AKSUM UNIVERSITY

OFFICE OF VICE PRESIDENT FOR RESEARCH AND COMMUNITY SERVICES

Research Terminal Report

On

Assessing the Impacts of War in Tigray on Electric Power Supply Reliability and Auditing Mechanisms –A Case Study for LV Feeder Lines of Aksum City–Ethiopia

Submitted To: Academic affairs and Research Vice Scientific Directorate

Submitted By

1. Hagos Gebrekidan Berhe (P.I): AIT, Department of Electrical Power Engineering
2. Milkias Birhanu Tuka (Co.I): AASTU, Department of Electrical Power and Control Engineering
3. Gebrehiwot Muruts Kebedew (Co.I): AIT, Department of Electrical Power Engineering

Feburary, 2025

Aksum, Ethiopia

.

ACKNOWLEDGMENTS

First, we would like to thank Almighty God for all rounded support throughout the process.

Second, we would like to express our genuine gratitude and appreciation for all people who we have meet them for their continuous help, guidance and support from the start to the end of this research work. They directed us to explore and understand the subject matter well as the technical actual data collection. Without their help and sincerity approach, this work has not been completed. They have been honestly responding to all our requests on time.

Then next, we will like to express our genuine gratitude and appreciation to the Ethiopian Electric Utility (EEU) Shire district staff members Amanuel M., Niguse G., Abrha Y., and Hawarya G., for their genuine collaboration and contribution in this research work. .

ABSTRACT

The war in Tigray has had significant consequences on infrastructure, including the electric power supply reliability in Aksum City. This study is focused in Aksum electric power distribution reliability study using reliability indices SAIDI, SAIFI, CAIDI, and EENS indices before, during, and after the conflict for K04 and K06 feeder lines. The findings indicate severe reliability deterioration due to power interruption (forced and due fault), infrastructure damage, loose line connection, displacement of skilled engineers due to conflict, and poor recovery efforts. The research employs a mixed-auditing mechanism, combining historical power outage data analysis, and performance evaluation of the reliability indices. Findings indicate that before the conflict, the power supply was relatively stable, with manageable outage durations and energy losses. However, during the nine-month conflict in 2013 EC, SAIDI peaked at 1,455.51 hours, CAIDI surged to 2,584.36 hours, and EENS escalated to 7,595.98 MWh, reflecting significant disruptions. In 2014 EC, partial recovery efforts reduced outage durations and improved restoration times, though reliability remained weak. By 2015 E.C, the worst recorded values were observed, with SAIDI reaching 2,866.29 hours, CAIDI peaking at 4,296.64 hours, and EENS soaring to 23,637.57 MWh, signaling extensive infrastructure failures. Six months post-war, significant recovery efforts improved these metrics, with SAIDI reducing to 162.14 hours, CAIDI to 190.71 hours, and EENS to 47.78 MWh, though supply stability challenges persist.

Aksum's power reliability indices exceeds international benchmarks, with SAIDI over 1–5 hours, SAIFI above 0.5, and CAIDI at 1–2 hours. Despite post-war improvements, high SAIFI values show supply instability. Strengthening infrastructure resilience, improving maintenance, and enhancing grid management are crucial for achieving long-term, reliable power distribution.

Key Words: Low voltage feeder line, Power interruptions (forced and operational), Power supply reliability, Power supply reliability auditing, standard reliability benchmarks.

TABLE OF CONTENTS

ACKNOWLEDGMENTS i
ABSTRACT ii
LIST OF FIGURES v
LIST OF TABLES vii
ACRONYMS vii
1. CHAPTER ONE 1
1.0. INTRODUCTION 1
1.1. Introduction 1
1.2. Background of the Study 2
1.3. Statement of the Problem 7
1.4. Objectives 8
1.4.1. General objective 8
1.4.2. Specific objectives 8
1.5. Motivation 9
2. CHAPTER TWO 10
LITERATURE REVIEW 10
2.1. Introduction 10
2.2. Impact of the War on skilled manpower and Infrastructure 10
2.2.1. Government and institutional efforts for power restoration 10
2.3. Main causes for power supply reliability problems 11
2.3.1. Power Interruption 11
2.3.2. Common LV Feeder line System Fault Types 13
2.4. Power Supply Reliability Auditing 15
2.4.1. Importance of Power Supply Reliability Auditing 15
2.4.2. Key Metrics in Power Supply Reliability Auditing 15
2.4.3. Types of Power Reliability Audits 16
2.5. Review of Literatures 17
3. CHAPTER THREE 18
METHODOLOGY 18

3.1. Introduction 18
3.2. Aksum Substation existing incoming – outgoing lines 18
3.3. Data collection and analysis 19
3.3.1. Feeder lines transformer ratings 19
3.3.2. Aksum substation feeder lines load profiles 20
3.3.3. Feeder Lines power interruptions 22
3.4. Basic Load Point Reliability Indices 27
3.4.1. Basic System Indices 27
4. CHAPTER –FOUR 29
FINDINGS AND DISCUSSION 29
4.1. Introduction 29
4.2. War's Impact on LV Feeder Line Reliability 29
4.2.1. Reliability Indicators before, during, and after the war 29
4.3. Audited reliability results and comparison with standard bench marks 32
4.3.1. Discussion 33
4.3.2. Comparison with international benchmarks 34
4.3.3. Audited results on physical damage of grid network equipment's **Error! Bookmark not defined.**
5. CHAPTER –FIVE 38
CONCLUSION AND RECOMMENDATIONS 38
5.1. Conclusion 38
5.2. Recommendations 38
REFERENCES 40

LIST OF FIGURES

Fig. 1:1: Electricity in Tigray's three major cities seen fading to black on NASA Black Marble high definition nighttime lights 3
Fig. 1:2: Power supply level in Addis Abeba Vs Mekelle during the war in Tigray 4
Fig. 1:3: Power supply profile in Tigray Vs in Ethiopia during the war in Tigray 5
Fig. 1:4: Aksum substation topographic view 6
Fig. 1:5: Study area map location generated from PVSyst V8 software. 7
Fig. 2:1: Power Interruption Duration 12
Fig. 2:2:Common power reliability problems overview in Aksum city 15
Fig. 3:1: K_04 and K_06 feeder lines total No of distribution transformers, capacity and length 20
Fig. 3:2:K_04 and K_06 feeder lines Residential, Commercial and Industrial load profiles 21
Fig. 3:3: Power interruption of feeder lines three months before the war 23
Fig. 3:4: Total average frequency and duration of interruptions for feeders K04 & K06 for 9 months in 2013 E.C 24
Fig. 3:5: Total average frequency and duration of interruptions for feeders K04 & K06 in 2014 E.C 25
Fig. 3:6: Total average frequent and duration of interruptions feeders K04 & K06 for 9months in 2015 E.C 26
Fig. 3:7: Total average frequency and duration of interruptions 6 month after the war 27

LIST OF TABLES

Table 3.1:Compiled data of Substation Feeders 19
Table 3.2: Feeder Line K04 & K06 Residential Load profile 21
Table 3. 3.Feeder Line K04 & K06 Commercial Load 22
Table 3.4: Feeder Line K04 & K06 Industrial Load 22
Table 3.5: Power Interruptions for 3-months before the war 23
Table 3.6: Aksum substation, Power Interruptions in 2013 E.C for K04 and K06 feeder lines 23
Table 3.7: Aksum substation, Power Interruptions in 2014 E.C for K04 and K06 feeder lines 24
Table 3.8: Aksum substation, Power Interruptions in 2015 E.C for K04 and K06 feeder lines 25
Table 3.9: Aksum substation, Power Interruptions in 2016 E.C for K04 and K06 feeder lines 26
Table 4.1: Summary of power System interruptions and their impact three months before the ware 30
Table 4.2: Summary of power interruptions and their impact in 2013 E.C (9 months) for K04 and K06 feeder lines...30
Table 4.3: Summary of power interruptions and their impact in 2014 E.C for K04 and K06 feeder lines........31
Table 4.4: Summary of power interruptions and their impact in 2015 E.C (9 months) for K04 and K06 feeder lines...31
Table 4.5: Summary of post ware power interruptions and their impact in 2016 E.C (6 months) in the feeder lines...32
Table 4.6: Summary of ccustomer-oriented indices before, during, and after the war for the feeder line.........33

ACRONYMS

CAIDI – Customer Average Interruption Duration Index

DPEF – Distribution Permanent Earth Fault

DPSC – Distribution Permanent Short Circuit

DTSC – Distribution Temporary Short Circuit

DTEF – Distribution Temporary Earth Fault

EC – Ethiopian Calendar

EEP – Ethiopian Electric Power

EEU – Ethiopian Electric Utility

EENS – Expected Energy Not Supplied

KV – Kilo Voltage

L-G-F – Line to Ground Fault

L-L-F – Line to Line Fault

L-L-G-F – Double Line to Ground Fault

LV – Low Voltage

MVA – Mega Voltage Amperage

PRA – Power Reliability Auditing

SAIDI – System Average Interruption Duration Index

SAIFI – System Average Interruption Frequency Index

1. CHAPTER ONE

INTRODUCTION

1.1. Introduction

The Tigray conflict, which escalated in late 2020, has had profound effects on the region's infrastructure, including the electrical power supply system. The war has killed thousands of people, distract the Electric power supply equipment’s giving services to the society, destroy industries schools, damage health centres & churches and seriously aggravated the country's already disastrous humanitarian situation. The war destructs the high voltage, medium voltage and low voltage components the electric power supply network in the entire region. In this study, we have focused on the impacts of the war at low voltage (LV) power supply grid networks power reliability specifically in Axum city K04 & K06 feeder lines. Here the war have affected the main components of grid network that causes poor power reliability & quality at the LV feeder line. This includes sever damage on protection devices, insulator materials, poles, towers, distribution transformers, transmission lines, genera ration & distribution substations. The study of power reliability audit helps identify potential vulnerabilities in the electrical system, allowing for maintenance and preventive measures on equipment failure. By using power reliability audit, the Ethiopian Electric Utility (EEU) can minimize downtime, extend equipment lifespan, and reduce maintenance costs and it can be easily determines reliability of electrical equipment operation, performance of the assigned functions by it within its service life. As we have audited, power reliability problems during Tigra’s war in Aksum feeder line are mainly caused by disturbances originating from utility feeding system due to faults (L-G-F, L-L-F, and L-L-G-F, destruction of protection devices (neutral wire, earth line system or low circuit breaker rating and transformer outgoing dropout fuse) and improper maintenance. These problems are highly affecting the power supply reliability of the city such burning of home appliances, regular power interruptions and very poor customer electricity satisfaction.

This paper have deduced the technical auditing approach of power reliability, specifically the permanent and temporary power interruptions in Axum Low voltage feeder line during the war in Tigray. To prove the validation of the study we have indicated the main power reliability problems that lead to poor power reliability including power interruptions. In addition, we have indicated the main distractions of components of the feeder line network equipment’s and we have compared the collected data with the standards and benchmarks.

1.2. Background of the Study

This days the Ethiopia's Tigray region, have an Electric Power (EEP) system of 400kV, 230kV, 132 kV primary transmission systems and 66kV, 45kV as sub transmission system and 33kV and 15kV as distribution system. The primary transmission lines used for high voltage power transmission for long distance, which is from the generation station to the sub transmission/distribution lines. In addition, the sub transmission systems carry a medium voltage power from the primary distribution station to low voltage distribution stations and the distribution system connects electric customers to the grid networks. Moreover, the 66 or 45kV substations power transformers of various ratings like those that 25/12 /6.3/3MVA has installed for step down of volt age to 15kV for feeding to distribution transformers [1]. In Aksum substation, currently there are two power transformers are existed to serve industrial, residential and commercial customers. The 132kV feed from Adwa substation and the 230 kV feed from Tekeze Hydropower. However, the 230 kV transformer is not functional as shown in Fig.1.4, only the 132 kV is currently working nameplate from the manufacturers.

Studying the reliability of low-voltage (LV) feeder lines is essential for addressing reliability, stability, and maintenance concerns, which can affect facility performance and an organization's bottom line. In today's technology-driven environment, consistent equipment protection and high-quality power supply are vital for efficient operations. Regular power reliability audits and maintenance are crucial to ensure the smooth functioning of electrical equipment. Both electrical utilities and consumers are emphasizing improvements in the quality and reliability of generated and distributed electrical energy, aiming for clean power distribution with acceptable performance cost-effectively. A power reliability assessment provides a detailed evaluation of the stability, availability, and performance of an electrical power system. It examines system availability by analysing downtime, outages, and key reliability indices like SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), and CAIDI (Customer Average Interruption Duration Index). Fault analysis ensures that protective devices effectively isolate issues such as short circuits and overloads. The assessment also reviews power quality parameters, including voltage fluctuations, harmonics, and transients, which impact system performance.

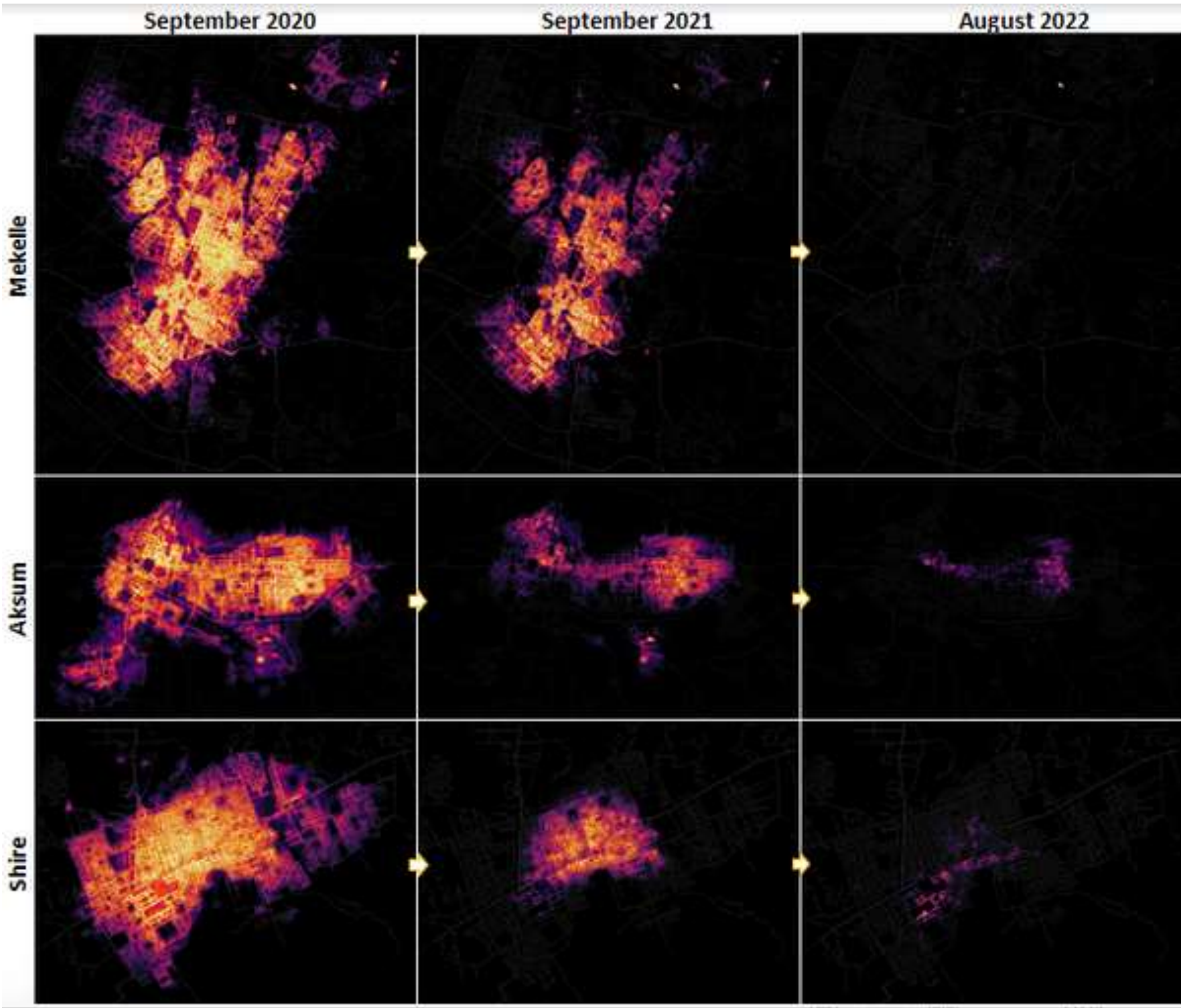


Fig. 1:1: Electricity in Tigray's three major cities seen fading to black on NASA Black Marble high definition nighttime lights [2]

We have indicated the power supply availability in most populated cities of Ethiopia's Tigray region, Mekelle, Shire and Aksum during and before the war as shown in Fig.1.1 [2]. Moreover, power blackout has happened during the war in Tigray intentionally ordered from the national grid operators, leads total economic crises in the entire region two years (from mid-2020 to 2022). As you see in 2022 there is little power supply in Aksum and Shire but, total blackot in Mekelle, is that there was partial supply from Tekeze hydropower.

Since the start of the conflict in November 2020, Tigray suffered a significant power outage, while power supply increased in most other areas of Ethiopia. During the conflict, the power supply kept increasing in Ethiopian capital Addis Abeba, while the power supply kept decreasing in Tigray region capital Mekelle as indicated in Fig.1.2 below.

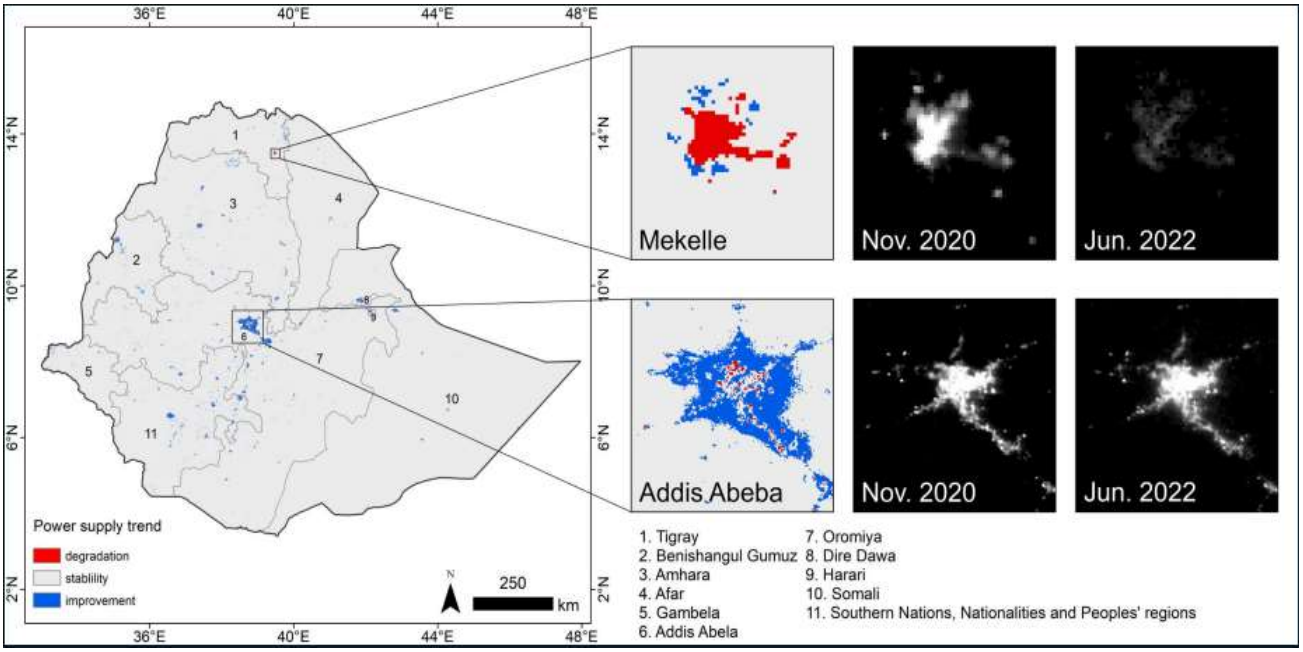
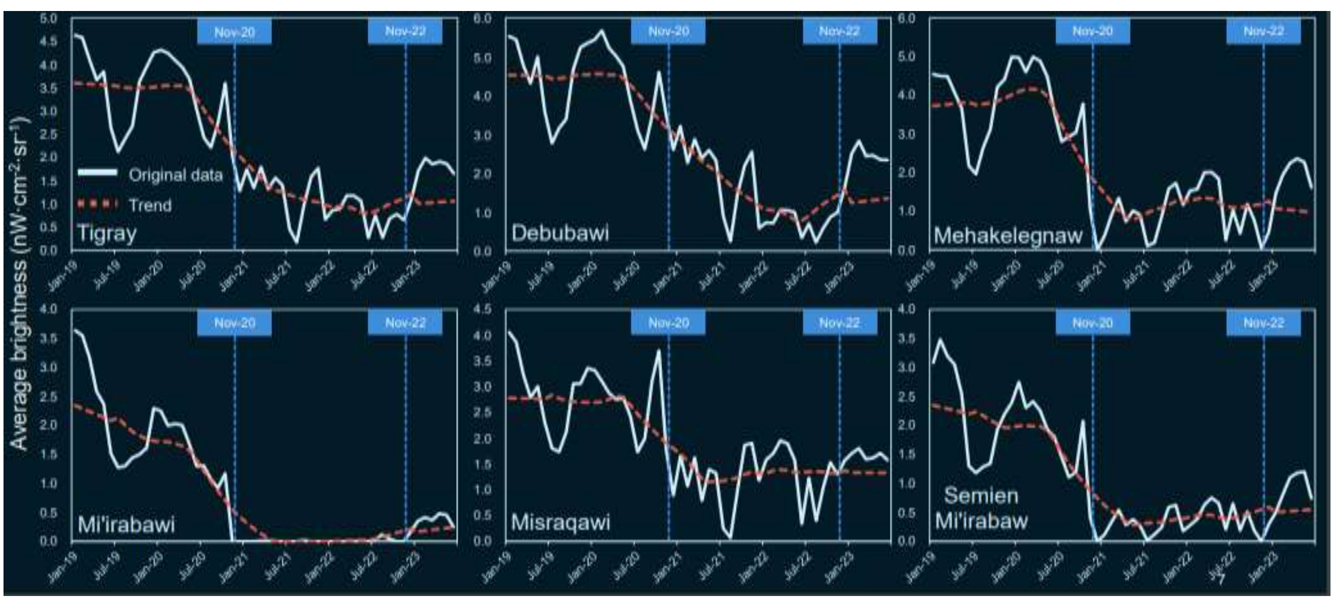


Fig. 1.2: Power supply level in Addis Abeba Vs Mekelle during the war in Tigray [2]

The power supply in Tigray has declined by more than 70% during the conflict as shown in Fig.1.3a below. Power supply in zones of Tigray is in recovery process, but has not yet returned to pre-conflict level by June 2023. During the conflict, power supply kept increasing in most regions of Ethiopia except Tigray as indicated in Fig.1.3b.



(a)Power decline in Tigray region during the war

(b). Increasing power supply in the rest regions of Ethiopia during the war in Tigray [2]

Fig. 1.3: Power supply profile in Tigray Vs in Ethiopia during the war in Tigray

Since the start of the conflict in November 2020, cities in Tigray region suffered a significant power outage. Power supply in most regions outside Tigray kept increasing during the conflict; since the end of the conflict in November 2022, power supply in Tigray was in recovery process, but has not yet returned to pre-conflict level by June 2023 [2].

When we overview, the sever war in Tigray, it was an armed conflict that lasted from 3 November 2020 to 3 November 2022. It was a civil war that have primarily fought in the Tigray Region of Ethiopia between forces allied to the Ethiopian federal government and Eritrea on one side and the Tigray People's Liberation Front (TPLF) the other. Between 162,000 and 600,000 people were killed, and war rape became a "daily" occurrence, with girls as young as 8 and women as old as 72 being raped, often in front of their families a major humanitarian crisis developed as a result of the war, which led to a widespread famine. It also inflicted immense economic damage on the region, with the cost of rebuilding alone estimated to be roughly $20 billion [2].

The existing grid of Aksum city has many power reliability problems caused due to the war in Tigray region, which causes effect on regular preventive maintenances on the Low Voltage (LV) grid networks, so we are proposing a power reliability auditing mechanisms for regular maintenance as a solution to solve the problems. The term Power Reliability Auditing (PRA) have various definitions of power reliability auditing—some functional, some technological, and some benefits-oriented. A common element in most definitions is the application of digital processing and systematic assessment of power system reliability. In the context of Aksum City, power reliability auditing focuses on evaluating the consistency, availability, and resilience of the power supply by analysing factors such as SAIFI, SAIDI and CAIDI. Implementing PRA mechanisms can help identify weaknesses in the generation, transmission, and distribution systems, leading to targeted improvements that enhance the city's overall power reliability.

Fig. 1.4: Aksum substation topographic view [3]

This work has conducted at Axum city, which is found in the northern part of Ethiopia around 605 miles / 974 km driving distance and 588.7 km air distance far from Addis Ababa, Ethiopia [4] as indicated in Fig 1.5 below. Axum city is located at an altitude of 14.74^0 N, longitude 38.73^0 E and an elevation of 2124 meters above sea level [4]. The city has a population number around above 120,000.

Fig. 1.5: Study area map location generated from PVSyst V8 software.

1.3. Statement of the Problem

The war in the northern Tigray region of Ethiopia had devastating socio-economic effects, particularly in Aksum City, where critical power supply infrastructure has been severely damaged. The conflict has also displaced of skilled personnel, including engineers, technicians, and maintenance workers, which hinders repair and restoration efforts. Without the necessary expertise, repairing and maintaining the power infrastructure becomes difficult, extending the recovery time and further destabilizing the power system. This has led to a significant deterioration in power reliability, causing frequent and prolonged power interruptions, voltage instability, and the failure of electric appliances. The Ethiopian Electric Utility (EEU) has reported from (2013-2015 E.C) extensive damage to the power system, including the destruction of 43 transformers, over 1000 transmission towers, and numerous feeder lines. These damages have resulted in recurring Line-to-Ground (L-G) and Line-to-Line (L-L) faults, poor quality of insulation, and malfunctioning protection devices. As a result, Aksum experiences up to 120 (5 days) hours of power outages per month, significantly affecting daily life and business activities during war at available power supplies.

The absence of regular maintenance and the use of outdated infrastructure have exacerbated the problem. The existing Low Voltage (LV) distribution systems and transformers have not been properly maintained since the onset of the conflict in 2013 EC. These power reliability issues have caused considerable losses in terms of damaged appliances and reduced productivity in the city.

To mitigate these challenges, there is a critical need to implement Power Supply Reliability Auditing (PSRA) for Aksum's electrical grid. Conducting a thorough audit will help identify weaknesses in the system, such as aging infrastructure, poor grounding, and faulty protection devices. By addressing these vulnerabilities, the power supply in Aksum can be made more reliable, ensuring stable and uninterrupted electricity for residents and businesses. The findings of this research will provide a comprehensive understanding of the issues affecting power reliability and offer actionable recommendations to improve the overall sustainability of Aksum's power supply system.

1.4. Objectives

We have depicted the general and specific objectives of this research work as follows:

1.4.1. General objective

Generally, this study is concerned with, the Impacts of War in Tigray on Electric Power Supply Reliability and Auditing mechanisms in feeder line grid networks for the selected area as a base case study.

1.4.2. Specific objectives

This research proposal focuses on identifying the main power impacts of the Tigray war on Power supply reliability, applying detailed auditing mechanism in Aksum city low voltage (LV) distribution feeder lines. Specifically, we have studied in the selected area in order to:

- Assess the current status of Aksum's electrical grid infrastructure
- Identify and assessment study on the main power reliability issues in the low voltage distribution feeder line of the specified site.
- Conduct detailed mechanism of power reliability auditing for the identified power quality issues
- Analyse the power reliability findings using reliability indices
- Validate the extent of war-induced damage to Aksum's power supply by comparing current performance against standard power reliability standards and benchmarks.

1.5. Motivation

The Tigray conflict (2020–2022 or 2013-2015 E.C) severely affected the region's electrical infrastructure, leading to widespread power outages, equipment destruction, and reduced power quality in cities like Aksum. This paper aims to assess the effects of the war on the low-voltage (LV) power grid in Aksum, identifying major power quality issues such as frequent interruptions, equipment failures, and voltage instability. By conducting a power quality audit, we highlight key vulnerabilities and propose maintenance strategies to enhance reliability, minimize downtime, and support the region's recovery efforts.

2. CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Throughout the research work, we read different literatures related to this study area. In connection, we have disclosed books of relevant importance and an internet browser for updated information and further guidance on a daily basis. The upcoming sections explain some of the system components, the review works conducted by various researchers in the area and found to be helpful for finalizing this research work.

2.2. Impact of the War on skilled manpower and Infrastructure

The war have affected widespread destruction of essential infrastructure, including electrical systems. In the context of Aksum, the war has severely damaged key components of the power grid, such as transmission towers, feeder lines, and transformers, distribution protection devices. Direct damage from attacks and indirect effects like resource scarcity and lack of personnel further exacerbate the situation [5]. This has resulted in frequent power outages and voltage instability, significantly impacting daily life and business activities.

The conflict has also displaced of skilled personnel, including engineers, technicians, and maintenance workers, which hinders repair and restoration efforts. Without the necessary expertise, repairing and maintaining the power infrastructure becomes difficult, extending the recovery time and further destabilizing the power system [6], [7].

In conflict areas of Tigray, logistics have a major challenge. Damaged roads, lack of security, and transport blockades make it difficult to transport materials needed for system repairs and upgrades. These challenges delay the restoration of the power system and increase the vulnerability of the infrastructure [7].

2.2.1. Government and institutional efforts for power restoration

The war in Tigray has caused severe damage to electrical infrastructure, leading to widespread power outages and instability in towns like Zalambessa, Adigrat, Bure, and Mekele. The rehabilitation and reconstruction of power supply systems in these regions are vital for restoring electricity access, improving power supply reliability, and addressing the economic crisis exacerbated by the conflict. The project involves rebuilding 65 km of high-voltage distribution lines, 27 km of low-voltage lines, 6 km of streetlights, and replacing 29 transformers. These efforts will restore reliable electricity transmission, ensure stable voltage, and reduce power disruptions, which are essential for supporting businesses, households, and critical services such as hospitals [8].

Additionally, the project will include the installation of backup power generators, restoring 550 customer connections, and providing retroactive financing for ongoing rehabilitation activities in Mekele and Adigrat [8]. These measures are critical for ensuring energy resilience in the face of infrastructure disruptions, providing emergency power to essential services, and facilitating economic recovery. By modernizing the grid, addressing the impacts of war on electric equipment, and expanding customer access, the initiative will revitalize local economies and improve the quality of life for affected populations, while ensuring long-term power supply reliability.

2.3. Main causes for power supply reliability problems

At the low voltage distribution, feeder lines power reliability problems mainly caused due to, faults, and loose connection of neutral line, improper groundings, Interruptions and load variations. Power reliability in these lines commonly related to long term and short-term voltage variations.

2.3.1. Power Interruption

Power interruptions that lead to poor power reliability are caused by various factors, including equipment failure, natural disasters, and grid instability. Equipment such as transformers, circuit breakers, and switches may malfunction due to aging or lack of maintenance, leading to widespread outages. Natural events like storms, floods, or lightning strikes can damage power lines and substations, causing prolonged interruptions. Transmission line faults, often triggered by environmental factors like fallen trees or ice, further disrupt the power supply. Additionally, grid instability, which occurs when demand exceeds capacity or there is an imbalance between generation and consumption, can result in blackouts or rolling outages [9], [10].

Other significant causes include voltage fluctuations, fuel shortages, and cyber-attacks on digital grid systems. Human error during maintenance or system upgrades, as well as overloading the grid during high demand periods, also contribute to power interruptions. Furthermore, deliberate sabotage or vandalism of critical infrastructure can severely disrupt electricity supply. Addressing these issues involves improving infrastructure, modernizing equipment, enhancing grid stability, investing in backup power solutions, and ensuring a rapid response to restore reliable power.

Types power interruption depending on the time duration of power outage as shown in Fig.2.1 are given.:

- Momentary interruption: A momentary interruption is a complete loss of voltage on one or more phase conductors for a time between 0.5 cycles and 3 seconds.
- Temporary interruption: A temporary interruption is a complete loss of voltage on one or more phase conductors for a time between 3 seconds and 1 minute.
- Sustained interruption: A sustained interruption is a complete loss of voltage on one or more phase conductors for more than 1 minute

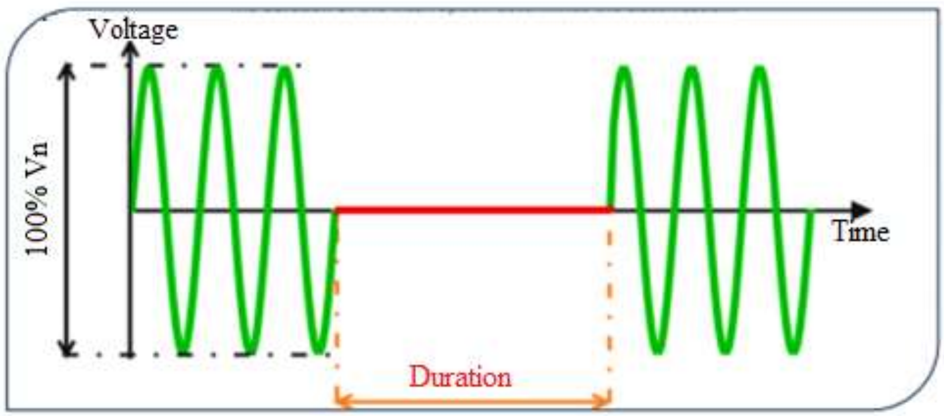


Fig. 2:1: Power Interruption Duration

Sources of Power Interruption

- ✓ Temporary Self-clearing faults in Power system
- ✓ Lightning strikes
- ✓ Utility switching operations
- ✓ Physical damage of power lines
- ✓ Load shedding

The reliability of the interconnected bulk power system is defined in two ways [11], [12]:

1) Adequacy: The ability of the electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements; and
2) Security: The ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

In brief, reliability has to do with total electric interruptions - complete loss of voltage, not just deformations of the electric sine wave. Reliability does not cover sags, swells, impulses or harmonics. Reliability indices typically consider such aspects as [11], [12]:

- ✓ The number of customers;
- ✓ The connected load;
- ✓ The duration of the interruption measured in seconds, minutes, hours, or days;
- ✓ The amount of power (kVA) interrupted; and the frequency of interruptions

2.3.2. Common LV Feeder line System Fault Types

In electrical distribution systems, faults can occur due to various reasons, leading to interruptions in service and potential damage to equipment. Understanding the different types of faults is crucial for effective management and mitigation strategies. Below is a detailed analysis of the specified fault types: [13]-[15].

2.3.2.1. Distribution Permanent Earth Fault (DPEF)

A Distribution Permanent Earth Fault occurs when there is a continuous connection between a phase conductor and the ground or earth. This type of fault typically results from insulation failure, physical damage to cables, or environmental factors such as moisture ingress.

The fault persists until it is manually cleared, it can lead to significant voltage drops in the affected phase, and protective devices like earth fault relays are activated to isolate the faulty section. The main consequences this fault type are continuous disruption of service until repaired, Safety hazards for the public and maintenance personnel. This can be mitigated using regular maintenance and insulation testing, and Ground fault protection devices to isolate faults rapidly.

2.3.2.2. Distribution Permanent Short Circuit (DPSC)

A Distribution Permanent Short Circuit occurs when conductors come into direct contact, creating a low-resistance path for current. Causes include equipment failure, insulation breakdown, and external factors like falling tree branches. This fault persists until cleared by protective devices and generates very high currents that can damage transformers. Its impact includes severe voltage dips and potential cascading failures. Mitigation strategies involve installing protective relays for quick fault detection and isolation, along with regular vegetation management programs to minimize tree-related outages and enhance system reliability. Proper measures are crucial to prevent damage and maintain network stability

2.3.2.3. Distribution Temporary Earth Fault (DTEF)

A Distribution Temporary Earth Fault is a transient connection between a phase conductor and ground, often caused by momentary insulation breakdowns due to environmental factors like lightning or moisture. This fault results in short-lived outages that typically self-clear when conditions improve but can cause operational issues if they recur frequently. To mitigate these risks, regular inspections of lines and clearance of overhanging vegetation are essential, along with the implementation of outage detection systems to quickly identify the nature of the fault for timely response.

2.3.2.4. Distribution Temporary Short Circuit (DTSC)

A Distribution Temporary Short Circuit occurs when there is a brief contact between conductors, often caused by transient events like switching operations or temporary debris on lines. This type of fault typically self-clears, allowing the system to return to normal operation quickly, although it can cause momentary voltage fluctuations without resulting in lasting damage.

Common causes include lightning strikes, wind-induced sway of lines, and momentary contact with foreign objects such as branches. While it generally results in momentary interruptions that do not require repair, frequent occurrences can raise concerns about system reliability. Mitigation strategies involve employing advanced protective devices that rapidly disconnect during faults and installing fuses and circuit breakers designed to handle transient faults efficiently.

2.3.2.5. Total Interruption (Forced + Operational)

Total interruption in a distribution network refers to a complete loss of power supply, which can be classified into forced interruptions, typically caused by faults, and operational interruptions, which are planned outages for maintenance or upgrades. The causes of these interruptions range from equipment malfunctions, severe weather, and accidents for forced interruptions, to necessary maintenance for operational interruptions. The consequences can significantly affect customer satisfaction and service reliability, as well as lead to financial implications for utilities due to penalties or loss of customer trust. To mitigate these effects, effective planning and communication with customers during operational interruptions are essential, along with comprehensive maintenance strategies aimed at minimizing the occurrence of forced interruptions.

Power reliability can be defined as the degree to which the performance of the elements in a bulk system results in electricity being delivered to customers within accepted standards and in the amount desired. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply [11], [16]-[19].

2.4. Power Supply Reliability Auditing

Power supply reliability auditing is a systematic process used to assess the consistency, efficiency, and quality of electricity delivery within a given system. It involves evaluating key reliability indices, identifying vulnerabilities, and recommending improvements to minimize power disruptions and enhance service quality.

In Axum city due the absence regular inspection and maintenance electric grid power components such as power meters, distribution transformer dropout fuses and loose connection neutral line are very common as shown in Fig. 2.2 below.

a) Power meter b) Distribution transformer without drop out Fuse Box

Fig. 2:2:Common power reliability problems overview in Aksum city [20]

2.4.1. Importance of Power Supply Reliability Auditing

- Ensures continuous electricity availability for critical sectors such as healthcare, education, and industries.
- Helps utilities and policymakers identify weak points in the power distribution network.
- Reduces economic losses associated with power outages.
- Supports sustainable energy planning and infrastructure development.

2.4.2. Key Metrics in Power Supply Reliability Auditing

Several standard reliability indices are used in auditing power systems includes [21]:

- SAIDI (System Average Interruption Duration Index) – Measures the total outage duration per customer per year.
- SAIFI (System Average Interruption Frequency Index) – Indicates the average number of power interruptions per customer annually.

- CAIDI (Customer Average Interruption Duration Index) – Represents the average time required to restore service per outage event.
- ASAI (Average Service Availability Index) – Evaluates the percentage of time electricity is available in a year.

2.4.3. Types of Power Reliability Audits

A power reliability audit is a structured evaluation process used to assess the consistency and dependability of electricity supply in a given system. It helps identify weaknesses, improve infrastructure resilience, and enhance power quality.

A. Preventive Audit [22], [23]

- Focuses on identifying potential risks before failures occur.
- Involves routine inspections, maintenance schedules, and system monitoring.
- Uses predictive analytics to anticipate faults.

B. Corrective Audit [22], [23]

- Conducted after a power failure to determine causes and corrective actions.
- Involves analyzing outage reports, failure logs, and maintenance history.
- Aims to improve response times and minimize future disruptions.

C. Compliance Audit [24], [25]

- Ensures adherence to industry standards, regulations, and policies.
- Evaluates compliance with IEEE, IEC, and national grid codes.
- Focuses on safety, operational efficiency, and environmental considerations.

D. Performance-Based Audit [11], [16]-[19]

- Assesses power system efficiency using reliability indices.
- Metrics include SAIDI, SAIFI, CAIDI, and ASAI.
- Helps benchmark against industry best practices.

E. Financial Audit [26]

- Evaluates the economic impact of power reliability issues.
- Analyzes operational costs, revenue losses, and investment in infrastructure upgrades.
- Supports cost-benefit analysis for future improvements.

2.5. Review of Literatures

A review of literature on power supply reliability in Ethiopia reveals a number of challenges and advancements in the sector. Here are some key points and findings:

A. Tarekegn, [27]: Ethiopia's power grid is subject to frequent outages, particularly during dry seasons when hydropower plants experience reduced generation capacity due to low water levels. These outages affect both urban and rural areas, leading to disruptions in daily activities, economic operations, and essential services such as healthcare and education.

S. Mulugeta [28]: Much of Ethiopia's power infrastructure is outdated and prone to failures. This includes transmission lines, substations, and transformers, which are often insufficient to meet the growing demand for electricity.

B. Abdisa [29]: The frequent and prolonged power outages result in significant economic losses, particularly for industries that rely on continuous power supply for operations. Manufacturing sectors, agriculture, and service industries are particularly impacted by unreliable electricity.

T. Basha [30]: Power interruptions lead to reduced productivity in both public and private sectors. In sectors like healthcare, frequent outages hinder the operation of critical equipment, jeopardizing patient care (Basha, 2021).

F. Kassahun [31]: Small businesses, especially in urban centers, experience severe losses due to frequent outages. The lack of reliable power also discourages investments and limits the potential for business growth.

H. Sisay [32]: Efforts have been made to modernize the national grid, including the introduction of smart grid technologies, enhanced maintenance practices, and upgrading transmission lines. However, challenges in financing and political will have delayed the full implementation of these improvements.

T. Fisseha [33]: Despite reforms, the regulatory environment remains underdeveloped, which can create barriers to efficient service delivery and foreign investment in the energy sector.

This review provides a comprehensive summary of power supply reliability issues in Ethiopia, drawing from existing literature on the challenges, impacts, and potential solutions for improving the electricity sector.

This research study focused on identification of power reliability issues in LV feeder lines using auditing mechanisms for Aksum city during the wartime in Tigray.

3. CHAPTER THREE

METHODOLOGY

3.1.Introduction

To understand and obtain the technical the reliability performance analysis for the specified site, it is necessary to conduct data collection & analysis, identify findings and compare with standard benchmarks.
To achieve this, we have conducted assessment study on the existing feeder lines of the selected area. Accordingly, we have determined the main power reliability key performance indicators, which includes SAIFI, SAIDI, CAIDI and EENS (Expected Energy not Served).
Generally, we have done the following main activities throughout the whole work:

- Necessary primary and secondary data have been collected and analyzed
- We have made Corrective and performance based reliability auditing mechanisms
- We have calculated the key reliability performance indicators (SAID, SAIFI, CAIDI and EENS) based on the existing collected data the at the study area.
- We have made detail analysis and discussion for the calculated findings
- We have validate the findings using international standards and benchmarks
- Then finally, we have deduced actionable recommendations.

3.2.Aksum Substation existing incoming – outgoing lines

Aksum distribution substation is currently supplied from Tekeze hydropower plant and Adwa substation, interconnected system (ICS) which Ethiopian Electric Power (EEP) generated and transmitted, Ethiopian Electric Utility (EEU) also distribute and sales electric power in the entire country. There is an incoming 230/132KV transmission line from Tekeze Hydropower plant and the outgoing Adwa substation High voltage (HV) transmission line respectively. The substation currently containing one operating power transformer rated 40/50MVA. The distribution system has a primary voltage of 15 kV with two feeders, reserve two switchgear panel. In addition, this voltage value is stepped down to 380 and 220 volts to customer's voltage level. The network topology for Aksum distribution system is radial. The bus bar schemes or bus bar layout is Single bus bar system. The single bus bar scheme has only one three-phase but to which the various incoming and outgoing circuits are connected. It is not preferred for major substation and it lack operational flexibility, in case of bus fault or circuit barker failure the entire bus has to be de -energized, but it is low cost, simple to operate, and requires simple protection. Fig. 3.1 illustrates the current arrangement of the distribution substation of Aksum distribution substation.

3.3.Data collection and analysis

Primarily, the load profile of the feeder lines (residential, commercial and industrial); Length of the feeder; Rating and type of each transformer; Topology and layout of the system; Conductor type and Topography of the feeder lines are collected. We have collected the primary and secondary data by the direct involvement of the researchers with specialized data collectors and Employees of Aksum, Adwa and Shire substations, Design, Engineering and Localization office. During the site survey, the primary data necessary for this study were the length of the feeder, rating & type of each transformer, topology & layout of the system, conductor type, topography and others are collected. For the Data collection, the researcher used systematic approach for gathering and measuring information from variety of source to get complete and accurate pictures of the distribution substation. The data collection enables the researcher to answer relevant questions and to make prediction about the future.

3.3.A. Feeder lines transformer ratings

In Aksum substation, currently there are two power transformers are existed to serve industrial, residential and commercial customers. The 132kV feed from Adwa substation and the 230 kV feed from Tekeze Hydropower. However, the 230 kV transformer is not functional, only the 132 kV is currently working nameplate from the manufacturers. The working Feeder line in Aksum Substation are feed by the substation transformer with ratings of 40/50 MVA; 132/15 KV; impedance voltage at 50MVA, 132/15 KV of 10.33%; Oil temp.60 K; winding temperature at altitude of 2900M is 65k radial feeder topology, which is the most used topology in the entire country [34].

The existing compiled data of Aksum substation 15kV outgoing feeders lines (K04 & K06) described in table 3.1 [34].

Table 3.1: Compiled data of Substation Feeders

15 KV Feeders	Feeders Name	Total No .Of Dis.transformers	Total Cap. Of Distr. Trans.	Total Length Of Feeders
K04	K04	120	23.385MVA	45km
K06	K06	80	24.120MVA	20km

The table shows the number of transformers, their total MVA capacity, and the feeder line length from Aksum city to the end. Feeder K06 has a high transformer capacity, while feeder K04 covers a larger transmission line length and more distribution transformers, as shown in Fig 3.1.

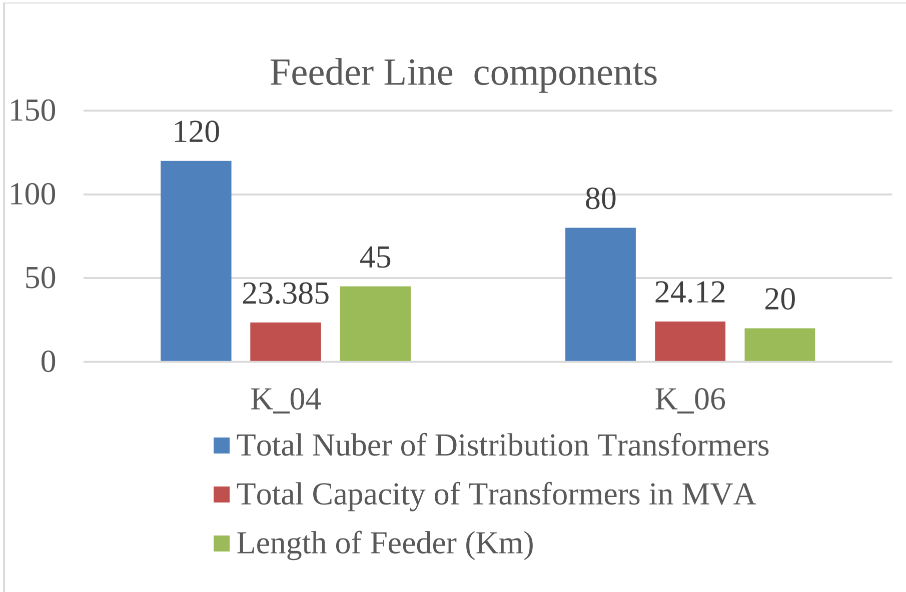


Fig. 3:1: K_04 and K_06 feeder lines total No of distribution transformers, capacity and length

3.3.B. Aksum substation feeder lines load profiles

Aksum Substation has two incoming power high voltage (HV) supply lines with 230 kV Tekeze line and 132 kV Adwa line 123kv with two different single bus bar topology. Currently [34], the substation has two operating feeder line, represented as K04 and K06 with voltage level of 15kV, which are supplying Aksum city and near cities. The feeder line with K06 is supplying residential loads, commercial loads and industrial loads in Aksum city. The feeder line with K04 is supplying the near cities with distance coverage of 45km including, Mahbere deigo, Daero hafash, Semema, Edaga berhe, Tsatsilo, Teregay fancha, chila, Chemo and Wiqro. This distribution feeder lines outgoing from Aksum substation, suffered from daily electric power supply interruptions and reliability problems.

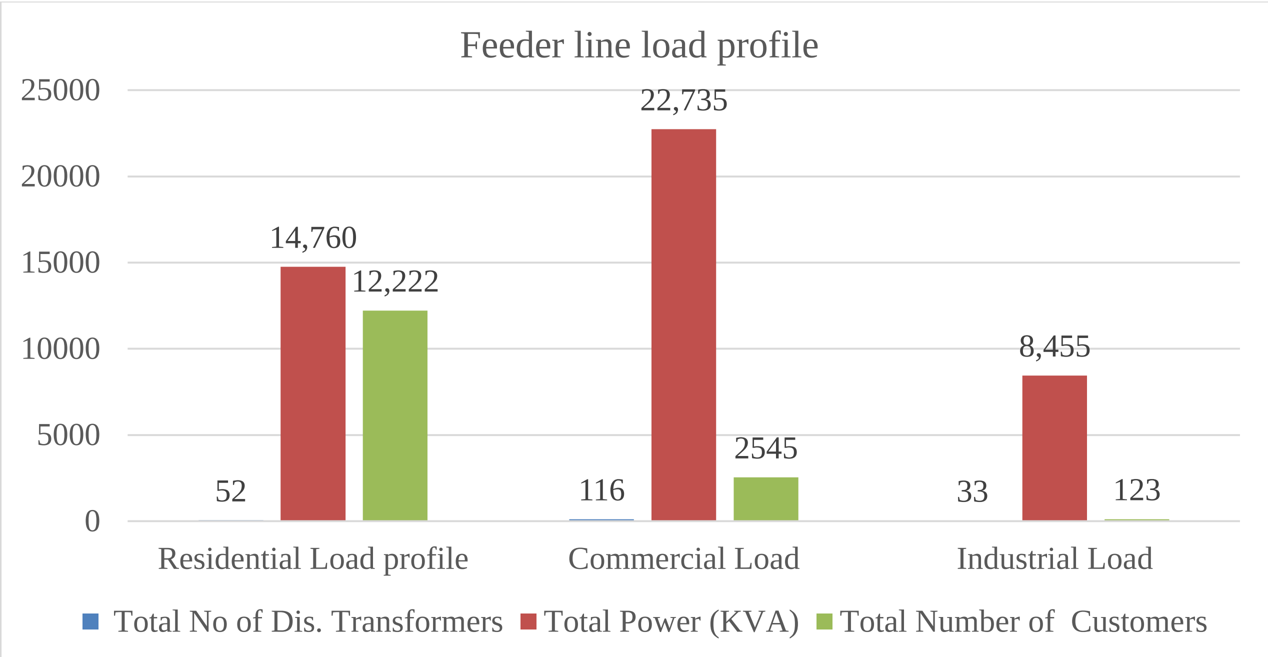


Fig. 3:2:K_04 and K_06 feeder lines Residential, Commercial and Industrial load profiles

Currently Aksum substation feeder lines contains total no of customers 14,890 (fourteen thousand eight hundred ninety) with Residential-12,222, commercial -2545 and industrial-123 (one hundred twenty three) connected to the feeder lines as shown in Fig 3.2. However, 97% of the total load of customers (14,443.3) is covered only by feeders K_04 &K_06. Below Tables 3.2, 3.3 and 3.4 shows the detail of connected loads. We have selected both (K04 & K06) feeders for evaluating yearly interruption operation, Forced Interruption, Total interruption (Forced +Operational), Distribution Permanent Earth Fault (DPEF), Distribution Permanent Short Circuit (DPSC), Distribution Temporary Earth Fault (DTEF), and Distribution Temporary Short Circuit (DTSC) [34].

As we have observed from Fig. 3.2, the city have high commercial loads as compared industrial and residential loads. From this load profile, the number of residential customers are high as compared to the number of commercial and industrial customers.

Table 3.2: Feeder Line K04 & K06 Residential Load profile

Types of connected Dis. Transformer rating in KVA	Quantity of Dis. Transformer	Total No of Dis. Transformer	Total Power (KVA)	Total No of Residence Customer
400 KVA	1	51	14,760	12,222
100KVA	6			
315KVA	28			
200KVA	8			
50KVA	4			

630KVA	3			
1250KV	1			

The type of each distribution transformer apparent power ratings in each transformer (KVA) with respect of its quantity and total KVA ratings in the residential load is indicated in table 3.2 above.

Table 3. 3.3: Feeder Line K04 & K06 Commercial Load

Types of connected Dis. Transformer rating in KVA	Quantity of Dis. Transformer	Total No of Dis. Transformer	Total Power	Total No of Commercial Customer
25KVA	38	116	22,735 KVA	2545
315KVA	21			
100KVA	17			
200KVA	11			
630KVA	2			
50KVA	18			
1250KVA	6			
800KVA	2			
10KVA	1			

The distribution transformers ratings in KVA in each and total power supplied to the commercial load is listed in the table 3.3 above.

Table 3.4: Feeder Line K04 & K06 Industrial Load

Types of connected Dis. Transformer rating in KVA	Quantity of Dis. Transformer	Total No of Dis. Transformer	Total Power	Total Length	Total No of Industrial Customer
100KVA	11	33	8,455KVA	45km	123
50 KVA	1				
200 KVA	5				
315 KVA	12				
630 KVA	2				
1250 KVA	1				
15 KVA	1				

Rated capacity of each transformer (kVA), number of transformers and total KVA ratings taped on the 45km Feeder line, which is supplying the industrial load, is indicated in table 3.4 above.

3.3.C. Feeder Lines power interruptions

According to the data collected from the from Aksum distribution substation, the main causes of momentary (unplanned) Interruptions are: - Distribution Permanent Earth Fault (DPEF), Distribution

Permanent Short Circuit (DPSC), General Fault/ Black out (GF), Distribution Temporary Earth Fault (DTEF), Distribution Temporary Short Circuit (DTSC) and System over Load.

We have collected a data for before the war, during the war and post war as indicated below. The fault profile for three months before the war have included in table 3.5 below. As we have observed form this table 233 frequent interruption have recorded, which are more than duration of interruption, 145.39 for K04 as indicated in Fig.3.1. In addition, 134 frequent interruptions and 84.01 duration of interruptions for K06.

Table 3.5: Power Interruptions for 3-months before the war

Feeder Name	DPSC		DTEF		DTSC		Interruption Operational		Forced Interruption		Total Interruption (Forced + Operational)	
	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)
KO4	34	30.39	52	46.17	0	0	86	76.56	147	68.43	233	145.39
KO6	28	35.46	19	12.15	0	0	47	48.01	87	36.00	134	84.01

Before the war, Feeder K04 had 233 interruptions totaling 145.39 hours; while K06 had 134 interruptions, lasting 84.04 hours is indicated in Fig. 3.1. Before the war, both feeders experienced fewer and shorter interruptions compared to during the war. Feeder K04 had more frequent outages than K06, but both showed a significant increase in interruption duration and frequency in Fig.3.2, highlighting the severe impact of the war on power reliability.

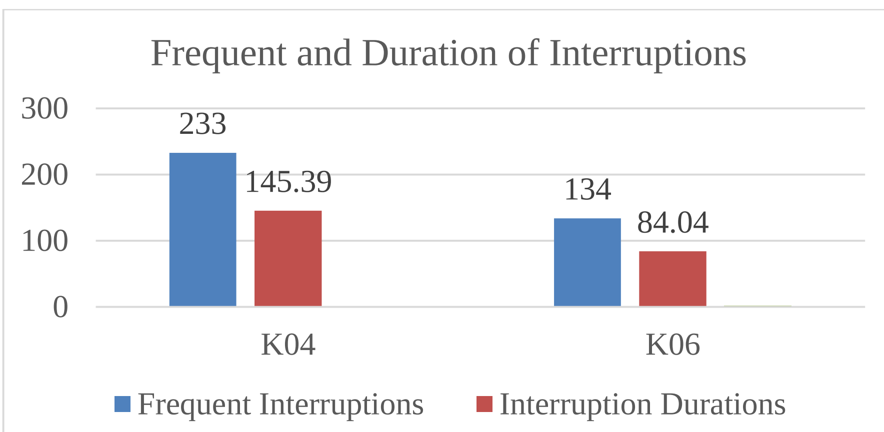


Fig. 3:3: Power interruption of feeder lines three months before the war

For the 9 months in 2013 E.C recorded frequent no of interruption-296, duration 2537 hours at the K04 feeder line and frequent no of interruption 153, interruption duration 2053.7 hours at K06 feeder line as indicated in 3.6 below.

Table 3.6: Aksum substation, Power Interruptions in 2013 E.C for K04 and K06 feeder lines

Feeder Name	DPSC		DTEF		DTSC		Interruption Operational		Forced Interruption		Total Interruption (Forced + Operational)	
	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)

KO4	70	64.06	43	33.51	0	0	113	98.00	183	2439	296	2537
KO6	20	13.15	32	37.56	0	0	52	51.71	101	2002	153	2053.7

The bar chart in Fig 3.2, illustrates the total average frequency and duration of power interruptions for feeders K04 and K06 over a 9-month period in 2013 E.C. Feeder K04 experienced 296 interruptions with a total outage duration of 2537 hours, whereas feeder K06 had 153 interruptions lasting 2053.7 hours. Although K04 had more frequent interruptions, the total outage duration for both feeders remained significantly high, indicating major power reliability issues. The data suggests that while K06 experienced fewer interruptions, its outage durations were still prolonged, highlighting the need for improvements in power distribution.

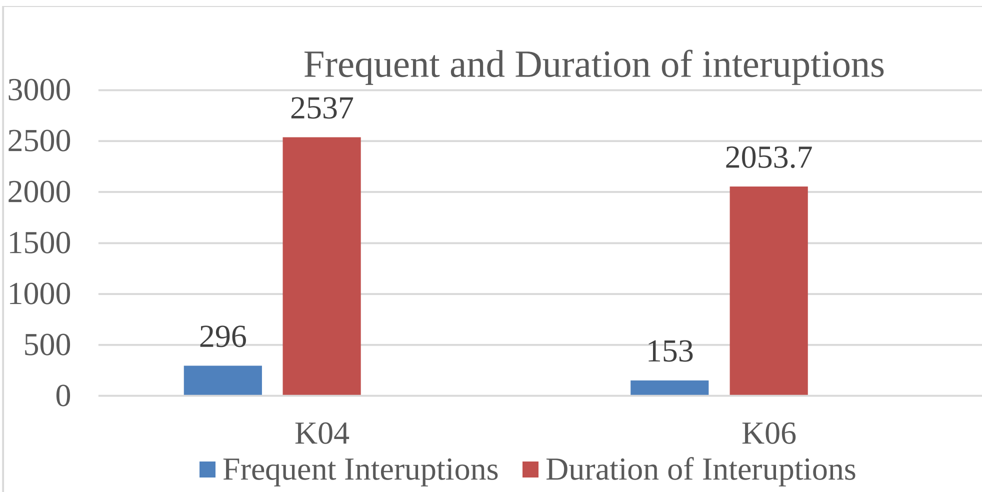


Fig. 3:4: Total average frequency and duration of interruptions for feeders K04 & K06 for 9 months in 2013 E.C

We have collected a data in 2014 E.C recorded frequent no of interruption-322, interruption duration 507.86 (Hr.) at the K04 feeder line and frequent no of interruption -136, interruption duration 374.72 (Hr.) at K06 feeder line as indicated in table 3.7.

Table 3.7: Aksum substation, Power Interruptions in 2014 E.C for K04 and K06 feeder lines

Feeder Name	DPSC		DTEF		DTSC		Interruption Operational		Forced Interruption		Total interruption (Forced +Operational)	
	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)
KO4	176	163.57	83	63.9	0	0	259	227.47	63	280.39	322	507.86
KO6	37	100.07	43	62.27	0	0	80	162.34	56	212.38	136	374.72

The total average frequency and duration of interruptions for feeders K04 and K06 in 2014 E.C as shown in Fig 3.3. Feeder K04 experienced 322 interruptions with a total outage duration of 507.86 hours, while Feeder K06 had 136 interruptions and a total outage duration of 374.72 hours. The data indicates that K04 faced more frequent and prolonged outages compared to K06, highlighting reliability concerns in both feeders.

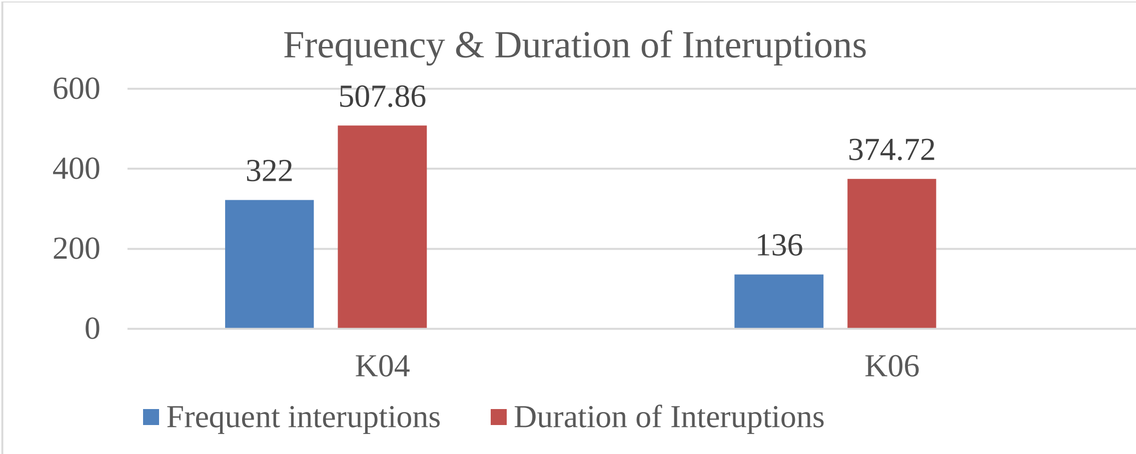


Fig. 3:5: Total average frequency and duration of interruptions for feeders K04 & K06 in 2014 E.C

We have collected a data of 9 months in 2015 E.C recorded frequent no of interruption-374, interruption duration 2471.69 (Hr) at the K04 feeder line and frequent no of interruption 1161.77, and interruption duration 2246 (Hr) at K06 feeder line as indicated Table 3.8 below.

Table 3.8: Aksum substation, Power Interruptions in 2015 E.C for K04 and K06 feeder lines

Feeder Name	DPSC		DTEF		DTSC		Interruption Operational		Forced Interruption		Total interruption (Forced +Operational)	
	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)
KO4	200	216.34	45	34.16	0	0	245	250.99	129	2221.2	374	2471.69
KO6	37	98.36	23	26.41	0	0	60	124.77	101.77	2,121.23	161.77	2246

The data in Fig. 3, 4 indicates that Feeder K04 experienced 374 interruptions, with a total outage duration of approximately 2471.69 hours. In contrast, Feeder K06 had fewer interruptions (161.77), but the total duration of power outages remained significantly high at 2246 hours. This suggests that while K04 had more frequent disruptions, K06 suffered from longer individual outages, highlighting potential reliability and maintenance concerns in both feeders.

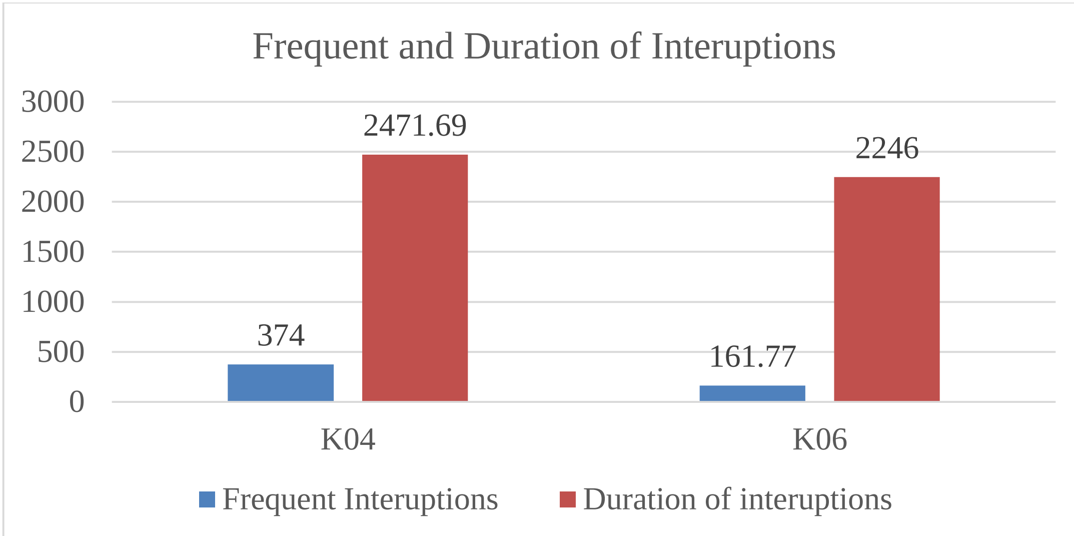


Fig. 3:6: Total average frequent and duration of interruptions feeders K04 & K06 for 9months in 2015 E.C

We have collected a data of 6 months in 2016 E.C recorded frequent no of interruption-247, duration 108.24H at the K04 feeder line and frequent no of interruption -161, duration 90.45H at K06 feeder line. Table 3.9 below contains detail interruption Data.

Table 3.9: Aksum substation, Power Interruptions three months in 2016 E.C for K04 and K06 feeder lines

Feeder Name	DPSC		DTEF		DTSC		Interruption Operational		Forced Interruption		Total interruption (Forced +Operational)	
	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)	F	D(Hr.)
KO4	119	57.55	22	12.23	0	0	141	70.18	106	38.06	247	108.24
KO6	37	35.52	20	15.07	0	0	57	50.59	104	39.86	161	90.45

Feeder K04 experienced 247 interruptions with a total outage duration of 108.24 hours, while Feeder K06 recorded 161 interruptions with a total outage duration of 90.45 hours as indicated in Fig.3.5. Compared to the previous wartime in 2015E.C, the frequency of interruptions has remained high, but the total duration has significantly decreased, indicating possible improvements in fault resolution time or maintenance practices. However, K04 still exhibits a higher frequency of interruptions, suggesting continued reliability challenges.

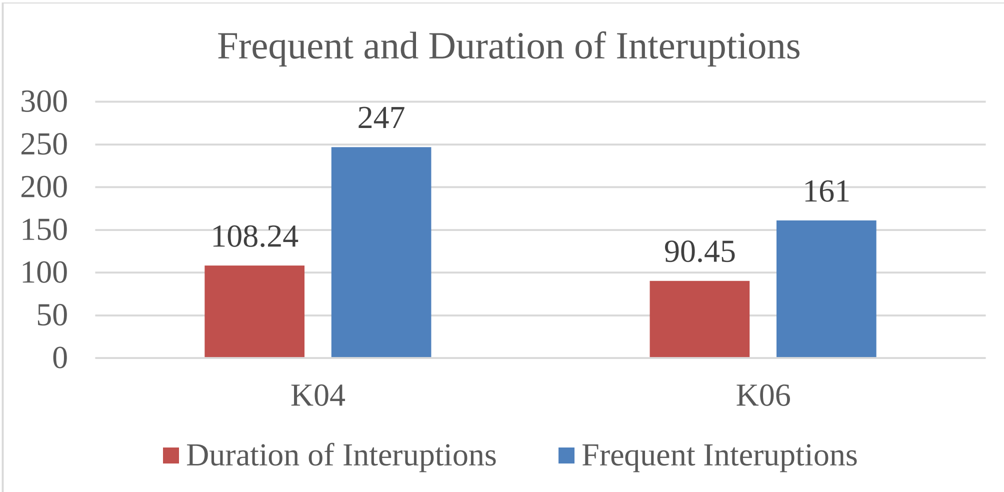


Fig. 3:7: Total average frequency and duration of interruptions 6 month after the war

3.4.Basic Load Point Reliability Indices

The term reliability in the utility context usually refers to the amount of time end users are totally without power for an extended period of time (i.e., a sustained interruption). The three basic load point reliability indices usually used are the average failure rate, the average outage timer and the average annual unavailability or average annual outage time. It should be noted that these indices are not deterministic values but are expected values of an underlying probability distribution and hence are long-run average values.

3.4.A. Basic System Indices

The three primary load point indices are fundamentally important parameters. They can be aggregated to provide an appreciation of the system performance using a series of system indices. The additional indices that are most commonly used are defined in the upcoming sections.

To calculate the SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index) and EENS (Expected Energy Not Supplied), considering failure rates at feeder lines, we need to define several key parameters and follow a systematic approach.

Failure Rate: The number of interruptions per year (or a similar time) per feeder line or fault type (e.g., forced, operational, DPEF, DPSC, etc.). The failure rate (denoted as λ\lambda) for each feeder line corresponds to the number of interruptions per year for that feeder. This might be a historical or predicted value. Considering this rate, the reliability indices are depicted as follows:

3.4.A.A. Customer-Oriented Indices

SAIDI (System Average Interruption Duration Index): measures the total duration of power outages for customers over a specific period, typically expressed in minutes or hours [35]. We have calculated the SAIDI using the formula

$$\text{SAIDI}=\frac{\text{Sum of customer interruption durations}}{\text{Total number of customers served}}=\sum_{i}\frac{r_i N_i}{N_T} \qquad (3.1)$$

Where: r_i is the outage time for each interruption event and N is number of faults that cause an interruption

SAIFI (System Average Interruption Frequency Index): measures the frequency of outages experienced by customers over a specific period, expressed as the average number of interruptions per customer. It is calculated using the formula [35]

$$\text{SAIFI}=\frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}}=\sum_{i}\frac{\lambda_i N_i}{N_T} \qquad (3.2)$$

Where; λ_i s the failure rate at load point i and N_i is the number of interrupted customers for each interruption event during the reporting period at load point i. N_T is the total no of customers served for the area.

CAIDI (Customer Average Interruption Duration Index):

To calculate CAIDI, we first need to assume that the interruptions affected all customers (as no specific information about customers interrupted is given). Here we can calculate the CAIDI using the total customers served and the total duration of interruptions [35].

$$CAIDI=\frac{Total\ Duration\ of\ Interruptions}{Total\ Number\ of\ Customers\ Interrupted}=\frac{SAIDI}{SAIFI} \qquad (3.3)$$

Summary of distribution Customer-Oriented Indices (COI) reliability index on interruptions from the year 2013 EC to 2016 EC is indicated in Table 3.9 below.

3.4.A.B. Load- and Energy-Oriented Indices:

Expected Energy Not Supplied (EENS): is a measure of the total energy not supplied, but the term is often used in the context of future reliability and expected outages. It can be calculated similarly to **ENS**, but it is typically used as an index for a system's reliability [35]:

$$EENS=\sum_{i=1}^{N} La(i)\times r_i \qquad (3.4)$$

Where; La(i) is the average load given by ; La(i) = Ed (i)/t; and Ed is the total energy demanded in the period of interest t for fault interruption i.

Average Energy Not Supplied (AENS): represents the average amount of energy not supplied per customer in a year. It is calculated as the total energy not supplied (ENS) divided by the total number of customers [35]:

$$AENS=\frac{EENS}{Total\ Number\ of\ Customers\ Served}=\sum_i\frac{La(i)\times r_i}{N_T} \qquad (3.5)$$

4. CHAPTER –FOUR

FINDINGS AND DISCUSSION

4.1. Introduction

In this chapter we have identified the main impacts of the war in Tigray's on power supply reliability mainly related to Infrastructure damage, power reliability issues, expected energy not served, which evaluates how the residents of Aksum have been affected in terms of service interruptions, frequency of outages and how to audit this issues specifically.

4.2. War's Impact on LV Feeder Line Reliability

The destruction of power plants substations, transmission lines and fuel shortages caused by war-related disruptions have significantly affect power generation capacity. This, in turn, affects the availability of electricity to consumers in Tigray region. In Aksum, this disruption has contributed to severe power shortages and instability and reliability problems in the grid.

4.2.1. Reliability Indicators before, during, and after the war

According to the data collected from Aksum distribution substation indicated in chapter three from table's 3.1-to-table 3.9, the main causes of momentary (unplanned) Interruptions are, Distribution Permanent Earth Fault (DPEF), Distribution Permanent Short Circuit (DPSC), General Fault/ Black out (GF), Distribution Temporary Earth Fault (DTEF), Distribution Temporary Short Circuit (DTSC) and System over Load. To show the impact of the war on power supply reliability in the indicated city, we have determined the reliability indices depending on failure rate and outage time as indicated in the upcoming tables.

As we have indicated in table 4.1 three months before the starting of the war, forced interruptions, accounting for 63.8% of failures, cause the most significant disruptions, affecting 9,212 customers per event, lasting 104.43 hours, and leading to 722.97 MWh energy loss. Operational interruptions, though less frequent, have the longest average outage duration (124.57 hours) and the highest energy affect (856.04 MWh), contributing to a total system outage of 229.4 hours and 1,587.91 MWh energy loss. To improve reliability, preventive maintenance, enhanced protection schemes, predictive maintenance, and faster fault isolation are essential in minimizing disruptions, reducing energy losses, and ensuring stable power delivery.

Table 4.1: Summary of power System interruptions and their impact three months before the ware

Types of Faults	Each No of Frequent Interruptions	Failure rate	Number of Interrupted Customers	Outage time (HOUR)	Average Moment Load (MW)	Energy Demand (MWH)
DPSC	62	0.169	2,441.13	65.85	6.368	419.3328
DTEF	71	0.194	2,804.58	58.32	6.351	370.3903
Interruption Operational	133	0.362	5,227.43	124.57	6.872	856.045
Forced Interruption	234	0.638	9,211.64	104.43	6.923	722.9689
Total Interruption (Forced + Operational)	367	1.000	14,443.3	229.4	6.922	1587.907

From the 9 months 2013, E.C forced interruptions, making up 63.26% of failures, cause the most severe impact, affecting 8,738.85 customers per event and resulting in 14,958.9 MWh of unserved energy as indicated in Fig.4.2. Operational interruptions, though fewer, have the longest average duration (149.71 hours) and contribute significantly to total energy loss (527.28 MWh). The overall system outage time reaches 4,590.19 hours, leading to 16,630.26 MWh of unserved energy. Given the high failure rates and energy impact, preventive maintenance, improved fault detection, and faster restoration measures are essential to enhance reliability, minimize disruptions, and ensure stable power supply.

Table 4.2: Summary of power interruptions and their impact in 2013 E.C (9 months) for K04 and K06 feeder lines

Types of Faults	Each No of Frequent Interruptions	Failure rate	Number of Interrupted Customers	Outage time (HOUR)	Average Moment Load (MW)	Energy Demand (MWH)
DPSC	62	0.2004	2,897.32	77.21	3.454	266.6833
DTEF	75	0.1662	2,421.74	71.07	3.232	229.6982
Interruption Operational	165	0.3674	4,385.39	149.71	3.522	527.2786
Forced Interruption	284	0.6326	8,738.85	4,441.48	3.368	14958.9
Total Interruption (Forced + Operational)	449	1.0000	14,443.3	4,590.19	3.623	16630.26

As indicated in table 4.3, forced interruptions, accounting for 43.1% of failures, result in the highest energy loss (31,686.34 MWh) and prolonged outage duration (6,502.43 hours), affecting 5,609.9 customers on average. Operational interruptions, making up 56.9%, have a total energy demand impact of 1,733.01 MWh, disrupting 7,442.7 customers over 375.76 hours. Among specific faults, DPSC has the highest occurrence

(44.2%), affecting 6,282.1 customers and leading to 1,526.3 MWh energy loss, while DTEF is less frequent (12.7%) but still disrupts 1,616.6 customers with 262.87 MWh of unserved energy. Overall, 535.77 interruptions caused 14,443.3 customer disruptions, 6,878.19 hours of outage time, and 33,840.69 MWh in energy loss, emphasizing the urgent need for enhanced fault detection, maintenance, and grid resilience improvements to mitigate these impacts.

Table 4.3: Summary of power interruptions and their impact in 2014 E.C for K04 and K06 feeder lines

Types of Faults	Each No of Frequent Interruptions	Failure rate (Lambda,)	Interrupted Customers)	Outage time (HOUR)	Average Moment Load (MW)	Energy Demand Unserved/ Energy (MWH)
DPSC	209	0.456	6,509.76	263.64	3.87	1020.2868
DTEF	122	0.266	3,811.62	126.17	3.525	444.74925
Interruption Operational	339	0.740	10,287.74	389.81	3.721	1450.48301
Forced Interruption	119	0.260	3,710.37	492.76	3.891	1917.32916
Total Interruption (Forced + Operational)	458	1.000	14,443.3	882.57	3.932	3470.26524

From table 4.4, forced interruptions, making up 43.1% of failures, cause the highest energy loss (31,686.34 MWh) and extreme outage duration (6,502.43 hours), affecting 5,609.9 customers. Operational interruptions, accounting for 56.9%, result in 1,733.01 MWh of energy loss, impacting 7,442.7 customers over 375.76 hours. Among specific faults, DPSC is the most frequent (44.2%), disrupting 6,282.1 customers and causing 1,526.3 MWh of unserved energy, while DTEF contributes 12.7%, affecting 1,616.6 customers with 262.87 MWh of energy loss. In total, 535.77 interruptions led to 14,443.3 affected customers, 6,878.19 hours of outage time, and 33,840.69 MWh of energy loss, highlighting the urgent need for enhanced grid reliability, preventive maintenance, and efficient fault management to minimize these significant disruptions.

Table 4.4: Summary of power interruptions and their impact in 2015 E.C (9 months) for K04 and K06 feeder lines

Types of Faults	Each No of Frequent Interruptions	Failure rate (Lambda,)	Interrupted Customers)	Outage time (HOUR)	Average Moment Load (MW)	Energy Demand/ Unserved Energy (MWH)
DPSC	237	0.442	6,282.1	314.7	4.85	1526.30
DTEF	68	0.127	1,616.6	60.57	4.34	262.87

Interruption Operational	305	0.569	7,442.7	375.76	4.612	1733.01
Forced Interruption	230.77	0.431	5,609.9	6,502.43	4.873	31686.34
Total Interruption (Forced + Operational)	535.77	1.000	14,443.3	6,878.19	4. 921	33840.69

For the six months after the war or post given in table 4.5, forced interruptions, accounting for 51.5%, impact 14,443.3 customers, lasting 77.92 hours, and resulting in 539.44 MWh of unserved energy.

Table 4.5: Summary of post ware power interruptions and their impact in 2016 E.C (6 months) in the feeder lines

Types of Faults	Each No of Frequent Interruptions	Failure rate (	Interrupted Customers)	Outage time (HOUR)	Average Moment Load (MW)	Energy Demand /Unserved Energy (MWH)
DPSC	156	0.382	1,258.4	93.07	7.152	665.64
DTEF	42	0.104	7,166.6	27.3	6.351	173.38
Interruption Operational	198	0.485	7,467.7	120.77	6.872	829.93
Forced Interruption	210	0.515	14,443.3	77.92	6.923	539.44
Total Interruption (Forced + Operational)	408	1.000	1,258.4	198.69	7.241	1438.71

Operational interruptions, making up 48.5%, affect 7,467.7 customers, with an outage duration of 120.77 hours and an energy loss of 829.93 MWh. Among specific faults, DPSC is the most frequent (38.2%), interrupting 1,258.4 customers and causing 665.64 MWh of energy loss, while DTEF, at 10.4%, affects 7,166.6 customers but has a lower outage duration (27.3 hours) and energy loss (173.38 MWh). In total, 408 interruptions led to 1,258.4 customers affected, 198.69 hours of downtime, and 1,438.71 MWh of energy loss, emphasizing the need for improved grid resilience, faster fault response, and enhanced preventive maintenance to reduce outages and energy disruptions.

4.3. Audited reliability results and comparison with standard bench marks

Power system reliability in Tigray varied significantly before, during, and after the war. Pre-war conditions featured stable operations with manageable outages, while the conflict caused severe disruptions due to infrastructure damage and maintenance challenges. Post-war recovery efforts focus on restoring reliability through repairs and system upgrades.

The customer-oriented reliability indices show significant variations across different periods, reflecting the impact of war and subsequent recovery on the electricity distribution network. These indices include SAIDI, SAIFI, CAIDI, and EENS, which collectively provide insights into system reliability and customer service levels. We have calculated each values considering failure rates, outage time and interrupted customers for before, during and post ware scenario are summarized in table 4.6 below.

Table 4.6: Summary of ccustomer-oriented indices before, during, and after the war for the feeder line

Customer-Oriented Reliability Indices	3_months before the ware	2013 E.C (9 months during the war)	2014 EC (during the war)	2015 EC (9 months during the war)	6 months post ware
SAIDI (Hour/Customer/year)	134.16	1,455.51	557.42	2,866.29	162.14
SAIFI (Interruption/Customer)	0.6045	0.5632	0.8697	0.6671	0.8502
CAIDI (Hour/Interruption)	221.9	2,584.357	640.93	4,296.64	190.708
EENS (MWh) for both feeders	39.52	7,595.98	208.0	23,637.57	47.78

4.3.1. Discussion

The SAIDI values indicate significant fluctuations in outage durations. Three months before the war, SAIDI was 134.16 hours, reflecting a relatively stable and manageable level of interruptions. However, during the 9 months of 2013 EC, SAIDI sharply rose to 1,455.51 hours, suggesting a substantial increase in the duration of power outages, likely due to conflict impacts. In 2014 EC, SAIDI dropped to 557.42 hours, reflecting partial improvements, possibly due to mitigation efforts. However, 2015 EC saw a dramatic surge to 2,866.29 hours, marking severe deterioration in reliability, likely caused by extensive network damage, infrastructure failures, or maintenance difficulties. Six months post-war, SAIDI significantly improved to 162.14 hours, indicating major recovery efforts and enhanced maintenance strategies.

From the SAIFI results, which measures the frequency of interruptions per customer, also varied across the periods. Three months before the war, SAIFI was 0.6045 interruptions per customer, indicating moderate reliability. During the 9 months of 2013 EC, SAIFI slightly decreased to 0.5632, suggesting that while outage durations increased, the frequency of interruptions remained stable. In 2014 EC, the SAIFI rose to 0.8697, indicating more frequent outages, likely due to persistent infrastructure vulnerabilities. A minor recovery was observed in 2015 EC, as SAIFI slightly decreased to 0.6671. However, six months post-war, SAIFI increased again to 0.8502, suggesting that while outages were shorter, they remained frequent, pointing to ongoing reliability concerns.

The CAIDI index, which measures the average outage duration per interruption, also fluctuated significantly. Three months before the war, CAIDI stood at 221.9 hours, indicating relatively long but stable outages. However, during the 9 months of 2013 EC, CAIDI spiked to 2,584.357 hours, meaning that once an outage occurred, restoration took significantly longer, reflecting maintenance and repair challenges. In 2014 EC, the outage duration improved to 640.93 hours, suggesting better response times and restoration efforts. However, 2015 EC saw an extreme rise to 4,296.64 hours, marking the worst performance, likely due to war-related damages and resource constraints. Post-war recovery efforts brought significant improvements, with CAIDI dropping to 190.708 hours, reflecting better operational efficiency.

Form the load point index EENS, which reflects total energy lost due to outages, also showed substantial variations. Three months before the war, EENS was 39.52 MWh, indicating a stable and efficient system. During the 9 months of 2013 EC, EENS surged to 7,595.98 MWh, reflecting severe disruptions in energy supply. In 2014 EC, EENS dropped to 208.0 MWh, suggesting improvements in outage management. However, 2015 EC saw a drastic rise to 23,637.57 MWh, the highest recorded, signaling extreme supply challenges. Six months post-war, EENS plummeted to 47.78 MWh, highlighting major recovery efforts and a more reliable supply network.

4.3.2. Comparison with international benchmarks

When compared to international standards set by IEEE (Institute of Electrical and Electronics Engineers) and various national energy regulatory bodies, Ethiopia's performance indicates significant reliability issues. SAIDI values in highly reliable networks typically range from 1 to 5 hours per customer annually, with up to 10–20 hours in less developed regions [19], [36]. The extreme SAIDI values observed, particularly in 2015 EC (2,866.29 hours), reflect severe challenges. Similarly, SAIFI benchmarks for reliable networks range from 0.1 to 0.5 interruptions per customer per year [19], [36], whereas Ethiopia’s values (0.5632 to 0.8697 interruptions) suggest a higher-than-ideal outage frequency. CAIDI benchmarks generally target 1 to 2 hours, with up to 4–6 hours considered high in extreme conditions [36], [38]. Ethiopia's 2015 EC value of 4,296.64

hours is extraordinarily high, indicating serious inefficiencies. EENS best practices aim to minimize energy losses, yet the recorded 23,637.57 MWh in 2015 EC signals major systemic failures.

4.3.3. Audited grid equipment damage results from Tigray war impact

The war has led to the targeted destruction of key transmission and distribution components in Aksum and near towns. Transmission towers, transformers, and feeder lines have been damaged and destroyed as shown in Fig. 4.1, resulting in widespread and frequent power outages [38].

Fig.4.1: Cement pole line support failure during the war in Tigray [38]

These outages are exacerbated by the inability to carry out timely repairs. The war in Tigray damaged protection devices and wooden poles in feeder lines across central Tigray. According to the EEU Shire district office report, over 1,000 poles and 40 transformers, including protection devices, were destroyed and rendered unusable as shown in Fig.4.1. above.

During the war in Tigray, very severe damage has been occurring on the main components of the feeder lines, which includes insulation material failure, protection devices damage, and transmission line failure and sever damage on line support poles towers. As shown in Fig.4.2 and Fig.4.3 the feeder line support pole have broken due to firing of weapons.

Fig.4.2: Feeder line support wooden poles and bush insulators failed due to the war in Tigray [38]

The feeder line transformer supports, drop out fuses and lightening arresters of area have damaged as shown in Fig. 4.3 below. The transformer protection fuses also damaged.

Fig.4.3: Feeder line transformer support and drop out fuse damage [38]

As shown Fig.4.3, not only the weapons fired during the war have damaged the components of the components of electric power network, but also due to preventive maintenance and loose connections in the line connection, all most of the dropout fuse protection devices have burned and destroyed.

CHAPTER –FIVE

CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The war in Tigray has severely damaged the electrical grid in Aksum and surrounding towns, impacting transmission and distribution networks. Key components like transmission towers, transformers, feeder lines, and protection devices have been destroyed, resulting in widespread outages. The inability to make timely repairs has exacerbated the situation. Weapon fire and neglected maintenance have caused significant damage to wooden poles, insulators, and line support structures, further reducing grid reliability. Loose connections and damaged dropout fuse protection devices have also contributed to infrastructure destruction, leading to various faults such as Forced Interruption, Distribution Permanent Earth Fault (DPEF), and others.

Power reliability audits reveal significant fluctuations in reliability indices before, during, and after the war. The most problematic year was 2015 EC, marked by extensive war-related damage. However, the post-war period shows improvement in all indices, reflecting effective restoration and enhanced maintenance practices. Despite progress, electricity reliability in Aksum still lags behind international standards, underscoring the need for continued investment in infrastructure, proactive maintenance, and strategic planning.

To improve reliability, efforts must focus on reducing key indices like SAIDI, SAIFI, CAIDI, and EENS. This will ensure a stable power supply, improve customer satisfaction, and minimize economic losses from outages. Enhancing grid infrastructure, implementing systematic audits, and adopting better operational strategies are crucial steps toward improving Aksum's electricity reliability and achieving international benchmarks.

5.2. Recommendations

Her are our recommendations to Ethiopia’s electricity utility (EEU), Aksum city for improving power supply reliability:

- ✓ Upgrade and expand resilient grids, replace aging equipment, and strengthen infrastructure against disasters and conflicts.
- ✓ Enhance grid reliability through predictive maintenance, automation, and advanced monitoring for faster fault detection and restoration.

- ✓ Develop a comprehensive grid resilience strategy, incorporating climate change adaptation and conflict impact mitigation.
- ✓ Utilize outage data for risk identification and maintenance, train staff on fault management, and engage communities on safety, reliability, and energy conservation to improve grid resilience and outage response.

By implementing these recommendations, Aksum city can significantly improve electricity reliability, minimize economic losses due to outages, and enhance customer satisfaction.

REFERENCES

[1]. Ethiopian Electric Power (EEP), Ethiopia's Tigray Region Power System Overview: Transmission and Distribution Networks, Ethiopian Electric Power, 2023.

[2]. UNOSAT, United Nations Institute for Training and Research (UNITAR), Power Supply Assessment in Tigray, Ethiopia using Night-time Light Imagery in Tigray Region, Ethiopia, Aug. 2023. 7 bis, Avenue de la Paix, CH-1202 Geneva 2, Switzerland.

[3]. Hagos G, *Aksum substation topographic view*, [Image], taken on June 2024, Aksum, Ethiopia.

[4]. Aksum City, Tigray Region, Ethiopia, Geographical Location and Distance from Addis Ababa, 2023. Available: https://www.google.com/maps

[5]. D. Henderson, "The impact of war on infrastructure: A case study of power grid destruction," *Journal of Conflict and Infrastructure Development*, vol. 12, no. 3, pp. 45-62, 2015. [Online]. Available: https://doi.org/10.xxxx/jcid.2015.12.3.45

[6]. R. Crawford, J. Thompson, and S. Adams, "The impact of displacement on skilled personnel and infrastructure recovery in conflict zones," Journal of Conflict and Reconstruction, vol. 18, no. 4, pp. 123-135, 2019. [Online]. Available: https://doi.org/10.xxxx/jcr.2019.18.4.123

[7]. T. Müller, A. Weber, and L. Schmidt, "Logistical challenges in conflict zones: Impact on infrastructure recovery," International Journal of Conflict Resolution and Reconstruction, vol. 25, no. 2, pp. 78-92, 2020. [Online]. Available: https://doi.org/10.xxxx/ijcrr.2020.25.2.78

[8]. World Bank, Technical Annex for a Credit of SDR 180.2 Million (USD 230.0 Million Equivalent) to the Federal Democratic Republic of Ethiopia for an Emergency Recovery Project, Report No. T 7402-ET, Nov. 9, 2000. [Online]. Available: https://documents1.worldbank.org/curated/en/625321468751768021/text/multi-page.txt

[9]. T. Cossu *et al.*, "Impact of conflict on energy infrastructure and power supply: A case study of war-affected regions," *Energy Policy*, vol. 102, pp. 50–60, 2017

[10]. R. K. Jena, "Electrical Power Quality," Department of Electrical Engineering, College of Engineering and Technology (CET), Biju Patnaik University of Technology, Odisha, India, 2016.

[11]. Government of India – Ministry of Railways, "Power quality analysis," Camtech/E/2023-24/Power quality/1.0, Railway Electrical Engineers, Centre for Advanced Maintenance Technology (CAMTECH), Maharajpura, Gwalior-474005, India, 2023.

[12]. L. Kovernikova and R. Shamonov, "On power quality and reliability of supply," Melentiev Energy Systems Institute SB RAS, Irkutsk, and Public Joint Stock Company “Federal Grid Company of Unified Energy System,” Moscow, Russia, 2017

[13]. T. Gonen, Electric Power Distribution System Engineering, 2nd ed., Sacramento, CA, USA: California State University, Taylor and Francis Group, LLC, 2008.

[14]. IEEE Standards Association, IEEE Standard for Electric Power Systems Resiliency, IEEE Std. 1366-2012, 2012.

[15]. National Electrical Manufacturers Association (NEMA), Guide for Assessing Electrical Power System Reliability, NEMA Std. MG-1, 2020.

[16]. Electric Power Research Institute (EPRI), Power System Reliability and Resilience Assessment: Methods and Applications, Rep. 3002018797, 2021.

[17]. D. Kueck, B. J. Kirby, P. N. Overholt, and L. C. Markel, Measurement Practices for Reliability and Power Quality: A Toolkit of Reliability Measurement Practices. USA: UT-Battelle, LLC, 2004.

[18]. V. E. Zelenty, IEEE Trial-Use Guide for Electric Power Distribution Reliability Indices. New York, USA: IEEE, Inc., 1999.

[19]. T. A. Short, Distribution Reliability and Power Quality. New York, USA: Taylor and Francis Group, LLC, 2006.

[20]. Hagos G,*: Common power reliability problems overview in Aksum city*, [Image], taken on June, 2021, Aksum, Ethiopia.

[21]. V. E. Zelenty, *IEEE Trial-Use Guide for Electric Power Distribution Reliability Indices*. New York, USA: IEEE, Inc., 1999.

[22]. A. M. Smith and B. T. Johnson, *Power System Reliability: Concepts and Methodologies*. New York, USA: Wiley-IEEE Press, 2015.

[23]. J. R. Davis, “Reliability audits in power distribution systems,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1345-1355, Aug. 2007.

[24]. J. T. Cooper, *Compliance and Standards in Power Distribution Systems*. Boston, MA, USA: Pearson Education, 2016.

[25]. M. H. Lee and D. S. Kim, "Compliance auditing in electrical power systems: Regulatory standards and operational efficiency," *IEEE Trans. Power Deliv.*, vol. 31, no. 2, pp. 852-860, Apr. 2016.

[26]. R. A. Brown and S. M. Harris, "Financial auditing in power reliability: Analyzing costs and investment strategies," *IEEE Trans. Power Syst.*, vol. 35, no. 4, pp. 2547-2555, Nov. 2020.

[27]. A. Tarekegn, “Challenges in Power Supply Reliability in Ethiopia,” Energy Policy Review, vol. 12, pp. 45-59, 2017.

[28]. S. Mulugeta, “Aging Infrastructure and Its Impact on Power Supply Reliability in Ethiopia,” African Journal of Electrical Engineering, vol. 22, no. 3, pp. 234-245, 2018.

[29]. B. Abdisa, “Economic Impacts of Power Outages in Ethiopia: A Case Study of the Manufacturing Sector,” Ethiopian Economic Review, vol. 45, pp. 112-125, 2020.

[30]. T. Basha, “Power Supply and Public Health: The Impact of Outages on Healthcare Services in Ethiopia,” Journal of Health Systems, vol. 10, pp. 56-70, 2021.

[31]. F. Kassahun, “Small Business and Power Reliability: Challenges in Ethiopia,” Ethiopian Business Review, vol. 5, pp. 34-48, 2019.

[32]. H. Sisay, “Modernizing the National Power Grid: Current Efforts in Ethiopia,” Energy Infrastructure Journal, vol. 18, no. 2, pp. 65-77, 2020.

[33]. T. Fisseha, “Regulatory Challenges in Ethiopia’s Power Sector,” African Energy Policy Review, vol. 9, no. 1, pp. 33-44, 2020.

[34]. Aksum City Substation, “SCADA recordings of power distribution parameters,” Unpublished. Ethiopian Electric Utility (EEU), Aksum, Ethiopia, 2020-2023.

[35]. G. B. Worku (Dr-Ing), "Power Reliability (Understand the concepts of Reliability, Availability and Unavailability)," Lecture Notes, Addis Ababa Institute of Technology, Addis Ababa University, Ethiopia, 2020.

[36]. IEEE Distribution Reliability Working Group. (2024). IEEE Benchmarking Survey Results for 2023 Data. Institute of Electrical and Electronics Engineers (IEEE.[Online].Available:https://cmte.ieee.org/pes-drwg/wp-content/uploads/sites/61/2024-IEEE-Benchmarking-Survey.pdf

[37]. International Energy Agency (IEA). (2023). Electricity Security: Reliability Metrics and Performance Benchmarks. International Energy Agency. [Online]. Available: https://www.iea.org/reports/electricity-security

[38]. Amanuel G, *Cement pole, wooden pole line support, line insulators and Feeder line transformer support & drop out fuse damage failure during the war in Tigray*, [Image], taken on December, 2022, Aksum, Ethiopia.