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Reliability Analysis of a Typical 33kV Distribution Network Using MATLAB (A Case Study of Ile-Oluji 33kV Distribution Line)

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***Abstract**: The significance of a dependable and sufficient electrical power supply in societal development cannot be overstated. The distribution of electrical power holds a crucial position in the power system chain, representing the final stage where it reaches consumers. At this phase, various types of losses, including technical loss and theft, among others are associated. The Ile-Oluji community is situated in Ondo State, a south-western part of Nigeria, A region which is host to federal, state, local and private institutions. This community grapples with inconsistent power supply experiencing intermittent trips without a clear originating cause from components in the Ile-Oluji injection substation and its feeder in Ondo. This study analyses the power distribution patterns in this locality focusing on three primary elements (transformer, switch gear and supply line) extracting data on; failures, outage time, numbers of customers and total hours for the year 2019 to 2022. Reliability indices were employed to assess its performance utilising the MATLAB software. Codes were crafted to extract these indices; Availability, Failure rates, Mean Time to Repair (MTTR), Mean Time Between failure (MTBF), System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI). The results show that there is a strong relationship among the reliability indices. It is adduced that the lower the failure rate, the higher the availability of a system. It was concluded that the power system switchgear recorded the highest failure rate amongst the three elements with 0.037341 hrs/year followed by supply line with 0.022541 hrs/year and the transformer with 0.0148 hrs/year in 2022. In corollary, transformer has the highest availability of 0.94441 followed by supply line with 0.81681 and switchgear with 0.78004 in 2021, switchgear recorded the highest failure rates because it is responsible for executing both forced and planned outages.*

***Keywords**: Reliability, Failure, Availability, Supply Line, Transformer, Switchgear, MATLAB Software.*

1. INTRODUCTION

The primary goal of an electric power distribution network system is to efficiently provide uninterrupted electricity to customers while ensuring reliable service at an affordable cost. In recent years, power distribution networks have experienced significant growth in both size and technological advancements. Consequently, utility companies must prioritize meeting customer reliability needs through strategic planning while minimizing operational costs [1]. The term “reliability” is a crucial factor in assessing the ability of the system to consistently provide an adequate supply of electrical energy. Reliability analysis of distribution networks has been a longstanding focus in the electric power industry. Extensive research and studies have been conducted, driven by the growing costs associated with blackouts and fault outages [2].

Indeed, ensuring a more reliable electricity supply is crucial for fostering technological advancements and promoting the development of modern society. It’s a fundamental requirement for powering innovation and improving the quality of life. Reliability in power distribution underpins numerous aspects of our daily lives, from innovation in technology to the overall well-being of communities. Thus, reliability plays a crucial role in power systems as it directly impacts the productivity and efficiency of electricity generation and distribution. A reliable power system ensures consistent access to electricity, benefiting various sectors of the economy and contributing to overall productivity and development. The power system consists of three main subsystems: generation, transmission, and distribution. Electricity is generated in power plants, and then transmitted at high voltages through transmission lines to distribution network substations, where it is further distributed to homes, businesses, and other end-users at lower voltages. This division allows for efficient and effective delivery of electricity to consumers. The distribution system substation typically serves as an intermediary point between the sub-transmission system, which carries electricity at higher voltages like 11 kV, and the final distribution to end-users, where voltages are reduced to the standard household levels of 415/240 V before reaching the consumer’s meter [3].

These voltage reduction and distribution networks ensure safe and reliable electricity supply to homes and businesses. Distribution substations are strategically located near customers to ensure effective and efficient electricity delivery. These substations play a critical role in not only distributing electricity to customers but also in maintaining and monitoring the system. They act as a hub that manages the transition from the primary transmission system to the secondary distribution network, ensuring reliable and timely power supply to end-users while allowing for easier maintenance and monitoring of the distribution system.

Thus, disturbances in the distribution system can lead to outages and affect the reliability of electricity supply to customers. Customer failure statistics often highlight that the distribution system is a significant contributor to supply unavailability, this underscores the importance of continuous improvement and maintenance in distribution networks to enhance reliability and minimize disruptions for end-users [4]. Absolutely, the entire purpose of generating electricity and overcoming transmission challenges is to ensure that it reliably reaches the end-users. Distribution system failures can undermine all the efforts made in power generation and transmission, leading to interruptions in electricity supply to consumers. This highlights the critical importance of maintaining and upgrading distribution networks to ensure the efficient and consistent delivery of electricity to users. Distribution systems are undeniably of utmost importance in the electricity supply chain, as they are responsible for a substantial majority, up to 90%, of customer reliability issues, focusing on enhancing the reliability of distribution systems is the central pathway to ensuring better overall reliability for customers, It underscores the critical role that these systems play in delivering consistent and dependable electricity service [5].

However, this research work is targeted towards analyzing the reliability system of Ile-Oluji substation in Ondo State using MATLAB software for provision of valuable insights for system planning and design in the power network. The research will analyze and assess the reliability of Ile-Oluji distribution network focusing on three primary elements (transformer, switchgear and supply line), extracting data on failures, number of customers, outage time and total hours for a period of 4 years (2019-2022).

2. LITERATURE REVIEW

Electrical power is of vital importance in our modern society. Meeting the challenges of supplying electricity efficiently and cost-effectively, from industrial areas to residential consumers, is crucial for sustaining economic development, technological progress, and the well-being of communities. A country's economic growth and development greatly hinge on the essential presence of an affordable, reliable and dependable power supply [6]. The reliability of a power system is typically defined as its capacity to consistently deliver consumers with a sufficient supply of electricity. Consumers anticipate uninterrupted, around-the-clock access to electric power. Outage occurrences in power distribution systems are nearly intolerable. The primary challenges that arise during such events include substantial losses incurred by companies. These losses are not solely due to stringent regulations but also stem from significant financial setbacks resulting from unsold energy and associated penalties. Furthermore, vulnerabilities may emerge within systems, primarily stemming from either excessive demand placed on a particular configuration or as a consequence of aging infrastructure. When assessing the reliability of power distribution networks, specific factors are taken into account as part of the prediction process [7]. However, System reliability is subdivided into two as shown in the figure below;

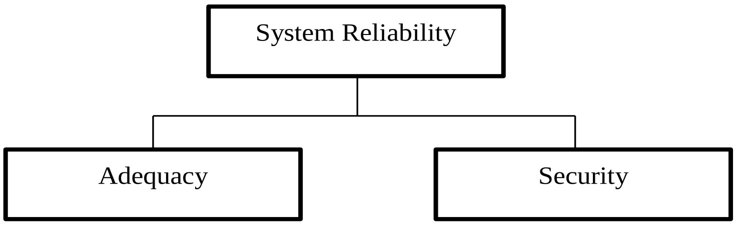

Figure. 1: Subdivision of system reliability [2]

From Figure 1 above, system adequacy pertains to the presence of sufficient infrastructure within the system to meet the demands of consumer load requirements. This encompasses the facilities required for generating enough energy, along with the associated transmission and distribution systems needed to convey this energy to the actual points of consumer demand. Security, on the other hand, is the system's capability to address and manage disruptions that emerge from within the system itself. Consequently, security is intertwined with the system's responsiveness to any disturbances it encounters [8].

2.1 Description of Previous work

Several academic journals have featured publications focusing on the analysis of the reliability of power system efficiency within distribution networks, specifically pertaining to feeders operating at 11 kV, 33 kV and more voltage levels, among this works are [9], who conducted a study titled "Reliability Analysis of a Distribution Network Using ETAP Software." This research involved the utilization of distribution system data and reliability data sourced from DELSUTH to construct a network model using ETAP 16.0. Subsequently, reliability analysis was performed on this network. Additionally, the study applied analytical methods to corroborate the reliability results obtained through ETAP 16.0. These analytical methods specifically focused on interruption frequency and duration as reliability metrics. Upon comparing the research findings with the IEEE standard 1366 of 2011, it became evident that while most of the distribution substations within the DELSUTH network appeared to conform to the IEEE standard in terms of interruption frequency (SAIFI), they fell short of meeting the standard's criteria in terms of interruption duration (SAIDI).

Olumuyiwa *et al.* [10] conducted a research study titled "Reliability Assessment on Secondary Distribution Network" with a specific focus on the Karu Substation in Abuja, Nigeria. This research paper aimed to evaluate the reliability of the Karu substation's electrical system to inform effective system planning and design within the broader power network. To accomplish this, the researchers employed network reduction and analytical methods, and their analysis was carried out using MATLAB 2015 software. The findings of the analysis revealed that the main issues affecting the substation were overloading and transformer failures, both of which contributed significantly to its unavailability. In conclusion, the overall reliability analysis of the distribution system indicated that the substation's performance fell below standard benchmarks, with a reliability rating of 88.46%, signifying a need for improvement.

Akhipemelo *et al.* [11] conducted a study focusing on the reliability analysis of power distribution networks. Their research involved the analysis of various case studies of distribution systems using the Electrical Transient and Analysis Programme (ETAP) software. The primary objective was to minimize interruptions to customers as much as possible. Achieving this goal necessitates a balance between enhancing reliability and concurrently reducing costs, given that distribution system failures are a well-documented cause of interruptions.

Jaya *et al.* [12] published a study that focused on the reliability analysis of an 11 kV distribution feeder, employing Markov Models as their analytical framework. These models were represented in various forms, including both discrete and continuous models across both time and space dimensions. The research paper delved into a detailed examination of the reliability of a crucial 11 kV feeder. The Markov analysis they conducted encompassed an assessment of three key parameters associated with the feeder: voltage levels, frequency, and power flow within the feeder.

Onime *et al.* [13] authored a study titled "Reliability Analysis of Power Distribution System in Nigeria: A Case Study of Ekpoma Network, Edo State." This study delved into the field of reliability engineering in the context of distribution systems, specifically focusing on the Ekpoma Network in Edo State, Nigeria. The essence of reliability engineering in this context involves the collection of outage data and an assessment of the system's design. The collected outage data encompassed detailed information about each instance of system failure.

2.1 Reliability Evaluation

The assessment of the reliability of distribution systems involves two primary approaches namely; Simulation and Analytical methods. [2]

i. Simulation methods for reliability assessment often utilize statistical distributions, such as Monte Carlo simulations, to model and analyze system performance. Monte Carlo techniques can be time-consuming because they require a substantial number of iterations to achieve precise results. This is particularly the case when modeling the fault distribution for each component based on statistical distributions of failure rates and outage times.

ii. Analytical methods for reliability assessment rely on solving mathematical models to evaluate system performance and reliability. The analytical method relies on presumptions regarding the statistical distribution of failure rates and repair durations. Commonly employed evaluation techniques involve utilizing a collection of approximate equations for failure mode analysis or conducting minimum cut analysis. While this approach is more time-efficient compared to the simulation method, it faces challenges when accurately representing repair times.

2.2. Reliability Indices

The primary challenge in assessing the reliability of electrical distribution networks lies in the difficulty of measuring the effectiveness of services delivered in the past. In a typical approach, the impact of service interruptions is summarized and condensed into system performance indices. Certain institutions, such as the Institute of Electrical and Electronics Engineers (IEEE), have put forth various performance indices [14]. These indices typically encompass the average yearly values of either interruption frequency or duration. They aim to assess the seriousness of disruptions based on the loss of load during each interruption and involve weighted indices calculated for specific load points. Among the most frequently used system performance indices are the following:

$$\text{System Average Interruption Frequency Index (SAIFI)} = \frac{\text{Frequency of Outages}}{\text{Total Number of Customer Served}} = \frac{\sum \lambda_i N_i}{N_T} \quad (1)$$

$$\text{System Average Interruption Duration Index (SAIDI)} = \frac{\text{Customer Interruption Duration}}{\text{Total Number of Customer Served}} = \frac{\sum R_i N_i}{N_T} \quad (2)$$

$$\text{Customer Average Interruption Duration Index (CAIDI)} = \frac{\text{Customer Interruption Duration}}{\text{Frequency of Outages}} = \frac{\text{SAIDI}}{\text{SAIFI}} = \frac{\sum R_i N_T}{\sum \lambda_i N_T} \quad (3)$$

$$\text{Customer Average Interruption Frequency Index (CAIFI)} = \frac{\text{Total Number of Interruptions}}{\text{Total Number of Customer Interrupted}} = \frac{\sum \lambda_i}{C_N} \quad (4)$$

$$\text{Average Service Availability Index (ASAI)} = \frac{\text{Customer hours service availablity}}{\text{Customer hours service demanded}} \quad (5)$$

Where C_N = total number of customers who experience a sustained interruption during the period
λ_i = the number of the interruption

R_i = the repair time for each interruption event
N_T = the total number of the customers
N_i = the number of the interrupted customers for each sustained interruption during the related time (period)

3. METHODOLOGY

3.1. Formulation of Evaluation

The reliability analysis was performed within the MATLAB software environment. Data collected over a span of four years (2019 to 2022) at the Ile-Oluji distribution substation underwent a detailed analysis for a period of twelve months each. Over the course of four years, primary data was diligently collected from the logbook at the Ile-Oluji Substation. This data encompassed crucial information such as system downtime (failures), outages, number of customers, total hours, as well as the nature and types of faults that occurred during this period.

3.2 Reliability Evaluation Formulae and Parameters

The reliability analysis formula used for this research paper is explained below;

$$\text{Failure rate } (\lambda)(N) = \frac{\text{Number of times that failure occured}}{\text{Number of unit–hours of operation}} \quad (6)$$

$$\text{Mean Time Between Failures (MTBF)} = \frac{\text{Total System Operating Hours}}{\text{Number of Failures}} \quad (7)$$

$$\text{Mean Time to Repair (MTTR)} = \frac{\text{Total Duration of Outage}}{\text{Frequency of Failure}} \quad (8)$$

$$\text{Availability (A)} = \frac{\text{MTBF}}{\text{MTBF+MTTR}} \quad (9)$$

$$\text{System Average Interruption Duration Index (SAIDI)} = \frac{\sum \text{Customer Interruption Duration}}{\text{Total Number of Customer Served}} \quad (10)$$

$$\text{System Average Interruption Frequency Index (SAIFI)} = \frac{\sum \text{Frequency of Outages}}{\text{Total Number of Customer Served}} \quad (11)$$

$$\text{Customer Average Interruption Duration Index (CAIDI)} = \frac{\sum \text{Customer Interruption Duration}}{\text{Frequency of Outages}} = \frac{\text{SAIDI}}{\text{SAIFI}} \quad (12)$$

3.3 Flowchart of Reliability Indices Calculation

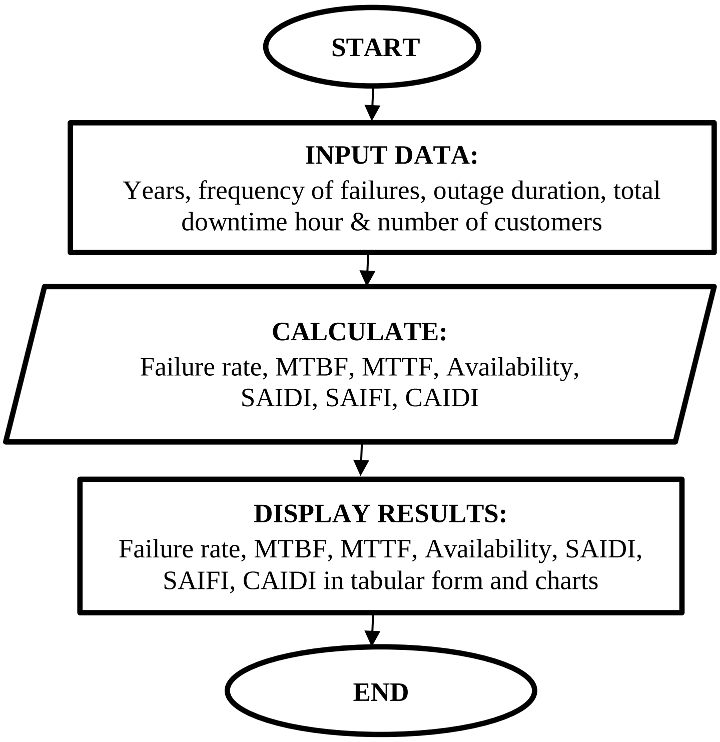

Figure 2: Flowchart for the calculation of reliability indices on Ile-Oluji distribution network

3.4 Algorithm of Reliability Indices Calculation

The pseudo-code algorithm for the reliability analysis is as shown:

1) Input data for supply line, transformer and switchgear
years = [i], failures = [i], outage time = [i], total hours = [i], number of customers = [i]

2) Initialize result arrays
lambda = [i], MTBF = [i], MTTR = [i], availability = [i], SAIDI= [i], SAIFI= [i], CAIDI = [i]

3) Calculate reliability indices
for i = 0 to length(years) - 1
lambda[i] = failures[i] / total hours[i], MBTF[i] = total hours[i] / failures[i],
MTTR[i] = outage time[i] / failures[i], availability[i] = MTBF[i] / (MTBF[i] + MTTR[i]),
SAIDI[i] = (outage time[i] / number of customers[i]) * 1000, SAIFI[i] = failures[i] / number of customers[i],
CAIDI[i] = SAIDI[i] / SAIFI[i]

4. RESULTS AND DISCUSSION

An analysis was conducted on three primary elements of the Ile-Oluji 33 kV injection substation, specifically focusing on the supply line, transformer, and switchgear. The findings for each component are outlined below:

4.1 Supply line

The output in MATLAB simulation is as shown in Table 1;

Table 1: Reliability indices table of Ile-Oluji 33 kV supply line

Year	Failures	Outage Time	Total Hours	Failure Rate	MTBF	MTTR	Availability	SAIDI	SAIFI	CAIDI
2019	243	1600	8784	0.027664	36.148	6.5844	0.84592	1621.1	0.2462	6584.4
2020	135	986	8784	0.015369	65.067	7.3037	0.89908	985.01	0.13487	7303.7
2021	210	1970	8784	0.023907	41.829	9.381	0.81681	1876.2	0.2	9381
2022	198	1350	8784	0.022541	44.364	6.8182	0.86679	1022.7	0.15	6818.2

The supply line recorded the highest failure rate in 2019 while the lowest was in 2020. MTBF was very high in 2020. In the same vein, Figure 3 highlights the salient indices;

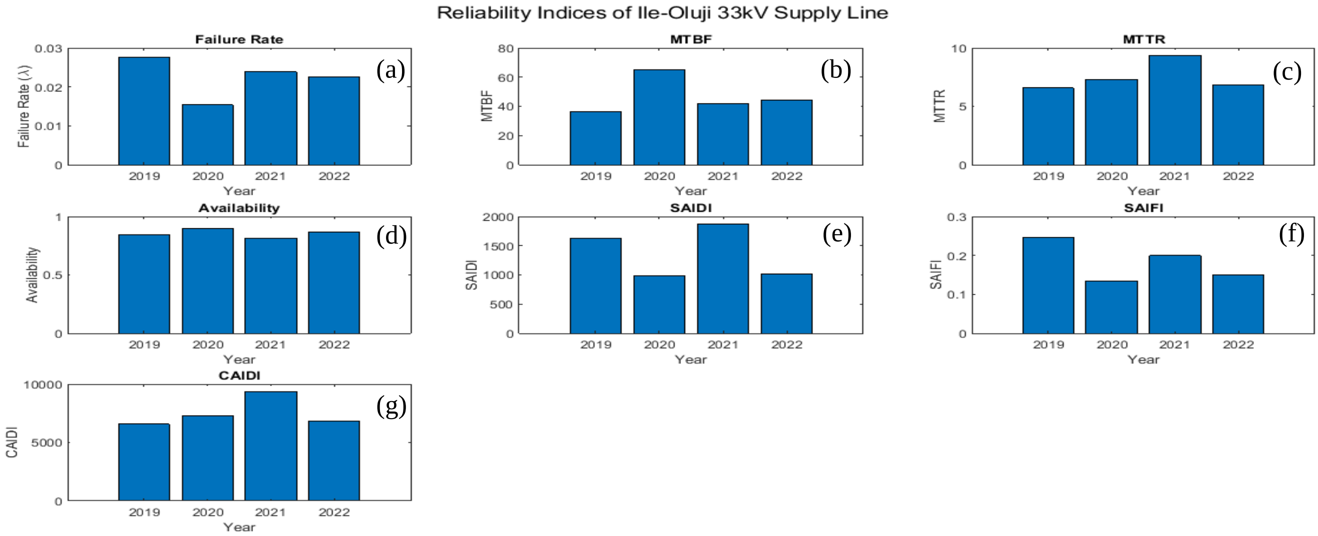

Figure 3: Reliability indices chart of Ile-Oluji 33 kV supply line (a) Failure rate (b) MTBF (c) MTTR (d) Availability (e) SAIDI (f) SAIFI (g) CAIDI

The peak occurrence of line failures was noted in 2019, with the highest Mean Time Between Failures (MTBF) being documented in 2020. The Maximum Time to Repair (MTTR) reached its zenith in 2021. In 2020, the supply line exhibited optimal availability, while System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Duration Index (CAIDI) reached their highest levels in 2021.

4.2 Transformer

The output of the MATLAB simulation is as shown in Table 2

Table 2: Reliability indices Table of Transformer

Year	Failures	Outage Time	Total Hours	Failure Rate	MTBF	MTTR	Availability	SAIDI	SAIFI	CAIDI
2019	170	950	8784	0.019353	51.671	5.5882	0.9024	962.51	0.17224	5588.2
2020	150	800	8784	0.017077	58.56	5.3333	0.91653	799.2	0.14985	5333.3
2021	105	517	8784	0.011954	83.657	4.9238	0.94441	492.38	0.1	4923.8
2022	130	600	8784	0.0148	67.569	4.6154	0.93606	454.55	0.098485	4615.4

From Table 2, the failure rate of the transformer is on the decline while availability keep on increasing and recorded the highest value in 2021. Similarly, Figure 4 highlights the important indices as show below;

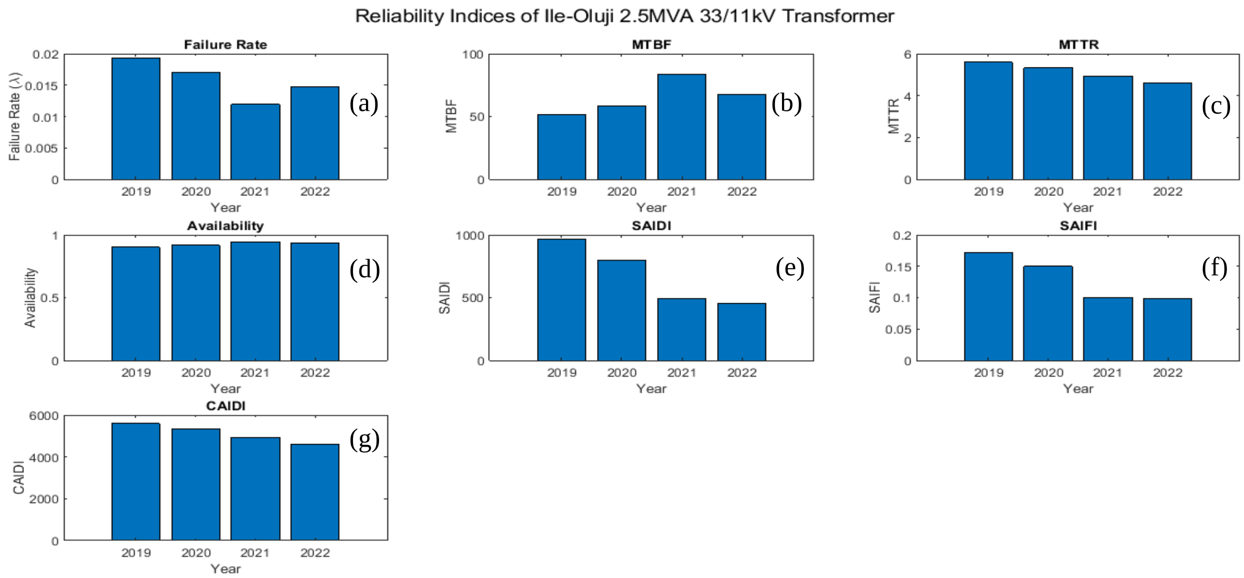

Figure 4: Reliability indices chart of Ile-Oluji transformer; (a) Failure Rate (b) MTBF (c) MTTR (d) Availability (e) SAIDI (f) SAIFI (g) CAIDI

Furthermore, as depicted in Figure 4, the transformers exhibited their highest values for failure rate, MTTR, SAIDI, SAIFI, and CAIDI in the year 2019.

4.3 Switchgear

The output of the MATLAB simulation is as shown in Table 3

Table 3: Reliability indices table of Switchgear

Year	Failures	Outage Time	Total Hours	Failure Rate	MTBF	MTTR	Availability	SAIDI	SAIFI	CAIDI
2019	413	2550	8784	0.047017	21.269	6.1743	0.77501	2583.6	0.41844	6174.3
2020	275	1786	8784	0.031307	31.942	6.4945	0.83103	1784.2	0.27473	6494.5
2021	315	2477	8784	0.035861	27.886	7.8635	0.78004	2359	0.3	7863.5
2022	328	1950	8784	0.037341	26.78	5.9451	0.81833	1477.3	0.24848	5945.1

Table 3 shows that the switchgear was highly available in the year 2020. Also, Figure 5 highlights the salient indices;

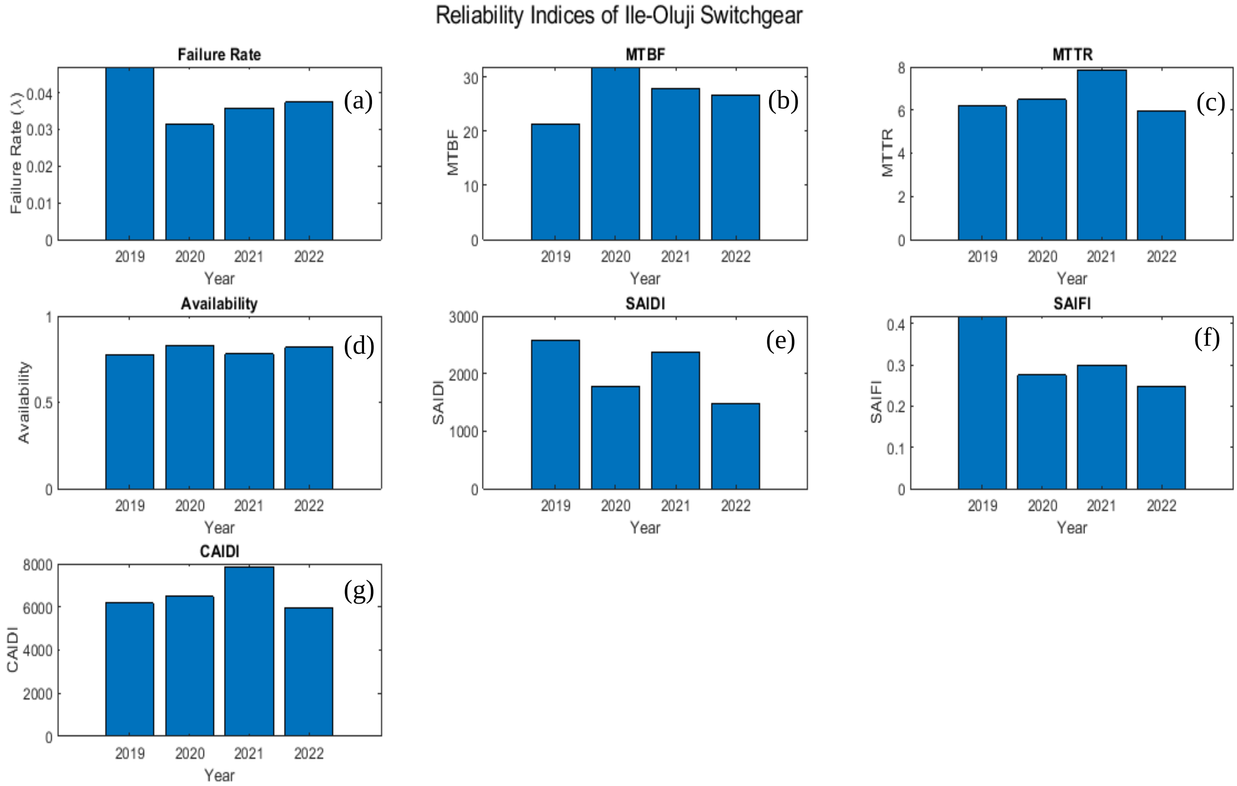

Figure 5: Reliability Indices chart of Ile-Oluji Switchgear.
(a)Failure Rate (b)MTBF (c)MTTR (d)Availability (e)SAIDI (f)SAIFI (g)CAIDI

Also, Figure 5 failure rate was high in 2019, MTBF high in 2020 accounting for high availability the same year under review and the lowest failure rate.

4.4 Comparison of Results

Comparing the SupplyLine, Transformer and Switchgear across all the reliability indices considered for the years 2019 to 2022, hence, the Figure 6 below;

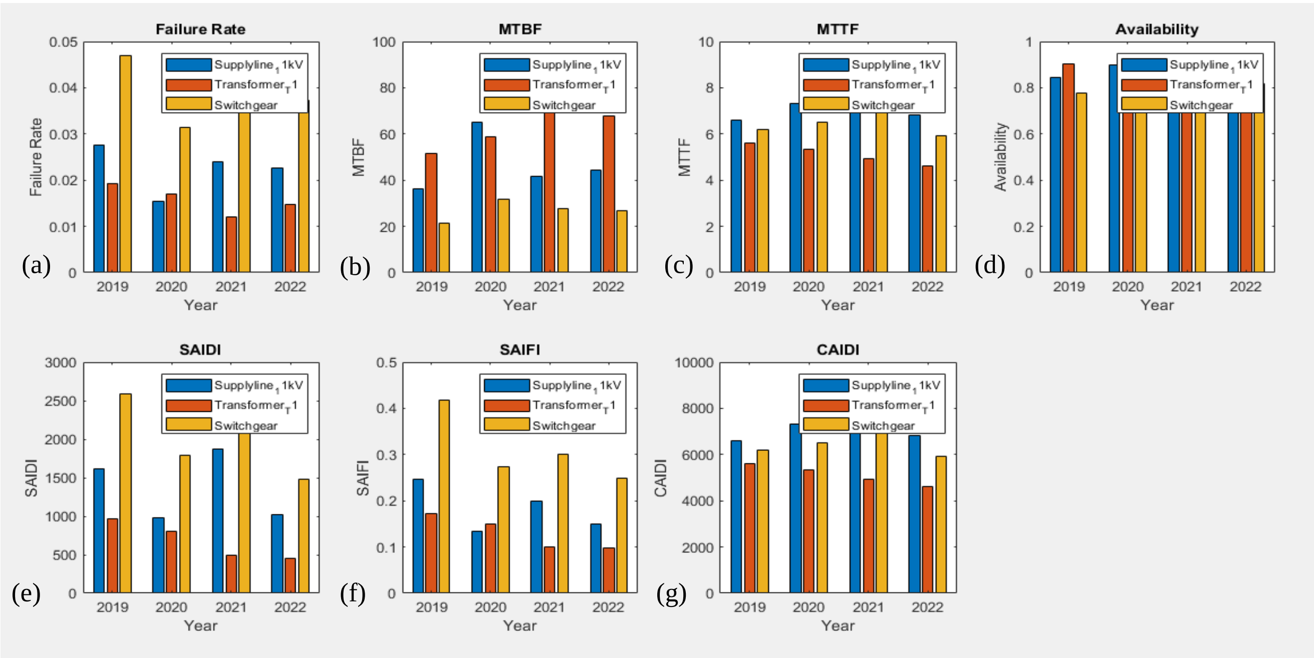

Figure 6: Comparison of results of supply line, transformer and switchgear across all reliability indices: (a) Failure Rate (b) MTBF (c) MTTF (d) Availability (e) SAIDI (f)SAIFI (g)CAIDI

In a comparative analysis spanning several years, Figure 6 illustrates that the switchgear consistently displays the highest failure rate, System Average Interruption Duration Index (SAIDI), and System Average Interruption Frequency Index (SAIFI), followed by the supply line. This pattern is comprehensible as switchgears are responsible for executing both forced and planned outages.

4.5 Discussion of Results

1) Failure rate

Concerning the Failure Rate, the 33 kV supply line exhibited the highest failure rates in both 2019 and 2021, whereas Transformer recorded the lowest failure rate in 2021. The Switchgear maintained a relatively consistent failure rate throughout the years.

2) MTBF (Mean Time Between Failures)

MTBF is highest for Transformer, which means it has the longest time between failures. In 2021, Transformer had the highest MTBF.

3) MTTF (Mean Time To Failure)

The highest Mean Time to Failure (MTTF) is observed for Transformer, indicating an extended average duration before failure. It's worth noting that the values for Transformer are decreasing over the years, suggesting a diminishing level of reliability in terms of time to failure.

4) Availability

In 2022, supply line exhibited the highest availability, signifying increased reliability and availability for that year. Transformer consistently maintained high availability levels across the years. The switchgear availability is inconsistent across the years as it also records the lowest over the years.

5) SAIDI (System Average Interruption Duration Index)

SAIDI gauges the average duration of interruptions. supply line recorded the highest SAIDI values in 2019 and 2021, signifying longer interruptions. In contrast, Transformer exhibited the lowest SAIDI values, indicating shorter interruptions while Switchgear records higher SAIDI across the years.

6) SAIFI (System Average Interruption Frequency Index)

SAIFI assesses the average frequency of interruptions. In 2019, supply line registered the highest SAIFI values, whereas Transformer recorded the lowest SAIFI values in 2021, indicating a lower frequency of interruptions and Switchgear records relatively higher SAIFI across the years.

7) CAIDI (Customer Average Interruption Duration Index)

CAIDI computes the average duration of interruptions per customer. Transformer consistently demonstrated the lowest CAIDI values, suggesting shorter interruptions per customer. Conversely, supply line and switchgear recorded the highest CAIDI in 2021.

In summary, the analysis shows that the performance of the three components (supply line, transformer, and switchgear) varies over the years for the selected parameters. Transformer stands out in terms of reliability, with high MTBF, MTTF, and availability. Switchgear, on the other hand, experiences higher failure rates and longer interruptions. supply line shows relatively consistent performance over the years.

5. CONCLUSION

The results have shown that there is a strong relationship among the reliability indices based on the fundamental equations of failure rate, MTBF, MTTF, Availability, SAIDI, SAIFI and CAIDI. It can be adduced that the lower the failure rate, the higher the availability of a system.

From this research work on Ile-Oluji 33 kV distribution system; reliability indices were accurately formulated and coded in MATLAB environment. It can be concluded that the power system switchgear recorded the highest failure rate amongst the elements with 0.037341 hrs/year followed by supply line with 0.022541 hrs/year and the transformer with 0.0148 hrs/year in 2022.

In corollary, transformer has the highest availability of 0.94441 followed by supply line with 0.81681 and switchgear with 0.78004 in 2021, switchgear recorded the highest failure rates because it is responsible for executing both forced and planned outages.

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