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Reliability Evaluation of an 86-Bus Power System Using ETAP: A Case Study of 11kv 8-Mile Feeder in Calabar, Nigeria

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ABSTRACT
Electric power systems are vital in modern societies, with distribution networks being particularly crucial due to their direct interface with end-users. However, the 11kV 8-Mile Feeder in Calabar, a critical component of the Port Harcourt Electricity Distribution Company (PHED) network, suffers from frequent outages, prolonged restoration periods, and deteriorating infrastructure, resulting in unreliable power supply and widespread customer dissatisfaction. This problem is exacerbated by reactive maintenance strategies, a lack of automation, and the absence of advanced analytical tools for effective fault diagnosis and system optimization.This study aimed to evaluate the reliability performance of the 11kV 8-Mile Feeder using ETAP simulation software, focusing on identifying key reliability challenges, quantifying standard indices, and recommending system improvements. Real-time data from PHED, collected over a three-year period, was analyzed using ETAP to simulate feeder behavior and fault scenarios. Key reliability indices computed included SAIFI, SAIDI, CAIDI, ASAI, and ENS. Findings revealed substandard reliability, voltage instability, and frequent overload conditions, particularly during peak demand periods. Additionally, frequency faults, constituting approximately **27%** of total recorded faults over the three years, were identified as significant contributors to service interruptions.The ETAP-based digital twin enabled hotspot identification and system stress analysis, forming the foundation for actionable recommendations. These include feeder overload upgrades, fault-tolerant reconfiguration, automation of switching operations, and proactive condition-based maintenance strategies. Implementation of these measures is expected to enhance operational efficiency, reduce downtime, and improve supply reliability across the network.

Keywords: Reliability, Distribution System, Reliability Indices, Frequency Faults

I. INTRODUCTION

The distribution segment of electric power systems is crucial as it directly interfaces with end-users and significantly impacts power quality, system reliability, and overall customer satisfaction. In an era where energy availability is closely tied to national productivity and socioeconomic development, the operational integrity of distribution systems has become more critical than ever. Globally, utilities strive to achieve high reliability standards by minimizing service interruptions and outages. However, in developing countries such as Nigeria, persistent systemic challengesranging from inadequate infrastructure to insufficient investmentcontinue to hinder the performance of distribution networks (Egbue& Long, 2012; Mustapha & Adepoju, 2017).

The 8-Mile Feeder in Calabar, operated by the Port Harcourt Electricity Distribution Company (PHED), exemplifies the infrastructural and operational problems faced by many urban distribution systems across sub-Saharan Africa. Serving a diverse customer baseincluding residential, commercial, and light industrial consumersthe feeder has experienced significant reliability deterioration in recent years. Consumers frequently report extended outages, unstable voltage conditions, and abrupt disconnections

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caused by overloaded transformers, poor protection coordination, and outdated manual fault isolation methods. These issues collectively erode service quality and trust in utility operations.

In this context, reliability refers to the power system's ability to consistently deliver electrical energy without interruption, accounting for both the frequency and duration of service failures (Baran & Wu, 1989). Key performance metrics such as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI) are widely used to quantitatively assess service dependability. These indices are recognized globally and form part of regulatory standards for evaluating electricity distribution performance (IEEE, 2012; CEER, 2016).

Simulation tools like the Electrical Transient Analyzer Program (ETAP) provide a robust digital platform for analyzing electrical distribution networks under various loading and fault conditions. ETAP is widely adopted for power flow simulations, fault current studies, protection coordination, and reliability assessment (ETAP, 2023; Raghavan & Subramaniam, 2017). In this study, a digital model of the 86-bus, 11kV 8-Mile feeder network was developed in ETAP to evaluate its reliability performance. The simulation focused on identifying weak points in the system, quantifying reliability indices, and proposing optimization strategies aimed at improving system stability and minimizing energy not supplied (Toma & Chicco, 2012; NERC, 2021). Through this methodology, data-driven insights were obtained to guide actionable improvements and policy recommendations for enhancing the resilience of Nigeria's urban distribution networks.

II. SIMULATION ENVIRONMENT

Modeling and analysis were conducted using ETAP v19.0.1. The software allows for a full-scale simulation of electrical systems, including real-time monitoring and contingency analysis. The 86-bus network was modeled using single-line diagrams, incorporating actual load data and geographical bus coordinates. Each system componentline segment, transformer, circuit breakerwas tagged with appropriate electrical parameters such as impedance, X/R ratios, and load capacity.

2.1Reliability Indices Used in Distribution System Evaluation

Reliability evaluation in power distribution systems often involves the use of well-established quantitative indices to measure the frequency, duration, and impact of service interruptions. These indices are commonly categorized into customer-oriented, load-oriented, and energy-oriented indices, each serving a specific evaluative purpose in determining system dependability (IEEE, 2012; Toma & Chicco, 2012). In this study, key reliability metrics such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI) are utilized to assess the performance of the 11 kV 8-Mile Feeder in Calabar, Nigeria. The analysis is based on simulations performed using the Electrical Transient Analyzer Program (ETAP) software, applied to a modeled 86-bus distribution network (ETAP, 2023; Raghavan & Subramaniam, 2017). The results provide actionable insights for identifying critical system weaknesses and optimizing operational strategies for enhanced reliability.

2.1.1 Customer-Oriented Indices

These indices are based on the number of customers affected and provide insights from the end-user perspective.

System Average Interruption Frequency Index (SAIFI)

Measures the average number of sustained interruptions experienced by a customer over a specified period (typically 1 year).

$$\text{SAIFI} = \frac{\sum N_i}{N_T} \quad (1)$$

Where:

N_i: Number of interrupted customers for each interruption event

N_T: Total number of customers served

$$\text{SAIDI} = \frac{\sum(N_i \times r_i)}{N_T} \quad (2)$$

Where:r_i is the restoration time for each interruption event.

Customer Average Interruption Duration Index (CAIDI)

Indicates the average outage duration for customers who actually experienced an interruption.

$$\text{CAIDI} = \frac{\sum(N_i \times r_i)}{N_T} = \frac{\text{SAIDI}}{\text{SAIFI}} \quad (3)$$

Where:

C_N: Number of unique customers interrupted

Average Service Availability Index (ASAI)

Reflects the proportion of time the power supply is available to customers.

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$$ASAI = \frac{\sum \text{Customer Hours Available}}{\sum \text{Customer Hours Demanded}} = \frac{N_T \times \text{Total Hours} - \sum(N_i \times r_i)}{N_T \times \text{Total Hours} NT} \quad (4)$$

Average Service Unavailability Index (ASUI)
The complement of ASAI, representing the proportion of time customers are without power.

$$ASUI = 1 - ASAI \quad (5)$$

These indices are critical in determining the level of reliability experienced by customers and serve as benchmarks for evaluating the performance of the 8-Mile feeder.

2.1.2 Interruption-Oriented Indices (Load-Based)

Unlike customer-oriented indices, these are based on the magnitude of load interrupted and are useful for evaluating the impact of interruptions on system loading.

Average System Interruption Frequency Index (ASIFI)
Estimates the frequency of interruptions per unit of load connected.

$$ASIFI = \frac{\sum L_i}{L_T} \quad (6)$$

Where L_i is the load interrupted due to each outage (in kVA or kW), and L_T is the total load connected to the system under consideration.

Average System Interruption Duration Index (ASIDI): Similar to ASIFI, ASIDI is load-based and computes the average duration for which load is interrupted when a sustained outage occurs. The units of ASIDI are hours or minutes for which load is interrupted.

$$ASIDI = \frac{\sum(L_i \times r_i)}{T_T} \quad (7)$$

Where L_i is the load interrupted due to each outage, r_i is the restoration time, and L_T is the total load connected to the system. ASIDI becomes equal to SAIDI when the load is homogeneously distributed amongst the customers in a system.

2.2.3 Energy-Oriented Indices

These indices quantify the amount of energy not supplied due to interruptions. The most important parameter required for evaluating load and energy-oriented indices is the average load at each load point busbar. The average load (La) is given by:

$$L_a = L_p \times f \quad (8)$$

Where L_p is the peak load demand, and f is the load factor. The average load L_a can also be defined as:

$$L_a = \frac{\text{Total Energy Consumed in Period}}{\text{Duration of Period (hours)}} \quad (9)$$

Energy Not Supplied Index (ENS): The total energy not supplied by the system due to outages is estimated using:

$$ENSI = \sum L_{a(i)} \times U_i \quad (10)$$

Where $L_{a(i)}$ is the average connected load at load point i, and U_i is the average annual outage time at load point i.

Average Energy Not Supplied Index (AENS): The average energy not supplied by the system is estimated using:

$$AENS = \frac{\sum L_{a(i)} \times U_i}{N_T} \quad (11)$$

Where $L_{a(i)}$ is the average connected load at load point i, U_i is the average annual outage time at load point i, and N_T is the total number of customers served in the area.

Expected Interruption Cost Index (ECOST): This index estimates the economic cost associated with power interruptions, considering the value of unserved energy to various customer classes.

Interrupted Energy Assessment Rate (IEAR): This is the cost per unit of interrupted energy.
These indices (EENS, ECOST, IEAR) can be evaluated specifically for each load point or for the overall system.

$$IEAR = \frac{ECOST}{ENS} \quad (12)$$

All of these indices are valuable for evaluating the reliability of an existing distribution system and for providing useful planning information regarding improvements to existing systems and the design of new distribution systems. Moreover, to analyze the sensitivity of reliability indices like EENS or ECOST with respect to the failure rate of different elements, element contributions to that index and their rankings can be used. These rankings can be for a specific load point or for the overall system.

These reliability indices, implemented in ETAP and applied to the 86-bus 11 kV system, form the foundation of evaluating system performance and suggesting improvements in the 8-Mile feeder in Calabar. Their application supports both technical performance review and economic assessment of distribution reliability.

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2.3 Assumptions and Limitations

To ensure a robust analysis, the following assumptions were made:

- Customer loads were assumed to remain constant throughout the simulation period, based on average daily load profiles.
- All protective devices (breakers, fuses, relays) were assumed to function correctly and isolate faults promptly.
- Weather-related outage impacts (lightning, wind) were not explicitly modeled due to limited local data.

Although the simulation environment allows high granularity, certain real-world conditions—like unauthorized network tapping, illegal load additions, and varying fault-clearing efficiencies—could not be fully captured. Nonetheless, the simulation provides a close approximation of operational behavior and failure dynamics.

2.4 Evaluation Criteria

The computed reliability indices were evaluated against performance standards from developed power systems. For example, North American utility averages show SAIFI < 1.1 interruptions/year and SAIDI < 2 hours/year as acceptable benchmarks [10]. Nigerian feeders typically exceed these values by wide margins. The calculated indices for the 8-Mile feeder were compared against such standards to assess the severity of reliability gaps and recommend necessary upgrades.

This study employed the ETAP software to model and analyze the reliability of the 11kV 8-Mile Feeder in Calabar, which falls under the Port Harcourt Electricity Distribution Company (PHED). Reliability assessments were based on operational and maintenance data collected from 2022 to 2024 from PHED substations. The focus was on scheduled outages, forced outages, and component failure patterns.

The following standard reliability indices were used:

1. SAIFI: System Average Interruption Frequency Index
2. SAIDI: System Average Interruption Duration Index
3. CAIDI: Customer Average Interruption Duration Index
4. ASAI/ASUI: Availability/Unavailability Indices

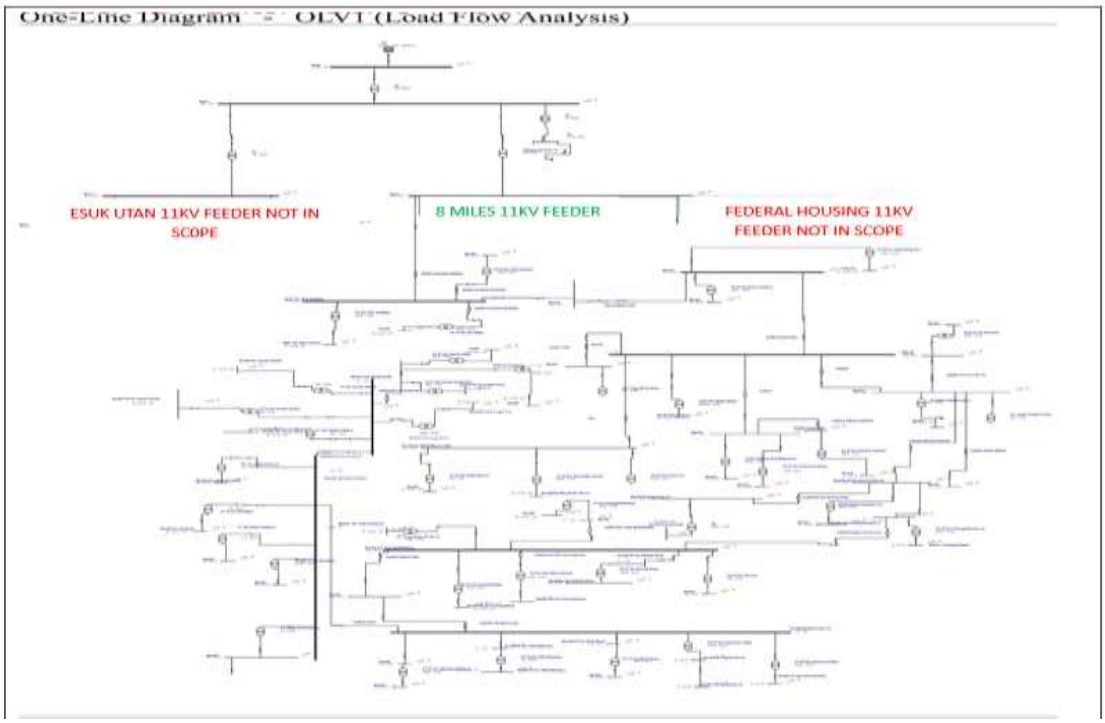

Figure 1:One-line schematic diagram of the 11kV 8-Mile Feeder showing buses, transformers, breakers, and load points using ETAP.

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Figure 1 shows the scheduled vs. forced outages for 2022. Figure 2 presents the outage durations for 2022, while Figure 3 and 4 provide frequency distributions for 2023.

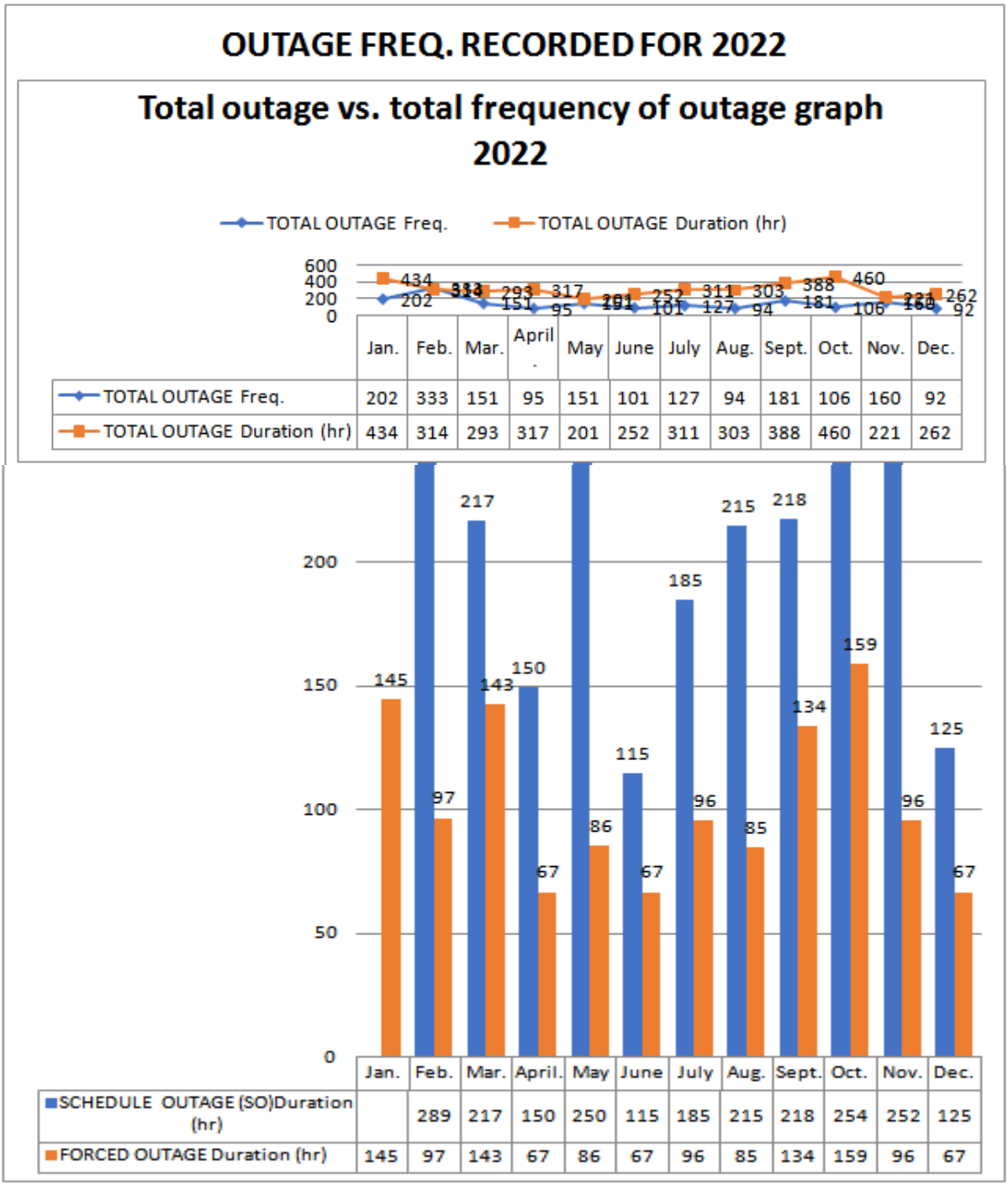

Figure 2: Schedule Outage (SO) Vs Forced Outage (FO) Recorded For 2022

Figure 2: Graph of Summary of Duration of Outage on 11kV 8-MILES FEEDER for 2022

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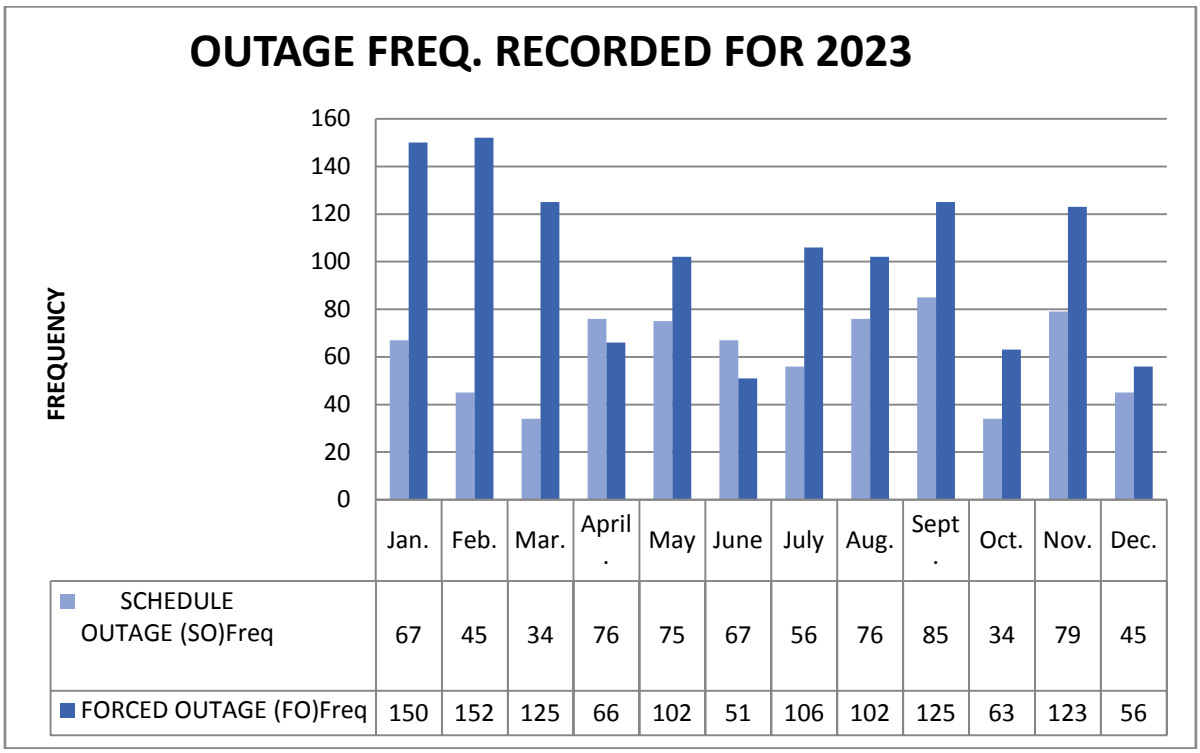

Figure 3: The Bar chart of Outage Frequency Recorded for 2023

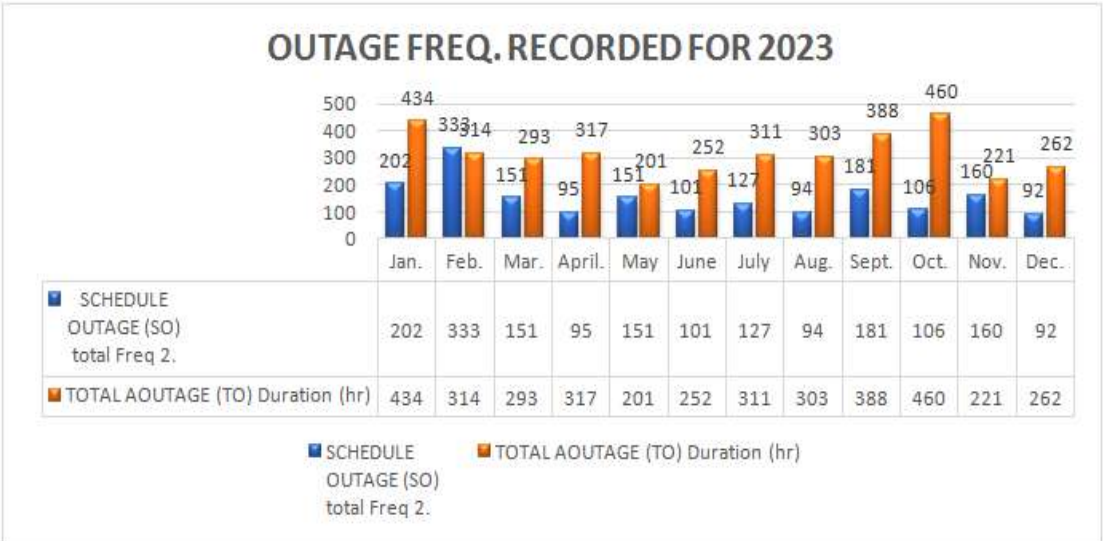

Figure 4: Bar chart of Outage Frequency Recorded for 2023

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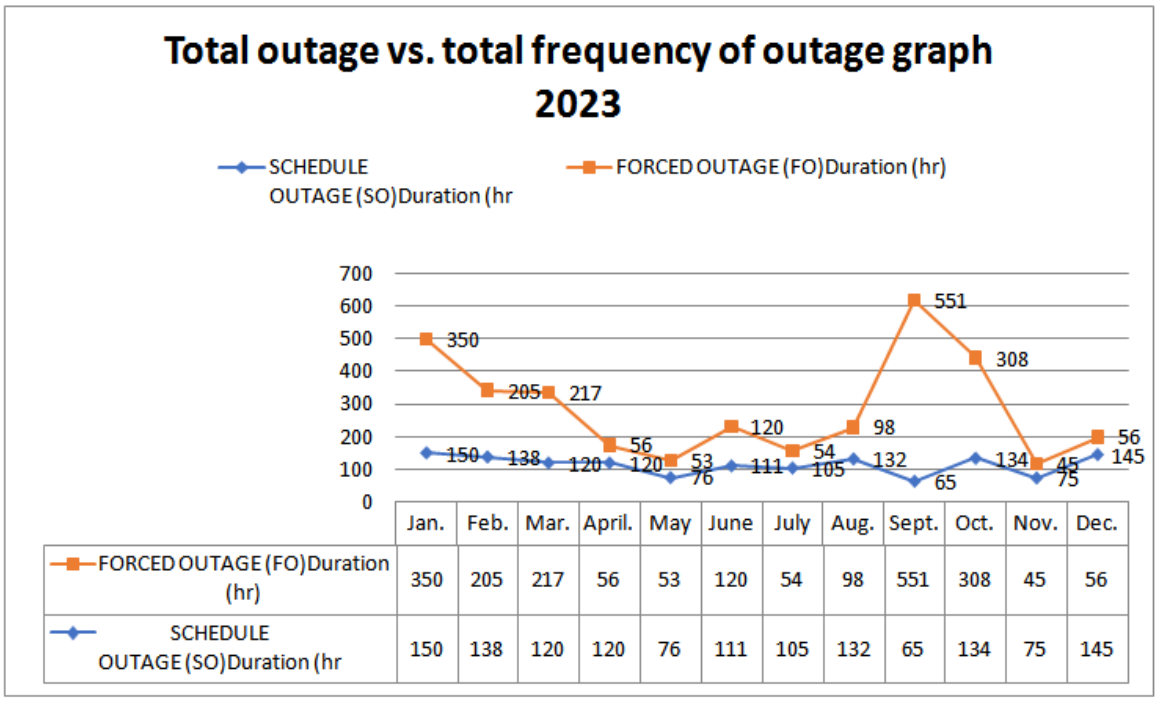
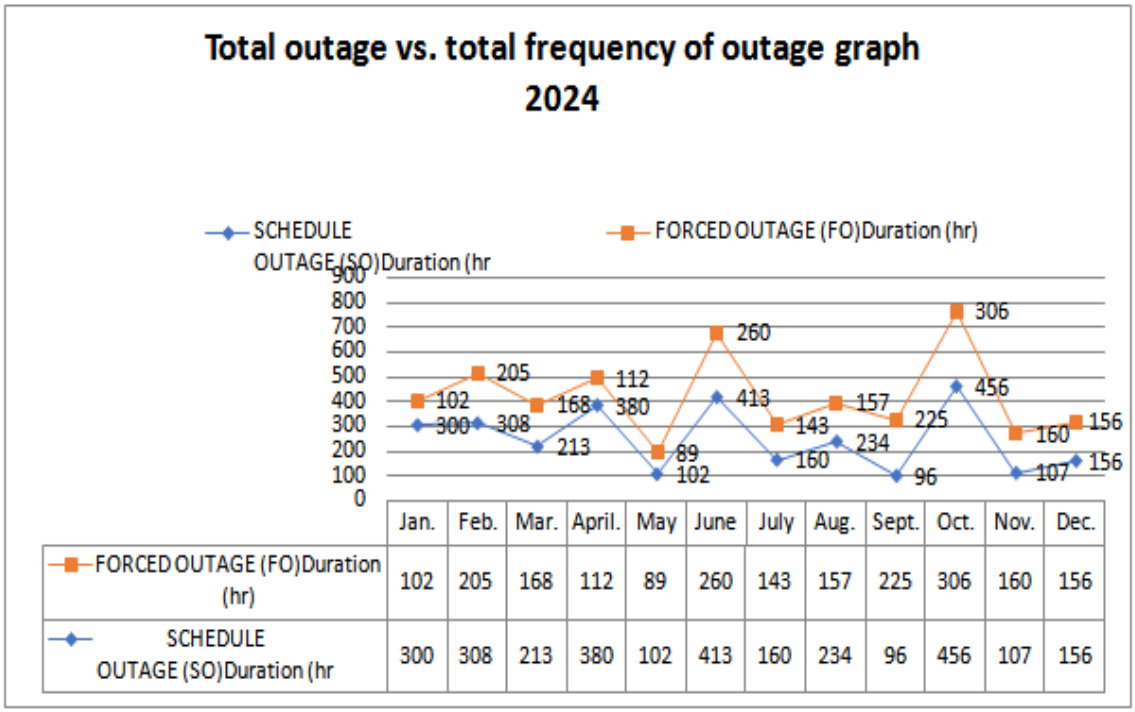


	Jan.	Feb.	Mar.	April.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
FORCED OUTAGE (FO)Duration (hr)	350	205	217	56	53	120	54	98	551	308	45	56
SCHEDULE OUTAGE (SO)Duration (hr	150	138	120	120	76	111	105	132	65	134	75	145

Figure 5: Total outage vs. total frequency of outage graph 2023



	Jan.	Feb.	Mar.	April.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
FORCED OUTAGE (FO)Duration (hr)	102	205	168	112	89	260	143	157	225	306	160	156
SCHEDULE OUTAGE (SO)Duration (hr	300	308	213	380	102	413	160	234	96	456	107	156

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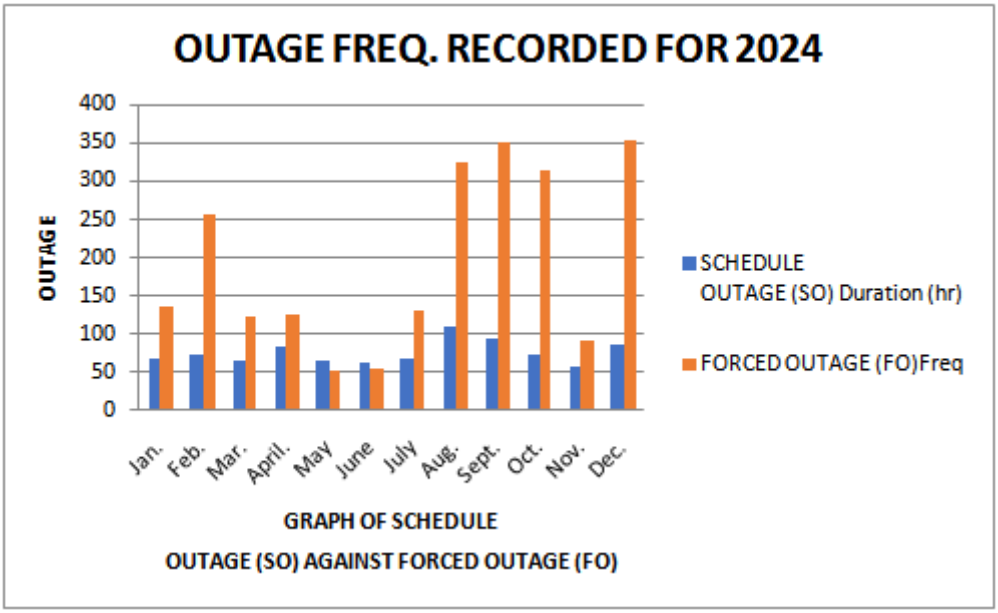

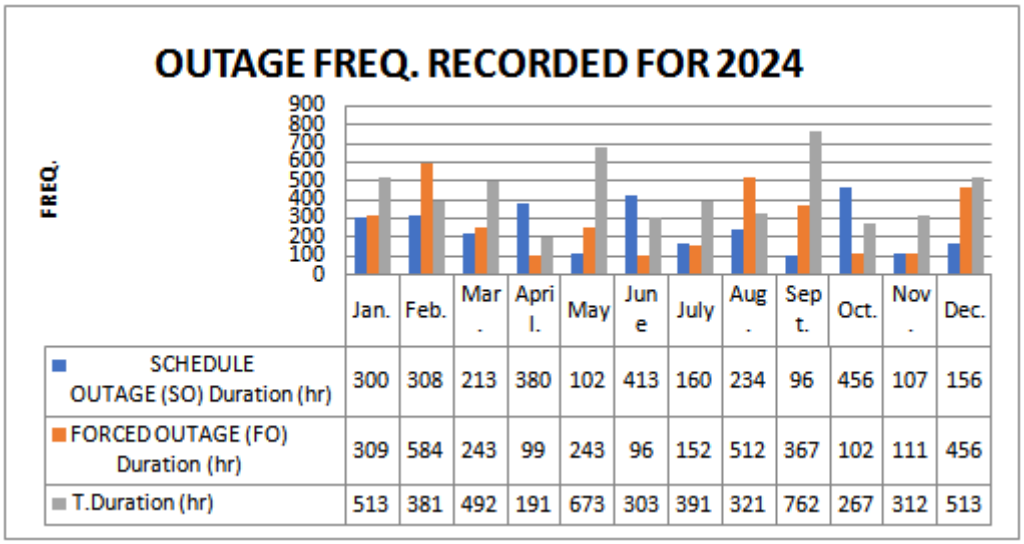

	Jan.	Feb.	Mar.	April.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
SCHEDULE OUTAGE (SO) Duration (hr)	300	308	213	380	102	413	160	234	96	456	107	156
FORCED OUTAGE (FO) Duration (hr)	309	584	243	99	243	96	152	512	367	102	111	456
T.Duration (hr)	513	381	492	191	673	303	391	321	762	267	312	513

Figure 6: (a) Total outage vs. total frequency of outage graph (b) Bar Chart of Outage Frequency Recorded For 2024

Table 4. YEARLY OUTAGE SUMMARY TABLE

YEAR	TOTAL OUTAGE (T.Freq.)	TOTAL OUTAGE (T.Duration (hr))	COMMENT
2022	1793	3756	High
2023	1960	3484	High
2024	2688	4606	high

Table 1: Yearly Outage Summary Table

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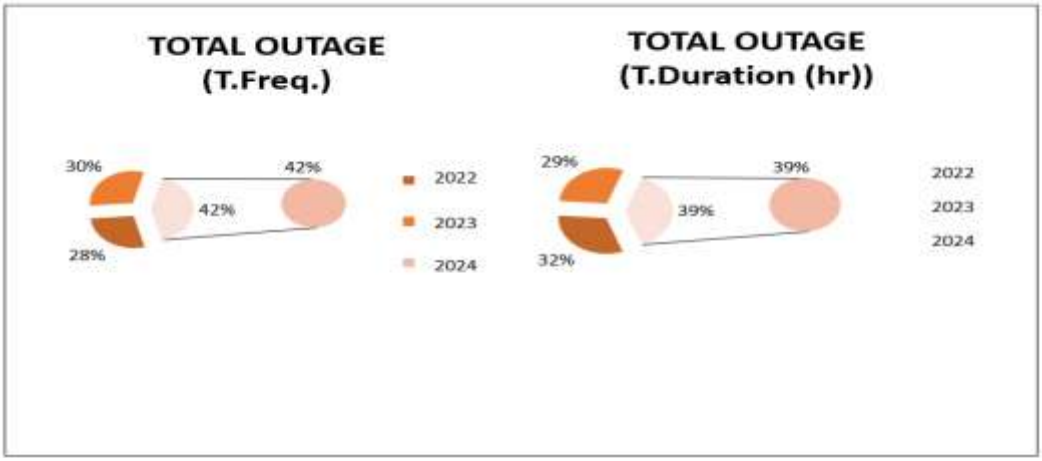

Figure 7: Pie chart of Total Outage (T.Freq.) and Total Outage (T.Duration (Hr))

III. RESULTS AND DISCUSSION

The ETAP simulations yielded the following reliability indices:

3.1 Reliability Indices Results

ETAP simulations generated reliability indices for each network segment and major substation components. Below is a summary of the calculated values

Table 2: Summary of Reliability Indices for the 11kV 8-Mile Feeder,

Index	Calculated Value	Interpretation
SAIFI	6.5 interruptions/year	High – indicates frequent outages per customer
SAIDI	22.4 hours/year	Indicates long durations of interruptions
CAIDI	3.45 hours	Average restoration time per interruption
ASAI	99.74%	Acceptable, but room for improvement
ASUI	0.26%	Reflects average annual unavailability

These values far exceed IEEE Standard 1366 benchmarks (SAIFI < 1.1, SAIDI < 1.5 hrs, CAIDI < 2 hrs). High interruption frequency and extended restoration durations underscore urgent system improvement needs.

3.2 Load and Transformer Performance

- 2024 Load Demand: 4.2 MW
- Installed Capacity: 9 MW across 87 substations

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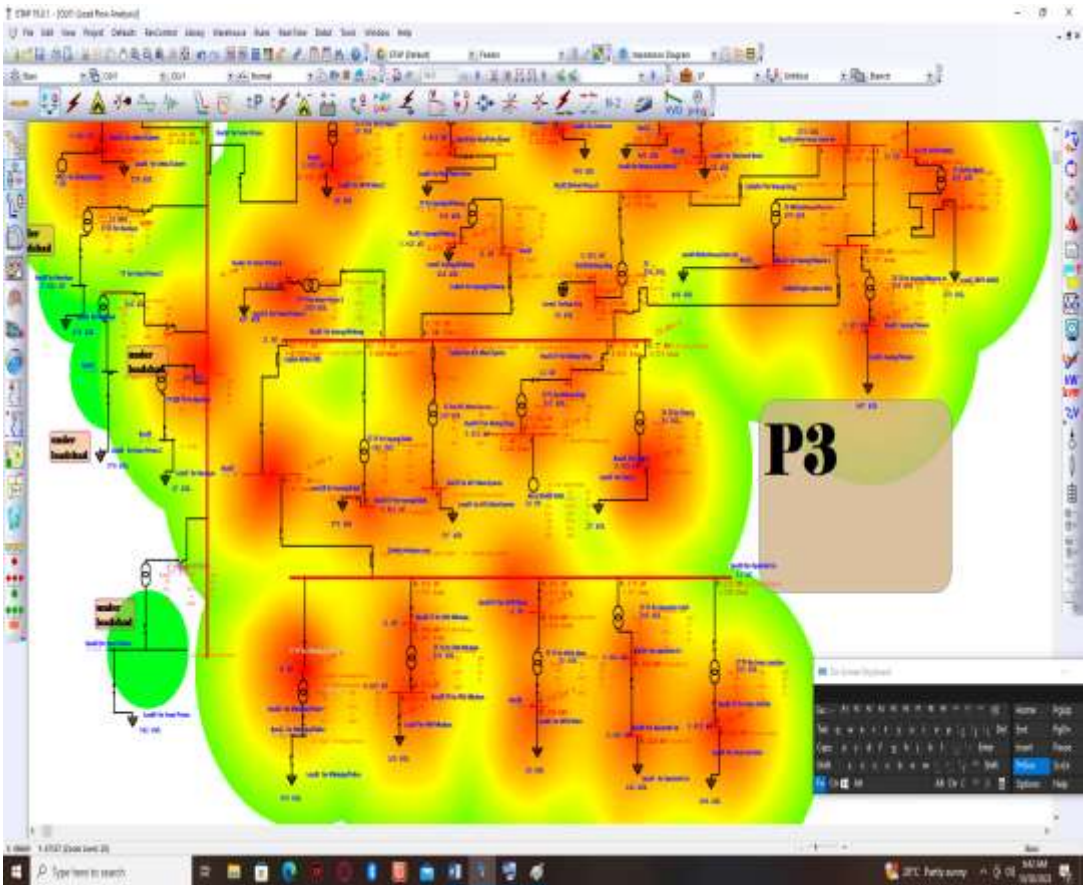

Figure 8: ETAP Screenshot - Section P3 of the 8 Miles 11kV Feeder (Load Flow Analysis)

Figure 8 (from ETAP) reveals severe load imbalances. Overloaded stations (e.g., Esuk Otu1, Palm Estate) operate beyond capacity, while underloaded areas (e.g., Lemna Estate HVDS) exhibit inefficiencies.

3.3 Component Failures

Table 3: Component-Specific Failures and SAIDI Contribution

Component	Failure Rate	Downtime (hrs)	SAIDI (hrs/year)
Transformers	0.015	9	1.8
Conductors	0.020	12	3.0
Breakers	0.008	6	1.2
Switches	0.006	4	0.9

Transformers and overhead conductors contribute the most to system downtime. Key issues include thermal overload, corrosion, and poor maintenance.

3.4 Voltage and Load Flow Issues

Voltage drops below 90% were observed between Bus 7 and 11. Overvoltage (>104%) occurred beyond Bus 25. This instability risks damaging sensitive equipment and affects power quality.

IV. CONCLUSION

This study demonstrates that the 8-Mile Feeder continues to experience significant reliability challenges, despite having surplus capacity to meet demand. The consistently high values of reliability indices such as the System Average Interruption Frequency Index (SAIFI) and the System Average Interruption Duration Index (SAIDI) highlight the feeder's vulnerability to frequent and prolonged service interruptions. These findings underscore the urgent need for comprehensive infrastructure upgrades, the integration of automated control and protection

systems, and the implementation of more effective load forecasting and management strategies. Addressing these issues is critical for enhancing the overall reliability, stability, and efficiency of the distribution network serving Calabar and its surrounding areas.

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