Reliability Assessment Of Electric Power Distribution: A Case Study OF 2x7.5 Mega Volt Ampere, 33kilo volt /11 kilo volt Etete Injection Sub-Station, Nigeria

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Abstract - This research conducted an in-depth assessment of the operational reliability of the 2x7.5 Mega Volt Ampere, 33 kilo Volt/11 kilo volts Etete Injection Substation by examining historical outage records, maintenance documentation, and long-term performance trends. To ensure a thorough analysis, a mixed-methods research design was employed, integrating quantitative statistical techniques with qualitative insights gathered from stakeholder interviews. This dual approach allowed for a holistic evaluation of the substation's performance, identifying both technical and operational factors contributing to system failures. The findings revealed that the substation experienced an average of nine outages per year over a five-year period, with each outage lasting approximately 3.5 hours. A seasonal pattern was observed, with outage frequency signific during the rainy season due to environmental factors such as moisture ingress and lightning strikes. Further analysis indicated that transformers and circuit breakers were the primary sources of disruptions, accounting for nearly 70% of all recorded outages. Predictive modeling based on current operational data projected a concerning 20% increase in outage occurrences within the next three years if no corrective measures or infrastructure upgrades are implemented. These results underscore the critical need for proactive interventions, including enhanced preventive maintenance schedules, equipment upgrades, and the adoption of advanced monitoring systems. By addressing these key failure points, the reliability and efficiency of the Etete Injection Substation can be significantly improved, ensuring consistent power supply and minimizing service disruptions for end-users. The study provides actionable recommendations for utility operators and policymakers to prioritize infrastructure resilience and long-term sustainability in power distribution networks.

Keywords: Reliability, mean time to failure, downtime, availability, substation, distribution network

1. Introduction

Electric power distribution plays a crucial role in providing reliable and uninterrupted electricity supply to consumers, enabling the functioning of residential, commercial, and industrial sectors [1]. The efficient operation of power distribution systems is essential for economic development, societal progress, and improved quality of life. Ensuring a high level of reliability in power distribution has become increasingly challenging due to factors such as growing energy demand, aging infrastructure, and evolving consumer expectations [2].

The reliability assessment of a 33kiloVolts/11kiloVolts injection substation is a crucial aspect of ensuring the uninterrupted and efficient supply of electricity to consumers. A substation acts as a vital link in the power distribution system, where high voltage electricity from the transmission network is stepped down to a lower voltage suitable for distribution to end-users. In the case of an injection substation, it is designed to handle substantial power loads and plays a pivotal role in maintaining a reliable power supply to a specific area or industrial complex [3].

This study focuses on the Etete Injection Substation with the following research objectives:

1.1. Reliability Assessment:

a. What is the operational reliability level of the Etete Injection Substation?

b. How have outage frequencies and durations evolved over time?

1.2. Failure Analysis:

a. What are the primary technical causes of power outages in this substation?

b. Which components (transformers, circuit breakers, protection systems) contribute most to failures?

1.3. Impact Evaluation:

a. How do seasonal variations (particularly rainy season effects) influence substation reliability?

b. What is the projected reliability trend under current operating conditions?

1.4. Improvement Framework:

a. What targeted interventions could enhance the substation's reliability performance?

b. How can maintenance strategies be optimized for critical components?

Reliability is critical in power distribution because it ensures uninterrupted electricity supply, which supports economic activities, healthcare, education, and daily life. Frequent outages disrupt industries, damage electrical appliances, and increase operational costs for businesses. A reliable power system enhances energy efficiency, reduces losses, and improves customer satisfaction.

1.5. Common Causes of Power Outages in Nigeria

a. Aging Infrastructure - Many substations and transmission lines are outdated, leading to frequent failures.

b. Overloading - Poor load management and excessive demand on transformers cause breakdowns.

c. Weather Conditions - Heavy rains, lightning, and storms damage power lines and equipment.

d. Poor Maintenance - Inadequate servicing of transformers, circuit breakers, and switchgear increases failure risks.

e. Vandalism & Theft - Illegal tampering with power infrastructure disrupts supply.

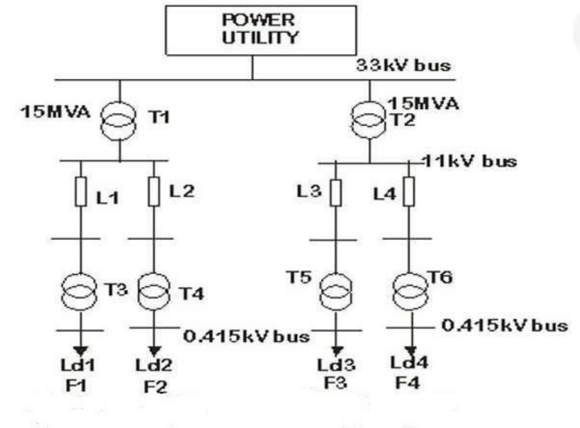

Fig.1. Line Diagram of a 33kV Feeder System Network [3]

Reliability in power distribution refers to the ability of the system to consistently provide a continuous and uninterrupted supply of electricity to consumers. A reliable distribution system minimizes power outages, reduces downtime, and ensures that electrical devices and systems function as intended. However, various factors can impact the reliability of a sub-station, including equipment failures, inadequate maintenance practices, environmental conditions, and operational challenges [4].

The Etete Injection Sub-station, with a capacity of 2x7.5Mega-Volt-Ampere and voltage level of 33kV/11kV, is a critical component of the power distribution network in its operational region. As an important link between the transmission network and the local distribution network, the sub-station receives high voltage power from the transmission lines and steps it down to a lower voltage suitable for distribution to end consumers. The sub-station comprises various equipment and components, including transformers, switchgear, circuit breakers, relays, and control systems, which collectively enable the safe and efficient distribution of electricity [5].

Power outages and disruptions not only inconvenience consumers but also result in significant economic losses for businesses and industries. Critical services such as hospitals, emergency response units, and data centers heavily rely on a reliable power supply to maintain operations. Furthermore, residential consumers rely on electricity for basic necessities and daily activities [6]. Therefore, it is essential to assess the reliability of sub-stations, such as the Etete Injection Sub-station, to identify areas for improvement and enhance the overall performance of the power distribution network.

Reliability assessments also encompass the assessment of the substation's protection and control systems. These systems are responsible for monitoring and safeguarding the substation equipment and ensuring the stability and security of the power supply. Fault detection and isolation, as well as quick response and restoration of power during faults, are critical aspects of maintaining high reliability [7].

To assess the reliability of an injection substation, various methods and techniques can be employed. One common approach is to conduct a failure mode and effects analysis, Failure Mode and Effects Analysis (FMEA), which systematically identifies potential failure modes of the substation components and analyzes their effects on the overall system. This analysis helps prioritize critical components and plan appropriate maintenance and replacement strategies. Another valuable tool in reliability assessment is Failure Tree Analysis (FTA). FTA is a graphical representation of the logical relationships between different failures that could lead to a system breakdown. By analyzing the fault tree, engineers can identify weak points in the substation design or operation and implement measures to mitigate the identified risks [8].

2. Literature Review

Electric power distribution systems play a vital role in delivering electricity from generation sources to end-users, ensuring reliable and efficient power supply. At its core, an electric power distribution system is responsible for the final stage of the electricity supply chain, distributing electrical energy to consumers. The system consists of various interconnected components designed to transmit and distribute electricity at different voltage levels, facilitating its delivery to residential, commercial, and industrial users [9].While previous studies focused primarily on transformer failure rates in Nigerian substations and analyzed rainfall impacts on transmission lines[10], this study provides a more comprehensive reliability assessment by:

a. Integrating both equipment performance and environmental factors specific to the 33kV/11kV voltage level,

b. Incorporating predictive modeling to project future outage trends - an approach notably absent in earlier regional studies.

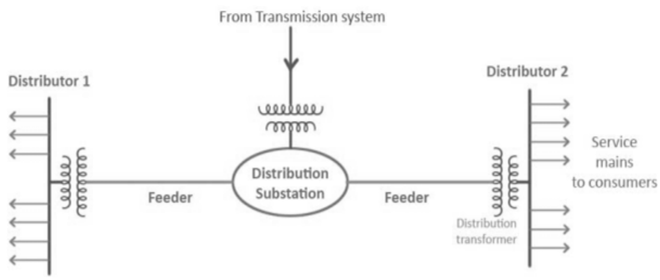

Fig. 2. Diagram of a Power Distribution System [10]

Transformers are key components in the distribution system, serving to step down the voltage from transmission levels to the appropriate distribution level. These step-down transformers are typically located at distribution substations, where electricity is received from the transmission system. Distribution substations act as intermediaries between the transmission and distribution networks, stepping down the voltage and distributing the electricity to customers through distribution lines [11].

Distribution lines, also known as feeders, are responsible for carrying electricity from distribution substations to individual customers. These lines can be overhead or underground, depending on the location and infrastructure requirements. Overhead lines are supported by utility poles, while underground lines are buried beneath the ground. Distribution lines are equipped with switches, reclosers, and protective devices to facilitate the isolation of faulty sections and minimize disruptions in the event of faults or outages [12].

At the local level, distribution transformers are installed in neighborhoods or specific areas to further step down the voltage for localized distribution. These transformers serve individual customers or groups of customers, adapting the voltage to match their requirements [13].

Electric power distribution systems can operate in either a radial or network configuration. In a radial configuration, power flows from the distribution substation to customers in a unidirectional manner. This configuration is suitable for areas with a lower density of customers and simpler network designs. On the other hand, a network configuration provides multiple paths for power flow, enhancing redundancy and improving reliability. Network configurations are typically found in densely populated areas or locations with critical power requirements, such as hospitals or data centers [14].

Various stakeholders play crucial roles in the operation and management of electric power distribution systems. Utility companies, also known as distribution system operators, are responsible for the maintenance and operation of the distribution infrastructure. They oversee activities such as network planning, system maintenance, and response to outages or faults. Utility companies are committed to ensuring the efficient and reliable delivery of electricity to customers while adhering to safety regulations and industry standards [15].

Reliability assessment is a fundamental aspect of electric power distribution systems. Assessing the reliability of the distribution system involves analyzing various metrics and indicators that measure the frequency and duration of power interruptions. Metrics such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI) provide quantitative measures of reliability performance. Reliability assessment helps identify weak points in the system, assess the impact of outages on customers, and guide the implementation of reliability improvement strategies.

According to reliability assessment in power distribution systems involves the evaluation of various concepts and metrics that quantitatively measure the reliability and performance of the system [16]. These concepts and metrics provide insights into the frequency and duration of power outages, outage management, restoration times, and overall system reliability. Understanding these key concepts and metrics is essential for conducting effective reliability assessments.

The following are some key concepts and metrics used in reliability assessment:

2.1. System Average Interruption Duration Index (SAIDI)

The System Average Interruption Duration Index (SAIDI) measures the average duration of power interruptions experienced by customers within a specified period. It represents the average outage duration per customer served and provides an indication of the overall reliability performance of the distribution system. SAIDI is calculated by dividing the total duration of interruptions by the total number of customers served.

2.2. System Average Interruption Frequency Index (SAIFI)

The System Average Interruption Frequency Index (SAIFI) measures the average number of power interruptions experienced by customers within a specified period. It represents the average frequency of outages per customer and provides insights into the reliability of the distribution system in terms of the number of interruptions. SAIFI is calculated by dividing the total number of interruptions by the total number of customers served.

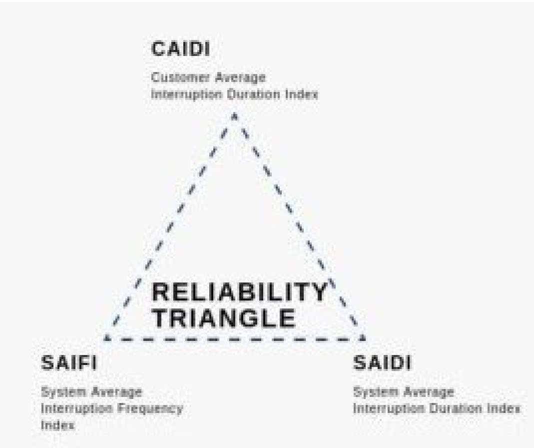

Fig.3. Diagram showing the major reliability indices to assess power distribution networks [16]

2.3. Customer Average Interruption Duration Index (CAIDI):

Customer Average Interruption Duration Index (CAIDI) is calculated by dividing the total duration of all power interruptions by the total number of customers affected during a specified period. CAIDI represents the average outage duration per customer and provides insights into the average time taken to restore power after an interruption. CAIDI can be used to assess the efficiency of outage restoration processes and identify areas for improvement.

2.4. Momentary Interruption Frequency Index (MIFI)

The Momentary Interruption Frequency Index (MIFI) measures the frequency of momentary interruptions, which are brief disruptions in power supply. It quantifies the number of momentary interruptions per customer and helps assess the quality of power supply. MIFI is particularly important for sensitive equipment and industries that require a high level of power quality.

2.5. Customer Minutes of Interruption (CMI)

CMI (Consumer Minutes of Interruption) measures the total number of minutes that customers experience interruptions within a specified period. It combines the duration of all interruptions and the number of customers affected to provide a comprehensive measure of the impact of power outages on customers.

2.6. System Average Restoration Time (SART)

System Average Restoration Time (SART) measures the average time taken to restore power after an interruption. It provides insights into the efficiency and effectiveness of the restoration process. SART is calculated by dividing the total duration of all interruptions by the total number of restoration events.

2.7. Customer Interruption Costs

Customer interruption costs refer to the economic impact of power outages on customers. These costs can include direct financial losses, reduced productivity, damage to equipment, and potential customer dissatisfaction. Customer interruption costs are important metrics for assessing the economic implications of reliability issues and guiding investment decisions to improve system reliability.

The Authors evaluated the reliability of 33kV Kaduna Electricity distribution feeders for a period of January 2011 to December 2012 [17]. Mogadishu and Rural Feeder lines showed highest failure rates in the month of November when compared to other feeders. The authors assessed the feeders using monthly, reliability indices of actual energy loss, Forced Outage Hour (FOH), failure rate, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR) as well as their availability. In conclusion, the results are analyzed, discussed and conclusion drawn and future research directions were also recommended.

The researchers carried out a comparative assessment of Etete and Government Reserve Area (GRA) 33kV feeders' data on both systems were collated and analyzed using Microsoft excel for estimation of reliability index [SAIFI, SAIDI, CAIDI and Average Service Availability Index (ASAI)] for a duration of 24 months [18].

The results obtained showed that at 83.4% compared to 69.9% the GRA feeder is reliable than the Etete Feeder. Strategies and Research direction that can be harnessed to improve the Etete Feeder line were suggested.

The authors presented an analytical approach in reliability assessment [19]. The 33/11kilo Volts Line was evaluated; data resulting from 2009 power outage were extracted from the monopolistic operator of Nigeria power system. The research gave valuable insights on the causes and frequency of outage in the particular line and areas of improving the line in terms maintenance and upgrade were highlighted.

3. Materials and Method

The study employs a mixed methods approach, combining quantitative and qualitative techniques for a thorough reliability assessment of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station.

3.1. Data Collection

Quantitative data was gathered through structured surveys (outage frequencies, downtime duration) and historical records (failure logs, maintenance data). Qualitative data was collected via interviews (engineers, operators) and physical observations (equipment condition, operational challenges).

3.2. Reliability Indices Calculation

Key reliability indices—SAIFI (outage frequency per customer), SAIDI (average outage duration), and ENS (energy not supplied)—were computed using historical outage data and real-time performance logs. These metrics provide standardized benchmarks for assessing sub-station reliability.

3.3. Rationale for Method Selection

The mixed methods approach ensures both statistical rigor (quantitative) and contextual depth (qualitative). Quantitative data offers measurable performance trends, while qualitative insights reveal operational and maintenance challenges. This dual approach strengthens findings, supporting actionable recommendations for improving sub-station reliability.

The research design chosen for this study is a mixed methods approach, combining both quantitative and qualitative methods. This approach allows for a comprehensive and nuanced understanding of the reliability assessment of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station. The integration of quantitative and qualitative data provides a more holistic view of the research topic, allowing for a deeper exploration of the various dimensions of sub-station reliability. The quantitative component enables the collection and analysis of numerical data related to sub-station performance, outage frequencies, and reliability indices. This data will be gathered through structured surveys and historical records. On the other hand, the qualitative component involves the collection and analysis of qualitative data through interviews and observations, focusing on stakeholder perspectives, operational challenges, and maintenance practices. The use of a mixed methods approach ensures that the research findings are robust, reliable, and well-rounded, providing a comprehensive understanding of the reliability assessment of the Etete Injection Sub-Station.

3.4. Data Collection Methods

To gather the necessary information for assessing the reliability of the 2x7.5MVA, 33kv/11kv Etete Injection Sub-Station, a combination of data collection methods will be employed. These methods have been chosen to capture both quantitative and qualitative data, allowing for a comprehensive analysis of the sub-station's reliability. The following data collection methods will be utilized such as Surveys, Interviews, Observations and Document Analysis.

The combination of surveys, interviews, observations, and document analysis ensures a comprehensive and multi-dimensional data collection process. This approach allows for triangulation of data from multiple sources, enhancing the validity and reliability of the findings. The collected data will be analyzed and synthesized in the subsequent chapters to assess the reliability of the Etete Injection Sub-Station and propose recommendations for improvement.

The Etete Injection Sub-Station is a 2x7.5MVA, 33kV/11kV sub-station located in a defined geographical area. It serves as a crucial node in the distribution network, responsible for injecting power into the local distribution grid. The sub-station consists of various components, including transformers, circuit breakers, switchgear, protection devices, control systems, and associated infrastructure. These components work together to ensure the reliable and efficient transfer of electricity from the transmission system to the distribution network. The Benin Electricity Distribution Company (BEDC) is responsible for distributing electricity to consumers in four states in Nigeria: Edo, Delta, Ekiti, and Ondo. The Etete 2×7.5 MVA, 33/11 kV distribution network consists of a single 33 kV sub-transmission line that supplies four separate feeders and is part of the Edo State distribution system. The Etete 33kV feeders are connected to the 132/33kV, 60MVA Power Transformer in the transmission station. The indoor 33kV feeder control panel at Benin Transmission Company for Etete controls and distributes supply to the Etete 33/11kV injection substation, which has four 11kV feeders described above and a dedicated 11kV feeder. The Etete 33kV injection substation has two 7.5MVA transformers, and its feeder also feeds the Stella Obasanjo injection substation (33/11kV). This substation further feeds four areas: Stella Obasanjo 11kV, Country Home 11kV, Akai 11kV, and Arugba 11kV.

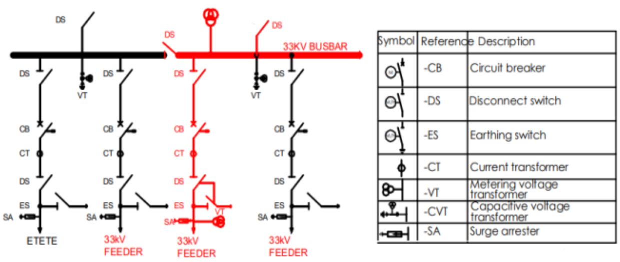

Fig. 4. Single line diagram showing the main components of Etete injection substation

The Etete Injection Sub-Station is typically connected to the transmission system, receiving high voltage power, which is then transformed and distributed at lower voltage levels to meet the demand of local consumers. The sub-station may also be equipped with communication systems for remote monitoring, control, and data acquisition.

3.5. Reliability Indices Calculation

Failure Rate (λ): This is defined as the basic index of reliability which measure the frequency at which fault occurs in the system.

$$\lambda = \frac{Frequency\ of\ outage\ per\ year\ or\ month}{Total\ hours\ of\ available\ per\ year\ or\ month} \quad (1)$$

3.6. Mean Time to Failure (MTTF)

This is a reliability metrics that defined the function of non-repairable equipment in a given system.

$$MTTF = \frac{1}{\lambda} \quad (2)$$

3.7. Mean Time to Repair or Recovery (MTTR)

This is the average time needed to repair a faulty system or component and bring it back to its full operating state.

$$MTTR = \frac{Total\ System\ Downtime}{Number\ of\ Outages} = \frac{1}{\mu} \quad (3)$$

3.8. Mean Time between Failure (MTBF)

It is the average time interval between consecutive failures of a repairable system or component.

$$MTBF = \frac{Total\ System\ Operating\ Hours}{Number\ of\ Outages} = MTTF + MTTR \quad (4)$$

3.9. Availability (A)

This is the probability that an equipment or system will be available to perform the desired function when needed.

$$A = \frac{Uptime}{Expected\ Uptime} = \frac{\mu}{\lambda + \mu} = \frac{MTBF - MTTR}{MTBF} = \frac{MTTF}{MTTF + MTTR} \quad (5)$$

3.10. Unavailability (Â)

This is the average time interval in which a system or component is not available to perform the required function.

$$\hat{A} = \frac{\lambda}{\lambda + \mu} = 1 - \frac{MTTF}{MTTF + MTTR} = 1 - A \quad (6)$$

3.11. Reliability (R)

This is the probability that a system or device perform a function correctly when needed to do so.

$$R = e^{-\lambda t} \quad (7)$$

3.12. System Average Interruption Frequency Index (SAIFI)

This is the measurement of how many sustained interruptions for an average consumer will experience during the period of a month or year. The estimated number of customers served by the Etete injection substation stands at 2800.

$$SAIFI = \frac{Frequency\ of\ Outage}{Number\ of\ Customers\ Served} \quad (8)$$

3.13. System Average Interruption Duration Index (SAIDI)

This defines the measurement of how many interruption hours an average customer will experience during the period of a month or year.

$$SAIDI = \frac{Total\ Outage\ Duration\ in\ Hours}{Number\ of\ Customers\ Served} \quad (9)$$

3.14. Customer Average Interruption Duration Index (CAIDI)

This defines the average length of an interruption as regard the number of customers affected for a specific period. It is also the average time required to restore supply to the average customer per sustained interruption.

$$CAIDI = \frac{Sum\ of\ Customer\ Interruption\ Duration}{Total\ Number\ of\ Customer\ Interruption} = \frac{SAIDI}{SAIFI} \quad (10)$$

3.15. Average Service Availability Index (ASAI)

This defines the measure of the average availability of the distribution network services to customers.

$$ASAI = \frac{Customer\ Hours\ of\ Available\ Service}{Customer\ Hours\ Demanded} \quad (11)$$

3.16. Average Service Unavailability Index (ASUI)

This defines the measure of the average unavailability of the distribution system services to customers.

$$ASUI = \frac{Customer\ Hours\ of\ Unavailable\ Service}{Customer\ Hours\ Demanded} \quad (12)$$

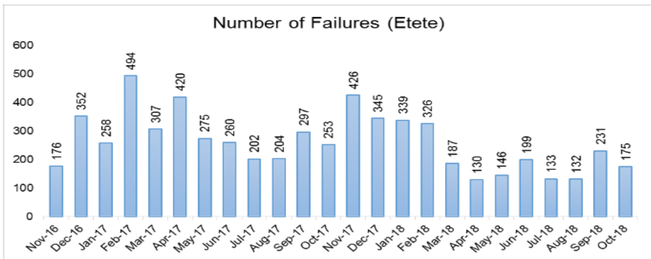

Fig. 5. The recorded number of failures at Etete injection substation throughout the study period

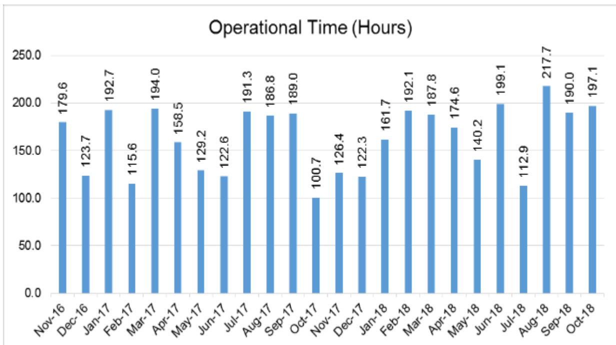

Fig. 6. The recorded operational time (in hours) at Etete injection substation throughout the study period

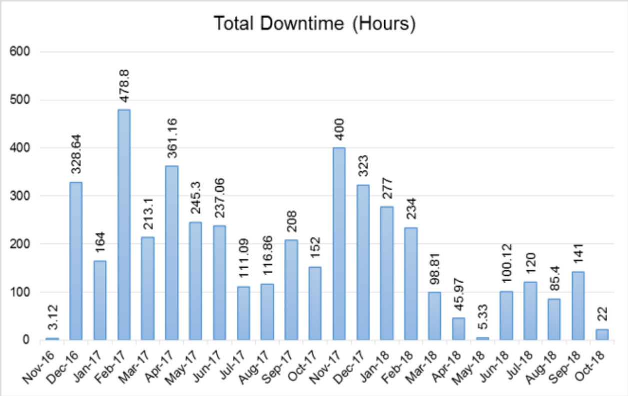

Fig. 7. The recorded total downtime (in hours) at Etete injection substation

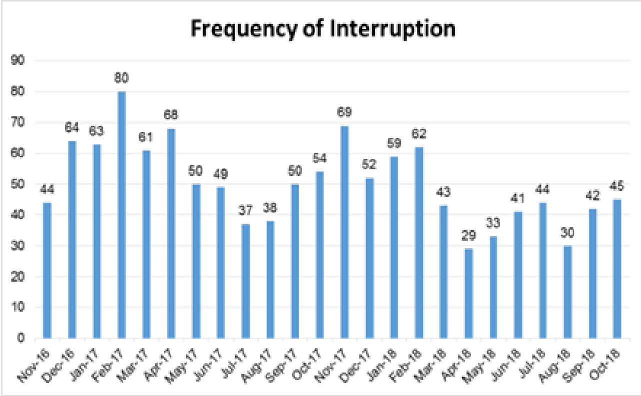

Fig. 8. The recorded frequency of interruption at Etete injection substation

4. Results and Discussion

The table presents a detailed reliability analysis of Etete injection substation by assessing several metrics of the station to determine its level of efficiency throughout the selected study period of November 2016 to October 2018.

4.1. Failure Rate (λ)

$$\lambda = \frac{Frequency\ of\ outage\ per\ year\ or\ month}{Total\ hours\ of\ available\ per\ year\ or\ month} \quad (13)$$

Table 1. Reliability indices recorded at Etete injection substation

Month	Frequency of Interruptions	Operational Time (Hours)	Number of Failures	Total Downtime (Hours)	Total Customer Interruption Duration (Hours)
November 2016	44	179.56	173	3.12	176.44
December 2016	64	123.68	351	328.64	355.68
January 2017	63	192.67	254	164	257.67
February 2017	80	115.60	491	478.8	494.40
March 2017	61	193.95	302	213.1	307.05
April 2017	68	158.52	418	361.16	419.68
May 2017	50	129.20	273	245.3	274.50
June 2017	49	122.64	258	237.06	259.70
July 2017	37	191.30	201	111.09	202.39
August 2017	38	186.82	204	116.86	203.68
September 2017	50	189.00	297	208	297.00
October 2017	54	100.72	253	152	252.72
November 2017	69	126.42	426	400	426.42
December 2017	52	122.28	345	323	345.28
January 2018	59	161.66	339	277	338.66
February 2018	62	192.12	326	234	326.12
March 2018	43	187.81	187	98.81	186.62
April 2018	29	174.60	130	45.97	129.63
May 2018	33	140.20	146	5.33	145.53
June 2018	41	199.14	199	100.12	199.26
July 2018	44	112.88	133	120	132.88
August 2018	30	217.70	132	85.4	132.30
September 2018	42	190.00	231	141	231.00
October 2018	45	197.05	175	22	175.05

Table 2. The Failure Rate (λ) of Etete Injection Substation throughout the Study Period.

Month	Frequency of Interruption	Total Hours Available	Failure Rate (λ)
November 2016	44	179.56	0.2450
December 2016	64	123.68	0.5175
January 2017	63	192.67	0.3270
February 2017	80	115.60	0.6920
March 2017	61	193.95	0.3145
April 2017	68	158.52	0.4290
May 2017	50	129.20	0.3870
June 2017	49	122.64	0.3995
July 2017	37	191.30	0.1934
August 2017	38	186.82	0.2034
September 2017	50	189.00	0.2646
October 2017	54	100.72	0.5361
November 2017	69	126.42	0.5458
December 2017	52	122.28	0.4253
January 2018	59	161.66	0.3650
February 2018	62	192.12	0.3227
March 2018	43	187.81	0.2290
April 2018	29	174.60	0.1661
May 2018	33	140.20	0.2354
June 2018	41	199.14	0.2059
July 2018	44	112.88	0.3898
August 2018	30	217.70	0.1378
September 2018	42	190.00	0.2211
October 2018	45	197.05	0.2284

4.2. Mean Time to Failure (MTTF):

MTTF values can help assess the substation's reliability, with some months showing better performance and longer periods without failures, while others had shorter intervals between interruptions.

$$MTTF = \frac{1}{\lambda} \tag{14}$$

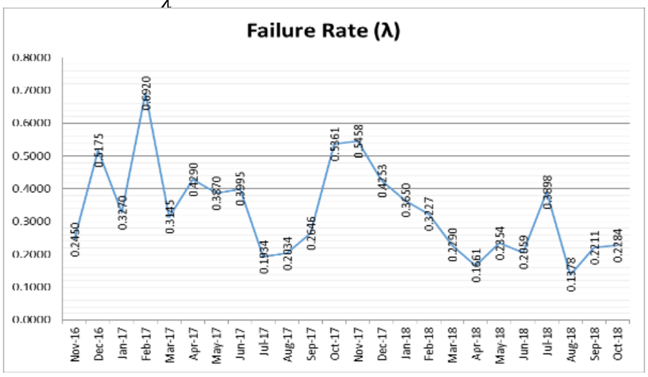

Fig.9. Progression of failure rate indices at Etete injection substation

Table 3. The Mean Time to Failure (MTTF) at Etete Injection Substation Through the Study Period

Month	Frequency of Interruption	Total Hours Available	Failure Rate (λ)	$MTTF = \frac{1}{\lambda}$
November 2016	44	179.56	0.2450	4.0809
December 2016	64	123.68	0.5175	1.9325
January 2017	63	192.67	0.3270	3.0583
February 2017	80	115.60	0.6920	1.4450
March 2017	61	193.95	0.3145	3.1795
April 2017	68	158.52	0.4290	2.3312
May 2017	50	129.20	0.3870	2.5840
June 2017	49	122.64	0.3995	2.5029
July 2017	37	191.30	0.1934	5.1703
August 2017	38	186.82	0.2034	4.9163
September 2017	50	189.00	0.2646	3.7800
October 2017	54	100.72	0.5361	1.8652
November 2017	69	126.42	0.5458	1.8322
December 2017	52	122.28	0.4253	2.3515
January 2018	59	161.66	0.3650	2.7400
February 2018	62	192.12	0.3227	3.0987
March 2018	43	187.81	0.2290	4.3677
April 2018	29	174.60	0.1661	6.0207
May 2018	33	140.20	0.2354	4.2485
June 2018	41	199.14	0.2059	4.8571
July 2018	44	112.88	0.3898	2.5655
August 2018	30	217.70	0.1378	7.2567
September 2018	42	190.00	0.2211	4.5238
October 2018	45	197.05	0.2284	4.3789

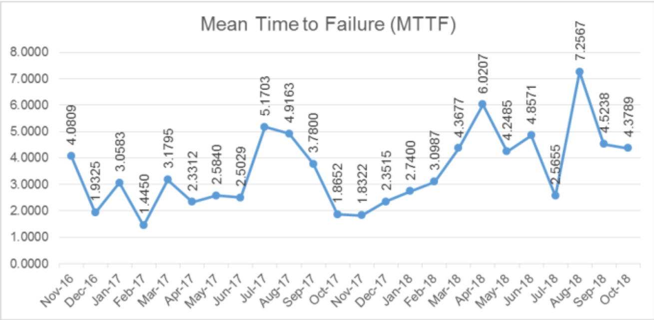

Fig.10. MTTF at Etete injection substation

4.3. Mean Time to Repair or Recovery (MTTR)

Overall, the MTTR data assists in assessing the reliability and resilience of the substation, with some months requiring longer repair times and others demonstrating faster recovery, influencing the overall continuity of electricity supply to consumers. Figure 11 also shows a bar chart comparing the number of failures and downtime (in hours) at the substation.

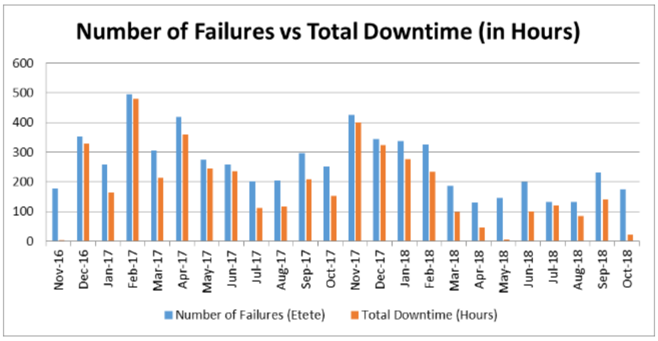

Fig. 11. Number of failures vs. total downtime (in hours)

The formula for mean time to repair or recovery is given below as:

$$MTTR = \frac{Total\ Downtime}{Number\ of\ Failures} = \frac{1}{\mu} \tag{15}$$

Table 4. The Mean Time to Repair or Recovery (MTTR) at Etete Injection Substation Through the Study Period

Month	Number of Failures (Etete)	Total Downtime (Hours)	$MTTR = \frac{1}{\mu}$
November 2016	44	3.12	0.0701
December 2016	64	328.64	5.1350
January 2017	63	164	2.6032
February 2017	80	478.8	5.9850
March 2017	61	213.1	3.4930
April 2017	68	361.16	3.8406
May 2017	50	245.3	4.9060
June 2017	49	237.06	4.8370
July 2017	37	111.09	3.0024
August 2017	38	116.86	3.0752
September 2017	50	208	4.1600
October 2017	54	152	2.8148
November 2017	69	400	5.7971
December 2017	52	323	6.2115
January 2018	59	277	4.6949
February 2018	62	234	3.7741
March 2018	43	98.81	2.2979
April 2018	29	45.97	1.5845
May 2018	33	5.33	0.1615
June 2018	41	100.12	2.4410
July 2018	44	120	2.7272
August 2018	30	85.4	2.8467
September 2018	42	141	3.3571
October 2018	45	22	0.4889

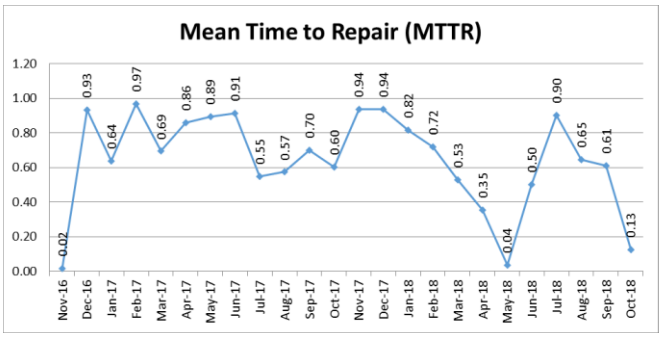

Fig. 12. MTTR at Etete injection substation

4.4. Mean Time Between Failure (MTBF)

Overall, MTBF data assists in assessing the substation's reliability, offering insights into the average time it operates without failures and the efficiency of recovery processes. These insights can inform maintenance and operational strategies to enhance the substation's performance and minimize disruptions.

$$MTBF = \frac{Total\ System\ Operating\ Hours}{Number\ of\ Outages} = MTTF + MTTR \tag{16}$$

Table 5. The Mean Time Between Failures (MTBF) at Etete Injection Substation Through the Study Period

Month	MTTF	MTTR	$MTTF + MTTR$ = MTBF
November 2016	4.0809	0.0701	4.1510
December 2016	1.9325	5.1350	7.0675
January 2017	3.0583	2.6032	5.6615
February 2017	1.4450	5.9850	7.4300
March 2017	3.1795	3.4930	6.6725
April 2017	2.3312	3.8406	6.1716
May 2017	2.5840	4.9060	7.4900

June 2017	2.5029	4.8370	7.3399
July 2017	5.1703	3.0024	8.1727
August 2017	4.9163	3.0752	7.9915
September 2017	3.7800	4.1600	7.9400
October 2017	1.8652	2.8148	4.6800
November 2017	1.8322	5.7971	7.6293
December 2017	2.3515	6.2115	8.5630
January 2018	2.7400	4.6949	7.4349
February 2018	3.0987	3.7741	6.8728
March 2018	4.3677	2.2979	6.6656
April 2018	6.0207	1.5845	7.6052
May 2018	4.2485	0.1615	4.4100
June 2018	4.8571	2.4410	7.2981
July 2018	2.5655	2.7272	5.2927
August 2018	7.2567	2.8467	10.1034
September 2018	4.5238	3.3571	7.8809
October 2018	4.3789	0.4889	4.8678

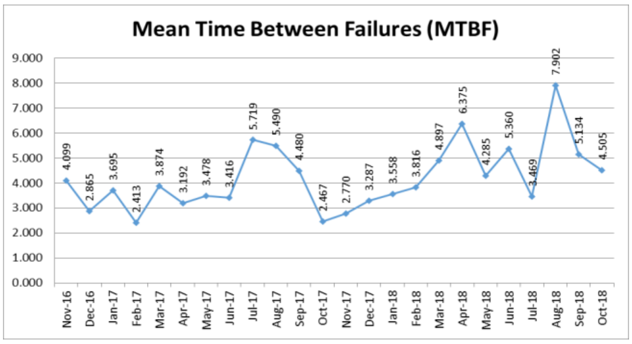

Fig. 13. MTBF at Etete injection substation

4.5. Availability (A)

These figures reflect fluctuations in the substation's availability, combining reliability and recovery aspects, offering valuable insights for decision-making and strategies to enhance overall reliability and availability.

$$A = \frac{Uptime}{Expected\ Uptime} = \frac{\mu}{\lambda + \mu} = \frac{MTBF - MTTR}{MTBF} = \frac{MTTF}{MTTF + MTTR} \quad (17)$$

$$\hat{A} = \frac{\lambda}{\lambda + \mu} = 1 - \frac{MTTF}{MTTF + MTTR} = 1 - A \quad (18)$$

Table 6. The Availability Index at Etete Injection Substation Through the Study Period

Month	MTBF	MTTF	Availability (A)
November 2016	4.1510	4.0809	0.9831
December 2016	7.0675	1.9325	0.2734
January 2017	5.6615	3.0583	0.5402
February 2017	7.4300	1.4450	0.1945
March 2017	6.6725	3.1795	0.4765
April 2017	6.1716	2.3312	0.3777
May 2017	7.4900	2.5840	0.3449
June 2017	7.3399	2.5029	0.3409
July 2017	8.1727	5.1703	0.6326
August 2017	7.9915	4.9163	0.6152
September 2017	7.9400	3.7800	0.4761
October 2017	4.6800	1.8652	0.3986
November 2017	7.6293	1.8322	0.2401
December 2017	8.5630	2.3515	0.2746
January 2018	7.4349	2.7400	0.3685
February 2018	6.8728	3.0987	0.4509
March 2018	6.6656	4.3677	0.6552
April 2018	7.6052	6.0207	0.7917
May 2018	4.4100	4.2485	0.9634
June 2018	7.2981	4.8571	0.6655
July 2018	5.2927	2.5655	0.4847
August 2018	10.1034	7.2567	0.7182
September 2018	7.8809	4.5238	0.5734
October 2018	4.8678	4.3789	0.8996

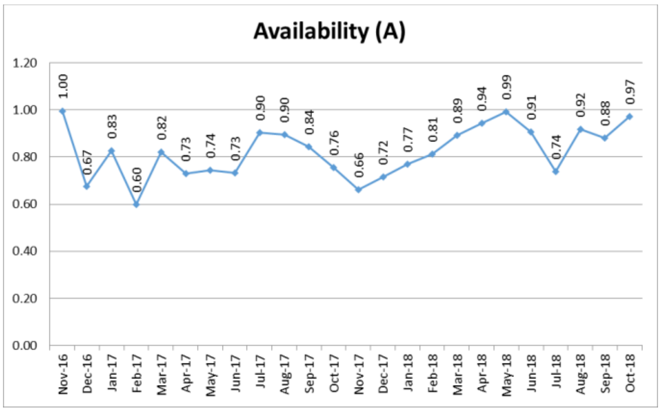

Fig. 14. Availability index at the substation

4.6. Unavailability ($\hat{A}$)

The unavailability index provides a clear picture of when the substation was less operational, highlighting periods of potential service interruptions and emphasizing the importance of reliability and recovery strategies to minimize unavailability and enhance service continuity.

Table 7. The Unavailability Index at Etete Injection Substation through the Study Period

Month	Availability (A)	Unavailability (1-A)
November 2016	0.9831	0.0169
December 2016	0.2734	0.7266

January 2017	0.5402	0.4598
February 2017	0.1945	0.8055
March 2017	0.4765	0.5235
April 2017	0.3777	0.6223
May 2017	0.3449	0.6551
June 2017	0.3409	0.6591
July 2017	0.6326	0.3674
August 2017	0.6152	0.3848
September 2017	0.4761	0.5239
October 2017	0.3986	0.6014
November 2017	0.2401	0.7599
December 2017	0.2746	0.7254
January 2018	0.3685	0.6315
February 2018	0.4509	0.5491
March 2018	0.6552	0.3448
April 2018	0.7917	0.2083
May 2018	0.9634	0.0366
June 2018	0.6655	0.3345
July 2018	0.4847	0.5153
August 2018	0.7182	0.2818
September 2018	0.5734	0.4266
October 2018	0.8996	0.1004

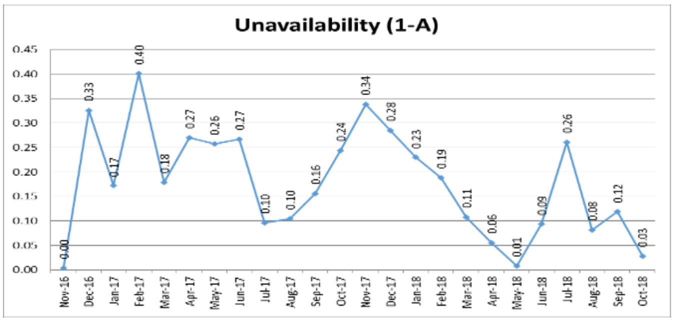

Fig. 15. Unavailability (1 – A) at Etete injection substation

4.7. Reliability (R)

The Reliability Index provides a quantitative measure of the substation's dependability, reflecting variations in performance throughout the study period and highlighting the need for reliability enhancement measures. The Reliability Index values offer valuable insights into the substation's performance, emphasizing the impact of varying failure rates on overall reliability.

$$\boldsymbol{R} = e^{-\lambda t} \quad (19)$$

Table 8. The Reliability Index at Etete Injection Substation through the Study Period

Month	Failure Rate (λ)	Reliability = $e^{-\lambda t}$
November 2016	0.2450	0.7827
December 2016	0.5175	0.5960
January 2017	0.3270	0.7211
February 2017	0.6920	0.5006
March 2017	0.3145	0.7301
April 2017	0.4290	0.6512
May 2017	0.3870	0.6791
June 2017	0.3995	0.6706
July 2017	0.1934	0.8241
August 2017	0.2034	0.8159
September 2017	0.2646	0.7676
October 2017	0.5361	0.5850
November 2017	0.5458	0.5794
December 2017	0.4253	0.6536
January 2018	0.3650	0.6942
February 2018	0.3227	0.7242
March 2018	0.2290	0.7954
April 2018	0.1661	0.8470
May 2018	0.2354	0.7903
June 2018	0.2059	0.8139
July 2018	0.3898	0.6772
August 2018	0.1378	0.8713
September 2018	0.2211	0.8017
October 2018	0.2284	0.7958

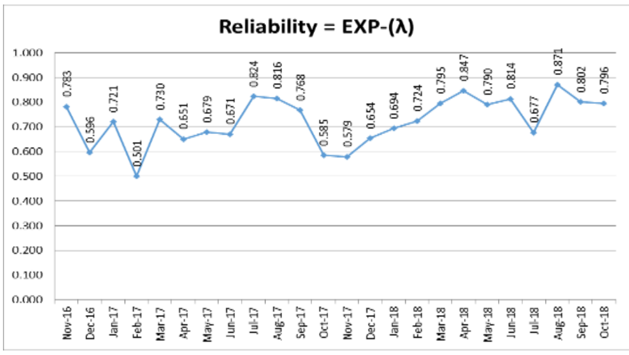

Fig. 16. Reliability index

4.8. System Average Interruption Frequency Index (SAIFI)

SAIFI is a crucial metric for assessing the impact of interruptions on customers, highlighting variations in service quality over the study period, and emphasizing the need for reliability improvements. These SAIFI measurements can inform strategies to minimize interruptions and enhance the reliability of the substation, ensuring a more consistent and satisfactory electricity supply for customers.

$$SAIFI = \frac{Frequency\ of\ Outage}{Number\ of\ Customers\ Served} \quad (20)$$

Table 9. The System Average Interruption Frequency Index (*SAIFI*) at Etete Injection Substation through the Study Period

Month	Frequency of Interruption	Number of Customers Served (Estimated)	SAIFI
November 2016	44	2800	0.0157
December 2016	64	2800	0.0229
January 2017	63	2800	0.0225
February 2017	80	2800	0.0286
March 2017	61	2800	0.0218
April 2017	68	2800	0.0243
May 2017	50	2800	0.0179
June 2017	49	2800	0.0175
July 2017	37	2800	0.0132
August 2017	38	2800	0.0136
September 2017	50	2800	0.0179
October 2017	54	2800	0.0193
November 2017	69	2800	0.0246
December 2017	52	2800	0.0186
January 2018	59	2800	0.0211
February 2018	62	2800	0.0221
March 2018	43	2800	0.0154
April 2018	29	2800	0.0104
May 2018	33	2800	0.0118
June 2018	41	2800	0.0146
July 2018	44	2800	0.0157
August 2018	30	2800	0.0107
September 2018	42	2800	0.0150
October 2018	45	2800	0.0161

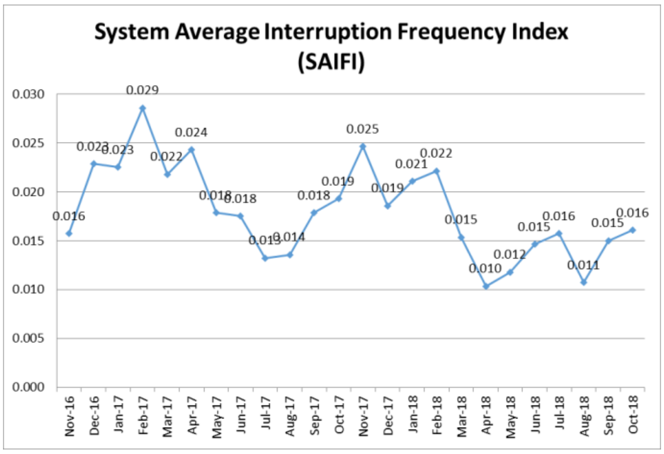

Fig. 17. SAIFI at the injection substation

4.9. System Average Interruption Duration Index (SAIDI)

SAIDI is a critical metric for assessing the impact of interruption durations on customers, highlighting variations in service quality over the study period, and underscoring the need for reliability enhancements to minimize disruptions.

$$SAIDI = \frac{Total\ Outage\ Duration\ in\ Hours}{Number\ of\ Customers\ Served} \quad (21)$$

Table 10. The System Average Interruption Duration Index (*SAIDI*) at Etete Injection Substation through the Study Period

Month	Total Customer Interruption Duration (Hours)	Customers Served (Estimated)	SAIDI
November 2016	176.44	2800	0.0630
December 2016	355.68	2800	0.1270
January 2017	257.67	2800	0.0920
February 2017	494.4	2800	0.1766
March 2017	307.05	2800	0.1097
April 2017	419.68	2800	0.1499
May 2017	274.5	2800	0.0980
June 2017	259.7	2800	0.0928
July 2017	202.39	2800	0.0723
August 2017	203.68	2800	0.0727
September 2017	297	2800	0.1061
October 2017	252.72	2800	0.0903
November 2017	426.42	2800	0.1523
December 2017	345.28	2800	0.1233
January 2018	338.66	2800	0.1210
February 2018	326.12	2800	0.1165
March 2018	186.62	2800	0.0667
April 2018	129.63	2800	0.0463
May 2018	145.53	2800	0.0520
June 2018	199.26	2800	0.0712

July 2018	132.88	2800	0.0475
August 2018	132.3	2800	0.0473
September 2018	231	2800	0.0825
October 2018	175.05	2800	0.0625

4.10. Customer Average Interruption Duration Index (CAIDI):

CAIDI is a vital metric for evaluating the duration of interruptions experienced by individual customers, highlighting variations in service quality over the study period, and emphasizing the need for reliability improvements to minimize customer inconvenience.

$$CAIDI = \frac{Sum\ of\ Customer\ Interruption\ Duration}{Total\ Number\ of\ Customer\ Interruption} = \frac{SAIDI}{SAIFI} \quad (22)$$

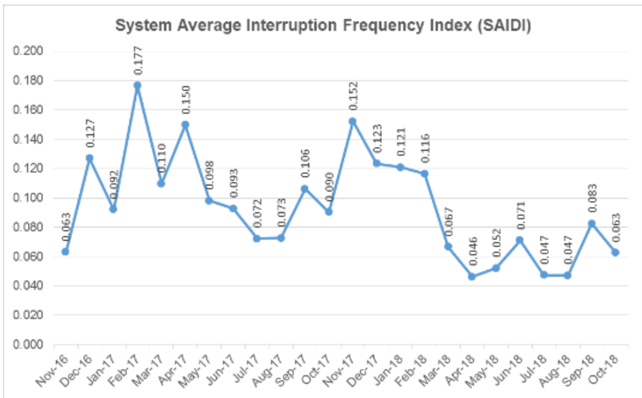

Fig. 18. SAIDI

Table 11. The Customer Average Interruption Duration Index (*CAIDI*) at Etete Injection Substation through the Study Period

Month	SAIDI	SAIFI	CAIDI
November 2016	0.0630	0.0157	4.0100
December 2016	0.1270	0.0229	5.5575
January 2017	0.0920	0.0225	4.0900
February 2017	0.1766	0.0286	6.1800
March 2017	0.1097	0.0218	5.0336
April 2017	0.1499	0.0243	6.1718
May 2017	0.0980	0.0179	5.4900
June 2017	0.0928	0.0175	5.3000
July 2017	0.0723	0.0132	5.4700
August 2017	0.0727	0.0136	5.3600
September 2017	0.1061	0.0179	5.9400
October 2017	0.0903	0.0193	4.6800
November 2017	0.1523	0.0246	6.1800
December 2017	0.1233	0.0186	6.6400
January 2018	0.1210	0.0211	5.7400
February 2018	0.1165	0.0221	5.2600
March 2018	0.0667	0.0154	4.3400
April 2018	0.0463	0.0104	4.4700
May 2018	0.0520	0.0118	4.4100
June 2018	0.0712	0.0146	4.8600
July 2018	0.0475	0.0157	3.0200
August 2018	0.0473	0.0107	4.4100
September 2018	0.0825	0.0150	5.5000
October 2018	0.0625	0.0161	3.8900

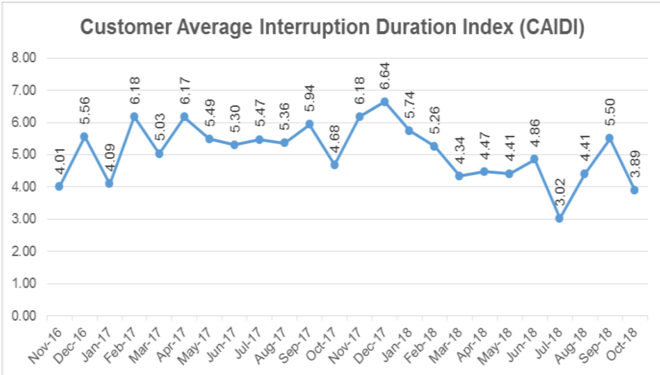

Fig. 19. CAIDI

4.11. Average Service Availability Index (ASAI)

ASAI is a critical metric for evaluating the adequacy of service availability, highlighting variations in performance over the study period, and emphasizing the need for reliability improvements to better meet customer demands.

$$ASAI = \frac{Customer\ Hours\ of\ Available\ Service}{Customer\ Hours\ Demanded} \quad (23)$$

Table 12. The Average Service Availability Index (*ASAI*) of Etete Injection Substation throughout the Study Period

Month	Total Hours Available	Customer Hours Demanded	ASAI	ASAI (%)
November 2016	179.56	720	0.2494	24.9389
December 2016	123.68	744	0.1662	16.6237
January 2017	192.67	744	0.2590	25.8965
February 2017	115.6	672	0.1720	17.2024
March 2017	193.95	744	0.2607	26.0685
April 2017	158.52	720	0.2202	22.0167
May 2017	129.2	744	0.1737	17.3656
June 2017	122.64	720	0.1703	17.0333
July 2017	191.3	744	0.2571	25.7124
August 2017	186.82	744	0.2511	25.1102

September 2017	189	720	0.2625	26.2500
October 2017	100.72	744	0.1354	13.5376
November 2017	126.42	720	0.1756	17.5583
December 2017	122.28	744	0.1644	16.4355
January 2018	161.66	744	0.2173	21.7285
February 2018	192.12	672	0.2859	28.5893
March 2018	187.81	744	0.2524	25.2433
April 2018	174.6	720	0.2425	24.2500
May 2018	140.2	744	0.1884	18.8441
June 2018	199.14	720	0.2766	27.6583
July 2018	112.88	744	0.1517	15.1720
August 2018	217.7	744	0.2926	29.2608
September 2018	190	720	0.2639	26.3889
October 2018	197.05	744	0.2649	26.4852

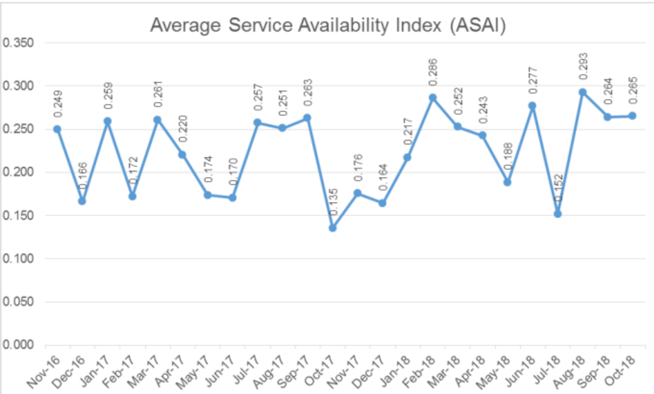

Fig. 20. ASAI

4.12. *Average Service Unavailability Index (ASUI)*

Average Service Unavailability Index (ASUI) is a vital metric for evaluating the average unavailability of service, highlighting variations in performance over the study period, and emphasizing the importance of reliability enhancements to minimize service unavailability and enhance customer satisfaction.

$$ASAI = \frac{Customer\ Hours\ of\ Unavailable\ Service}{Customer\ Hours\ Demanded} = 1 - \text{ASAI} \quad (24)$$

Table 13. The Average Service Unavailability Index (*ASUI*) of Etete Injection Substation Throughout the Study Period

Month	ASAI	ASUI	ASUI (%)
November 2016	0.2494	0.7506	75.06
December 2016	0.1662	0.8338	83.38
January 2017	0.2590	0.7410	74.10
February 2017	0.1720	0.8280	82.80
March 2017	0.2607	0.7393	73.93
April 2017	0.2202	0.7798	77.98
May 2017	0.1737	0.8263	82.63
June 2017	0.1703	0.8297	82.97
July 2017	0.2571	0.7429	74.29
August 2017	0.2511	0.7489	74.89
September 2017	0.2625	0.7375	73.75
October 2017	0.1354	0.8646	86.46
November 2017	0.1756	0.8244	82.44
December 2017	0.1644	0.8356	83.56
January 2018	0.2173	0.7827	78.27
February 2018	0.2859	0.7141	71.41
March 2018	0.2524	0.7476	74.76
April 2018	0.2425	0.7575	75.75
May 2018	0.1884	0.8116	81.16
June 2018	0.2766	0.7234	72.34
July 2018	0.1517	0.8483	84.83
August 2018	0.2926	0.7074	70.74
September 2018	0.2639	0.7361	73.61
October 2018	0.2649	0.7351	73.51

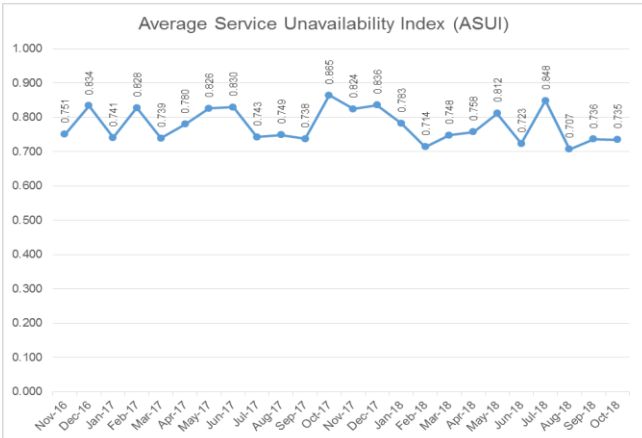

Fig. 21. ASUI

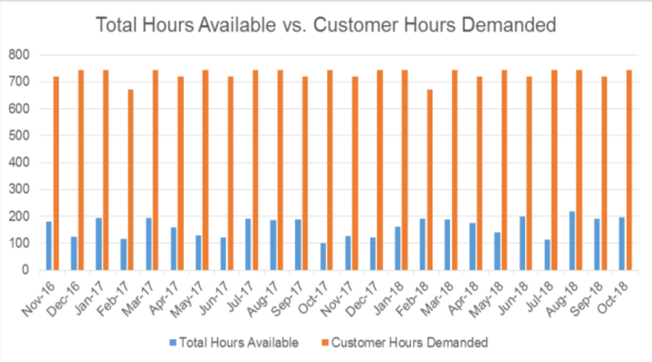

Fig. 22. Total Hours Available vs. Customer Hours Demanded

It is worth noting that failures at the injection substation and repair hours are not the only factors that directly affect the availability of constant power to consumers. Other factors out of the substation's control could limit the steady supply of electricity to consumers served through its network.

The failure rate data; reveal fluctuations in the substation's reliability over the study period.

5. Conclusion

Enhancing Reliability at the Etete Injection Sub-Station: While the study identifies key reliability challenges, it also provides practical solutions to improve performance:

Reducing Outages:

Preventive Measures: Implement fault detection systems (e.g., surge arresters, relay upgrades) to minimize equipment failure.

Load Management:

Balance transformer loads to avoid overloading and reduce stress-induced outages.

Vegetation Control: Regular tree-trimming near power lines to prevent weather-related faults.

Improved Maintenance Strategies

Predictive Maintenance: Use condition monitoring (e.g., thermal imaging, dissolved gas analysis for transformers) to detect issues before failures occur.

Scheduled Overhauls:

Routine inspections and timely replacement of aging components (e.g., circuit breakers, insulators).

Training Programs:

Enhance staff skills in modern maintenance techniques and emergency response.

Adopting New Technologies

Automation: Deploy SCADA systems for real-time monitoring and faster fault isolation.

Smart Sensors: Install IoT-based sensors to track equipment health and predict failures.

Renewable Integration: Use battery storage to provide backup power during outages and stabilize grid fluctuations.

The study concludes that the reliability of the Etete Injection Substation is subject to significant fluctuations, based on the observed variation in key reliability metrics over the study period.

Analysis of the substation's performance metrics, including failure rates, mean time to failure (MTTF), mean time to repair or recovery (MTTR), mean time between failure (MTBF), availability, unavailability, reliability, system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), average service availability index (ASAI), and average service unavailability index (ASUI), has provided valuable insights into the substation's operational challenges.

The reliability of the substation is not consistent throughout the year, with certain months experiencing higher failure rates and shorter MTTF, indicating lower reliability during those periods. These fluctuations can be attributed to various factors, including environmental conditions, equipment aging, and maintenance practices.

The efficiency of repair and recovery processes also impacts the overall reliability of the substation. Prolonged MTTR values lead to extended downtime and customer interruptions, further underscoring the need for efficient maintenance procedures.

SAIFI, SAIDI, and CAIDI values have highlighted the impact of these fluctuations on customers, revealing the frequency and duration of interruptions they experience. These metrics emphasize the importance of reducing disruptions and improving service continuity.

Moreover, the substation's availability and unavailability metrics reflect its operational status, demonstrating periods of uptime and downtime due to failures and maintenance activities. The analysis of ASAI and ASUI values has provided insights into the adequacy of service provision in meeting customer demand.

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