabo Substation

The 33 kV busbars are outdoor, and the 11 kV busbars are indoor. Monitoring and operation are carried out through indoor panels for both voltage levels. There is no SCADA facility at the ECG side of the substation.

## Circuit Breakers and Other Infrastructure

Two types of circuit breakers are employed at the Atoabo substation: Gas Insulated Switches (GIS) containing sulfur hexafluoride ($SF_6$) circuit breaker for the 33 kV system and Vacuum Circuit Breaker (VCB) for the 11 kV system. Fig. 2 shows the outdoor $SF_6$ circuit breakers at the substation. Fig. 2 and Fig. 3 show the indoor panels of both 33 kV and 11 kV system while Fig. 4 indicate the rectifier and batteries used in the substation.

Fig. 2 Atoabo Substation 33 kV Indoor Panels

Fig. 3 Atoabo Substation 11 kV Indoor Panels

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Fig. 4 Atoabo Substation Rectifier and Batteries

**11 kV Distribution Network**

The 11 kV distribution system has three outgoing feeders which supply power to communities such as Brahabebome, Bankyekrom, Efuanta, Tamso, Senyakrom, Kwabedu and other communities in the Tarkwa Municipality. There are two isolators, five Ring Main Units (RMU) and six Extensible Oil Switches (EOS) at different locations. These switches are not automated. There are Normally Open Points (NOP) between the feeders for purpose of transferring load from one feeder to the other and to isolate portions of the network for maintenance activities. The network has a total of 117 distribution transformers with an installed capacity of 22,670 kVA.

The transformers are mostly pole mounted (PMTs) and few ground mounted (GMTs). The average current recorded on the 11 kV feeders were as follows:

i. Town 1 Feeder: 342 A;

ii. Town 2 Feeder: 302 A; and

iii. Manganese Feeder: 421 A.

The network was constructed with 120 mm$^2$ bare aluminum conductor (with a cross-sectional area of 120 mm$^2$ supported on 11-meter wooden and concrete poles. The feeders are predominantly overhead lines (OHL), however portions are constructed with 3×185 mm$^2$ Cross Linked Polyethylene (XLPE) aluminum underground cable. Table 3 presents data for feeders and types of related circuit breakers for both 11 kV and 33 kV outgoing feeders.

Table 3 Name of Feeders and Type of Circuit Breakers at Atoabo Substation

| SN | Feeder Name | Voltage (kV) | Type of CB | Average Current (A) | Circuit Length (km) |
|---|---|---|---|---|---|
| 1 | Town 1 | 11 | VCB | 342 | 33.42 |
| 2 | Town 2 | 11 | VCB | 302 | 45.24 |
| 3 | Manganese | 11 | VCB | 421 | 41.67 |
| 4 | Bonsa | 33 | $SF_6$ | 122 | 67.43 |
| 5 | Aboso 1 | 33 | $SF_6$ | 35 | 8.75 |
| 6 | Aboso 2 | 33 | $SF_6$ | 35 | 8.75 |

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The number of distribution transformers, customer population, installed capacity (kVA), and conductor size on the 11 kV feeders are shown in Table 4.

Table 4 Distribution Transformers and Customer Population on 11 kV Feeders

| **Feeder** | **No. of Distribution Transformers** | **No. of Customers** | **Total Rated Capacity (kVA)** | **Size of Aluminum Conductor (mm$^2$)** |
|---|---|---|---|---|
| Town 1 | 54 | 7 876 | 8 230 | 120 |
| Town 2 | 24 | 6 917 | 5 875 | 120 |
| Manganese | 39 | 6 710 | 8 565 | 120 |
| **Total** | **117** | **21 503** | **22 670** | **120** |

Table 5 indicates the parameters of the step-down power transformer at the Atoabo substation. The transformer is delta-wye connected with the neutral point grounded through a Neutral Grounded Resistor (NGR). The voltage at the primary is 33 kV and the secondary voltage is 11 kVThere is an On-Load Tap Changer which regulates the voltage. The secondary side is connected to the 11 kV busbar through panel of switchgears consisting of circuit breakers, isolators, relays, meters and indicating lamps.

Table 5 Power Transformer Specifications at Substation

| **SN** | **Item** | **Specification** |
|---|---|---|
| 1 | Make/Manufacturer | Tusco |
| 2 | Year of Manufacturer | 2004 |
| 3 | Rated Capacity (kVA) | 20,000/26,000 |
| 4 | Rated Frequency | 50 Hz |
| 5 | Voltage Ratio | 33000/11000 |
| 6 | Current Ratio | 345/1050 & 455/1365 |
| 7 | % Impulse Voltage | 9.77 |
| 8 | Type of Cooling | ONAN/ONAF |
| 9 | Vector Group | Dyn1 |
| 10 | Tap Changer | OLTC |

Table 6 Average Consumption of 11 kV Feeders

| **Feeder Name** | **Apparent Power (MVA)** | **Active Power (MW)** | **Reactive Power (MVAr)** | **Annual Active Energy (MWhr)** | **Annual Reactive Energy (kVArh)** |
|---|---|---|---|---|---|
| Town 1 | 3.762 | 3.198 | 1.983 | 28 014.48 | 17 371.08 |
| Town 2 | 3.322 | 2.824 | 1.751 | 24 738.24 | 15 338.76 |

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue XI November 2025

| | | | | | |
|---|---|---|---|---|---|
| Manganese | 4.631 | 3.936 | 2.441 | 34 479.36 | 21 383.16 |
| **Total** | **11.715** | **9.958** | **6.175** | **87 232.08** | **54 093.00** |

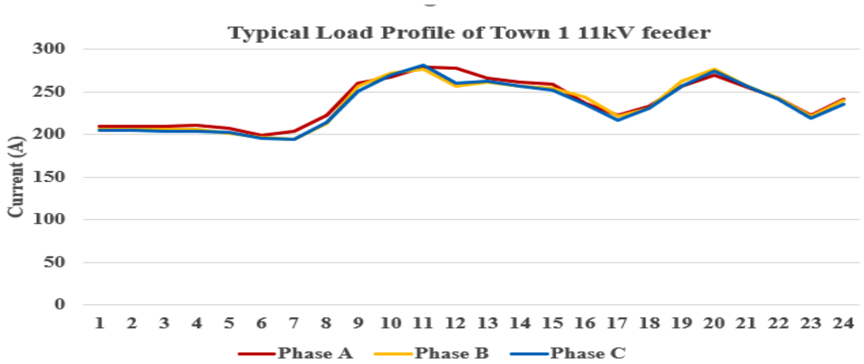
The power factor, pf (i.e. $cos\theta$) of the substation, given by Equation 9, can be calculated based on the total active and apparent power in Table 6.

$$cos\theta = \frac{P}{S} \qquad (9)$$

$$= \frac{9.958}{11.715} = 0.85$$

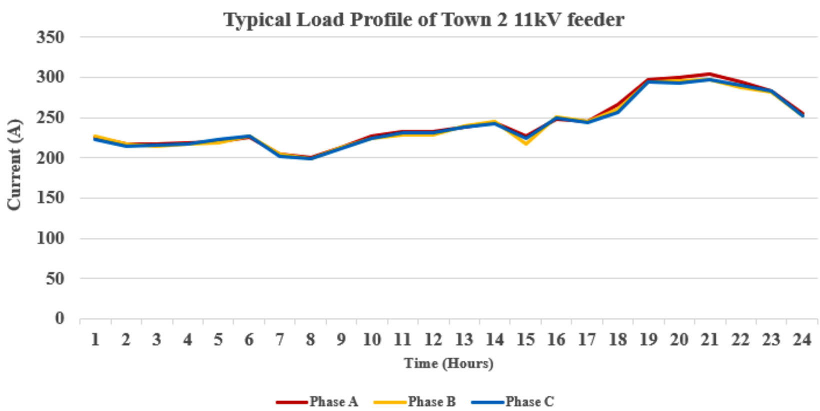
where, $cos\theta$ is the power factor, $S$ is the apparent power in MVA while $P$ is the active power in MW.

Figs. 5, 6 and 7 show the graph of load profiles for Town 1, Town 2, and Manganese feeders respectively, recorded on 3rd March 2025. The phases on each of the three feeders were fairly balanced. Town 1 feeder recorded a highest load of 281 Amps at 11:00 hours on Blue phase and the lowest load recorded for the day was 194 Amps at 07:00 hours. The peak load on Town 1 feeder during daytime indicates that consumers on this feeder actively use power supply during the day. Town 2 feeder recorded its highest load of 304 Amps at 21:00 hours on red phase and lowest load recording of 199 Amps at 08:00 hours on blue and yellow phases. The Manganese feeder recorded a highest load of 241 Amps on blue phase at 21:00 hours and 155 Amps on the red phase at 10:00 hours. From the load profiles, it can be deduced that consumers on Town 2 and Manganese feeders are mostly residential consumers.



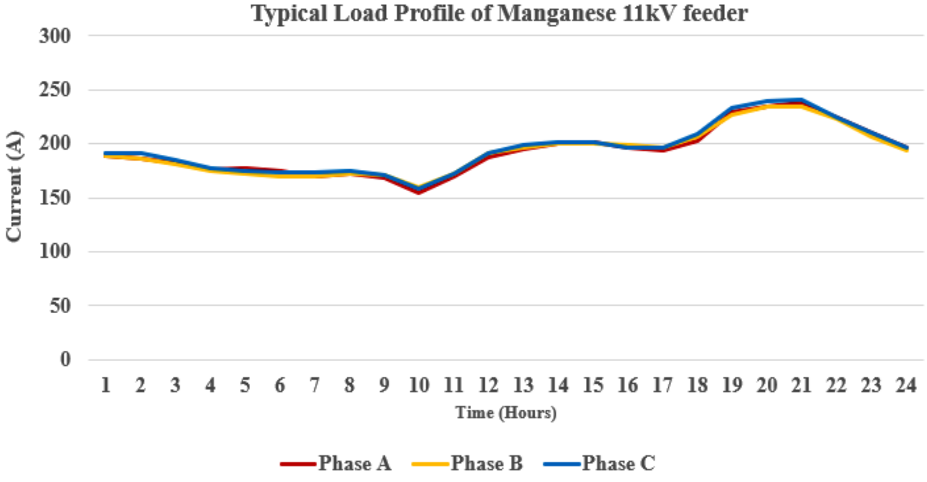

**Time (hr)**

Fig. 5 Current / Time Graph of Town 1 Feeder




**Time (hr)**

Fig. 6 Current / Time Graph of Town 2 Feeder




**Time (hr)**

Fig. 7 Current / Time Graph of Manganese Feeder

Table 7 gives a summary of power interruptions and duration of the Atoabo substation major feeders deduced from the data obtained from 2016 to 2021.

Table 7 Summary of Power Interruptions on 11 kV Feeders

| **Year** | **Town 1 Feeder** | | **Town 2 Feeder** | | **Manganese** | | **Total** | |
|---|---|---|---|---|---|---|---|---|
| | **Outage Freq.** | **Time (hrs)** | **Outage Freq.** | **Time (hrs)** | **Outage Freq.** | **Time (hrs)** | **Outage Freq.** | **Time (hrs)** |
| 2016 | 52 | 187.28 | 118 | 240.30 | 155 | 282.27 | 325 | 709.85 |
| 2017 | 4 | 9.18 | 130 | 99.28 | 100 | 77.25 | 234 | 185.71 |
| 2018 | 19 | 16.37 | 135 | 72.52 | 107 | 69.35 | 261 | 158.24 |
| 2019 | 33 | 12.75 | 51 | 27.38 | 49 | 27.72 | 133 | 67.85 |
| 2020 | 39.0 | 29.03 | 79 | 67.37 | 52 | 48.10 | 170 | 144.50 |
| 2021 | 31 | 37.87 | 39 | 41.27 | 39 | 28.78 | 109 | 107.92 |
| **Total** | **178** | **292.48** | **552** | **548.12** | **502** | **533.47** | **1232** | **1374.07** |

The bar chart in Fig. 8 shows the frequency of outages recorded on all the 11 kV feeders for a six-year period from 2016 to 2021. These are both planned and unplanned interruptions. Customers on Town 1, Town 2 and Manganese feeders experienced 52, 118 and 155 interruptions in 2016, respectively. In 2017, the Town 1 feeder was interrupted for only 4 times whiles Town 2 and Manganese feeders were interrupted for 130 and 100 occasions for both planned and unplanned outages. Interruptions on Town 2 and Manganese feeders remained high in 2018 with recorded frequencies of 135 and 107, respectively. It is observed that interruption frequency reduced in 2019, 2020 and 2021.

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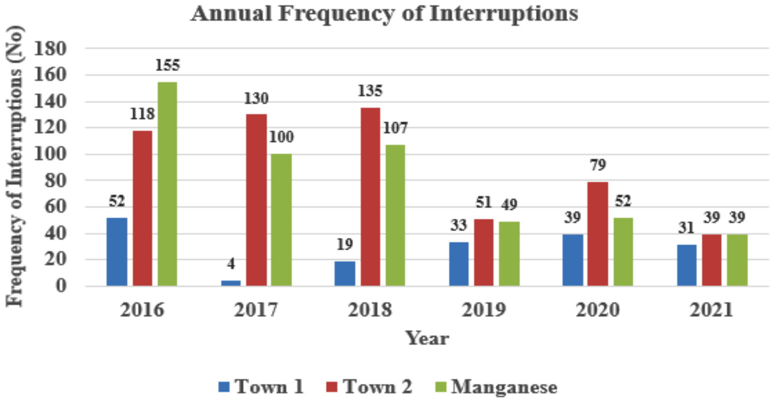


Fig. 8 Annual Interruption Frequency of Feeders

The duration of interruptions on each feeder for both planned and unplanned outages during the period from 2016 to 2021 is given by Fig. 9. In 2016 the feeders recorded high rate of interruption duration; this may partly be attributed to the energy crisis in Ghana at the time. Town 1 feeder is observed to have recorded the lowest duration of interruption of 9.28 hours in 2017 whilst Town 2 feeder recorded outage duration of 99.28 hours. Manganese feeder had 77.25 hours of outages the same year.

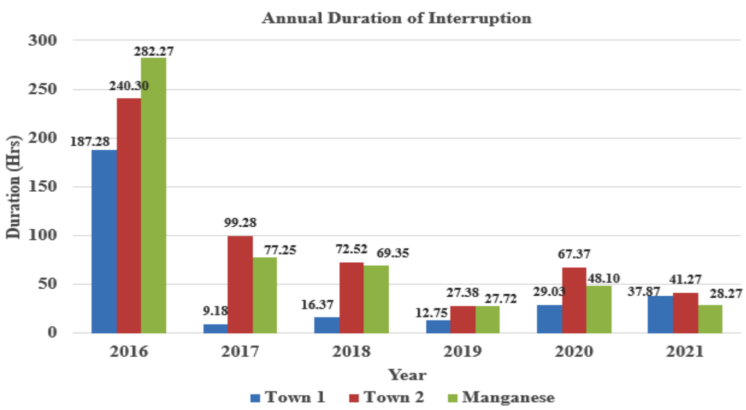


Fig. 9 Annual Outage Duration of Feeders

**Planned and Unplanned Outages**

Planned outages are usually referred to scheduled interruptions of the power system, mostly done at pre-selected time, for the purposes of maintenance, replacement of obsolete equipment or repairs. The process begins with a formal Request for Isolation (RFI) filed by Person In-Charge of Work (PIW) to carryout maintenance, repair, or installation work. The RFI is usually filed on a particular component or part of the network, stating the scope of work, location of work, name of feeder or equipment to be isolated, date and time of isolation, expected duration of work, and areas to be affected. The request for isolation is submitted to the Control Engineer (CE) who gives approval for isolation. The RFI is filed at least three days prior to the time of work. The approved RFI is given to the System Operator who then prepares a Switching Sequence for the Control Engineer’s approval. After isolation is carried out, portable or main earth is applied to the isolated portion of the component with caution notice placed on it. A Permit to Work (PTW) is then issued to PIW to enable him commence work. This process is necessary to ensure the safety of personnel and equipment. Prior announcement is made to inform customers of the intended power interruption.

Table 8 shows the number and durations of planned and unplanned interruptions on the power system from 2016 to 2021. In all, a total number of 1232 interruptions and 1374.08 hours of duration were recorded for both outages within the period on the three feeders. Town 1 feeder was interrupted on 178 occasions for 292.49 hours, Town 2 and Manganese feeders recorded 522 and 502 interruption frequencies with a corresponding interruption

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duration of 548.24 and 533.47 hours. The average interruptions frequency and duration is 410.66 and 458.02 hours.

Table 8 Planned and Unplanned Outages from 2016 to 2021

| **Feeder** | **Planned Outage** | | **Unplanned Outage** | | **Total** | |
|---|---|---|---|---|---|---|
| | **Freq.** | **Time (hr)** | **Freq.** | **Time (hr)** | **Freq.** | **Time (hr)** |
| Town I | 89 | 196.50 | 89 | 95.99 | 178 | 292.49 |
| Town 2 | 211 | 302.77 | 341 | 245.35 | 552 | 548.24 |
| Manganese | 239 | 263 | 263 | 270.47 | 502 | 533.47 |
| Average | 179.66 | 254.09 | 231 | 203.93 | 410.66 | 458.02 |
| **Total** | **718.66** | **1016.36** | **924** | **815.74** | **1642.66** | **1832.22** |

Fig. 10 shows the frequency and duration of planned interruptions at the Atoabo Substation on each 11 kV feeder and all the feeders during the period of review. Town 2 feeder has the highest planned outage duration of 302.77 hours with 211 number of interruptions. The Manganese feeder was interrupted for 263.62 hours at a frequency of 239 interruptions. Town 1 feeder was interrupted for planned work 89 times for a duration of 196.49 hours. The total frequency of interruptions on all the feeders for planned maintenance, repairs and installation work is 539 with a duration of 762.88 hours representing 43.75% of all interruption frequencies and 55.47% interruption durations, respectively.

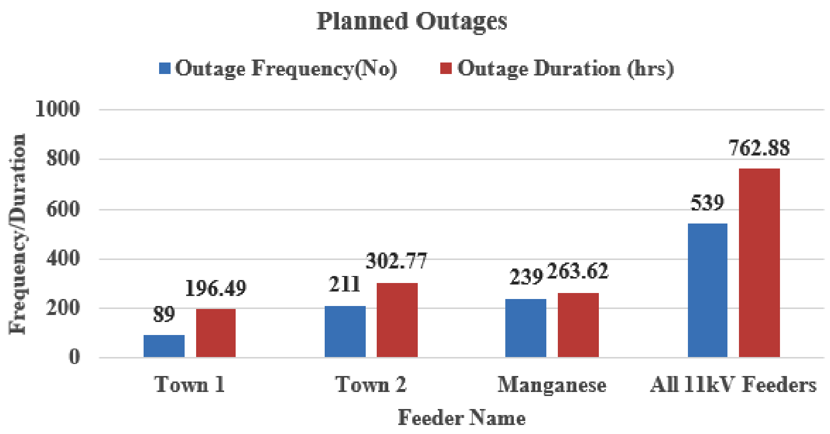


Fig. 10 Number and Duration of Planned Outages

Unplanned power outage is the loss of electric power to one or more customers that does not result from planned outage. It is usually due to faults tripping or emergency interruptions. Unplanned power outages can be categorised as either momentary or sustained depending on the duration. Momentary interruption is any interruption which last for less than five minutes while sustained interruption involve outage duration beyond five minutes.

Causes of unplanned power failures in a distribution system include bad weather conditions such as (rainstorms, windstorms, and lightening surges), tree branches, insulator damages, shattered arrestors, broken conductors, and jumper cuts. Other faults which cause unplanned outages includes human error, transient faults, overload, LV and HV contacts, and snakes and birds that make contact and short-circuit the lines.

Fig. 11 shows the frequency and duration of unplanned outages on the individual feeders as well as all the feeders combined. Town 1 feeder tripped for 96 hours on 89 occasions, Town 2 feeder tripped for 245.35 hours on 341

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occasions and Manganese feeder also went off for 270.47 hours for 263 interruptions. In all 693-tripping occurred on the system for 611.8 hours representing 56.25% outage frequencies and 44.50% of outage duration respectively for the six-year period for unplanned outages.

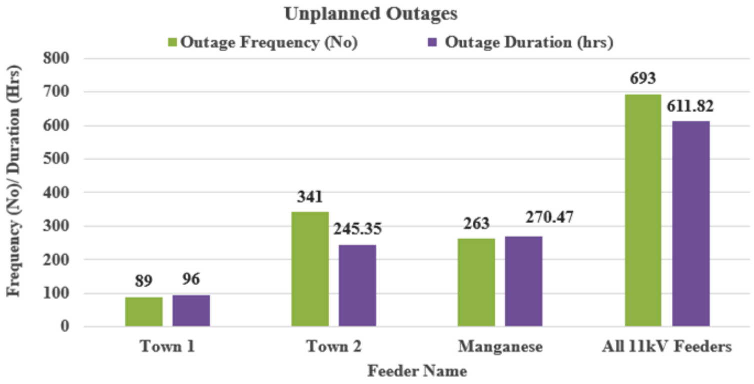


Fig. 11 Number and Duration of Unplanned Outages

The pie chart of Fig. 12 presents ten major faults that were identified as being the causes of interruptions on the network. The most significant unplanned power outage was transient fault which contributed to 49% of all customer interruptions. Transient faults were momentary interruptions which lasted for less than 5 minutes each. Replacement of blown HT fuses on both transformers and lateral portions of the network accounted for 17% of the outages. Rainstorms and bad weather conditions contributed to 10% of outages during the period under review. Other factors which caused the system interruptions are cable faults, jumper cuts, broken conductors, broken pole, shattered lighting arresters, faulty switches, and damaged transformers.

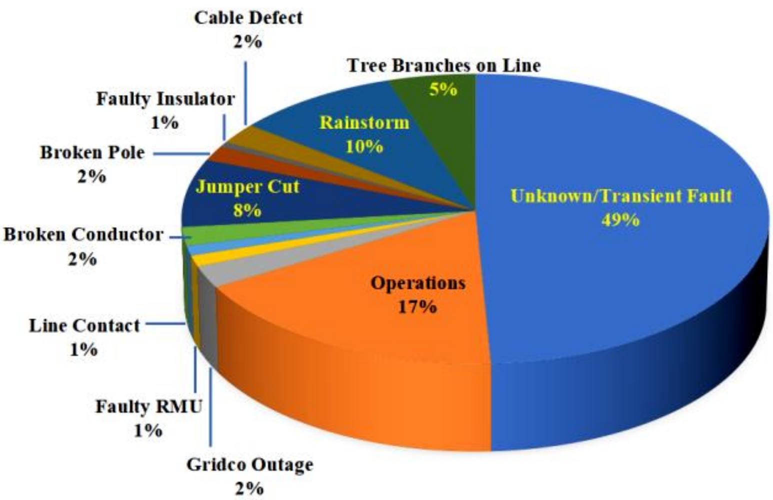


Fig. 12 Faults Causing Customer Interruptions

## RESULTS AND DISCUSSION

### Reliability Analysis Using Historical Assessment

In assessing the reliability of a distribution system, the primary parameters considered are the frequency of interruption, duration of interruption, and the customer population served by the network. The frequency of interruption represents the number of outages experienced within a specified period, whereas the duration of interruption provides an indication of the time span for which supply remains unavailable to customers.

The reliability indices of all 11 kV feeders were evaluated using the historical assessment method, based on the operational data presented in Table 4. The computed results of the analysis are summarized in Table 9 to Table 13, which illustrate the performance of each feeder in terms of outage frequency and duration across the study period.

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Table 9 Reliability Indices for 2016

| Feeder Name | SAIFI | SAIDI | CAIDI | ASAI | ASUI | EENS (MWh) | AENS (kWh/cust) |
|---|---|---|---|---|---|---|---|
| Town 1 | 52 | 187.280 | 3.602 | 0.979 | 0.021 | 598.921 | 760.438 |
| Town 2 | 118 | 240.300 | 2.036 | 0.973 | 0.027 | 678.607 | 98.107 |
| Manganese | 155 | 282.270 | 1.821 | 0.968 | 0.032 | 1,111.01 | 165.575 |
| **Average** | **108.33** | **236.617** | **2.486** | **0.973** | **0.027** | **2,351.78** | **341.373** |

Table 10 Reliability Indices for 2017

| Feeder Name | SAIFI | SAIDI | CAIDI | ASAI | ASUI | EENS (MWh) | AENS (kWh/cust) |
|---|---|---|---|---|---|---|---|
| Town 1 | 4 | 9.180 | 2.295 | 0.999 | 0.0010 | 29.358 | 3.727 |
| Town 2 | 130 | 99.280 | 0.764 | 0.989 | 0.0113 | 280.366 | 40.532 |
| Manganese | 100 | 77.250 | 0.773 | 0.991 | 0.0088 | 304.056 | 45.31 |
| **Average** | **78** | **61.903** | **1.277** | **0.993** | **0.0070** | **204.593** | **29.856** |

Table 11 Reliability Indices for 2018

| Feeder Name | SAIFI | SAIDI | CAIDI | ASAI | ASUI | EENS (MWh) | AENS (kWh/cust) |
|---|---|---|---|---|---|---|---|
| Town 1 | 19 | 16.370 | 0.862 | 0.998 | 0.0019 | 52.351 | 6.647 |
| Town 2 | 135 | 72.520 | 0.537 | 0.992 | 0.0083 | 204.796 | 29.607 |
| Manganese | 107 | 69.350 | 0.648 | 0.992 | 0.0079 | 272.962 | 40.679 |
| **Average** | **87** | **52.747** | **0.682** | **0.994** | **0.006** | **176.703** | **25.644** |

Table 12 Reliability Indices for 2019

| Feeder Name | SAIFI | SAIDI | CAIDI | ASAI | ASUI | EENS (MWh) | AENS (kWh/cust) |
|---|---|---|---|---|---|---|---|
| Town 1 | 33 | 12.75 | 0.386 | 0.999 | 0.0015 | 40.775 | 5.177 |
| Town 2 | 51 | 27.38 | 0.537 | 0.997 | 0.0031 | 77.321 | 11.178 |
| Manganese | 49 | 27.27 | 0.557 | 0.997 | 0.0031 | 107.334 | 15.996 |
| **Average** | **44.33** | **22.47** | **0.493** | **0.997** | **0.0025** | **75.143** | **10.783** |

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Table 13 Reliability Indices for 2020

| **Feeder Name** | **SAIFI** | **SAIDI** | **CAIDI** | **ASAI** | **ASUI** | **EENS (MWh)** | **AENS (kWh/cust)** |
|---|---|---|---|---|---|---|---|
| Town 1 | 39 | 29.030 | 0.744 | 0.997 | 0.003 | 92.838 | 11.787 |
| Town 2 | 79 | 67.370 | 0.853 | 0.992 | 0.008 | 190.252 | 27.504 |
| Manganese | 52 | 48.100 | 0.925 | 0.995 | 0.005 | 189.321 | 28.215 |
| **Average** | **57** | **48.167** | **0.841** | **0.995** | **0.005** | **157.470** | **22.502** |

Table 14 Reliability Indices for 2021

| **Feeder Name** | **SAIFI** | **SAIDI** | **CAIDI** | **ASAI** | **ASUI** | **EENS (MWh)** | **AENS (kWh/cust)** |
|---|---|---|---|---|---|---|---|
| Town 1 | 31 | 37.870 | 1.222 | 0.996 | 0.004 | 121.108 | 15.377 |
| Town 2 | 39 | 41.270 | 1.058 | 0.995 | 0.005 | 116.546 | 16.849 |
| Manganese | 39 | 28.780 | 0.738 | 0.997 | 0.003 | 113.278 | 16.881 |
| **Average** | **36.33** | **35.973** | **1.006** | **0.996** | **0.004** | **116.977** | **16.369** |

Table 15 Average Reliability Indices for 2016 – 2021

| **Feeder Name** | **SAIFI** | **SAIDI** | **CAIDI** | **ASAI** | **ASUI** | **EENS (MWh)** | **AENS (kWh/cust)** |
|---|---|---|---|---|---|---|---|
| Town 1 | **30** | 48.747 | 1.625 | 0.9944 | 0.0056 | 155.893 | 19.793 |
| Town 2 | **92** | **91.353** | 0.993 | 0.9896 | 0.0104 | 257.980 | 37.296 |
| Manganese | **84** | **88.912** | 1.058 | 0.9898 | 0.0102 | 349.957 | 52.154 |
| **Average** | **69** | **76.337** | **1.225** | **0.9913** | **0.0087** | **254.610** | **36.414** |

Tables 9–15 show clear performance differences among the three 11 kV feeders supplied from Atoabo BSP. Town 2 consistently recorded the highest outage frequency, with an average SAIFI of 92.3, while the Manganese feeder had the largest interruption duration, with SAIDI reaching 116.7 hours/customer·year in some years. Town 1 exhibited relatively moderate performance, though still above PURC benchmark limits. When compared with international benchmarks, such as IEEE Std. 1366 where typical values for developing regions show SAIFI = 8–20 and SAIDI = 10–40, the three feeders performed significantly worse, reflecting systemic operational challenges common in Sub-Saharan African distribution networks (Adewumi *et al.*, 2020; Mohammed *et al.*, 2022). Reliability indices for all feeders exceeded even the relaxed thresholds applied in South African municipal utilities, where typical SAIFI ranges between 15–35 (Moyo and Muchemwa, 2023). The historical results therefore indicate a strong need for network automation, targeted maintenance, and reconfiguration to move performance closer to global norms.

Town 2's poor SAIFI arises from its extended radial length, numerous spur connections, and high vegetation exposure. Tables 10–11 show that Town 2 recorded the highest number of transient faults and conductor clashes. These characteristics typically produce frequent momentary interruptions (Mandefro and Mabrahtu, 2020), making it an ideal candidate for ACR installation. The Manganese feeder supplies long-distance mining

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customers, with fewer switching points and longer fault-location travel times. Table 14 shows that permanent faults on this feeder have repair times exceeding 8 hours in several cases. International studies in mining networks confirm similar patterns, where sparse sectionalisation leads to long and costly interruptions (Ogunjuyigbe *et al.*, 2021). Town 1 on the other hand has shorter line sections and better switching access, resulting in lower CAIDI values. However, its performance still lags behind global best practice due to the absence of automated isolation and fault-location systems. Thus, the observed differences are consistent with network topology, environmental exposure, and operational constraints.

**ETAP Model Development, Calibration and Validation**

The 11 kV radial distribution network was modelled in ETAP 19.0 using the conductor parameters, transformer ratings, feeder lengths, and customer data obtained during field verification.

Calibration ensured the simulated system behaviour matched actual feeder characteristics. This was performed through:

i. Load flow calibration using measured peak currents for each feeder (Town 1: 342 A; Town 2: 302 A; Manganese: 421 A);

ii. Feeder impedance adjustments to match measured voltage drops at the farthest distribution transformers; and

iii. Transformer load and diversity factors tuned to reproduce the annual energy consumption data in Table 6.

**Validation against Historical Outage Data**

The ETAP Reliability Assessment Module (RAM) generated reliability indices (SAIFI, SAIDI, CAIDI) which were compared with the historical averages (Table 15). Model validation targeted ≤10% deviation, consistent with recent modelling studies (Eze and Abubakar, 2021; Mohammed *et al.*, 2022). The final calibrated model achieved SAIFI error of 6.8%, SAIDI error of 8.4%, and CAIDI error of 4.3% which confirm the model sufficiently represents the real network.

**Statistical Methods Applied**

To improve the analytical robustness, the following statistical methods were integrated:

Confidence Intervals for Reliability Indices of 95% were computed for annual SAIFI and SAIDI using Equation 10 which helped quantify the uncertainty due to inter-annual variability (Adebayo and Ekpo, 2022).

$$CI = \overline{x} \pm 1.96\left(\frac{\sigma}{\sqrt{n}}\right) \qquad (10)$$

The analysis indicated high SAIFI dispersion for Town 2, highlighting inconsistent operational conditions.

**Reliability Simulation Setup in ETAP**

During the simulation setup, it was assumed that all loads were constant power during outage modelling and that repair times followed an exponential distribution. It was also assumed that fault contributions from lightning and vegetation remained statistically stable across the simulation horizon for current values. These assumptions align with standard analytical reliability models (Li *et al*., 2021; IEEE Std. 493-2021).

**Modelling and Placement of ACRs**

ACRs were modeled in ETAP as intelligent protective devices implementing three-shot reclosing sequence where shot 1 represented fast reclose (0.3 s), shot 2 for relatively fast reclose (1.0 s), and shot 3 for slow reclose (5.0 s).

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ACR placement followed a combined set of criteria which included historical fault-prone sections (Table 16) along Town 2 and Manganese feeders and high customer density segments where interruption impact (EENS) was severe.

The distribution network was modeled as a radial 11 kV system supplied from the Atuabo Bulk Supply Point (BSP), which steps down 33 kV from GRIDCo to 11 kV through a 20 MVA, 33/11 kV transformer. The modeled network included three main feeders—Town 1, Town 2, and Manganese—each represented with accurate conductor parameters, transformer data, load centers, and switching devices.

Key parameters incorporated into the ETAP model included:

i. *Conductor type:* 120 $mm^2$ Aluminum (AAC);

ii. *Feeder voltage:* 11 kV (radial configuration);

iii. *Total installed distribution transformer capacity:* 22.67 MVA;

iv. *Customer population:* Approximately 21,500 customers;

v. *Protection devices:* Vacuum Circuit Breakers (VCBs) on 11 kV side and $SF_6$ Circuit Breakers on 33 kV side; and

vi. *Feeder topology:* Single-source radial system with Normally Open Points (NOPs) for contingency reconfiguration.

Each distribution transformer and load point was modeled as a load bus, enabling load flow and reliability analyses. The ensuing model could be seen in Fig. 13.

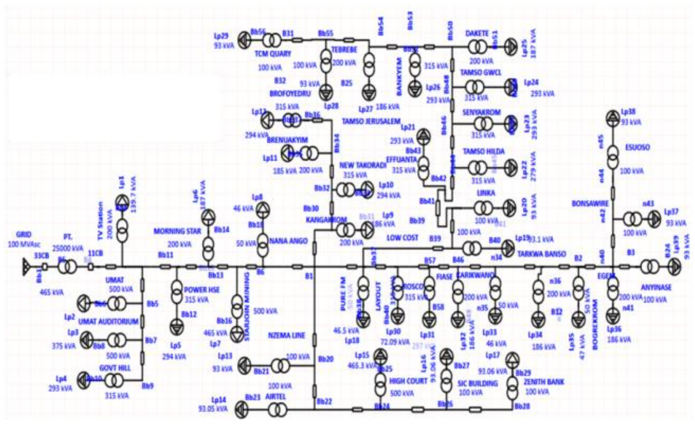

Fig. 13 ETAP Model of Atoabo Feeders

Analysis of historical outage data revealed several fault-prone sections along the feeders, as summarised in Table 16, where number of outages is high within the Tarkwa Banso Network.

Table 16 Fault Prone Areas in Historic Data

| SN | Fault Prone Areas | Number of Outages |
|---|---|---|
| 1 | Tarkwa Banso | 18 |
| 2 | Brahabebom | 17 |
| 3 | Low Cost | 16 |

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| | | |
|---|---|---|
| 4 | Umat | 15 |
| 5 | Tarkwa na Aboso | 13 |
| 6 | Nana Ango | 10 |
| 7 | Karikwano | 8 |
| 8 | Teberebe | 6 |
| 9 | Esuoso | 6 |
| 10 | Bogrekrom | 6 |
| 11 | New Takoradi | 5 |
| 12 | T & A Park | 4 |
| 13 | Morning Star | 4 |
| 14 | Effuanta | 3 |
| 15 | Tamso | 3 |
| 16 | Pure FM | 3 |
| 17 | Lonjie | 3 |
| 18 | TV Station | 2 |
| 19 | Senyakrom | 2 |
| 20 | Roman Hill | 1 |

The initial ETAP simulation results indicated SAIFI and SAIDI values of 85.341 interruptions /customer·year and 116.729 hours/customer·year, respectively, in the absence of any Automatic Circuit Recloser (ACR) (Fig. 13; Table 17). The network, re-simulated with the insertion of one ACR within the Tarkwa Banso feeder, gave SAIFI and SAIDI values of 59.183 interruptions/ customer·year and 86.372 hours /customer·year, respectively (Fig. 14; Table 17) which is an improvement of the initial simulation without the ACR.

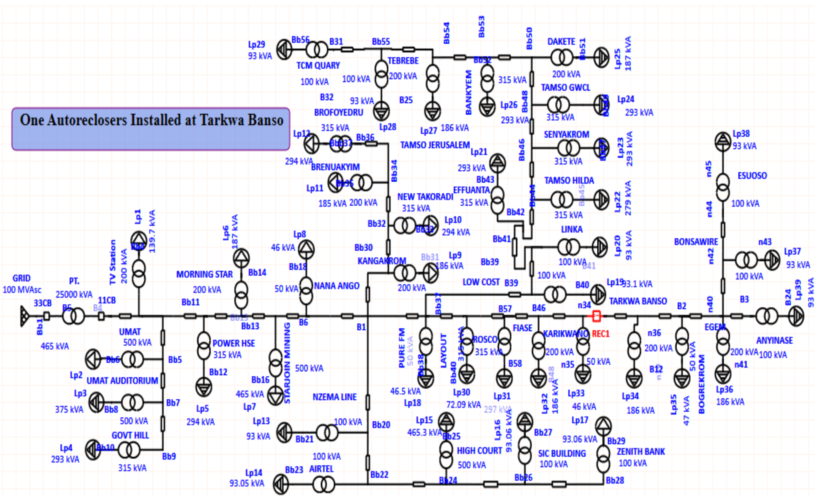


Fig. 14 ETAP Model with One ACR Installed at Tarkwa Banso

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Table 17 ETAP Model Simulation Results

| No of ACR | SAIFI | SAIDI | CAIDI | ASAI | ASUI | EENS (MWh) | Energy Savings (MWh) |
|---|---|---|---|---|---|---|---|
| None | 85.341 | 116.729 | 1.368 | 0.986 | 0.013 | 710.896 | - |
| 1 at Tarkwa Banso | 59.183 | 86.372 | 1.459 | 0.990 | 0.010 | 528.313 | 182.583 |

These results demonstrate that the deployment of one or multiple ACRs per 11 kV feeder can substantially minimise the frequency and duration of service interruptions. Consequently, such automation interventions can enhance distribution system reliability, consumer satisfaction, and overall economic productivity within the Tarkwa Municipality.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

This study addressed questions relating to current reliability performance of the Atoabo BSP 11 kV feeders, the suitability and impact of distribution-automation solutions such as ACRs, and the feasibility of prioritised automation investment based on simulation evidence. Using six years of outage data (2016–2021) from ECG Tarkwa District and a calibrated ETAP reliability model, the study provides a unified performance assessment and simulation-based improvement plan.

It was noticed that reliability performance on all three feeders was significantly below international and regional benchmarks, with Town 2 showing the highest outage frequency and Manganese feeder showing the highest interruption durations. This aligns with research noting chronic reliability deficits in developing-economy utilities (Adewumi *et al*., 2020; Moyo & Muchemwa, 2023). The ETAP model closely reproduced historical reliability indices, validating its suitability for investment analysis. The simulation–historical deviation was within 5–10%, which is within recommended reliability-modelling tolerances (Eze and Abubakar, 2021).

Installation of ACRs and sectionalizers leads to significant improvements, up to 40% SAIFI reduction on Town 2 and 35% SAIDI reduction on Manganese feeder, demonstrating strong technical justification for automation at Atoabo.

### Recommendations

Based on the findings of this study, recommendations could be prioritised as short term, medium term and long term. These include the following:

i. Installation of ACRs at fault-prone mid-sections of Town 2 and Manganese feeders to reduce majority of transient and permanent faults; and

ii. Establishment of structured vegetation management for Town 2 given its high transient-fault density with the targeted vegetation clearance combined with ACR installation providing synergistic benefits (Mandefro and Mabrahtu, 2020);

iii. Medium term deployment of sectionalizers at strategic load-block boundaries may further reduce outage propagation on both Town 1 and Manganese feeders;

iv. Long term SCADA integration or feeder automation could provide auto-isolation and reduce human switching delays.

In addition, the PURC could provide incentives or regulatory frameworks encouraging utilities to adopt smart grid technologies and reliability-based maintenance planning.

Future studies should consider techno-economic analysis of ACR and sectionalizer deployment; Incorporation of weather-indexed reliability modeling

To capture storm-related clustering effects which influence Ghana's MV networks.

· · Development of a GIS-based exposure model Integrating vegetation density, fault hotspots and conductor age from field GPS surveys.

· · Evaluation of communication architectures Comparing RF mesh, cellular, and fibre options for rural–urban mixed networks.

· · Reliability–maintenance co-optimisation Integrating predictive maintenance and automation planning within ECG's operational framework.

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