



Causes and Impacts of Power Outages in Overhead Distribution Lines and Propose Strategies for Enhancing their Resilience and Reliability. A Case Study of Zaria, Nigeria

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ABSTRACT

This study investigates the causes and impacts of power outages in the 33kV and 11kV overhead distribution network in Zaria, Kaduna State, Nigeria. Using outage data from 2022 and 2023 obtained from Kaduna Electric (KEDCO) and the Transmission Company of Nigeria (TCN), the study analyzed key reliability indices such as SAIDI, SAIFI, CAIDI, CAIFI, and ASAI. Results showed a notable year-on-year deterioration in network performance across Sabon Gari, Samaru, and Zaria City. For instance, in Sabon Gari, SAIDI increased from 0.41 in 2022 to 0.70 in 2023, and SAIFI rose from 0.08 to 0.12, while Zaria City's CAIFI moved from 0.19 to 0.21. Projections for 2024 further highlight this declining trend, with SAIDI forecasted to reach 1.21 in Sabon Gari, 0.71 in Samaru, and 0.96 in Zaria City. Likewise, CAIFI is projected to rise to 0.88, 0.66, and 1.47, respectively, indicating worsening customer experiences in the absence of urgent intervention. Dominant outage causes were identified as "out-of-service" faults, load shedding, and frequency instabilities. The study also estimated that energy not served (ENS) in 2023 resulted in over ₦526 million in economic losses. Based on these findings, the research recommends preventive maintenance, infrastructure upgrades, deployment of smart grid technology, and better regulatory oversight. This study provides practical insights for improving the reliability and resilience of Zaria's power distribution system.

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INTRODUCTION

In this modern era, electricity has become indispensable, powering our homes, businesses, and industries. However, the reliability of electricity supply can be compromised by various factors, with power outages being a common occurrence (Okorie & Abdu, 2015). Among the myriads of reasons for power disruptions, faults in overhead distribution lines stand out as a significant contributor. Understanding the dynamics of power outages in overhead distribution lines is essential for ensuring a robust and resilient electricity infrastructure (Kor et al., 2020).

At its core, an overhead distribution line comprises a network of poles, conductors, insulators, transformers, and other components, designed to deliver electricity from the generation source to end-users. Despite advancements in technology and maintenance practices, overhead distribution lines remain vulnerable to outages due to several factors (Omoroghomwan et al., 2021).

Weather-related phenomena, such as storms, strong winds, lightning, and ice accumulation, pose a constant threat to the integrity of overhead distribution lines. The exposure of these lines to the elements makes them susceptible to physical damage, leading to line faults and subsequent power outages.

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Additionally, vegetation interference, where trees or branches come into contact with the lines, is a common cause of disruptions, especially in rural or wooded areas (Omoroghomwan et al., 2021).

Beyond environmental factors, equipment failures and human error can also trigger power outages in overhead distribution lines. Aging infrastructure, inadequate maintenance, and substandard construction can contribute to the deterioration of line components, increasing the likelihood of failures. Furthermore, accidental incidents, such as vehicular collisions, construction activities, and vandalism, can disrupt the normal functioning of overhead distribution lines, leading to service interruptions (Kondrateva et al., 2021).

The consequences of power outages in overhead distribution lines extend beyond mere inconvenience, impacting various facets of modern life. Residential consumers experience disruptions in household activities, including lighting, heating, cooling, and electronic devices (Bashkari et al., 2021). Commercial and industrial sectors suffer financial losses due to downtime, decreased productivity, and damage to equipment. Moreover, critical facilities, such as hospitals, emergency services, and communication networks, rely heavily on uninterrupted power supply for public safety and disaster response (Omoroghomwan et al., 2021). Addressing the challenges associated with power outages in overhead distribution lines requires a multifaceted approach. Proactive maintenance strategies, including regular inspections, equipment upgrades, and vegetation management, are essential for enhancing the resilience of the distribution infrastructure. Investments in technology, such as automated monitoring systems, predictive analytics, and smart grid solutions, can improve fault detection and response times, minimizing the impact of outages on consumers (Omoroghomwan et al., 2021).

Furthermore, collaboration among utilities, regulatory bodies, government agencies, and the community is vital for implementing effective outage prevention and mitigation measures. Public awareness campaigns,

education initiatives, and emergency preparedness plans can empower consumers to respond effectively to power outages and reduce their vulnerability (Sayarshad & Ghorbanloo, 2023). The aim of this paper is to investigate the causes and impacts of power outages in overhead distribution lines and propose strategies for enhancing their resilience and reliability in Zaria, Nigeria. So many literature were consulted for the purpose of this study which are related the subject matter among which includes, Vinogradov et al., (2020) this paper presents an analysis of the frequency and causes of outages in low and medium voltage (LV/MV) electric grids, using data from a regional power supply company's network.

In Kondrateva et al., (2021), the researchers conducted an analysis of how climatic factors affect the reliability of overhead transmission lines. Omoroghomwan et al., (2021) the researchers presented an assessment of the vulnerability of components in a typical rural Nigerian power distribution system. Sun et al., (2022) this study introduces a method for classifying outage causes in power distribution systems through machine learning and real-world data. Yusri, (2023) the author introduced a study titled "Quantifying the Impact of Investments on Distribution System Wind Resilience Using Area Outage Rate Curves." Bashkari et al., (2021) in this paper, outage cause detection in power distribution systems based on data mining was presented. Okoye & Omolola, (2019) studied power outage in Nigeria's transmission line and Vinogradov et al, (202) presented analysis on the frequency and causes of power outages on electric grid plus many others researchers such as Casey et al, (2020), Mohmoud et al, (2021), Mahzamia et al, (2020) all presented paper on outage analysis respectively.

PROPOSED APPROACH

This research is adopting methods involving analysis and evaluation of reliability of the distribution network in Zaria Injection Substation network to see how reliability could be improved in the distribution system by incorporating reliability analysis in the systematic planning approach so that optimum reliability is

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achieved. The reliability indices of the present system shall be evaluated, assessed and compared and sees how risk of failure could be mitigated. The reliability indices for the year 2019 are being considered as base year for the case study.

Reliability indices such as SAIFI, SAIDI and CAIDI/MTBF, MTTR, MTTF and Failure Rate can be calculated using equations given in section 2.3.5. These indices provide a relative measure for a group of load points or for the entire system. Analysis will be carried out at distribution network substation Zaria 33/11kV system. But the selection of distribution substation depends on the availability of data and information required for

calculation and analysis. Result from these approaches will be compare with the actual value of reliability indices obtain from year 2019. In this project, we will apply two analytical methods to determine the reliability indices which are Predictive model and Network modelling. The research is conducting in phase's basis as shown in flowchart in Figure 1.

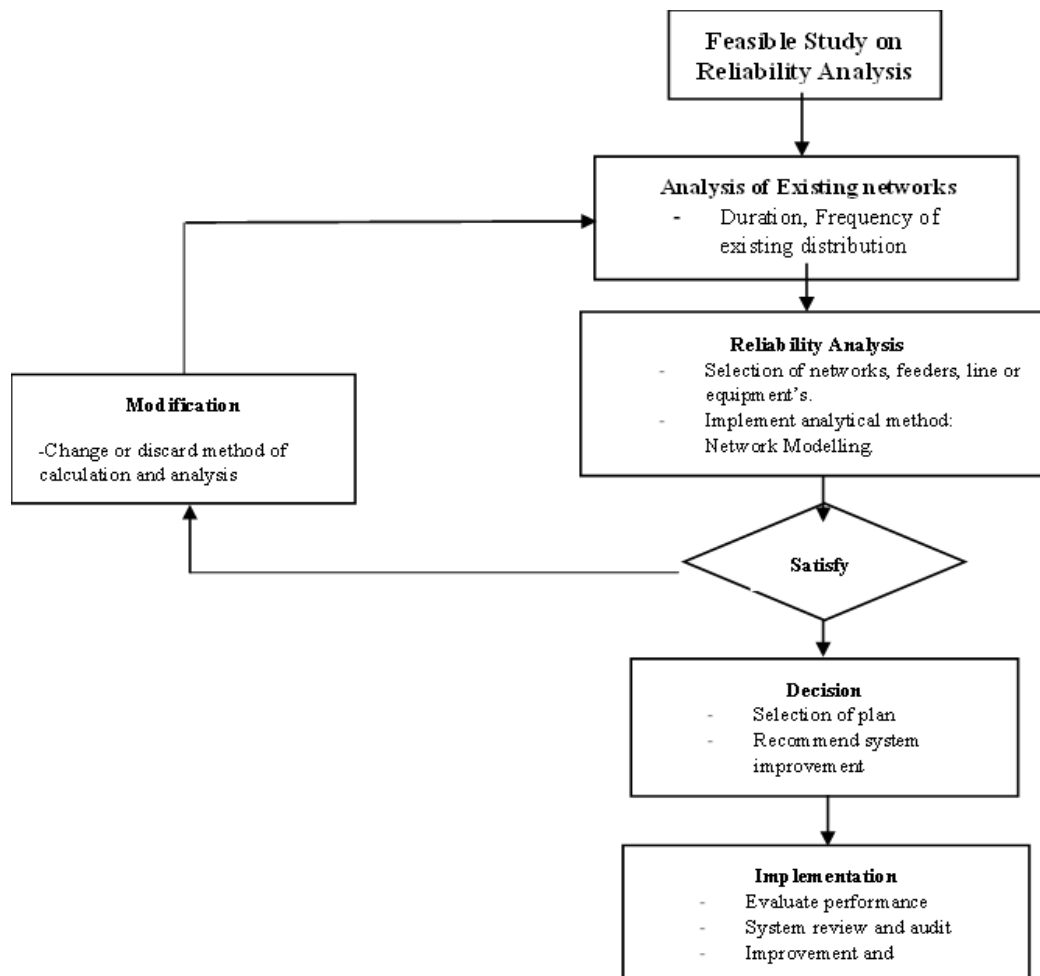


Figure 1: The planning approach for the Reliability Analysis of Distribution Network.

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The Objective Function

The main objective is to find the optimum number and location of sectionalizing switches in order to minimize the customer interruption cost, investment cost of line switches and maintenance cost. Hence, the objective can be expressed as follows.

Minimize Cost= Customer Interruption Cost + Σ Switch cost + Σ Maintenance cost (1)

Subject to constraints,

- Reliability parameters (Duration, Frequency or SAIDI, SAIFI)
- Approved Budget
- Switch locations
- Geography

Where, Customer Interruption Cost are simply revenue lost by the utility companies due to power interruption to the connected customers.

Feasible study on reliability analysis

The feasible study on reliability analysis concentrates on the previous methods used for reliability evaluation and assessment. The existing system network will be bench mark and compare with the previous study and research so that the methods that need to be apply is suitable with the current systems. In order to achieve this, details study and research is required to be conduct by

referring to Zaria distribution system operation and design/Daily Logbook.

The technique required to analyze a distribution system depend on the type of system being considered and depth of analysis needed. Firstly, we need to know the basic evaluation technique then extend to more complex system inclusive of more refined modelling aspects. This research will be based on two methods which are Network modelling including basic evaluation technique for distribution system and analytical model. More concentration on the basic evaluation technique as the existing distribution network system is more compatible with this technique.

Network modelling

Network modelling is the use of series-parallel combinations to reduce the network. It determines the load point indices and aggregates them to get the system wide indices. A radial system basically consists of set of series components like; breakers, lines, switches, transformers and at the end a "Customers". In the series structure both components must be intact for the system to function, "a chain is no stronger than its part" while in the parallel structure both must fail for the system to stop functioning. In this case, all the components are connected in series as shown in Figure 2 and the equations needed to evaluate the basic indices are as follows;



Figure 2: Series Structure

- (a) Average Failure rate of the system:

$$\lambda_s = \lambda_1 + \lambda_2 = \sum_{i=1}^2 \lambda_i \quad (3.1)$$

- (b) Average outage time of the system:

$$r_s = \frac{\lambda_1 r_1 + \lambda_2 r_2 + \lambda_1 \lambda_2 r_1 r_2}{\lambda_1 + \lambda_2} = \frac{\sum \lambda_i r_i}{\sum \lambda_i} = \frac{U_s}{\lambda_s} \quad (3.2)$$

- if $\lambda_1 \lambda_2 r_1 r_2 \ll \lambda_1 r_1$ or $\lambda_2 r_1 r_2$
(c) Average Annual Outage time of the system:

$$U_s = f_s \cdot r_s = \lambda_s \cdot r_s \quad (3.3)$$

Where λ_i the failure rate at node i , r_i is the outage time at node i . In parallel system, the failure modes of the load point involve overlapping outages, i.e. two or more components must be on outage at the

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same time in order to interrupt a load point as shown in Figure 3. It is assumed that the failures are independent and that restoration involves repair or replacement, the equations used to evaluate the indices of the overlapping outage are as shown below.

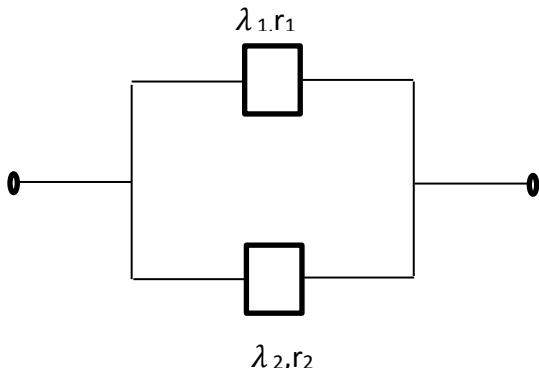


Figure 3: Parallel Structure

- (a) Average Failure rate of the system:

$$\lambda_p = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} = \lambda_2 \lambda_1 \lambda_2 (r_1 + r_2) \quad (3.4)$$

Where $\lambda_1 r_1$ and $\lambda_2 r_2$ usually $\ll 1$

- (b) Average outage time of the system:

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \quad (3.5)$$
- (c) Average Annual Outage time of the System:

$$U_p = \lambda_p r_p \quad (3.6)$$

These are adequate for simple radial systems and more extended indices have to be used for general distribution systems (mixed radial and meshed systems). In this master project, the following alternatives which may improve reliability in the system shall be considered:

- Assessment of the existing network
- Change in the network configuration
- Use of additional sectionalizing switches
- Automation and control facilities via control centre monitoring and supervision.

In this project, we will assume that the distribution system are design and construct as single radial and parallel systems:

- Single radial system
 - 11kV feeder supply direct to customer
 - 33kV feeder for interconnection between substation
- Parallel System
 - 33kV transformer (incomer) connected to two bus bar system (reserve and main) to supply 11kV feeder connected to customer.

Three basic reliability parameters require for analysis:

Average failure rate:

$$\lambda_s = \sum_i \lambda_i \quad (3.7)$$

Average annual outage time:

$$U_s = \sum_i \lambda_i r_i \quad (3.8)$$

Average outage time:

$$r_s = \frac{U_s}{\lambda_s} = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i} \quad (3.9)$$

Analytical modelling

Analytical models are mathematical models that have a closed form solution, i.e. the solution to the equations used to describe changes in a system can be expressed as a mathematical analytic function. An analytical model estimates or classifies data values by essentially drawing a line through data points. When applied to new data or records, a model can predict outcomes based on historical patterns. Block diagrams are widely used in engineering and science and exist in many different forms. For the purposes of system reliability analysis, they can be used to describe the interrelation between the components and to define the system.

In system reliability analysis, we construct a "system" model from these component models. In other words, we are concerned with the construction of a model (life distribution) that represents the times-to-failure of the entire system based on the life distributions of the subsystems, assemblies and/or components ("black boxes") from which it is composed.



Data Analysis Method and Its Advantages

This study employed **Jupyter Notebook** as the primary tool for analyzing outage data collected from Kaduna Electric and the Transmission Company of Nigeria (TCN) for 2022 and 2023. Through the use of **Python programming**, particularly libraries like **Pandas**, **Matplotlib**, and **Seaborn**, key reliability indices such as SAIDI, SAIFI, CAIDI, CAIFI, ASAI, and Energy Not Served (ENS) were computed.

Jupyter Notebook provided a flexible and interactive environment where data could be processed, visualized, and documented simultaneously. This improved the transparency and reproducibility of the analysis. The use of Python allowed for efficient data grouping, trend analysis, and visualization across the three study areas: Zaria City, Sabon Gari, and Samaru.

The approach offered several advantages, including cost-effectiveness (as the tools are open-source), ease of updates, clear visualization of results, and the ability to export analysis in various formats for reporting and presentation. Overall, this method facilitated a structured, transparent, and scalable analytical process aligned with the study's objectives.

Reliability and Validity of Data

To ensure data reliability:

1. Only documented faults verified by engineers and logged by operations personnel were used.
2. Cross-validation of data was done between fault registers and outage summary reports.
3. Incomplete or questionable entries were excluded from the analysis.
4. The sources (KEDCO/TCN logs) are considered credible, as they form the basis for internal utility performance reporting and compliance with NERC standards.

RESULTS AND DISCUSSION

This section presents the results obtained from the analysis of outage data across

Zaria's 33kV and 11kV overhead distribution networks. The chapter begins with an overview of fault trends by district and year, followed by an evaluation of reliability indices for each location. It further discusses the types and frequency of faults, energy not served (ENS), and economic losses associated with service interruptions. The results are then interpreted in relation to the study's objectives and existing literature.

Reliability Failure Frequency

The data collected covered a twenty-four-month outage duration. Like other substations in Nigeria, this substation lacks intelligent devices that can alert the distribution company in the event of equipment failure or any disruption in electricity delivery to customers. This study considers only forced outages and those caused by faults and failures. To avoid extraneous factors, outages due to scheduled maintenance and load shedding were excluded, as these are intentional and not linked to component failures. Including them would make it difficult to identify weak components through analysis. Instead, the focus is on the substation's inability to deliver electricity due to its own deficiencies, despite the availability of power for distribution.

Sabon Gari Reliability Analysis from January to December 2022/2023

The Sabon Gari Figure 4 shows generally higher failure rates in 2023 than in 2022, with a notable peak in March 2023 —the highest single-month rate among all three locations. After starting the year at around 0.12 in January 2023 briefly dips to about 0.07 in April but then rises again to roughly 0.09–0.10 from mid-year onward. Meanwhile, 2022 hovers between 0.07 and 0.10, peaking around 0.10 in November. These elevated 2023 values mirror the upward trends seen in Samaru and Zaria City, suggesting systemic reliability challenges likely linked to weather stress, aging infrastructure, or both.

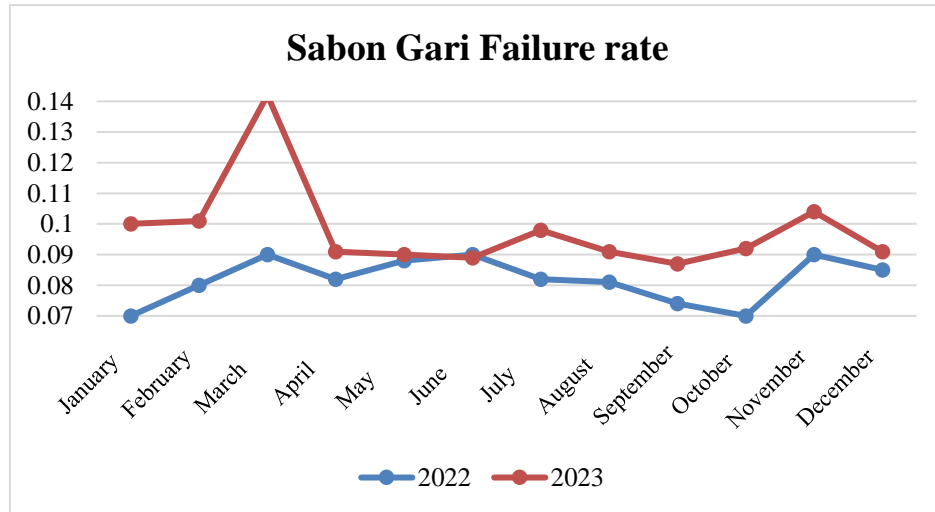


Fig 4: Monthly failure trend of Sabon Gari

Samaru Reliability Analysis from January to December 2022/2023

Figure 5 present monthly failure trend of Samaru. The figure 5 highlights consistently higher failure rates in 2023 compared to 2022, with a pronounced spike in February 2023 (about

0.05 failures per customer) and a secondary peak in March (around 0.10). Monsoon months (June–September) show moderate but persistent outages in 2023 (roughly 0.03–0.04), indicating infrastructure vulnerability during adverse weather. By contrast, 2022 remains relatively stable (mostly 0.02–0.04), with a modest uptick in December (about 0.045).

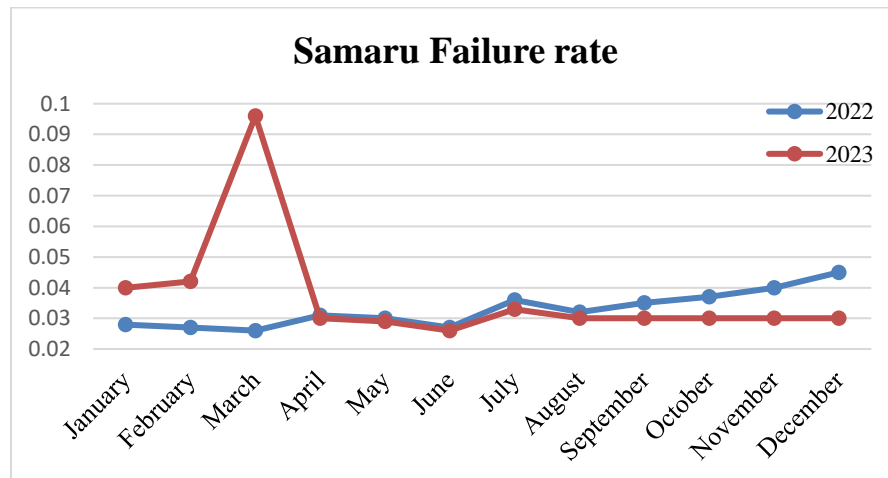


Fig 5: Monthly failure trend of Samaru

Zaria City Reliability Analysis from January to December 2022/2023

Fig 6 present the monthly failure trend of Zaria City. The figure 6 shows a fluctuating failure rate trend for Zaria City, with 2023 generally

experiencing higher failure rates than 2022. The most significant spike in 2023 occurred in November, reaching approximately 0.09 failures per customer, followed by a peak in February (around 0.08). Failure rates remain relatively high in early 2023 but gradually decline from March to June, stabilizing around 0.05. Meanwhile, 2022

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shows a steadier trend with a noticeable increase in July (around 0.06) and a peak in August (approximately 0.075). The rising trend in late 2023, especially in October and November,

suggests worsening system reliability, potentially due to seasonal weather impacts or infrastructure weaknesses.

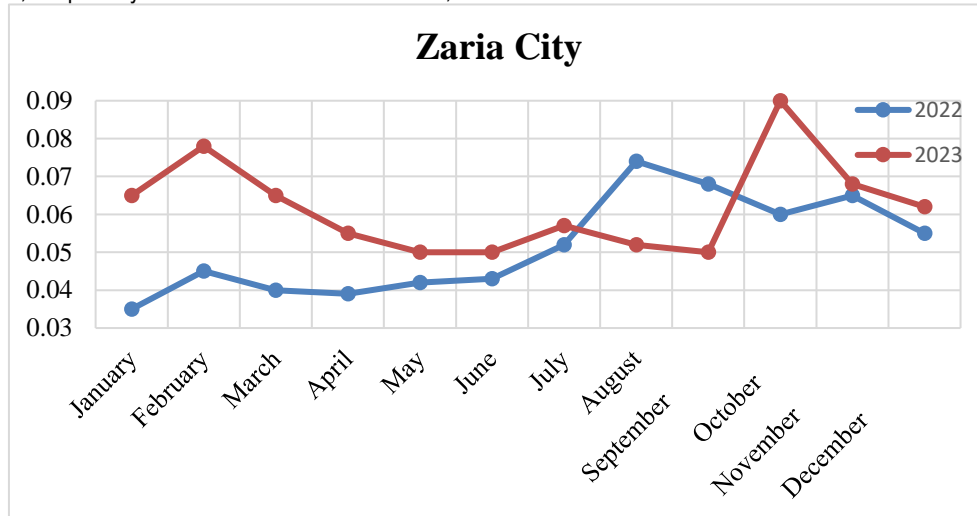


Fig 6: Monthly failure trend of Zaria City

Reliability Indices Analysis

Table 1 present the reliability of the Zaria metropolis distribution network analysis for the period of study.

Table 1: Reliability indices analysis

Area Office	Year	SAIDI	ASAI	ASUI	SAIFI	CAIDI	CAIFI
SABON GARI	2022	0.41	0.999954	0.0000464	0.08	4.97	0.22
SABON GARI	2023	0.70	0.999928	0.0000720	0.12	9.62	0.24
SAMARU	2022	0.22	0.999974	0.0000257	0.03	6.95	0.19
SAMARU	2023	0.40	0.99997	0.0000304	0.06	7.29	0.22
ZARIA CITY	2022	0.31	0.999965	0.0000354	0.05	5.98	0.19
ZARIA CITY	2023	0.55	0.99997	0.0000302	0.10	6.72	0.21

CONCLUSION

Having rigorously explored the trends, causes, and impacts of power outages in Zaria's overhead distribution lines, several key conclusions can now be drawn:

1. Outages Are Systemic, Not Sporadic: The data revealed that outages are not isolated incidents but recurring systemic failures. The network's exposure to

- harsh weather, component aging, and human-related faults reflects broader structural weaknesses in the system.
2. Reliability Indices Show Worsening Performance: A comparison between 2022 and 2023 clearly indicated a downward trend in performance across all districts. For instance, in Zaria City, SAIFI doubled from 0.05 to 0.10, meaning customers experienced twice

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as many outages in 2023. CAIDI and CAIFI values also rose, highlighting not just more frequent outages but slower restoration times.

3. Financial and Social Costs Are Alarming: Energy Not Served (ENS) reached alarming levels, with Sabon Gari recording losses of over ₦180 billion in 2023. This is not just a technical issue—it is an economic and social one. Power instability has far-reaching consequences for health care delivery, education, productivity, and security in the region.
4. The Most Vulnerable Components Are Known: Field assessments and fault categorization clearly identified sagging conductors, ruptured fuses, corroded terminals, and transformer overloads as recurring culprits. These are faults that can be predicted and mitigated with proper maintenance and upgrades.
5. Data Deficiency Limits Proactive Decision-Making: The lack of intelligent monitoring systems (e.g., SCADA) in Zaria means that utility companies often operate reactively, responding to faults only after consumers have been affected. This significantly delays restoration and prevents predictive maintenance.
6. Current Strategies Are Inadequate: Despite routine maintenance, the frequency and intensity of outages have increased. This signals that existing approaches are insufficient and that more robust, data-driven, and technology-enabled interventions are needed.

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