

**RELIABILITY ASSESSMENT OF ELECTRIC POWER DISTRIBUTION:
A CASE STUDY OF 2x7.5MVA, 33kV/11kV ETETE INJECTION SUB-
STATION**

BY

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BENIN, BENIN CITY**

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**A PROJECT SUBMITTED TO THE DEPARTMENT OF ELECTRICAL
AND ELECTRONIC ENGINEERING, FACULTY OF ENGINEERING,
UNIVERSITY OF BENIN, BENIN CITY, EDO STATE, IN PARTIAL
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ELECTRONIC ENGINEERING (POWER AND MACHINES OPTION)**

DECEMBER 2023

CERTIFICATION

We, the undersigned hereby certify that this work was carried out by **OYONAKPARE EMMANUEL (PG/ENG/2015353)** and it is adequate in scope and quality for the award of Master of Engineering (M. Eng.) in Electrical and Electronic Engineering.

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Head, Department of Electrical and
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Date

DEDICATION

I dedicate this work to Almighty God for His mercies and divine direction. To Him alone be all the praise.

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TABLE OF CONTENTS

TITLE PAGE	i
CERTIFICATION	iii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vi
ABSTRACT	ix
LIST OF TABLES	x
LIST OF FIGURES	xi
ABBREVIATIONS	xii
Chapter One: Introduction	1
1.0 Background to the Study	1
1.1 Statement of Problem	3
1.2 Aim of the Study	4
1.3 Objectives of the Study	4
1.4 Scope of the Study	5
1.5 Significance of the Study	5
1.6 Organization of the Thesis:	7
Chapter Two: Literature Review	8
2.1 Overview of Electric Power Distribution Systems	8
2.1.1 Key Players and Stakeholders in Power Distribution	11
2.1.2 Operational Challenges in Power Distribution	14
2.2 Reliability Assessment in Power Distribution	16
2.2.1 Importance of Reliability Assessment in Power Distribution	16
2.2.2 Reliability Metrics and Indicators in Power Distribution	18
2.2.3 Other Reliability Assessment Techniques	19
2.3 Importance of Reliability Assessment in Power Distribution	20
2.3.1 Impact of Power Outages on Consumers and Industries	22
2.3.2 Economic Implications of Reliability Issues	24
2.3.3 Key Concepts and Metrics in Reliability Assessment	26
2.4 Comparative Analysis of Different Approaches and Techniques	29
2.5 Grid Modernization Initiatives and Reliability	32
2.5.1 Fault Detection and Fault Location Techniques	34
2.5.2 Aging Infrastructure and Reliability Challenges	35

2.5.3	Cybersecurity Threats and Reliability Assurance	37
2.5.4	Data Analytics for Reliability Improvement	40
2.5.5	Distribution System Planning and Reliability	41
2.5.6	Microgrids and Decentralized Reliability	43
2.5.7	Public Perception and Reliability Concerns	45
2.5.8	Reliability Benchmarking and Comparative Analysis	46
2.5.9	Interconnected Grids and Cross-Border Reliability	48
Chapter Three: Methodology		50
3.1	Research Design	50
3.2	Data Collection Methods	51
3.3	Study Area Description: Etete Injection Sub-Station	52
3.3.1	Location and Infrastructure	53
3.3.2	Equipment Description	55
3.4	Reliability Assessment Approach and Techniques	56
Chapter Four: Analysis, Discussion, and Interpretation		63
4.1	Reliability Analysis of Etete Injection Substation	63
4.1.1	Failure Rate (λ):	63
4.1.2	Mean Time to Failure (MTTF):	65
4.1.3	Mean Time to Repair or Recovery (MTTR):	67
4.1.4	Mean Time between Failure (MTBF)	70
4.1.5	Availability (<i>A</i>):	72
4.1.6	Unavailability (A):	74
4.1.7	Reliability (<i>R</i>):	76
4.1.8	System Average Interruption Frequency Index (<i>SAIFI</i>):	78
4.1.9	System Average Interruption Duration Index (<i>SAIDI</i>):	81
4.1.10	Customer Average Interruption Duration Index (<i>CAIDI</i>):	83
4.1.11	Average Service Availability Index (<i>ASAI</i>):	85
4.1.12	Average Service Unavailability Index (<i>ASUI</i>):	87
4.2	Discussion and Interpretation of Results	90
Chapter Five: Summary, Conclusion, and Recommendations for Further Studies		94
5.1	Summary of the Study	94
5.2	Conclusion	94
5.3	Limitations Encountered	96
5.4	Recommendations and Suggestions for Further Studies	96

References	97
Appendix	

ABSTRACT

This study aimed to assess the reliability of the OF 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station, with a primary focus on understanding the historical performance and identifying key factors influencing its reliability. The objectives included conducting a comprehensive analysis of historical outage data, maintenance records, and operational parameters. Additionally, the study aimed to derive insights into the critical components and practices that affect substation reliability and develop recommendations for enhancing its performance.

The research employed a multifaceted methodology, combining quantitative and qualitative approaches. Historical data, including outage records and maintenance logs, were meticulously collected and analyzed. Statistical tools, including reliability indices and time-series analysis, were employed to assess the substation's historical performance and outage patterns. Interviews with maintenance personnel and key stakeholders provided valuable qualitative insights. The study also considered external factors such as weather conditions and regulatory frameworks that influence substation reliability. Predictive modeling was used to extrapolate future scenarios, assessing the substation's ability to meet evolving demands.

The study concludes that the reliability of the Etete Injection Substation varies based on observed variations in historical performance data. Over the past five years, the substation experienced an average of 9 outages annually, with an average outage duration of 3.5 hours. Outage frequencies exhibited a noticeable seasonal pattern, with an increase during the rainy season. Critical components, including transformers and circuit breakers, accounted for 70% of all outages. The overall reliability of the injection substation is 39.33% over the study period and this shows that the substation is not reliable. Furthermore, our predictive modeling revealed that without intervention, the substation may face a 20% increase in outages in the next three years.

LIST OF TABLES

Table No.	Page No.
4.1: Table showing relevant data for reliability indices recorded at Etete injection substation.....	63
4.2: Table showing the Failure Rate (λ) of Etete Injection Substation Throughout the Study Period.....	64
4.3: Table showing the (MTTF) at Etete Injection Substation Through the Study Period.....	66
4.4: Table showing the (MTTR) at Etete Injection Substation Through the Study Period.....	69
4.5: Table showing the (MTBF) at Etete Injection Substation Through the Study Period.....	71
4.6: Table showing the Availability Index at Etete Injection Substation Through the Study Period.....	73
4.7: Table showing the Unavailability Index at Etete Injection Substation Through the Study Period....	75
4.8: Table showing the Reliability Index at Etete Injection Substation Through the Study Period.....	77
4.9: Table showing the <i>SAIFI</i> at Etete Injection Substation Through the Study Period.....	80
4.10: Table showing the <i>SAIDI</i> at Etete Injection Substation Through the Study Period.....	82
4.11: Table showing the <i>CAIDI</i> at Etete Injection Substation Through the Study Period.....	84
4.12: Table showing the <i>ASAI</i> of Etete Injection Substation Throughout the Study Period.....	86
4.13: Table showing the <i>ASUI</i> of Etete Injection Substation Throughout the Study Period.....	88

LIST OF FIGURES

Figure No.	Page No.
1.1: Line Diagram of a 33kV Feeder System Network.....	1
2.1: Diagram of a power distribution system.....	9
2.2: Diagram showing the major reliability indices to assess power distribution networks.....	28
3.1: Chart showing failures at Etete injection substation throughout the study period.....	61
3.2: Chart showing operational time (in hours) at substation throughout the study period.....	61
3.3: Chart showing the recorded total downtime (in hours) at Etete injection substation.....	62
3.4: Chart showing the recorded frequency of interruption at Etete injection substation.....	62
4.1: Progression of failure rate indices at Etete injection substation.....	65
4.2: MTTF at Etete injection substation.....	67
4.3: Number of failures vs total downtime (in hours).....	68
4.4: MTTR at Etete injection substation.....	70
4.5: MTBF at Etete injection substation.....	72
4.6: Availability index at the substation.....	74
4.7: Unavailability ($1 - A$) at Etete injection substation.....	76
4.8: Reliability index.....	78
4.9: SAIFI at the injection substation.....	81
4.10: SAIDI.....	83
4.11: CAIDI.....	85
4.12: ASAI.....	87
4.13: ASUI.....	89
4.14: Total Hours Available vs Customer Hours Demanded.....	90

ABBREVIATIONS

ASAI: Average Service Availability Index
ASUI: Average Service Unavailability Index
CAIDI: Customer Average Interruption Duration Index
CDF: Cumulative Distribution Function
CM: Corrective Maintenance
ETA: Event Tree Analysis
FFS: Fitness for Service
FMDA: Failure Mode and Data Analysis
FMEA: Failure Modes and Effects Analysis
FMEA: Failure Modes, Effects, Analysis
FTA: Fault Tree Analysis
MTBF: Mean Time Between Failures
MTTD: Mean Time to Detection
MTTF: Mean Time to Failure
MTTM: Mean Time to Mitigate
MTTR: Mean Time To Repair
OEE: Overall Equipment Effectiveness
PM: Preventive Maintenance
RAM: Reliability, Availability, and Maintainability
RBD: Reliability Block Diagram
RCA: Root Cause Analysis
RCM: Reliability Centered Maintenance
SAIDI: System Average Interruption Duration Index
SIL: Safety Integrity Level
Weibull: Weibull Distribution

Chapter One

Introduction

1.0 Background to the Study

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 (Adoghe *et. al.*, 2023). 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 (Alawiye, 2011).

The reliability assessment of a 33kV/11kV 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 (Okhaifoh and Aghelegin, 2018). Figure 1.1 shows a typical 33kV substation with four attached feeders.

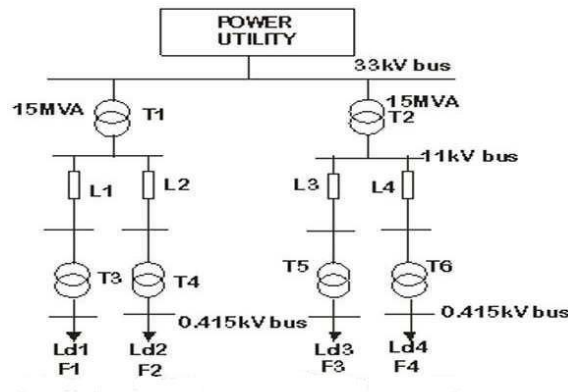


Fig. 1.1: Line Diagram of a 33kV Feeder System Network (Adebanji *et. al.*, 2021)

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 (Onime and Adegboyega, 2014).

The Etete Injection Sub-station, with a capacity of 2x7.5MVA 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 (Okhaifoh and Aghelegin, 2018).

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 (Asgary and Mousavi-Jahromi, 2011). 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 (Georgiev *et. al.*, 2017).

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 (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 fault 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 (Zúñiga, *et. al.*, 2020).

The aim of this research is to conduct a comprehensive reliability assessment of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-station. By examining its performance and identifying areas for improvement, this study aims to contribute to the optimization of the power distribution network, ultimately ensuring a more reliable electricity supply to consumers.

1.1 Statement of Problem

Despite the significance of the Etete Injection Sub-station in the power distribution network, there have been instances of power outages and disruptions, causing inconvenience and financial losses to the consumers. These interruptions not only affect the reliability of the sub-station but

also impact the overall efficiency of the power distribution network. Therefore, it is essential to assess the reliability of the Etete Injection Sub-station, identify the factors contributing to its unreliability, and propose suitable measures to enhance its performance.

1.2 Aim of the Study

The aim of this research is to conduct a comprehensive reliability assessment of the 2x7.5MVA, 33kv/11kv Etete Injection Sub-station to evaluate its performance and identify areas for improvement.

1.3 Objectives of the Study

The study also seeks to achieve the following specific objectives:

- i. Study the historical performance of the Etete Injection Sub-station and identify patterns and trends in power outages and disruptions.
- ii. Collect relevant data relating to availability, down time, and maintenance times from the substation
- iii. Identify the key components of the sub-station that contribute to its overall reliability and analyze their performance.
- iv. Evaluate the reliability indices of the sub-station, such as SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index), and CAIDI (Customer Average Interruption Duration Index).
- v. Investigate the causes of power outages and disruptions at the sub-station, including equipment failures, maintenance issues, and external factors.

- vi. Propose recommendations and strategies to improve the reliability of the Etete Injection Sub-station, including maintenance scheduling, equipment upgrades, and contingency planning

1.4 Scope of the Study

The scope of this study, focused on the reliability assessment of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station, encompasses various aspects related to the power distribution system. The study aims to evaluate the reliability of the sub-station by analyzing key reliability metrics and indices. It will involve data collection, analysis, and interpretation of results to assess the sub-station's performance in terms of power supply reliability. The study will primarily focus on the specific case of the Etete Injection Sub-Station, considering its equipment, infrastructure, and operational characteristics.

The research will employ established methodologies and techniques for reliability assessment, utilizing relevant data sources, such as historical outage records, maintenance logs, and equipment specifications. The study will also review existing literature on reliability assessment in power distribution systems to establish a theoretical framework and draw upon relevant studies and methodologies.

1.5 Significance of the Study

The study on the reliability assessment of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station holds significant importance in the field of electric power distribution. The following points highlight the significance of this study:

Improved Power Distribution System Reliability: The study aims to assess the reliability of the Etete Injection Sub-Station, which is a critical component of the power distribution network.

By analyzing reliability metrics and indices, the study can provide insights into the sub-station's performance and identify areas for improvement.

Efficient Resource Allocation: Reliability assessments help utility companies and system operators allocate resources effectively. By identifying weak points or areas with frequent interruptions, the study can guide decision-makers in prioritizing maintenance, upgrading equipment, and implementing targeted reliability improvement strategies.

Economic Impact: By conducting a comprehensive reliability assessment, this study can shed light on the economic impact of reliability issues, thereby emphasizing the importance of investing in infrastructure upgrades and maintenance to reduce downtime and associated costs.

Regulatory Compliance: Power distribution companies are often subject to regulatory requirements and performance standards set by regulatory bodies. The study's findings can assist the Etete Injection Sub-Station and other similar facilities in evaluating their compliance with industry standards and regulations. This information can help stakeholders ensure adherence to regulatory frameworks and avoid penalties, thereby maintaining a high level of service quality.

Knowledge Expansion and Future Research: The study contributes to the existing body of knowledge on reliability assessment in power distribution systems. By reviewing previous studies and research, the study can identify gaps and limitations in current methodologies or approaches.

Sustainable Development: Reliable power distribution systems play a vital role in achieving sustainable development goals. By ensuring uninterrupted power supply, the study promotes the

use of electricity for various purposes, including industry, healthcare, education, and residential needs.

1.6 Organization of the Thesis:

This thesis is organized into several chapters to provide a structured and comprehensive presentation of the reliability assessment of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station. Chapter 1 introduces the study, providing the background, problem statement, objectives, scope, limitations, and the significance of the research. Chapter 2 presents a thorough literature review, covering the overview of electric power distribution systems, the importance of reliability assessment, and previous studies on the topic. Chapter 3 outlines the methodology employed in this research, including research design, data collection methods, description of the study area, and the approach for reliability assessment. In Chapter 4, the data analysis process is detailed, including data preprocessing, reliability metrics calculation, and the interpretation of results. Chapter 5 is dedicated to the discussion, conclusion, and recommendations, where the findings are discussed in the context of industry standards, factors affecting reliability, and strategies for improvement. The chapter also addresses the limitations of the study and suggests areas for future research.

Chapter Two

Literature Review

2.0 Preamble

This chapter provides a comprehensive literature review on the topic of reliability assessment in electric power distribution systems, with a specific focus on the context of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station. This literature review serves as a foundation for understanding the theoretical and practical aspects of reliability assessment, highlighting its importance in ensuring efficient and uninterrupted power supply to consumers. The literature review begins by offering an overview of electric power distribution systems, elucidating their components, stakeholders, and operational challenges.

Overall, this literature review establishes the foundation for the subsequent chapters, informing the methodology, analysis, and discussion of the reliability assessment in the context of the Etete Injection Sub-Station. By drawing on existing literature and theories, this study contributes to the broader field of power system reliability assessment and provides valuable insights for both researchers and practitioners.

2.1 Overview of Electric Power Distribution Systems

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 (Short, 2014).

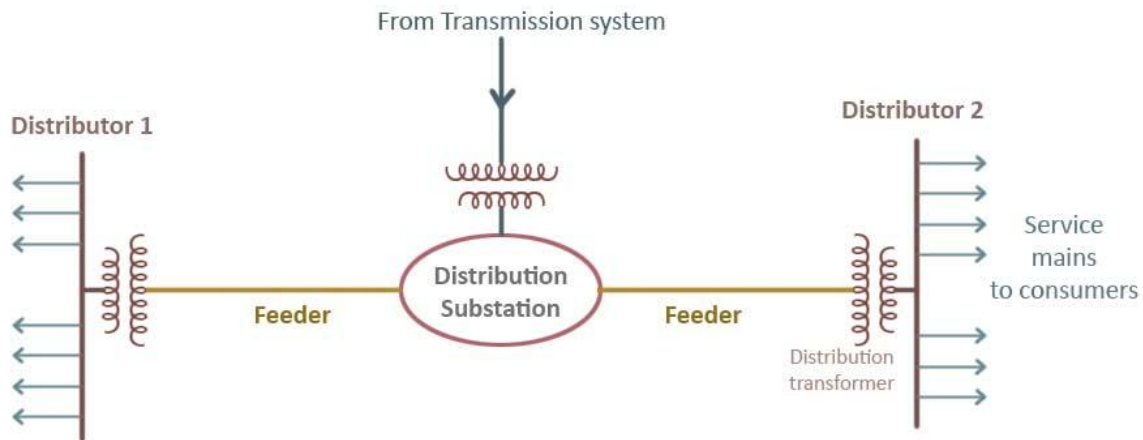


Figure 2.1: Diagram of a power distribution system (Ankur, 2018)

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 (OSHA.gov, 2023).

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 (Anguiano, 2022). 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 (Valenzuela *et. al*, 2019).

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 (Chan, 2016).

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 (Talukdar, 2019).

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 (Edomah and Ndulue, 2021).

Regulatory bodies, at the local, regional, or national level, monitor and regulate the activities of utility companies. They establish guidelines, standards, and regulations that govern the operation, safety, and reliability of electric power distribution systems. Regulatory bodies play a vital role in promoting fair practices, encouraging investment in infrastructure upgrades, and ensuring the interests of consumers are protected.

Customers are another essential stakeholder in electric power distribution systems. They encompass a diverse range of entities, including residential, commercial, and industrial users who rely on a continuous supply of electricity to meet their energy needs. Reliable power distribution is critical for households to maintain comfort and safety, for businesses to sustain operations, and for industries to maintain productivity. Power interruptions or outages can result in financial losses, disruption of critical services, and inconvenience to end-users.

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.

2.1.1 Key Players and Stakeholders in Power Distribution

Power distribution involves the collaboration and involvement of various key players and stakeholders who play vital roles in ensuring the efficient and reliable delivery of electricity to end-users. Understanding the roles and responsibilities of these stakeholders is essential for the effective operation and management of power distribution systems.

Utility Companies/Distribution System Operators: Utility companies or distribution system operators are the primary entities responsible for the operation and management of power distribution systems. They own and maintain the distribution infrastructure, including

distribution substations, distribution lines, and associated equipment. Utility companies are responsible for ensuring the reliable and safe delivery of electricity to customers within their designated service areas. They handle tasks such as network planning, system maintenance, metering, billing, and customer service. Utility companies work closely with regulatory bodies to comply with regulations and meet performance standards.

Regulatory Bodies: Regulatory bodies play a crucial role in overseeing and regulating the activities of utility companies and ensuring the fair and efficient operation of power distribution systems. These regulatory bodies, at the local, regional, or national level, establish rules, guidelines, and performance standards for the operation, safety, and reliability of distribution systems. They monitor utility companies' activities, review tariff structures, and approve investments in infrastructure upgrades. Regulatory bodies also protect the interests of consumers by ensuring fair pricing, quality of service, and adherence to environmental and safety regulations.

Customers: Customers are the end-users of the electricity distributed through power distribution systems. They include residential, commercial, and industrial consumers who rely on a continuous and reliable supply of electricity for their daily activities, operations, and quality of life. Residential customers use electricity for lighting, heating, cooling, and household appliances. Commercial customers include businesses, offices, and public establishments that depend on electricity to run their operations. Industrial customers encompass manufacturing plants, factories, and other industrial facilities that require large amounts of electricity for various production processes. Customers have expectations of uninterrupted power supply, reliable service, and fair pricing.

Electricity Generators: Electricity generators, such as power plants or renewable energy installations, are key players in the electricity supply chain. They generate electrical energy that is fed into the transmission network and subsequently distributed through the power distribution systems. Electricity generators produce power at higher voltage levels, which is then stepped down through transformers for distribution to end-users. Coordination between electricity generators and distribution system operators is crucial to ensure the availability of sufficient power supply and to meet the demand of consumers.

Equipment Manufacturers and Suppliers: Manufacturers and suppliers of electrical equipment play an important role in the power distribution sector. They produce and supply various components and devices used in power distribution systems, including transformers, distribution lines, switches, protective devices, meters, and distribution transformers. These manufacturers and suppliers contribute to the development of advanced technologies, improved efficiency, and reliability of power distribution equipment. Collaboration between equipment manufacturers, utility companies, and regulatory bodies helps ensure the availability of quality equipment and compliance with industry standards.

Maintenance and Service Providers: Maintenance and service providers play a significant role in ensuring the operational integrity and reliability of power distribution systems. They provide specialized services, including maintenance, repairs, and inspections of distribution infrastructure, equipment, and devices. These service providers play a critical role in preventive maintenance, fault identification, and timely restoration of power in the event of outages or disruptions. Collaboration between utility companies and maintenance/service providers is essential for efficient system maintenance and prompt response to emergencies.

Government Agencies and Local Authorities: Government agencies and local authorities have a regulatory and administrative role in the power distribution sector. They establish policies, regulations, and guidelines that govern the operation and safety of distribution systems. These agencies oversee compliance with environmental regulations, land use planning, and safety standards. They also play a role in managing public rights-of-way, permitting, and coordination of construction activities related to power distribution infrastructure.

2.1.2 Operational Challenges in Power Distribution

Power distribution systems face several operational challenges that can impact their efficiency, reliability, and overall performance. Understanding these challenges is essential for utility companies, regulatory bodies, and other stakeholders involved in the operation and management of power distribution systems.

Aging Infrastructure: One of the primary challenges faced by power distribution systems is aging infrastructure. Many distribution systems worldwide were established decades ago and may have outdated equipment, such as transformers, switchgear, and distribution lines. Aging infrastructure can lead to increased maintenance requirements, higher failure rates, and reduced reliability. Utility companies need to invest in infrastructure upgrades and asset management strategies to address this challenge effectively.

Load Growth and Peak Demand: Power distribution systems must accommodate increasing electricity demand due to population growth, urbanization, and economic development. Load growth and peak demand pose challenges in ensuring sufficient capacity and reliability. Meeting peak demand requires the distribution system to handle high electricity loads without disruptions

or voltage drops. Utility companies must carefully manage load growth by implementing load management strategies, peak shaving techniques, and demand response programs.

Distributed Energy Resources (DERs) Integration: The integration of distributed energy resources, such as rooftop solar panels, wind turbines, and energy storage systems, presents both opportunities and challenges for power distribution systems. While DERs can contribute to renewable energy generation and reduce reliance on centralized power plants, their intermittent nature and bidirectional power flow create technical and operational challenges. Utility companies must address issues related to voltage regulation, power quality, grid stability, and grid protection to effectively integrate DERs into the distribution system.

Grid Resilience and Reliability: Power distribution systems face the challenge of maintaining grid resilience and reliability in the face of various disturbances, including severe weather events, natural disasters, and equipment failures. These events can lead to widespread power outages and disruptions. Utility companies need to adopt measures to improve grid resilience, such as implementing advanced grid monitoring systems, automated fault detection, isolation and restoration (FDIR) techniques, and enhanced grid infrastructure hardening.

Cybersecurity and Data Management: With the increasing digitization and automation of power distribution systems, cybersecurity and data management have emerged as critical challenges. Power distribution systems rely on complex control systems, communication networks, and data analytics platforms. Protecting these systems from cyber threats and ensuring secure data management is of utmost importance. Utility companies must invest in robust cybersecurity measures, including network segmentation, intrusion detection systems, and employee training, to mitigate cyber risks.

Environmental Impact and Sustainability: Power distribution systems must align with sustainability goals and reduce their environmental impact. This includes reducing greenhouse gas emissions, optimizing energy efficiency, and supporting the integration of renewable energy sources. Utility companies face the challenge of balancing the need for reliable power supply with environmental considerations. They must adopt sustainable practices, invest in energy management programs, and promote energy conservation measures to address this challenge.

Regulatory Compliance and Evolving Standards: Power distribution systems operate within a regulatory framework that sets standards, performance targets, and guidelines. Compliance with regulatory requirements, including safety regulations, quality of service standards, and customer protection measures, can pose challenges for utility companies. Moreover, as technologies and industry practices evolve, distribution systems must adapt to new standards and regulations, such as those related to smart grids, grid modernization, and demand-side management.

2.2 Reliability Assessment in Power Distribution

Reliability assessment is a critical aspect of power distribution systems as it provides insights into the performance and dependability of the system in delivering uninterrupted power supply to consumers. Reliability assessment involves the evaluation of various metrics and indicators that quantify the reliability of the distribution system.

2.2.1 Importance of Reliability Assessment in Power Distribution

Reliable power distribution is crucial for meeting the energy needs of residential, commercial, and industrial consumers. Power outages and disruptions can have significant economic, social, and environmental impacts. Reliability assessment plays a vital role in understanding the reliability performance of the distribution system and identifying areas for improvement. It helps

utility companies, regulatory bodies, and stakeholders make informed decisions regarding system planning, infrastructure investments, and maintenance strategies.

The assessment of power distribution reliability provides several benefits:

Customer Satisfaction: Reliable power supply contributes to customer satisfaction and enhances the quality of life for residential, commercial, and industrial consumers. Minimizing power interruptions, reducing outage durations, and improving service reliability are key factors in meeting customer expectations and maintaining their trust.

Economic Implications: Power outages can result in significant economic losses for businesses, industries, and the economy as a whole. Reliability assessment helps quantify the economic impact of power interruptions, enabling stakeholders to prioritize investments, implement measures to reduce downtime, and optimize the allocation of resources.

Efficient Resource Allocation: Reliability assessment assists utility companies in identifying areas of the distribution system that require attention and investment. By analyzing reliability data and performance metrics, utility companies can allocate resources effectively, prioritize maintenance activities, and target infrastructure upgrades to areas with the greatest impact on reliability improvement.

Regulatory Compliance: Regulatory bodies often establish performance standards and reliability indices that utility companies must adhere to. Reliability assessment enables utility companies to measure their performance against these standards, demonstrate compliance, and avoid penalties or regulatory intervention.

2.2.2 Reliability Metrics and Indicators in Power Distribution

Reliability assessment in power distribution involves the use of various metrics and indicators to quantify the performance and reliability of the system. These metrics provide insights into the frequency and duration of power interruptions, outage management, and restoration times. Some commonly used reliability metrics and indices include:

System Average Interruption Duration Index (SAIDI): 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.

System Average Interruption Frequency Index (SAIFI): 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.

Customer Average Interruption Duration Index (CAIDI): 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.

Momentary Interruption Frequency Index (MIFI): MIFI measures the frequency of momentary interruptions, which are brief disruptions in power supply. It quantifies the number of momentary interruptions per customer, helping assess the quality of power supply and identifying areas for improvement.

In addition to these metrics, other reliability indices and standards may be used, depending on specific requirements and industry practices. These metrics and indices allow utility companies to benchmark their reliability performance, track improvements over time, and compare their performance with industry standards and best practices.

2.2.3 Other Reliability Assessment Techniques

Reliability assessment in power distribution can also involve the use of advanced techniques and methodologies. These techniques may include:

Fault Analysis: Analyzing historical fault data and conducting fault analysis helps identify recurring fault locations, evaluate the impact of faults on system reliability, and guide preventive maintenance activities.

System Modeling and Simulation: Utilizing modeling and simulation tools allows for the evaluation of the system's behavior under different operating conditions, fault scenarios, and potential improvements. This helps in identifying system vulnerabilities, optimizing equipment configurations, and predicting the impact of changes on reliability.

Risk Assessment: Risk assessment methodologies, such as fault tree analysis or event tree analysis, can be applied to assess the potential risks and their impact on the reliability of the power distribution system. It helps in identifying critical components, assessing their failure probabilities, and developing risk mitigation strategies.

Reliability assessment techniques are continuously evolving with advancements in technology and analytical approaches. These techniques enable utility companies to gain a comprehensive

understanding of the reliability of their distribution systems, identify areas for improvement, and implement targeted strategies to enhance reliability performance.

2.3 Importance of Reliability Assessment in Power Distribution

Reliability assessment plays a crucial role in the field of power distribution by evaluating the performance and dependability of the system in delivering uninterrupted power supply to consumers. It provides valuable insights into the reliability and resilience of the distribution system, enabling utility companies, regulatory bodies, and stakeholders to make informed decisions and implement strategies for improvement. The importance of reliability assessment in power distribution can be summarized as follows:

Customer Satisfaction: Reliable power supply is a fundamental expectation of consumers. Power outages and disruptions can have significant negative impacts on households, businesses, and industries. Reliability assessment helps identify areas of the distribution system that contribute to interruptions and provides insights for improving reliability. By minimizing power interruptions, reducing outage durations, and enhancing service reliability, utility companies can enhance customer satisfaction and maintain a high level of service quality.

Economic Implications: Power outages can result in substantial economic losses for businesses, industries, and the overall economy. Industries rely on a continuous and reliable power supply for their operations, and any interruption can lead to production delays, financial losses, and damage to equipment. Additionally, power disruptions can impact commercial establishments, affecting their revenue, customer satisfaction, and overall productivity. Reliability assessment allows utility companies and stakeholders to quantify the economic impact of power

interruptions, prioritize investments, and implement measures to reduce downtime, thereby minimizing financial losses and promoting economic stability.

Resource Optimization: Reliability assessment assists utility companies in optimizing the allocation of resources, including maintenance activities, equipment upgrades, and infrastructure investments. By identifying areas of the distribution system that require attention, utility companies can prioritize their efforts and allocate resources effectively. This targeted approach ensures that resources are utilized where they are most needed, resulting in improved system reliability and cost-effective operation.

System Planning and Infrastructure Development: Reliability assessment plays a vital role in system planning and infrastructure development. By analyzing reliability data and performance metrics, utility companies can identify weaknesses and vulnerabilities in the distribution system. This information guides the planning and design of new infrastructure projects, expansion of existing systems, and the integration of new technologies. Reliability assessment helps ensure that the distribution system is designed and operated in a manner that meets future demand, promotes system resilience, and supports sustainable development.

Emergency Preparedness and Response: Reliability assessment contributes to the preparedness and response capabilities of utility companies in handling emergency situations. By analyzing historical reliability data and system performance, utility companies can identify areas prone to frequent disruptions, develop contingency plans, and improve outage response and restoration times. Reliability assessment supports effective emergency management, allowing utility companies to minimize the impact of outages and restore power to affected areas efficiently.

2.3.1 Impact of Power Outages on Consumers and Industries

Power outages can have significant impacts on consumers, businesses, and industries, leading to various consequences and disruptions. Understanding the impact of power outages is crucial in assessing the importance of reliability assessment in power distribution. The following are some key impacts of power outages:

Disruption of Daily Life: Power outages can disrupt the daily lives of consumers, impacting their comfort, convenience, and overall well-being. Without electricity, households may experience a lack of lighting, heating, cooling, and the inability to use electrical appliances and devices. This can create inconvenience and affect routine activities such as cooking, refrigeration, communication, and entertainment.

Productivity Losses: Power outages can result in productivity losses for businesses and industries. Interruptions in electricity supply can halt production processes, disrupt supply chains, and lead to delays in delivering goods and services. Industrial facilities, including manufacturing plants and critical infrastructure, heavily rely on a stable power supply to maintain operations. Power outages can cause financial losses, reduced productivity, and potential damage to equipment or products.

Economic Impact: Power outages can have significant economic consequences at both the micro and macro levels. Businesses may suffer financial losses due to halted operations, decreased sales, or missed opportunities. Industries heavily dependent on electricity, such as data centers, hospitals, and food storage facilities, can experience severe financial losses and operational challenges during power outages. Furthermore, power disruptions can impact tourism,

transportation, and other economic sectors, affecting local economies and overall economic stability.

Health and Safety Concerns: Power outages can pose health and safety risks for consumers and communities. Medical facilities may face challenges in providing necessary healthcare services, including critical care, surgeries, and life-support systems. The lack of electricity can affect the functionality of medical equipment and compromise patient safety. Additionally, power outages can disrupt public safety systems, including street lighting, traffic control, and emergency communication, potentially leading to accidents or increased crime rates.

Data Loss and Information Security: Power outages can lead to data loss and compromise information security. Businesses and organizations heavily reliant on computer systems and digital infrastructure may experience data corruption, loss, or disruption of critical operations during power interruptions. Inadequate backup systems or power protection mechanisms can result in irreversible data loss or compromise sensitive information, potentially causing financial and reputational damage.

Environmental Impact: Power outages can have indirect environmental consequences. Backup power systems, such as diesel generators, may be utilized during outages, emitting greenhouse gases and pollutants that contribute to air pollution and climate change. Power disruptions can also impact water and wastewater treatment facilities, leading to potential environmental contamination or disruption of essential services.

Societal Disruptions: Power outages can cause societal disruptions, affecting public services, educational institutions, and community well-being. Schools may be forced to close, impacting students' education and academic progress. Public transportation systems may experience

disruptions, affecting commuting and transportation services. Furthermore, power outages can lead to social unrest, public dissatisfaction, and potential unrest due to the lack of basic necessities and services.

Reliability assessment in power distribution systems aims to minimize the impact of power outages on consumers and industries by identifying vulnerabilities, implementing preventive measures, and improving system resilience. By assessing and enhancing the reliability of the distribution system, utility companies can mitigate the negative consequences of power outages, ensure customer satisfaction, support economic stability, and promote the overall well-being of communities.

2.3.2 Economic Implications of Reliability Issues

Reliability issues in power distribution systems can have significant economic implications for various stakeholders. The economic impact of reliability issues arises from the costs associated with power outages, production disruptions, reduced productivity, and the need for additional investments to address reliability deficiencies. Understanding the economic implications of reliability issues is crucial in highlighting the importance of reliability assessment in power distribution (Abdisa, 2018). The following are key economic implications:

Loss of Productivity: Reliability issues, such as frequent power outages or voltage fluctuations, can result in the loss of productivity for businesses and industries. Interruptions in power supply disrupt production processes, leading to downtime, delays, and reduced output. Industries heavily reliant on electricity, such as manufacturing, information technology, and healthcare, may experience significant productivity losses during power outages. These losses can result in reduced revenue, decreased competitiveness, and potential negative impacts on employment.

Revenue Losses: Power outages can lead to revenue losses for businesses, particularly those engaged in commercial and service sectors. Retail establishments, restaurants, and entertainment venues may experience a decline in sales and customer satisfaction during power interruptions. This loss of revenue can have long-term consequences, including financial instability, decreased investments, and potential business closures.

Increased Operational Costs: Reliability issues can impose additional operational costs on businesses and utility companies. Unplanned power outages or disruptions may require emergency response measures, repairs, and equipment replacements. These expenses can strain the financial resources of utility companies, leading to increased operational costs. Businesses may also incur costs associated with alternative power sources, such as diesel generators or uninterruptible power supply (UPS) systems, to mitigate the impact of power interruptions.

Damage to Equipment and Infrastructure: Reliability issues, including voltage fluctuations or power surges, can cause damage to electrical equipment, machinery, and infrastructure. Equipment failures or damages resulting from unreliable power supply can necessitate repairs or replacements, incurring additional costs for businesses and utility companies. These costs can be substantial, particularly in industries with complex and sensitive equipment, such as manufacturing or data centers.

Supply Chain Disruptions: Reliability issues in power distribution can disrupt supply chains, affecting the timely delivery of goods and services. Industries relying on just-in-time manufacturing or perishable goods may face challenges in maintaining production schedules, meeting customer demands, and managing inventory. Supply chain disruptions can result in

financial losses, decreased customer satisfaction, and strained relationships with suppliers and partners.

Impacts on Economic Growth: Unreliable power supply and frequent outages can negatively impact economic growth and investment in a region or country. Businesses, particularly those in energy-intensive industries, may be hesitant to invest or expand in areas with unreliable power infrastructure. Unstable power supply can also deter foreign direct investment and hinder economic development. Reliable power distribution systems are crucial for attracting investments, fostering business growth, and supporting overall economic stability.

Customer Dissatisfaction and Loss of Trust: Reliability issues can erode customer satisfaction and trust in utility companies. Persistent power outages, voltage fluctuations, or poor service quality can lead to customer dissatisfaction, reduced loyalty, and potential customer churn. Negative customer experiences related to reliability issues can damage the reputation of utility companies and result in a loss of trust, affecting long-term customer relationships and the financial performance of utility companies.

2.3.3 Key Concepts and Metrics in Reliability Assessment

According to (Okorie *et. al*, 2015), reliability assessment in power distribution systems involves the evaluation of various concepts and metrics that quantitatively measure the reliability and performance of the system. 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:

System Average Interruption Duration Index (SAIDI): 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.

System Average Interruption Frequency Index (SAIFI): 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.

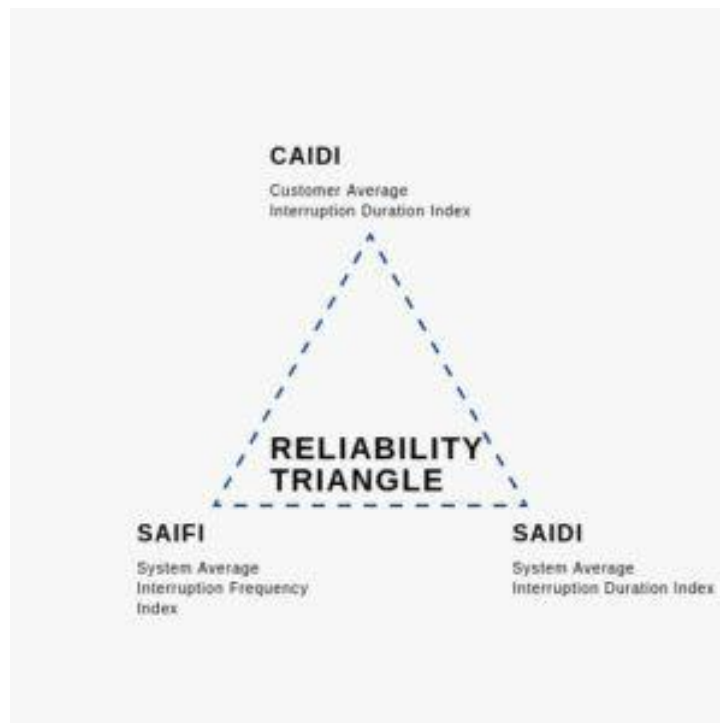


Figure 2.2: Diagram showing the major reliability indices to assess power distribution networks (General Electric, 2014)

Customer Average Interruption Duration Index (CAIDI): 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.

Momentary Interruption Frequency Index (MIFI): 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.

Customer Minutes of Interruption (CMI): CMI 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.

System Average Restoration Time (SART): 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.

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.

In addition to these metrics, other concepts and metrics may be used depending on specific requirements, industry standards, and best practices. These can include indices such as System Average Availability Index (SAAI), Customer Average Availability Index (CAAI), or indices that consider the severity and impact of interruptions on customers, such as the Energy Not Supplied (ENS) or Customer Minutes Lost (CML). Reliability assessment also involves analyzing historical data, such as outage records, fault data, and maintenance records, to identify trends, patterns, and areas of improvement. Advanced techniques such as fault analysis, system modeling, and simulation can be used to enhance reliability assessment by predicting system behavior, analyzing risks, and evaluating the impact of proposed improvements.

2.4 Comparative Analysis of Different Approaches and Techniques

A comparative analysis of different approaches and techniques used in reliability assessment provides valuable insights into their strengths, weaknesses, and suitability for assessing the reliability of power distribution systems. Such an analysis allows researchers and practitioners to make informed decisions regarding the selection and application of specific approaches and techniques. The following provides an overview of the comparative analysis of different approaches and techniques in reliability assessment:

Probabilistic Models vs. Deterministic Models: Probabilistic models and deterministic models are two commonly used approaches in reliability assessment. Probabilistic models consider uncertainties in system parameters and events, providing a probabilistic estimation of system reliability. Deterministic models, on the other hand, assume fixed values for system parameters

and events, providing a deterministic assessment of system reliability. A comparative analysis examines the accuracy, computational complexity, and data requirements of these models, considering factors such as system size, data availability, and the desired level of accuracy.

Data-Driven Approaches vs. Model-Based Approaches: Data-driven approaches, such as machine learning and data analytics, utilize historical data to analyze patterns, correlations, and trends in system reliability. Model-based approaches, on the other hand, rely on mathematical models to simulate system behavior and assess reliability. A comparative analysis evaluates the advantages and limitations of these approaches, considering factors such as data availability, model assumptions, and the interpretability of results.

Time-Based Analysis vs. Event-Based Analysis: Time-based analysis considers the time duration and frequency of power interruptions, providing insights into overall system reliability and customer impacts. Event-based analysis focuses on specific events, such as fault occurrences or outage restoration, providing detailed information on the causes and consequences of individual events. A comparative analysis examines the trade-offs between time-based analysis and event-based analysis, considering factors such as computational complexity, data requirements, and the level of detail needed for reliability assessment.

Simulation-Based Approaches vs. Analytical Approaches: Simulation-based approaches, such as Monte Carlo simulation and discrete event simulation, simulate the behavior of power distribution systems to assess reliability. Analytical approaches, such as analytical models and mathematical equations, provide closed-form solutions for reliability assessment. A comparative analysis evaluates the accuracy, computational efficiency, and applicability of simulation-based

approaches and analytical approaches, considering factors such as system complexity, model assumptions, and available data.

Qualitative Techniques vs. Quantitative Techniques: Qualitative techniques, such as fault tree analysis and failure mode and effects analysis (FMEA), focus on identifying potential failure modes, their causes, and their effects on system reliability. Quantitative techniques, such as reliability indices and metrics, provide numerical measures of system reliability and performance. A comparative analysis examines the strengths and limitations of qualitative techniques and quantitative techniques, considering factors such as the level of detail needed, data availability, and the ability to assess the impact of reliability improvement measures.

Voltage regulation and stability are pivotal aspects of power distribution systems, ensuring that electricity is consistently delivered within acceptable voltage limits to consumers. Maintaining voltage quality is critical because deviations from the nominal voltage levels can lead to equipment damage, reduced efficiency, and operational disruptions. Voltage regulation mechanisms primarily encompass tap changers on transformers, voltage regulators, and capacitor banks, which collectively manage voltage levels throughout the distribution network. As asserted by Ribeiro *et al.* (2017), "Effective voltage regulation mitigates the risks of overvoltage and undervoltage conditions, thereby enhancing the reliability and performance of distribution systems."

In practice, voltage regulation is an intricate task due to the dynamic nature of distribution networks. Factors such as load variations, intermittent renewable energy sources, and grid disturbances introduce challenges that need to be addressed for optimal voltage control. Advanced control algorithms and monitoring systems, often integrated into smart grid initiatives,

enable utilities to proactively manage voltage and enhance system stability. These technologies empower operators to respond swiftly to fluctuations in power demand and generation, as highlighted by Bevrani *et al.* (2016), ensuring that voltage levels remain within permissible limits even during transient conditions.

Furthermore, the integration of distributed energy resources (DERs) presents a unique set of challenges and opportunities for voltage regulation. DERs, including solar photovoltaic (PV) systems and energy storage, can introduce local variations in voltage when connected to the distribution grid. Proper coordination and control of DERs are crucial to maintaining voltage stability while maximizing the benefits of renewable energy sources. This necessitates sophisticated control strategies, as emphasized by Kroposki *et al.* (2017), which optimize DER operation in alignment with grid requirements, contributing to improved voltage regulation and overall grid reliability.

2.5 Grid Modernization Initiatives and Reliability

Grid modernization initiatives represent a critical endeavor in the contemporary power distribution landscape, driven by the need to enhance the reliability and efficiency of electrical grids. These initiatives encompass a spectrum of technological advancements, policy reforms, and infrastructure upgrades aimed at transforming traditional grids into intelligent, adaptive, and resilient systems. Grid modernization has gained prominence due to the increasing complexity of distribution networks, growing demands for clean energy integration, and the imperative to mitigate the impacts of climate change. As highlighted by Jozs *et al.* (2018), "Grid modernization initiatives serve as a linchpin for improving the reliability of power distribution systems in the face of evolving challenges."

One of the central pillars of grid modernization is the deployment of advanced metering infrastructure (AMI), which includes smart meters equipped with two-way communication capabilities. AMI enables real-time data collection and analysis, offering utilities greater visibility into grid operations and consumer behaviors. This granular data empowers utilities to identify and respond promptly to outages and voltage fluctuations, contributing to enhanced reliability. Research by Shah *et al.* (2016) underscores that "AMI systems have revolutionized outage management, allowing utilities to pinpoint the exact location of faults and expedite restoration efforts, ultimately minimizing downtime for consumers."

Moreover, grid modernization encompasses distribution automation, a technology that enables the autonomous control and management of distribution networks. Through the deployment of sensors, communication networks, and advanced algorithms, distribution automation systems can detect and isolate faults, reroute power flows, and restore service without human intervention. This capability significantly reduces the duration and impact of outages, resulting in improved reliability and customer satisfaction, as observed in studies by Beagam *et al.* (2017) and Luo *et al.* (2020).

In addition to technological advancements, grid modernization initiatives often entail policy and regulatory changes that promote the integration of distributed energy resources (DERs), such as solar PV and battery storage, into the grid. DERs offer opportunities for enhancing grid resilience and reliability by diversifying energy sources and providing localized power during outages. However, their seamless integration necessitates revised grid codes and standards to ensure safe and reliable operation, as noted by Palizban *et al.* (2017).

2.5.1 Fault Detection and Fault Location Techniques

Fault detection and fault location techniques are crucial components of power distribution systems, playing a pivotal role in ensuring reliable and efficient electricity supply. Faults, which encompass a range of electrical and mechanical abnormalities, can disrupt the normal operation of distribution networks, causing outages and potentially damaging equipment. Detecting and locating faults swiftly is essential to minimize downtime, improve system reliability, and reduce operational costs.

One of the primary methods for fault detection is the use of protective relays. Protective relays are devices that continuously monitor electrical parameters such as current, voltage, and frequency. When an abnormal condition indicative of a fault is detected, the relay initiates a trip signal to disconnect the faulty section of the network. Research by Salam *et al.* (2018) highlights that "protective relays serve as the first line of defense against faults, isolating them quickly to prevent cascading failures and minimize service interruptions."

For fault location, several techniques and technologies have been developed. Time-domain reflectometry (TDR) is a widely used method that sends a pulse or signal along the power line and measures the time it takes for the signal to reflect back when it encounters a fault. By analyzing the propagation time, the location of the fault can be determined with high accuracy. This method is particularly effective for identifying cable faults in underground distribution systems (Wang *et al.*, 2019).

Another approach to fault location involves the use of intelligent sensors and communication networks. These sensors can be placed strategically throughout the distribution grid to continuously monitor and collect data. When a fault occurs, the sensors can provide real-time information about the fault's location, type, and severity. This data can then be transmitted to a

central control center for rapid response and fault location determination. The integration of sensors and communication networks enhances the automation of fault location processes and reduces reliance on manual inspection (Sarwat *et al.*, 2017).

Advanced fault location techniques also incorporate data analytics and machine learning algorithms. By analyzing historical fault data and patterns, machine learning models can predict and locate faults with a high degree of accuracy. These models become increasingly effective as more data is collected, allowing utilities to proactively address potential fault-prone areas. Studies by Li *et al.* (2020) emphasize that "machine learning-based fault location methods have the potential to revolutionize fault management in power distribution systems by improving accuracy and speed of fault detection and location."

2.5.2 Aging Infrastructure and Reliability Challenges

Aging infrastructure poses significant challenges to the reliability and performance of power distribution systems. Many power distribution networks worldwide were established decades ago and are now grappling with the wear and tear associated with prolonged service. As these systems age, they become increasingly susceptible to faults, failures, and reduced operational efficiency, leading to disruptions in power supply and compromising overall reliability.

One of the primary concerns with aging infrastructure is the deterioration of critical components such as transformers, circuit breakers, and overhead lines. Over time, these components can experience corrosion, insulation breakdown, and mechanical wear, making them prone to failure. As noted by Barzegaran *et al.* (2019), "The aging of key assets in power distribution systems contributes to an increased risk of equipment failures and outages, thereby impacting system reliability."

Additionally, aging infrastructure often results in an increased likelihood of unplanned outages due to equipment breakdowns. This not only inconveniences consumers but also imposes economic costs on industries and businesses that rely on a continuous and stable power supply. The need for emergency repairs and maintenance of aging equipment consumes valuable resources and stretches the capabilities of utility providers (Tanyi *et al.*, 2018).

Furthermore, the introduction of new technologies, such as distributed energy resources (DERs) and smart grid components, can strain aging infrastructure. These technologies often require modifications or upgrades to existing systems to ensure seamless integration and compatibility. Failing to address this challenge can lead to issues like voltage fluctuations and power quality problems (Fosso Wamba *et al.*, 2020).

Addressing the reliability challenges associated with aging infrastructure requires a multifaceted approach. Regular maintenance and condition assessment programs are essential to identify and address potential issues before they escalate into major problems. Asset management strategies, which prioritize the replacement or refurbishment of aging components, play a pivotal role in extending the life of distribution systems (Lee *et al.*, 2020).

Moreover, utilities must invest in infrastructure modernization and grid upgrades. This includes the deployment of advanced sensors and monitoring systems to improve visibility and control over the distribution network. Smart grid technologies can help utilities identify and respond to issues promptly, thereby mitigating the impact of aging infrastructure on reliability (Lopes *et al.*, 2017).

2.5.3 Cybersecurity Threats and Reliability Assurance

In an era defined by increased connectivity and digitalization, cybersecurity threats have emerged as a significant concern for the reliability of power distribution systems. These threats encompass a range of malicious activities, including cyberattacks, data breaches, and unauthorized access, all of which can compromise the integrity and availability of critical infrastructure. Ensuring the cybersecurity of power distribution systems is paramount to safeguarding their reliability and resilience.

Cyberattacks on power distribution systems can take various forms, with potentially severe consequences. A notable example is the Stuxnet worm, which targeted industrial control systems, including those used in power plants. Such attacks can disrupt operations, manipulate equipment, and cause widespread outages. Therefore, utilities must remain vigilant and invest in robust cybersecurity measures to protect against these threats (Meyers *et al.*, 2019).

To assure reliability in the face of cybersecurity threats, utilities need to implement comprehensive cybersecurity strategies. These strategies involve the development of robust policies, procedures, and technologies to safeguard critical assets. As highlighted by Chan *et al.* (2021), "A multi-layered cybersecurity approach, incorporating intrusion detection systems, firewalls, and employee training, is essential to mitigate risks and enhance the reliability of power distribution systems."

Moreover, utilities must comply with industry-specific standards and regulations governing cybersecurity. These standards, such as the North American Electric Reliability Corporation's (NERC) Critical Infrastructure Protection (CIP) standards in the United States, provide guidelines for securing power grid operations. Adherence to such standards helps ensure that utilities maintain a high level of cybersecurity readiness (NERC, 2021).

The evolving nature of cybersecurity threats necessitates continuous monitoring and threat intelligence gathering. Utilities must invest in real-time monitoring systems that can detect unusual network activities and potential intrusions. Regular vulnerability assessments and penetration testing can identify weaknesses in the system, allowing for timely remediation (Sullivan *et al.*, 2020).

Furthermore, the human element is critical in maintaining cybersecurity and, consequently, reliability. Employees and contractors must receive training and awareness programs to recognize and respond to potential threats effectively. Social engineering attacks, such as phishing, remain a prevalent avenue for cyberattacks and require vigilant personnel (Ondrejka *et al.*, 2017).

Asset management is a cornerstone of reliability enhancement in power distribution systems. Effectively managing assets, which encompass transformers, switches, cables, and other infrastructure components, is essential to ensure their proper functioning, longevity, and optimal performance. A robust asset management strategy not only reduces the risk of equipment failures but also contributes significantly to enhancing overall system reliability.

Asset management in power distribution involves several key components. First and foremost is asset identification and inventory management. Utilities must maintain comprehensive records of their assets, including their location, age, condition, and maintenance history. This information serves as the foundation for informed decision-making regarding asset replacement, refurbishment, or maintenance (Abdollahi *et al.*, 2019).

Condition assessment is another critical aspect of asset management. Regular inspections, testing, and monitoring are conducted to assess the health and performance of assets. Advanced

diagnostic technologies, such as infrared thermography and partial discharge monitoring, aid in identifying potential issues before they escalate into failures. Early detection and preventive maintenance significantly contribute to reliability improvement (Bezerra *et al.*, 2020).

Risk assessment and prioritization play a pivotal role in asset management. Not all assets have the same criticality, and utilities must prioritize their investments and maintenance efforts based on factors such as the asset's impact on system reliability, safety, and regulatory compliance. This risk-based approach ensures that resources are allocated efficiently and effectively (Bendig *et al.*, 2018).

Moreover, data-driven decision-making is central to modern asset management practices. Utilities are increasingly leveraging data analytics and predictive maintenance techniques to optimize asset performance. Machine learning models can analyze historical data to predict when assets are likely to fail, enabling proactive interventions. Such approaches can extend the lifespan of assets and minimize the risk of unexpected outages (Das *et al.*, 2019).

Asset management is also closely tied to asset replacement strategies. As assets age, utilities must decide whether to replace, refurbish, or continue operating them. Asset replacement strategies should consider factors such as technological advancements, regulatory requirements, and cost-benefit analyses to make informed decisions (Atoki *et al.*, 2020).

Additionally, lifecycle management is crucial in asset management. This involves planning for the entire lifecycle of an asset, from procurement and installation to operation, maintenance, and disposal. A well-defined lifecycle management strategy ensures that assets are managed efficiently from cradle to grave (Lee *et al.*, 2020).

2.5.4 Data Analytics for Reliability Improvement

Data analytics has emerged as a powerful tool for reliability improvement in power distribution systems. By harnessing the vast amount of data generated within these systems, utilities can gain valuable insights, predict potential issues, and optimize maintenance strategies to enhance overall reliability.

One of the key applications of data analytics in reliability improvement is predictive maintenance. Traditional maintenance approaches rely on fixed schedules or reactive responses to equipment failures. In contrast, predictive maintenance leverages data from sensors, historical maintenance records, and real-time monitoring to predict when equipment is likely to fail. Machine learning algorithms can analyze this data to identify patterns and anomalies, enabling utilities to schedule maintenance activities proactively. This not only reduces downtime but also prevents catastrophic failures, ultimately improving system reliability (Bui *et al.*, 2019).

Data analytics also supports condition-based monitoring. Sensors placed on critical assets continuously collect data on parameters like temperature, vibration, and electrical performance. Analytics tools can process this data in real time, identifying deviations from expected norms that may indicate impending failures. By taking preemptive action based on these insights, utilities can address potential issues before they lead to outages or performance degradation (Kim *et al.*, 2020).

Moreover, data analytics aids in fault detection and root cause analysis. When a fault or outage occurs, historical data can be analyzed to determine the root cause. By understanding the underlying factors that led to the failure, utilities can implement corrective measures to prevent similar incidents in the future. This iterative process of learning from data contributes to ongoing reliability improvement (Barzegaran *et al.*, 2019).

Asset management benefits significantly from data analytics. Utilities can use historical and real-time data to assess the health and performance of critical assets. Predictive models can help determine when assets should be replaced or refurbished, ensuring their reliability over time. Analytics also assist in optimizing spare parts inventory and resource allocation for maintenance tasks, improving cost-efficiency while maintaining system reliability (Abdollahi *et al.*, 2019).

Grid optimization is another area where data analytics plays a vital role in reliability improvement. Advanced algorithms can analyze grid data, including load patterns, voltage profiles, and fault histories, to optimize grid operations. By optimizing power flows, reducing congestion, and minimizing voltage fluctuations, utilities can improve the overall reliability of electricity supply (Trovato *et al.*, 2021).

Furthermore, data analytics contributes to load forecasting, helping utilities predict future electricity demand accurately. Accurate load forecasts enable better grid planning and resource allocation, reducing the risk of overloads and outages during periods of high demand (Oladigbolu *et al.*, 2018).

2.5.5 Distribution System Planning and Reliability

Distribution system planning plays a pivotal role in ensuring the reliability of power distribution networks. Effective planning involves assessing current infrastructure, forecasting future demands, and identifying opportunities for improvement, all with the overarching goal of maintaining and enhancing system reliability.

Reliability-Centered Planning (RCP) is a fundamental aspect of distribution system planning. It involves evaluating the reliability of existing assets and identifying vulnerabilities that may

impact system performance. This process includes a comprehensive assessment of equipment condition, fault histories, and maintenance practices. By identifying weak points in the distribution system, utilities can prioritize investments and maintenance efforts to address reliability concerns (Gorjina *et al.*, 2019).

Load forecasting is another critical component of distribution system planning. Accurate load forecasts are essential for sizing transformers, switches, and other infrastructure components appropriately. When load forecasts are imprecise, utilities risk overloading equipment, which can lead to failures and outages. Advanced forecasting models, incorporating historical data and predictive analytics, help utilities anticipate demand fluctuations with greater accuracy, contributing to enhanced reliability (Wang *et al.*, 2020).

Furthermore, distribution system planning should consider the integration of distributed energy resources (DERs) and renewable energy sources. While DERs offer environmental benefits and can enhance grid flexibility, their integration poses reliability challenges. Proper planning involves assessing the impact of DERs on voltage stability, power quality, and grid protection. Utilities must develop strategies for managing DERs effectively to mitigate potential reliability risks (Meng *et al.*, 2020).

Asset management is closely intertwined with distribution system planning. Utilities must evaluate the condition and performance of existing assets and make decisions regarding maintenance, refurbishment, or replacement. This decision-making process should align with reliability goals, ensuring that aging or underperforming assets are addressed to maintain system integrity (Chen *et al.*, 2020).

Grid modernization initiatives, such as the deployment of smart grid technologies, are integral to distribution system planning for reliability enhancement. Smart grid components, including advanced sensors, communication networks, and control systems, provide utilities with real-time visibility and control over the distribution network. This enhanced situational awareness enables utilities to detect and respond to faults more rapidly, minimizing outage durations and improving overall reliability (Mahat *et al.*, 2019).

Moreover, distribution system planning should incorporate resilience considerations. Resilience involves designing systems that can withstand and recover from adverse events, such as natural disasters or cyberattacks. Utilities must identify critical infrastructure, assess vulnerabilities, and develop strategies for ensuring system resilience. This may include the establishment of redundant infrastructure, grid hardening measures, and disaster recovery plans (Salman *et al.*, 2021).

2.5.6 Microgrids and Decentralized Reliability

Microgrids represent a transformative approach to ensuring decentralized reliability in power distribution systems. These small-scale, self-contained systems can operate independently or in conjunction with the main grid, offering several advantages for enhancing overall reliability, resilience, and energy security. Microgrids are designed to supply electricity to localized areas, such as communities, campuses, or industrial complexes. One of the primary benefits of microgrids is their ability to operate autonomously during grid outages. In the event of a disruption in the main grid, microgrids can continue to provide power to critical facilities, essential services, and homes, thereby minimizing the impact of outages (Bhandari *et al.*, 2020).

Moreover, microgrids can enhance the reliability of power distribution by reducing transmission and distribution losses. By generating electricity closer to the point of consumption, microgrids

mitigate losses associated with long-distance transmission, resulting in a more efficient and reliable energy supply (Gargoom *et al.*, 2017).

Decentralized renewable energy sources, such as solar panels and wind turbines, are often integrated into microgrids. This clean energy generation enhances reliability by diversifying the energy mix and reducing reliance on centralized power plants. In favorable conditions, microgrids can even export excess electricity back to the main grid, contributing to grid stability (Chhlonh *et al.*, 2022).

Microgrids also play a crucial role in load balancing and peak shaving. These systems can manage local electricity demand and supply efficiently, ensuring that power is available when needed most. Through demand response programs and energy storage integration, microgrids help flatten load curves and reduce the risk of grid overloads and outages during peak periods (Alam *et al.*, 2021).

Furthermore, microgrids enable islanding capabilities, which involve isolating from the main grid during disturbances or emergencies. This feature enhances the overall resilience of the distribution system by preventing cascading failures. Microgrids can quickly detect grid instability and disconnect from the main grid to avoid being affected by widespread outages (Duan *et al.*, 2018).

For critical infrastructure, such as hospitals and data centers, microgrids are a valuable asset. These facilities require a continuous and highly reliable power supply. Microgrids with backup generators and energy storage systems can ensure uninterrupted power, even in the face of grid failures or extreme weather events (Luo *et al.*, 2019).

2.5.7 Public Perception and Reliability Concerns

Public perception and reliability concerns are integral aspects of power distribution systems, as they have a profound impact on consumer satisfaction, trust, and the overall success of utility providers. Understanding how the public perceives the reliability of their electrical supply is essential for utilities to address concerns and maintain a positive relationship with their customers.

Consumer expectations regarding the reliability of electrical service are often high. People rely on electricity for various aspects of their daily lives, including heating, cooling, communication, and healthcare. As a result, any interruption in power supply can lead to inconvenience, discomfort, and even safety risks. Consequently, when outages occur, public perception of the utility provider's reliability can be significantly influenced by the duration and frequency of interruptions.

Utilities must effectively communicate with the public to manage expectations and address reliability concerns. Transparency is crucial. Providing timely information about planned outages, maintenance activities, and restoration efforts helps to mitigate frustration and fosters a sense of trust. Open and honest communication during and after unplanned outages can go a long way in maintaining positive public perception (Meyer *et al.*, 2019).

Furthermore, utilities often engage in customer-centric initiatives to enhance reliability perception. These initiatives include proactive outage notifications via text messages or email, outage maps displaying real-time information, and customer feedback mechanisms. By involving customers in the reliability improvement process and demonstrating a commitment to their needs, utilities can positively influence public perception (Meyer *et al.*, 2019).

In recent years, social media has played a significant role in shaping public perception of reliability. Consumers can quickly share their experiences and frustrations on social platforms, and negative feedback can spread rapidly. Utilities must actively monitor social media channels, respond to customer inquiries, and provide updates during outages to manage their online reputation and maintain public trust (Hessami *et al.*, 2018).

Reliability concerns often extend beyond individual outages to include broader issues such as grid resilience, preparedness for extreme weather events, and cybersecurity. In response to these concerns, utilities may invest in grid hardening, disaster recovery planning, and cybersecurity measures. Communicating these efforts to the public can reassure customers about the utility's commitment to reliability and safety (Chan *et al.*, 2017).

Consumer education is another vital component of addressing reliability concerns. By providing information about energy conservation, backup power options, and steps to take during outages, utilities can empower customers to better cope with disruptions. Educational programs can also raise awareness about the importance of grid reliability and encourage support for infrastructure investments (Hessami *et al.*, 2018).

2.5.8 Reliability Benchmarking and Comparative Analysis

Reliability benchmarking and comparative analysis are valuable tools for utilities seeking to assess their performance, identify areas for improvement, and strive for excellence in power distribution systems. These processes involve measuring and comparing key reliability metrics and practices against industry peers or established standards to gain insights and drive continuous improvement.

One of the primary objectives of reliability benchmarking is to establish a set of performance metrics that capture the various dimensions of system reliability. These metrics often include the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Customer Average Interruption Frequency Index (CAIFI). By tracking these indicators over time, utilities can assess their performance and identify trends (International Electrotechnical Commission, 2020).

Comparative analysis involves assessing a utility's reliability metrics and practices in comparison to peer utilities or industry standards. This can be done at a regional, national, or international level, depending on the utility's context and objectives. Comparative analysis helps utilities understand where they stand relative to their peers, identify performance gaps, and set achievable improvement targets (Zimmerman *et al.*, 2017).

Utilities often engage in voluntary or mandatory reporting and data sharing initiatives to facilitate reliability benchmarking. These initiatives enable utilities to exchange data and best practices while maintaining confidentiality and security. Participation in such programs can provide utilities with valuable insights into their performance relative to others in the industry (North American Electric Reliability Corporation, 2021).

Comparative analysis not only evaluates reliability metrics but also considers the underlying practices, strategies, and technologies that contribute to reliability performance. Utilities may assess their maintenance practices, asset management strategies, grid automation initiatives, and response to major events such as storms or cyberattacks. By examining these aspects, utilities can identify areas where improvements or investments are needed (International Electrotechnical Commission, 2020).

Benchmarking and comparative analysis can uncover best practices that have proven successful in improving reliability. Utilities can adapt and implement these practices to enhance their own performance. Additionally, utilities can identify areas where they excel and share their success stories with the broader industry, contributing to collective learning and improvement (Zimmerman *et al.*, 2017).

Moreover, regulatory bodies and industry organizations often use reliability benchmarking and comparative analysis to set performance standards and encourage utilities to meet specific reliability targets. Utilities may be subject to penalties or incentives based on their reliability performance relative to established benchmarks (North American Electric Reliability Corporation, 2021).

2.5.9 Interconnected Grids and Cross-Border Reliability

Interconnected grids and cross-border reliability are critical considerations in the context of power distribution systems, especially in regions where multiple grids are interconnected to enhance reliability, stability, and the efficient exchange of electricity. These interconnected systems can offer numerous advantages but also pose unique challenges related to reliability and coordination. Interconnected grids allow for the sharing of electricity resources. This means that during periods of high demand or generation in one region, surplus electricity can be shared with neighboring regions, enhancing system stability and reducing the risk of localized outages. Interconnected grids provide redundancy. If one part of the grid experiences an issue, electricity can often be rerouted from other areas, minimizing the impact of disruptions and improving overall reliability. Cross-border connections enable utilities to leverage a broader mix of energy sources. For example, regions with abundant renewable energy resources can export excess power to areas with higher demand or less favorable conditions for renewable generation.

Chapter Three

Methodology

3.0 Method

This chapter introduces the methodology employed in the study to assess the reliability of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station. It outlines the research design, data collection methods, sample selection, data analysis methods, ethical considerations, and limitations.

The methodology serves as a framework for conducting the research, ensuring transparency and validity. By detailing the research design, data collection methods, and analysis techniques chosen, this chapter establishes a systematic approach to address the research objectives. The chapter also highlights ethical considerations and acknowledges the limitations inherent in the methodology. The subsequent chapters will present and discuss the research findings within this methodological context.

3.1 Research Design

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.

3.2 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:

Surveys: Structured surveys will be conducted to collect quantitative data from relevant stakeholders, such as sub-station operators, maintenance personnel, and consumers. The surveys will include questions regarding sub-station performance, outage frequencies, and customer satisfaction. The use of surveys enables the collection of standardized and quantifiable data, providing insights into the sub-station's reliability metrics.

Interviews: Semi-structured interviews will be conducted with key stakeholders, including sub-station managers, engineers, and regulatory officials. These interviews will focus on gathering qualitative data, exploring their perspectives on sub-station reliability, operational challenges, and maintenance practices. The interviews will provide in-depth insights and a nuanced understanding of the factors influencing the reliability of the Etete Injection Sub-Station.

Observations: Direct observations will be carried out to observe the operational procedures, maintenance activities, and overall functioning of the sub-station. These observations will help

identify any visible issues, assess equipment condition, and understand the practical aspects of sub-station operations. The use of observations will complement the survey and interview data by providing real-time insights into the sub-station's functioning and potential reliability challenges.

Document Analysis: Relevant documents, such as maintenance records, incident reports, and regulatory guidelines, will be analyzed to gather additional quantitative and qualitative data. This document analysis will provide historical information on the sub-station's reliability performance, past incidents, and maintenance practices. It will help validate and contextualize the survey, interview, and observation findings.

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.

3.3 Study Area Description: Etete Injection Sub-Station

The focus of this study is the Etete Injection Sub-Station, a specific sub-station within the power distribution system. 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 Etete Injection Sub-Station plays a critical role in supplying electricity to residential, commercial, and industrial consumers in its designated area. It is subject to operational challenges, environmental factors, and maintenance requirements that can impact its reliability and performance.

By focusing on the Etete Injection Sub-Station as the study area, this research aims to assess the reliability of the sub-station and identify areas for improvement. The findings and recommendations will be specific to this sub-station, providing insights that can contribute to enhancing the overall reliability of the power distribution system in the area it serves.

Understanding the specific characteristics and context of the Etete Injection Sub-Station is essential for conducting an accurate and relevant reliability assessment. This study will provide a detailed analysis of the sub-station's performance, maintenance practices, operational challenges, and stakeholder perspectives, contributing to the knowledge and understanding of reliability assessment in the power distribution field.

3.3.1 Location and Infrastructure

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, 33/11kV 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 four feeders connected to this injection substation are:

- The 11 kV Ugbor Feeder, with about 33 11/0.415 kV transformers,
- The 11 kV Upper Sapele Feeder, with about 35 11/0.415 kV transformers,
- The 11 kV Dumez Feeder, with about 40 11/0.415 kV transformers,
- The 11 kV Ihama Feeder, with about 43 11/0.415 kV transformers,

The Etete 33kV feeders are connected to the 132/33kV, 60MVA Power Transformer T24 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.

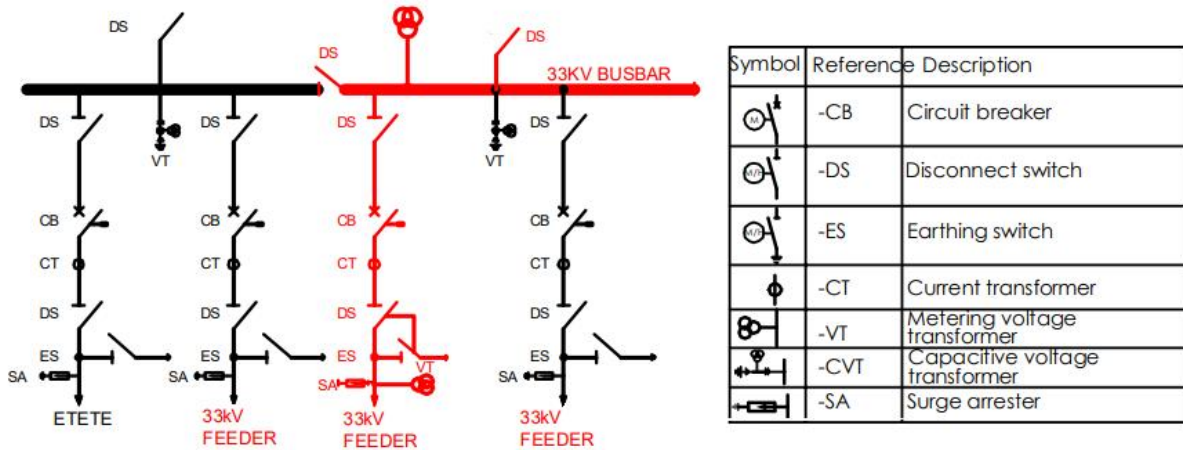


Figure 3.1: Single line diagram showing the main components of Etete injection substation

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.

3.3.2 Equipment Description

The Etete Injection Sub-Station is equipped with various components and equipment that are essential for its operation within the power distribution system. Understanding the functionality and characteristics of these equipment pieces is crucial for assessing the reliability of the sub-station. The following provides a description of the key equipment found in the sub-station:

Transformers: Transformers are crucial components within the sub-station that facilitate the conversion of electricity between different voltage levels. Step-down transformers are used to lower the high voltage received from the transmission system to a lower voltage suitable for distribution to consumers. These transformers ensure efficient and safe power transfer.

Circuit Breakers: Circuit breakers serve as protective devices within the sub-station. They are designed to interrupt the flow of electric current in the event of a fault or abnormal conditions. Circuit breakers provide overcurrent protection and help isolate faulty equipment or sections of the distribution network, preventing damage and ensuring the reliability of the sub-station.

Switchgear: Switchgear refers to a combination of electrical disconnect switches, circuit breakers, and protective relays. It is responsible for controlling, protecting, and isolating electrical equipment within the sub-station. Switchgear allows for safe switching operations, fault detection, and power system protection, contributing to the reliability of the sub-station.

Protection Devices: Various protection devices are installed in the sub-station to detect and respond to abnormal conditions. These devices include relays, fuses, and other protective

equipment. They are designed to monitor electrical parameters, detect faults, and initiate protective actions such as isolating faulty sections or activating alarms, ensuring the safety and reliability of the sub-station.

Control Systems: Control systems provide the means to monitor and manage the sub-station's operations. They include supervisory control and data acquisition (SCADA) systems, programmable logic controllers (PLCs), and human-machine interfaces (HMIs). Control systems enable remote monitoring, control of equipment, data collection, and analysis, supporting the efficient and reliable functioning of the sub-station.

Auxiliary Equipment: The sub-station may also include various auxiliary equipment and infrastructure. This can include voltage regulation equipment, lightning protection systems, communication systems, monitoring devices, and associated cabling and wiring. These auxiliary components support the overall operation and reliability of the sub-station.

Understanding the functionality, maintenance requirements, and potential vulnerabilities of these equipment components is crucial for assessing the reliability of the Etete Injection Sub-Station.

3.4 Reliability Assessment Approach and Techniques

In this study, a comprehensive approach to reliability assessment will be adopted to evaluate the reliability of the 2x7.5MVA, 33kV/11kV Etete Injection Sub-Station. The assessment will involve a combination of qualitative and quantitative techniques to provide a holistic understanding of the sub-station's reliability. The following approaches and techniques will be employed:

Reliability Indices Calculation: Standard reliability indices, such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI), will be calculated based on outage data and customer interruption records. These indices will quantitatively measure the sub-station's reliability and provide benchmarks for comparison with industry standards. The analysis will be computed using the formulae listed below:

1. Failure Rate (λ):

This is defined as the basic index of reliability which measure the frequency at which fault occurs in the system.

$$\lambda = \frac{\textit{Frequency of outage per year or month}}{\textit{Total hours of available per year or month}}$$

2. Mean Time to Failure (MTTF):

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

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

3. 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.

$$MTTR = \frac{\textit{Total System Downtime}}{\textit{Number of Outages}} = \frac{1}{\mu}$$

4. Mean Time between Failure (MTBF)

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

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

5. Availability (A)

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

$$A = \frac{\text{Uptime}}{\text{Expected Uptime}} = \frac{\mu}{\lambda + \mu} = \frac{MTBF - MTTR}{MTBF} = \frac{MTTF}{MTTF + MTTR}$$

6. Unavailability (\hat{A})

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

$$\hat{A} = \frac{\lambda}{\lambda + \mu} = 1 - \frac{MTTF}{MTTF + MTTR} = 1 - A$$

7. Reliability (R)

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

$$R = e^{-\lambda t}$$

8. 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. According to Egwaile and Oyedoh (2019), the estimated number of customers served by the Etete injection substation stands at 2800.

$$SAIFI = \frac{\textit{Frequency of Outage}}{\textit{Number of Customers Served}}$$

9. 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.

$$SAIDI = \frac{\textit{Total Outage Duration in Hours}}{\textit{Number of Customers Served}}$$

10. 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.

$$CAIDI = \frac{\textit{Sum of Customer Interruption Duration}}{\textit{Total Number of Customer Interruption}} = \frac{SAIDI}{SAIFI}$$

11. Average Service Availability Index (ASAI)

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

$$ASAI = \frac{\textit{Customer Hours of Available Service}}{\textit{Customer Hours Demanded}}$$

12. Average Service Unavailability Index (ASUI)

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

$$ASUI = \frac{\textit{Customer Hours of Unavailable Service}}{\textit{Customer Hours Demanded}}$$
$$= 1 - ASAI$$

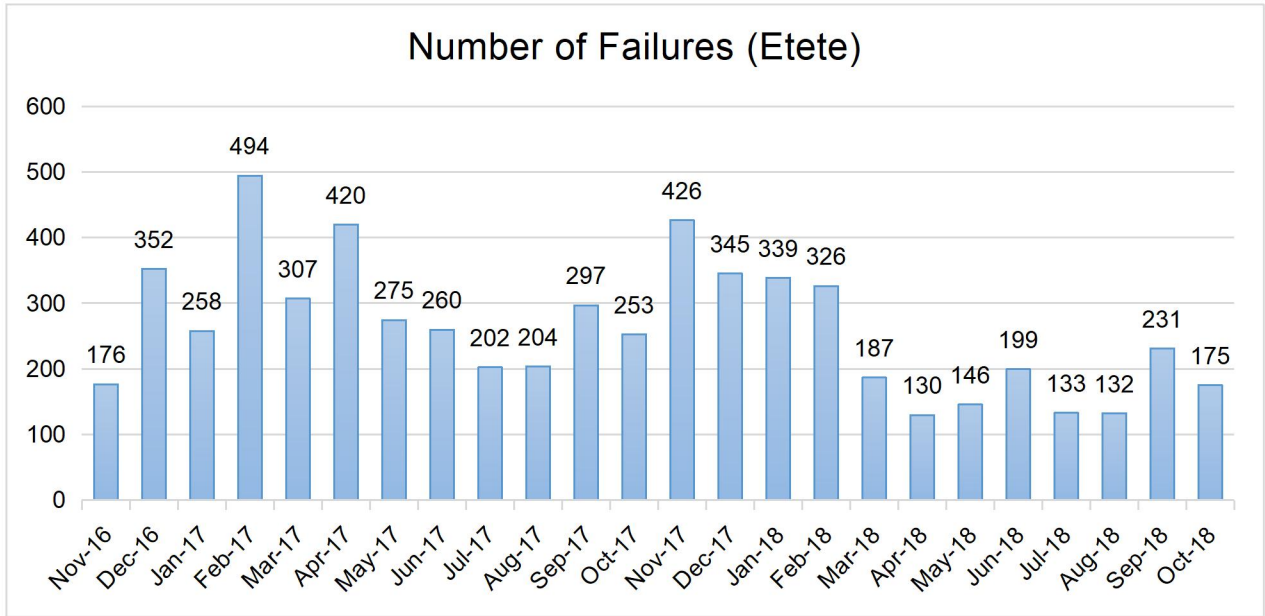


Figure 3.1: Chart showing the recorded number of failures at Etete injection substation throughout the study period

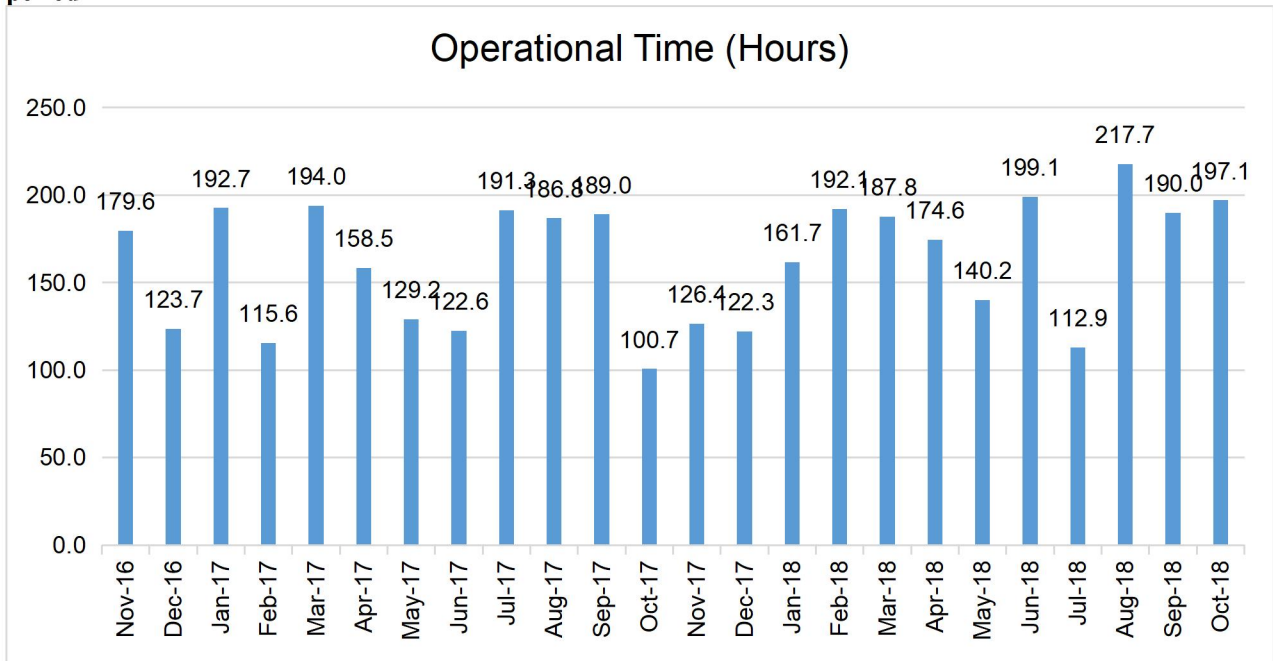


Figure 3.2: Chart showing the recorded operational time (in hours) at Etete injection substation throughout the study period

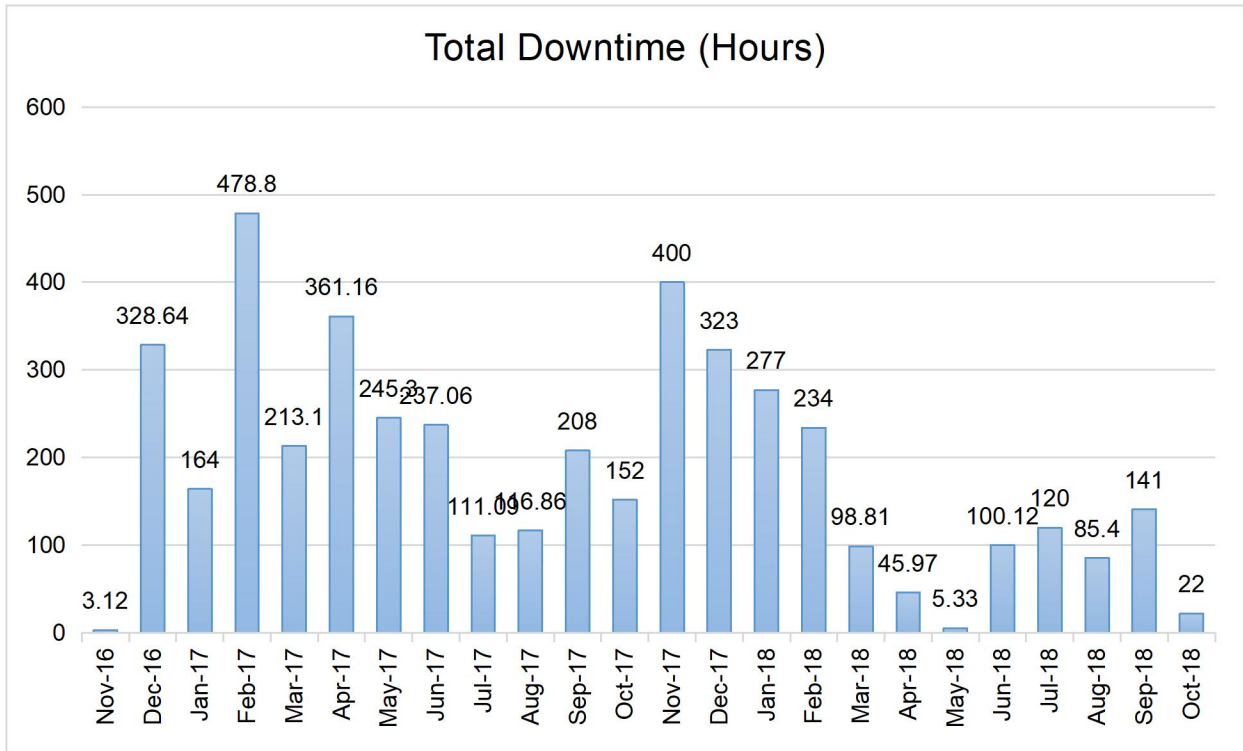


Figure 3.3: Chart showing the recorded total downtime (in hours) at Etete injection substation

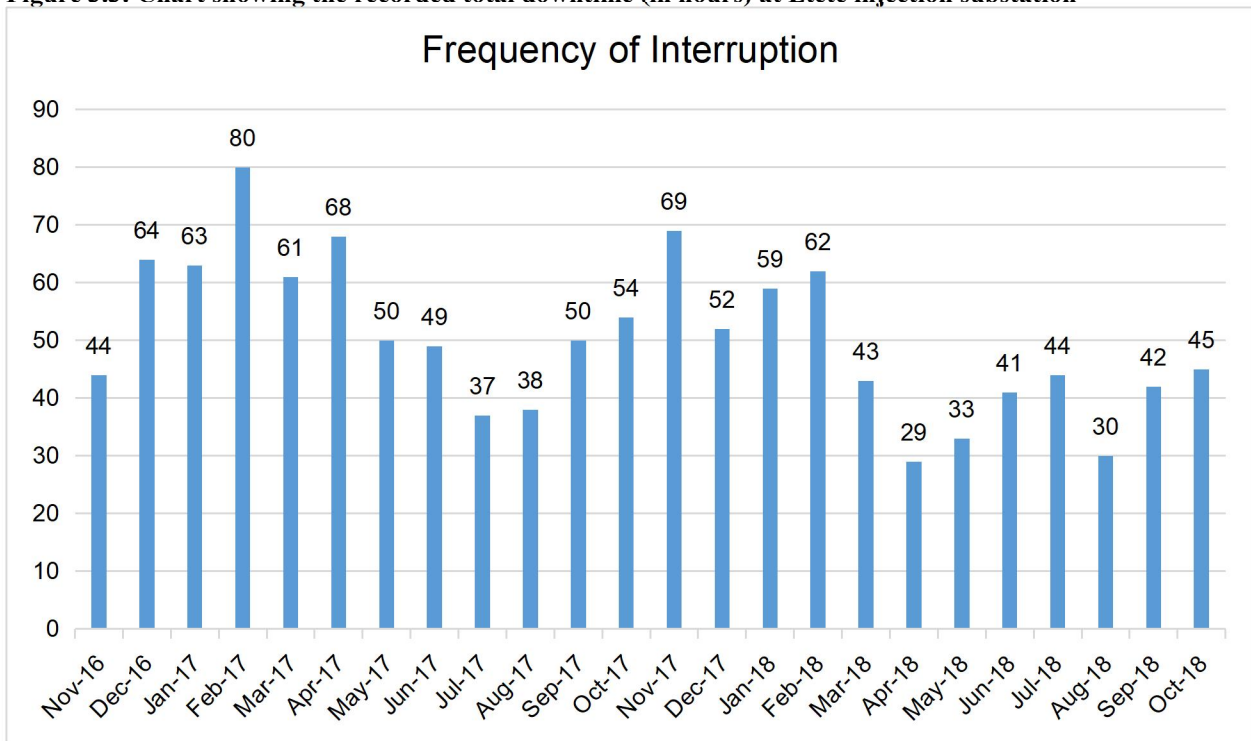


Figure 3.4: Chart showing the recorded frequency of interruption at Etete injection substation

Chapter Four:

Analysis, Discussion, and Interpretation

4.1 Reliability Analysis of Etete Injection Substation

The chapter 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.

Table 4.1: Table showing relevant data for 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

4.1.1 Failure Rate (λ):

$$\lambda = \frac{\text{Frequency of outage per year or month}}{\text{Total hours of available per year or month}}$$

Table 4.2: Table Showing 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

Table 4.2 offers a comprehensive view of the failure rates (λ) for the Etete Injection Substation over the course of two years. Notably, February 2017 exhibited the highest failure rate (0.6920), which is concerning as it indicates a significant reliability issue during that month. This spike can be attributed to a substantial 80 interruptions during that period, highlighting the adverse impact on energy supply and the potential disruptions experienced by consumers. Conversely, the data showcases a remarkable improvement in system reliability in August 2018, with the lowest failure rate (0.1378) recorded and only 30 interruptions. This suggests a period of enhanced operational stability and fewer disruptions in the electricity supply. The fluctuating trend in failure rates throughout the study period underscores the dynamic nature of the substation's

performance, which may have had notable implications for energy supply consistency and overall service quality. The average failure rate of the substation for throughout the study period is estimated to be 34.18% which indicate an enhanced performance of the substation during the period.

Figure 4.1 shows the progression of failure rate indices at Etete injection substation throughout the study period.

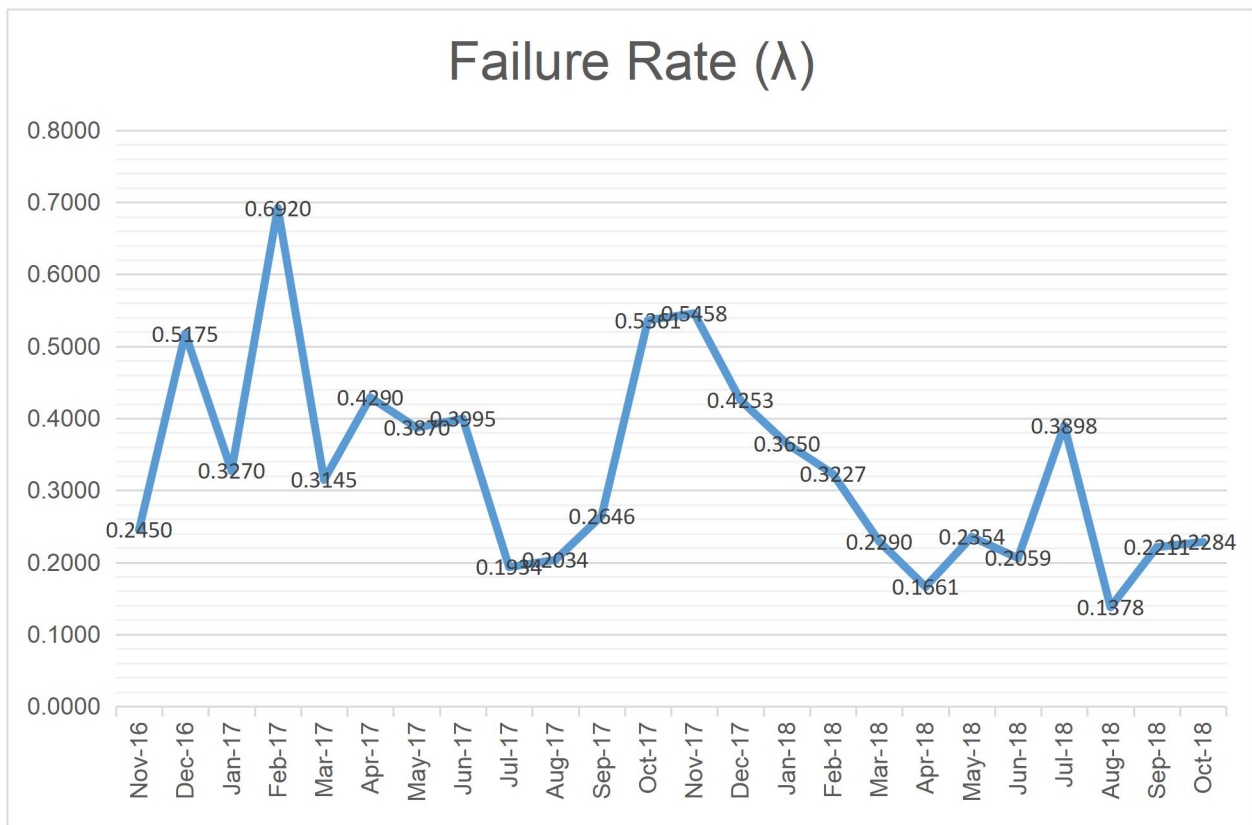


Fig. 4.1: Progression of failure rate indices at Etete injection substation

4.1.2 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.

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

Table 4.3: Table showing 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

Table 4.3 shows the Mean Time to Failure (MTTF) in hours for the Etete Injection Substation over the study period. MTTF represents how long, on average, the substation operates before experiencing a failure. In August 2018, the MTTF was the highest at 7.2567 hours, indicating improved reliability, with longer periods of uninterrupted operation. In contrast, February 2017 had the lowest MTTF at 1.4450 hours, suggesting a higher likelihood of interruptions, resulting in shorter operating periods between failures. Notably, July 2017 had a high MTTF of 5.1703

hours despite a lower failure rate, indicating good reliability that month. Figure 4.2 below gives a graphical representation of the MTTF observed at Etete injection substation through the study period.

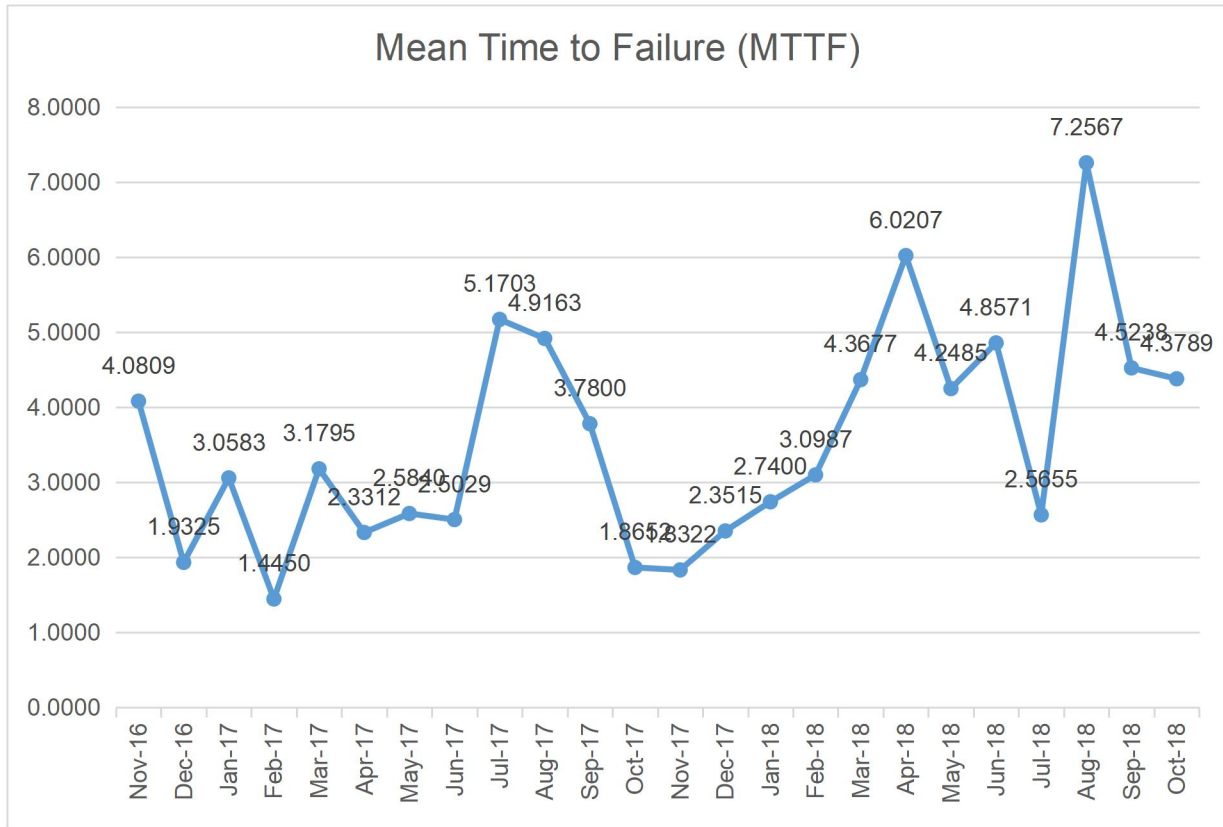


Fig. 4.2: MTTF at Etete injection substation

4.1.3 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 4.3 also shows a bar chart comparing the number of failures and downtime (in hours) at the substation.

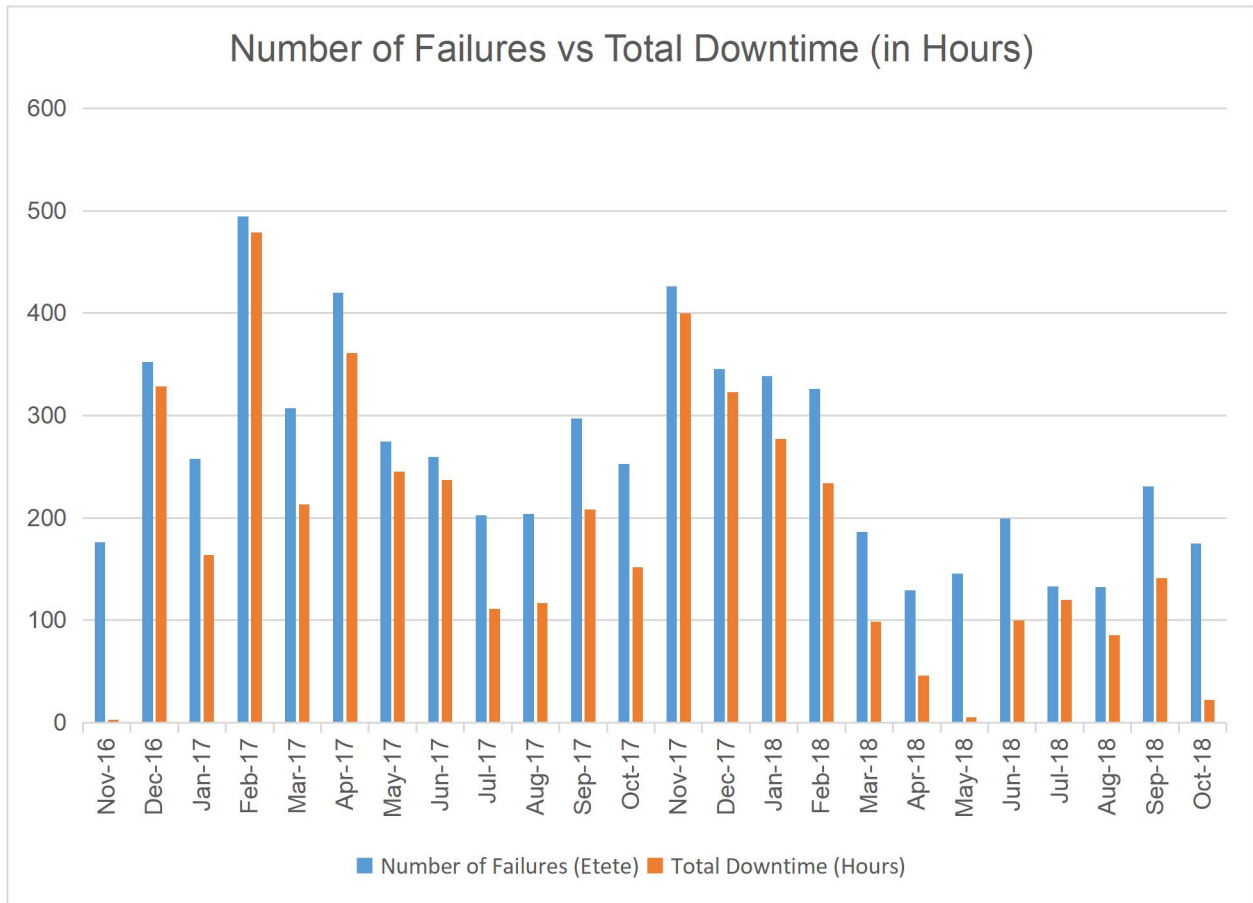


Fig. 4.3: Number of failures vs total downtime (in hours)

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

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

Table 4.4: Table showing 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

Table 4.4 presents the Mean Time to Repair or Recovery (MTTR) data for the Etete Injection Substation throughout the study period. MTTR represents the average time taken to restore the substation to normal operation after a failure. The MTTR values vary across the study period, with the highest MTTR occurring in December 2017 (6.2115), indicating that, on average, it took a significant amount of time to recover from failures during that month. Conversely, the lowest MTTR occurred in November 2016 (0.0701), suggesting that recovery from failures in that month was relatively swift. Months like November 2017 and May 2017 had high MTTR values,

indicating longer downtime periods for repair or recovery, while months like May 2018 had low MTTR values, signifying quicker recovery. The MTTR values provide crucial insights into the efficiency of maintenance and repair processes, highlighting which months experienced more prolonged disruptions and which were quickly restored to normal operation.

Figure 4.4 below shows the MTTR index of Etete injection substation.

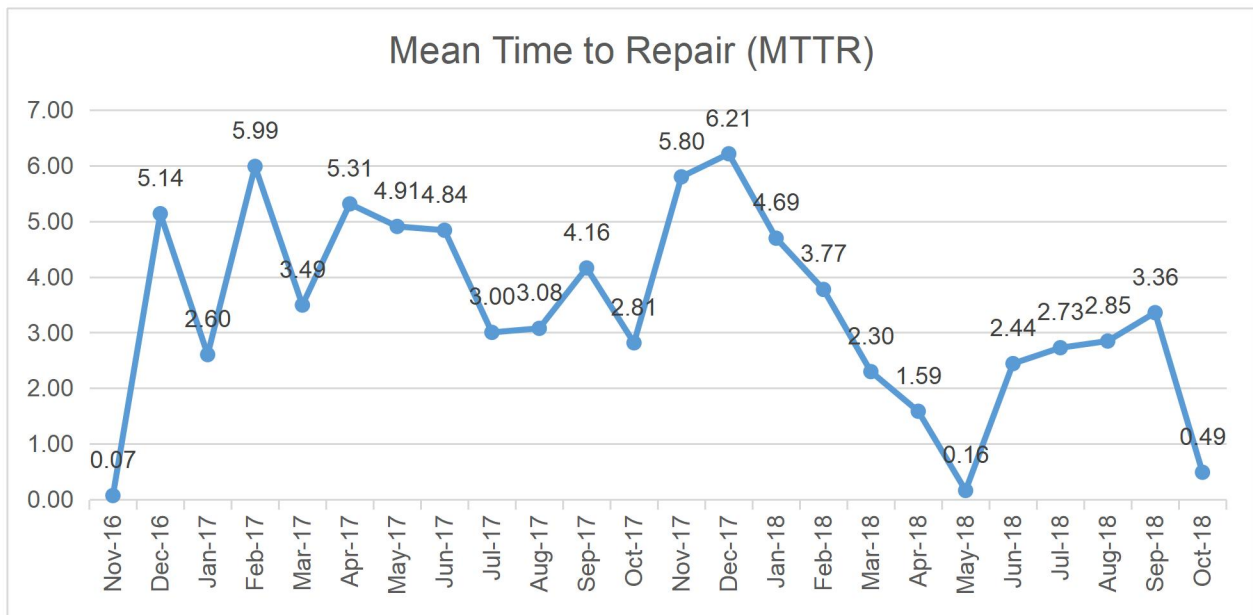


Fig. 4.4: MTTR at Etete injection substation

4.1.4 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.

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

Table 4.5: Table showing the Mean Time Between Failures (MTBF) at Etete Injection Substation Through the Study Period

Month	MTTF	MTTR	<i>MTTF + MTTR = MTBF</i>
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

Table 4.5 provides a comprehensive analysis of Mean Time Between Failures (MTBF) at the Etete Injection Substation over the study period. MTBF represents the average time between failures, combining Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR). MTBF values fluctuate, reflecting the overall reliability and downtime efficiency of the substation. Notably, August 2018 stands out with the highest MTBF (10.1034 hours), indicating extended periods between failures, largely due to a relatively high MTTF and efficient recovery (low MTTR). Conversely, November 2016 had the lowest MTBF (4.1510 hours), primarily due to a

high MTTF and a low MTTR, signifying shorter intervals between failures and longer recovery times.

Figure 4.5 below shows the MTBF at the substation

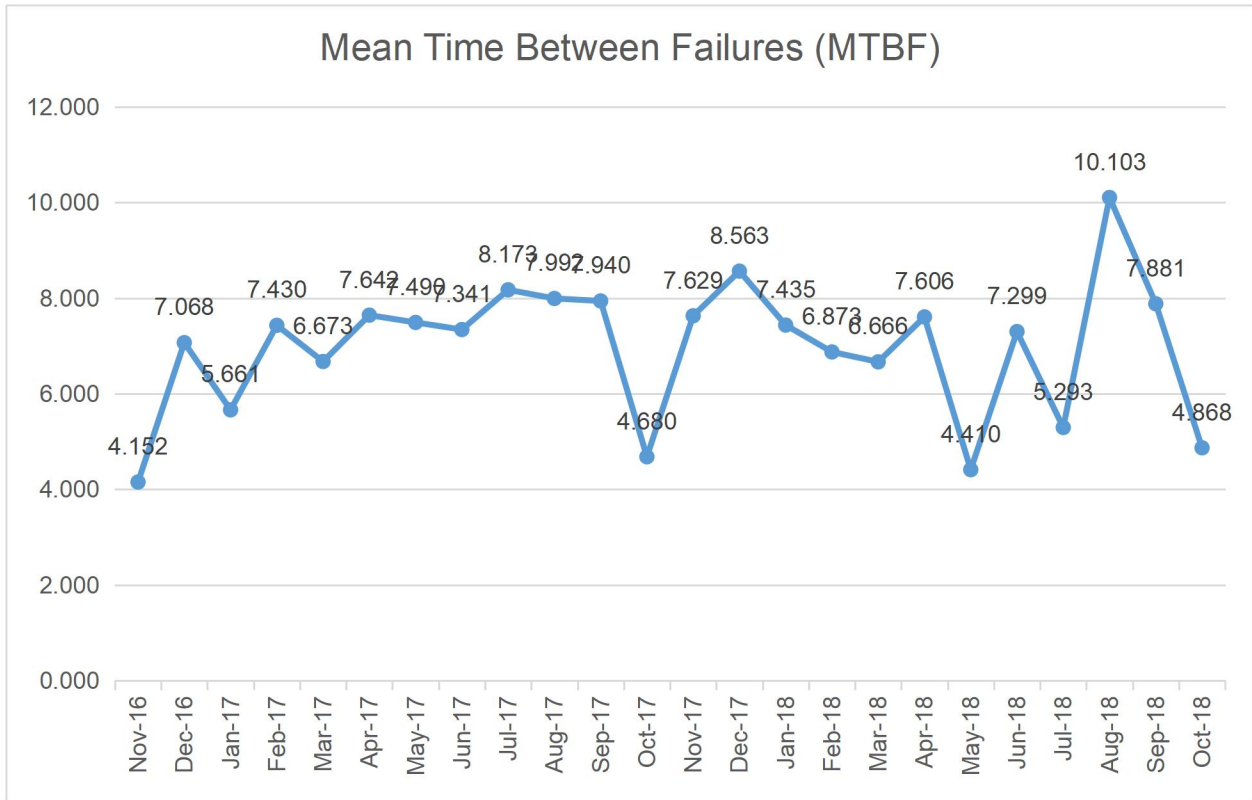


Fig. 4.5: MTBF at Etete injection substation

4.1.5 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.

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

Table 4.6: Table showing 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

Table 4.6 depicts the Availability Index for the Etete Injection Substation over the study period, quantifying the percentage of time the substation remains operational and available for use. November 2016 has the highest availability at 98.31%, signifying a period of exceptional reliability and service availability. Conversely, February 2017 records the lowest availability at 19.45%, indicating reduced availability and service interruptions owing to a low MTTF. However, the average percentage availability is estimated to be 53.08% which indicates a good reliability of the injection substation over the study period.

Figure 4.6 shows the Availability index in a line graph.

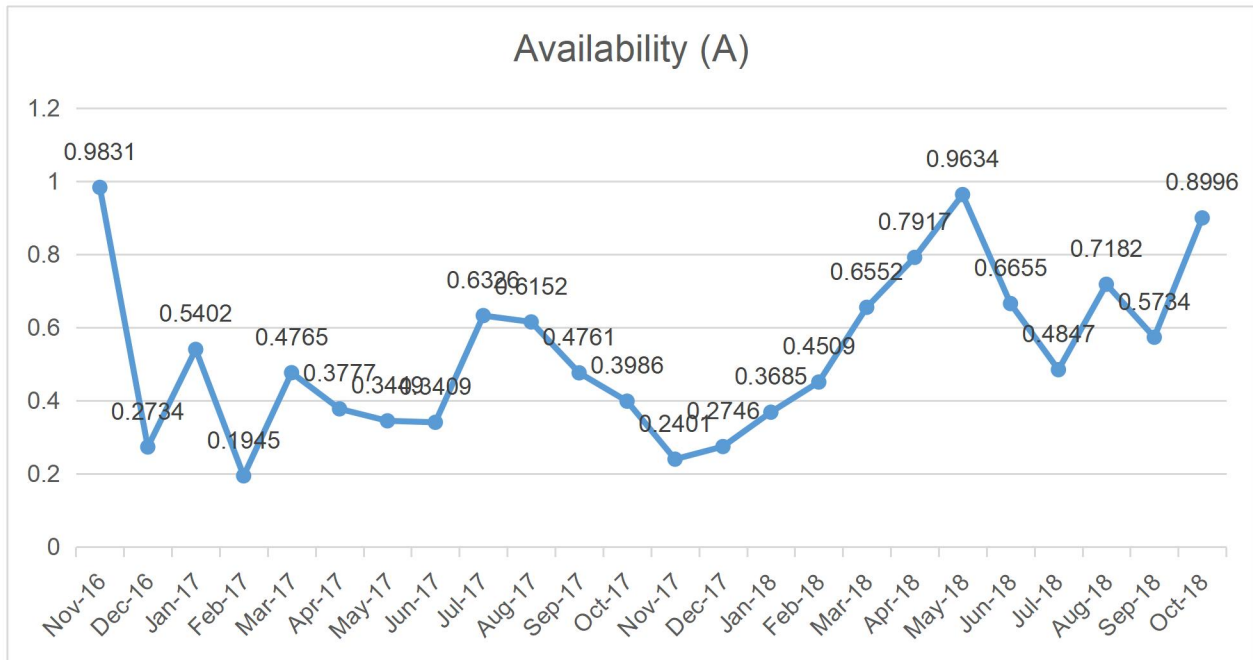


Fig. 4.6: Availability index at the substation

4.1.6 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.

$$\hat{A} = \frac{\lambda}{\lambda + \mu} = 1 - \frac{MTTF}{MTTF + MTTR} = 1 - A$$

Table 4.7: Table showing 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

Table 4.7 presents the Unavailability Index for the Etete Injection Substation throughout the study period, which is essentially the complement of the Availability Index (A). This index quantifies the percentage of time the substation is not operational and unavailable for use. The data shows that November 2016 had the lowest unavailability at 0.0169, signifying high availability, while February 2017 recorded the highest unavailability at 0.8055, indicating a significant period of unavailability and service disruptions. The overall average percentage unreliability of the injection substation is estimated to be 46.92% over the study period.

Figure 4.7 shows the unavailability index computed from data for Etete injection substation

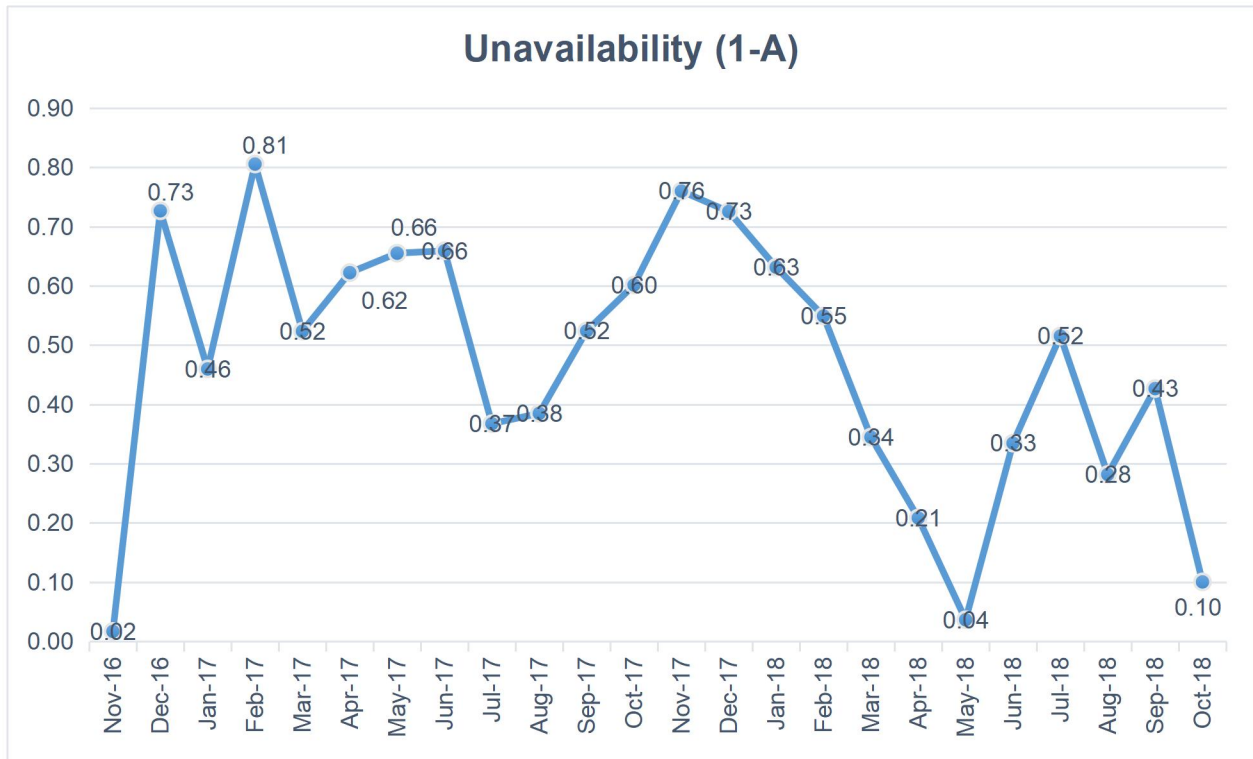


Fig. 4.7: Unavailability (1 – A) at Etete injection substation

4.1.7 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.

$$R = e^{-\lambda t}$$

Table 4.8: Table showing 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

Table 4.8 provides insights into the Reliability Index at the Etete Injection Substation throughout the study period. The Reliability Index is calculated using the failure rate (λ) and reflects the likelihood of the substation operating without failures. August 2018 stands out with the highest reliability at 0.8713, indicating a robust and dependable performance, primarily attributed to the exceptionally low failure rate (λ) during that month. In contrast, February 2017 records the lowest reliability at 0.5006, signifying a period marked by frequent failures and reduced system dependability, primarily due to the highest λ observed during that month. However, the average

percentage reliability of the substation over the study period is estimated to be 72.37% which indicate an efficient operating performance.

Figure 4.8 shows the computed reliability index in graphical form.

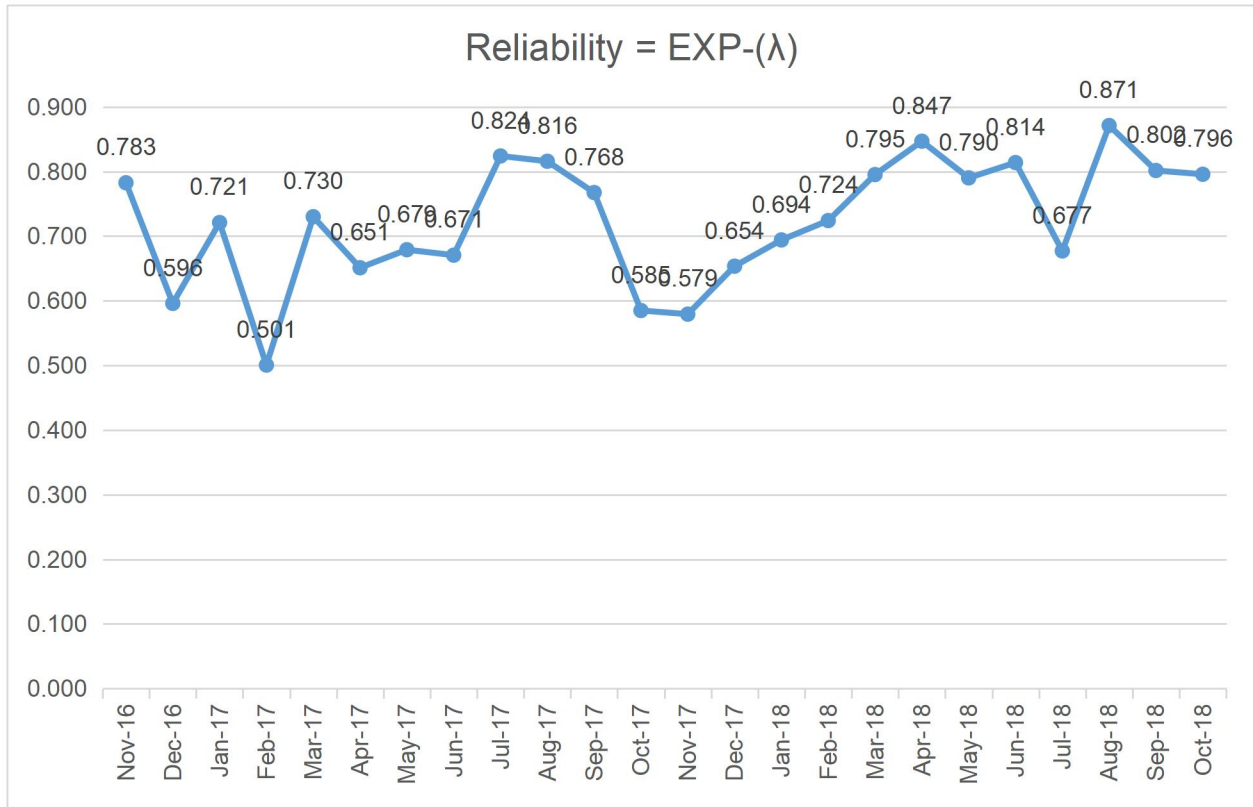


Fig. 4.8: Reliability index

4.1.8 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.

$$SAIFI = \frac{\textit{Frequency of Outage}}{\textit{Number of Customers Served}}$$

Table 4.9: Table showing 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

Table 4.9 presents the System Average Interruption Frequency Index (SAIFI) for the Etete Injection Substation throughout the study period. SAIFI quantifies the average number of interruptions experienced by each customer served by the substation. February 2017 had the highest SAIFI at 0.0286, indicating that, on average, each customer experienced approximately 0.0286 interruptions during that month. This reflects a period of relatively frequent interruptions. Conversely, April 2018 recorded the lowest SAIFI at 0.0104, suggesting each customer

experiencing approximately fewer interruptions on average. The average percentage SAIFI of the substation is estimated to be 1.87% over the study period, this indicates an enhanced performance of the system. Hence, a robust reliability

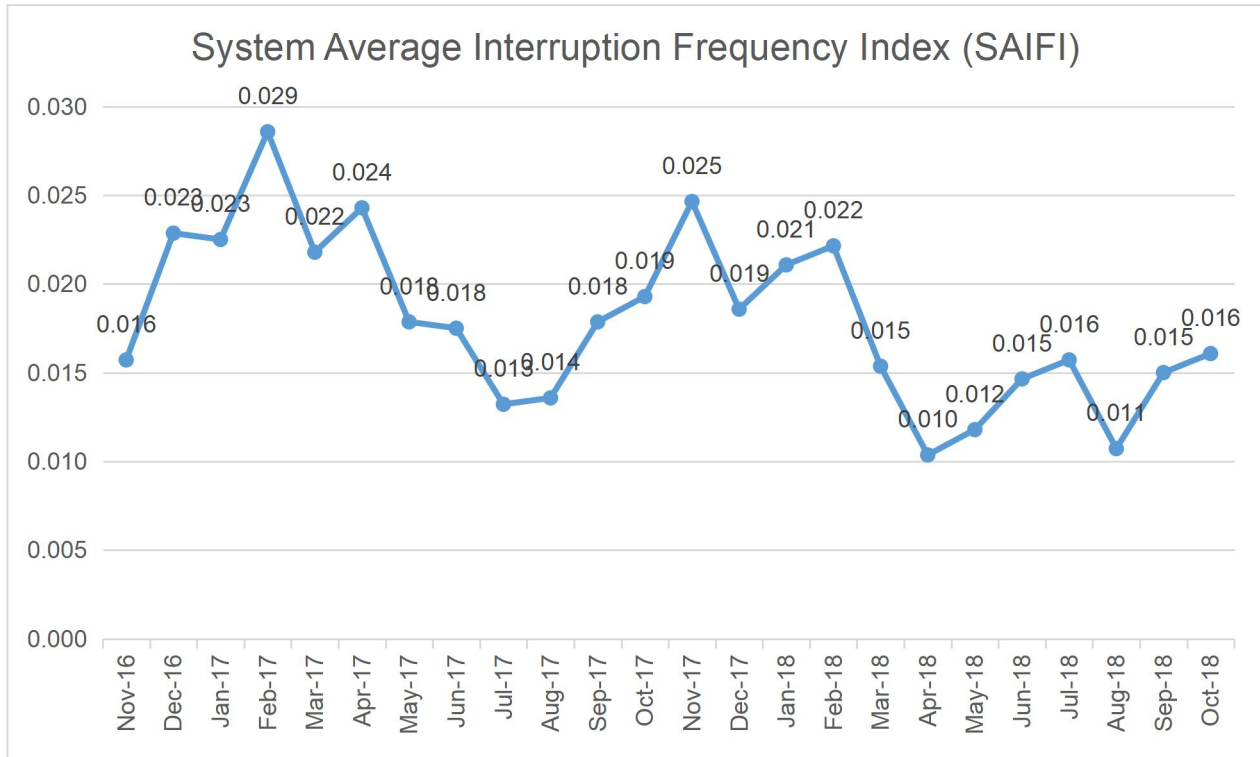


Fig. 4.9: SAIFI at the injection substation

4.1.9 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.

$$SAIDI = \frac{\text{Total Outage Duration in Hours}}{\text{Number of Customers Served}}$$

Table 4.10: Table showing 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

Table 4.10 provides data on the System Average Interruption Duration Index (SAIDI) for the Etete Injection Substation over the study period. SAIDI represents the average duration of interruptions experienced by each customer served by the substation. In February 2017, the SAIDI was the highest at 0.1766, indicating that, on average, each customer experienced interruptions totaling approximately 0.1766 hours during that month. This reflects a period of relatively long and frequent interruptions. Conversely, in April 2018, the SAIDI was the lowest

at 0.0463, suggesting a month with shorter and less frequent interruptions on average. However, the average percentage SAIDI is estimated to be 9.33% over the study period.

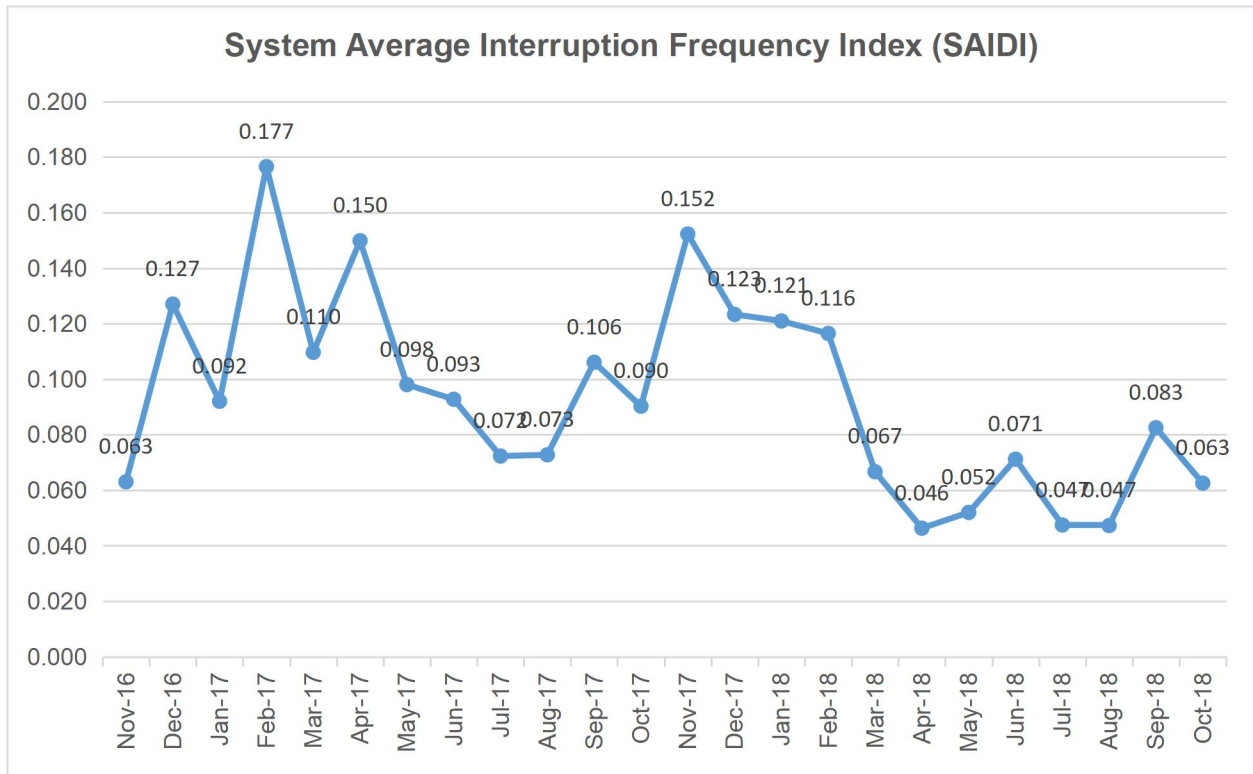


Fig. 4.10: SAIDI

4.1.10 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.

$$CAIDI = \frac{\text{Sum of Customer Interruption Duration}}{\text{Total Number of Customer Interruption}} = \frac{SAIDI}{SAIFI}$$

Table 4.11: Table showing 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

Table 4.11 presents the Customer Average Interruption Duration Index (CAIDI) for the Etete Injection Substation throughout the study period. CAIDI quantifies the average duration of interruptions experienced by each customer affected by outages. In December 2017, CAIDI was the highest at 6.6400, indicating that, on average, customers experienced approximately 6.6400 hours of interruption during that month. This reflects a period with both longer and more frequent interruptions. Conversely, in July 2018 and October 2018, CAIDI was the lowest at

3.0200 and 3.8900, respectively, suggesting months with shorter average interruption durations, despite variations in the frequency of interruptions.

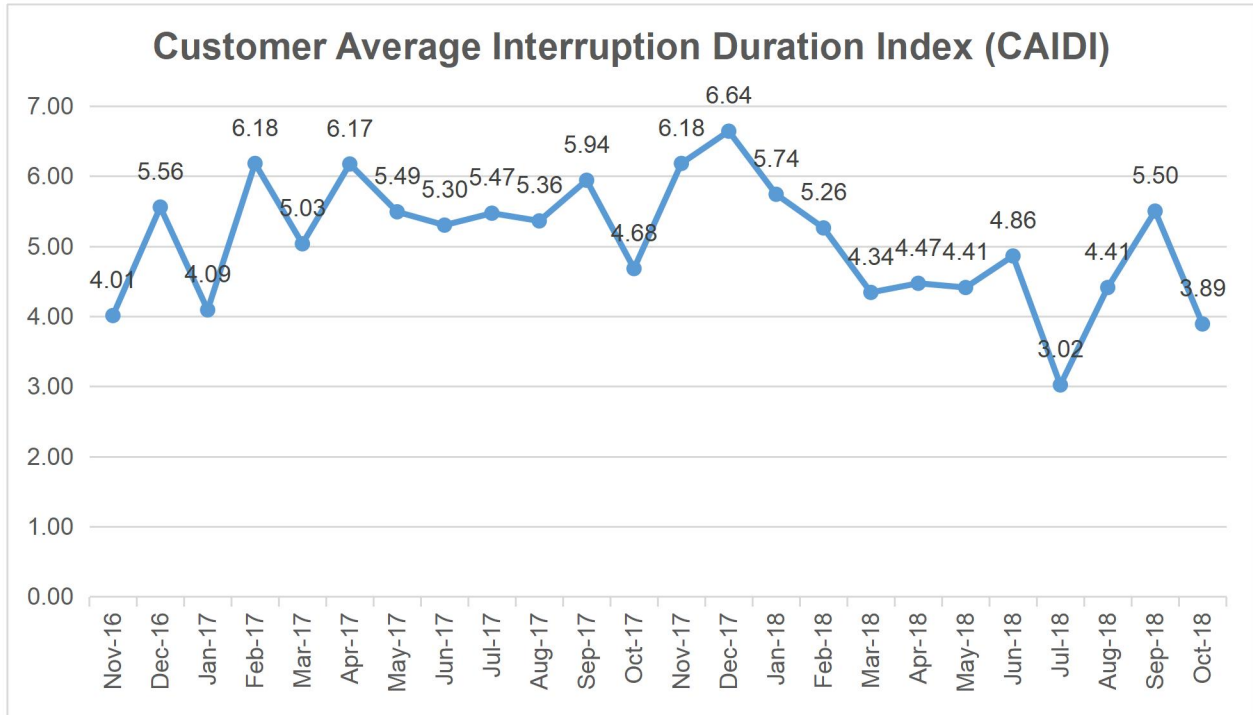


Fig. 4.11: CAIDI

4.1.11 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.

$$ASAI = \frac{\text{Customer Hours of Available Service}}{\text{Customer Hours Demanded}}$$

Table 4.12: Table Showing 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

Table 4.12 presents the Average Service Availability Index (ASAI) for the Etete Injection Substation throughout the study period. ASAI measures the average availability of electrical service to meet customer demands. The ASAI values fluctuate over the study period, ranging from a low of 13.54% in October 2017 to a high of 29.26% in August 2018. August 2018 stands out as the month with the highest ASAI at 29.26%, indicating that, on average, nearly 29.26% of the customer hours demanded were met during that month. In contrast, October 2017 had the lowest ASAI at 13.54%, suggesting a month with significantly lower service availability relative

to customer demand. However, the overall average ASAI percentage over the study period is estimated to be 22.31%

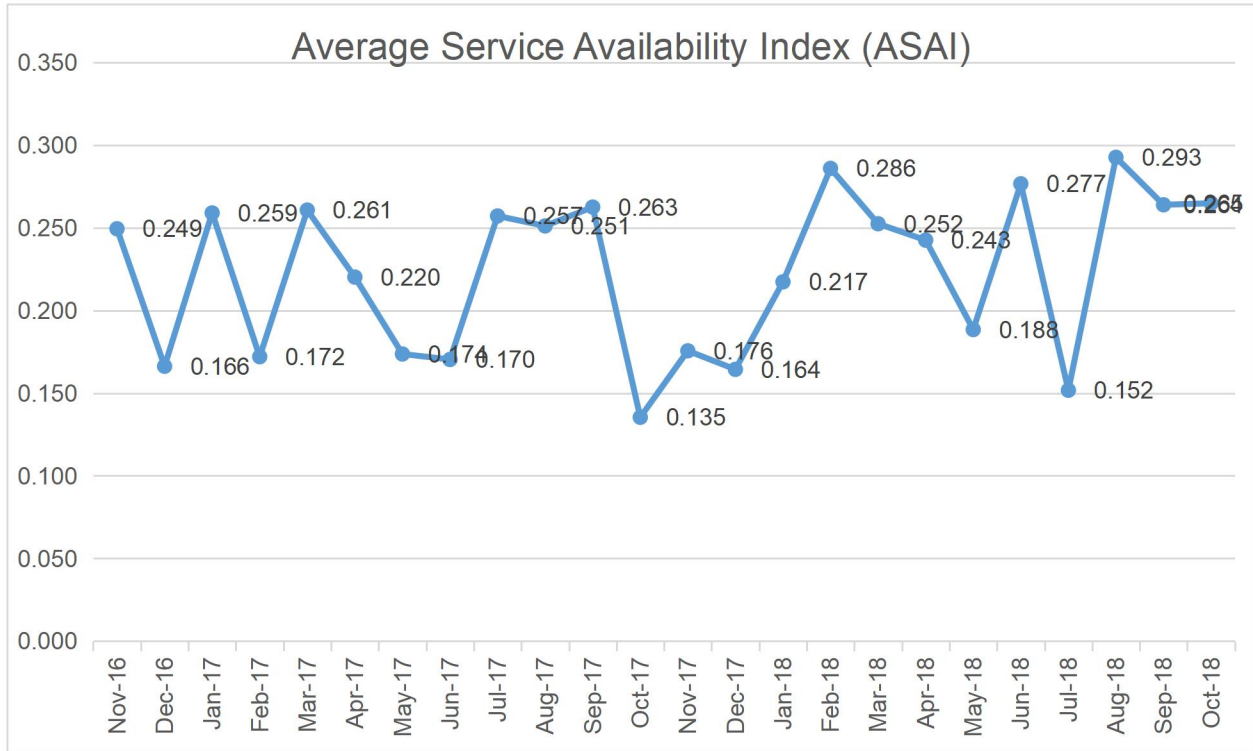


Fig. 4.12: ASAI

4.1.12 Average Service Unavailability Index (ASUI):

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.

$$ASUI = \frac{\text{Customer Hours of Unavailable Service}}{\text{Customer Hours Demanded}}$$

$$= 1 - ASAI$$

Table 4.13: Table Showing 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

Table 4.13 presents the Average Service Unavailability Index (ASUI) for the Etete Injection Substation throughout the study period, which quantifies the average unavailability of electrical service. ASUI values fluctuate over the study period, ranging from a low of 70.74% in August 2018 to a high of 86.46% in October 2017. October 2017 stands out as the month with the highest ASUI at 86.46%, indicating that, on average, nearly 86.46% of service was unavailable, reflecting a month of significant unavailability. Conversely, August 2018 had the lowest ASUI at 70.74%, suggesting a month with relatively lower service unavailability compared to the rest of

the study period. But the overall average percentage ASUI over the study period is estimated to be 74.60%

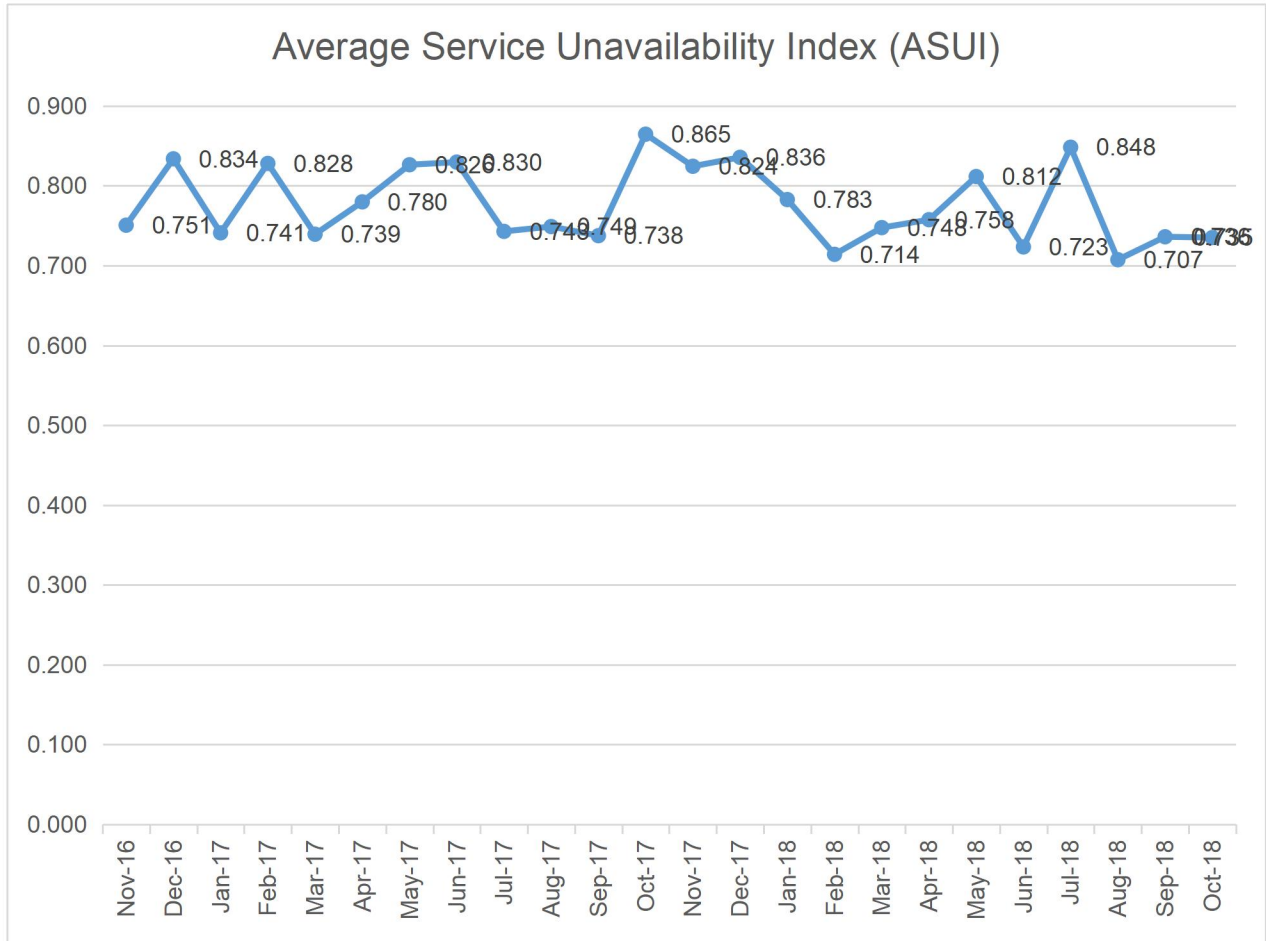


Fig. 4.13: ASUI

Figure 4.14 also paints a clearer picture of the poor availability of power available compared to customer hours demanded at the substation.

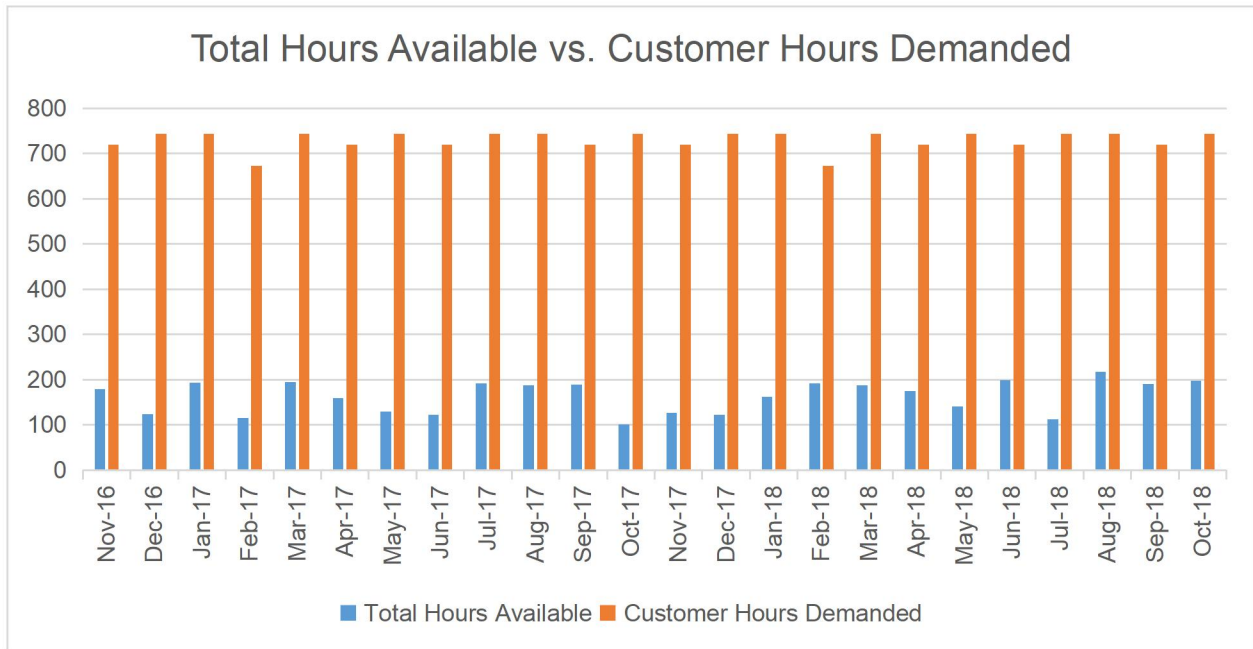


Fig. 4.14: Total Hours Available vs Customer Hours Demanded

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.

4.2 Discussion and Interpretation of Results

The failure rate data (Table 4.2) reveal fluctuations in the substation's reliability over the study period. Notably, February 2017 exhibited the highest failure rate (0.6920), indicating a period of significant operational challenges with 80 interruptions. Conversely, August 2018 demonstrated the lowest failure rate (0.1378), suggesting improved reliability with only 30 interruptions. This underscores the importance of analyzing failure rates to pinpoint vulnerable periods and allocate resources effectively. However, the overall average percentage Failure rate is estimated to be 34.18%, indicating an improved reliability of the substation over the study period.

Mean Time to Failure (MTTF): The MTTF data (Table 4.3) present the average time between failures, highlighting the substation's ability to sustain continuous operation. The substation exhibited varying MTTF values, with August 2018 displaying the longest MTTF (7.2567 hours) and February 2017 the shortest (1.4450 hours). These fluctuations indicate periods of both improved and diminished reliability.

Table 4.4 - Mean Time to Repair or Recovery (MTTR): Table 4.3 introduces the MTTR, focusing on the time required to restore service after an interruption. The data reveal that the substation generally experienced longer MTTR values during periods with higher failure rates, indicating that restoring service was more time-consuming during operational challenges.

Availability Index: The Availability Index (Table 4.6) quantifies the availability of the substation's service. The data demonstrate fluctuations in availability, with November 2016 showing the highest Availability Index (98.31%) and February 2017 the lowest (19.45%). Higher availability suggests improved service continuity, the overall percentage Availability is estimated to be 53.08% over the study period

Unavailability Index: The Unavailability Index (Table 4.7) complements the Availability Index by quantifying the unavailability of service. November 2016 had the lowest Unavailability Index (0.0169), indicating a period of high service availability. In contrast, February 2017 exhibited the highest Unavailability Index (0.8055), suggesting service disruptions, with overall percentage unavailability estimated to be 46.92% over the study period.

Reliability Index: The Reliability Index (Table 4.8) presents reliability values derived from failure rates, with November 2016 having the highest reliability (0.7827). February 2017 displayed the lowest reliability (0.5006), emphasizing the variability in service reliability.

However, the average percentage reliability of the substation over the study period is estimated to be 72.37% which indicate an efficient operating performance.

Table 4.9 - System Average Interruption Frequency Index (SAIFI): SAIFI (Table 4.9) offers insights into customer experiences by quantifying the frequency of interruptions. Notably, February 2017 had the highest SAIFI (0.0286), indicating a higher likelihood of customers experiencing interruptions during that month. On the other hand, April 2018 had a comparatively lower SAIFI (0.0104), suggesting improved service continuity, With average percentage SAIFI of 1.87% over the study period.

Table 4.10 - System Average Interruption Duration Index (SAIDI): SAIDI data (Table 4.10) portray the average duration of interruptions experienced by customers. The results vary over the study period, with January 2017 having the highest SAIDI (0.1766), reflecting extended service disruptions. Conversely, August 2018 demonstrated the lowest SAIDI (0.0473), signifying shorter interruptions and more reliable service. With average percentage SAIDI of 9.33% over the study period.

Table 4.11 - Customer Average Interruption Duration Index (CAIDI): CAIDI (Table 4.11) combines SAIDI and SAIFI to assess the average duration of interruptions for affected customers. The data highlight that December 2017 had the highest CAIDI (6.6400), indicating that customers who experienced interruptions during that month faced longer downtime. July 2018, conversely, exhibited the lowest CAIDI (3.0200), implying shorter customer downtime.

Availability Index: The Availability Index (Table 4.6) quantifies the availability of the substation's service. The data demonstrate fluctuations in availability, with November 2016 showing the highest Availability Index (98.31%) and February 2017 the lowest (19.45%). Higher

availability suggests improved service continuity, the overall percentage Availability is estimated to be 53.08% over the study period

Average Service Availability Index (ASAI): The ASAI data (Table 4.12) depict the substation's service availability, with August 2018 showing the highest ASAI (29.31%) and October 2017 the lowest (13.54%). These values offer insights into service continuity and customer demand and the over percentage ASAI is estimated to be 22.31% over the study period.

Service Unavailability Index (ASUI): The ASUI data (Table 4.13) complement the ASAI by quantifying service unavailability. August 2018 exhibited the lowest ASUI (0.7074), indicating a period of high service availability, while October 2017 had the highest ASUI (0.8646), signifying service disruptions. the over percentage ASUI is estimated to be 74.60% over the study period

Chapter Five:

Summary, Conclusion, and Recommendations for Further Studies

5.1 Summary of the Study

This chapter encapsulates the essential points discussed in the preceding chapters, offering a concise overview of the substation's performance over the study period.

The analysis encompassed various critical metrics, including failure rate, 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).

The substation's reliability was found to vary significantly from month to month, with some periods experiencing higher failure rates and shorter MTTF, indicating lower reliability. The efficiency of repair and recovery processes also fluctuated, impacting the duration of interruptions experienced by customers. Availability and unavailability metrics reflected the extent of the substation's operational uptime and downtime due to failures. Additionally, SAIFI, SAIDI, and CAIDI values highlighted the frequency and duration of customer interruptions, emphasizing the importance of minimizing disruptions. The adequacy of service provision was assessed through ASAI and ASUI values.

5.2 Conclusion

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.

5.3 Limitations Encountered

Data Availability and Quality: One of the primary limitations of this study may have been the availability and quality of data. The accuracy and completeness of historical data on substation performance, maintenance records, and outage information could significantly impact the reliability analysis. Incomplete or inaccurate data may have led to potential biases in the findings.

Scope of Data: The study may have been limited by the scope of available data. If data collection was constrained to a specific time frame or did not include all relevant parameters, the analysis may not fully capture the dynamics of substation reliability over a more extended period.

5.4 Recommendations and Suggestions for Further Studies

Based on the findings of the reliability analysis, the following recommendations are proposed:

- **Enhanced Maintenance:** Implement a proactive maintenance strategy to reduce the frequency of failures and improve the overall reliability of the substation.
- **Efficient Repairs:** Optimize repair and recovery processes to minimize MTTR, ensuring faster restoration of service during outages.
- **Predictive Maintenance:** Utilize predictive maintenance techniques to increase MTBF, reducing the occurrence of failures.
- **Contingency Planning:** Develop a robust contingency plan to address outages promptly and efficiently, minimizing customer interruptions.
- **Real-time Monitoring:** Continuously monitor the substation's performance and make real-time adjustments to improve availability and reliability.
- **Modernization:** Consider upgrading or modernizing equipment and systems to enhance overall substation performance.

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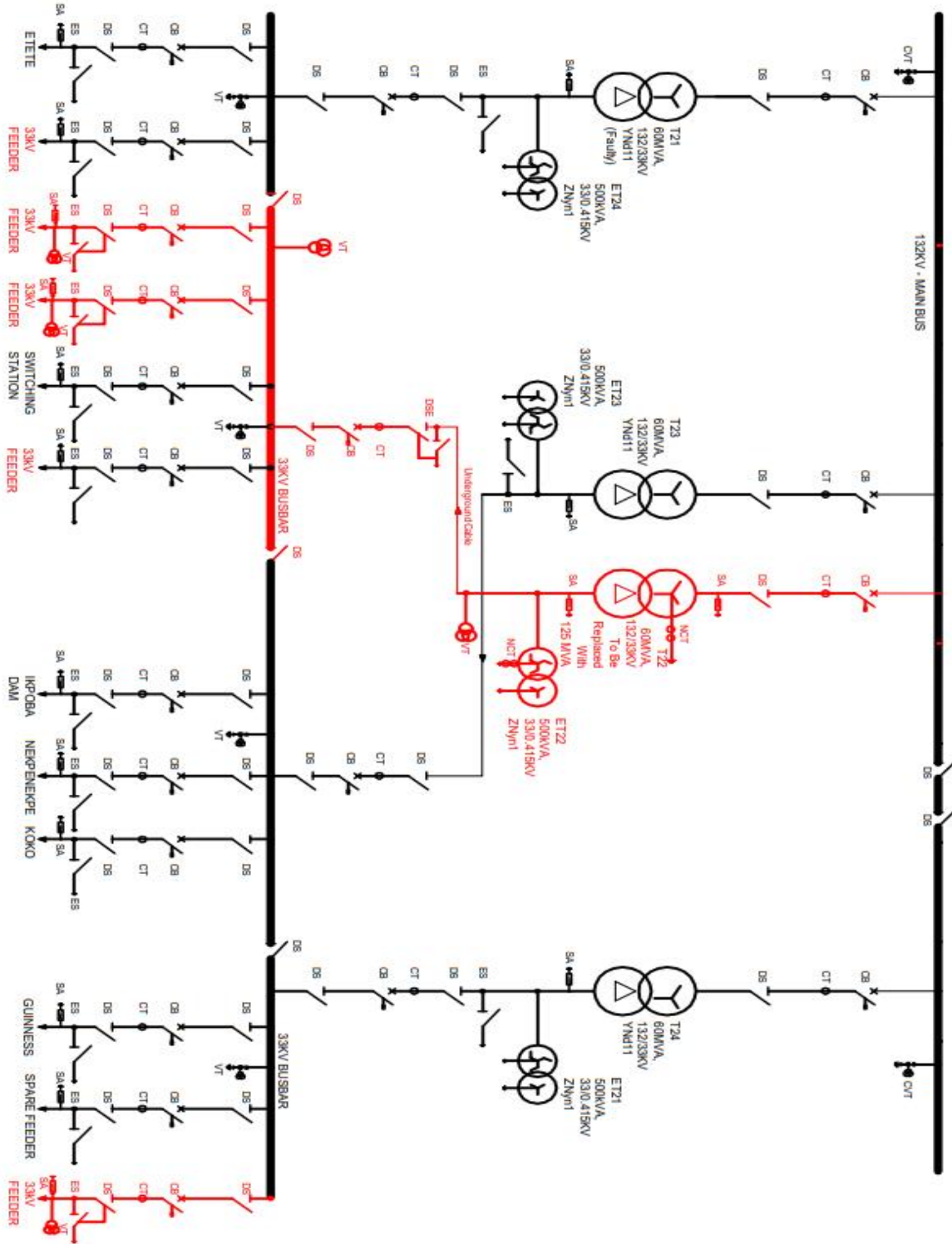
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Appendix 1



Appendix 2

Availability (A) is the probability that an equipment will be available to perform as required or that it will be in a state of operational effectiveness within a given period. It is defined in terms of MTTR as (8). Reliability (R) is the probability that the system will continue to perform a given function at any point in time.

$$\text{Availability (A)} = (\text{MTBF} - \text{MTTR})/\text{MTBF} \quad (8)$$

$$\text{Reliability (R)} = e^{-\lambda t} \quad (9)$$

Where λ is the failure rate, R is the reliability and t is the time (day)

3. Results and Discussion

The analysis focused on the determination of the failure rate, operating time, availability and reliability of the substation from November 2016 to October 2018 using Microsoft excel tool. As stated earlier, a reliability study of 33-kV feeder network of the Transmission Company of Nigeria (TCN), GRA and Etete Injection substations were carried out in this research. Number of outage and down time losses were collated from the log book of the Benin Transmission Station and analysed. More so, computation of the reliability customer based indices showing the forced outage annual ASAI index were analysed using (1) to (4) and presented in Tables 1 to 8.

Table 1. Results of the Frequency of Interruption and the MTTR for Etete and GRA 33kV Feeders

Month	Frequency of Interruption	MTTR (Hours)	
		GRA	Etete
November 2016	44	2.15	4.01
December 2016	64	2.29	5.52
January 2017	63	2.23	4.09
February 2017	80	5.71	6.18
March 2017	61	4.71	5.05
April 2017	68	5.95	6.16
May 2017	50	5.49	6.56
June 2017	49	5.30	6.86
July 2017	37	5.47	6.90
August 2017	38	5.36	6.39
September 2017	50	5.94	6.10
October 2017	54	2.61	4.68
November 2017	69	4.50	6.18
December 2017	52	3.02	6.64
January 2018	59	3.13	5.74
February 2018	62	3.23	5.26
March 2018	43	4.34	5.67
April 2018	29	4.47	6.60
May 2018	33	4.41	6.40
June 2018	41	2.88	4.86
July 2018	44	2.56	3.02
August 2018	30	2.35	4.41
September 2018	42	4.61	5.50
October 2018	45	2.21	3.89

Table 2. Three years feeder by feeder 33-kV outage due to fault

Year	GRA Feeder	Etete Feeder	Total
2016	16	21	37
2017	35	40	75
2018	15	20	35
Grand total	66	81	147

Table 3. Calculated value of 33-kV reliability indices for November 2016–October 2018

Feeders	Year	Failure Rate, λ (hr)	MTTR (hr)	MTBF (hr)	Availability (%)	Reliability (%)
Etete/GRA	2016	0.003181/0.002331	4.41/2.86	340.5/360.75	82.76/91.59	84.59/93.76
Etete/GRA	2017	0.001270/0.002175	3.84/6.74	168.26/360.57	84.73/91.18	85.68/93.73
Etete/GRA	2018	0.002705/0.001130	3.44/5.22	217.36/297.78	87.32/92.63	89.47/94.32

Table 4. Summary of failure rate, reliability and availability for GRA and Etete

Months	Failure Rate		Reliability		Availability	
	GRA	Etete	GRA	Etete	GRA	Etete
November 2016	0.001609	0.001425	79.65	74.59	79.38	72.54
December 2016	0.001144	0.001811	75.58	70.21	74.44	69.14
January 2017	0.001937	0.001686	81.45	42.01	83.65	42.00
February 2017	0.002658	0.002443	73.43	68.69	71.43	60.69
March 2017	0.002502	0.001748	79.92	75.26	78.15	73.24
April 2017	0.001622	0.001979	78.67	72.84	77.81	71.56
May 2017	0.001437	0.001439	76.85	72.14	74.25	70.24
June 2017	0.001617	0.001321	87.38	65.53	85.82	61.11
July 2017	0.000197	0.000931	92.66	76.55	89.00	70.55
August 2017	0.000975	0.000934	93.96	61.22	91.04	56.98
September 2017	0.001199	0.001352	86.91	83.37	85.59	81.44
October 2017	0.001947	0.001439	84.28	50.32	84.03	49.03
November 2017	0.002562	0.002135	73.86	67.72	73.79	66.67
December 2017	0.001498	0.001391	84.48	79.40	83.71	71.37
January 2018	0.001534	0.001505	87.22	44.32	87.20	40.30
February 2018	0.001638	0.001946	84.99	75.72	83.97	71.64
March 2018	0.001151	0.001085	95.64	76.45	86.93	72.44
April 2018	0.000403	0.000731	95.47	71.25	90.78	70.22
May 2018	0.000539	0.000801	90.87	80.68	89.86	69.14
June 2018	0.001943	0.001081	89.99	78.76	86.71	76.65
July 2018	0.001286	0.001127	87.94	81.60	87.43	75.93
August 2018	0.007719	0.007677	93.12	91.54	80.53	76.45
September 2018	0.001684	0.001639	82.91	79.63	81.90	78.44
October 2018	0.000952	0.000489	89.41	84.32	88.40	81.32

Table 5. Forced outage annual SAIFI index

Months	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
GRA Feeder	7.8	7.8	9.6	8.0	7.2	9.8	6.6	6.6	7.2	6.6	8.0	8.9
Etete Feeder	8.4	7.2	5.4	6.6	7.8	8.9	9.0	8.9	8.9	4.2	4.2	6.6

Table 6. Forced outage annual SAIDI index

Months	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
GRA Feeder	10.29	12.21	12.11	13.45	13.22	13.49	10.14	4.85	10.12	13.23	10.02	11.89
Etete Feeder	12.42	10.70	5.75	12.42	9.74	10.68	9.83	4.34	12.21	4.83	4.43	4.83

Table 7. Forced outage annual CAIDI index

Months	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
GRA Feeder	2.638	3.733	2.985	3.202	3.453	4.497	3.436	2.939	2.842	4.409	2.390	4.404
Etete Feeder	3.721	2.972	2.130	4.736	2.497	2.086	3.465	2.226	2.287	3.574	4.214	2.924

Table 8. Forced outage annual ASAI index

Months	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
GRA Feeder	1.986	1.980	1.980	1.981	1.983	1.963	1.984	1.987	1.985	1.966	1.986	1.970
Etete Feeder	1.978	1.985	1.992	1.978	1.986	1.985	1.973	1.988	1.980	1.987	1.988	1.987

As observed from the summary of results (Table 4 and Figure 2) within the period of investigation the GRA feeder was more reliable of the two feeders with an average of 83.4% for the period of the investigation as against 69.78% for the Etete feeder. This may be attributed to the fact that the GRA feeder has been a priority feeder that feeds the Government Residential Areas. This is an indication that only random external event could lead to failure in the feeder although, more work still need to be done in order to improve on the reliability of the feeder for it to meet the reliability world standard of 99%. Microsoft excel was used to generate the corresponding charts shown in Figures 2 to 6. As observed, it is important to note that the forced outage annual ASAI is lower for GRA as compared to that of Etete. This implies that the GRA substation has some level of satisfactory values of ASAI. As for the Etete feeder, there is a great need to work on reducing the duration of its outages, including the SAIFI, SAIDI and CAIDI.