Mekelle University

Ethiopian Institute of Technology-Mekelle

School of Electrical and Computer Engineering

Chair of Electrical Power Engineering

Reliability Enhancement of Distribution System by Using Feeder Reconfiguration (Case Study: Mekelle City Distribution System)

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Thesis submitted in fulfillment of the requirements for the degree of Masters of Science in Electrical Power Engineering in the school of Electrical and Computer Engineering

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DECLARATION

I hereby declare that this thesis work is my original work, has not been presented for part or full for any other Diploma or Degree of this or other University and I have fully acknowledged all material and results that are not original to this thesis.

Place: Ethiopian Institute of Technology-Mekelle (EIT-M), Mekelle University

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This thesis has been submitted for examination with my approval as a university advisor.

Abstract

Equipment failures and customer interruptions are the primary factors that affect distribution reliability. In many developing nations, including Ethiopia, reliability modeling and evaluation of distribution networks receive less attention "compared to" generating and transmitting systems. Since electric power is now used directly or indirectly for many of our activities, the utility should provide dependable electricity every day of the year to meet consumer demands and enable employees to do their jobs as efficiently as possible.

However, several fault types affect the power supply's reliability and quality. Power quality issues and interruptions are common in Mekelle distribution substation. Short-circuit faults, whether permanent or transient, system overloading and other factors are the primary causes of these interruptions. As a result, consumers are not receiving reliable power.

The main goal of this work is the enhancement of the 15 kV side Mekelle distribution networks at a reasonable cost. Because several factors are causing power outages that mostly affect the 15 kV side. The reliability assessment has been done on fifteen feeders of the 15 kV Mekelle city distribution network. A reliability assessment of feeders on the 15 kV side has been carried out in order to assess the effectiveness of the current system and predict upcoming reliability evaluations. All the interruption data of five years (2011 E.C. up to 2015 E.C.) has been used which have been collected from Mekelle substation as well as north region Ethiopian electric power. Different alternatives have been assessed using ETAP 19.0.1 software method and the alternative with low SAIDI, SAIFI and EENS with a reasonable cost has been preferred.

The reliability of Mekelle city distribution network has been enhanced significantly by implementing auto-reclosers that are justified economically. Even if the ambiguity of the input data is taken into account, SAIFI has been reduced by 59% as compared with the average reliability indices values of the existing system. In the similar way SAIDI and EENS have been decreased by 61% and 78.1% respectively.

Keywords:- Distribution System Reliability, Network Reconfiguration, Reliability Enhancement, Reliability Indices and ETAP

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LIST OF Symbols

λ	Failure rate
N_i	Number of interrupted customers for each interruption event
U_i	Annual outage time for an event
V	Voltage
A	Ampere
T	Time
μ_A	Active failure rates
μ_p	Passive failure rates
Al	Aluminium
L_i	Average load connected to load point i
r_i	Outage duration for event i
$L_a(i)$	Average load connected to load point i
$I >>$	Short circuit
Ie/Io	Earth fault
$I >$	Overload
hr	Hour
yr	Year
B	Net benefits
C	Total costs for recloser installation
$	Dollar
Al	Aluminium
A	Amper
D	Duration
E	East
ETB	Ethiopian Birr
F	Frequency
Km	Killo meter
$kcmil$	Kilo circular mils
kV	Kilovolt
kVA	Kilovolt-Ampere
$kWhr$	Kilo watt hour
MVA	Mega Volt-Ampere (unit of apparent power)
MW	Megawatt
M	Meter
mm^2	Millimeter square
N	North
kW	Kilowatt
$MWhr$	Megawatt-hour
N_o	number of interruptions

LIST OF ACRONYMS

AAAC	All Aluminium Alloy Conductor
AAC	All Aluminum Conductor
AENS	Average Energy Not Supplied
ASAI	Average Service Availability Index
CT	Current Transformer
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
DTL	Definite Time Lag
DG	Distributed Generation
E.C.	Ethiopian Calendar
EEA	Ethiopian Electric Authority
EEP	Ethiopian Electric Power
EEPCO	Ethiopian Electric Power Corporate
EEU	Ethiopian Electric Utility
EENS	Expected Energy Not Supplied
ECOST	Cost of energy not supplied
ETAP	Electrical Transient Analyzer Program
HRC	High rupturing capacity
IEEE	Institute of Electrical and Electronics Engineers
LDC	Load Dispatch Center
LTCs	Load tap changers
MTTR	Mean Time to Repair
ONAN	Oil Natural Air Natural
OL	Over Load
PEF	Permanent Earth Fault:
PSC	Permanent Short Circuit
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
TEF	Temporary Earth Fault
TSC	Temporary Short circuit
USD	US Dollar
VT	Voltage Transformer
$Rec - 1$	Recloser one
$Rec - 2$	Recloser two
$Rec - 3$	Recloser three
$Rec - 4$	Recloser four
$Rec - 5$	Recloser five
$Rec - 6$	Recloser six
$Rec - 7$	Recloser seven
$Rec - 8$	Recloser eight

$Rec-9$	Recloser nine
$Rec-10$	Recloser ten
$Rec-11$	Recloser eleven
$Rec-12$	Recloser twelve
$SCADA$	Supervisory Control and Data Acquisition
CB	Circuit Breaker
ACR	Automatic circuit recloser
CBA	Cost-benefit analysis
MV	medium voltage

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Chapter 1

Introduction

1.1 Background of the Study Area

The primary goal of a power system is to transfer electrical energy from generation to end users efficiently and dependably. Delivering electrical energy to consumers in a satisfactory quality or uninterrupted, dependable power to happy consumers is the main purpose of the electric power distribution system.

Mekelle is the capital city of Tigray, located in northern Ethiopia. It sits at an elevation of 2,340 meters above sea level and has coordinates of 39.47° North (N) latitude and 13.49° East (E) longitude. The city is situated 980 kilometers from Addis Ababa. Mekelle is one of the largest cities in northern Ethiopia and is part of one of Tigray's five major zones.

Year after year, the town's population is growing and spreading out. Consequently, there is a growing demand for the consumption of electrical energy. Mekelle distribution network is experiencing low power supplies, power outages, and interruptions. This suggests that the consumer is receiving unimproved performance from unstable electricity.

Figure 1.1: Geographical Map of Mekelle/Lachi Substation

Mekelle substation, also known as the Lachi substation, was constructed in 1990 E.C and has provided power to Mekelle town and surrounding. All generations are connected to the national grid Load Dispatch Center (LDC) found in Addis Ababa. Mekelle substation receives power from the national grid interconnected substations and generations those are: Alamata substation-Ashegoda wind generation (230 kV single line), Mehoni substation (230 kV double line;

one line idle), and Tekeze hydropower generation (230 kV double line). This substation functions as a transmission substation as well as a distribution substation. It serves as a transmission substation connecting the transmission lines of Alamata, Mehoni, and Tekeze. Additionally, it functions as a distribution substation, transferring power to the distribution lines (15 KV & 33 KV).

The substation consists of two 230/132/15 kV autotransformers with a rated of 125/125/37.5 MVA each, one 132/45/15 kV mobile transformer with a rated of 50/50/50 MVA (45 kV idle), one 132/33/15 kV transformer with a rated of 16/16/8 MVA (15 kV idle), one 230/132 kV with a rated of 63/63 MVA that feeds to the Messobo cement factory. The two autotransformers are step-down transformers from 230 kV to 132 kV which supplies to Adwa, Adigrat, mobile transformer and 132/33/15 kV transformer and also to 15 kV which is provided to Mekelle distribution system and the surrounding areas.

Mekelle distribution substation has three 15 kV incoming feeders (KO-1, KO-7, and R-1) with 16 outgoing lines, and one 33 kV incoming feeder (DTF1) with four outgoing lines: Industry Zone (DLF1), Hagereselam (DLF2), Adikeyh (DLF3), and ITACA factory (DLF4). The incoming feeder for KO-1 feeds to KO-4, KO-5, KO-6, KO-10 and KO-12. The incoming feeder for KO-0, KO-2, KO-3, KO-8, and KO-11 is feeder KO-7. The mobile substation or feeder R-1 supplies to the feeders KO-9, R-2, R-3, R-4, R-5, and R-6 outgoing lines.

There are fifteen 15 kV radial outgoing lines in Mekelle city and those lines are arranged radially. The majority of these feeders are pole-mounted which are connected to a step-down distribution transformer. The step-down distribution transformer decreases the voltage from 15 kV to 380 V three-phase and 220 V single-phase before distributing it to loads in homes, offices, buildings, and industries.

Table 1.1: Transformers and their ratings of Mekelle substation

Transformer	**Type**	**Power Rating (MVA)**	**Voltage Rating (kV)**
Transformer 1	Autotransformer	125/125/37.5	230/132/15
Transformer 2	Autotransformer	125/125/37.5	230/132/15
Transformer 3	Three winding transformer	16/16/8	132/33/15
Transformer 4	Two winding transformer	63/63	230/132
Transformer 5	Mobile transformer	50/50/50	132/45/15

The first two 230/132/15 kV transformers, with a rating of 125/125/37.5 MVA, step down 230 kV to 132 kV to supply 132 kV substations like Adwa & Adigrat and also to supply a 132/33/15 kV transformer, which feeds to 33 kV customers. The tertiary winding 15 kV feeds to 15kV customers, including small industries.

Transformer 3 receives 132 kV from transformers 1 and 2 and feeds it to 33 kV customers. Its 15 kV side is idle.

Transformer 4 is a dedicated line to the Messebo cement factory.

Transformer 5 is a mobile transformer that receives 132 kV from transformers 1 and 2 then it feeds to 15 kV customers with its secondary side idle.

Figure 1.2: Outdoor (Switchyard) of Mekelle substation

As shown in figure 1.2 the substation is constructed on an area has been filled with solid stone. Figure 1.2 shows that the outdoor part of the substation contains power transformers, circuit breakers, current transformers, voltage transformers, lightning arrestors, etc.

Figure 1.3: Control room of Mekelle substation

Figure 1.3 shows that 15 kV control rooms of the substation contain protection panels that protect the system from damage and control panels used for measuring and on/off the system.

Figure 1.3 shows a 15 kV circuit breaker (CB) with a protection relay for incoming and outgoing lines, a current transformer (CT) for both incoming and outgoing lines, and a voltage transformer (VT) for incoming feeders only. The circuit breakers in the substation could be controlled locally from outdoors or remotely from the control room. The control room have two 15 kV incoming feeders of (KO-1 and KO-7) with the rating of 1600/1A which feeds to ten outgoing feeders of KO-0, KO-2, KO-3, KO-4, KO-5, KO-6, KO-8, KO-10, KO-11 and KO-12.

Figure 1.4: Mobile substation of Mekelle substation

Figure 1.4 shows the mobile substation (mobile transformer) which includes its CT, VT, CB, and Arrestor. A mobile substation is a movable and temporary substation. A mobile substation was started in 2008 E.C. in Mekelle substation. It has one incoming feeder of (R-1) with a rating of 2500/1 A which has six outgoing lines of KO-9, R-2, R-3, R-4, R-5, and R-6.

1.2 Statement of the problems

Due to the existence of sensitive loads and a continuous increase in power demand, Mekelle City's current distribution networks have not provided reliable power. The primary causes are long distance between the distribution substation and end users, outdated components, lack of sectionalizing switches and protection devices, poor cable design, and inclusion of more customers to transformers with low ratings (transformer loaded).

There is no dependable power source in Mekelle city 15 kV distribution line, which results in more frequent and longer power outages. There is no enough and accurate data in the distribution system. Large and small industries, business areas, governmental and non-governmental offices, and residential customers are being harmed by this interruption issue. To solve this issue and provide consumers with a dependable power supply, the most severe feeder that experiences more interruptions is considered and reconfigured to improve reliability.

1.3 Objectives

1.3.1 General Objective

The main objective of this thesis is to enhance the reliability of the overhead distribution system by reconfiguring feeders.

1.3.2 Specific Objective

- To assess the reliability of the 15 kV side distribution network in Mekelle city.
- To improve the reliability of the most interrupted feeder by feeder reconfiguration.
- To estimate the cost-benefit analysis of the proposed solution.

1.4 Methodology

The mode in this thesis will include these components in a precise and selective manner.

- **Literature review:** A range of journals, article books, manuals, standards, and papers on power distribution system reliability assessment, feeder reconfiguration, and other related works-some of which are listed in the literature review-have been referred.
- **Assessment of existing network:** Assessment of the physical system in the case study area, understanding and adopting the system as a whole.
- **Data collection:** Collecting data necessary for this study is one of the initial tasks.
    - Five years (2011 E.C., 2012 E.C., 2013 E.C., 2014 E.C. and 2015 E.C.) interruption data and average load have been collected from the Northern region Ethiopian Electric Power (EEP) office as well as Mekelle substation.
    - Feeder length, number of transformers and rating capacity, type and size of cable, poles, and installed topology have been collected from the North region Ethiopian Electric Utility (EEU) Mekelle district.
    - The collected data has been used to model the existing Mekelle distribution network and identify the severe feeder under the study.
- **System Design and Analysis using Electrical Transient Analyzer Program (ETAP) software:**
    - Modelling the existing distribution system
    - Reliability indices have been calculated for the existing distribution system.
    - Based on the result of this analysis, the severe feeder is selected and the network is reconfigured with additional reclosers.
    - The network topology is improved with protection devices.

1.5 Scope and limitation of the study

The scope and limitation of this thesis is the assessment of planned and unplanned interruption data for existing Mekelle distribution system from 2011 E.C up-to 2015 E.C and improve the reliability of the selected feeder with proper mitigation solutions using ETAP software.

1.6 Thesis layout

The thesis work has been done in such a way that it gives a clear flow and is considerate regarding the thesis work.

Chapter Two: discusses the theory of reliability, methods of reliability improvement, causes of interruption, and protection and it includes a review of works of literature focusing on reliability, distribution systems, and related works that have been presented in this chapter.

Chapter Three: collecting interruption data, average load and types of faults data analysis, and system modeling based on the failure data is presented in this chapter.

Chapter Four: discuss the result and discussion of the existing Mekelle distribution system, select the most severe feeders, and compare it without reclosers and with reclosers.

Chapter Five: discusses conclusions and recommendations for future work.

Chapter 2

Theoretical Background and Literature Review

2.1 Introduction

The power distribution system is an important component that offers the last connection between the utility and the consumers. Power distribution systems consist of wires, transformers, and poles commonly found in residential circuits. Electricity travels via the distribution system to industrial, commercial, and residential centers after the substation lowers the voltage. From the substation, feeders, a type of conductor, extend themselves to deliver electricity to consumers. Distribution transformers step down the voltage at strategic points along the distribution system to the voltage required by clients or end users. Due to increasingly sophisticated electrical and electronic equipment, customers demand higher quality service. Efficiency serves as a proxy for a power distribution system's effectiveness.

Most distribution systems are radially configured and have a single-circuit main feeder. The radial distribution system is frequently employed due to its simple design, reasonable cost, and useful protective strategy. According to reliability theory, this configuration implies that every part connecting a load point to the supply point must function; as a result, poor reliability is to be expected since the failure of any one part would result in the load point being disconnected.

The frequency, duration, and severity of adverse effects on the electric supply are used to judge reliability [1].
Reconfiguring the network can increase the reliability of a distribution system. This is achieved by closing normally open switches and opening normally closed switches [2]. In the event of a system failure, these switches are crucial in shortening the duration of interruptions. Two switches are typically installed along the main feeders and laterals: tie switches, which are normally open, and sectionalizing switches, which are typically closed. The former is a device that maintains the electrical supply to the healthy part of the system while isolating the defective part from it. By transferring some of the loads to other supporting distribution feeders, the latter device recovers disconnected loads without going against engineering and operation constraints [3].

2.2 Electrical substation

Power is produced at a low voltage level, then increased with transformers. After being transmitted over high-voltage transmission lines, the power is again reduced to a low-voltage level for customer distribution. Power transmission at a high voltage level is cost-effective. Electricity is distributed at a lower voltage level per customer request. To keep this numerous transformation and switching stations between the generating station and customer ends are necessary to provide higher voltage levels and more stability. Substations for electricity are the general term for this transformation and switching facilities.

Substations generally have:

- ◇ Switching Equipment
- ◇ Protection Equipment
- ◇ Control Equipment
- ◇ One or more transformers

Large substations use circuit breakers to cut off hazardous overload currents, ground faults, and short circuits in the network system. In small distribution stations, fuses or reclosers can used to protect the distribution circuit. Additional equipment like capacitors and voltage regulators could also be placed at the substation. Substations consist of fenced-in yards with electrical equipment such as transformers and switches. Substations can be found underground, in fenced enclosures on the surface, or special-purpose buildings [4].

Auxiliaries, power transformers, voltage and current transformers, isolators, lightning arrestors, bus bars, and other electrical components are assembled to form electrical substations. An electrical distribution, transmission, and generation system makes up a substation. Substations carry out several other crucial tasks, such as converting voltage from high to low or the reverse. The voltage may change over time as it passes through several substations from the generating plant to the user.

Substations are typically essential components of a power system that serve as vital conduits between the load points, distribution systems, generating station, and transmission systems [1].

2.3 Distribution substation

Distribution substations are installed where the principal distribution voltages are stepped down to provide voltages for feeding the actual consumers through a distribution network. The distribution substation receives power from transmission or sub-transmission lines and transmits it to distribution feeders. Ethiopia's distribution substations reduce transmission line voltages to 33 kV and 15 kV or lower. Distribution transformers lower the voltage even further to the utilization voltages of 220 V single-phase or 380 V three-phase supply, which the common users require. To supply the end users, the feeders radiate outward from the substation. Transformers are permanently installed in the substations to decrease the voltage to the primary distribution voltage level. These transformers will always be three-phase banks or three single-phase banks connected in three-phase mode.

The transmission system sends power to the distribution system through a distribution substation. Usually, two transmission lines or more serve as the input for a distribution substation. Depending on the size of the area served and the local utility's policies, distribution voltages are normally medium voltage, ranging from 2.4 kV to 33 kV.

Distribution substations isolate faults that occur in the transmission or distribution systems. Although voltage regulation equipment may also be installed along long distribution circuits (several kilometers or miles), distribution substations are not always the points of voltage regulation. Large cities' downtown areas often house complex distribution substations [4].

Transformers located in distribution substations are connected to substation buses via corresponding circuit breakers and surge arresters' protection. Substation buses are connected to three-phase primary distribution lines known as distribution circuits or feeders via circuit breakers.

Usually, each substation bus supplies several feeders. A feeder is a circuit that emerges from the substation. The main feeder, the mains, or mainline, is the circuit's three-phase backbone. The mainline is usually a rather big conductor, such as a 500-kcmil or 750-kilo circular mils (kcmil) aluminum (Al) conductor.

The primary feeder is frequently designed for 400 Amperes (A) by utilities, and an emergency rating of 600 A is regularly permitted. It has one or more laterals, sometimes known as taps, lateral taps, branches, or branch lines, and branch of the mains. There are three-phase, two-phase, and single-phase options for these laterals. If the laterals are faulted, fuses are typically installed to isolate them from the main line. The typical rating of a distribution substation ranges from 15 MVA for older installations to 200 MVA or more for more recent ones. Distribution substations may additionally have separate voltage regulators or load tap changers (LTCs) on the transformers to regulate the primary voltage.

2.4 Types of distribution systems

There are three general classifications of electrical power distribution systems based on configuration; these are radial, ring, and meshed distribution system [5].

1. **Radial distribution systems**

   Systems with radial distribution are the most basic kind because they rely on a single power source. Radial lines that are extended to all parts of a community are used by a generating system to supply power from the substation. Since there isn't a backup distribution system linked to a single power source, in the event of a power outage, radial systems are the least dependable when it comes to continuous operation. One or more loads will experience complete interruption if a power line opens or breaks. Power outages are more likely. The radial system is the least expensive, though. In remote locations where other distribution methods are not economically feasible, this system is employed.

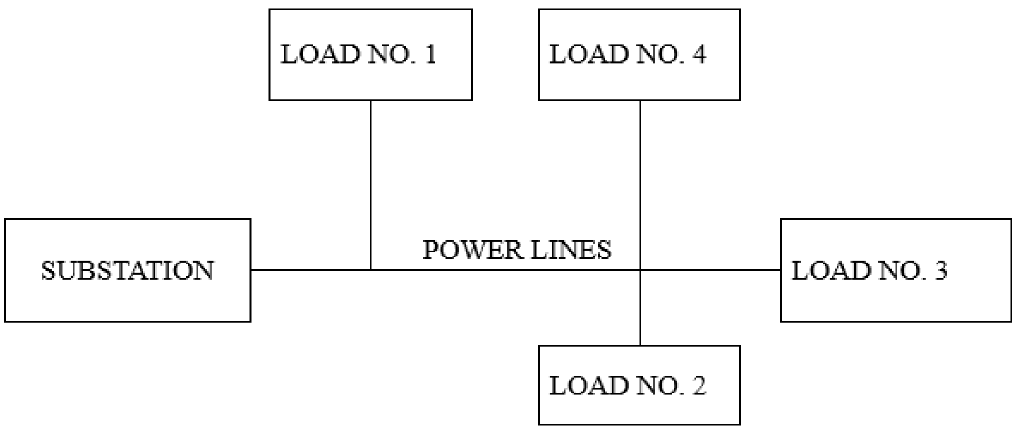

Figure 2.1: Radial power distribution system [5]

2. **Ring distribution systems**

   In densely populated clients, ring distribution systems are employed. To reduce disruptions, the service area is enclosed by the distribution lines. Substations close to the service area receive power delivery from one or more sources, and the substations subsequently distribute the power via radial power lines. Unlike radial distribution systems, no other loads are interrupted when a power line is opened or cut. When it comes to continuous service, the ring system performs the radial system. Increased circuit complexity and additional power lines have driven up the cost of the ring distribution system.

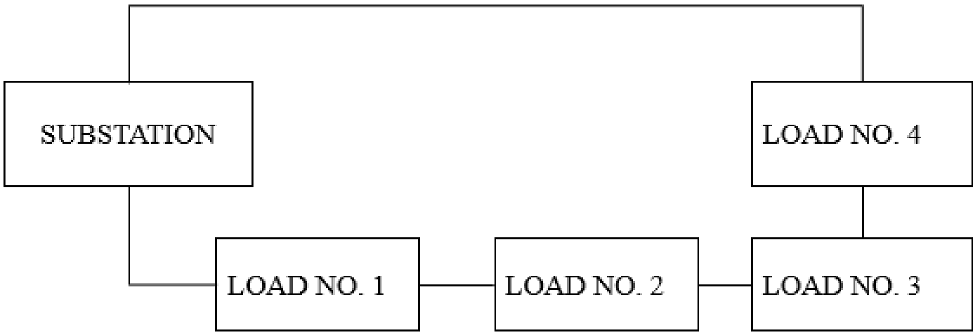

Figure 2.2: Ring power distribution system [5]

3. **Meshed distribution systems**

   Meshed distribution systems are a combination of radial and ring distribution systems. This system is more complex, but it provides very reliable service to end-use consumers. In a meshed distribution system, each load is fed by two or more circuits

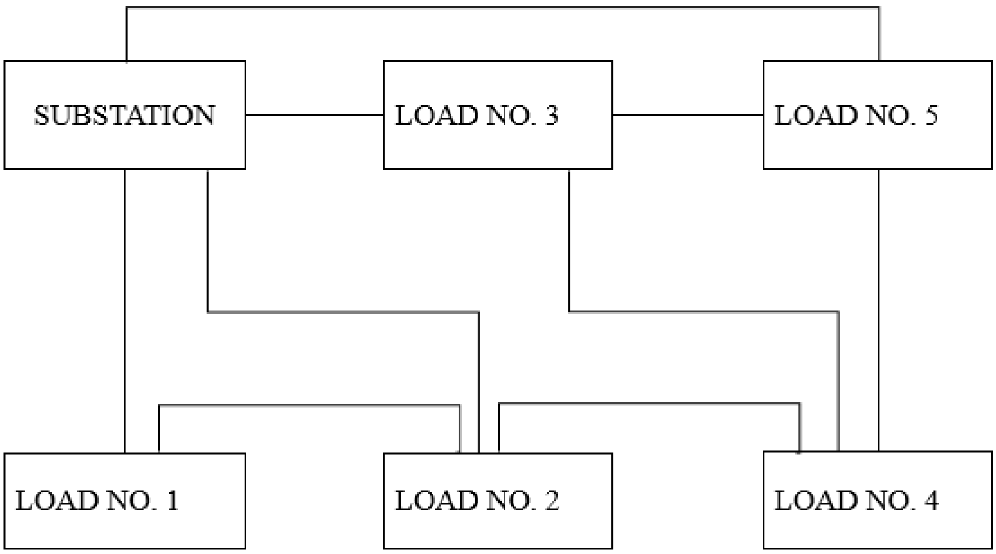

Figure 2.3: Meshed power distribution system [5]

2.5 Reliability of distribution network

The capacity of a power distribution system to provide end users with uninterrupted power service is known as reliability. Distribution systems are primarily responsible for most issues with customer reliability. Consumers encounter power disruptions and outages. Between 70 and 80 minutes of a typical residential customer's 90 minutes of annual power outages can be attributed to distribution system issues [6]. The radial nature of the majority of distribution systems, the age of the components, the sparseness of sectionalizing switches and protection devices, and the proximity of the distribution system to end-user customers are the main causes of this [7].

In the world, power systems are among the most complicated infrastructures, and must function with exceptional quality and dependability. Power systems are primarily designed to transfer electrical energy from points of generation to customer end users cost-effectively and dependably. Power system planning and management can be difficult due to the potential for mutually exclusive reliability and economic constraints [8].

The complexity of the electric power distribution system service provided to the customer is the root cause of nearly 90% of reliability issues, leading to a significant number of reliability problems [9]. Transmission and generation systems are responsible for the remaining 10% [9]. To enhance the electric supply to load points, electric companies and utilities place a high priority on the reliability of distribution systems [9].

Reliability in distribution systems is mostly related to equipment outage and customer interruption [7].

2.5.1 Equipment outage

When a piece of equipment becomes de-energized. It characterizes a component's state when an event directly related to that component prevents it from carrying out its intended function. An outage may or may not cause an interruption of service to consumers depending on system configuration.

Forced outage: an outage brought on by an emergency directly related to a component that necessitates its immediate removal from service, either automatically or as soon as switching operations can be completed; alternatively, an outage brought on by faulty equipment operation or human error.

Scheduled outage: an outage that results when a component is deliberately taken out of service at a selected time, usually for purposes of construction, preventive maintenance, or repair.

Partial outage: describes a component state where the size of the component to perform its function is reduced but not eliminated.

Transient forced outage: a component outage whose cause is immediately self-clearing so that the affected component can be restored to service either automatically or as soon as a switch or circuit breaker can be reclosed or a fuse replaced.

Persistent forced outage: a component outage whose cause is not immediately self-clearing but must be corrected by eliminating the hazard or by repairing or replacing the affected component before it can be returned to service. Thereby disabling the component until repair or replacement can be made.

2.5.2 Interruption of customers

The loss of service to one or more consumers or other facilities results from one or more component outages, depending on system configuration.

Types of interruptions in distribution network

A. **Forced interruption:** an interruption caused by a forced outage.

B. **Scheduled interruption:** an interruption caused by a scheduled outage.

C. **Momentary interruption:** when a customer is de-energized for less than a few minutes (a few seconds).

D. **Temporary interruption:** when a customer is de-energized for a few minutes. It is limited to the period required to restore service by manual switching at locations where an operator is not immediately available. Such switching operations are typically completed within 1-2 hours [10].

E. **Sustained interruption:** when a customer is de-energized for more than a few minutes (a few hours). It is any interruption not classified as momentary or temporary.

The precise meaning of "a few minutes" varies from utility to utility, but is typically between 1 and 5 min. The IEEE defines a momentary interruption based on 5 min. (Note: some references classify interruptions into four categories rather than two. Instantaneous interruptions last a few seconds, momentary interruptions last a few minutes, temporary interruptions last a few hours, and sustained interruptions last many hours) [11].

Causes of interruptions in distribution network

There is different man made and natural causes of interruption for distribution system. Among those causes of interruption tree, animal, vehicle and lightning have been analyzed by many researchers [3].

1. **Tree-caused faults (overhead line):**

   There are various ways in which trees can lead to faults: they can grow into conductors; they can bridge gaps or push conductors together; they can also cause mechanical damage from failing trees or branches.

2. **Animal-caused faults (overhead line):**

   Numerous species of animals, such as birds, snakes, tree squirrels, and more, can disrupt the electrical system. Additionally, substations, transmission lines, overhead distribution lines, and underground distribution circuits may all experience animal-caused faults. In fact, some equipment's are more susceptible to animal-caused damage and outages.

3. **Lightning-caused faults (overhead line):**

   Lightning mostly creates transient faults on distribution circuits by arcing externally through insulation; however, neither the fault arc nor the lightning itself permanently harms any equipment. Typically, less than 20% of lightning strikes result in long-term harm [12]. The majority of damage caused by lightning occurs when it strikes an overhead phase wire directly, creating a massive current surge that raises a high voltage. Flashovers are almost always caused by direct lightning strikes. Furthermore, a pole fire or conductor burns could be caused by the lightning current.

4. **Vehicle caused faults (overhead line):**

   This kind of fault has an irregular stochastic fault process feature. The faults always cause pole damage. Most faults in an electrical utility system with a network of overhead lines are one - phase - to - ground faults resulting primarily from lightning induced transient high voltage and from falling trees and tree limbs. In the overhead distribution systems, momentary tree contact caused by wind is another major cause of faults. Ice, freezing snow, and wind during severe storms can cause many faults and much damage.

   These faults include the following percentages of occurrence: Single phase - to - ground: 70-80%, Phase - to - phase - to ground: 17-10%, Phase -to-phase: 10-8%, Three - phase: 3-2% [3].

Reduction of interruptions in a distribution network

There are three possible strategies for decreasing interruption indices [13]:

A. Reduction of the number of faults

B. Reduction of time of interruption

C. Reduction of the number of affected customers

A. **Reduction of the number of faults**

The frequency of interruptions can be decreased by lowering the network component's failure rates. A tree trimming program, for instance, can reduce the number of problems in an overhead line by ensuring the clearance distance. As a result, there will be fewer interruptions, a lower failure rate, and increased system reliability. There are fewer interruptions, which results in lower interruption indices. In conclusion, fewer defects result in fewer interruptions and unavailability opportunities. We can discover the most crucial steps to lower failure rates in the following list.

- ◇ Preventive maintenance
- ◇ Monitoring critical components
- ◇ Preventive replacement of components that have reached the end of their useful life
- ◇ Isolated or tree wires in overhead lines to prevent tree contact with the conductor
- ◇ Tree trimming and periodical trimming of the adjacent vegetation to avoid contact with the conductors
- ◇ Protection against animals' contact with conductors

B. **Reduction of time of interruption**

The amount of time needed to restore the power supply is known as the interruption time. By disconnecting the impacted sector, a distribution network fault-affected zone can be separated from the network's healthy portion. To isolate the smallest portion of the network affected by the problem, it is necessary that the switching activities of the restoration process are optimized. Although the time interruption in the fault-affected zone is not decreased by this procedure, the network's unaffected sector will see a significant improvement. Additionally, automated sectioning locations can allow faster power supply restoration. Short interruptions are not regarded as long interruptions if the supply is restored in less than three minutes. The unavailability indices decrease when the time processes are shortened, but the frequency of interruptions is unaffected.

The following list shows some of the most important measures for reducing the time of interruption:

- ◇ Distribution network automatization
- ◇ System reconfiguration after the fault
- ◇ Fault current detection in order to localize the fault in the network
- ◇ Faster crew response due to the implementation of an outage management system, travel time coordination, and an increased number of crews and dispatch centers

C. **Reduction of the number of affected customers**

Finally, due to the reduction of the number of customers affected by a fault, it is possible to reduce the interruption frequency and the unavailability of a supply region. Possible reduction measures include:

- ◇ Permanent reconfiguration of the distribution network

- ◇ More protective elements (reclosers, etc.)
- ◇ Resonant transformer grounding

By introducing additional and shorter feeders per substation, permanent reconfiguration lowers the number of customers per feeder. More protective elements, such as reclosers, separate the fault-affected network section from the healthy one and reduce the number of customers interrupted. Finally, the number of temporary phases to ground faults in overhead networks is decreased by resonant grounding with arc suppression coils in transformer stations.

2.5.3 Reliability analysis in distribution network

There are two main types of reliability analysis of power system [4]:

Security: Is the ability of the electric systems to respond sudden disturbances arising within that system, such as electric short circuits. It is assessed using dynamic calculation.

Adequacy: Relates to the existence of sufficient facilities within the system to satisfy the consumers load demand at all times; taking into account scheduled or unscheduled outages. The unscheduled events may be as a result of errors during installation or maintenance operations and faults. The scheduled events are usually as a result of the need to carry out maintenance operations on the equipment, consumer request, and usually consumers do get notice of interruption of supply in advance. From this, both scheduled and unscheduled events lead to operational interruptions.

2.5.4 Reliability evaluation in distribution network

Reliability evaluation is a process of determining whether an existing system have achieved a specified level of operational reliability (desired, agreed upon, or contracted behavior). The distribution system reliability evaluation considers the ability of the distribution system to transfer energy from bulk supply points such as typical transmission system end-stations, and from local generation points, to end customer loads. In the early stages of widespread power system construction relatively less attention was given to distribution networks because of their lower capital intensiveness when compared to generation and transmission systems [14].

The reliability evaluation techniques can be classified into analytical and simulation techniques [15].

Mathematical design and analysis are utilized to represent the system in analytical methods. Simulation techniques estimate the indicators by means of simulating the process and the network's random behavior.

Table 2.1: Presented the comparison between analytical and simulation techniques [15]

Analytical / Statistical	**Simulation**
In this technique, the design gives constant output of numerical result to the same system, same design and same set of input document.	It depends on the selection data used and the total times of simulation.
It is used to simplification of any electrical distribution network for give the output to short time simulation.	This method, however, can incorporate and simulate any system characteristic that can be recognized.
In this technique outputs are sometimes limited only to expected values.	It can produce a wide range of output parameters probability density functions and their respective moments
Its solution time is relatively short due to this partially overcome by the development of modern computational facilities.	The solution time for simulation techniques is relatively long The solution time remains high in applications that demand several reliability assessments.

2.5.5 Distribution system reliability indices

Different types of reliability indices can be done for the analysis of reliability to all electrical power parts (components) i.e., generation, transmission, and distribution, and comparing the reliability of different electric utility companies. Reliability indices are statistical aggregations of reliability data for a set of loads, components or customers. The reliability of the power supply is assessed using the known reliability indices [16].

Reliability indices typically consider such aspects as [8, 17]:

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

Metrics, or precisely defined measurement units, are necessary for distribution reliability. The electric power utility developed a number of reliability indices or performance metrics for reliability evaluation. The power distribution system reliability of the case study area is assessed by using different reliability indices. The Institute of Electrical and Electronics Engineers (IEEE) Standard 1366^{TM}-2012 defines customer-oriented and energy-oriented indices as part of the indices used for power distribution system analysis [14].

A. Customer-Oriented Indices

1. **System Average Interruption Frequency Index (SAIFI):** It is the average frequency of sustained interruptions per customers over a predefined area. Total number of customer interruptions per year divided by the total number of customers served by the network. It

is defined in term of interruption/customer/year. It is usually measured over the course of a year. The expression for the calculation of SAIFI in IEEE Guide for Electric Power Reliability Indices [9] is as given by equation 2.1;

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} = \frac{\sum_i \lambda_i N_i}{\sum_i N_i} \tag{2.1}$$

Where, N_i is the number of interrupted customers for each interruption event i during the reporting period, λ_i is the failure rate at load point i.

SAIFI typical value is mostly between one and two sustained interruptions per year [11]. The value depends on the system configuration and is higher for radial configuration, smaller for underground residential, and the smallest for the grid network [11].

2. **System Average Interruption Duration Index (SAIDI):** It is commonly referred to as customer minutes of interruption or customer hours and provides information as to the average time the customers are interrupted. Total duration of all interruptions in customers/total number of customer served by the network hr/int/yr. The expression for the calculation of SAIDI in IEEE Guide for Electric Power Reliability Indices [9] is as given by equation 2.2;

$$\text{SAIDI} = \frac{\text{Sum of interruption durations}}{\text{Total number of customers served}} = \frac{\sum_i U_i N_i}{\sum_i \lambda_i N_i} \tag{2.2}$$

Where N_i is the number of interrupted customers for each interruption event i during the reporting period, and U_i is the annual outage time for an event i.

3. **Customer Average Interruption Frequency Index (CAIFI):** This index gives the average frequency of sustained interruptions for those customers experiencing sustained interruptions. It is the value of the total number of customer interruptions divided by the total number of customers affected. The expression for the calculation of $CAIFI$ in the IEEE Guide for Electric Power Reliability Indices [9] is as given by equation 2.3.

$$\text{CAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers affected}} = \frac{\sum_i N_i}{\sum_i N_o} \tag{2.3}$$

Where; No is number of interruptions and N_i is total number of customers interrupted

4. **Customer Average Interruption Duration Index (CAIDI):** It is the average time needed to restore service to the average customer per sustained interruption. It is the sum of customer interruption durations divided by the total number of customer interruptions. The expression for the calculation of $CAIDI$ in IEEE Guide for Electric Power Reliability Indices [9] is as given by equation 2.4.

$$\text{CAIFI} = \frac{\text{Customer interruption duration}}{\text{Total number of customer interruption}} = \frac{SAIDI}{SAIFI} \tag{2.4}$$

It is a measure of how long an average interruption lasts, and is used as a measure of utility response time to system contingencies. $CAIDI$ represents the average time required to restore service. It is expressed in units of time per interruption, usually in minutes. The value depends on the system configuration and is lower for radial configuration, higher for underground residential, and highest for the grid network [11].

5. **Average Service Availability Index (ASAI):** This index represents the fraction of time (often in percentage) that a customer has power provided during one year or the defined reporting period. A higher $ASAI$ value indicates higher levels of reliability. The

expression for the calculation of $ASAI$ in the IEEE Guide for Electric Power Reliability Indices [9] is as given by equation 2.5.

$$\text{ASAI} = \frac{\text{Customer hours of available service}}{\text{Customers hours demanded}} = \frac{\sum_i N_i \times 8760 - \sum_i U_i N_i}{\sum_i N_i \times 8760} \tag{2.5}$$

Where: U_i is the annual outage time at load point i and N_i is the number of customers at load point i.

B. Load or Energy Oriented Indices

6. **Expected Energy Not Supplied Index (EENS):** This index represents the total energy not supplied by the system.

$$\text{EENS} = \sum_i L_i \times r_i \tag{2.6}$$

Where L_i is the average load is connected to load point i and r_i is the outage duration for event i.

7. **Average Energy Not Supplied Index (AENS)**

This index represents the average energy not supplied by the system.

$$\text{AENS} = \frac{\text{Total energy not supplied}}{\text{Total number of customers served}} = \frac{\sum_i La(i)U_i}{\sum_i N_i} \tag{2.7}$$

Where $L_a(i)$ is the average load connected to load point i

SAIFI, SAIDI, and EENS are the most used and known indices to measure reliability performance of utilities [9].

2.5.6 Reliability improvement methods in the distribution system

The likelihood that a system, product, or service will function as intended for a given amount of time or that it will function flawlessly in each environment is known as reliability. The performance of the distribution system determines more than 80% of the dependability of the service that customers receive. The high-voltage transmission and generation system determines the other factors. To improve reliability, attention must be paid to the distribution system [18].

To meet consumer needs and keep costs as low as feasible, utilities must work to maximize reliability. By carefully addressing regions that are prone to problems, utilities can optimize network performance and provide better customer service. Finding the interruption's primary cause is the first step. Eliminating problems and then reducing their impact on customers is the primary method for increasing dependability [19].

The ability of various mitigation solution alternatives, including system reconfiguration, the addition of protective devices (such as fuses and reclosers) or upgrades, and the addition of switching devices (such as automated and manual switches and feeder reconductoring, etc.), to increase system reliability at a reasonable cost can be assessed and contrasted. The following are the fundamental options that were looked at [20]:

Transfer Path Upgrades: An alternative route to serve load in the event of a fault is called a transfer path. Reconductoring could be a cost-effective method of increasing reliability if tiny conductor sizes limit the capacity of a transfer path.

New Tie Points: A tie point is a normally open switch that allows a feeder to be connected to an adjacent feeder. Adding new tie points increases the number of possible transfer paths and may be a cost-effective way to improve reliability on feeders with low transfer capability.

Increased Line Sectionalizing: Increased line sectionalizing is accomplished by placing normally closed switching devices on a feeder. Adding fault interrupting devices (reclosers and fuses) improves reliability by reducing the number of customers interrupted by downstream faults. Adding switches without fault interrupting capability improves reliability by allowing more flexibility during post-fault system reconfiguration.

For faults on the line-sectionalizing device (recloser or sectionalize) the main feeder line can be used to divide the feeder into smaller line segments. All taps should have a protective device (fuses for small taps, a recloser or sectionalize for larger taps) where they connect to the main feeder. The shorter line segment minimizes the number of customers affected and minimalizes the time required to patrol the line and locate the fault [12].

Feeder Automation: The term "feeder automation" describes Supervisory Control and Data Acquisition (SCADA) controlled feeder switches. Compared to manual switches, these automated switches enable post-fault system reconfiguration much more quickly, allowing some customers to experience a momentary interruption rather than sustained interruption.

Distribution network reconfiguration using a protection device is one of the most significant strategies among the reliability improvement methods to be applied in this thesis.

Benefits and challenges of reliability improvement methods with protection devices [12]

- ◇ **By considering component aging:** The benefit of this system is the result of reliability evaluation is more objective and realistic. And the evaluating results are more compressive and direct view by classification of reliability. The drawback was large time consumption, it requires high investment cost and improper protection.
- ◇ **By using recloser:** has less investment cost, proper protection and it improves reliability. Its drawback is it makes interruption in Nano second.
- ◇ **Using combination of auto recloser, sectionalizer and limit fuse:** used for clearing permanent or temporary fault before the source side device interrupt, outage restricted, improve voltage profile and decrease loading existing electric equipment, less operation cost. And it requires replacement cost for fuse, high installation cost.
- ◇ **Using fuse and recloser:** It can prevent long term outage by detecting and interrupting temporary fault. It requires replacement cost for fuse.

Due to less investment cost and proper protection device, reliability improvement methods used in this thesis is protection devices by recloser. This method is used for clearing temporary fault before the source side device interrupts, outage is restricted, and less operation cost [8].

Protection System

Protection in a system uses to detect and isolate the affected portion of the system only whenever a short circuit, ground fault or overload occurs that might cause damage of equipment, or may affect operation of healthy part of the system. As a result, they must rapidly cut off earth faults and short circuits and isolate the power system's faulty or sensitive components only. Various protection devices in power systems with rated voltages above 1 kV are available to protect generators, transformers, cables, busbars and consumers [19]. The purpose of these devices is to detect faults and to switch off and isolate these selectively and quickly from the network. So that the consequences of the fault are limited as much as possible. High fault current may cause direct harm to equipment or indirectly loss of production. Protection relays must therefore act very fast with the greatest possible reliability and availability to isolate the faulty parts only [19]. Those listed below are some of the protections [19];

1. **Overcurrent protection**

   The current power grids are overloaded because of rising electricity demand. When a single- or three-phase current reaches the time-setting value, it will be detected and turned off. The tripping time is independent of the amount of limit exceeding (it trips at a fixed time value regardless of the amount of fault current). This protection is called as Definite Time Lag (DTL) relay.

   In English-speaking nations, overcurrent relays are preferred because they respond faster. Radial network systems with a single infeed use an overcurrent relay.

   The relays are connected via a current transformer which is an instrument transformer. With a direction-sensing function, measuring current and voltage and considering changing phase relations in case of fault, the relay is extended to a directional time-overcurrent protection. Such protective devices are preferably used for parallel lines and for the undervoltage sides of parallel operating transformers.

2. **Short circuit protection**

   If there is a short circuit fault occurred in between two phases between three phases the relay will act then the circuit breaker/ recloser will trip automatically. A short circuit occurs when an electric current travels along a path that is different from the planned one in an electrical circuit or two different phases (or, rarely, all three) come into direct or indirect contact with each other, for example, if a bird with a large wingspan touches two conductors simultaneously. When this happens, there is an excessive electric current which can lead to circuit damage, fire, and explosion.

3. **Ground fault protection**

   If there is a ground fault occurred at the distribution system that means any phase with ground the relay will act then the circuit breaker will trip automatically. It is a conducting connection whether intentional or accidental between any electric conductor and any conducting material that is grounded. A ground fault means that one or more conductors make electrical contact with the ground, or point of zero-volt potential, such as a line meeting a tree (which, owing to its moisture, will conduct a current to ground). Electricity always wants to find a path to the ground.

   Electrical circuit protection refers to a scheme for disconnecting sections or components of an electric circuit at a time of fault. A fault means that an unintended electrical connection is made between an energized component and something at a different potential [20].

   Circuit breakers, Re-closers, and fuses are the most used protection devices in power distribution systems. In the case of medium-voltage circuit breakers, the sensing devices are separate current transformers and protective relays or combinations of relays. A fuse is both a sensing and interrupting device, but not a switching device. It is connected in series with the circuit and responds to thermal effects produced by the current flowing through it.

   Re-closers are devices that can identify overcurrent conditions that are phase-to-phase or phase-to-ground. It is an over current protective device that trips and recloses a preset number of times to clear transient faults or to isolate permanent faults. If the overcurrent proceeds for a predefined amount of time, they can interrupt the circuit and then automatically reclose to re-energize the line. If the fault that originated the operation still exists, then the re-closer will stay open after a pre-set number of operations, thus isolating the faulted section from the rest of the system. Thus, the recloser, with its opening/closing characteristic, prevents a distribution circuit being left out of service for temporary faults.

In an overhead distribution system, the faults more than 80% are of a temporary nature and last, for a few cycles or seconds. Those temporary faults on overhead distribution circuit are caused by tree limb contact, by animal interference, by wind bringing bare conductors in contact, or by lightening. Because of its opening and closing properties, the re-closer thus keeps distribution circuits from being temporarily shut down due to faults. Auto reclosers are used on overhead distribution systems to detect and interrupt momentary faults, since many short-circuits on overhead lines clear themselves, an auto recloser improves service continuity by automatically restoring power to the line after a momentary fault, which can be restored without human intervention through the automatic reclosing function of the recloser' greatly improving the reliability of power supply. Compared to manual patrols to repair faults can be faster restoration of power supply, greatly reducing costs.

Re-closers usually have three open-close operations in total, followed by one last open operation to lock out the sequence. Typically, a single additional manual closing operation is permitted. The phase or ground-fault units' counting mechanisms record their operations, which can also be started by externally controlled devices if suitable communication channels are available.

Re-closing mechanisms are typically chosen with the goal of coordinating with mechanisms upstream toward the source, both in terms of time characteristic and operation order. Correct coordination is achieved by adjusting the devices downstream after the re-closer's size and operation sequence have been selected.

Re-closers are used at the following points on a distribution network:

- ◇ In substations, to provide primary protection for a circuit;
- ◇ In main feeder circuits, to permit the sectioning of long lines and thus prevent the loss of a complete circuit due to a fault towards the end of the circuit;
- ◇ In branches, to prevent the tripping of the main circuit due to faults on the branches.

When installing re-closers, it is necessary to consider the following factors:

- ◇ System voltage
- ◇ Maximum load current
- ◇ Minimum short-circuit current within the zone to be protected by the re-closer
- ◇ Coordination with other mechanisms located upstream towards the source, and downstream towards the load.

The voltage rating and the short-circuit capacity of the re-closer should be equal to, or greater than, the values that exist at the point of installation. The same criteria should be applied to the current capability of the re-closer in respect of the maximum load current to be carried by the circuit [21].

Figure 2.4: Different types of reclosers [18]

Coordination of Protection device

Protection coordination is performed among protection devices to prevent unwanted operation of the equipment for a fault occurred in the system.

The main objectives of distribution system protection and coordination are:

- ◇ To detect and isolate the faulted area from the system
- ◇ To minimize the duration of the outage or problem
- ◇ Minimize the actual problem on the system so the damage is minimal
- ◇ Provide alternate circuits or supply in short time where applicable

Power system protection must be carefully designed to interrupt the circuit as close to the fault location as possible to minimize service interruption. Additionally, there is redundancy in the protection, so if one breaker fails to trip, the subsequent breaker must trip. Because the system's protection is synchronized, the closest breaker will trip first in the event of a fault. Protection zones, or the portions of the system that a particular device is "responsible" for isolating the malfunctioning system from, are used to analyze such a scheme [12].

The required characteristics necessary for protective equipment (relay) to function properly are sensitivity, selectivity, speed, and reliability.

Sensitivity: applies to the ability of the relay to operate reliably under the definite condition that produces the least operating tendency.

Selectivity: is the ability of the relay to differentiate between those conditions for which immediate action is required and those for which no action or a time-delayed operation is required. The relays must be able to recognize faults on their own protected equipment and ignore, in certain cases, all faults outside their protective area. It is the purpose of the relay to be selective in the sense that, for a given fault condition, the minimum number of devices operate to isolate the fault and interrupt service to the fewest customers possible.

Speed: is the ability of the relay to operate in the required time. Speed is important in clearing a fault since it has a direct bearing on the damage done by the short-circuit current; thus, the goal of the protective equipment is to disconnect the faulty equipment or system as quickly as possible.

Recloser - Recloser Coordination

The downstream re-closer must be faster than the upstream re-closer, and the clearance time of the downstream re-closer plus its tolerance should be lower than the upstream re-closer clearance time less its tolerance. Normally, the setting of the re-closer at the substation is used to achieve at least one fast re-closer, to clear temporary faults on the line between the substation and the load re-closer. The same procedure and science is followed for relay-relay and relay – recloser coordination [22].

The best results are achieved with the correct coordination of reclosers and sectionalizes downstream, installed in strategic locations i.e., at junctions, or to split the network into more sub-areas. The use of sectionalizes permit, in case of a permanent fault, to limit the number of customers affected by it. Some utilities even use reclosers as sectionalizes as they have all what it takes to function as sectionalizes [23].

Auto recloser consists of:

- ◇ Vacuum interrupter: Interrupts fault currents.
- ◇ Sensor unit: Detect current and voltage differences.
- ◇ Control unit: Processes data and controls reclosing.
- ◇ Operating mechanism: Opens and closes the interrupter.
- ◇ Battery: Provides power for the control unit and mechanism.

Auto reclosers located on the top of distribution poles and are used typically on very long distribution feeders. Their function is to detect line current and isolate a section of the feeder in fault or overload conditions and thereby diminish the number.

2.6 Related works on reliability improvement

Reliability assessment and methods of improvements in electric power distribution network has been studied by different researchers using different approaches. Some of those researches are briefly summarized here:

In [15], the researchers presented a reliability assessment of the distribution system using an analytical method. This study focuses only the analysis of the distribution system using analytical methods as a result the researcher conclude that the reliability index of study area distribution systems (SAIFI, SAIDI) is high which mean that the system is very low reliable. That is why most customers in the study area are more compile daily to Ethiopia utility. The EENS also high which tells the company losses its money by power interruption in addition to transmission, generation and distribution power losses. This paper considers only the assessment of reliability but not done reliability improvement.

In [24], the paper focuses on improving the reliability of distribution systems and minimizing system losses using network reconfiguration techniques. The mathematical formulation is used to evaluate the changes in system reliability indices through network reconfiguration. For the system reliability, different cases are compared and determined based on the system reliability indices considering tie line connections at the system voltage weak nodes. But this paper is not considering to commercial and residential customers. Even tie line is connects to the voltage weak nodes the SAIFI and SAIDI are reduced by 0.33% and 39% respectively only and cost is not doing for this paper.

In [25], this work aims to ensure the proper installation of DG at a suitable location in a distribution network, which increases its reliability. Using artificial neural network (ANN) technique was utilized to find the optimal location of the DG and the reliability was enhanced, as the SAIFI value was reduced by almost 40%, the SAIDI value by 25%, and the EENS value by 25% after injecting DG into the distribution network.

In [26], a study on the reliability analysis and improvement of the Debre Berhan power distribution system using network reconfiguration was conducted. In this thesis, the reliability of the case study was improved by optimally placing switches and using ETAP software. As the result of the optimal placement of switches, the number and location of sectionalize switches; SAIFI, SAIDI and ECOST are reduced. In this thesis the reliability is improved by 8.5%, 17.2% and 11.5% only.

Chapter 3

Data Analysis and System Modeling

3.1 Introduction

Mekelle substation has one double line 230 kV from Tekeze hydropower generation, one 230 kV single line from Alamata substation, and one double line 230 kV from Mehoni substation to Ashegoda wind generation connected to the main bus bar that corresponds to the substation transformer, which is connected to two autotransformers 230/132/15 kV, which have sixteen outgoing lines of 15 kV, four 33 kV outgoing lines, and three 132 kV outgoing lines. Among those sixteen 15 kV outgoing lines, fifteen feeders are configured radially with the voltage level of 15 kV, which is supplied for Mekelle town as well as the surrounding area of the city, and one 15 kV outgoing feeder is supplied out of Mekelle city, i.e., Adigdom town and the surrounding area of the town. However, this thesis focused only on the city line feeders because, as Mekelle is the capital city of Tigray, it consists of many customers, large industries, small industries, governmental and non-governmental offices, higher institutions, etc.

From those fifteen outgoing lines, this thesis considered only the faultiest/interrupted line, which must be reconfigured. Most of these feeders are pole-mounted and are connected to a step-down distribution transformer that steps down 15 kV voltage to 380 V three-phase and 220 V single-phase and then distributes it to loads in homes, businesses, and industries.

The overall layout diagram of Mekelle substation is modeled using ETAP software as shown in figure 3.1.

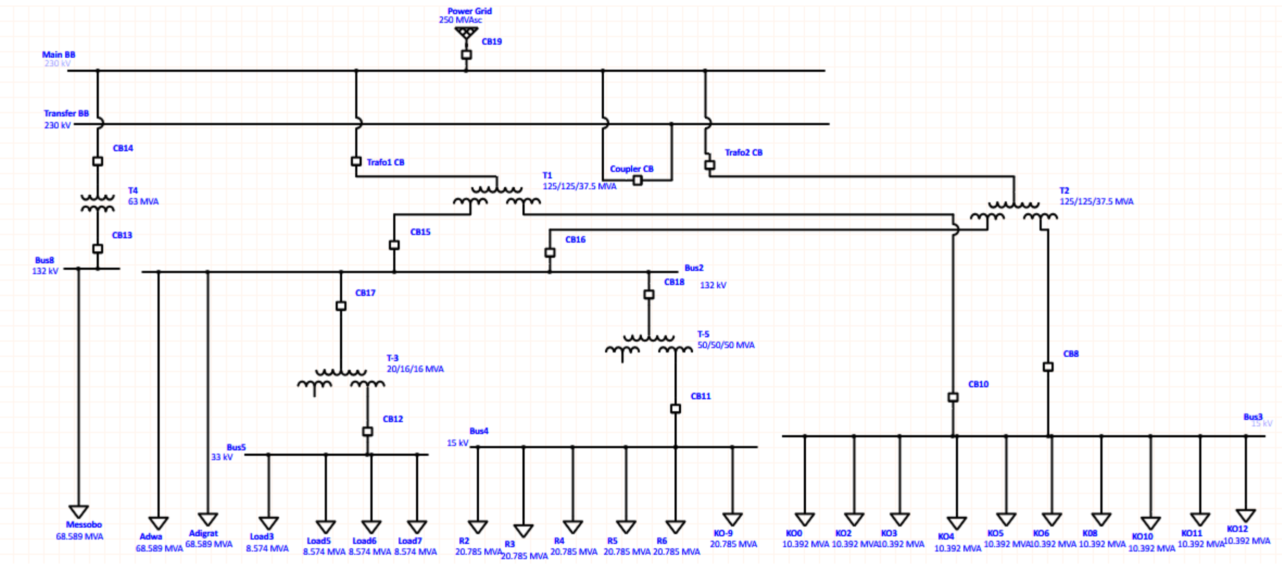

Figure 3.1: Single line diagram of Mekelle substation

From figure 3.1, the distribution substation has three 15 kV incoming feeders (KO-1, KO-7, and R-1) with 16 outgoing lines that are connected to a step-down distribution transformer, which steps down 15 kV voltage to 380 V three-phase and 220 V single-phase and then distributes it to loads in homes, businesses, and industries. Feeder KO-1 feeds to KO-4, KO-5, KO-6, KO-10, and KO-12. Feeder KO-7 feeds to KO-0, KO-3, KO-8, and KO-11. The outgoing lines of KO-9, R-2, R-3, R-4, R-5, and R-6 are supplied from the mobile substation or feeder R-1.

3.2 Data collection

Reliability analysis needs interruption duration, interruption frequency, peak load, type of fault transmission line data (length in kilometers, conductor type, conductor size, configuration type, pole height and line spacing), transformer ratings in kVA, lumped load data (ratings in kVA, power factor and load sector) and so on. These data have been collected from Mekelle substation, north region Ethiopian Electric Power (EEP), and north region Ethiopian Electric Utility (EEU) Mekelle district. To collect data that are related to this thesis, an official letter is written from Mekelle University to those concerned organizations. Five-year (from 2011 E.C. up to 2015 E.C.) interruption duration, interruption frequency, type of faults, peak load, and average load were collected from the recorded data in the substation as well as from the reported data to the north region of Ethiopian Electric Power.

The interruption data and peak loads are recorded from the relay in the substation daily for 24 hours by the operators. These data were recorded manually since there is no SCADA system in the substation. The power interruptions of each feeder are recorded when the outgoing circuit in the substation breaker is open, then all customers connected to the feeder are interrupted. The interruptions occurred at each load point of transformer connection point and service line of customers is not included.

The total number of transformers with their rating capacity and span length between the poles of each feeder was collected from the Ethiopian Electric Utility (EEU) Mekelle district. These data are the latest data, which are gathered from utility managers. This data is reliable.

3.3 Data analysis of Mekelle distribution network

In this thesis, the current network system is designed either directly or indirectly using the primary and secondary data gathered from Mekelle substation, EEP (north region), and EEU (Mekelle district). The primary issue of interruption and the present dependability status of the distribution substation is determined by analyzing these data.

For most of the feeders in Mekelle distribution system, the protection device is a circuit breaker in the substation. Since there is no auto recloser on the main feeder, if a fault occurs on the feeder line, the circuit breaker in the substation becomes open until the fault on the feeder line is cleared. After the fault location has been identified and the fault area is isolated, the circuit breaker in the substation will be reclosed by the operators to energize the feeder lines for permanent faults. Distribution transformers are protected from overcurrent damage by a drop-out fuse. At the low-voltage side of the transformer, there is a high rupturing capacity (HRC) fuse to protect from the overcurrent on the low-voltage side.

Power distribution system along the feeder evaluated using ETAP software. Using necessary collected data, analyzed and modeled have been done in this chapter and the result would discuss in chapter-four.

Table 3.1: Voltage level, Covered area, CT ratio, Load capacity, and Peak load of each feeder in Mekelle distribution substation

Feeder name	Voltage level in (KV)	Covered areas	CT ratio	Currently connected CT ratio	Load capacity in MW	Measured peak load in MW
KO-0	15	Medebr, Adha, korekonchi, May alem	200-400/1/1A	400/1A	8.314	10.475
KO-3	15	Medrok, Mekelakeya camp, Motogo, May mekden	200-400/1/1A	400/1A	8.314	5.4
KO-4	15	Trans Ethiopia, SOS, Mekelle Hospital, Kebelle08,09,14,15,16,17,18, Zban daero	200-400/1/1A	400/1A	8.314	8.2
KO-5	15	Lachi nebar tihizto, Lachi hadush mender, 03, Adishumdhun	200-400/1/1A	400/1A	8.314	8.5
KO-6	15	Lachi nebar tihizto, Lachi hadush mender, Aider, Hamidi, Bethintset	200-400/1/1A	400/1A	8.314	8.5
KO-8	15	Quiha	200-400/1/1A	400/1A	8.314	6.8
KO-9	15	Diaspora, Gereb Segen	400-800/1/1A	800/1A	16.628	2.4
KO-10	15	Lachi, Elala, Kebelle 05 Masjid, Rimna, Adha edaga, GG hotel, Daero	200-400/1/1A	400/1A	8.314	10.1
KO-11	15	Moha Arid, Aynalem	200-400/1/1A	400/1A	8.314	4.8
KO-12	15	Lachi Substation gibi, Velocity factory	200-400/1/1A	400/1A	8.314	0.5
R2	15	Ethio Shewit factory	400-800/1/1A	800/1A	16.628	0.075
R3	15	Lachi Abuna Aregawi, Dagmamsal, Kelkel Debry, Kisanet school, Mariam Adihawsi, Meles foundation, Northern star, Chelekot, Samre	400-800/1/1A	800/1A	16.628	13.95
R4	15	Kebelle 17,18	400-800/1/1A	800/1A	16.628	15.6
R5	15	Aider referral hospital, kebele 07, SOS, Adiwelel,	400-800/1/1A	800/1A	16.628	12.55
R6	15	TG steel factory	400-800/1/1A	800/1A	16.628	0.05

As demand increases from time to time, it is necessary to check out the relay setting as well as the current transformer of the substation. In table 3.1, the currently connected CT ratio means it is already on an operational value. For CT Ratio 200 – 400/1/1A means, the CT can be used either as 200/1A or 400/1A. So, the 400 value shows the CT ratio currently in service from the primary side. And 400-800/1/1A means, the CT can be used as 400/1A or 800/1A. So, the 800 value shows the CT ratio currently in service from the primary side. The outgoing lines supplied from feeder KO-1 (1600/1A) and feeder KO-7(1600/1A) are currently connected CT ratio of 400/1A and the outgoing lines which are supplied from the mobile substation of feeder R-1 (2500/1A), are currently connected CT ratio of 800/1A.

From table 3.1, the outgoing feeders, which are feeds from the incoming feeders of KO-1 and KO-7, have the same installed load capacity of 8.314 MW, and the outgoing lines, which are feeds from the mobile substation, have the same installed load capacity of 16.628 MW with a power factor of 0.8.

The peak load of the above feeder line is taken from the one-year relay report in the substation. As seen from table 3.1, outgoing feeders of KO-0, KO-10, KO-5, and KO-6 are above the installed rating capacity of the feeders. These outgoing feeders are loaded since they cover wide areas. Outgoing lines KO-12, R2, and R6 have light loads because they are dedicated lines to the Lachi substation gibi and Velocity factory, Ethio Shewit factory, and TG steel factory, respectively.

These outgoing feeders are extended from the substation to different areas of Mekelle city and surrounding towns around Mekelle city. The length of each outgoing medium voltage and the total number of transformers with their ratings connected to each feeder line are discussed below in table 3.2. This data is found in the north region Ethiopian Electric Utility office of distribution system operation and maintenance in Mekelle district.

Table 3.2: Number of transformers with its rating and medium voltage length of each feeder in Mekelle distribution substation

Feeder name	Voltage level in (kV)	Number of transformers	Total rating of transformers in (KVA)	MV Length in (km)
KO-0 (Hamiday Switching Station)	15	78	22,750	19.955
KO-3	15	48	22,535	9.815
KO-4	15	104	34,585	22.1
KO-5	15	48	14,240	8.515
KO-6	15	142	62,120	13.715
KO-8 (Quiha Switching Station)	15	81	17,300	24.57
KO-9	15	14	7,925	17.68
KO-10	15	73	19,490	17.875
KO-11	15	60	26,285	23.725
KO-12	15	25	18,720	18.785
R-2	15	7	16,650	5.2
R-3 (Desta Hotel Switching Station)	15	102	35,650	14.83
R-4 (Abrha Castle Switching Station)	15	120	40,290	23.4
R-5 (Ayder Switching Station)	15	132	35,830	24.83
R-6	15	7	11,750	6.37

As shown from the above table 3.2 the length of the outgoing feeder is taken the longest length of the medium voltage starting from the substation in kilo meter (km). The outgoing feeders of R-5, KO-8, KO-11 and R-4 are extended to long distance. Although these outgoing feeders are far apart from the substation most of them have a switching station to minimize interruption. Only feeder KO-11 has no switching station to minimize the interruption. Outgoing lines which have long distance from the supply point to end users with no switching station is highly affected by interruption. Outgoing feeders of R-2, R-6, KO-3 and KO-5 are extended to short distance. Those outgoing feeders are closest to the substation. So, those are affected not as much of by interruption.

All outgoing feeders have their distribution transformers, which supply small factories, business areas, higher institutions, and residences. Feeders KO-6, R-4, R-5, R-3, KO-4, KO-11, and KO-0 have a high rating capacity of transformers, but still they are loaded. Among 15 kV outgoing lines, some of those feeders have a greater number of transformers with small rating capacity, some of them have a small number of transformers with high rating capacity, and some of them have the same number of transformers with different rating capacities. For instance, feeder KO-8 has 81 transformers with a rating capacity of 17,300 MVA, and feeder R-2 has 7 transformers with a rating capacity of 16,650 MVA. Those feeders have almost similar rating capacities but have a very large difference in several transformers. This indicates that the transformers in feeder KO-8 have a small rating capacity, which supplies residential loads, and the transformers in feeder R-2 have a large rating capacity, which supplies factories. Similarly, feeder KO-3 and feeder KO-5 have the same number of transformers, which is 48, but have different rating capacities of 22,535 MVA and 14,240 MVA, respectively. This also indicates that transformers of feeder KO-3 supply to different factories like Medroc factory, plastic factory, bag factory, and others, which have high power capacity in addition to residential, but feeder KO-5 supplies to residential loads.

From table 3.2, feeders KO-4, KO-6, R-3, R-4, R-5, and KO-0 have a greater number of transformers with large rating capacity, but feeder KO-11 has a smaller number of transformers with large rating capacity. This indicates that feeder KO-11 supplies to factories like Moha factory and Ma garment factory.

Interruption in Mekelle distribution substation

The feeder lines, interruption frequency, and duration are highly annoying customers from time to time. Table 3.3 shows the feeder line relay report of interruption frequency and interruption duration of Mekelle distribution system for five consecutive years due to different faults. Each outgoing line interruption data is tabulated in the following tables. Based on the interruption condition, these data are classified as planned and unplanned interruptions. For all 15 KV feeders planned and unplanned interruption frequency (F) and duration (D) is seen at appendix A and appendix B respectively and also daily interruption frequency, interruption duration and types of faults for 2015 E.C for the selected feeder line (feeder KO-11) network can be seen at appendix C.

Table 3.3: Annual interruption frequency, interruption duration and average of five years of each feeder

Feeder Name	2011E.C		2012E.C		2013E.C		2014E.C		2015E.C		Average	
	F (Int/yr)	D (Hr/yr)	F (Int/yr.)	D (Hr/yr)	F (Int/yr.)	D (Hr/yr)	F (Int/yr.)	D (Hr/yr)	F (Int/yr.)	D (Hr/yr)	F (Int/yr.)	D (Hr/yr)
KO-0	163	395.50	257	141.47	199	338.98	328	561.97	329	475.98	255.2	382.78
KO-3	238	408.43	108	239.27	151	494.86	141	215.11	168	317.82	161.2	335.1
KO-4	280	573.53	213	144.20	197	441.75	346	595.66	350	596.02	277.2	470.23
KO-5	183	295.02	245	132.80	218	449.24	325	553.64	341	702.95	262.4	426.73
KO-6	345	389.62	323	227.58	222	440.16	201	371.14	212	214.53	260.6	328.61
KO-8	16	60.27	62	154.35	238	426.34	335	795.68	310	543.50	192.2	396.03
KO-9	405	521.05	182	268.82	150	431.86	146	433.89	159	280.23	208.4	387.17
KO-10	324	503.38	334	217.70	257	379.47	358	521.01	310	659.34	316.6	456.18
KO-11	69	123.37	62	139.78	100	316.91	100	248.08	172	342.57	100.6	234.14
KO-12	44	89.05	54	120.97	52	134.06	66	100.46	157	128.02	74.6	114.51
R-2			3	10.63	39	221.61	62	73.26	57	63.82	40.25	92.33
R-3	122	497.42	165	161.37	211	480.53	270	524.63	366	534.50	226.8	439.69
R-4	112	451.32	119	102.87	110	279.59	254	394.03	207	361.18	160.4	317.8
R-5			5	20.47	29	99.58	319	572.43	289	494.29	160.5	296.7
R-6					42	188.63	42	25.36	33	29.28	39	81.09

From the above table 3.3, feeder KO-9 has the highest interruption frequency in the year 2011 E.C.; then it decreases from the year 2012 E.C. up to 2015 E.C. The main reason for this decrement is the rehabilitation of the network in the year 2012 E.C., which means some loads have shifted from KO-9 to other feeders (Alshaday school and veterinary campus have been supplied from R3 and R4, respectively). The frequency decreases by 55.1% after rehabilitation work.

Feeder KO-8 had the lowest interruption frequency in the year 2011 E.C.; then it increased from the year 2012 E.C. up to 2015 E.C. Up to 2012 E.C., the feeder KO-8 was the dedicated line to the garment factory only, but from 2013 E.C. up to 2015 E.C., KO-8 supplies to Quiha town, Feleg Daero, Chira Kelkel, and the surrounding area. Feeder KO-8 increases its interruption frequency by 74.2%. And the interruption duration of feeder KO-8 is increased by 60.95%.

In 2012 E.C., they added additional feeders: feeder R-2 and feeder R-5, to increase the performance of the network. Due to this, the overall system average of interruption frequency and interruption duration decreased from 2011 E.C. to 2012 E.C. by 20.6% and 58.6%, respectively. This means its reliability is improved due to the additional feeders of R2 and R5 in the year 2012 E.C. Feeder R6 was used as a spare.

In 2013 E.C. feeder R-6 was added to the system, but it is a dedicated line to the TG steel factory only. But still, the network needs rehabilitation to improve reliability. Feeders of KO-4, KO-5, and KO-10 have the longest interruption duration. This indicates that the network coverage of those feeders is too complex, which makes it difficult to find out the fault location in a short period, or it consumes a long time.

In the years 2014 E.C. and 2015 E.C., the planned interruption frequency and planned interruption duration became too high because, in those two years, there was load shedding since the source was only the Tekeze hydropower plant.

In general, from the average interruption frequency and interruption duration of five years, feeder KO-10 has the highest interruption frequency of 316.6 per year, and feeder KO-4 has the longest interruption duration of 470.23 hours per year. This indicates feeder KO-10 is extended to a long distance; due to this, the feeder's outage is frequently out of service, and feeder KO-4 is too loaded and complex a network, then it takes more time to identify the fault location. Feeder line R-2 and feeder line R-6 have the least interruption frequency and interruption duration because those feeders are dedicated lines that supply to small factories only. When a fault occurs on these feeders, it does not take much time to search for fault locations since those feeders have no complex network. So, load and length are the main factors to increase interruption.

In Mekelle distribution system, there are five switching stations, which are used as mini substations. The main advantage of those switching stations is to increase the overall performance of the distribution network to satisfy customers' needs. It is one method of decreasing reliability problems, which consists of its circuit breaker.

Those switching stations are installed at:

Feders, KO-0 (around Hamiday), R-3 (around Desta Hotel), R-4 (around Abreha Castle), R-5(around Ayder) and KO-8(Quiha town).

From the above tables, 3.1, 3.2 and 3.3:

1. The peak load of feeders KO-0, KO-10, KO-5 and KO-6 have above the installed rating capacity of the feeders.
2. The outgoing feeders of R-5, KO-8, KO-11 and R-4 are extended to long distance, but all those feeders expect feeder KO-11 have a switching station to protect interruptions.
3. Feeders KO-6, R-4, R-5, R-3, KO-4, KO-11 and KO-0 have high MVA rating capacity of transformers. From those all feeders expect feeder KO-11 has a greater number of transformers with a highest total rating capacity, but KO-11 has a small number of transformers with high total rating capacity.
4. KO-10 has the highest interruption frequency and feeder KO-4 has the longest interruption duration. This implies due to the complexness of the network it is difficult to identify and isolate the fault location.

As shown from the above table 3.3 interruptions in Mekelle distribution substation are recorded as planned and unplanned interruptions.

Planned interruption: Those are happened for construction, maintenances, or repair, such as; transformer replacement, transformer oil testing and changing burning transformer, relay testing, for pole replacement, to connect section, to maintain broken jumper, for safety to work on the network and so on. It is operational and request interruptions that occurs at a selected time less problematic for the customers and the customers have been notified beforehand of the interruption. As shown from the interruption data load shedding, for maintenance and for safety are the major planned interruption.

Unplanned interruption: The occurrence time of the interruption has not been selected, such as Permanent Short circuit (PSC), Permanent Earth Fault (PEF), Temporary Earth fault (TEF), Temporary Short circuit (TSC), over load (OL), Total blackout and, so on. Unplanned interruption occurs, for example, due to fault clearing, maloperation of the protection system or due to unintentional initiation of opening a switching device by the technician. As shown from the interruption data permanent/temporary short circuit ($I >>$), permanent/temporary earth fault (Ie/Io), over load (I>) are common unplanned interruptions. The type of interruptions is identified by over current relay and several trials is done to re-energize circuit breaker. In Mekelle substation there is one digital relay to send command to line circuit breakers.

TEF: Indicated by over current relay. Line is re-energized by one or two trial of circuit breakers.

TSC: Indicated by over current relay. Line is re-energized by one or two trial of circuit breakers.

PSC: Indicated by over current relay. The fault can't be cleared by one or two trial of circuit breakers in the substation. It needs to solve existing fault to re-energize line again.

PEF: Indicated by over current relay. The fault can't be cleared by one or two trial of circuit breakers in the substation.

OL: Indicated by over current relay. Line will be energized after 3 trials without identifying fault area.

In Mekelle substation 15 kV feeder bus bar control relay is digital relay. The fault current stage of $I >>$ for phase faults and I_o or I_e for earth fault and $I >$ for over load are recorded for every line interruption from digital feeder relay report.

Causes of power interruptions in Mekelle distribution network

In Mekelle distribution network, each interruption frequency, duration of interruptions the loads for each feeder per hour, and type of interruption are recorded in the substation. According to the information gathered from the substation operators, substation maintenance, and distribution line technicians, the most common causes of power interruptions are: trees, overload, windy rain, lightning, accidents, animals, human error, grid outage, equipment malfunction, component aging are causes for unplanned interruptions and scheduled interruptions are causes for planned interruptions.

Tree: Trees have been identified as the source of power outages, based on discussions with the distribution line technicians, tree trimming is a vital utility operation that involves routinely cutting back vegetation near power lines to guarantee safe and dependable clearances. Many customers have extremely negative responses to tree trimming.

In Ethiopian Electric Utility Northern Region, Mekelle, tree trimming is held rarely once a year. Tree trimming should always be performed by a trained crew to ensure safety, maintain tree health and direct re-growth away from conductor location. But in Mekelle city trimming is performed by the community and it is not done as per standard.

Over Load: Overload is ranked as the primary cause of power interruptions based on the conversation with line technicians. Many customers are connected to the current distribution system, overloading transformers, lines, and equipment beyond their capacity. Most of feeders are over loaded because large number of customers and small factories are connected to the nominal current transformer ratio.

Human Errors: Customer interruptions are frequently caused by errors, negligence, and improper work (by daily laborers and junior technicians) by utility workers. Long-lasting power outages are caused by carelessly felling trees and dumping large branches over power distribution lines. Conductors are regularly thrown over the power lines by people who are living far from the city line.

Vehicle Accidents: Drunk drivers, speeding cars, illegal drivers (obtaining a license without a permit or without being skilled drivers), and other people may strike a wooden distribution pole by accident. This usually results in the pole leaning, which poses a risk to line clearances and necessitates repair. In addition to sagging lines into the ground or completely damaging the pole, these collisions may cause conductors to swing together, which could lead to a fault.

Additionally, conductors are damaged, swing together, and poles topple when vehicles are loaded with height above the line clearance.

Scheduled Interruptions: When working on radial distribution systems, it is occasionally necessary to pause customer service. Customers are informed about the time and anticipated duration of the disruption because this work is scheduled in advance. The financial impact and unfavorable impression that interruptions leave on consumers are significantly diminished by advanced knowledge. Certain types of distribution maintenance require equipment to be de-energized and grounded. During maintenance, all customers downstream of the maintenance location will experience interruptions unless they can be fed from an alternate path. Even if the system can be reconfigured to restore certain customers, brief interruptions may be necessary since many switches can only be switched while de-energized.

Scheduled interruptions are also necessary for feeder expansions. It is essential to interrupt service to all customers downstream of this point (on the existing feeder) because the expansion location needs to be de-energized before a feeder extension can be connected. These kinds of interruptions can be prevented by utilizing live-line construction techniques.

To predict the reliability indices of a distribution system, values of failure rates and mean time to repair for each component are necessary. Components used in this analysis from the ETAP 19.0.1 software are feeders, breakers, power transformers, loads, external grids, busbars, and so on. The basic reliabilities input parameters used in ETAP 19.0.1 software for reliability analysis are entered on this page. ETAP 19.0.1 uses a combination of active failure rates (μ_A) and passive failure rates (μ_p) together. The active failure rate is associated with the component failure mode that causes the operation of the primary protection zone around the failed component and can therefore cause the removal of the other healthy components and branches from service after the actively failed component is isolated, then the protection breakers in the substation are reclosed. This leads to service being restored to some or all the load points. It should be noted that the failed component itself (and those components that are directly connected to this failed component) could be restored to service only after repair or replacement. while the passive failure rate is associated with the component failure mode that does not cause the operation of protection breakers and therefore does not have an impact on the remaining healthy components. Repairing or replacing the failed component will restore service from the Software Library. As there is no means of isolating a specific faulty area in the system, μ_p is assumed as zero in the model.

The existing Mekelle distribution network has been modeled using all the necessary data collected from the north region Ethiopian electric utility Mekelle district. There is no failure data for each component in the company (Mekelle distribution system) as well as in EEP and EEU. Even at the national level, there is no research done on the failure rate of a distribution network for each electrical component. Values of failure rate and mean time to repair are obtained from different researches which have the same distribution network configuration and size of conductors with Mekelle city distribution network. In both networks, the larger cross-section conductor of the main feeder line is 200 mm^2 and the network is configured and operated radially. Every component has its failure rate inputs as shown in table 3.4.

Table 3.4: Failure rate of distribution network component [27, 28]

Equipment Name	Failure Rate (f/yr)	Repair Time (hr.)
Line/cable per (km)	1.4	5
Circuit breaker	0.006	4
Transformer	0.015	15
Bus	0.001	2

All feeders have their type and size of conductor, pole length, and distance in kilometers. The feeders have been constructed with 200 mm^2, 160 mm^2, 95 mm^2, 50 mm^2, and 25 mm^2 all aluminum conductors (AAC) and copper conductors. This almost matches with Pirelli NEON Code All Aluminum Alloy Conductor (AAAC) 210 mm^2 19 strands, Pirelli KRYPTON Code AAAC 158 mm^2 19 strands, Pirelli MERCURY Code AAC 111 mm^2 7 strands, Pirelli LIBRA Code AAC 49.5 mm^2 7 strands and Pirelli LEO Code AAC 34.5 mm^2 7 strands respectively which is available in ETAP library. The overhead three-phase line is mounted on wooden and concrete poles of height 14 meters (m), 12 meters, 11 meters, 10 meters, and 9 meters with horizontal configuration. Most distribution transformers are pole-mounted, liquid fill type, and Oil Natural Air Natural (ONAN) classes. Most of distribution transformers have consists of from 25 kVA up to 1250 kVA rating capacity. The lumped load rating in kVA have assuming 80% of transformer ratings in kVA and have a power factor of 0.85.The reliability indices (SAIFI and SAIDI) for the Mekelle distribution substation are calculated using ETAP software.

3.4 System modeling

As explained in the software help index, (ETAP) is a fully graphical enterprise package that runs on different microsoft windows operating systems. It is the most comprehensive analysis tool for the design and enhancement of power systems available. Using its standard offline simulation modules, ETAP can utilize real-time operating data for advanced monitoring, real-time simulation, optimization, energy management systems, and high-speed intelligent load shedding. ETAP allows you to easily create and edit graphical one-line diagrams, underground cable raceway systems, three-dimensional cable systems, advanced time-current coordination and selectivity plots, geographic information system schematics, as well as three-dimensional ground grid systems. ETAP incorporates advanced concepts for determining protective device coordination directly from the one-line diagram. ETAP is one of the foremost-integrated databases for electrical systems, allowing engineers to have multiple presentations of a system for different analysis or design purposes. The software uses to analyze different electrical analysis, like reliability, short circuit, load flow, arc flash, protection coordination and others. As discussed above ETAP is one of power system reliability analysis software.

In this thesis ETAP 19.0.1 has been used as a design, simulation and reliability assessment analysis tool. By using some of the necessary collecting data, the distribution network is modeling in ETAP software and make a decision from the simulation result using the steps in figure 3.2.

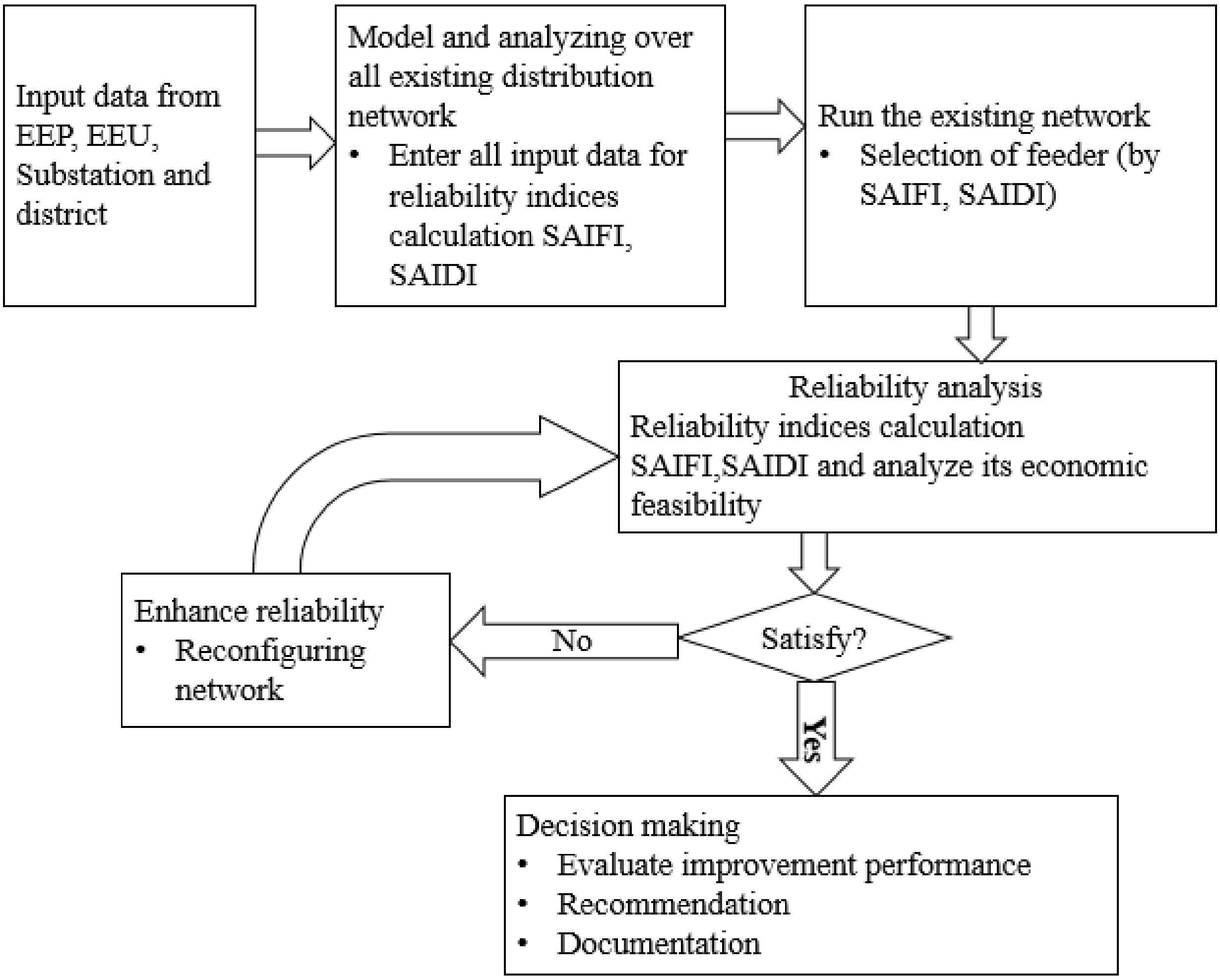

Figure 3.2: Reliability improvement decision-making flow chart

The reliability assessment model is quantifying reliability characteristics based on feeder topology and component failure data. Assessment and modeling of existing network uses to identify weak areas and it needs reinforcement. Reliability assessment model helps to quantify the impact of design improvement options.

In ETAP 19.0.1, electric distribution system reliability analysis involves modeling different components of distribution systems, computing reliability indices at load points and for the overall system and ranking the elements that contribute to the load system indices.

Figure 3.3 shows the composite network for all Mekelle distribution network.

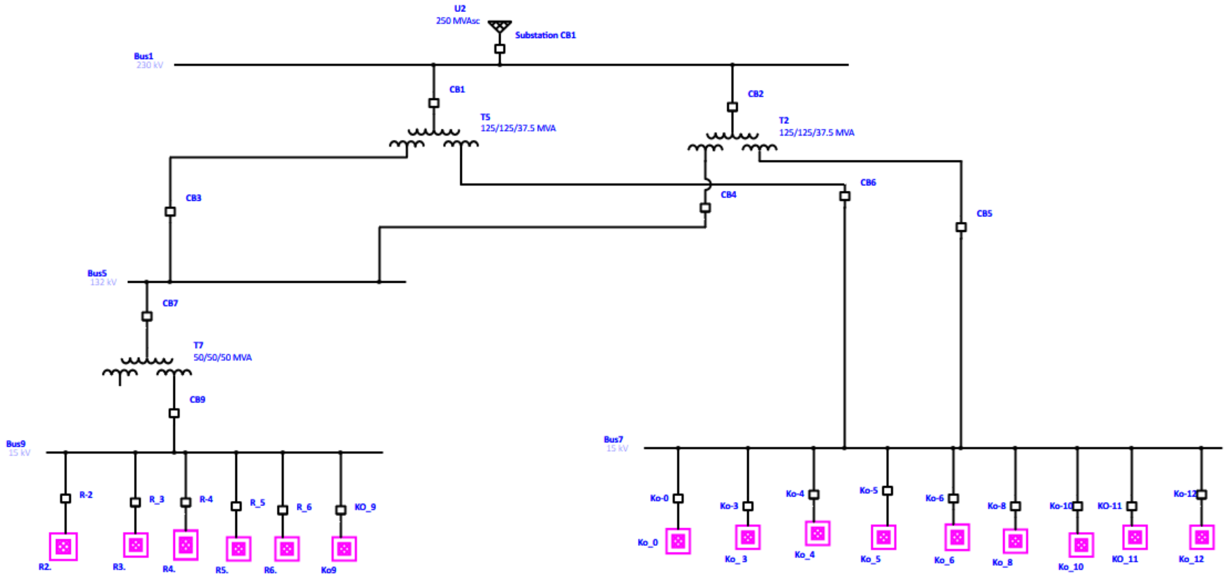

Figure 3.3: Existing single line diagram of composite 15 kV overall Mekelle distribution network

Figure 3.4 shows the project editor view, with the reliability page open. Parameters used in designing and assessment analysis for enhancement reliability of the system are those shown on this page. These data are: transmission line; length in (Km), conductor type, conductor size, configuration type and reliability parameters: transformer ratings and reliability parameters; load; rating in kVA, power factor and load sectors for interruption cost.

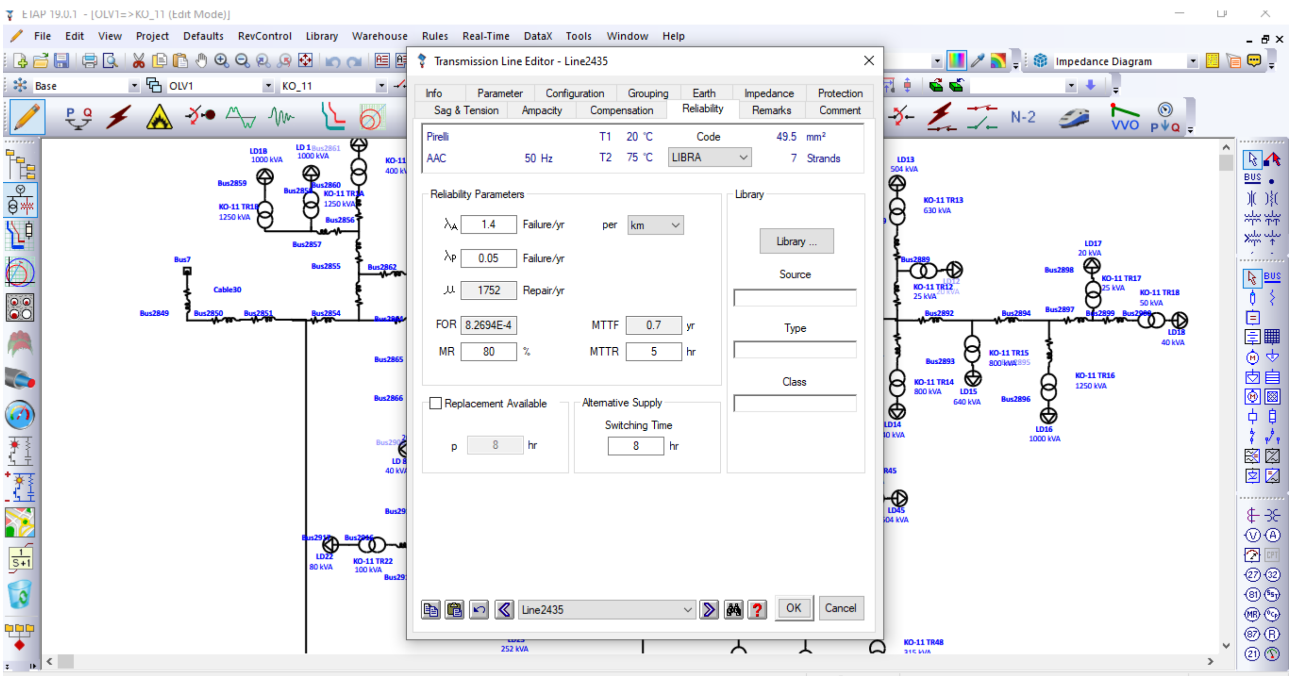

Figure 3.4: Window of ETAP19.0.1 software as reliability page opened

The reliability parameters in the reliability page are defining as follows:

λ_A

This parameter is defined as the active failure rate in number of failures per year. The active failure rate is associated with the component failure mode that causes the operation of the primary protection zone around the failed component. Therefore, this setting can cause the removal of other healthy components and branches from service. After the actively failed component is isolated, the protection breakers are recluse. This leads to service being restored to some or all the load points. Note, however, that the failed component itself (and those components that are directly connected to this failed component) can be restored to service only after repair or replacement.

MTTR

This is the Mean Time to Repair (MTTR) in hours. It is the expected time for a crew to repair a component outage and/or restore the system to its normal operating state.

As shown from the above ETAP model since there is no failure data in the substation or in EEP and EEU failure rate and MTTR for line, transformer, breaker and bus are obtained from different researches which has the same distribution network configuration with Mekelle distribution system listed in the above table 3.4. The failure data of the remaining component are the default data in ETAP library.

Chapter 4

Result Analysis and Discussion

4.1 Introduction

All the existing Mekelle distribution networks were assessed and modeled in chapter three and the result is discussed in this chapter. The result of the reliability indices are calculated by analytically using the statistical data and by simulating the model using ETAP software. The annual reliability indices of Mekelle distribution networks for five years are discussed in table 4.1 below:

Table 4.1: Reliability indices of Mekelle distribution network

Reliability indices	**2011 E.C**	**2012 E.C**	**2013 E.C**	**2014 E.C**	**2015 E.C**
SAIFI (f /customer. yr)	191.75	152.29	147.67	219.53	230.67
SAIDI (hr/ customer. yr)	359	148.73	341.57	399.09	382.94

4.2 Simulation result

The simulation result of the reliability analysis is obtained by performing the following procedures in ETAP 19.0.1 software.

- ◇ Single line diagram of all the existing 15 kV distribution system (Mekelle distribution network) has been designed on the working plane of the software.
- ◇ The necessary parameters of the Mekelle distribution network for reliability calculations have been specified and entered.
- ◇ Run the reliability assessment of the existing Mekelle distribution network.
- ◇ Select one feeder that has the highest reliability indices and redesigns it with mitigation solutions.

In ETAP software, electric distribution system reliability analysis involves modeling different components of distribution systems, computing reliability indices at load points and for the overall system, and ranking the elements that contribute to the load point/bus/system indices.

Reliability indices are calculated to indicate the general reliability characteristics of the distribution system. The reliability indices also used to know the status of the distribution system. If the system has high-reliability indices, it can be concluded that the system has reliability issues. There are different types of reliability indices, but in this study common reliability indices are used to determine the reliability of the system, such as SAIFI, SAIDI, and EENS. All the existing Mekelle city distribution networks are modeled using ETAP 19.0.1 software in chapter three, and the result is discussed in this chapter. The network is very complex, and it is bulky to be modeled. The length, component failure data, transformer rating, and type of load are the main considerations in modeling the whole city distribution network, and the overall simulation result is tabulated in table 4.2 below.

Table 4.2: The overall simulation result of existing Mekelle distribution network

Feeder Name	**SAIFI (f/customer·yr)**	**SAIDI (hr/customer·yr)**	**EENS (MW hr/yr)**
KO0	62.5454	358.4039	5339.374
KO3	55.0578	323.3931	4979.996
KO4	66.5313	439.0583	10346.840
KO5	42.2811	259.4330	71730.170
KO6	72.6760	506.3340	3355614.000
KO8	76.1346	459.9700	4897.988
KO9	31.1989	168.7119	905.219
KO10	63.6011	392.3478	4977.788
KO11	82.3435	472.2644	132,393.200
KO12	46.0488	254.3191	7715.896
R2	9.1817	51.3536	2526.699
R3	28.4538	170.5435	22342.220
R4	52.4447	323.1494	31037.360
R5	52.5497	313.8186	8318.432
R6	9.4653	46.4895	39.516
System Overall	**50.3**	**302.7**	**244,211**

The above table, table 4.2 shows the reliability indices, which are evaluated using the active failure rate in many failures per year per unit length and mean time to repair the overall existing distribution system.

The output result helps to quantitatively describe the reliability of the network with standard performance indicators and compare it with the standard values of the Ethiopian Electric Authority and the best-experienced country.

4.3 Comparison of reliability indices with benchmark

Reliability benchmarks are needed to compare if the system has reliability issues by comparing with the standard. The main purpose of reliability standard benchmarks is to identify or assess the minimum or average performance of the distribution network. There are different recommended values of reliability standards. According to the benchmarking report on the quality of electricity supply, the reliability index values of different countries are shown in table 4.3. These countries place high emphasis on power quality and reliability.

The higher number of reliability indices indicates a lower reliability performance that is a high-reliability issue. A lower reliability index shows better reliability performance and lower reliability issues. As compared with the standard benchmark, Mekelle distribution substation has high-reliability indices or worse reliability performance, which indicates it has lower reliability performance than the standard benchmark of best-experienced countries and the country of Ethiopia.

Table 4.3: Standard benchmark of different countries [29]

Country	SAIDI (hr/customer·yr)	SAIFI (f/customer·yr)
United States	4	1.5
Australia	1.2	0.9
France	1.03	1.0
Germany	0.383	0.5
Italy	0.967	2.2
Spain	1.733	2.2
UK	1.5	0.8
India	1.7	2
Uganda	50	10
South-Africa	50	10
Ethiopia	25	20

SAIFI indicates the frequency of interruption per customer per year. As shown in table 4.2, the SAIFI of the overall Mekelle distribution system is 50.03 interruptions per customer per year. From table 4.3 Ethiopian Electrical Authority (EEA) standards, SAIFI should not exceed 20 frequencies per customer per year, which indicates that the current value of the overall Mekelle distribution system is above the acceptable value. It is 2.5 times the Ethiopian standard value. Also, when comparing the simulation SAIFI value with the best-experienced country, the Germany, which is 0.5 f/yr. customer, it is much greater than the acceptable limit and 100.06 times the Germany standard value [29].

SAIDI indicates the duration of interruption per customer per year. Table 4.2 shows that the SAIDI of the overall Mekelle distribution system is 302.7 hours per customer per year, this indicates that every customer experiences 302.7 hours per year. Based on the standard benchmark of Ethiopia and different countries from table 4.3, Mekelle distribution system has an excessive reliability problem when compared with Ethiopia as well as with the best-experienced country, Germany. As per (EEA), the SAIDI value should not exceed 25 hours per customer per year, which indicates that the current value of the overall Mekelle distribution system is above the acceptable value, which is 12.1 times the Ethiopian standard value. The acceptable SAIDI value in Germany is 0.383 hours per customer per year [29].

Summary of the existing feeder (present system)

In general, based on the simulation result in table 4.2, the following points can be drawn:

1. The reliability of Mekelle distribution substation is not good enough as compared to the international reliability indices of the best-experienced countries.
2. The reliability of Mekelle distribution substation does not meet the requirements set by the regulatory body, which is the Ethiopian Electric Authority (EEA).
3. From Mekelle distribution system, feeder R-2 and feeder R-6 have an acceptable value of SAIFI, but the SAIDI of those feeders is above the acceptable value when compared with Ethiopia's standard value. Those feeders are supplied to the Ethio Shewit factory and TG Steel factory feeder R-2 and feeder R-6, respectively. Feeder R-6 is a dedicated line. Factories must be more reliable than other loads.
4. Feeder KO-11 has the highest SAIFI and SAIDI value as compared to other outgoing lines, which are found at Mekelle distribution substation. It supplies to Moha factory, Ma garment factory, Arid, Aynalem, and others (Mekelle University).
5. From Mekelle distribution system feeder KO-11 has the highest SAIFI value as shown in table 4.2 i.e.,82.3 frequency per customer per year. Also, when compared with Ethiopian

Electric Authority which has 20 interruptions per customer per year, it is 4.115 times the standard value of Ethiopia accepted by the EEA [29].

6. KO-11 has the highest SAIDI value, as shown in table 4.2, i.e., 472.2 hours per customer per year. When compared with the Ethiopian Electric Authority, which is 25 hours per customer per year, the SAIDI value is 18.89 times the standard value of Ethiopia accepted by the EEA [29].

7. EENS of the study area is 132,393.2 MWhr. It indicates the high value of unserved or unsold energy of the feeder.

Generally, from the above reliability analysis, KO-11 has a high-reliability problem. Feeder KO-11 has the highest reliability issue or the most interrupted feeder, which covers the longest distance from the substation to end users as compared with other feeders. As shown from the data listed in table 3.2, the main reason for the increase in the value of SAIFI is the length of the feeder. As a radial system, the SAIFI value increases as the load points are farther from the supply point. If the line is extended far apart from the substation, an interruption happens repeatedly or frequently due to temporary faults caused by external factors like birds, wind, ice, lightning, plants during the rainy season, and others, but it re-energizes itself in a short period.

As indicated by the EEU data, feeder KO-11 is far apart from the substation to end users by a length of about 23.725 km and has 95 mm^2, 50 mm^2, and 25 mm^2 AAC. This feeder covers a long distance for about 11.05 segmented line sections by a small conductor size of 95 mm^2 rather than 200 mm^2 or 160 mm^2 before branching or connecting to transformers. This is one cause of increased customer interruption frequency by transient faults due to weather conditioning and lightning.

As discussed in chapter three, feeder KO-11 is one of the longest feeders, which has no switching stations, a small conductor size, and a large power-rating transformer among 15 kV feeders. There are 60 distribution transformers with a total rating capacity of 26,285 kVA and 970 total estimated customers connected to the KO-11 city feeder line as shown in appendix E. Based on the data gathered from the utility, those customers are grouped into four sectors, namely, residential, commercial, small industrial, and government & institutions. Those transformers have been supplied to:

1. Small industries: like the Moha soft drink manufacturer industry, which has two large 1250 kVA transformers; the Ma garment clothing manufacturer industry, which also has two large 1250 kVA transformers; the Terrazzo industry, which has one 1250 kVA transformer; and the DBL industry, which has two 1250 kVA transformers.

2. Residential customers: The transformers are assumed to be 80% loaded, and each customer can use 5 kW. Then the total number of customers is 950, and the total number of transformers supplied to those residential customers is 37, with a total rating capacity of 7160 kVA. This sector covers a long area from Zban Daero Ayer Hayl's menoria and military staff up to Aynalem and Enda Mariam Shafat.

3. Government & Institutions: Mekelle University, clinic, airport, tele tower, and FM radio are included in this sector. Those sectors have 15 transformers with a total rating capacity of 10,060 kVA.

4. Commercial customer: One transformer with a rating of 315 kVA has been used for this type of sector around the Arid campus.

The data clearly indicates that power interruption per day is a common phenomenon in the case study area, and due to this problem, day-to-day activities of society are highly affected. The distribution transformers in KO-11 with their rating capacity and customer type have been shown in appendix E.

Even though all outgoing lines have a reliability problem as compared with the reliability standard benchmark of the country Ethiopia, reliability improvement of all 15 kV outgoing lines of Mekelle distribution network at the same time is a very difficult task due to the lack of the economy.

Therefore, this thesis focuses only on the reliability improvement of feeder KO-11's outgoing line, which is the most interrupted feeder. The SAIFI value frequency per customer per year of the selected feeder (feeder KO-11) is 4.1 times the standard set by the Ethiopian Electric Authority (EEA). Similarly, the SAIDI value in hours per customer per year of the distribution system (feeder KO-11) is 18.9 times the standard set by the Ethiopian Electric Authority (EEA).

Reliability indices of the study case have been evaluated using different mitigation alternatives to improve the system's reliability at a reasonable cost. As discussed in chapter two, various alternatives of mitigation solutions, such as system reconfiguration, addition of protective devices (reclosers and fuses) or upgrades, and addition of switching devices (manual and automated switches and feeder reconductoring, etc.), can be evaluated and compared in terms of their ability to cost-effectively improve system reliability. Distribution network reconfiguration using a protection device is one of the most significant strategies among the reliability improvement methods that must be applied in this thesis.

Due to less investment cost, lightweight, easy to install on poles, and proper protection device, reclosers are take as reliability improvement methods in this thesis. This method is used for clearing temporary faults before the source-side device interrupts, the outage is restricted, and fewer operation costs are incurred [8].

4.4 Reliability evaluation of power distribution system with reclosers

In an overhead distribution system, more than 80% of the faults are temporary and last for a few cycles or seconds. Because of its opening and closing properties, the re-closer thus keeps distribution circuits from being temporarily shut down due to faults. Auto reclosers are used on overhead distribution systems to detect and interrupt momentary faults. Since many short circuits on overhead lines clear themselves, an auto recloser improves service continuity by automatically restoring power to the line after a momentary fault, which can be restored without human intervention through the automatic reclosing function of the recloser, greatly improving the reliability of the power supply. Compared to manual patrols, repair faults can result in faster restoration of power supply, greatly reducing costs. Therefore, due to those reasons, using an auto recloser to solve the interruption is better for Mekelle distribution system feeder KO-11.

For the study case, most of the faults on feeder KO-11 are temporary faults that may clear themselves and can be restored without human intervention through the automatic reclosing function of the recloser. Due to their reclosing capability and most faults in this case study being temporary, reclosers are selected to improve the reliability of this power distribution system. The recloser normally will try to operate three times before staying open. This is to give whatever is causing the problem a chance to remove itself from the feeder, like lightning, tree limb, squirrel self-destruction, etc.

There are two types of reclosers. These are hydraulic and electronic reclosers. The electronic recloser is the latest and has a longer reclosing time. Unlike hydraulic recloses, min trip is independent of the reclosers' continuous rating. Typical reclosing intervals are 2, 5, and 15 seconds, which is better than that of hydraulic reclosers.

Since auto reclosers are used characteristically on very long distribution feeders to isolate a section of the feeder in fault or overload conditions, thereby reducing the number of outages. So, in this study, feeder KO-11 has a long distance, as discussed in the above description, and solved the reliability problem with this protection system.

The length of the feeder line affects the probability of a fault; the system's dependability is dependent on the line's length. The entire customer would experience interruption to the existing network wherever a failure occurred along the feeder. As the longest feeder is about 23.725 kilometers from the substation to the end users, there was a power outage for all the customers because there was no protection device. System reliability is enhanced when automatic reconfiguration is provided. The simulation centers on assessing the effect of utilizing reclosers on the reliability of the feeder. Reclosers allow utilities to carry out automatic back feed restoration (loop automation), fault detection, and fault segregation. Automatic circuit reclosers are intended for application on overhead distribution lines as well as distribution substations for various voltage classes such as 15 kV, 27 kV, and 38 kV [30].

Reclosers are typically set to trip and reclose two or three times before a lockout condition occurs. Lock-out means that a person working on the line must manually reset the recloser for power to be restored. If the fault condition clears before the recloser locks out, the protective relaying resets back to the start of the sequence. Reclosers can also be tripped manually. This allows the recloser to be used as a load-break switch [31].

For placing reclosers, the following are chosen by considering the location of the load or customers (beginning of branches or sections and end of sections), lengths of segmented sections within the feeder, and sensitivity of the load as industrial, commercial, and intuitional offices considered.

The Nu-Lec 15 kV outdoor pole-mounted automatic circuit recloser is selected for this thesis work. The recloser is available in the ETAP software library and is applicable in the real world. Nu-Lec reclosers have a modular design, are solid and lightweight, are easy to install on poles or substations, are free to maintain throughout life, are highly resistant to ozone, and are a cost-effective way to improve reliability. Generally, this is remote operation, fast and safe maintenance, and reduced labor operation and maintenance costs. Nu-Lec Industries is Schneider Electric's core business unit for recloser technology [32].

An automatic circuit recloser (ACR) is an intellectual protective device capable of interrupting fault current, and the purpose is to increase distribution system reliability. Their function is to disconnect a section automatically from the feeder in the event of a fault or auto-reclosing, such as a short circuit. After a certain period, the recloser makes a specified number of attempts to re-energize the line to restore power supply to consumers.

Benefits of reclosers [30]

- ✓ Maximum installation altitude: 3000 m above sea level
- ✓ High-performance protection and control functions, easy to configure
- ✓ Easy integration of multiple controller options for modern grid applications
- ✓ Small and lightweight, easy to install in outdoor utility poles or substations
- ✓ Remote operation, simple, fast, and safe maintenance, reducing labor operation and maintenance costs

Working principles of reclosers

When the line is short-circuited, the recloser will automatically cut off the power supply after a while (return to the original state) and automatically close. If the line fault is not cleared, the recloser will continue to open the line, and after a while, it will automatically close. If the fault is permanent, after 3 repetitions, the recloser will be locked out. Electricity personnel are then required to perform on-site troubleshooting to repair the line to supply power. For maintenance purposes or to isolate faulted areas in the case of permanent faults, auto reclosers can be manually operated to use as load break switches, and this prevents frequent opening and closing of the substation breaker.

It can save a lot of time and cost for power companies, reduce the number of on-site operation and maintenance personnel, quickly restore power supply, and avoid changes caused by frequent power outages [30].

The recloser is designed to solve the following task [30]:

- ◇ Switching operations for the electrical network reconfiguration.
- ◇ Fault current detection
- ◇ Automatic disconnection of damaged line sections
- ◇ Remote control, local and remote network reconfiguration
- ◇ Automatic restoration of power supply from the network of alternative power sources
- ◇ Reclose operation.
- ◇ Automatic back feed restoration.
- ◇ Restoring power supply to undamaged sections.
- ◇ Automatic collection of information about the parameters of the distribution network operating mode.

The output result of the existing distribution network feeder KO-11 (without auto recloser):

For Mekelle city line feeder KO-11 without reclosers, the probability of fault depends on the length of the feeder line, the reliability of this system is modeled to be evaluated depending on the length of the line. Wherever a fault happens along the feeder, the whole customer would face an interruption for the existing network. The total feeder length is 23.725 km, contributing to an outage of power to all customers. But, for a segmented feeder, any recloser is responsible for its section. So, the probability of fault occurrence in each section depends on the length of that section. For the existing power distribution network, feeder KO-11 city feeder is considered a single section. The simulation result for the modeling of the existing feeder KO-11 power distribution system is shown below, which verifies calculated index values. Every necessary parameters used for distribution network reliability analysis are entered into ETAP 19.0.1 software, as shown in the modeling in figures 3.3 and 3.4, then the simulation result is discussed in table 4.4 below.

Table 4.4: Reliability indexes of the existing selected feeder (KO-11)

Reliability indices	**Simulation result**
SAIFI (f/ customer. yr)	82.3551
SAIDI (hr/ customer. yr)	472.322
EENS (MWhr/ yr)	132,393.2

As shown from the above table 4.4 the simulation result is before applying the improvement methods for feeder KO-11. The table shows the common reliability indices of SAIFI, SAIDI and EENS value and the simulation summary report of the model before and after improvement have been tabulated in appendix F.

The redesigned distribution network models use five cases:

A fault in a radial sub-system is interrupted by the nearest overcurrent protection device on its source side; so, in this thesis, a different power distribution model with auto-recloser placements at different positions is considered to study reliability improvement for Mekelle city feeder KO-11. Adding a line recloser on a feeder will protect all upstream consumers from downstream faults, increasing reliability. But to increase reliability, the re-closer should be placed to maximize its benefits.

For placing auto-reclosers with the feeder, consider the location of the load or customers (beginning of branches or sections and end of sections), number of customers, long segmented sections, load types, or sensitivity of loads such as industrial, higher governmental institutions, and low-reliability indices of load points.

Case 1: Beginning of branches (using two auto reclosers)

Starting from the substation up to Arid, it extends in a straight line, which means that without branching, when reaching this location, there is a branched line that is separated into two different areas, which are Zban Daero, Moha soft drink factory, and Aynalem, Quiha, and MA garment factory. These reclosers (Rec-1 and Rec-2) are located at the exits of Arid and Aynalem.

Therefore, by placing one auto-recloser at line 2394 or between (B2851 and B 3328) and one auto-recloser at line 2396 or between (B2851 and B 2854), the system reliability indexes output (SAIFI, SAIDI, EENS) of Mekelle distribution feeder KO-11 is decreased.

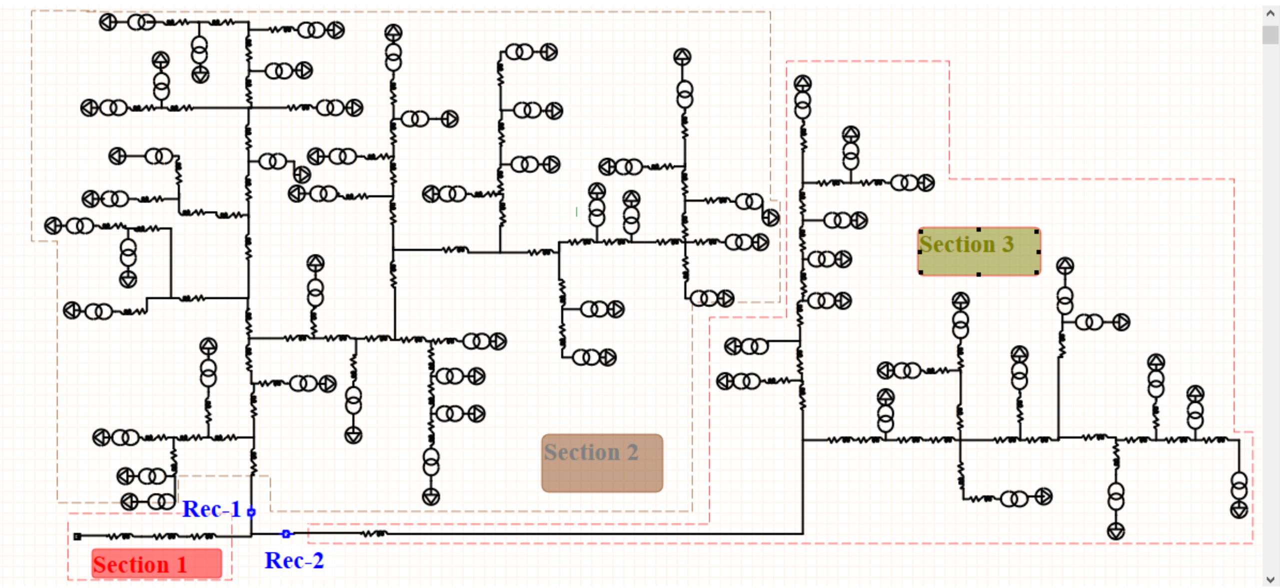

Figure 4.1: Mekelle city distribution feeder line (Feeder KO-11) model with two auto-reclosers using ETAP software for case 1

This distribution line is segmented into three sections.

Section one: In this section, when a fault occurs from the substation, including section one, the circuit breaker in the substation is responsible for isolating the fault. Then each customer faced an interruption, i.e., all the customers (970 customers) connected to the feeder line became out of service.

Section two: In this section, when a fault occurs in section two, Rec-1 is responsible for isolating the fault, then the customers who are connected in this section (683 customers) are out of service, but the rest of the customers (287 customers) who are connected to section three stay in service.

Section three: In this section, when a fault occurs in section three, Rec-2 is responsible for isolating the fault. Then the customers who are connected to this section line (287 customers) become out of service, but the rest of the customers (683 customers) who are connected to section 2 stay in service. The overall reliability performance of this model is shown in table 4.5 below:

Table 4.5: Reliability indexes of the selected feeder (KO-11) for case-1

Reliability indices	**Simulation result**
SAIFI (f/ customer. yr)	50.5394
SAIDI (hr/ customer. yr)	286.1645
EENS (MWhr/ yr)	83,657.47

Case 1, shown above, demonstrates the effect of using two auto reclosers in the feeder.When the line is segmented into three parts, the SAIFI of the city line is reduced to 50.5394 frequency per customer year, and SAIDI has been reduced to 286.1645 hours per customer year. The expected energy not supplied has been reduced to 83,657.47 MWhr/yr.

Case 2: Long segmented section (using three auto reclosers)

In this model, reclosers are located at the Quiha entrance, Meles's campus intersection, and the end of the Aynalem taxi station. The selection of places to insert an auto-recloser is based on the length of the segmented line. The segment line with a long distance has a probability of affecting high faults, and a segmented line with a short distance has a probability of fewer faults occurring. Three auto reclosers (Rec-3, Rec-4, and Rec-5) are placed on lines 2475, 2528, and 2570 with lengths of 1.17 km, 1.885 km, and 2.275 km, respectively. Therefore, placing an auto recloser at those sections in addition to case 1, the output of system reliability indexes (SAIFI, SAIDI, and EENS) is decreasing as shown in the modeling single line diagram below:

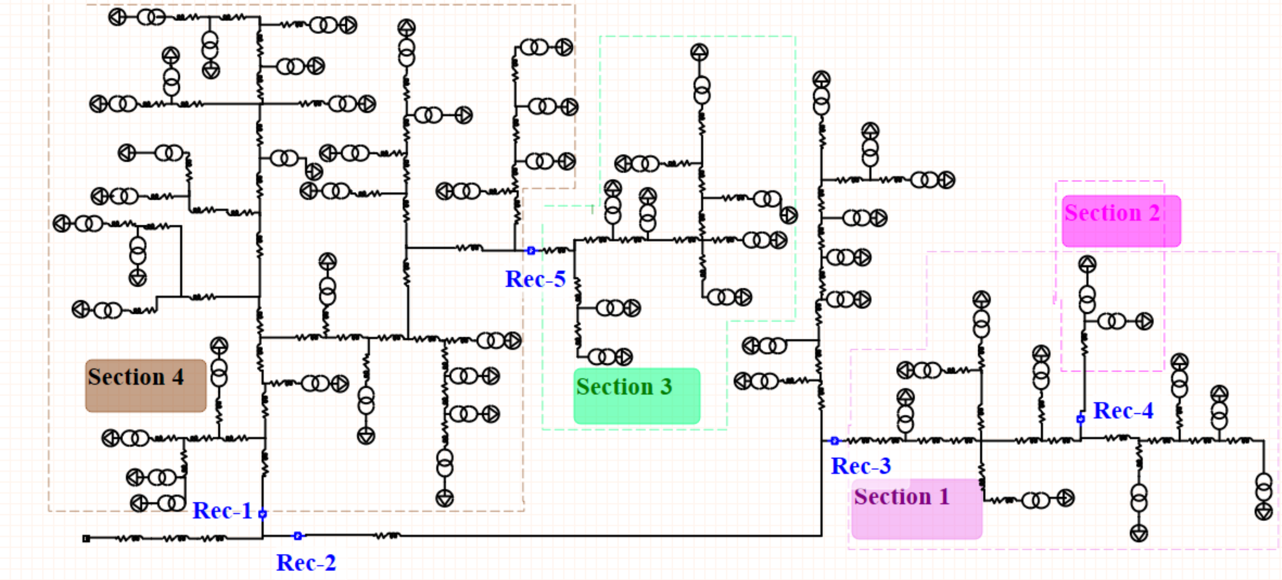

Figure 4.2: Mekelle city distribution feeder line (Feeder KO-11) model with five auto-reclosers using ETAP software for case-2

This distribution line is segmented into four sections.

Section one: In this section, when a fault occurs in section one due to a long-segmented line of 1.855 km, Rec-3 is responsible for isolating the fault. Then each customer faced an interruption, i.e., all the customers connected to this section (139 customers) were out of service. But the customers who connect to the rest of the sections (831 customers) stay in service.

Section two: In this section, when a fault occurs in section two due to a long-segmented line of 2.275 km, Rec-4 is responsible for isolating the fault, then the customers who are connected in this section, the DBL industry, become out of service, but the rest of the customers who are connected to sections one, three, and four (969 customers) stay in service.

Section three: In this section, when a fault occurs in section three due to a long-segmented line of 1.17 km, Rec-5 is responsible for isolating the fault. Then the customers who are connected to this section line (286 customers) become out of service, but the rest of the customers (684 customers), who are connected to sections one, two, and four, stay in service.

Section four: In this section, when a fault occurs in section four, Rec-1 is responsible for isolating the faults. Then the customers who are connected to this section line (397 customers) become out of service, but the rest of the customers (573 customers) who are connected to sections one, two, and three stay in service. The overall reliability performance of this model is shown in table 4.6 below:

Table 4.6: Reliability indices of the selected feeder (KO-11) for case-2

Reliability indices	Simulation result
SAIFI (f/ customer. yr)	42.7137
SAIDI (hr/ customer. yr)	240.1814
EENS (MWhr/ yr)	68,934.80

Case 2, shown above, demonstrates the effect of using five auto reclosers in the feeder. By adding three reclosers as shown in the above simulation result, the reliability of the overall system has been improved. When the line is segmented into four parts, the frequency of interruptions and interruption duration of feeder KO-11 has been reduced to 42.7137 frequency per customer year and 240.1814 hours per customer year, respectively. The expected energy not supplied has been reduced to 68,934.8 MWhr/year.

Case 3: Moha and Ma garment factory (Using three auto reclosers)

In this case, the sensitivity of the load is considered to select the auto recloser location. In this model, three auto-reclosers (Rec-6, Rec-7, and Rec-8) are located at line 2400, line 2526, and line 2556, respectively, in addition to the above previous cases. In this case, when adding three auto reclosers at line 2400, line 2526, and line 2556 in addition to case 1 and case 2, the output of reliability indexes reduces from the existing case 1 and case 2 reliability indexes. Those lines are selected to insert a recloser because they consist of a sensitive load (Moha soft drink factory and Ma garment factory) around it. For better distribution reliability, loads or customers should be separated by specifying industrial, commercial, and residential consumers.

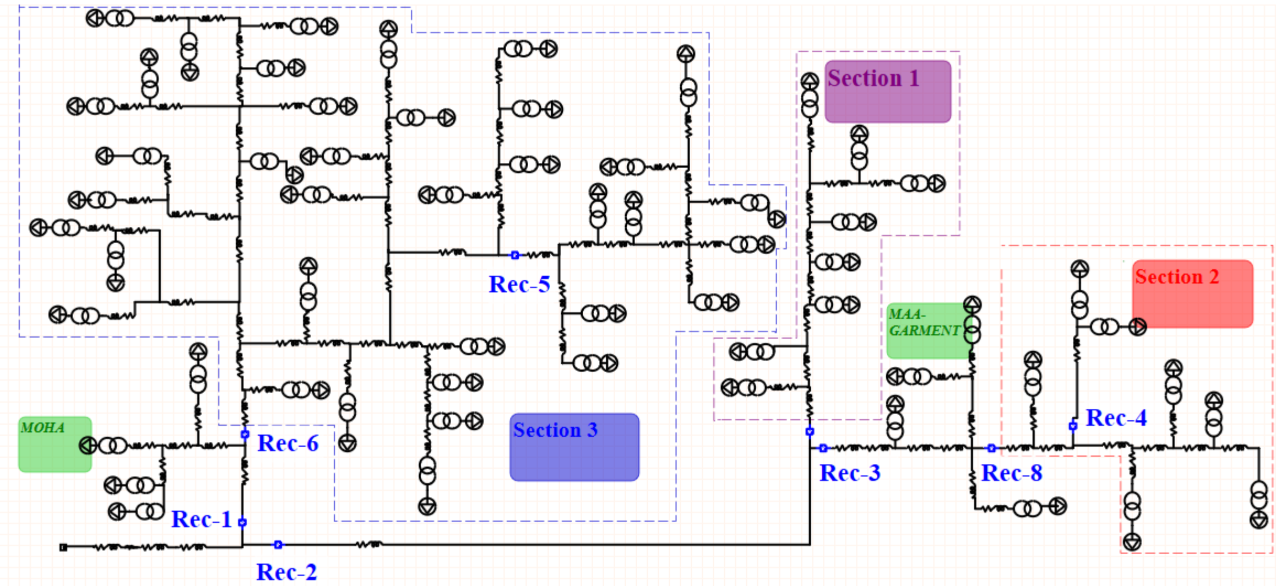

Figure 4.3: Mekelle city distribution feeder line (Feeder KO-11) model with eight auto-reclosers using ETAP software for case 3

This distribution line is segmented into three sections.

Moha and Ma garment factories have more sensitive loads, so they must be in service every time. To have reliable power, Moha, and Maa-garment factories need three auto-reclosers on both sides of the segmented line.

Section one: In this section, when a fault occurs in section one, Rec-7 is responsible for isolating the fault, then all the customers connected to this section (148 customers) are out of service, but still Ma garment factory stays in service.

Section two: In this section, when a fault occurs in section two, Rec-8 is responsible for isolating the fault, then the customers who are connected in this section (96 customers) are out of service, but the Ma garment factory stays in service. So even if faults occurred on both sides of the factory, it cannot be affected by those faults.

Section Three: This section is protecting to the Moha soft drink factory. When a fault occurs in section three, Rec-6 is responsible for isolating the fault, and then the customers who are connected in this section (629 customers) are out of service, but the Moha soft drink factory stays in service.

The overall reliability performance of this model is shown in table 4.7 below:

Table 4.7: Reliability indices of the selected feeder (KO-11) for case-3

Reliability indices	Simulation result
SAIFI (f/ customer. yr)	39.6425
SAIDI (hr/ customer. yr)	220.9942
EENS (MWhr/ yr)	29,550.58

Case 3, shown above, demonstrates the effect of using eight auto reclosers in the feeder.

By adding two auto-reclosers to the Ma garment factory and one auto recloser to the Moha factory in addition to case 1, and case 2 as shown in the above simulation result, the reliability of the overall has been improved. When the line is segmented into three parts, the frequency of interruptions and interruption duration of feeder KO-11 has been reduced to 39.6425 frequency per customer year and 220.9942 hour per customer year respectively. The expected energy not supplied has been reduced to 29550.58 MWhr/year.

Case-4: Mekelle University (Using two auto reclosers)

In this case, the sensitivity of the load is considered to select auto reclosers place. In this model, two auto-reclosers (Rec-9 and Rec-10) are located at line 2418 and line 2414 in addition to the above previous cases. In this case when adding two auto reclosers at line 2418 and line 2414 in addition to case 1, case 2, and case 3 the output of reliability indexes reduces from the exiting, case 1, case 2, and case 3 reliability indexes. Those lines are selected to insert recloser because it has higher organizational institutions and offices (Mekelle University Arid Campus) around it. For better distribution reliability, loads, or customers should be separated by specifying industrial, commercial, and residential consumers.

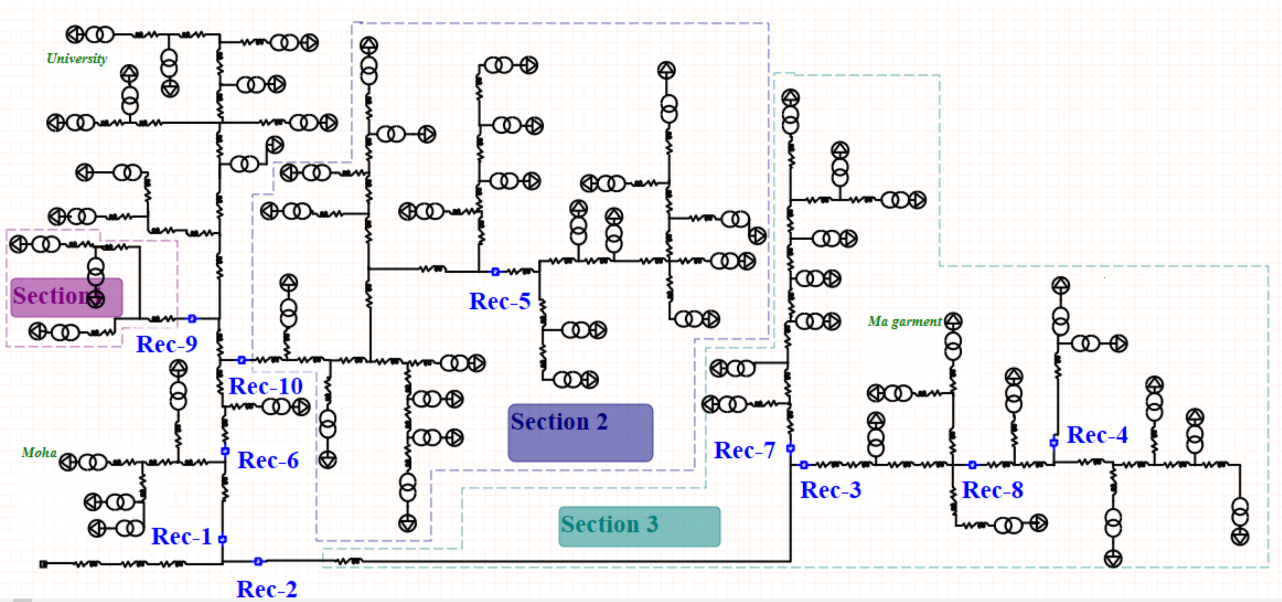

Figure 4.4: Mekelle city distribution feeder line (Feeder KO-11) model with ten auto-reclosers using ETAP software for case 4

This distribution line is segmented into three sections.

Since Mekelle University is a higher institution, which is a sensitive load, it must be in service every time. To have reliable power, this organization needs two auto-reclosers on both sides of the segmented line.

Section one: In this section, when a fault occurs in section one, Rec-9 is responsible for isolating the fault, then all the customers connected to this section (89 customers) are out of service, but still Mekelle University stays in service.

Section two: In this section, when a fault occurs in section two, Rec-10 is responsible for isolating the fault, and then the customers who are connected in this section (526 customers) are out of service, but Mekelle University stays in service. So even if faults occur on both sides of the organization, it cannot be affected by those faults.

Section three: In this section, when a fault occurs in section three, Rec-2 is responsible for isolating the fault, then the customers who are connected in this section (287 customers) are out of service, but Mekelle University stays in service.

The overall reliability performance of this model is shown in table 4.8 below:

Table 4.8: Reliability indices of the selected feeder (KO-11) for case-4

Reliability indices	Simulation result
SAIFI (f/ customer. yr)	35.3782
SAIDI (hr/ customer. yr)	194.4879
EENS (MWhr/ yr)	29,017.77

Case 4, shown above, demonstrates the effect of using ten auto reclosers in the feeder. By adding two auto-reclosers to Mekelle University in addition to case 1, case 2, and case 3 as shown in the above simulation result, the reliability of the overall has been improved. When the line is segmented into three parts, the frequency of interruptions and interruption duration of feeder KO-11 has been reduced to 35.3782 frequency per customer year and 194.4879 hours per customer year, respectively. The expected energy not supplied has been reduced to 29,017.77 MWhr/year.

Case 5: Low-reliability indices of branches (adding two auto-reclosers)

In this case, when adding one auto recloser at line 2477 and one auto recloser at line 2511 in addition to the previous cases, the output of reliability indices reduces from the existing reliability indices. Two auto-reclosers (Rec-11 and Rec-12) are placed on the last branched sections, which have low-reliability indices at the endpoint of these lines as compared to other load points.

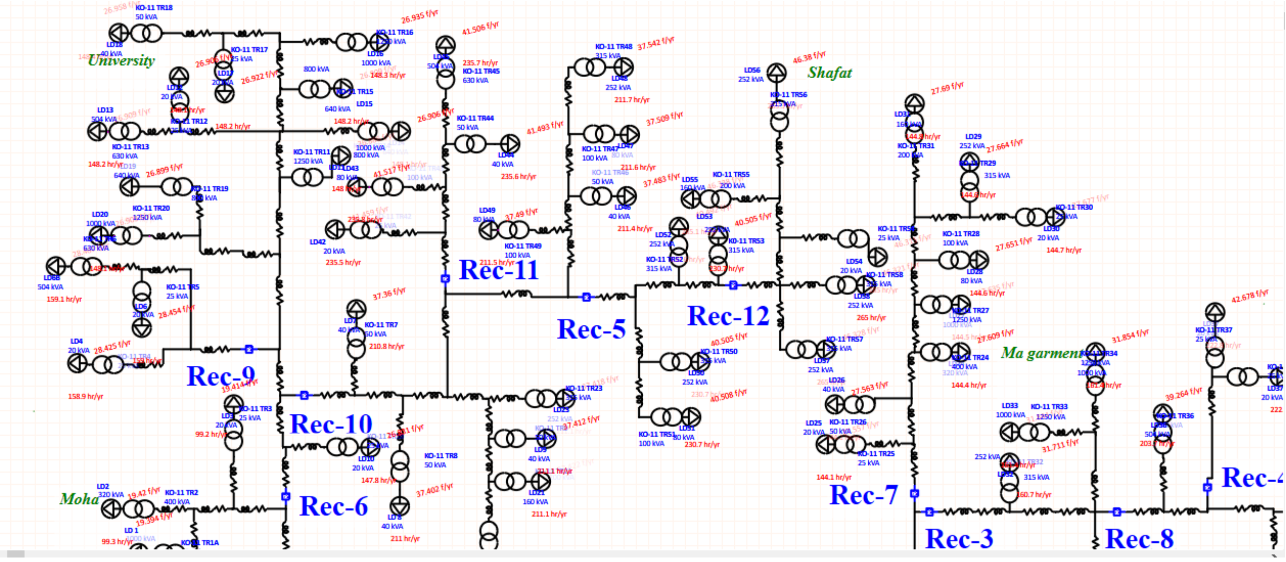

Figure 4.5: Mekelle city distribution feeder line (Feeder KO-11) model with twelve auto-reclosers using ETAP software for case 5

In this case, the load points (load 48 and load 56) have high-reliability indices. By adding one auto-recloser at line 2477 and one at line 2511, the load point reliability indices of SAIFI, SAIDI, and EENS are reduced from 50.38 f/yr/customer to 289.5 hr/yr/customer and 62.01 MWhr/yr to 46.38 f/customer/yr, 265.3 hr/customer/yr and 56.82 MWhr/yr for load 56 and 41.55 f/customer/yr, 236 hr/customer/yr and 50.5401 MWhr/yr to 37.54 f/customer/yr, 211.7 hr/customer/yr and 45.35 MWhr/yr for load 48, respectively.

The overall reliability performance of this model is shown in table 4.9 below:

Table 4.9: Reliability indices of the selected feeder (KO-11) for case-4

Reliability indices	Simulation result
SAIFI (f/ customer. yr)	3.726
SAIDI (hr/ customer. yr)	184.555
EENS (MWhr/ yr)	28,935.28

Case 5 illustrates the effect of twelve auto-reclosers in the system. As can be seen from the simulation result, adding two auto-reclosers at the end branch to Enda Mariam Shafat and the feeder, together with the previous cases, significantly improved the reliability of the system. From the simulation result, SAIFI has been reduced to 33.726 f/customer per year, SAIDI has been reduced to 184.555 hr/customer per year, and EENS has been reduced to 28935.28 MWhr/yr.

When the number of auto-reclosers increases by segmenting the feeder line into sections the reliability of the system became improved. Therefore, according to the result many auto-reclosers, located with different location areas summarized as:

When the number of sections is three and the number of reclosers is two, the reliability improvement is 38.6%, 39.4%, and 36.8% for SAIFI, SAIDI, and EENS, respectively. Also, when the number of sections is four and the number of reclosers is five, the reliability indices will be improved by 48.1%, 49.1%, and 47.9% for SAIFI, SAIDI, and EENS, respectively. Similarly, when the number of segments is three and the number of reclosers is eight, the reliability is improved by 51.9%, 53.2%, and 77.7% for SAIFI, SAIDI, and EENS, respectively. When the number of segments is three and the number of reclosers is ten, the reliability is improved by 57%, 59%, and 78% for SAIFI, SAIDI, and EENS, respectively. The last model shows that the radial feeder of Mekelle city feeder KO-11 using twelve reclosers will improve the reliability indices by 59%, 61%, and 78.1% for SAIFI, SAIDI, and EENS, respectively. So, this shows that further segmentation of radial feeders using protection devices improves the reliability of the distribution system.

From the above cases, the reliability indices of the distribution system improved with different percentages. The reliability improvement of the above five cases compared to the existing values of the selected common reliability indices is shows in figures 4.6, 4.7, and 4.8.

The chart below shows that the reliability indices, which are evaluated using the active failure rate in the number of failures per year per unit length and meantime to repair of Mekelle city feeder KO-11 redesigned using auto-reclosers.

1. The SAIFI value of the redesigned system is reduced from 82.3435 f/customer. yr to 50.5394 f/customer. yr,42.7137 f/customer. yr,39.6425 f/customer. yr,35.3782 f/customer. yr and 33.726 f/customer. yr for five different cases. The system improved from 38.6% to 59%.

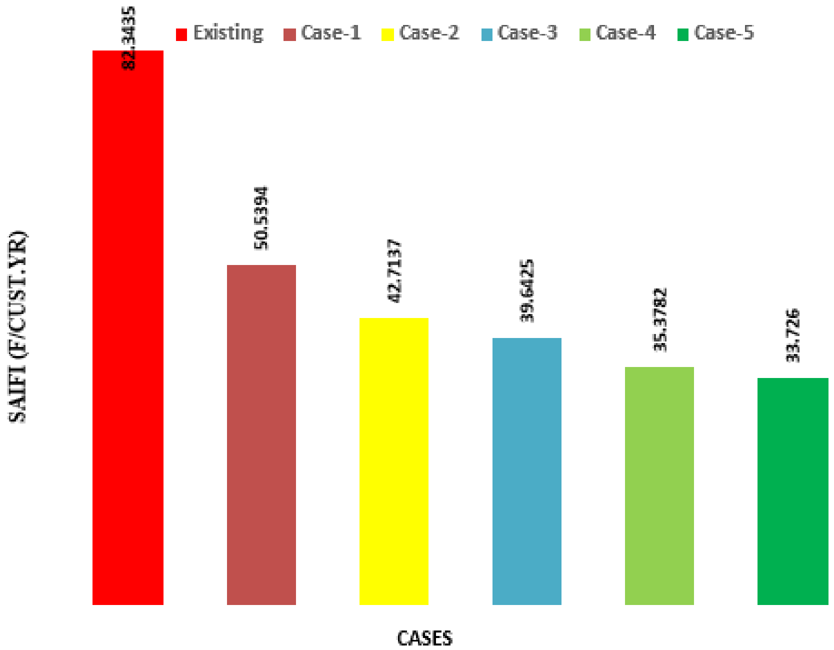

Figure 4.6: Chart that shows SAIFI improvement by adding reclosers for different cases

2. The SAIDI value of the redesigned system is reduced from 472.2644 hr/customer.yr into 286.1645 hr/customer.yr, 240.1814 hr/customer.yr, 220.9942 hr/customer.yr, 194.4879 hr/customer.yr, and 184.555 hr/customer.yr for five different cases. The system has improved from 39.4% to 61%.

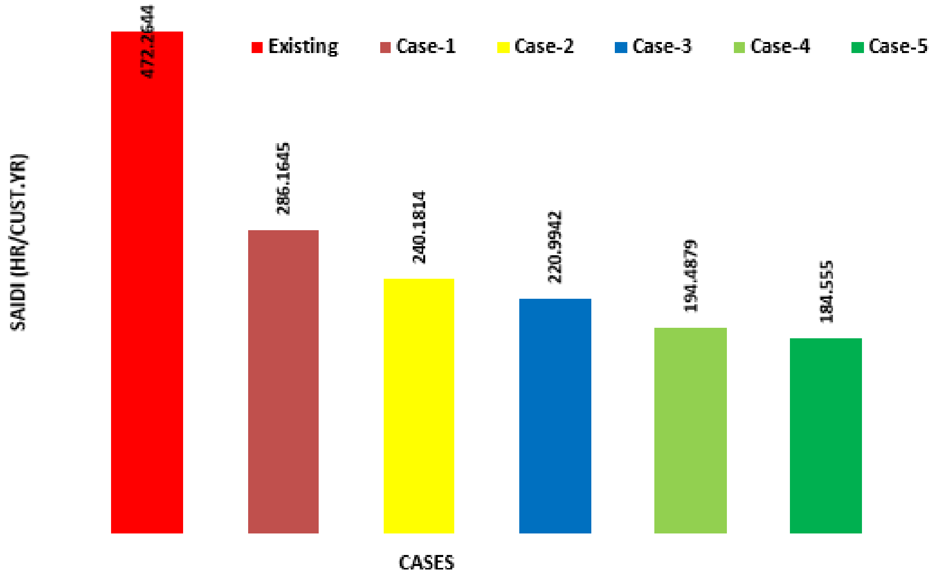

Figure 4.7: Chart that shows SAIDI improvement by adding auto-reclosers for different cases

3. EENS of the existing system was 132,393.2 MWhr/yr. The redesigned system was reduced to 83,657.47 MWhr/yr, 68,934.8 MWhr/yr, 29,550.58 MWhr/yr, 29,017.77 MWhr/yr, and 28,935.28 MWhr/yr by placing auto-recloser at different reasonable locations and the system improved from 36.80% to 78.1%.

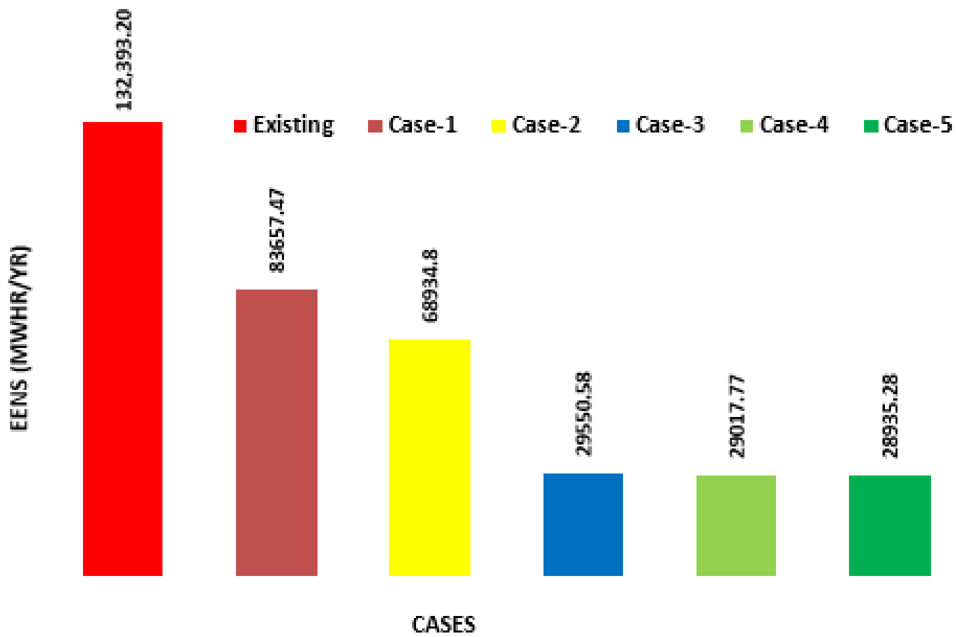

Figure 4.8: Chart that shows EENS improvement by adding auto-reclosers for different cases

In figures 4.6, 4.7, and 4.8, reliability indices changed radically from existing to case 1. Again, there is a significant improvement from case 1 to case 2, case 2 to case 3, case 3 to case 4, and case 4 to case 5 in all indicators. But from overall models, case 5 has better reliability improvement than other cases. Generally, adding auto reclosers in case one and case two the percentage reduction of SAIFI, SAIDI, and EENS is reduced by large number, but from case three up to case five the percentage reduction is reduced slowly. After this case even reclosers are adding to the system, there is no improvement of reliability indices in the network. So, adding auto recloser after a certain time is not change at all over the system but have an increment of investment cost only.

As discovered from the cases, adding auto reclosers to the selective places improves the system reliability indices, but adding these devices to the system should not be considered the only solution. Scheduled preventive maintenance, additional rehabilitation works on the entire system network, improving manpower problems, and solving other related complications will greatly enhance the system's reliability. Dividing the whole network in to small sections have been decreased the affected customers by reducing interruption frequency and duration.

4.5 Cost Analysis

Cost-effectiveness can be evaluated by calculating all the costs associated with each proposed improvement and dividing the additional benefits by the higher prices. While it is crucial to quantify the extra costs related to enhanced reliability, further factors must also be considered for a comprehensive evaluation. The expenses linked to outages are aligned alongside the investment costs for comparison, aiding in identifying the most effective reliability solution. Outage expenses are typically categorized into utility and customer outage costs [33].

In utility services, the overall costs incurred during an outage include the revenue lost from unsupplied energy, as well as expenses related to maintaining and replacing equipment needed to restore power to customers. While the costs incurred by the utility during an outage can be considerable, the financial impact on customers is often much higher. These costs differ significantly depending on the type of customer sector and their geographical location. For small industries, electricity supply interruption costs are strongly related to production losses and the costs involved in restoring production. In addition, interruptions also cause property damages and revenue losses for industries, commercial customers, and private individuals. Residential customers incur costs during an outage, which include food spoilage, and lack of light during dark times for the individual customers but it is less costly than small industries and commercials. The customer interruption cost when an electric supply failure occurs depends on many factors. It is difficult to estimate the exact value of customer interruption costs and economic losses since each customer's properties are different, and important data is difficult to find. Therefore, in this thesis costs only with respect to utility is done.

Cost with respect of the utility

When a cost-benefit analysis is applied to electrical networks, the cost of the energy not sold to the customer is one method of conveying cost to the utility (as revenue is lost) whenever supply is interrupted. The energy that is not sold due to a planned or fault network interruption is also referred to as the unsold energy or energy not supplied (ENS) and is measured in kilowatt-hour (kWhr).

With the successful installation of the additional auto reclosers, faults should be isolated more effectively and fewer customers should be interrupted. The result should yield a reduction in energy not supplied (ENS) and hence a reduction in the cost of energy not supplied (ECOST). This can also be expressed as the difference between the ECOST before and after the installation of reclosers [34].

The cost-benefit analysis (CBA) can be expressed as in eqn 4.1:

$$CBA = \frac{\text{Net benefits (B)}}{\text{Net cost (C)}} = \frac{\text{Saving in cost of energy not supplied (ECOST)}}{\text{Recloser cost + maintenance cost}} \tag{4.1}$$

$$= \frac{\text{ECOST before} - \text{ECOST after}}{\text{Investment cost}}$$

For the installation (project) to prove feasible, the equation must yield an answer greater than one, or: CBA $>$ 1 [34]. For the projects that do not prove to be feasible in year one, a pay-back period can be determined for when the CBA becomes good-looking after covering the period of evaluation. Projects should be favorable if B > C and not accepted if B < C [34].

Where CBA is the cost benefit analysis of utility, B is net benefits and C is total costs for recloser installation.

In this thesis costs related to the utility have been analyzed using the expected energy not supplied (EENS).

From the simulation, the output result for the interruption cost in the modeling system is done based on the ETAP library which is calculated based on the international best-experienced countries. However, the interruption cost in this analysis is calculated based on EEU's tariff which is categorized in terms of ranges are discussed in appendix D. Energy is an important term to estimate the interruption cost of the system for a typical year. The basic factor used for cost estimation is the tariff (price in birr or dollars per kWhr) for different types of customers.

Based on the Ethiopian Electric Power Corporate (EEPCO) marketing and sales process estimation manual, which is currently applicable, expected interruption cost (ECOST) or unsold electricity for feeder KO-11 distribution substation is calculated as expressed in eqn 4.2;

$$\text{Expected Interruption Cost} = \text{Energy(kWhr)} \times \text{Tarrif}(\frac{Birr}{kWhr}) \tag{4.2}$$

4.5.1 Calculating Cost Benefit Analysis and Payback Period

A utility cost-benefit analysis model was used to calculate the years to payback period and investment cost for the proposed solution. The alternative which is the shortest payback period indicates the reliability improvements that it is the most economical way to serve the load considering the customer value of reliability. Quantitatively adding auto reclosers to the distribution feeder will improve the reliability of the distribution system but adding many reclosers leads to over-investment for initial cost. So, it is necessary to compare the above different scenarios concerning their investment cost and payback period of all cases. Using the Ethiopian electric utility tariff and the cost of a recloser, the payback period of the modeling system is calculated.

The investment cost is the total cost of reclosers to redesign the system (cost of recloser, maintenance cost, and installation cost). The cost of 15 kV, 800 A outdoor pole-mounted recloser is $ 15000 (USD) [35] based on the currency exchange rate of the Commercial Bank of Ethiopia on 23 December 2024 which equates to One US Dollar (USD) to 127.45 Ethiopian Birr (ETB), the cost of one 15 kV, 800 A pole-mounted outdoor Recloser is: 15,000*127.45 = 1,911,750 ETB.

The lifetime of the recloser is expected to be 25 years based on the smart reclosers and other accessories lifetime [31]. On the other hand, the payback period of the redesigned system is an important factor. The payback period is the time required to recover the cost of an investment. The payback period of a given investment cost is an important determinant of whether to undertake the position, as longer payback periods are typically not desirable for investment positions. The payback period in years can be calculated as expressed in eqn 4.3;

$$\text{Payback Period} = \frac{\text{Investment cost(birr)}}{\text{Annual saving}\left(\frac{\text{birr}}{\text{year}}\right)} \tag{4.3}$$

The utility costs, which include capital, maintenance, and installation expenses, are based on the number of devices added.

The benefit is determined by the difference between the ECOST of the existing network with zero additional switches and the ECOST with additional switches. A ratio of the benefit in birr to the total cost is determined to establish the most feasible option. A solution that provides a balance between the outage and investment costs and is preferred by both the customer and the utility is required.

There is power interruption cost in both the utility and the customer side. Customers in the study area (feeder KO-11) are roughly divided into four categories: residential, commercial, government & institutions, and small industrial customers.

Existing: these are the outputs without protection devices for the utility and the customers. Energy not sold for the existing city feeder line is 132,393.2 MWhr/yr: Using Ethiopian electric utility tariff average of below 50 kilowatt hour (kWhr) and above 500 kWhr for residential, below 50 KWhr, and above 50 kWhr for commercial and for low voltage industrial three-phase customers, Cost of energy not sold for existing feeder line is calculated using eqn 4.2. The utility cost of energy for the existing system is 122,725,848.54 birr/year or 962,933.3 $/year.

Case 1: Energy not sold for city feeder line using two auto reclosers is 83,657.47 MWhr/yr:

Using Ethiopian electric utility tariff average of below 50 kWhr and above 500 kWhr for residential, below 50 kWhr and above 50 kWhr for commercial, and low voltage industrial three-phase customers, the cost of energy not sold using two auto-reclosers is calculated using eqn 4.2. The interruption cost of energy for the utility is 77,548,801.54 birr/year or 608,464.5 $/year.

The net benefit or saving is the difference between the cost of interruption before using an auto-recloser and via two auto-recloser. The saving is 354,468.8 $/year. The cost-benefit analysis (CBA) for the utility is the ratio of the total benefits or savings (354,468.8 $/yr) to investment costs (33,222.46 $) using eqn 4.1 which is 10.7. Since the cost-benefit analysis value is above unity, this case is acceptable.

The payback period is calculated as the ratio of the investment cost (33,222.46 $) to the total benefits (354,468.8 $/yr) using eqn 4.3 which is 0.09 year.

Case two: Energy not sold for city feeder line using five auto reclosers is 68,934.8 MWhr/yr:

Using Ethiopian electric utility tariff average of, below 50 kWhr and above 500 kWhr for residential, below 50 kWhr and above 50 kWhr for commercial, and for low voltage industrial three-phase customers, Cost of energy not sold using five auto-reclosers is calculated using eqn 4.2. The interruption cost of energy for the utility is 63,901,180 birr/year or 501,382.3 $/year.

The net benefit or saving is the difference between the cost of interruption before using an auto-recloser and via five auto-recloser. The saving is 461,551 $/year. The cost-benefit analysis (CBA) for the utility is the ratio of the total benefits or savings (461,551 $/year) to investment costs (83,056.15 $) using eqn 4.1 which is 5.6. Since the cost-benefit analysis value is above unity, this case is acceptable.

The payback period is calculated as the ratio of the investment cost (83,056.15 $) to the total benefits (461,551 $/year) using eqn 4.3 which is 0.18 year.

Case three: Energy not sold for city feeder line using eight auto reclosers is 29,550.58 MWhr/yr: Using Ethiopian electric utility tariff average of below 50 kWhr and above 500 kWhr for residential, below 50 kWhr and above 50 kWhr for commercial, and for low voltage industrial three-phase customers, Cost of energy not sold for using eight auto-reclosers is calculated using eqn 4.2. The interruption cost of energy for the utility is 27,392,796 birr/year or 214,929.7 $/year

The net benefit or saving is the difference between the cost of interruption before using an auto-recloser and via eight auto-recloser. The saving is 748,003.6 $/year. The cost-benefit analysis (CBA) for the utility is the ratio of the total benefits or savings 748,003.6 $/year to investment costs 132,889.8 $ using eqn 4.1 which is 5.6. Since the cost-benefit analysis value is above unity, this case is acceptable.

The payback period is calculated as the ratio of the investment cost (132,889.8 $) to the total benefits (748,003.6 $/year) using eqn 4.3 which is 0.18 year.

Case four: Energy not sold for city feeder line using ten auto reclosers is 29,017.77 MWhr/yr: Using Ethiopian electric utility tariff average of below 50 kWhr and above 500 kWhr for residential, below 50 kWhr and above 50 kWhr for commercial, and for low voltage industrial three-phase customers, Cost of energy not sold for using ten auto-reclosers is calculated using eqn 4.2. The interruption cost of energy for the utility is 26,898,892.43 birr/year or 211,054.5 $/year.

The net benefit or saving is the difference between the cost of interruption before using an auto-recloser and via ten auto-recloser. The saving is 751,878.8 $/year. The cost-benefit analysis (CBA) for the utility is the ratio of the total benefits or savings (751,878.8 $/year) to investment costs (166,112.3 $) which is 4.5. Since the cost-benefit analysis value is above unity, this case is acceptable.

The payback period is calculated as the ratio of the investment cost (166,112.3 $) to the total benefits (751,878.8 $/year) using eqn 4.3 which is 0.22 year.

Case Five: Energy not sold for city feeder line using twelve auto reclosers is 28,935.28 MWhr/yr: Using Ethiopian electric utility tariff average of below 50 kWhr and above 500 kWhr for residential, below 50 kWhr and above 50 kWhr for commercial, and for low voltage industrial three-phase customers, the Cost of energy not sold for the utility is 26,822,425.85 birr/year or 210,454.5 $/year.

The net benefit or saving is the difference between the cost of interruption before using an auto-recloser and via twelve auto-recloser. The saving is 752478.8 $/year. The cost-benefit analysis (CBA) for the utility is the ratio of the total benefits or savings (752,478.8 $/year) to investment costs (199,334.8 $) using eqn 4.1 which is 3.8. Since the cost-benefit analysis value is above unity, this case is acceptable.

The payback period is calculated as the ratio of the investment cost (199,334.8 $) to the total benefits (752,478.8 $/year) using eqn 4.3 which is 0.26 year.

Expected interruption cost, investment cost, saving, CBA, and the payback period are shown below for each cases the outputs without protection device and after using protection devices for each case are calculated as follows.

Table 4.10: Summary and comparison of saving with respect to pay-back period for all the cases (Feeder KO-11)

Cases	ECOST (Dollar)	Investment cost (Dollar)	Saving or net benefit (Dollar)	CBA	Payback period (year)
Existing	962,933.3	-	-	-	-
Case-1	608,464.5	33,222.46	354,468.80	10.7	0.09
Case-2	501,382.3	83,056.15	461,551.00	5.6	0.18
Case-3	214,929.7	132,889.8	748,003.60	5.6	0.18
Case-4	211,054.5	166,112.3	751,878.80	4.5	0.22
Case-5	210,454.5	199,334.8	752,478.80	3.8	0.26

Table 4.10 reveals that the net benefit increased from case 1 up to case 4 but in case 4 and case 5, the net benefit is almost similar. As the number of reclosers increases investment costs also increase from case 1 to case 5.

In general, from table 4.10 payback period varies from 0.09 to 0.26 year in these models. This shows that as reliability of the power distribution system improved, the investment cost will increase. Since the life time of the recloser is for 25 years, all payback period is acceptable and the cost benefit analysis in all cases are acceptable, that is above unity. The saving which obtained by adding several auto-reclosers in different reasonable locations are increased from case one to case five but not more change from case four up-to case five. As cost of protection device increases, investment cost for the utility is increased, but cost of production due to interruption outage is decreases and reliability is improved with in the given lifetime of reclosers. Case five has been enhanced the reliability of the system very well compared to existing case and to each other. Therefore, case five takes as the best scenario to enhance reliability of the feeder line with reasonable cost.

Table 4.11: Comparison of reliability indices of Mekelle city with different countries after improvement

Country		SAIDI (hr/customer·yr)	SAIFI (f/customer·yr)
United States		4	1.5
Australia		1.2	0.9
France		1.03	1.0
Germany		0.383	0.5
Italy		0.967	2.2
Spain		1.733	2.2
UK		1.5	0.8
India		1.7	2
Uganda		50	10
South-Africa		50	10
Ethiopia		25	20
Mekelle city line	existing	472.2644	82.3435
	after improvement	184.555	33.726

Table 4.11 shows the comparison of the most used reliability indices (SAIFI and SAIDI) of Mekelle city line, with the requirements of the Ethiopian Electric Authority (EEA) and the best experienced countries. As it is observed from table 4.11, both the SAIFI value in interruptions per year per customer and the SAIDI value in hours per year per customer of city feeder has been reduced to 59% and 61% respectively as compared with the existing system values.

The reliability indices values of the case study area should be further improved by replacement of older distribution equipment such as conductors and transformers, tree trimming, re-wiring lines, upgrades of problematic circuits, crew staffing and training for fast responses to outages and rapid restoration of service, formal maintenance programs, and public awareness programs to reduce hazards in the district of distribution equipment. And the values of SAIFI and SAID should be comparable with the other countries best values and the Ethiopian Electric Authority settled values. Using scheduled preventive maintenance, strategic management system, by further rehabilitating all the system and by solving other related problems.

Chapter 5

Conclusions, Recommendations and Future Work

5.1 Conclusion

This thesis was conducted in Mekelle city, which has a complex and poor electrical distribution system. The overall 15 kV city line was assessed and modeled using ETAP 19.0.1 software. Based on ETAP simulation result study is carried out on the scenarios of one 15 kV distribution feeder of KO-11 to improve the reliability of the present system and predictive reliability analysis for the future. Reliability indices values for the selected case study has unreliable power. Therefore, protection devices such as reclosers can be used to solve the problems of the existing case study distribution network.

This thesis was done by placing of 12 reclosers for the long line goes to Aynalem, Shafat and the sensitive load of Ma garment, Moha and Mekelle university arid campus should be an effective and reasonable solutions for the overloading problems and temporary faults. By placing 12 reclosers, average frequency of interruptions is improved from 38.6% to 59%, interruption durations are improved from 39.4% to 61%, and the unsold energy is improved from 36.8% to 78.1% respectively.

Based on the results of this thesis work, the reliability of the feeder line power distribution system is enhanced but does not meet the standards set by the regulatory body that is, Ethiopian Electric Authority (EEA). The system average interruption frequency index (SAIFI) is 1.685 times the standard value of Ethiopia accepted by the EEA and the system average interruption duration index (SAIDI) is 7.38 times the standard value of Ethiopia accepted by the Ethiopian Electric Authority.

By comparing the values with the standard benchmark of best experienced countries and Ethiopian, it is found that the values of reliability indices, is still not up to the satisfactory levels, but are improved by 59%, 61% and 78.1% for SAIFI, SAIDI and EENS respectively comparing with the existing network.

In this thesis costs related to the utility has been analyzed by using Expected Energy Not Supplied (EENS) of each case. Adding several auto-reclosers to the distribution feeder will improve reliability of distribution system. The proposed solution is acceptable which means net benefit is greater than net cost and the cost benefit analysis is positive as the installation cost increases investment cost for the utility is increased but cost of production due to interruption outage is decreased and reliability is improved with in the given lifetime of reclosers.

For this proposed solution the utility has been saved 95.9 million/year from the unsold energy of one feeder only with the investment cost of 25.4 million and the payback period is 0.26 years or three months.

5.2 Recommendation

Based on the thesis work the following recommendations are drawn:

- Reliability Analysis requires: total number of customers, number of customers interrupted, connected loads, number of transformers and their ratings, and so on. So, power system faults, power system components (lines, buses, transformers, circuit breakers, and disconnectors on each feeder) and total number of customers served and interrupted should be correctly documented by EEU and EEP.

- The distance from supply to end users are very long so, distribution system could be designed nearer to the end users or must have its own switching station.

- Reliability problems arise from the complicated construction of electric lines, improper installation of their conductor size and aged transformers. Therefore, the substation should be upgraded and should be constructed additional distribution substation by considering customer size to solve this issue.

- The Ethiopian Electric Utility (EEU) should work to improve the reliability of the power distribution system at Mekelle city to meet the standard set by the regulatory body that is, Ethiopian Electric Authority (EEA). It is necessary to reduce causes of faults in this city. This can be done by tree trimming, scheduled inspection of poles and conductors' clearance, inspection of distribution transformers and conduct regular changing of oil are viable for economy.

- Engineers must to put their hands on north region EEU (Mekelle distribution network) to solve such real time problems.

- It was difficult to identify each load point and the corresponding data of that load point. This made the analysis to each load point in this thesis to be difficult. So, I recommend to EEP and EEU to distinguish each load point and their corresponding failure data of each component to reduce the customers interruption by identifying and isolate the faultiest area only and to analysis each type of customer's satisfactions.

5.3 Future work

The following tasks are suggested as most important areas of study in the future.

- Adding auto recloser to the selective places leads to improvement in the system reliability indices, but only adding these devices to the system should not be considered as the only solution. Scheduled preventive maintenance, additional rehabilitation works on entire network of the system, improving man power problem, and solve other related problems will have a great role to the system reliability enhancement.

- As this thesis is conducted on one feeder, doing reliability assessment analysis for whole part of the city line will be done.

- The integration of smart grid technology with advanced energy storage systems, backup distribution generators, and renewable energy sources like solar and wind power.

References

[1] P. Ass and S. Hameed, "Electrical Substation Protection and Sizing Prof . Ass . Saady Abd-El Hameed Electrical Substation Protection and Sizing Under Supervision of," 2014.

[2] R. E. Brown, "Distribution reliability assessment and reconfiguration optimization," Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf., vol. 2, no. C, pp. 994–999, 2001, doi: 10.1109/tdc.2001.971382.

[3] L. Wang, "The Fault Causes of Overhead Lines in Distribution Network," vol. 02017, no. 2016, 2017.

[4] C. Meteku, "Reliability Analysis of 15kv Distribution System Network (Case Study: Addis Alem Substation Network)," no. January, 2020.

[5] S. W. Fardo and D. R. Patrick, Electrical Power Systems Technology 3 ed, vol. 84. 2013.

[6] R. Billinton and S. Jonnavitihula, "A test System for Teaching Overall Power System Reliability Assesment, IEEE Transaction on Power Systems, Vol. 11," 1996.

[7] G.B. Sheblé, "Power system planning — a reliability perspective Sheblé , Gerald B. 'Power system Planning (Reliability)' The Electric Power Engineering Handbook Boca Raton: CRC Press LLC , 2001," vol. 7796, no. September 1995, 2018, doi: 10.1016/0378-7796(95)00976-X.

[8] S. Hussen and K. Ibrahim, "Assessment of Distribution System Reliability and Possible Mitigation by Using Reclosers and Disconnectors: The Case of Cotobie Distribution Station," Int. J. Innov. Res. Appl. Sci. Eng., vol. 4, no. 5, pp. 774–784, 2020, doi: 10.29027/ijirase.v4.i5.2020.774-784.

[9] E. Berhanu, "Studies on Power Distribution System Reliability Assessment and Improvement (Case Study: Jimma Town Distribution System)," 2017.

[10] T. Gönen, "Electric power distribution system engineering," 1986.

[11] N. Bloom and J. Van Reenen, Assesment of power system reliability. 2013.

[12] H. Seada, A. Frie, and I. Kemal, "Assessment of Distribution System Reliability and Its Possible Mitigations: A Review," Int. Conf. Adv. Manag. Technol., vol. 1, no. November, pp. 3–13, 2020.

[13] Y. Kifle, B. Khan, and P. Singh, "Assessment and enhancement of distribution system reliability by renewable energy sources and energy storage," J. Green Eng., vol. 8, no. 3, pp. 219–262, 2018, doi: 10.13052/jge1904-4720.832.

[14] L. Zemite and J. Gerhards, Reliability evaluation of distribution systems. 2014.

[15] D. Anteneh, "Reliability Assessment of Distribution Sys-tem Using Analytical Method: A Case Study of Debre Berhan Distribution Network," J. Informatics Electr. Electron. Eng., vol. 1, no. 1, pp. 1–9, 2020, doi: 10.54060/jieee/001.01.002.

[16] E.B. Abrha, G. B. Worku, and T.A. Abose, Power distribution system reliability assessment and improvement case of Jimma Town, Ethiopia, vol. 308 LNICST. Springer International Publishing, 2020. doi: 10.1007/978-3-030-43690-2_28.

[17] Behailu Abebe, "Designing of an Improved Distribution Substation to Mitigate the Power Reliability at Bishoftu City," 2015.

[18] T. Tolesa, "Reliability improvement of power distribution system using protection devices: case study of Bedele power distribution system," Pub, no. 047111, p. 112202, 2015.

[19] U. Seite, "14 Protection and Control in Substations and Power Networks," 2007.

[20] A. von Meier, "Electric Power Systems A Conceptual Introduction Alexandra von Meier A John," Library of Congress Cataloging-in-Publication Data, 2006.

[21] I. of E. and E. Engineers, IEEE recommended practice for protection and coordination of industrial and commercial power systems. Ieee, 2001.

[22] H. Hosseinzadeh, "Distribution system protection," Univ. West. Ontario, 2008.

[23] C. Val and L. Fornasari, "How Utilities enable savings by investing in the digital intelligent grid towards a self-healing distribution network," pp. 1–17, 2018.

[24] T. T. M. Ei Ei Phyu, Kyaw Myo Lin, "Loss Reduction and Reliability Improvement of Industrial Distribution System through Network Reconfiguration," WASET, Int. J. Energy Power Eng., vol. 12, no. 11, pp. 822–828, 2018, doi: doi.org/10.5281/zenodo.2021563.

[25] S. Ahmad and A. U. Asar, "Reliability enhancement of electric distribution network using optimal placement of distributed generation," Sustain., vol. 13, no. 20, 2021, doi: 10.3390/su132011407.

[26] D. T. Asradew, "Reliability Analysis and Improvement of Electric Power Distribution System Using Network-Reconfiguration: A Case Study of Debre Berhan Power Distribution System," no. August, 1990, doi: 10.13140/RG.2.2.33253.47847.

[27] S. Ahmad, S. Sardar, A. ul Asar, and F. W. Kara, "Reliability analysis of distribution system using ETAP," Int J Comput. Sci Inf Secur., vol. 15, no. 3, pp. 197–201, 2017.

[28] M. Gilvanejad, H. Askarian Abyaneh, and K. Mazlumi, "A methodology to include real-life failure data in the failure rate estimation of power distribution systems," Turkish J. Electr. Eng. Comput. Sci., vol. 25, no. 2, pp. 1082–1094, 2017, doi: 10.3906/elk-1509-5.

[29] S. Derbie, "Assessment of Power Reliability and Improvement Potential By Using Smart Reclosers," Zede J., vol. 31, no. 0, pp. 26–32, 2014, doi: 10.13140/RG.2.2.20388.73609.

[30] S. Power and E. Co, "Automatic circuit recloser," 2021.

[31] Solomon Derbie, "Study On Reliability Improvement Of Adama City Power Supply Using Smart Grid Technology," Addis Ababa Univ. Addis Ababa Inst. Technol. Sch. Electr. Comput. Eng., 2014.

[32] N. O'Sullivan and B. Kimura, "Only Smart Reclosers Build Smart Grids," Internet http://www. nojapower.co. uk/dl/.../only-smartreclosers-build0-smart-grids. pdf,[May 10, 2013.

[33] T. Gönen, "Electrical power Distribution System Engineering." 2007.

[34] J. Pretorius and C. T. Gaunt, "Cost-benefit analysis of recloser placement for reliability," no. i, pp. 153–163, 2015.

[35] "China-12kv-15kv-Outdoor-Pole-Mounted-Auto-Circuit-Recloser."

APPENDICES

Appendix A

Planned and unplanned interruption frequency of 2011E.C-2015E.C (Int/yr) of each feeder in Mekelle distribution substation

Name of feeder line	2011E.C		2012E.C		2013E.C		2014E.C		2015E.C		Total planned	Total Unplanned	Total
	Planned	Unplanned	planned	Unplanned	planned	Unplanned	planned	Unplanned	planned	Unplanned			
KO-0	58	105	129	128	163	190	239	89	163	166	752	678	1430
KO-3	141	97	37	71	92	81	52	89	92	76	414	414	828
KO-4	153	127	118	95	240	129	271	75	240	110	1022	536	1558
KO-5	110	73	116	129	238	131	279	46	238	103	981	482	1463
KO-6	192	153	149	174	132	82	84	117	132	80	689	606	1295
KO-8	4	12	22	40	192	140	230	105	192	118	640	415	1055
KO-9	202	203	69	113	83	71	75	71	83	76	512	534	1046
KO-10	196	128	182	152	222	120	303	55	222	88	1125	543	1668
KO-11	31	38	26	36	76	93	50	50	76	96	259	313	572
KO-12	22	22	24	30	84	75	44	22	84	73	258	222	480
R-2			0	3	27	16	55	7	27	30	109	56	165
R-3	22	100	35	130	102	272	210	60	102	264	471	826	1297
R-4	25	87	23	96	128	93	213	41	128	79	517	396	913
R-5			4	1	1	28	209	110	158	131	372	270	642
R-6					2	40	41	1	9	24	52	65	117
System over all	1156	1145	934	1198	1782	1561	2355	938	1946	1514	8173	6356	14529

Appendix B

Planned and unplanned interruption duration of 2011E.C-2015E.C (Hr/yr) of each feeder in Mekelle distribution substation

Name of feeder line	2011E.C		2012E.C		2013E.C		2014E.C		2015E.C		Total		
	planned	Unplanned	planned	Unplanned	planned	unplanned	planned	unplanned	planned	unplanned	planned	unplanned	Total
KO0	34.83	360.67	55.12	86.35	100.66	238.32	89.01	472.96	312.05	163.9333	591.67	1322.233	1913.903
KO3	98.43	310	43.42	195.85	102.1	392.76	184.1	31.01	78.32	239.5	506.37	1169.12	1675.49
KO4	66.38	507.15	38.22	105.98	125.6	316.15	226.31	369.35	312.8	283.2167	769.31	1581.847	2351.157
KO5	52.62	242.4	47.68	85.12	135.58	313.66	124.98	428.66	378.57	324.3833	739.43	1394.223	2133.653
KO6	89.63	299.98	77.38	150.2	130.38	309.78	276.78	94.36	83.75	130.7833	657.92	985.1033	1643.023
KO8	7.98	52.28	36.12	118.23	96.51	329.83	413.05	382.63	291.68	251.8167	845.34	1134.787	1980.127
KO9	88.97	432.08	58.77	210.05	66.75	365.11	313.66	120.23	77.58	202.65	605.73	1330.12	1935.85
KO10	79.97	423.42	72.3	145.4	178.31	201.16	75.61	445.4	440.62	208.7167	846.81	1424.097	2270.907
KO11	20.82	102.55	24.47	115.32	61.98	254.93	181.43	66.65	102.1	240.4667	390.8	779.9167	1170.717
KO12	26.53	62.52	42.48	78.48	22.63	111.43	67.26	33.2	52.27	75.75	211.17	361.38	572.55
R2			0	10.63	23.4	198.21	47.61	25.65	21.85	41.96667	92.86	276.4567	369.3167
R3	37.17	460.25	49.02	112.35	133.45	347.08	78.9	445.73	269.52	264.9833	568.06	1630.393	2198.453
R4	15.72	435.6	12.8	90.07	90.88	188.71	26.2	367.83	274.35	86.83333	419.95	1169.043	1588.993
R5			19.73	0.73	11.47	88.11	189.43	383	342.22	152.0667	562.85	623.9067	1186.757
R6					22.93	165.7	0.08	25.28	12.13	17.15	35.14	208.13	243.27
System over all	619.05	3688.9	577.51	1504.76	1302.63	3820.94	2294.41	3691.94	3049.81	2684.217	7843.41	15390.76	23234.17

Appendix C

Daily interruption frequency, interruption duration and types of faults for 2015 E.C for the selected feeder line (feeder KO-11) network

No	Feeder (Bay)	Relay Acted	Interruption Date	Interruption Time	Reconnection Date	Reconnection Time	Duration in Time	Faults Occurred
1	KO 11	P123MICOM	21/11/2015	07:15	21/11/2015	07:44	0:29	*I* >>, IO>
2	KO 11	P123MICOM	23/11/2015	07:37	23/11/2015	08:22	0:45	*I* >>, IO>
3	KO 11	P123MICOM	23/11/2015	14:46	23/11/2015	15:58	1:12	*I* >>, IO>
4	KO 11	P123MICOM	24/11/2015	07:02	24/11/2015	07:37	0:35	*I* >>, IO>
5	KO 11	P123MICOM	24/11/2015	15:03	24/11/2015	16:08	1:05	I>, *I* >>, IO>
6	KO 11	P123MICOM	25/11/2015	07:27	25/11/2015	11:40	4:13	I>, *I* >>, IO>
7	KO 11	P123MICOM	25/11/2015	14:43	25/11/2015	15:35	0:52	I>, *I* >>, IO>
8	KO 11	P123MICOM	25/11/2015	17:35	25/11/2015	18:46	1:11	I>, IO>
9	KO 11	P123MICOM	13/12/2015	00:55	13/12/2015	01:31	0:36	I, *I* >>, IO>
10	KO 11	MICOM	14/12/2015	18:34	14/12/2015	19:01	0:27	*I* >>, IO>
11	KO 11	P123MICOM	16/12/2015	10:51	16/12/2015	11:53	1:02	*I* >>, IO>
12	KO 11	P123MICOM	20/12/2015	11:30	20/12/2015	13:41	2:11	I>,IO>, IA=468.5A, IB=, 69.50A IC=60.00A, IN=435.6A
13	KO-11	MEKELLE SS	22/11/2015	12:44	22/11/2015	12:58	0:14	CAUSE OF BURNING HIGH TENSION LINE
14	KO-11	MEKELLE SS	22/11/2015	15:15	22/11/2015	15:25	0:10	FOR MAINTAIN BROKEN JUMPER
15	KO-11	MEKELLE SS	25/11/2015	11:43	25/11/2015	13:05	1:22	TO CONNECT SECTION
16	KO-11	MEKELLE SS	28/11/2015	15:25	28/11/2015	15:48	0:23	TEST RELAY
17	KO-11	MEKELLE SS	01/12/2015	14:58	01/12/2015	15:37	0:39	TO CONNECT SECTION
18	KO-11	MEKELLE SS	03/12/2015	11:58	03/12/2015	12:39	0:41	TO CONNECT TRAFO SECTION
19	KO-11	MEKELLE SS	04/12/2015	10:43	04/12/2015	11:02	0:19	FOR MAINTAIN BROKEN JUMPER
20	KO-11	MEKELLE SS	06/12/2015	13:56	06/12/2015	14:09	0:13	FOR MAINTAIN BROKEN JUMPER
21	KO-11	MEKELLE SS	17/12/2015	11:44	17/12/2015	11:54	0:10	For Maintain Missing Phase
22	KO-11	MEKELLE SS	18/12/2015	11:15	18/12/2015	11:22	0:07	TO CONNECTSECTION
23	KO-11	P123MICOM	21/12/2015	19:15	21/12/2015	19:40	0:25	I>, *I* >>, IO>
24	KO-11	P123MICOM	23/12/2015	12:42	23/12/2015	14:16	1:34	I>, *I* >>, IO>
25	KO-11	P123MICOM	23/12/2015	19:19	23/12/2015	19:45	0:26	I>, *I* >>, IO>
26	KO-11	P123MICOM	26/12/2015	15:36	26 /12/2015	16:01	0:25	I>, *I* >>, IO>
27	KO-11	P123MICOM	1/13/2015	14:00	1/13/2015	14:50	0:50	I>, *I* >>, IO>, (IA=20.5A, IB=1.508 KA, IC=1.498KA, IN=0.12A)
28	KO-11	P123MICOM	02/13/2015	16:37	02/13/2015	19:12	2:35	I>, *I* >>, IO>, Ie>
29	KO-11	P123MICOM	13/01/2016	17:49	13/01/2016	20:18	2:29	I>, *I* >>, IO>
30	KO-11	P123MICOM	14/01/2016	7:11	14/01/2016	7:30	0:19	I>, *I* >>, IO>
31	KO-11	P123MICOM	14/01/2016	8:13	14/01/2016	11:26	3:13	I>, *I* >>, IO>
32	KO-11	P123MICOM	14/01/2016	14:52	14/01/2016	14:57	0:05	I>, *I* >>, IO>
33	KO-11	P123MICOM	15/01/2016	21:15	15/01/2016	21:49	0:34	*I* >>
34	KO-11	P123MICOM	18/01/2016	10:45	18/01/2016	16:08	5:23	I>, *I* >>, IO>, IA=0.50A, IB= 0.50, IC=923.5A, IN=923.1A
35	KO-11	P123MICOM	20/01/2016	16:30	20/01/2016	17:34	1:04	*I* >>
36	KO-11	MEKELLE SS	27/12/2015	14:55	27/12/2015	15:05	0:10	For Maintain Broken Jumper
37	KO-11	MEKELLE SS	02/01/2016	7:22	02/01/2016	7:37	0:15	FOR MISSING PHASE
38	KO-11	MEKELLE SS	07/01/2016	16:46	07/01/2016	17:05	0:19	FOR SAFETY
39	KO-11	MEKELLE SS	13/01/2016	12:01	13/01/2016	17:49	5:48	FOR PREVENTIVE MAINTENANCE WORK
40	KO-11	MEKELLE SS	18/01/2016	16:21	18/01/2016	16:35	0:14	TO CONNECT SECTION LINE
41	KO-11	P123MICOM	07/02/2015	13:09	07/02/2015	13:49	0:40	I>, *I* >>
42	KO-11	P123MICOM	08/02/2015	12:25	08/02/2015	13:10	0:45	I>, IO>
43	KO-11	P123MICOM	08/02/2015	13:16	08/02/2015	15:42	2:26	I>, IO>
44	KO-11	P123MICOM	09/02/2015	11:42	09/02/2015	14:39	2:57	I>, *I* >>, IO>
45	KO-11	P123MICOM	10/02/2015	13:35	10/02/2015	14:15	0:40	I>, *I* >>, IO>
46	KO-11	P123MICOM	11/2/2015	7:18	11/2/2015	10:52	3:34	I>, *I* >>, IO>
47	KO-11	P123MICOM	11/2/2015	11:54	11/2/2015	16:41	4:47	I>, *I* >>, IO>
48	KO-11	P123MICOM	15/02/2015	10:24	15/02/2015	10:25	0:01	I>, *I* >>, IO>
49	KO-11	P123MICOM	16/02/2015	0:10	16/02/2015	10:08	9:58	I>, *I* >>, IO>
50	KO-11	MEKELLE SS	25/01/2015	7:05	25/01/2015	7:15	0:10	FOR SAFETY R3 AND R4 LINE SPARK
51	KO-11	MEKELLE SS	08/02/2015	6:35	08/02/2015	11:47	5:12	LOAD SHEDING (1 MW)

No	Feeder (Bay)	Relay Acted	Interruption Date	Interruption Time	Reconnection Date	Reconnection Time	Duration in Time	Faults Occurred
52	KO-11	MEKELLE SS	08/02/2015	6:04	08/02/2015	12:45	6:41	LOAD SHEDING (1.1MW)
53	KO-11	MEKELLE SS	10/02/2015	14:15	10/02/2015	15:50	1:35	LOAD SHEDING /1.1MW/
54	KO-11	MEKELLE SS	10\02\2015	18:50	10\02\2015	21:56	3:06	LOAD SHEDING /2.1 MW/
55	KO-11	MEKELLE SS	15\02\2015	16:13	15\02\2015	17:18	1:05	For Maintain Missing phase
56	KO-11	P123MICOM	25\02\2015	6:41	25\02\2015	7:49	1:08	I>, I >>, IO>
57	KO-11	P123MICOM	06\03\2015	18:26	06\03\2015	19:35	1:09	I>, I >>, IO>
58	KO-11	P123MICOM	15/03/2015	14:08	15/03/2015	20:24	6:16	I >> Io>
59	KO-11	MEKELLE SS	25\02\2015	11:29	25\02\2015	12:22	0:53	for safety to work R3 line
60	KO-11	MEKELLE SS	13/03/2015	14:46	13/03/2015	16:21	1:35	TO CHECK TRAFO
61	KO-11	MEKELLE SS	14/03/2015	11:21	14/03/2015	14:44	3:23	FOR DISCONNEC SECTION
62	KO-11	MEKELLE SS	20/03/2015	6:44	20/03/2015	8:38	1:54	LOAD SHEDING (1.3M W)
63	KO-11	MEKELLE SS	20/03/2015	18:02	20/03/2015	19:30	1:28	LOAD SHEDING (1.8 M W)
64	KO-11	P123MICOM	22\03\2015	9:19	22\03\2015	0:00	14:41	I>, IO>
65	KO-11	P123MICOM	23\03\2015	0:00	23\03\2015	16:31	16:31	I>, IO>
66	KO-11	P123MICOM	05\04\2015	16:53	05\04\2015	22:16	5:23	IO>, I >>
67	KO-11	P123MICOM	06\04\2015	15:08	06\04\2015	17:31	2:23	I>, I >>
68	KO-11	P123MICOM	07\04\2015	16:10	07\04\2015	23:01	6:51	I>, I >>
69	KO-11	P123MICOM	10\04\2015	16:19	10\04\2015	19:15	2:56	I>, I >>
70	KO-11	P123MICOM	11\04\2015	10:47	11\04\2015	12:05	1:18	I>, I >>
71	KO-11	P123MICOM	19/04/2015	22:43	19/04/2015	0:00	1:17	I>, I >>, IO>
72	KO-11	P123MICOM	20/04/2015	0:00	20/04/2015	11:37	11:37	I>, I >>, IO>
73	KO-11	MEKELLE SS	24\03\2015	7:36	24\03\2015	9:32	1:56	TO CONNECT SECTION
74	KO-11	P123MICOM	27\04\2015	12:48	27\04\2015	13:37	0:49	I >>, IO>
75	KO-11	P123MICOM	01\05\2015	12:54	01\05\2015	14:08	1:14	I>, I >>, IO>
76	KO-11	P123MICOM	12\05\2015	12:45	12\05\2015	15:02	2:17	I>, I >>, IO>
77	KO-11	P123MICOM	13\05\2015	12:35	13\05\2015	12:47	0:12	I>, I >>, IO>
78	KO-11	P123MICOM	14\05\2015	11:34	14\05\2015	15:01	3:27	I>, I >>, IO>
79	KO-11	P123MICOM	14\05\2015	15:09	14\05\2015	16:41	1:32	I>, I >>, IO>
80	KO-11	P123MICOM	15\05\2015	12:55	15\05\2015	13:54	0:59	I>, I >>, IO>
81	KO-11	P123MICOM	15\05\2015	14:12	15\05\2015	14:27	0:15	I>, I >>, IO>
82	KO-11	MEKELLE SS	27/04/2015	14:02	27/04/2015	15:15	1:13	TO CONNECT SECTION
83	KO-11	MEKELLE SS	27/04/2015	10:50	27/04/2015	11:42	0:52	TO CONNECT SECTION
84	KO-11	MEKELLE SS	27/04/2015	17:30	27/04/2015	17:54	0:24	TO CONNECT SECTION
85	KO-11	MEKELLE SS	02\05\2015	9:30	02\05\2015	9:44	0:14	TO MAINTEN BROKEN JAMBER
86	KO-11	MEKELLE SS	02\05\2015	14:29	02\05\2015	14:38	0:09	TO CONNECT SECTION
87	KO-11	MEKELLE SS	13\05\2015	11:02	13\05\2015	11:08	0:06	TO CONNECT SECTION
88	KO-11	MEKELLE SS	15\05\2015	10:04	15\05\2015	10:20	0:16	FOR MISSING PHASE
89	KO-11	MEKELLE SS	16\05\2015	10:36	16\05\2015	11:02	0:26	TO CONNECT SECTION
90	KO-11	MEKELLE SS	17\05\2015	9:30	17\05\2015	9:42	0:12	FOR MAINTAIN JUMPER
91	KO-11	P123MICOM	27/05/2015	7:06	27/05/2015	8:23	1:17	I >>, IO>
92	KO-11	P123MICOM	29/05/2015	8:05	29/05/2015	8:57	0:52	I >>, IO>
93	KO-11	MEKELLE SS	30/05/2015	15:35	30/05/2015	15:45	0:10	TO disconnect section
94	KO-11	P123MICOM	30/06/2015	15:20	30/06/2015	18:02	2:42	I >>, IO>
95	KO-11	P123MICOM	03\07\2015	18:47	03\07\2015	19:46	0:59	I >>, IO>
96	KO-11	P123MICOM	09\07\2015	6:31	09\07\2015	7:39	1:08	I>, I >>, IO>
97	KO-11	P123MICOM	14\07\2015	15:01	14\07\2015	15:40	0:39	I>, I >>, IO>
98	KO-11	P123MICOM	14\07\2015	17:37	14\07\2015	17:42	0:05	I>, I >>, IO>
99	KO-11	P123MICOM	14\07\2015	17:56	14\07\2015	18:01	0:05	I>, I >>, IO>
100	KO-11	P123MICOM	15\07\2015	15:55	15\07\2015	16:06	0:11	I>, I >>>, IO>
101	KO-11	MEKELLE SS	28/06/2015	10:15	28/06/2015	10:31	0:16	To connect section
102	KO-11	MEKELLE SS	03\07\2015	0:05	03\07\2015	0:18	0:13	For accident fire
103	KO-11	MEKELLE SS	03\07\2015	8:56	03\07\2015	9:12	0:16	For Maintain Broken Jumper

No	Feeder (Bay)	Relay Acted	Interruption Date	Interruption Time	Reconnection Date	Reconnection Time	Duration in Time	Faults Occurred
104	KO-11	MEKELLE SS	09\07\2015	10:35	09\07\2015	11:10	0:35	for maintain broken jumper
105	KO-11	MEKELLE SS	20/07/2015	10:12	20/07/2015	10:39	0:27	FOR disconnect section line
106	KO-11	P123MICOM	04\08\2015	21:20	04\08\2015	22:50	1:30	I>, $I >>$, IO>
107	KO-11	P123MICOM	11\08\2015	7:52	11\08\2015	8:33	0:41	I>, $I >>$, IO>
108	KO-11	P123MICOM	11\08\2015	15:17	11\08\2015	18:14	2:57	I>, $I >>$, IO>
109	KO-11	P123MICOM	17\08\2015	7:30	17\08\2015	7:57	0:27	$I >>$, IO>
110	KO-11	P123MICOM	18\08\2015	13:48	18\08\2015	16:48	3:00	$I >>$, IO>
111	KO-11	MEKELLE SS	22\07\2015	12:07	22\07\2015	12:29	0:22	burning transformer
112	KO-11	MEKELLE SS	25\07\2015	11:32	25\07\2015	11:50	0:18	FOR SEFTY TO WORK KO3
113	KO-11	MEKELLE SS	05\08\2015	17:09	05\08\2015	17:27	0:18	FOR SAFETY TO WORK KO3 LINE
114	KO-11	MEKELLE SS	8/8/2015	17:42	8/8/2015	17:55	0:13	For Connect Section Switch
115	KO-11	MEKELLE SS	12\08\2015	10:02	12\08\2015	10:19	0:17	FOR MAINTAIN BROKEN JUMPER
116	KO-11	MEKELLE SS	12\08\2015	11:02	12\08\2015	11:45	0:43	TO CONNECT SECTION
117	KO-11	MEKELLE SS	14\08\2015	12:21	14\08\2015	12:26	0:05	FOR MAINTAIN BROKEN JUMPER
118	KO-11	P123MICOM	22\08\2015	3:49	22\08\2015	11:29	7:40	$I >>$, IO>
119	KO-11	P123MICOM	23/08/2015	15:08	23/08/2015	16:02	0:54	$I >>$, IO>
120	KO-11	P123MICOM	27/08/2015	15:48	27/08/2015	16:30:00	0:42	$I >>$, IO>
121	KO-11	P123MICOM	29\08\2015	7:37	29\08\2015	8:35	0:58	$I >>$, IO>
122	KO-11	P123MICOM	29\08\2015	15:55	29\08\2015	17:03:00	1:08	$I >>$, IO>
123	KO-11	P123MICOM	02\09\2015	6:46	02\09\2015	7:22	0:36	$I >>$, IO>
124	KO-11	P123MICOM	10\09\2015	9:11	10\09\2015	9:28	0:17	$I >>$, IO>
125	KO-11	P123MICOM	12\09\2015	20:08	12\09\2015	20:45:00	0:37	$I >>$& IO>
126	KO-11	P123MICOM	12\09\2015	23:18	12\09\2015	0:00	0:42	$I >>$& IO>
127	KO-11	P123MICOM	13\09\2015	0:00	13\09\2015	9:39	9:39	$I >>$& IO>
128	KO-11	MEKELLE SS	22\08\2015	12:17	22\08\2015	12:27	0:10	FOR CONNECT SECTION
129	KO-11	MEKELLE SS	22\08\2015	16:31	22\08\2015	17:10	0:39	FOR MAINTAIN BROKEN JUMPER
130	KO-11	MEKELLE SS	23/08/2015	9:34	23/08/2015	9:50	0:16	FOR CONNECT SECTION
131	KO-11	MEKELLE SS	28/07/2015	9:31	28/07/2015	9:46	0:15	TO CONNECT SECTION
132	KO-11	MEKELLE SS	16\09\2015	9:39	16\09\2015	9:51	0:12	FOR SAFETY KO9 MAINTAIN
133	KO-11	P123MICOM	21\09\2015	13:17	21\09\2015	0:00	10:43	I>, $I >>$, IO>
134	KO-11	P123MICOM	22\09\2015	0:00	22\09\2015	11:18	11:18	I>, $I >>$, IO>
135	KO-11	P123MICOM	24/09/2015	16:05	24/09/2015	17:36	1:31	I>, $I >>$, IO>
136	KO-11	P123MICOM	08\10\2015	9:54	08\10\2015	10:22	0:28	IO>, $I >>$
137	KO-11	P123MICOM	17/10/215	10:52	17/10/215	11:27	0:35	IO>$I >>$
138	KO-11	P123MICOM	19\10\2015	15:18	19\10\2015	16:36	1:18	IO>$I >>$
139	KO-11	P123MICOM	19\10\2015	17:07	19\10\2015	17:19	0:12	IO>$I >>$
140	KO-11	MEKELLE SS	22\09\2015	11:18	22\09\2015	13:45	2:27	FOR CONNECT SECTION
141	KO-11	MEKELLE SS	22\09\2015	14:13	22\09\2015	14:29	0:16	FOR CONNECT SECTION
142	KO-11	MEKELLE SS	23/09/2015	11:22	23/09/2015	12:06	0:44	FOR CONNECT SECTION
143	KO-11	MEKELLE SS	24/09/2015	19:30	24/09/2015	20:05	0:35	FOR CONNECT SECTION
144	KO-11	MEKELLE SS	28/09/2015	9:12	28/09/2015	15:13	6:01	for maintenance (voluntary)
145	KO-11	MEKELLE SS	13\10\2015	13:28	13\10\2015	13:56	0:28	For Connect Section
146	KO-11	MEKELLE SS	15\10\2015	7:40	15\10\2015	13:54	6:14	FOR REHABLITATION
147	KO-11	P123MICOM	30\10\2015	11:30	30\10\2015	13:37	2:07	$I >>$, IO>
148	KO-11	P123MICOM	30\10\2015	20:36	30\10\2015	0:00	3:24	$I >>$, IO>
149	KO-11	P123MICOM	01\11\2015	0:00	01\11\2015	9:06	9:06	$I >>$, IO>
150	KO-11	P123MICOM	3/11/2015	12:09	3/11/2015	14:28	2:19	$I >>$, IO>
151	KO-11	P123MICOM	08\11\2015	15:47	08\11\2015	20:58	5:11	$I >>$, IO>
152	KO-11	P123MICOM	09\11\2015	9:47	09\11\2015	11:47	2:00	$I >>$, IO>
153	KO-11	P123MICOM	18\11\2015	16:27	18\11\2015	17:57	1:30	I>, $I >>$, IO> (IA=1.342KA, IB= 1.316A, IC=43.50A, IN=0.12A)
154	KO-11	P123MICOM	19\11\2015	6:27	19\11\2015	8:59	2:32	$I >>$, IO>
155	KO-11	P123MICOM	19\11\2015	16:29	19\11\2015	18:09	1:40	$I >>$, IO>
156	KO-11	P123MICOM	19\11\2015	20:01	19\11\2015	21:50	1:49	$I >>$, IO>

No	Feeder (Bay)	Relay Acted	Interruption Date	Interruption Time	Reconnection Date	Reconnection Time	Duration in Time	Faults Occurred
157	KO-11	P123MICOM	20\11\2015	6:45	20\11\2015	7:41	0:56	$I >>$, IO>
158	KO-11	MEKELLE SS	26\10\2015	17:17	26\10\2015	19:50	2:33	TO CONECT SECTION SW
159	KO-11	MEKELLE SS	27\10\2015	14:50	27\10\2015	15:02	0:12	FOR CONNECT SECTION
160	KO-11	MEKELLE SS	28\10\2015	16:02	28\10\2015	16:12	0:10	TO CONNECT SECTION
161	KO-11	MEKELLE SS	29\10\2015	9:53	29\10\2015	10:03	0:10	TO DISCONNECT SECTION
162	KO-11	MEKELLE SS	01\11\2015	9:50	01\11\2015	10:10	0:20	FOR CONNECT SECTION
163	KO-11	MEKELLE SS	02\11\2015	7:40	02\11\2015	7:50	0:10	FOR CONNECT SECTION
164	KO-11	MEKELLE SS	06\11\2015	16:11	06\11\2015	16:16	0:05	For Maintain Burning High-Tension Line
165	KO-11	MEKELLE SS	08\11\2015	6:44	08\11\2015	15:47	9:03	FOR MAINTENANCE (FOR REHABILTATION)
166	KO-11	MEKELLE SS	09\11\2015	9:06	09\11\2015	9:20	0:14	FOR MAINTAIN BROKEN JUMPER
167	KO-11	MEKELLE SS	10\11\2015	19:45	10\11\2015	20:03	0:18	FOR CONNECT SECTION
168	KO-11	MEKELLE SS	10\11\2015	22:18	10\11\2015	22:30	0:12	FOR MAINTAIN BROKEN JUMPER
169	KO-11	MEKELLE SS	16\11\2015	6:55	16\11\2015	15:03	8:08	FOR REHABTATION
170	KO-11	MEKELLE SS	17\11\2015	9:47	17\11\2015	9:59	0:12	TO CONNECT SECTION
171	KO-11	MEKELLE SS	18\11\2015	19:28	18\11\2015	19:36	0:08	FOR MAINTAIN TRAFO
172	KO-11	MEKELLE SS	20\11\2015	10:06	20\11\2015	11:26	1:20	FOR MAINTAIN BROKEN JUMPER
Total							330:07	

Appendix D

EEU electricity tariff (birr/kwhr)

Tariff category	Block identification	Monthly consumption in (KWH/month)	Birr /KWH
Domestic	1st block	0-50	0.273
	2nd block	51-100	0.7670
	3rd block	101-200	1.6250
	4th block	201-300	2
	5th block	300-400	2.2
	6th block	401-500	2.4
	7th block	Above 500	2.481
Commercial	1st block	0-50	0.6088
	2nd block	Above 50	0.6943
Industrial	Low voltage time day of industry three phase		0.5778
	High voltage time day of industry @ 15KV		0.4086
	High voltage industry @ 132KV		0.3805
Street light	Street light tariff		0.4843

Appendix E

Estimated number of customers and types of load

Pole Loc No	Conductor Size	Trafo_Name Code_ID	Rated Capacity	Sector Type	Estimated No Customers
KO-11_P186	50	KO-11_TR01	1250	Industrial	1
	50	KO-11_TR01	1250	Industrial	
KO-11_P188	50	KO-11_TR03	400	Residential	52
KO-11_P207	50	KO-11_TR04	25	Gov& Inst	1
KO-11_P238	50	KO-11_TR05	25	Residential	4
KO-11_P248	50	KO-11_TR06	25	Residential	4
KO-11_P252	50	KO-11_TR07	630	Residential	81
KO-11_P261	50	KO-11_TR08	50	Residential	7
KO-11_P276	50	KO-11_TR09	50	Residential	7
KO-11_P289	50	KO-11_TR10	50	Residential	7
KO-11_P293	50	KO-11_TR11	25	Residential	4
KO-11_P305	50	KO-11_TR12	1250	Gov& Inst	1
KO-11_P311	50	KO-11_TR13	25	Gov& Inst	1
KO-11_P312	50	KO-11_TR14	630	Gov& Inst	1
KO-11_P316	50	KO-11_TR15	800	Gov& Inst	1
KO-11_P321	25	KO-11_TR16	800	Gov& Inst	1
KO-11_P329	25	KO-11_TR17	1250	Gov& Inst	1
KO-11_P330	25	KO-11_TR18	25	Gov& Inst	1
KO-11_P341	25	KO-11_TR19	50	Gov& Inst	1
KO-11_P343	25	KO-11_TR20	800	Gov& Inst	1
KO-11_P350	50	KO-11_TR21	1250	Gov& Inst	1
KO-11_P375	50	KO-11_TR22	200	Residential	26
KO-11_P386	25	KO-11_TR23	100	Residential	13
KO-11_P391	95	KO-11_TR24	315	Commercial	1
KO-11_P433	50	KO-11_TR25	25	Residential	4
KO-11_P436	50	KO-11_TR26	50	Residential	7
KO-11_P454	95	KO-11_TR27	400	Residential	52
KO-11_P462	95	KO-11_TR28	1250	Industrial	1
KO-11_P467	50	KO-11_TR29	100	Residential	13
KO-11_P472	50	KO-11_TR30	315	Residential	41
KO-11_P476	50	KO-11_TR31	25	Residential	4
KO-11_P487	50	KO-11_TR32	200	Residential	26
KO-11_P543	50	KO-11_TR33	315	Residential	41
KO-11_P582	95	KO-11_TR34	1250	Industrial	1
KO-11_P590	50	KO-11_TR35	1250	Industrial	
KO-11_P603	50	KO-11_TR36	1250	Gov& Inst	1
KO-11_P641	50	KO-11_TR37	630	Gov& Inst	1
KO-11_P692	50	KO-11_TR38	1250	Industrial	1
KO-11_P692	50	KO-11_TR39	1250	Industrial	
KO-11_P714	50	KO-11_TR40	200	Residential	26
KO-11_P720	50	KO-11_TR41	100	Residential	26
KO-11_P724	50	KO-11_TR42	315	Residential	41
KO-11_P435	50	KO-11_TR43	1250	Gov& Inst	1
KO-11_P771	50	KO-11_TR44	25	Residential	4
KO-11_P794	50	KO-11_TR45	100	Residential	13
KO-11_P801	50	KO-11_TR46	50	Residential	7
KO-11_P805	50	KO-11_TR47	630	Residential	81
KO-11_P816	50	KO-11_TR48	50	Residential	7
KO-11_P824	50	KO-11_TR49	100	Residential	13
KO-11_P834	50	KO-11_TR50	315	Residential	41
KO-11_P839	50	KO-11_TR51	100	Residential	13
KO-11_P858	50	KO-11_TR52	315	Residential	41
KO-11_P860	50	KO-11_TR53	100	Residential	13
KO-11_P862	50	KO-11_TR54	315	Residential	41
KO-11_P866	50	KO-11_TR55	315	Residential	41
KO-11_P887	50	KO-11_TR56	25	Gov& Inst	1
KO-11_P897	50	KO-11_TR57	200	Residential	26
KO-11_P912	50	KO-11_TR58	315	Residential	41
KO-11_P915	50	KO-11_TR59	315	Residential	41
KO-11_P930	50	KO-11_TR60	315	Residential	41
Total			26285		970

Appendix F

Simulation result of reliability indices for the modelled feeder from existing up to case 5

SUMMARY

System Indexes

ACCI	452487.70 kVA / customer
AENS	2206.5540 MW hr / customer.yr
ALII	82.15 pu (kVA)
ASAI	0.9461 pu
ASUI	0.05391 pu
CAIDI	5.735 hr / customer interruption
CTAIDI	472.264 hr / customer.yr
ECOST	895,481,400.00 $ / yr
EENS	132393.200 MW hr / yr
IEAR	6.764 $ / kW hr
SAIDI	472.2644 hr / customer.yr
SAIFI	82.3435 f / customer.yr

SUMMARY

System Indexes

ACCI	283748.70 kVA / customer
AENS	1394.2910 MW hr / customer.yr
ALII	51.51 pu (kVA)
ASAI	0.9673 pu
ASUI	0.03267 pu
CAIDI	5.662 hr / customer interruption
CTAIDI	286.165 hr / customer.yr
ECOST	566,945,800.00 $ / yr
EENS	83657.470 MW hr / yr
IEAR	6.777 $ / kW hr
SAIDI	286.1645 hr / customer.yr
SAIFI	50.5394 f / customer.yr

SUMMARY

System Indexes

ACCI	236186.00 kVA / customer
AENS	1148.9130 MW hr / customer.yr
ALII	42.88 pu (kVA)
ASAI	0.9726 pu
ASUI	0.02742 pu
CAIDI	5.623 hr / customer interruption
CTAIDI	240.181 hr / customer.yr
ECOST	466,600,100.00 $ / yr
EENS	68934.800 MW hr / yr
IEAR	6.769 $ / kW hr
SAIDI	240.1814 hr / customer.yr
SAIFI	42.7137 f / customer.yr

SUMMARY

System Indexes

ACCI	112459.90 kVA / customer
AENS	492.5096 MW hr / customer.yr
ALII	20.42 pu (kVA)
ASAI	0.9748 pu
ASUI	0.02523 pu
CAIDI	5.575 hr / customer interruption
CTAIDI	220.994 hr / customer.yr
ECOST	200,982,900.00 $ / yr
EENS	29550.580 MW hr / yr
IEAR	6.801 $ / kW hr
SAIDI	220.9942 hr / customer.yr
SAIFI	39.6425 f / customer.yr

SUMMARY

System Indexes

ACCI	110759.80 kVA / customer
AENS	483.6295 MW hr / customer.yr
ALII	20.11 pu (kVA)
ASAI	0.9778 pu
ASUI	0.02220 pu
CAIDI	5.497 hr / customer interruption
CTAIDI	194.488 hr / customer.yr
ECOST	193,644,100.00 $ / yr
EENS	29017.770 MW hr / yr
IEAR	6.673 $ / kW hr
SAIDI	194.4879 hr / customer.yr
SAIFI	35.3782 f / customer.yr

SUMMARY

System Indexes

ACCI	110490.40 kVA / customer
AENS	482.2547 MW hr / customer.yr
ALII	20.06 pu (kVA)
ASAI	0.9789 pu
ASUI	0.02107 pu
CAIDI	5.472 hr / customer interruption
CTAIDI	184.555 hr / customer.yr
ECOST	193,468,300.00 $ / yr
EENS	28935.280 MW hr / yr
IEAR	6.686 $ / kW hr
SAIDI	184.5550 hr / customer.yr
SAIFI	33.7260 f / customer.yr