



**ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF
TECHNOLOGY**

**School of Electrical and Computer Engineering
Master of Science in Power Engineering**

**Power Distribution System Failure and Vulnerability
Analysis in Ethiopia
Case Study : Kotebe Distribution System**

**By
Ayalsew Tariku**

**A Thesis Submitted to the School of Graduate Studies of
Addis Ababa University in Partial Fulfilment of the
Requirements for the Degree of Masters of Science in Power
Engineering**

Thesis Advisor: Dr. Getachew Bekele

November 2021

Addis Ababa, Ethiopia



**ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF
TECHNOLOGY**

**School of Electrical and Computer Engineering
Master of Science in Power Engineering**

**Power Distribution System Failure and Vulnerability
Analysis in Ethiopia
Case Study : Kotebe Distribution System**

**By
Ayalsew Tariku**

APPROVED BY BOARD OF EXAMINERS

**Chairman, Department of Graduate
Committee**

Signature

Advisor

Signature

Internal Examiner

Signature

External Examiner

Signature

Declaration

I declare that the work entitled “**Power distribution system failure and vulnerability analysis in Ethiopia**” is my original work and has not been presented for any degree in this or any other universities or colleges, and all sources of material used for the thesis are duly acknowledged.

Ayalsew Tariku

Date

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

Advisor Name

Signature

Acknowledgments

Thanks to the Almighty God, the King of King and the only creator of everything. No word to express thanks to my advisor, **Dr. Getachew Bekele**, for his great support and guidance throughout the whole work and my life. His plentiful experiences have encouraged me in all the time of my academic research and daily life. Thanks a lot!

I would like to thanks the members of the Ethiopian Electric Utility (EEU) in East Addis Ababa Region (EAAR) and Kotebe substation workers. It is their kind help and supports that have made me get data for my study.

I am deeply indebted to my friends for their continuous support and encouragement over the years. I also would like to thank my family for their support.

Dedication

This paper is dedicated to
my dad Tariku Bitewu

Abstract

Distribution systems are usually the main areas where power outages occur. Electric power interruptions in the capital city of Ethiopia, i.e. Addis Ababa, are usual problems. Even there are situations that electric power interruption occurs several times a day.

This thesis tries to identify the causes of power interruptions for the Kotebe distribution system and the vulnerability of the existing components. It is a component-based failure analysis on a selected feeder of the distribution system. It is selected considering the total annual frequency of interruptions for each feeder of the distribution system. Feeder 6 of the Kotebe substation is the most frequently interrupted line. The existing conditions of the components on the feeder are inspected. Distribution poles, conductors, insulators, transformers, protection and other auxiliary devices are the inspected components. The probable effect of the most frequent causes of interruptions identified in the distribution on the poor distribution components is studied.

Interruption during operation and maintenance is the common cause identified in the distribution. But this is through the order of the maintenance workers of the utility. Sudden faults are usually due to weather influences. It accounts for 48.66% of the total known faults excluding interruption due to operation. The vulnerability to failure of the existing distribution poles is identified through modelling the distribution poles, gravitational force of tilted poles and weather influence by COMSOL software. Decay depth of wooden poles considering the selected area weather condition is studied using TimberLife software, and its effect for failure is simulated using COMSOL. Poles will deflect upto 3.05^0 and 1.749^0 with and without considering decay depth at the worst condition of a certain weather influence, respectively. Poles resilience condition is also identified by analyzing deflection and stress on their surface.

Many of the existing distribution transformers are working overloaded. The loss of life of distribution transformers and their vulnerability is studied using the IEEE standard (C57.19-1995) guidelines. The hot spot temperature, ageing acceleration factor, and percent loss of life of each transformer are calculated. 83 of 157 transformers are expected to sustain below the IEEE standard expected life (i.e., 20.55 years). The effect of lightning considering soil resistivity of the area is also studied by modelling the feeder 6 of Kotebe distribution system using Matlab/Simulink. Metal Oxide Varistor(MOV) Surge arresters with grounding resistance above 25Ω

would have higher surge magnitude that could damage the transformers and surge arresters.

Keywords— Distribution components, Distribution system, Failure analysis, Loss of life of transformer, Resilience, Soil resistivity, Vulnerability

List of publications

Based on the thesis work, the following papers have been published in conferences as listed below:

- Ayalsew T, Getachew B, "Distribution transformer failure study and solution proposal in Ethiopia," 2020 IEEE PES/IAS PowerAfrica, Kenya, Nairobi, October 2020
DOI:10.1109/PowerAfrica49420.2020.9219933

This paper was presented at the IEEE Power and Energy Society (PES), Industrial Applications Society (IAS) conference held in Kenya, August 23-27, 2020.

- Ayalsew T, Getachew B, "Power distribution system failure and vulnerability analysis in Ethiopia, " 2021 International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town, South Africa, 11 February 2022
DOI:10.1109/ICECET52533.2021.9698804

This paper was presented at the IEEE International Conference on Electrical, Computer and Energy Technologies (ICECET) conference held in Cape Town, South Africa, on 09-10 December 2021.

Contents

List of Figures	ix
List of Tables	xi
List of Abbreviations	xii
List of Symbols and Variables	xiii
Chapter 1 Introduction	1
1.1 Background	1
1.2 Motivation	2
1.3 Problem statement	2
1.4 Objective of the thesis	3
1.5 Scope of the study	4
1.6 Significance of the study	4
1.7 Methodology	4
1.8 Thesis outline	6
Chapter 2 Power Distribution System Failure and Literature Review	7
2.1 Introduction	7
2.2 General concept of failure	7
2.3 Distribution components failure	8
2.3.1 Distribution poles failure	9
2.3.2 Distribution conductors failure	14
2.3.3 Distribution insulator failure	14
2.3.4 Distribution transformers failure	15
2.3.5 Loss of life of distribution transformers due to overloading	17
2.4 Distribution system failure due to lightning	19
2.5 Literature review	21
Chapter 3 Data Collection and Failure Analysis of Kotebe Distribution System	23
3.1 Introduction	23
3.2 Kotebe distribution substation	23
3.3 Frequency and duration of interruption	24
3.4 Causes of Kotebe distribution system failure	26
3.5 Distribution components inspection and analysis	27
3.5.1 Distribution poles failure	27

3.5.2	Conductor inspection	36
3.5.3	Insulators inspection	36
3.5.4	Distribution transformers inspection	37
3.5.5	Distribution transformers on feeder 6 of Kotebe substation	38
3.5.6	Transformers and loading	40
3.5.7	Loss of life of overloaded transformers	41
Chapter 4	Simulation Studies and Analysis of Results	43
4.1	Introduction	43
4.2	Weather influence and tilt angle on distribution poles	43
4.2.1	Decay of distribution poles	47
4.2.2	Effect of weather influence on decayed distribution poles	48
4.3	Effect of lightning on distribution transformers	51
4.3.1	Methods to reduce grounding resistance	62
4.4	Proposed solutions for failure reduction	63
Chapter 5	Conclusions, Recommendations and Future Works	65
5.1	Conclusions	65
5.2	Recommendations	66
5.3	Suggestions for future work	67
Bibliography		68
Appendix A	Causes of Kotebe Distribution System Failure	72
Appendix B	Kotebe Distribution System Transformers Loading	73
Appendix C	Transformers Hotspot Temperature and Loss of Life	78
Appendix D	Transformers Greater Percentage of Loss of Life than the Standards	83
Appendix E	EEU Overhead Medium Voltage Distribution Conductors Size	86

List of Figures

1.1	Distribution system hierarchy	1
1.2	Distribution system failure due to different causes (Source: google images)	3
1.3	Flow chart for methodology followed throughout the thesis work	5
2.1	Tilted pole (left side) and a tree risk for distribution system (right) (Source: photo from the study area (left side) and website (right))	9
2.2	Wind load and gravitational force on tilted poles	11
2.3	Decay of distribution pole due to climate influence [17]	12
2.4	Damaged insulator due to flash over	15
2.5	Color of silica jelly before and after absorbing excessive moisture	15
2.6	Oil natural air natural (ONAN) cooling system	17
2.7	Lightning distribution in different areas of Ethiopia [26]	19
2.8	Characteristics of lightning using Heidler equation	20
3.1	Kotebe substation	23
3.2	New substation transformers	24
3.3	Monthly frequency and duration of interruptions (September 2018-August 2019)	25
3.4	Frequency and duration of interruption	25
3.5	Block diagram of work flow in EEU during interruption	26
3.6	Causes of Kotebe distribution system failure	27
3.7	Location of cracked, poor foundation and tilted wooden poles around CMC and Ayat area	29
3.8	Illustration of the procedure for distribution poles failure analysis	30
3.9	Number of transformers in different regions of Ethiopia (Source: EEU South Addis Ababa District)	37
3.10	Location of overloaded transformers using 3D Google view	40
3.11	Expected number of transformers that could sustain certain years	42
4.1	Model of wooden distribution pole on COMSOL software	44
4.2	Deflection of wooden pole due to weather influence ($\theta = 0^0$)	45
4.3	Angular deflection of tilted poles by 0^0 , 5^0 and 10^0 respectively	45
4.4	Graph of stress and displacement along surface of 0^0 tilted pole	45
4.5	Displacement of poles for tilt angle of 5^0 (left) and 10^0 (right side)	46
4.6	Surface and Centre decay of the inground distribution poles	47
4.7	Surface decay of distribution pole above ground	48

4.8	Weather influence on decayed wooden distribution poles of 5, 10 and 15 years age ($\theta = 0^0$)	48
4.9	Deflection (left side) and stress (right side) of 15 years aged decayed poles ($\theta = 0^0$)	49
4.10	Deflection of poles with increased ageing	50
4.11	Lightning block of the Matlab/Simulink	52
4.12	Lightning characteristics for 10kA magnitude	53
4.13	Over all model of the Matlab/Simulink lightning model	53
4.14	The distribution subsystem model of figure 4.13 (transformers without surge arrester)	54
4.15	Surge voltage at bus 1 when lightning occur at bus 1 of the transformer .	54
4.16	Surge voltage at bus 2 to 5 of the transformers when lightning occur at bus 1 of the transformer	55
4.17	The distribution subsystem model of transformers having surge arrester .	55
4.18	Surge voltage at different bus of transformers with 25Ω grounding resistance	57
4.19	MOV surge arrester current and voltage waveform at different buses . . .	57
4.20	Surge voltage at different terminal of transformers for 274Ω	58
4.21	MOV surge arrester current and voltage waveform from bus 2 to 5	58
4.22	Surge voltage at different buses of transformers for 382Ω grounding resistance	59
4.23	MOV surge arrester current and voltage waveform for 382Ω grounding resistance	59
4.24	Surge voltage at bus 2, 3, 4 and 5 terminals of 523Ω grounding resistance	60
4.25	Surge voltage from bus 2 to 5 terminals of 657Ω grounding resistance . .	60
4.26	Surge magnitude at different buses for a lightning strike at sending and receiving end	62

List of Tables

2.1	Resilience condition of distribution poles based on its deflection	13
3.1	Summary of distribution poles inspection data	29
3.2	Mean annual and monthly temperature ($^{\circ}C$)	30
3.3	Mean monthly rainfall data (2015 - 2019 G.C)	31
3.4	The five years annual rainfall data	32
3.5	Force on distribution poles considering different factors	32
3.6	Depth of poles decay due to climate influence	34
3.7	Allowable reduced circumferences for NESC rules [36]	34
3.8	Summary of identified conductor problems	36
3.9	Summary of insulators identified problems	37
3.10	Rating and number of transformers	39
3.11	Number of transformers with identified problems	40
3.12	IEEE standard of parameters used for transformers [23]	41
4.1	Specification of parameters used for the distribution poles [12]	43
4.2	Deflection angle of tilted poles due to the weather influence	46
4.3	Summary of the simulation result for deflection of decayed poles	49
4.4	Stress developed at different tilt angle of decayed poles	50
4.5	Standard probability of lightning level [27]	51
4.6	IEEE standards of soil type and its resistivity [42]	56
4.7	Grounding resistance considering standards of soil resistivity and rod size	56
4.8	Surge magnitude when lightning happens at sending end bus of the line .	61
4.9	Surge magnitude when lightning happens at receiving end of the line . .	61
A.1	Causes of Kotebe distribution system failure in each month	72
B.1	Loading of the distribution transformers on feeder 6 of Kotebe substation	73
C.1	Summary of hotspot temperature (T_{HS}), ageing acceleration factor (F_{AA}) and % of loss of life transformers	78
D.1	Transformers having above the standard T_{HS} , F_{AA} and % loss of life . . .	83
E.1	EEU overhead medium voltage distribution conductors specifications . .	86

List of Abbreviations

AC	Alternating Current
BIL	Basic Insulation Level
DC	Direct Current
DP	Distribution Pole
DT	Distribution Transformer
EAAR	East Addis Ababa Region
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
FEM	Finite Element Method
HV	High Voltage
HRC	High Rupturing Capacity
IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronics Engineers
Km	Kilo-Meters
kV	Kilo Volt
LV	Low Voltage
MOV	Metal oxide Varistor
MVA	Mega Volt Ampere
MW	Mega Watt
NMA	National Meteorology Agency
TDI	Total Duration of Interruption
TFI	Total Frequency of Interruption

List of Symbols and Variables

C	Capacitance
I	Current
L	Inductance
P	Active power
Q	Reactive power
R	Resistance
T	Temperature
τ	Time constant
V_{busi}	Voltage at bus i
X	Reactance
Ω	Ohm

Chapter 1

Introduction

1.1 Background

The power distribution system is the final stage in the supply of electric power, carrying electricity out of the transmission system to individual customers. The distribution of electric power to most consumers is done with a network of low voltage levels. Distribution system of power supply consist of the following main parts.

- i. Distribution substation
- ii. Primary distribution feeder
- iii. Distribution transformer
- iv. Secondary distribution feeder

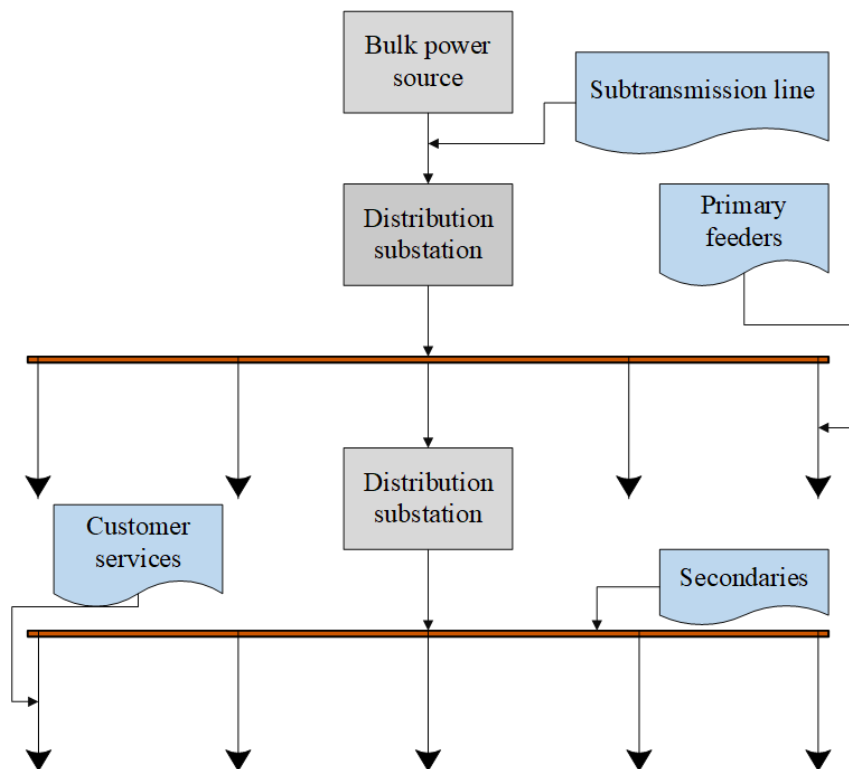


Figure 1.1: Distribution system hierarchy

v. Service mains (customer service)

The reliable distribution system supplies play a significant role in modern society for the growth of countries' economies where it is utilized in the industries, households, and the commercial sector. The power outage affects human life activities and the economic performance of a country. The growing use of sensitive electronic equipment and the increasing demand of utility customers demonstrate the importance of a reliable power supply [1]. Failure of the distribution components is one of the major factor which affects the reliability of power supply.

From some utilities and agencies surveys, most of the power outages are caused by the fault in the distribution system (i.e., about 80% based on the statistics in Norway) [2]. Many causes could lead to power outages, including equipment failure, weather, trees, and so on. In general, failures of electric power systems could be caused by external factors (environmental) and internal (component failure). External factors can be: lightning, wind, rain, tree, car accidents, animals and etc.

Lightning is one of the common causes of faults on overhead power lines and destroys or disrupts sensitive electronic equipment. Transformers are one of the most common equipment in a power line that falls significantly due to lightning. The solutions to such problems are the interest of both utilities and customers.

Internal failures are usually due to infrastructure problems. Improper installing and the absence of periodic maintenance of protection and control devices are the usual problems for internal failures. The consequence causes overloading, unbalance loading, and failure of components.

Vulnerability is finding out the weak points in the network of the power system area [3]. When these weak points are subjected to external interference or influence, it is simpler to results in failures of components in the network. Therefore, through vulnerability assessment and analysis, we can find out the weak points in the power network in advance and improve these weak points. These could help to reduce the possibility of distribution system failure.

1.2 Motivation

The great inconvenience on the supply of electric power due to the distribution system problems is the most common complaint of customers in Ethiopian Electric Utility. The need for a reliable power supply is increasing. But the problems on the utility side are far increasing. Emphasis on the loss of capital due to interruption and component failure also doesn't seem a serious issue by the utility. Such type of study can enforce the utility to focus on problems identification and solution study. Trying to know the causes of the problems is a primary input to reduce it, and could give an alarm for the utility to emphasize it.

1.3 Problem statement

The daily power interruption problems and other associated effects in the distribution are becoming apparent in Ethiopia. It is common to see frequent power interruptions in every interval of time each day. Trying to investigate the actual causes of the fault and reduce the problems is needed rather than maintenance with the usual trend, which is the actual

practice of the utility.



Figure 1.2: Distribution system failure due to different causes (Source: google images)

The distribution system in the city, Addis Ababa, is identified with various weak infrastructure and can be affected with simpler disturbances. When certain weak points in the distribution network are subjected to any influence, it results in failures of the distribution system. Thus, a vulnerability of components in the distribution is an essential problem needed to be analyzed. Study how far the distribution system is prone to failure by analyzing faults threatening its operation is required to take effective actions for preventions and adjustments.

Overhead power distribution components mainly poles, conductors, insulators, and transformers needed analysis of the existing condition for proper maintenance and solution study. Transformers failure, which lasts a long time until replacement or maintenance, is another usual problem of the utility.

Kotebe substation supplies large areas in as well as outside the city. In the distribution coverage area, interruption is frequent and needs appropriate study. The actual condition of components in use for the distribution system needs to be studied for trouble-shooting the weak points. The vulnerability of these components for identifying the probable power interruption is an essential issue needed to be studied.

1.4 Objective of the thesis

★ Main objective

The main objective of this thesis is to study the causes of frequent distribution system failure and their effects on the vulnerability of the existing distribution components in the capital, Addis Ababa.

★ Specific objective

The specific objectives of the study include;

- To collect relevant data from the selected site using direct survey and from previous records in the substation and at the East Addis Ababa Region(EAAR) EEU district
- To identify the causes of distribution system failure around Kotebe distribution supply area
- To select the most frequently interrupted feeder
- To inspect components condition on the selected feeder

- To study vulnerability of the distribution components considering identified causes and simulate through MATLAB/Simulink, COMSOL, and TimberLife software
- To analyze the results and propose solutions that needed to be taken
- To conclude and recommend solutions to the electric utility

1.5 Scope of the study

This thesis tries to investigate the selected distribution feeder interruption causes. The effects of the most frequent causes for the vulnerability of the existing distribution system are analyzed, and solutions that needed to be taken are proposed.

1.6 Significance of the study

Some of the importances of the thesis work are the following:

- The identified causes of the distribution system will help the utility to fix problems efficiently, in time and cost.
- Precaution could be undertaken before the distribution system failure happens.
- Reliable and quality supply of power in the distribution system could exist.
- Economic advantage for both utility and customers will be improved through reducing interruption.

1.7 Methodology

The procedures followed throughout the thesis are the following:

- **Literature review:** a number of journals, article, papers and any relevant document for the thesis are reviewed throughout the study.
- **Data collection from previous records and through site visit:** data is collected from East Addis Ababa Region (EAAR) and Kotebe substation. Also, relevant data about the problems is collected by direct survey of the distribution.
- **Data analysis:** the data collected is analyzed considering different conditions and factors.
- **Simulation:** the vulnerability to failure of the distribution component due to the effect of those factors which cause frequent interruption is simulated through appropriate software.
- **Conclusion and suggestion to the authorize body:** Summary of the study and solution are suggested.

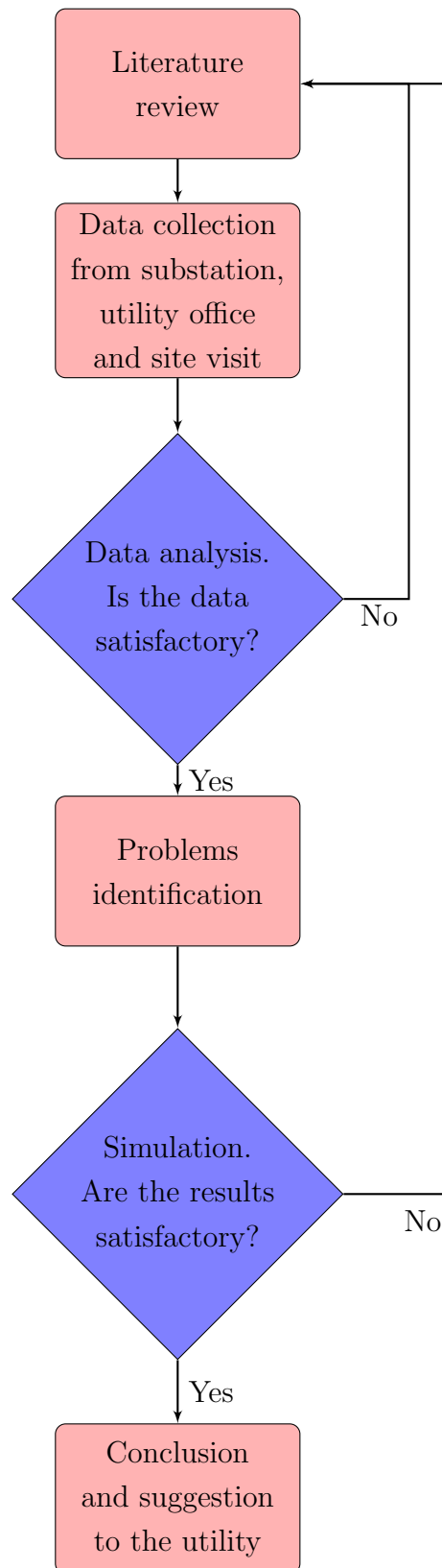


Figure 1.3: Flow chart for methodology followed throughout the thesis work

1.8 Thesis outline

The thesis is organized into five chapters.

Chapter One presents the thesis introduction, problem statements, objectives, thesis significance, and methodologies followed to complete the thesis work.

Chapter Two explains the distribution system failure causes and related equations. Also, related works to the study are included.

Under **Chapter Three**, the frequently interrupted distribution feeder selection based on the identified causes and the problems on this feeder are studied. The model of these causes for the existing distribution component vulnerability is included.

Chapter Four includes a simulation of the causes for the distribution system failure using different software and discussions of the results.

At last, **Chapter five** focuses on the summary of the study and recommended solutions to reduce the problems on the distribution.

Chapter 2

Power Distribution System Failure and Literature Review

2.1 Introduction

In this chapter, the theoretical studies related to the thesis work are discussed. The general overview of failure concept is described in section 2.2. The common causes for the distribution component failure by different researchers and influence of common causes like weather are discussed in section 2.3. Methods of analysis for loss of life of distribution transformers due to overloading is identified using different standards. The effect of lightning on the distribution transformers by different researchers is discussed in section 2.4. Also, researches done by different researchers related to distribution system failure and vulnerability are included in section 2.5.

2.2 General concept of failure

”Failure is the termination of the system or components function that it carries out” [4]. A component or system is designed to sustain regular nominal stress from the surrounding environment. Failure or breakdown of components may occur due to the increase of operational stress above the rated value.

Many factors lead to components or systems failing. Among them, tear and wear of the components, the frequency of usage, the downgraded strength and quality of the devices, weather or environmental influence, loads applied on the components structure, repair and rectification, and durability or quality of the component are the the most significant factors.

According to IEC 50(191) [5], the cause of failure is the circumstance during design, operation, or manufacturing.

- Design failure: improper and faulty design could cause sudden failure of the product or the system. This would increase the failure rate. Usually, such types of failure occur during an early stage.
- Weakness failure: it happens when the system is too weak to withstand the normal stress designed for it. Such failure occurs due to the incompatibility of the design with the operation.

- Manufacturing failure: occurs due to poor quality control of the manufacturing product.
- Aging failure: is the degradation of components over time because of the usage or age.
- Misuse failure: occurs due to improper use of the system beyond its design specification.
- Mishandling failure- happens as a result of careless operation and lack of proper maintenance.

Based on the suddenness of the condition during the failure, it can be classified as [4]:

- Drift failure: is gradual degradation with time to failure. Proper inspection helps to detect such type of failure.
- Sudden failure: is failure without any prior notice and not predicted by monitoring through regular inspection. Progressive loss or degradation is not experienced for such type of failure.

Considering the degree of failure of the system or components, it can be:

- Complete failure: is complete malfunction of the system or component.
- Partial failure: unlike the complete failure, the failed system may be useable for a short time.
- Catastrophic failure: is a combination of both complete and sudden breakdown. This is very dangerous type failure and could results loss of system and lives.
- Degradation failure: is a combination of partial and gradual failure. This can turns to a complete failure.

2.3 Distribution components failure

The component-based study requires identifying the effect during influences of different factors. The components usually considered for the distribution system study are poles, conductors, insulators, transformers, and protection devices.

Each electrical equipment on a distribution system has a probability of failing. When first installed, a piece of equipment may fail due to poor manufacturing, damage during shipping, or improper installation. Healthy equipment can fail due to extreme currents, extreme voltages, mischievous animals, severe weather, and many other causes [6].

Sometimes equipment will fail spontaneously for reasons such as chronological age, thermal age, state of chemical decomposition, state of contamination, and state of mechanical wear [3].

The sources of failures in distribution systems can be sum up to external or internal sources [7]. External sources can be in two aspects. Firstly, force majeure such as natural disasters and weather conditions. These include storms, high temperatures, hail, thunderstorms, flooding, forest fires, plants, and animal-triggered failures. Secondly, artificial faults that

includes the misuse of the system operator, control and protection system error, etc. Internal sources include components fault in distribution networks, protection and control systems failure, information and communication system failures, unstable distribution system, inadequate distribution network modeling and assessment, the vulnerability of electricity market competition, criminals' high-tech data intrusion, and tampering [7]. The vulnerability of distribution network caused by hidden fault expose when it occurs. This affects the performance of the networks to remain normal and stable supply of electricity to users.

2.3.1 Distribution poles failure

Components failure frequently incurs power outages in power distribution systems. Among the various components of the power distribution system, the poles are frequently damaged by weather-related disasters and structural deterioration [8]. Ultimately, this leads to hours to days power outages that extend for days or even weeks, depending on the intensity of a particular problem.

Thus, evaluation of the condition of poles is essential. The ability to predict potential damage to poles before the occurrence of weather-influenced disaster enables decision-makers to plan preventive maintenance operations promptly and helps to allocate resources effectively. So, it is necessary to understand the properties of wooden poles during weather influence.



Figure 2.1: Tilted pole (left side) and a tree risk for distribution system (right) (Source: photo from the study area (left side) and website (right))

Damages typically can also occur due to fungus or termite attacks, and result in various effects on the strength properties of poles. The strength of wooden poles is highly essential in resisting bending load from the top. Due to influential soil factors, the diameter and strength of poles start to decrease. These cause rotting from Center to outward or outward to Center by accelerating fungal and insect (termite) attacks. Most of the distribution poles failures are due to the decrease in peripheral dimensions below the ground level [4]. High moisture content in the soil increases the chance of biological attack. In clay soils, the moisture and chemicals are trapped inside the soil. These cause algae, moss, and mold to grow and attack the wood, which causes rapid deterioration. On the other hand, under their permeability, sandy soils allow drainage and protect from biological attack. The vulnerability of poles to decay is generally proportionate to the decay zone in which

they are located [9].

The average lifetime of treated-wood utility poles in Artvin, Turkey is typically 40 to 50 years [10]. However, the average lifetime of a treated-wood utility pole around the Eastern Black sea regions of Artvin is only about 10–15 years. Studies show that the other most significant factors affecting the service life of utility poles are the decay due to fungi, insects, inadequate impregnation, the deep cracks and splits [11, 10]. Vulnerability assessment of this component is also needed with continuous event recognition, network analysis, and decision analysis.

An assessment of the wind pressures effect is necessary to determine its influence on the distribution system components. It can be identified by analyzing:

- Wind load on the poles surface (i.e., on titled as well as normal poles)
- Transverse wind load of distribution conductors on poles
- Wind load on insulators, cross arms and other fittings

★ Effect of wind on distribution poles surface

The effect of wind can be predicted based on the angular deflection and measurement of the resilience of poles [12]. The geometry of a pole is an important parameter for designing and determining its angular deflection. The wind force (F_W) is assumed to be parallel to the ground and uniformly distributed on the poles surface. It can be expressed by [12]:

$$F_W = PA \quad (2.1)$$

Where,

P: wind pressure

A: cross-sectional area of the poles

The wind pressure (P) can be determined by;

$$P = \frac{1}{2}C\rho V^2 \quad (2.2)$$

Where,

C: is a constant usually taken as 1.0

ρ : is the density of the air (kg/m^3)

V: wind speed (m/s^2)

Area (A) of the distribution poles that the wind would act on is considered as rectangular surface;

$$A = Dh \quad (2.3)$$

Where, D is the diameter, and h is the height of poles

Thus, the wind force acting on the poles surface will be;

$$F_W = \frac{1}{2}C\rho V^2 Dh \quad (2.4)$$

The effect of wind speed has significant factor for failure of poles.

★ Tilted distribution poles

The other aspect of failure analysis is predicting wind effects for deflection of tilted poles, and measures its resilience condition. The effect of wind changes with a certain value for

tilted poles. If poles are tilted at a certain angle θ as shown in the figure below, the part of the wind force acting perpendicular to its surface would be,

$$F_{W\perp} = \frac{1}{2} C \rho V^2 D h \cos \theta \quad (2.5)$$

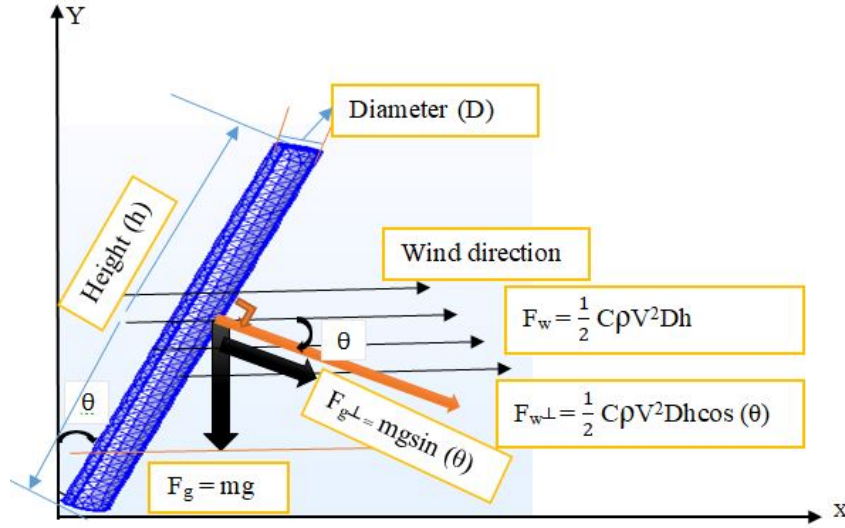


Figure 2.2: Wind load and gravitational force on tilted poles

Gravitational force also causes additional load for its failure. The gravitational force that acts perpendicular to the distribution poles ($F_{g\perp}$) is given by:

$$F_{g\perp}(\theta) = mg \sin \theta \quad (2.6)$$

Where, m is mass of the pole, g is gravitational acceleration, and θ is tilt angle of poles from the vertical position

★ Transverse wind load of distribution conductor on poles

Wind load influencing poles by swinging conductors could cause to failure. This transverse wind force applying on the poles can be calculated using the following [13]:

$$F_C = \frac{1}{2} C L D P F_{SR} \cos^2 \alpha \quad (2.7)$$

Where,

F_C : is the transverse force applied on the pole due to conductor windage,

L : denotes the span length

D : is the projected diameter of conductors

P : is the design wind pressure on conductors

C : is the drag coefficient of conductors

F_{SR} : is the span reduction factor, and

α : represents the angle between wind direction and normal to the conductors

F_{SR} can be ignored as the span lengths tended to be short, and drag coefficient (C) is always set as 1.16 [13]. Wind pressure (P) of 900 Pa is widely used by utilities for

distribution line design. Assuming the wind direction is perpendicular to the conductors, the angle α shall be 0° and the value of $\cos^2 \alpha$ would be 1.

★ Overall effect of factors for distribution pole failure

The worst conditions can be identified for the above factors that influence the distribution system, which would occur within a specific time interval. The total force (F_T) due to the above overall factors effect will be the sum of the forces indicated above.

$$\begin{aligned} F_T &= F_{w\perp} + F_c + F_g \\ &= \frac{1}{2}C\rho V^2 Dh \cos \theta + mg \sin \theta + \frac{1}{2}CLDPF_{SR} \cos^2 \alpha \end{aligned} \quad (2.8)$$

★ Decay of DP due to climate influence

Thousands of wooden poles are condemned every year due to decay [14]. Decay over time decrease the area of the pole, which can significantly reduce their strength. In practice, damages are more likely to occur at the ground level than in any other parts of the poles, and can have severe consequences. Therefore, for practical applications, it is reasonable to focus on the influence of ground-level damage for the strength of the poles.

The decay rate depends on factors such as wood type, climatic conditions (temperature, rainfall, and humidity), soil properties, initial preservative treatment, termite attack, and the nature of fungal attack [15]. Climate influence is the most significant factor for the decay of wooden poles. After 50 years of installation, the residual strength under climate change could be almost 25% less than that without climate changes [16].



Figure 2.3: Decay of distribution pole due to climate influence [17]

The equation to relate rate of decay due to climate influence is given by [18];

$$r = k_w [f(R)]^{0.3} [g(T)]^{0.2} \quad (2.9)$$

Where,

r : is the decay rate in mm/year

k_w : is wood specific parameter

$$k_w = \begin{cases} 0.23, & \text{for durability class 1} \\ 0.48, & \text{for durability class 2} \\ 0.76, & \text{for durability class 3} \end{cases} \quad (2.10)$$

$f(R)$ is a climate function considering the effect of rain fall and number of dry months, and is given by;

$$f(R) = \begin{cases} 10(1 - \exp^{-0.001(R-250)})(1 - \frac{N_{dm}}{6}), \\ \text{if } R > 250mm \text{ and } 0 \leq N_{dm} \leq 6 \\ 0, \text{ otherwise} \end{cases} \quad (2.11)$$

R is the mean annual rainfall, and N_{dm} is the number of dry months per year (i.e., months with rainfall records of below 5mm).

$g(T)$ is a climate function considering the effect of temperature, and is given by:

$$g(T) = \begin{cases} 0, \text{ if } T < 5^\circ C \\ -1 + 0.2T, \text{ if } 5^\circ C < T \leq 20^\circ C \\ -25 + 1.4T, \text{ if } T > 20^\circ C \end{cases} \quad (2.12)$$

Where, T is the mean annual temperature (in $^\circ C$)

Once the distribution poles are installed, it takes time for the decay to start. The time lag before decay start is given by [18]:

$$t_{lag} = 5.5r^{-0.95} \quad (2.13)$$

Thus, the decay depth of the poles at t year (d_t) after the decay start is calculated using the equation below [18];

$$d_t = \begin{cases} Kt^2, \text{ if } t \leq t_{lag} \\ r(t - t_{lag}), \text{ if } t > t_{lag} \end{cases} \quad (2.14)$$

Where, $K = \frac{d_0}{t_{lag}^2}$, d_0 is initial decay depth

★ Resilience condition of distribution poles considering tilt angle

The resilience conditions of poles can be determined based on their tilt angle [19]. If a pole is under healthy condition, then an immediate mitigation action is not needed. If it is in a critical condition, then an examination should follow to determine whether a corrective action must take place immediately or not. Lastly, if a pole is under unhealthy condition, then immediate corrective maintenance or complete replacement is needed.

Table 2.1: Resilience condition of distribution poles based on its deflection

Pole tilt angle range	Resilience condition
$\theta < 15^\circ$	Healthy (resilient condition)
$15^\circ \leq \theta < 25^\circ$	Critical (moderately resilient condition)
$25^\circ \leq \theta$	Unhealthy (non-resilient condition)

2.3.2 Distribution conductors failure

The reliability of overhead lines is affected by different factors. A high current is one factor. It is a common cause of lines sag, which reduces ground clearance and increases the probability of phase conductors swinging into contact. It can cause conductors to anneal, reducing tensile strength and increase the chance of a break occurring [20]. Fault currents, if not cleared fast enough, can cause conductors to fuse and burn down. The standard current rating of overhead lines is often limited by phase to ground clearances. Ambient temperature increases can also elongate conductors based on their coefficients of thermal expansion. This expansion will cause lower sags and may result in unsafe clearances.

Due to thermal properties, the conductor sag will not occur instantaneously [21]. Each line has its thermal time constants, allowing temporary overloading without sag concerns. If not cleared fast enough, short circuit currents can cause conductors to melt and fall to the ground. The short circuit current depends upon clearing time, conductor resistance, thermal capacity, initial temperature, and fusing temperature.

2.3.3 Distribution insulator failure

For the U.S. and many parts of the world, insulator breakdown is one of the leading causes of power distribution failure [22]. Such failures are known to seriously affect power supply reliability, resource utilization, and customer satisfaction. Insulator failures are associated with dielectric breakdown. A dielectric breakdown of insulators allows current to arc across the device. Sometimes these current will be small or self-extinguishing. It can lead to a low impedance arc with time, resulting in a short circuit and a potentially catastrophic failure of insulators.

Insulators can lose dielectric strength when exposed to contamination such as industrial pollution, salt fog, and dust from the environment [8]. Dielectric strength gradually decreases with contamination, and highly contaminated insulators under wet conditions may be likely to flashover. In general, the causes of the failure of insulators can be:

- Insulator cracking: cracking is caused by unequal expansion and contraction stress of seasonal heat cold, dryness, and dampness or heating of the insulators.
- Defective of materials: if the material is defective anywhere, it will puncture and become unfit for further use.
- Porosity of materials: porcelain manufactured at lower temperatures will absorb moisture from the air or cement and becomes porous.
- Improper glaze: if the material is not properly glazed, the water will stick to it, which will result in the deposition of dust. This reduces the flashover distance and causes the insulators to damage.
- Flashover: If there is a flash from one metal part to other, it will cause over-heating and shattering.
- Mechanical Stress: The pulling of insulators may sometimes cause mechanical stress for it.

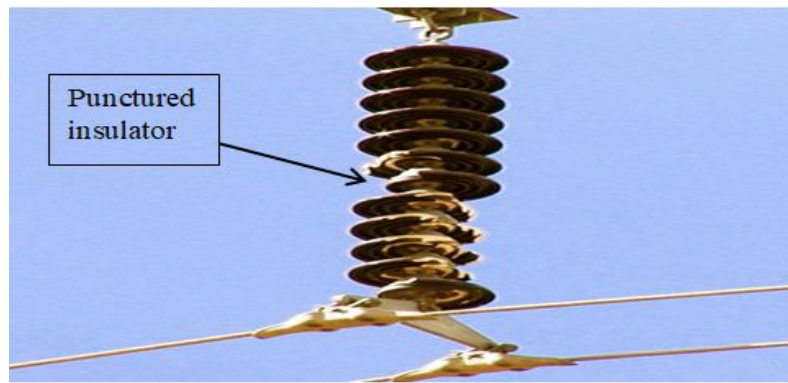


Figure 2.4: Damaged insulator due to flash over

2.3.4 Distribution transformers failure

Transformers influence distribution system reliability in two related ways: failures and overloads. Transformers failure can result in interruptions to many customers. It could occur due to different factors. Overload is one of the typical causes, which results in the loss of transformers' life. The distribution system may supply the customers for the moment while the distribution transformers are working overloaded. But the probability that the overloaded transformers will lose its life at a future date would increase rapidly. The failure of transformers can also occur due to different factors like poor protection devices and accessories failure. Failures associated with these components reduce the ability of transformers to function properly, and in due time cause them to fail.

- **Silica jelly**

A silica gel is used for filtering air from moisture during the breath in of the transformers. Silica gel crystal has a tremendous capacity for absorbing moisture. When air passes through these crystals in the breather, it could absorb the air moisture. Therefore, the air that reaches the conservator is quite dry.

The too much absorption of moisture in silica gel breather tends it to stop working. It will be useless as the transformers will not be able to absorb any moisture in the transformer. As a result, the insulation in the transformers will be potentially harmed.



Figure 2.5: Color of silica jelly before and after absorbing excessive moisture

- **Oil leakage**

The other problem is leakage for oil-immersed transformers. Once leakage happens, the insulation level reduces. This causes a short circuit and reduces the life of transformers. Oil leakage can occur due to different factors, such as:

- Ageing and corrosion which result in cracking
- Quality of transformers manufacturing
- Improper installation and other factors
- **Protection device**

Protection devices used in the distribution transformers are usually dropout fuse and surge arrester at the high voltage (HV) side and high rupturing capacity (HRC) fuse at the low voltage side. Earthing wire is also used for safety and protection. Dropout fuse and lightning arrester protect over current and lightning surge coming from the supply side from damaging the transformers. On the other hand, HRC fuses help to protect the customer from excessive current damage. The absence or failure of these devices could result in damage to transformers and customer equipment.

- **Transformers cooling**

No transformer is an ideal, and hence each will incur some losses, most of which get converted into heat. If this heat is not dissipated properly, the excess temperature in the transformer may cause serious problems like insulation failure. Most of our country's MV distribution transformers used oil-immersed type cooling. There are different types of oil-immersed transformers cooling [23].

- i. Oil Natural Air Natural (ONAN)
- ii. Oil Natural Air Forced (ONAF)
- iii. Oil Forced Air Forced (OFAF)
- iv. Oil Forced Water Forced (OFWF)

- **Oil Natural Air Natural (ONAN)**

In this method of cooling, the heat generated in the core and winding is transferred to the oil. According to the principle of convection, the heated oil flows in the upward direction and then in the radiator. The vacant place will fill with cooled oil from the radiator.

The heat from the oil will dissipate in the atmosphere due to the natural airflow around the transformer. In this way, the oil in the transformer keeps circulating due to natural convection and dissipating heat in the atmosphere using natural conduction. This method is used for transformers up to 30 MVA [23]. Most of the distribution transformers found in EEU have this type of cooling. Thus, the parameters of ONAN are used for the study.

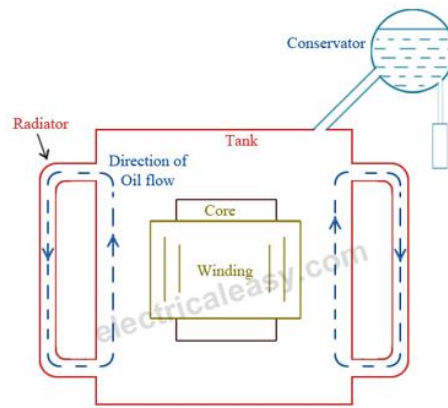


Figure 2.6: Oil natural air natural (ONAN) cooling system

- **Oil Natural Air Forced (ONAF)**

The heat dissipation can be improved further by applying forced air on the dissipating surface. Forced air provides faster heat dissipation than natural airflow. In this method, fans are mounted near the radiator and may be provided with an automatic starting arrangement, which turns on when temperature increases beyond settled value. This cooling method is generally used for large transformers up to about 60 MVA [23].

- **Oil Forced Air Forced (OFAF)**

For this type of cooling, oil circulates with the help of a pump and will be forced to flow through heat exchangers. Then compressed air flows on the heat exchanger with the help of fans [23]. The heat exchangers may be mounted separately from the transformer tank and connect through pipes at the top and bottom. This type of cooling provides for higher rating transformers at substations or power stations.

- **Oil Forced Water Forced (OFWF)**

This cooling type is similar to the OFAF method, but the forced water flow helps to dissipate heat from the heat exchangers. The oil will be forced to flow through the heat exchanger with the help of a pump. The heat will dissipate in the water while forced to flow. The heated water will be taken away to cool in separate coolers. This type of cooling is used in very large transformers having a rating of several hundred MVA.

2.3.5 Loss of life of distribution transformers due to overloading

One cause for the vulnerability of distribution transformers is overloading above its capacity. Loading has a significant influence on transformers' life and is a typical aspect of distribution reliability problems. Overloading causes the insulation to become sufficiently brittle, which will result in insulation failure and an internal transformers fault.

About 49% of the distribution transformers' failure in the East Addis Ababa Region (EAAR) is due to overloading [24]. The overall life expectancy and overloading capabilities of transformers depend on several factors. Load cycles, ambient conditions, future load growth, and possible overloading uncertainties are significant factors that affect the transformer's life. The utility should evaluate the remaining life of the existing transformers due to these factors, together with economic evaluation.

★ Loading data and hottest spot temperature

An important method to determine the hotspot temperature is by using the transformers' thermal model or calculation method. Calculation of the internal transformer's temperature (hotspot temperature) is a complicated and very difficult task. However, generally accepted methods simplifying assumptions for calculating the temperature of power transformers are applicable in IEEE standard (C57.19-1995 [25], C57.91TM-2011 [11]) and IEC 354, 1991 standard. Using these standards, the hotspot temperature can be determined having the historical loading and ambient temperature profiles. The life of transformers can be predicted from the calculated temperature.

The IEEE Std. C57.91TM-2011 [11] guide for loading oil-immersed transformers is used for the study, and the top oil hottest spot temperature (T_{HS}) is assumed to consist of three components given by the following equation:

$$T_{HS} = T_A + \Delta T_{TO} + \Delta T_H \quad (2.15)$$

Where,

T_A : is the average ambient temperature, (in $^{\circ}C$)

ΔT_{TO} : is the top-oil rise over ambient temperature, (in $^{\circ}C$)

ΔT_H : is the winding hottest-spot rise over top-oil temperature, (in $^{\circ}C$)

The top oil rise is the top-oil temperature above the ambient temperature.

$$T_{TO} = T_A + \Delta T_{TO} \quad (2.16)$$

The Top oil temperature rise due to over loading is calculated using the following equation.

$$\Delta T_{TO} = \Delta T_{TOR} \left[\frac{K^2 R + 1}{R + 1} \right]^n \quad (2.17)$$

The winding hottest-spot rise over top-oil temperature (ΔT_H) is also given by:

$$\Delta T_H = \Delta T_{HR} K^{2m} \quad (2.18)$$

Where,

ΔT_{TOR} : is the top-oil rise over ambient temperature at rated load, (in $^{\circ}C$)

K: per unit loading (actual load/rated load)

R: loss ratio (load loss at rated load/no load loss)

n: is an empirically derived exponent used to calculate the variation of ΔT_{TO} with change of load

ΔT_{HR} : is the winding hottest-spot rise over top-oil temperature at rated load

m: is an empirically derived exponent used to calculate the variation of ΔT_H with changes in load

★ Transformer ageing acceleration factor

Ageing acceleration factor (F_{AA}) is the degree to which the rate of aging is accelerated above the standard reference temperature of 110 $^{\circ}C$.

Aging or deterioration of insulation is a time function of temperature, moisture content, and oxygen content. Since the temperature distribution is not uniform in most apparatus, the part which operates at the highest temperature will ordinarily undergo the highest

deterioration. In aging studies, it is usual to consider the effect of the highest (hottest-spot) temperature [25].

The per-unit transformer insulation life is the basis for the aging acceleration factor (F_{AA}) of a given load and temperature [11].

$$\begin{aligned} \text{Relative ageing acceleration factor}(F_{AA}) &= e^{\frac{15000}{383} - \frac{15000}{T_{HS}+273}} \\ &= e^{39.1645 - \frac{15000}{T_{HS}+273}} \end{aligned} \quad (2.19)$$

According to the standards [11, 25], the (F_{AA}) for transformers to operate continuously should be less or equal to one. It can be used to calculate equivalent aging of transformers.

★ Percent loss of life of transformers

Percent loss of insulation life for a given period is the equivalent hours of life consumed divided by the definition of total normal insulation life (T) and multiplied by 100 [25].

Using F_{AA} , the percent of loss of life for transformers can be determined using the following equation.

$$\% \text{ loss of life} = \frac{TF_{AA}}{\text{Normal insulation life}} 100 \quad (2.20)$$

Distribution and power transformer model tests indicate that the standards life expectancy at a continuous hottest-spot temperature of 110°C is 180,000 hours (i.e., 20.55 years) [25].

The standard % loss of life for transformers to operate continuously is 0.0133%.

Its F_{AA} should be one or less. Otherwise, the percent of loss of life would be higher, and its life would be below 20.55 years.

2.4 Distribution system failure due to lightning

Lightning strikes can cause permanent damages to distribution components. Insulated conductors coating prevents the high surge current from moving along the line, and therefore a flashover between phases for such lines may cause a mechanical breakdown of the conductors. Its effect for distribution transformers is higher.

The Lighting effect can be associated with its distribution around the study area. The distribution varies within every second in different parts of the world. In Ethiopia, lightning

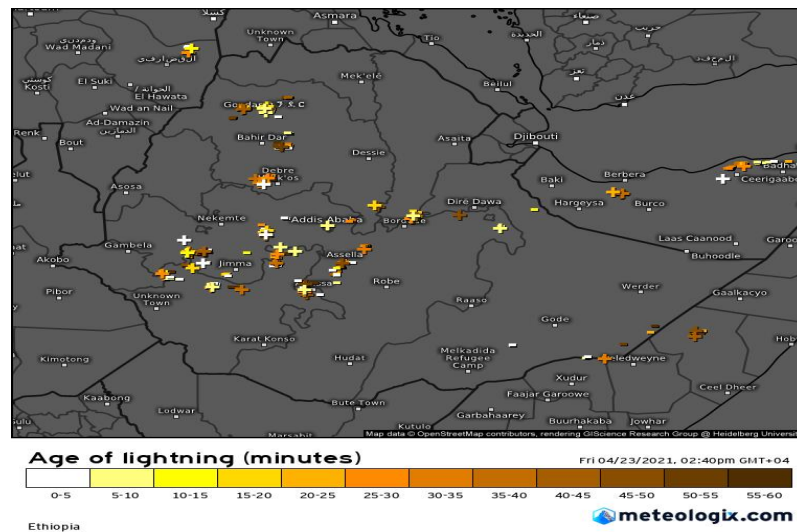


Figure 2.7: Lightning distribution in different areas of Ethiopia [26]

distribution varies from place to place. From the website data of international lightning recorders, the lightning level at the selected site for a certain time record is 44kA [26]. A certain times record of lightning distribution at different areas from the website is shown in figure 2.7.

Lightning caused distribution system failure is a usual problem in the Addis Ababa distribution system. Its effect on distribution transformers is common in the city. Previous studies on East Addis Ababa Region(EAAR) indicates that lightning caused failure during the summer season accounts for more than 17% of the summer transformers' failure [24]. The absence and poor functioning of protective devices are commonly stated as a cause. The lightning characteristic is usually represented by the Heidler equation, which has greater acceptance to represent it [7].

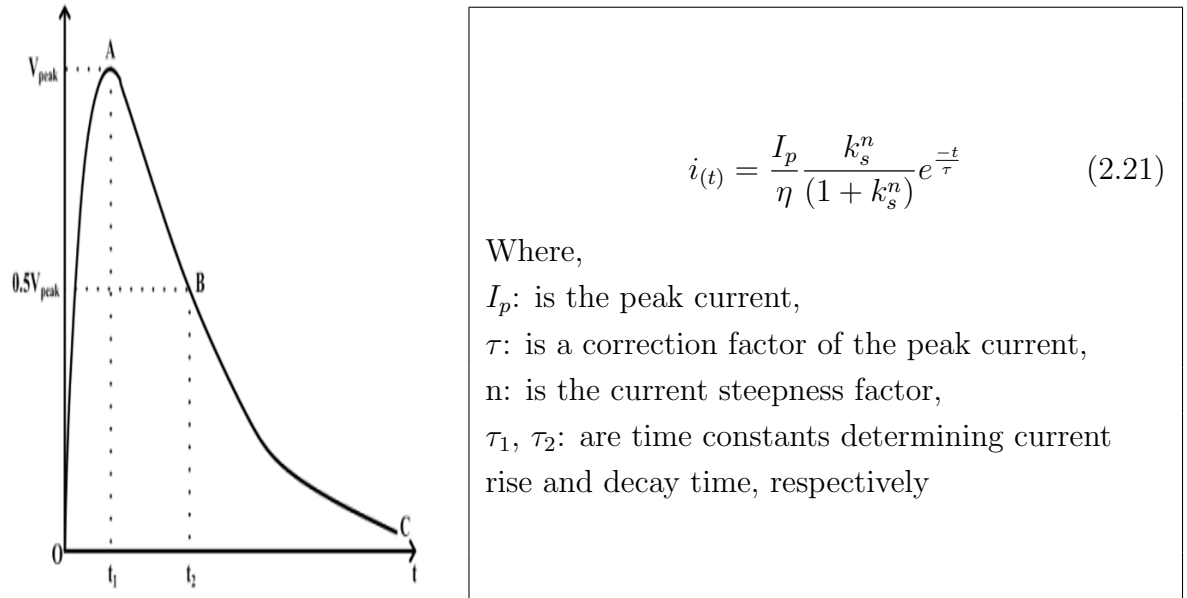


Figure 2.8: Characteristics of lightning using Heidler equation

The wave shapes of lightning current basic parameters indicated at the graph above are time instants to reach its peak value t_1 and the front duration (t_2), where the lightning fail above 50% of the peak current.

Lightning surge magnitude depends on the natural lightning level during strikes, the resistivity of soil, and the distance of strike from the equipment. The surge capability of the surge arrester is affected by the soil resistivity of the environment, the rod size used for grounding, and the arrester quality. For the study, the effect of lightning on distribution transformers considering these factors is simulated with Matlab/Simulink.

★ Soil resistivity effect for lightning surge magnitude

Soil resistivity is a basic factor that affects lightning surge magnitude. High grounding impedances can result in increased voltages surge and severe effects on distribution components.

The types and sizes of ground electrodes needed to achieve the required footing impedance have to be studied before installation since the resistance of the soil depends on electrode

sizes and the type of rod.

The grounding resistance (R_g) can be modelled by a concentrated resistance. It is a function of the soil resistivity ρ_{earth} in ($\Omega.m$), electrode length l (m) and radius α (m) and can be obtained using the following equation [16].

$$R_g = \frac{\rho_{earth}}{2\pi l} \left[\ln\left(\frac{4l}{\alpha}\right) - 1 \right] \quad (2.22)$$

2.5 Literature review

The causes of distribution system failure are usually related to environmental conditions, infrastructure, utility management problems and etc.

Many scholars studied distribution system failure causes and associated problems. Few of the related works to this paper are included.

According to O. A. Quiroga [2] investigation, atmospheric influences are the most important causes of overhead feeders failure and can result in mechanical damage to the distribution components. Aging is another significant cause of failures for underground feeders. Li Wang's [3] study indicates that overhead line fault is usually related to weather conditions in Nordic countries. The tree-caused faults are more frequent under high wind conditions. The animal-caused interruption is common in North America, which commonly happens during spring.

A study by C.M. Chu [27] on distribution system failure considering regional effects shows that the failure rate around the industrial area is highest because of load level and pollution by soil. Also, the failure rate around remote areas is lowest for open conductor wires. William F. [28] study on Pacific Gas and Electric Company (PG and E) shows that loss of power service can occur through failures of components, external factors, and order of a loss of supply for operation. Weather-related events, such as ice, high winds, flooding, and lightning strikes cause about 78% of the major power interruptions in the U.S. power distribution system [29].

Wilson A. [30] research illustrated that loading and weather circumstances could have greater influence on the aging failure probability of overhead conductors if the conductors' temperature is higher than the maximum standard operating temperature. The unavailability of overhead conductors increases as the maximum continuous operating temperature is exceeded. E. D. Gezer [10] study in Turkey show that the service life of utility poles is affected by fungi attack, insects, inadequate impregnation, deep crack and splits. Also, Paraic C. [31] identified that distribution poles are vulnerable to climate changes like wind speeds, rainfall and temperature. Rainfall and temperature could accelerate timber decay, which affects the residual capacity of timber poles.

The common insulators failure forms are the failure of sheds and sheaths, brittle and decayed fracture of cores. The fracture of insulators core has a greatest threat for the efficient operation of lines [32]. Insulator failures initiates when leakage currents flow over a wet contaminated surface. This current may self-extinguish, continues periodically, could increase and become destructive high-current flashover [22].

Transformers overloading would results in rapid aging. The rate of the transformers thermal breakdown approximately doubles for every $10^\circ C$. The insulation become brittle and the next fault current that passes through the transformers will mechanically shake the

windings. Thus, crack will form in the insulation and internal fault will results [33]. There is no generally accepted definition of the concept of vulnerability. It can be stated as a condition of missing inadequately administered safeguard or control that allows a threat to occur with a higher impact or frequency [2]. It can be the condition of components' susceptibility to failure. It helps to describe the collection of properties of an infrastructure system that may weaken or limit its ability to maintain its intended function or services when exposed to threats and hazards that originate both within and outside of the system boundaries [34]. The physical vulnerability which indicate degree of loss of components and supply interruption due to external factors is the basic concern of this thesis study. Vulnerability assessment helps to allocate resources more cost-effectively, increase reliability, and decrease the risk of severe events. It also helps to understand threats better, determine acceptable levels of risk, and stimulate action to mitigate identified vulnerabilities [35]. The direct benefits of performing a vulnerability assessment include; build and broaden awareness, establish or evaluate against a baseline and develop quick responses. Different approaches can be used for vulnerability assessment like network architecture study, environment threat analysis, testing existing systems, physical analysis, risk calculation, and others. Utilities should routinely perform vulnerability assessments to decrease identified risks.

In general, the problems considering different areas indicate that various factors can be stated for the causes of distribution system failure. From the review on the study of the power distribution components failure, it is not common practice in Ethiopia as well developing countries to assess the problems and analyze the factors affecting the distribution system. This could affect the value of future expansion, and other solution measures need to be taken. The study is thus to address these identified gaps.

Chapter 3

Data Collection and Failure Analysis of Kotebe Distribution System

3.1 Introduction

In this chapter, general description about Kotebe substation is discussed in section 3.2. The frequency and duration of interruption for analyzing the probable causes of the distribution system failure is included in section 3.3. The data collected for the distribution system interruption causes are analyzed in section 3.4. The component condition are inspected and the problems associated to each components are identified in section 3.5. Based on the problems identified, methods to analyze the vulnerability are discussed.

3.2 Kotebe distribution substation

Kotebe substation is one of the six East Addis Ababa Region (EAAR) substations. The substation supplies eastern parts of the city (i.e., Yeka and Bole sub-city) and few areas outside the city. The substation has a large capacity with new and old partitions. It can supply 100MVA and 47.5MVA through new and old substations to the MV distribution system, respectively.

- **New Substation**



Figure 3.1: Kotebe substation

The new substation has a large capacity with double 230kV lines incoming supply from Legatafo substation. There are two 230/132kV autotransformers having 125MVA ratings and two power transformers with 50MVA ratings each. Two 132kV outgoing lines from the autotransformers supply the Addis East (I and II) and Kotebe new and old substations.



Figure 3.2: New substation transformers

Nine 15kV outgoing feeders from the two 50MVA power transformers supply the distribution system. Also, control and protection devices used in the substation are identified.

- **Old substation**

It has incoming supplies from Kaliti I and the new Kotebe substation with 132kV. Currently, two power transformers with 132/15kV of 31.5MVA rating and 132/33kV of 16MVA rating are in use.

Six 15kV and three 33kV outgoing feeders are installed from 132/15kV and 132/33kV transformers respectively. But only four feeders with 15kV and one feeder with 33kV are supplying.

In general, the components in the substation are working good for both control and protection functions. Thus, trying to study the interruption causes considering substation components problem is not far essential. The interruption is mostly due to the distribution system. So the study focuses on possible causes of failure on the outgoing feeder components.

3.3 Frequency and duration of interruption

The causes of the distribution system failure can be visualized using the interruption records. Monthly variation of interruptions are vital indicator of the probable causes for the failures.

As shown from the figure 3.3, interruptions during May and June are highly frequent. Two basic things can be considered for the interruption. Firstly, during the data collected year, there was a shortage of water supply at the hydro-power generation, especially on May and June. Thus, there was load shedding that accounts for many of the interruptions. The other one is during summer and spring there is rain, associated wind effect, and other natural phenomenon. Thus, the weather effect can be considered as the factor for the interruption.

The study focuses on component-based failure analysis by selecting the most frequently

interrupted feeder. Thus, a specific feeder needed to be selected. It is selected based on the frequency of interruption from the network.

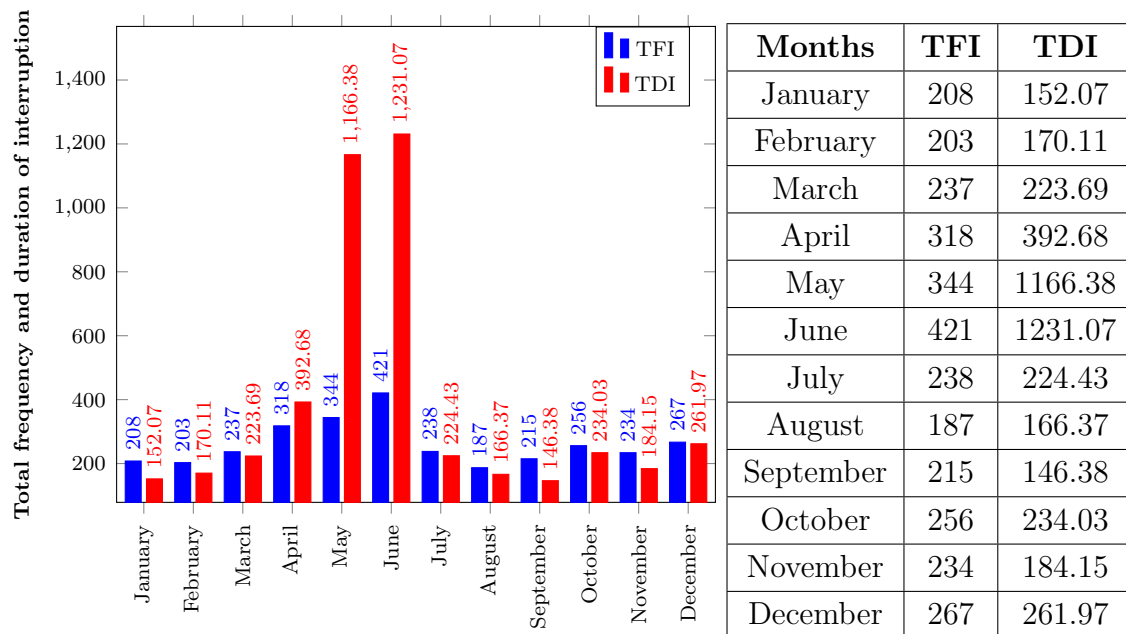


Figure 3.3: Monthly frequency and duration of interruptions (September 2018-August 2019)

TFI: Total Frequency of Interruption, **TDI:** Total Duration of Interruptions

TFI and TDI indicates the total annual frequency of interruption and total annual duration of interruption for the Kotebe substation respectively.

- **Total frequency and duration of interruption for Kotebe substation feeders**

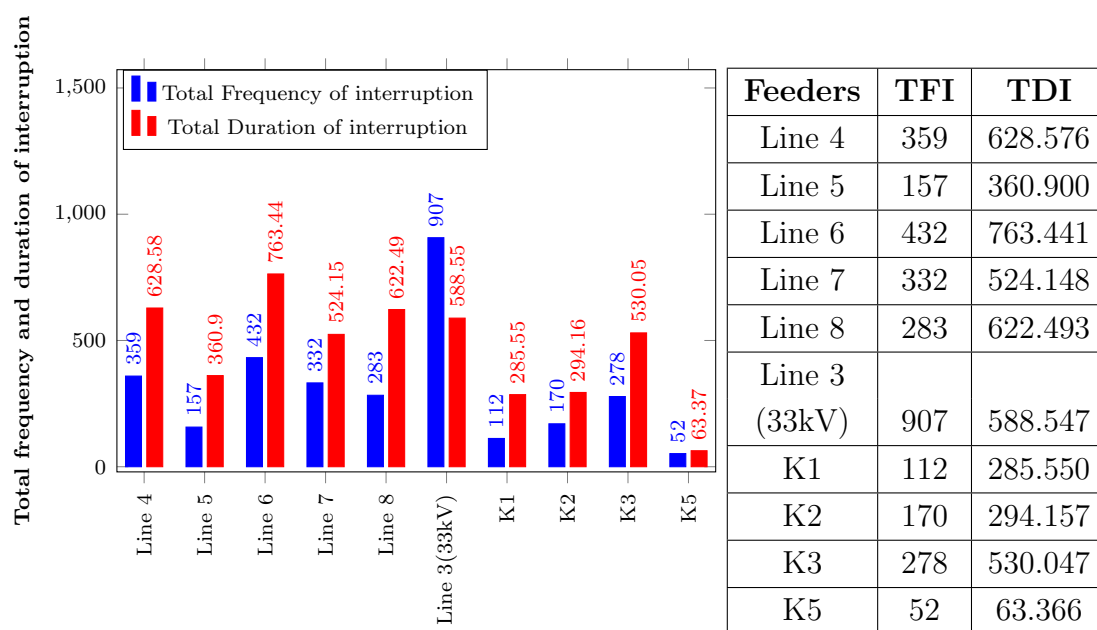


Figure 3.4: Frequency and duration of interruption

From the data shown above, line 6 (Kotebe 6) and line 33 (Kotebe 33) feeders are the most frequently interrupted lines. The study is to focus on the problems in the city, Addis Ababa. Kotebe 6 feeder supplies in the capital around the Ayat zone and CMC. But Kotebe 33 supplies outside Addis Ababa, around North Shewa, Sheno and Sendafa areas. Thus, feeder 6 of Kotebe substation is selected for the component-based study of the distribution system failure as a case study.

3.4 Causes of Kotebe distribution system failure

The job trend at the substation is after a fault happens and the breaker opens, the operator tries to close it once by first calling towards Menesha (i.e., EEU maintenance workers to EEP substation aggregators). If it holds, the fault is transient, and it would be difficult to know its causes. If it opens automatically, the fault will be recognized as permanent, and maintenance will be done. The location of the permanent faults will be accessed through customer calls. After maintenance, the operation will be reported to the utility office and Menesha as well. The overall work flow of the EEU during interruption is summarized as shown below.

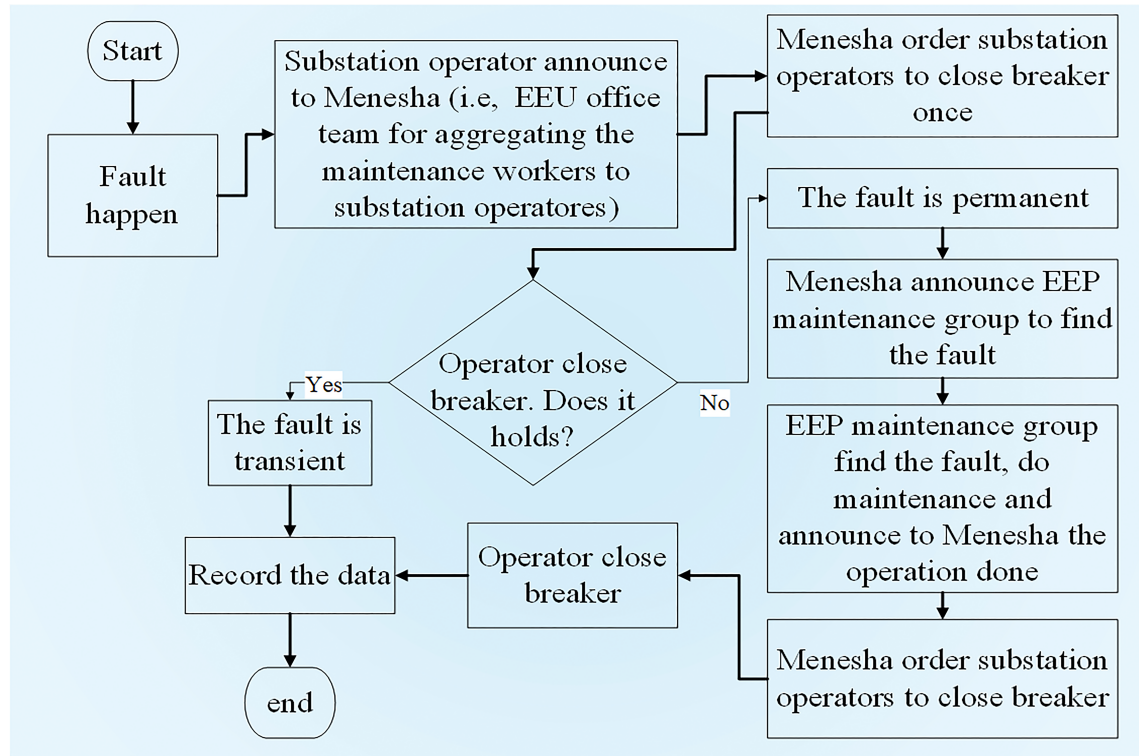


Figure 3.5: Block diagram of work flow in EEU during interruption

The causes identified used for the study are the data from the maintenance reports. The causes of distribution system failure in the region are summarized as shown in figure 3.6. From the data, it can be shown that many of the interruptions are due to operation and maintenance, weather influence, and accidents.

The weather influences are rain, wind, and lightning. They are among the most common identified causes of interruption. Above 48.6% of the known failures causes excluding interruption due to operation, and 25.3% of the known failures including interruptions due to operation, are caused by weather influences. Usually, while there is rain or wind in the

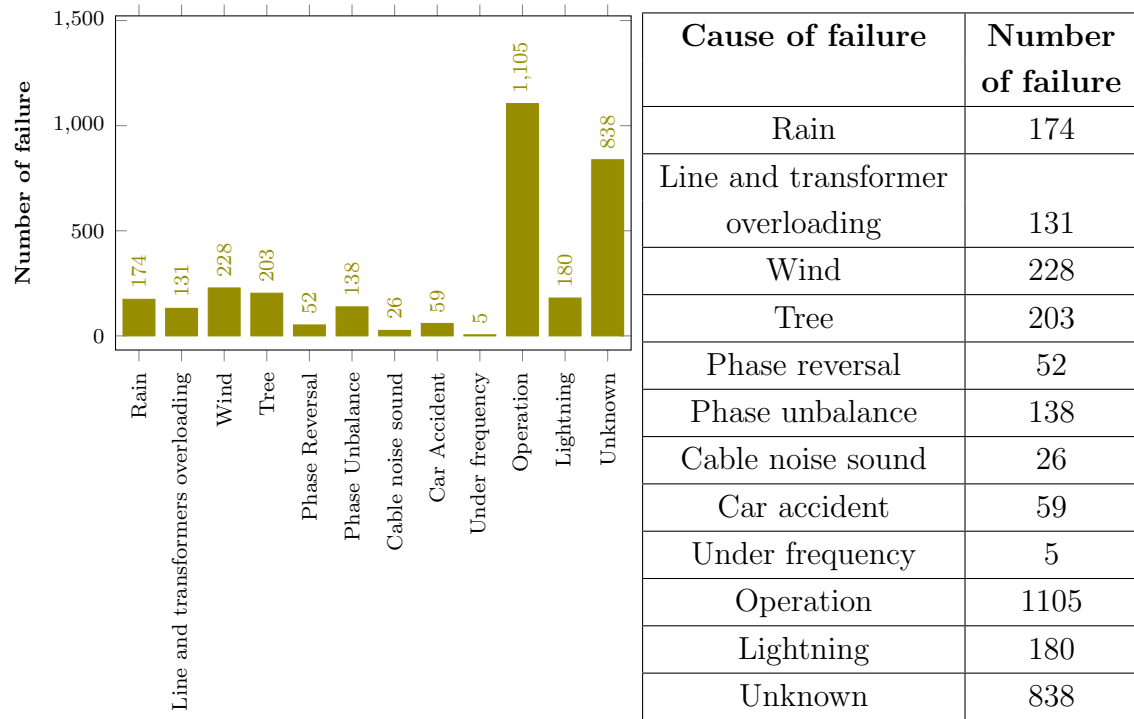


Figure 3.6: Causes of Kotebe distribution system failure

city, there is an interruption.

A lightning strike is the other factor for failure during the summer season. It accounts for 15% of the total known failure causes, excluding interruption due to operation.

Overloading is identified as a significant factor in distribution failure. Its effect on the distribution transformers is studied with special consideration.

Trees endangering the distribution line are causes of interruption, especially during windy weather. Other miscellaneous causes are also identified for the interruptions.

The interruptions can be minimized if the utility components could withstand simpler problems. But the infrastructure is too weak to withstand even simpler disturbances. Thus, the study emphasizes the influences of weather considering the distribution component vulnerability and failure. Its effect is simulated using appropriate software.

3.5 Distribution components inspection and analysis

3.5.1 Distribution poles failure

The selected feeder (i.e., feeder 6 of Kotebe substation) covers over 24km distance. During the inspection, around 705 poles are assessed in this feeder. The data collected from pole inspection includes;

- Poles type used
- Condition of poles (tilted or not)
- Cracking condition
- Guy wire condition

- Earthing wire condition
- Poles foundation condition
- Tree endangering the distribution feeder

- **Types of poles**

The types of poles used for the EEU distribution are wooden, concrete, and steel. Wooden poles are widely used in the distribution. About 629 poles of feeder 6 are wooden type (i.e., about 89% of the total poles). They are timbers species mostly imported from Australia. Since its cost is low compared to the other, wooden poles are usually used by the utility company. But its strength and natural property make it not to be used beyond a few years. Concrete poles are also used in some areas of the feeder. Around 76 poles are concrete type. Steel-type poles are not employed for the selected feeder.

- **Tilted poles**

During inspections, poles that are tilted and endangering the distribution system are identified. Tilted poles are highly prone to failure since continuous weather and other external influence on the distribution feeder can easily cause interruption. As the feeder is radial, a failure of a single-pole or any component can result in an hour to days interruption. Around 328 poles are tilted, which need exigent maintenance or replacement.

- **Cracked poles**

Weather, manufacturing defect, and other associated factors can cause poles to crack. Cracking causes rapid decay and failure of the distribution poles. It can also cause earth fault during raining. About 281 of the feeder poles have cracking problems.

- **Guy wires**

The other problems for the distribution system are the absence of guy wire. Distribution poles with no guy wire have stability problems. About 92 poles have no guy wire.

- **Foundation problem**

A poor foundation could cause stability problems for poles, which causes poles to tilt and become more vulnerable to failure with simple disturbance. About 333 poles are identified with bad foundation problems.

- **Tree clearance**

As indicated above, trees are common causes of distribution network failure. Improper clearance distance from trees is commonly identified problem. Simple disturbance can cause short circuits or earth faults to the distribution system. About 62 poles need tree clearance maintenance.

★ Location of poor distribution poles

From the data noted above, wooden distribution poles with both tilted and poor foundations are identified. Typical poles with these problems are 205. Special attention needs to be given to cracked, poor foundation and tilted wooden poles to take serious measures. About 149 poles are inspected with these problems. Using GPS data, the area where these poles are located is inspected and depicted using 3d Google map, as shown in figure 3.7. Locating and visualizing those poles with the problems helps to make it easy for quick repair and maintenance. Also, the area that EEU should give more attention for



Figure 3.7: Location of cracked, poor foundation and tilted wooden poles around CMC and Ayat area

rehabilitation or other solution studies can be identified easily.

Table 3.1: Summary of distribution poles inspection data

Inspection type	Number of poles	(in %) from the total 705 poles
Wooden pole	629	89.22%
Concrete poles	76	10.78%
Tilted poles	328	46.52%
Cracked poles	281	39.86%
Poor guy wires	126	17.87%
Danger tree	62	8.79%
Bad foundation poles	323	47.09%
Tilted and poor foundation wooden poles	205	29.08%
Tilted, cracked and poor foundation wooden poles	149	21.13%

Most of the poles are wooden type. Thus, specifications of wooden pole types are used for the study. From the identified problems, the condition of the tilted poles is one of the most serious issues. The vulnerability of these poles is included in the study. The existing conditions of the distribution components are used for the study.

★ Distribution poles failure considering weather

Using the identified most frequent weather influences, the failure of distribution poles is studied. The weather data is collected from the National Meteorology Agency (NMA). Five years of wind speed, precipitation (rainfall), and temperature data are collected. Using the data, the effects of these factors on tilted and not tilted poles are investigated. For the study, the factors considered for distribution poles failure are:

- Effect of wind acting on the surface of poles
- Gravitational force of tilted poles
- Transverse wind load of distribution conductors on poles

The sum of the factors indicated above is considered for the distribution poles failure. The procedures followed for the study are indicated using the block diagram shown figure 3.8.

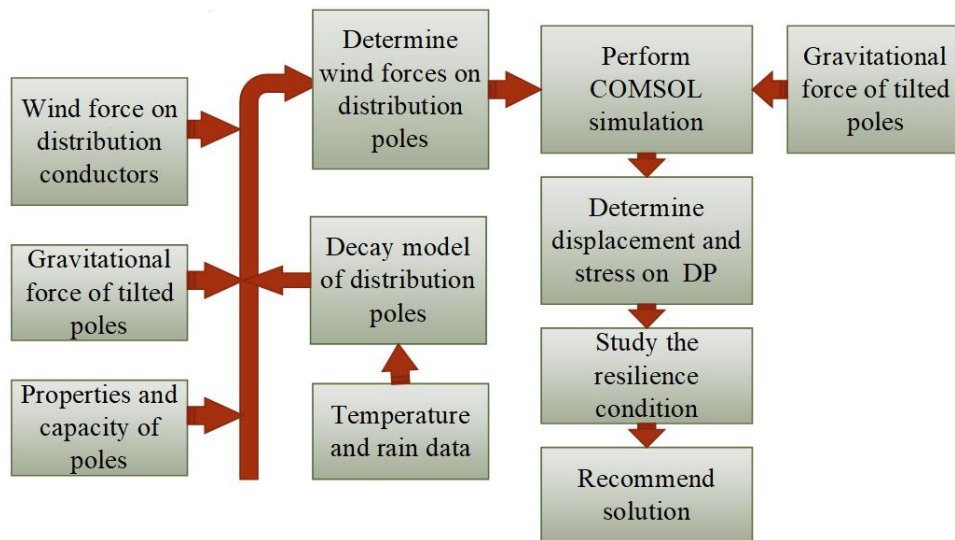


Figure 3.8: Illustration of the procedure for distribution poles failure analysis

★ Weather data and decay depth modeling

The five years weather data of the region is collected from the NMA station of Bole areas since the feeder supplies areas around CMC and Ayat zone of the city. The five years mean monthly and annual temperature of the area records are indicated as shown below.

Table 3.2: Mean annual and monthly temperature ($^{\circ}C$)

Months	2015	2016	2017	2018	2019	Average temperature ($^{\circ}C$)
January	16.05	16.00	15.55	16.15	16.10	15.97
February	18.30	18.25	18.20	17.55	18.70	18.20
March	19.15	19.16	19.50	18.40	19.40	19.12
April	19.00	19.35	19.45	18.50	18.	18.96
May	25.20	18.60	18.95	18.60	18.10	19.89
June	18.45	17.95	18.85	17.30	17.30	17.97

Table 3.2 – *Continued from previous page*

July	17.80	17.05	17.15	16.50	17.40	17.18
August	22.10	16.95	16.95	16.50	18.30	18.16
September	17.60	17.35	17.00	17.55	17.90	17.47
October	18.25	17.25	17.40	17.45	17.60	17.59
November	17.70	16.40	16.25	16.60	16.75	16.74
December	16.70	15.35	14.85	16.45	16.50	15.97
Average	18.86	17.47	17.51	17.30	17.71	17.77

The monthly average temperature varies from 15.97°C to 19.87°C . The annual mean temperature of the study area is 17.77°C .

The maximum and mean wind speed records of the area are 20m/s and 3.76m/s at 10 meter height, respectively. The effect of the worst condition of wind speed is considered for the study.

The decay of wooden poles is a function of both rainfall and temperature. The mean monthly and annual rainfall data is indicated as shown in the table below.

Table 3.3: Mean monthly rainfall data (2015 - 2019 G.C)

Months	Mean monthly rainfall data (mm/month)
January	0.0
February	10.3
March	46.4
April	106.3
May	125.4
June	121.5
July	243.8
August	275.3
September	154.4
October	18.6
November	2.5
December	0.4

The decay rate will be lower as the number of driest months increases and vice versa. The monthly rainfall data helps to indicate the driest months of the region. The dries months are the rainfall record of below 5mm/month [18]. From the data, November, December, and January are the dries months.

Table 3.4: The five years annual rainfall data

Years	Annual rainfall data (mm/year)
2015	1286.2
2016	908.5
2017	1042.1
2018	1205.4
2019	1358.4
Average rainfall	1160.12

- **Force calculation**

Tilted poles above 25^0 are considered as non-resilience [19]. Maintenance is difficult for poles above 25^0 tilt angle. Thus, the study considers the effect of weather for tilted poles with angle 0^0 to 25^0 ranges. The following assumptions are considered during the study.

- Uniform distribution of wind on the surface of poles
- The wind direction is considered parallel to the earth surface
- The direction of wind applied on distribution conductor (F_c) for the transverse force on the poles is assumed to be perpendicular to conductors.

The force of wind ($F_{w\perp}$) for poles height of 10.4m is calculated by considering the assumption indicated above (i.e., 1.6m is embedment to the ground). The tilt angle of each pole is roughly inspected using a camera angle meter as each pole tilt angles is not indicated by utility workers during the inspection. There are many poles with higher tilt angles. Also, the above NMA data are used. The number of conductors is considered for the effect of the transverse wind effect.

Table 3.5: Force on distribution poles considering different factors

Tilt angle (θ)	Force (N)			
	Wind force on poles surface $F_{w\perp} = \frac{1}{2}C\rho V^2 Dh \cos \theta$	Transverse force of conductor $F_c = \frac{1}{2}CLDPF_{SR} \cos^2 \alpha$	Gravitational force of tilted pole $F_{g\perp}(\theta) = mg \sin \theta$	Total Force (N)
0^0	781.25	2114.1	0	2895.35
5^0	778.27	2114.1	353.11	3245.48
10^0	769.38	2114.1	703.54	3587.02
15^0	754.63	2114.1	1048.61	3917.34
20^0	734.13	2114.1	1385.70	4233.93
25^0	708.05	2114.1	1712.25	4534.4

• **Decay depth model of the distribution poles**

Modeling in-ground decay of wood poles is essential for predicting vulnerability and deciding inspection and maintenance. The decay rate (r) of wooden poles is a function of the temperature, rainfall, and wood property (from eq 2.8):

$$r = k_w [f(R)]^{0.3} [g(T)]^{0.2}$$

k_w is selected 0.76 since the wooden poles are durability class 3 in the distribution [9]. The climate function $f(R)$ is a function of number of driest months and mean annual rainfall. The number of driest months (N_{dm}) with rainfall record less than 5mm/month are three, and the mean annual rainfall (R) is 1160.12mm/year.

$$\begin{aligned} f(R) &= 10(1 - \exp^{-0.001(1160.12-250)})(1 - \frac{3}{6}) \\ &= 2.988 \end{aligned}$$

Considering the effect of temperature, the climate function $g(T)$ is calculated from the mean annual temperature (T) records in the city.

$$\begin{aligned} g(T) &= -1 + 0.2T, \text{ since } 5^\circ C < T \leq 20^\circ C \\ &= -1 + 0.2 * 17.77 \\ &= 2.554 \end{aligned}$$

Thus, the decay rate (r) will be;

$$\begin{aligned} r &= 0.76 * 2.988^{0.3} * 2.554^{0.2} \\ &= 1.273 \frac{mm}{year} \end{aligned}$$

Using the decay rate value, the time lag before the decay starts can be calculated by:

$$\begin{aligned} t_{lag} &= 5.5r^{-0.95} \\ &= 5.5 * 1.27^{-0.95} \\ &= 4.38year \end{aligned}$$

Thus, the significant depth of decay starts after 4.38 years of poles installation. But it doesn't mean that there is no decay in the distribution poles before t_{lag} . Instead, it follows slower decay characteristics. The d_t value in the distribution network at t years is calculated using eq (2.10).

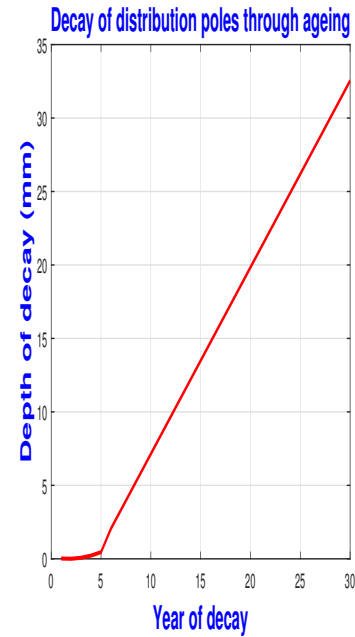
$$\begin{aligned} d_t &= r(t - T_{lag}) \\ &= 1.27(t - 4.38)mm, t > 4.38years \end{aligned}$$

Before significant decay starts, it follows slowly decaying characteristics eq (2.9)

$$\begin{aligned} d_t &= \frac{d_0}{t_{d0}^2} t^2, t \leq T_{lag}, d_0 \text{ is determined using the above decay depth equation} \\ &= \frac{0.604}{4.38^2} t^2 \end{aligned}$$

Table 3.6: Depth of poles decay due to climate influence

Years	Decay depth (mm)	Years	Decay depth (mm)
4.38	0.604	15	13.487
5	0.787	16	14.757
6	2.057	17	16.027
7	3.327	18	17.297
8	4.597	19	18.567
9	5.867	20	19.837
10	7.137	21	21.107
11	8.407	22	22.377
12	9.677	23	23.647
13	10.947	24	24.917
14	12.217	25	26.187



The life of the wooden poles class is expected to be 25 to 50 years [18]. With appropriate maintenance, it can extend even longer life. The significant decay depth until the age of 25 years is as indicated above table 3.6 above. As indicated from the data, the decay depth increases with time. Its strength decreases with increase decay depth, which causes poles to fail with simple disturbance.

The effect of weather and effects of tilt on these wooden poles is simulated using COMSOL software.

The preventive maintenance is needed to be carried out before the strength of the poles fall below 2/3 of the initial strength [36]. The actually reduced circumference is the original minus the reduction circumference. Based on this standard, if the actual circumference is lower than the acceptable value, replacement or rehabilitation is required.

Table 3.7: Allowable reduced circumferences for NESC rules [36]

Original circumference (cm)	Combined wind district and other Loading	Extreme wind other loading
	Minimum reduced circumference (cm)	Minimum reduced circumference (cm)
76.20	66.546	69.342
78.74	68.834	71.628
81.28	71.120	73.914
83.82	73.152	76.200
86.36	75.438	78.486
88.90	77.724	80.772
91.44	80.010	83.058
93.98	82.042	85.344

Table 3.7 – *Continued from previous page*

96.52	84.328	87.630
99.06	86.614	89.916
101.6	88.900	92.202
104.14	90.932	94.742
106.68	93.218	97.028
109.22	95.504	99.314
111.76	97.536	101.600
114.30	99.822	103.886
116.84	102.108	106.172
119.38	104.394	108.458
121.92	106.426	110.744
124.46	108.712	113.030
127.00	110.998	115.316
129.54	113.030	117.602
132.08	115.316	120.142
134.62	117.602	122.428
137.16	119.888	120.714
139.70	122.174	127.000
142.24	124.206	129.286
144.78	126.492	131.572
147.32	128.778	133.858
149.86	130.810	136.144
152.40	133.096	138.430

During installation, the poles in the distribution have 98.33 to 78.40cm circumference at the bottom and top, respectively. As the inground of poles are mainly affected by the decay, it can be considered that its circumference is 98.33cm. Using extrapolation, the standard for the minimum reduced circumference of the utility distribution poles is 85.92cm. Therefore, the in-ground outer surface decay depth calculated above indicates that poles above 20 years of life in the utility distribution are at risk of failure and need replacement or exigent maintenance. But the effect will be higher if Centre decay is considered.

★ Finite element method (FEM)

COMSOL Multiphysics is a powerful interactive simulation environment used to model and solve many scientific and engineering problems. The software provides a powerful integrated environment with a model builder that gives a full overview of the model and access to all functionality [37]. With COMSOL Multiphysics, one can easily extend conventional models for one type of physics into multiphysics models that solve coupled phenomena. Accessing this power does not require in-depth knowledge of mathematics or numerical analysis.

Using the built-in physics interfaces and the advanced support for material properties, models can be built by defining the relevant physical quantities such as material properties, loads, constraints, sources, and fluxes rather than by defining the underlying equations. These variables, expressions, or numbers can be applied directly to solid and fluid domains, boundaries, edges, and points independently of the computational mesh. The COMSOL Multiphysics software then internally compiles a set of equations representing the entire model. It works using the Finite Element Method (FEM) in calculations.

The COMSOL software is selected for the study since it's better to visualize the 3D model of the distribution poles and the effect of the common causes, especially the weather influence on its surface. It is possible to pair several physics together in COMSOL. Also, It is easier, simpler, and powerful to use than other similar software like ANSYS and ABAQUS.

3.5.2 Conductor inspection

Conductor types used in the distribution are all aluminum conductor (AAC), aluminum conductor steel reinforced (ACSR), and all-aluminum alloy conductors (AAA). Breaking of conductors, poor gap between lines and poor terminals are identified problems during the inspection. Conductor breaking causes lines to be influenced and fails with weather influence easily. Frequent transient and permanent faults could result from this problem. Conductors having this problem are 243 lines. The numbers of lines indicate conductors between two poles.

The other significant problem which causes transient short circuits is the poor gap between lines. The sag beyond the limit increases this effect. During windy conditions, these lines are common causes of short circuit fault. Around 362 lines have poor gaps between conductors. The poor terminal of conductors used in the distribution is also another problem.

Table 3.8: Summary of identified conductor problems

Conductor inspection	Number of identified problems
Conductor breaking	243
Poor gap between poles	362
Poor terminal	215

3.5.3 Insulators inspection

Insulators used in the distribution are mostly imported from China and India. Typical insulators used are pin and suspension types. Auxiliary devices of insulators are also inspected. Components identified during insulators inspection are:

- Cross arm
- Pin
- Hook pin, and
- Insulator itself

Poor cross arm can cause earth fault during raining. Number of insulators having poor cross arm are 200. About 250 pins are inspected with poor condition. The problems at the insulator itself like crack, broken parts and surface erosion for dirt accumulation are identified. Above 125 insulators are under poor condition and need exigent maintenance or replacement.

It should be noted that any of the distribution components failure could results the distribution system failure since the network is radial.

Table 3.9: Summary of insulators identified problems

Identified insulator problems	Number of components
Poor cross arm	200
Poor pins	250
Poor hook pins	85
Broken insulators	125

Insulators and their auxiliary equipment failure can cause breaking the line to the earth clearance, which can cause of earth fault, especially during raining.

3.5.4 Distribution transformers inspection

In Ethiopia, there are many distribution transformers located in different areas. The number of transformers in Addis Ababa is among the highest relative to the others. Thus problems can be applied to the other regions as well.

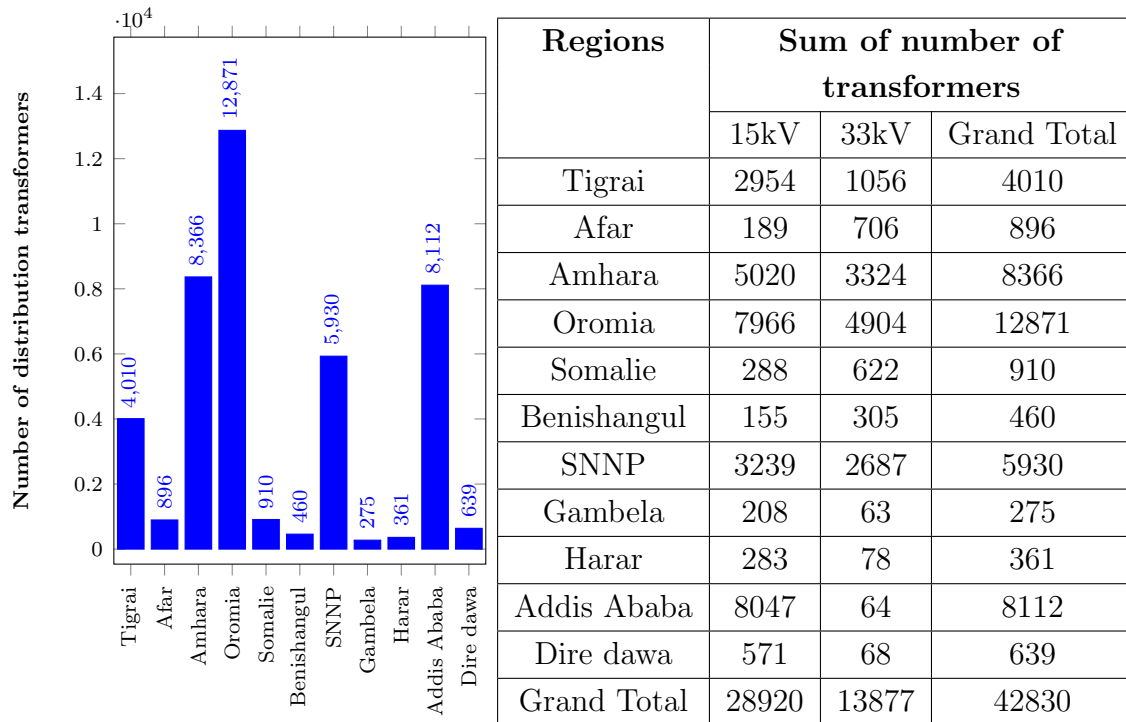


Figure 3.9: Number of transformers in different regions of Ethiopia (Source: EEU South Addis Ababa District)

The general overview of the number of transformers in different regions of the country is shown above. Most of the distribution transformers (above 99%) in Addis Ababa are 15/0.4kV, and below 1% of the total transformers are 33/0.4kV. The study is on 15/0.4kV transformers, which could be applicable to many of the transformers in the city.

3.5.5 Distribution transformers on feeder 6 of Kotebe sub-station

Distribution transformers problems are one of the common causes of long-duration power interruption. Protection and control components are its essential guards. Improper functioning of any of these components can cause transformers vulnerable to failure.

The feeder supplies the customers through 157 distribution transformers. Many problems of the transformers and their protection components are identified during the inspection. The following are identified during inspection of Kotebe line 6 distribution transformers.

- Location of each transformer (exact and relative location)
- Date of manufacturing
- Capacity (kVA) rating of each transformer
- Condition of silica jelly
- Oil leakage of transformers
- Earthing wire conditions
- Corrosion of transformers
- Protective device conditions
- Type of poles support used and its performance
- Customer class
- Size of conductors and fuses
- Current loading records
- **Location of transformers**

The transformers are found on the area coverage of the feeder (i.e., Ayat zone, Meri, few areas of Summit and CMC). The Specific location (latitude-longitude) of each transformer is identified. This is important to access the exact location using GPS during maintenance or replacement.

- **Rating of transformers**

Transformers with a capacity of 25 to 1250kVA ratings are recorded. About 41% of the total transformers have 315kVA ratings. The typical capacities are 100, 200, and 315kVA ratings. The overall number of the transformers and their ratings are summarized as shown in table below.

Table 3.10: Rating and number of transformers

Transformers rating (kVA)	Number of transformers	In percent (%) from the total 157 transformers
25	12	7.64%
50	8	5.09%
100	20	12.74%
200	65	41.40%
315	35	22.29%
400	1	0.64%
630	11	7.01%
800	4	2.55%
1250	1	0.64%

From the data, the total capacity of the transformers is about 38.505MVA. On the other hand, each feeder has 12.4MW rating. As usual, 0.9 power factor is used for transformers of the utility. So the capacity of the transformers is about 34.655MW. The feeder has only 35.78% of the overall capacity of the transformers.

- **Silica gel**

Silica gel breathers will be blue when installed, and they turn to pink color when it absorbs moisture, which indicates that crystals should be replaced. During inspection, some transformers are identified with pink color and even empty silica gel. 20 transformers are identified with this problem.

- **Oil leakage**

Oil leakage at the radiator is the other problem. Leakage reduces the insulation level, and short circuits could happen. About 35 transformers are identified with this problem on the distribution feeder.

- **Corrosion of transformers**

Corrosion of transformers weakens its mechanical protection and accelerates its electrical failure. During the inspection, nine transformers are identified as having corrosion problems.

- **Protection device**

Protection devices used in the distribution are the dropout fuse, HRC fuse, and lightning arrester. The ratings of fuses used in the distribution are 80, 100, 160, 200, 250, 300, 350, and 400A. Seven transformers are found with no dropout fuse. Cross wiring instead of fuse is also noticed. For such transformers, it is better to say there is no protective device. Lightning arresters are used for lightning and high current protection. There are 16 transformers with no surge arrester. Also, 12 transformers are inspected with no earthing wire. Other accessories like link and spark gap problems are inspected. There are 10 transformers of these accessories problem.

- **Customers class**

The distribution feeder supplies industrial, commercial and residential customers. Most of them are used for commercial and residential customers. Total transformers for residential customers are 110, and 42 for commercial users. The remaining 5 transformers supplies for industrial customers. Identified transformers problems are summarized below.

Table 3.11: Number of transformers with identified problems

Inspection type	Number of transformers for the identified problems
Poor silica gel	20
Oil leakage	35
No earthing wire	12
Corrosion of transformers	9
No drop out fuse (HT) and HRC fuse	7
No surge arrester	16
Poor arc horn and link	10

3.5.6 Transformers and loading

Overloading is the common cause of transformers failure. About 49% of the transformers failure in East Addis Ababa Region (EAAR) is due to overloading [24]. So, in the distribution, this problem is highly pronounced. Average of the three days at a time loading data is recorded using clamp meter during the usual working hours, and the data is used for the study. From data records, many of the transformers are overloaded. About 102 transformers of 157 are working overloaded, which is one of the factors which could reduce the performance of transformers, and the distribution.

Locating the transformers which are working overloaded helps the utility to take appropriate measures easily before failure happens. The exact locations of overloaded transformers are indicated using the 3D map shown below. The location of those transformers looks



Figure 3.10: Location of overloaded transformers using 3D Google view

clustered on 3D map view. But it is a sound indicator to visualize the location of those transformers and take immediate action. The area is around CMC square and the Ayat zone.

3.5.7 Loss of life of overloaded transformers

Using the loading data, ambient temperature, and standards, it is possible to estimate the life of transformers. Ambient temperature is an essential factor to determine the load capacity of transformers. The temperature rises for any load must be added to the ambient to determine operating temperatures.

Transformer ratings are based on the expected life of winding insulation at a specified temperature. Ratings typically assume an ambient temperature of 30°C , an average winding temperature rise of either 55°C or 65°C , and an additional hot spot rise of 10°C or 15°C [25]. 55°C rise transformers have a hot spot design temperature of 95°C , and 65°C rises have 110°C .

Transformer ratings are based on 24 hours average ambient of 30°C [25]. For every increase of temperature by 10°C , the dielectric aging of transformers will reduce twice faster [13]. Average winding temperatures of 15°C and an average winding temperature rise of 65°C is used in IEEE standard [25]. The hottest-spot conductor temperature for operating continuously with normal life expectancy is 110°C [25, 23]. The peak short-duration loading of power transformers less than 100MVA should never exceed 200% of the nameplate rating.

Table 3.12: IEEE standard of parameters used for transformers [23]

Parameters	Distribution transformers	Power transformers			
	ONAN	ONAN	ONAF	OFAF	OFWF
Oil exponent (n)	0.8	0.8	0.9	0.9	1.0
Winding exponent (m)	0.8	0.8	0.8	0.8	1.0
Loss ratio (R)	5	6	6	6	6
Hot spot factor (H)	1.1	1.3	1.3	1.3	1.3
Oil time constant (τ_o)	180	210	150	90	90
Winding time constant (τ_w)	4	10	7	7	7
Ambient temperature (T_A)	30	30	30	30	30
Top oil temperature rise (ΔT_{TOR})	65	62	62	66	59
Hot spot to top oil (in tank) gradient at rated current (ΔT_{HR})	15	18	18	14	21
Hot spot temperature (T_{HS})	110	110	110	110	110

The hottest spot temperature is determined using the actual mean ambient temperature (T_A) collected from the National Meteorology Agency (NMA), average load data of the transformers, and standard parameters. The transformer loading inspection is taken during August and September. Thus, the mean temperature during these months is taken as ambient temperature. The loading data is indicated in Appendix B.

The Standard of aging acceleration factor for transformers to operate continuously should be less or equal to one. The standard percent of loss of life for transformers (i.e., 0.0133%) is used for comparison to the existing transformers. Using the above F_{AA} values, percent of loss of life is calculated. The T_{HS} , F_{AA} , and percent of loss of life for each transformer is calculated, indicated at appendix C.

From the percent of loss of life determined, 82 of the transformers operate above the IEEE standard, $110^\circ C$. The life of these transformers is expected to be below the required standard. Even though 102 of the transformers operate with overloading, the ambient temperature in the city is below the standard ambient, $30^\circ C$ [25]. Thus, there are transformers that can operate above the rated loading limit continuously.

The ambient temperature used is the average value during loading record months. But ambient temperature during the records time could be above the average temperature. Thus, the hotspot temperature will be higher than the calculated value, which could cause the loss of the transformer's life to be higher. Thus, ambient temperature is an influential factor for transformer vulnerability to failure.

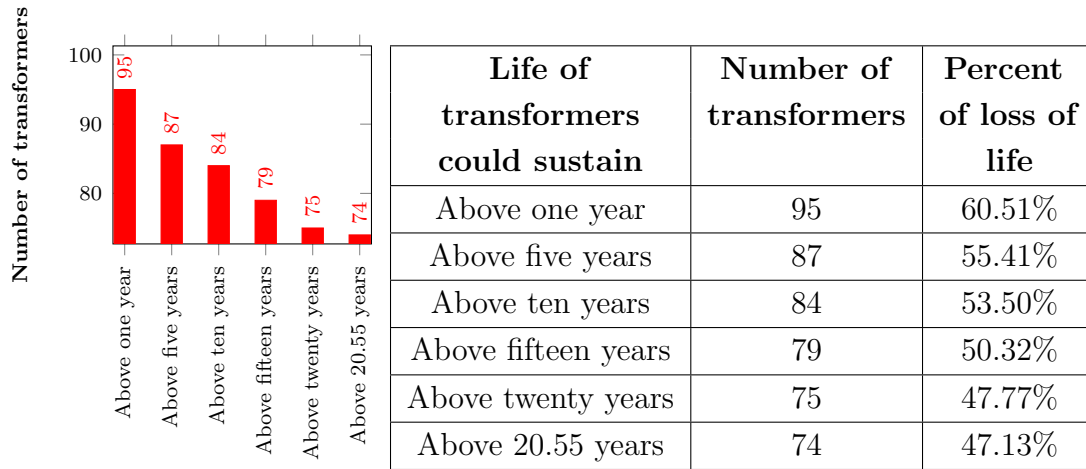


Figure 3.11: Expected number of transformers that could sustain certain years

The above analysis indicates the number of transformers that could sustain the required life. For instance, only 74 of 157 transformers could sustain the standard 20.55 years (i.e., 47.13% of the total number of transformers). The remaining 83 transformers sustain below 20.55 years. The others also follow the same principle.

The study is based on the loading data record taken for a certain time of inspection. More reliable life estimation needs 24 hours of loading records for many days. In this study, it is required to emphasize the vulnerability of distribution transformers for failure due to overloading.

Chapter 4

Simulation Studies and Analysis of Results

4.1 Introduction

Based on the data collected and the identified problems, the vulnerability of the distribution components is analyzed using different software. The effect of weather influence and tilt angle for the vulnerability of distribution poles is simulated through COMSOL software and the results are discussed in section 4.2. In this section, the decay characteristics of wooden poles is also studied through TimberLife software. The effect of lightning for the failure distribution transformers is simulated through Matlab/Simulink in section 4.3. The solutions need to be taken based on the identified problems are also proposed in section 4.4.

4.2 Weather influence and tilt angle on distribution poles

From the analysis on the causes of distribution system failure, weather influence is the major factor. Its effect for the vulnerability of the existing weak distribution system is analyzed using different software's.

Finite element analysis of COMSOL Multiphysics is used to evaluate the resilience condition of the poles based on their angular deflection. It is assumed that the wooden poles are homogeneous throughout the cross-section. The distribution of wooden poles properties and the existing identified conditions are used for the simulation. Many of the distribution poles used for EEU are imported from Australia. The specifications are from Australian timber poles standards. The typical poles used are spruce (solid wood). The type, area, physical properties (i.e., young modulus, shear modulus, density, etc.) of the wooden poles and size of conductors used for the simulation are shown in table 4.1 below.

Table 4.1: Specification of parameters used for the distribution poles [12]

Parameter type	Specifications
Young modulus (MPa)	8963.2

Table 4.1 – Continued from previous page

Density of wooden poles (kg/m ³)	554
Density of air (kg/m ³)	1.2
Shear modulus (MPa)	3447.4
Bulk modulus (MPa)	7469.3
Poisson ratio	0.3
Height (m)	12
Embedment (m)	1.6
Diameter of poles (mm)	313 – 250
Mass (kg)	413
Diameter of conductor (mm)	13.5
Span length between consecutive poles (m)	50
Gravity (m/s ²)	9.81
Design standard pressure (Pascal)	900
Tensile ultimate strength (MPa)	55.158
Compressive ultimate strength (MPa)	31.026

The weather effect considering tilt angle of existing wooden poles (θ) up to 25° with 5° differences is used for the investigation.

★ Modelling of the distribution poles

The distribution poles are modelled using COMSOL Multi Physics software. The parameters specifications of wooden poles and the weather data are incorporated for the simulation. The model of wooden poles using COMSOL software is as shown in figure 4.1 below.

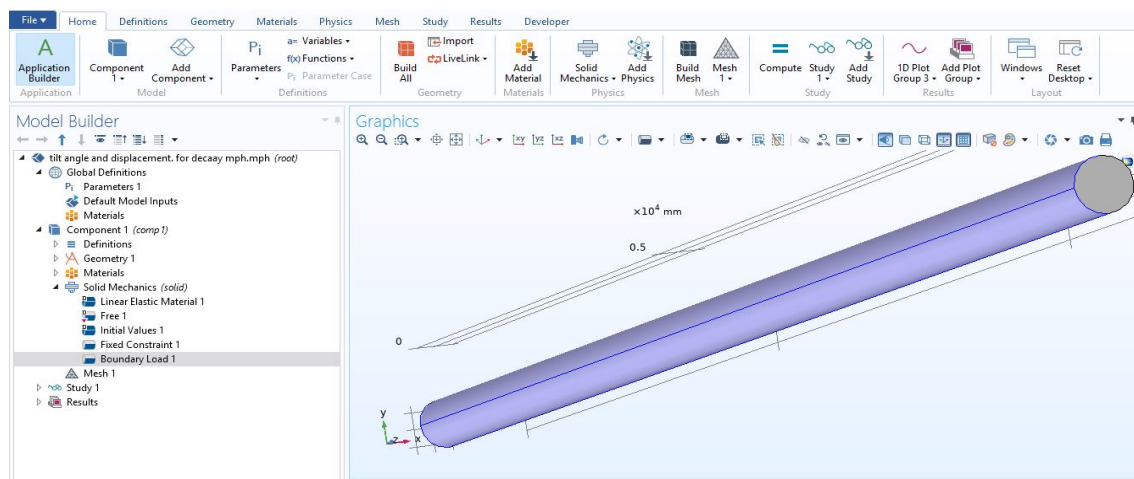


Figure 4.1: Model of wooden distribution pole on COMSOL software

Considering the probable existing inclination angle of poles and weather influence, the angular deflection is simulated using COMSOL software. Using the deflection angle, its resilience conditions are identified.

The distribution poles are considered as one end fixed 3D beam. The forces due to weather influences calculated previously are used for the simulation. Finer mesh is used for FEM analysis during simulation.

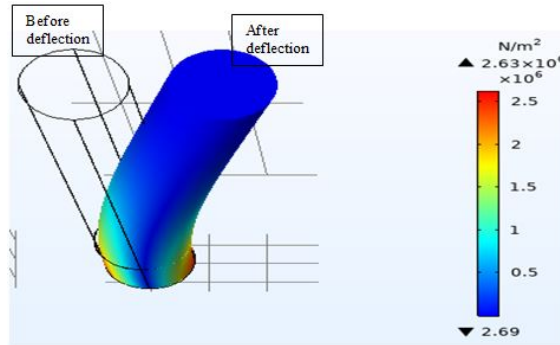


Figure 4.2: Deflection of wooden pole due to weather influence ($\theta = 0^\circ$)

The maximum deflection occurs at the top of a pole and the minimum deflection at its bottom. The stress distribution along the poles and displacement from the original position is simulated. Tilted poles and their effects are also considered.

The tilt angles of poles considered are 0° , 5° , 10° , 15° and 25° . The resulting angular deflections will be added to the selected angles. The result looks like the figure 4.2 shown

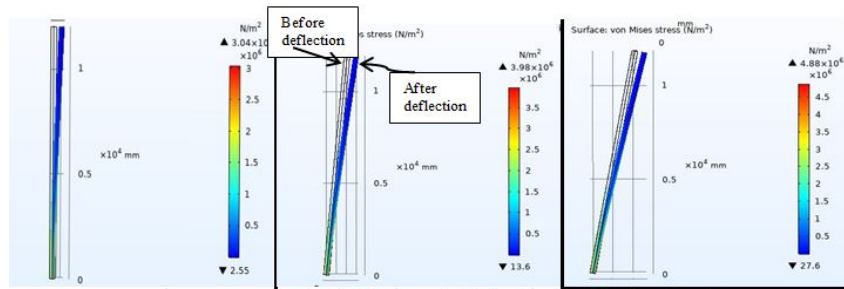


Figure 4.3: Angular deflection of tilted poles by 0° , 5° and 10° respectively

above when it is enlarged. Many conditions were considered and simulated, but only few of the results are included here. The results of the other tilted poles deflection (i.e., 15° , 20° and 25°) have similar characteristics with those shown figure 4.3 above.

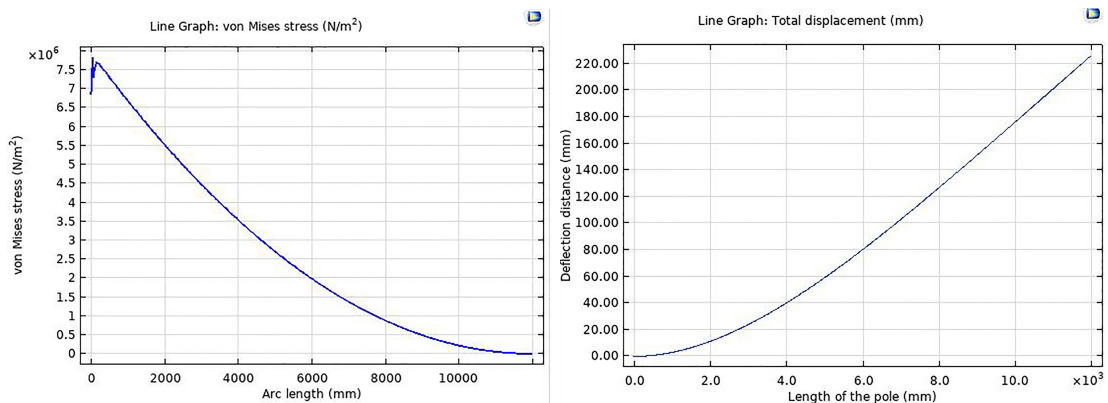


Figure 4.4: Graph of stress and displacement along surface of 0° tilted pole

The results from the simulation indicate that deflection angle due to weather influence ranges from 0^0 to 1.288^0 at the bottom and top of the poles, respectively. Stress developed at different heights of the poles is also indicated.

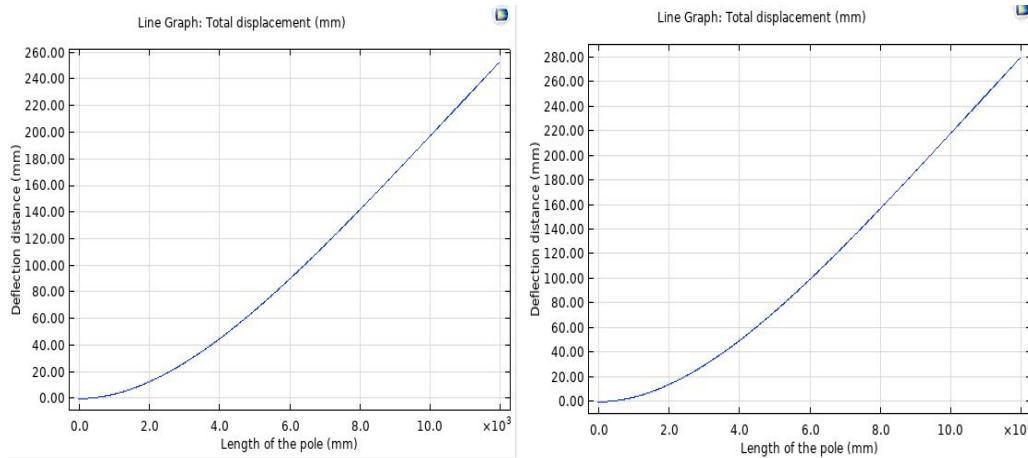


Figure 4.5: Displacement of poles for tilt angle of 5^0 (left) and 10^0 (right side)

As the tilt angle increase, the effect of weather and gravitational force becomes higher, and the deflection angle would increase. The deflection displacement at the top of the pole is 262.16mm (1.444^0) and 282.53mm (1.596^0) for poles tilted by 5^0 and 10^0 respectively. The deflection angles for 15^0 , 20^0 and 25^0 are 1.7434^0 , 1.884^0 and 2.018^0 , respectively. The results for more tilted poles have similar characteristics.

Summary of simulation results for the distribution poles deflection angle due to the above weather influence is shown in the table below.

Table 4.2: Deflection angle of tilted poles due to the weather influence

Tilt angle	Maximum stress developed at the distribution pole($10^6 N/m^2$)	Deflection angle (θ)	Total deflection (θ)
0^0	8.091	1.117	1.117
5^0	9.069	1.252	6.252
10^0	10.024	1.383	11.383
15^0	10.947	1.511	16.511
20^0	11.832	1.633	21.633
25^0	12.671	1.749	26.749

The results show that the weather thrust can result in a significant problem to the poles. Due to the influence, poles can move from resilient to moderately resilient regions and from moderately resilient to non-resilient regions. Once it moves to a non-resilient region, the vulnerability of the distribution network increase, and it needs higher investment to restore to the healthy condition. From the result, poles with tilt angle 13^0 could enter in to moderately resilience conditions with a certain disturbance. Also, poles above 23^0 degree could enter in to non-resilient conditions. Under worst conditions or continuous weather effects, poles with lower tilt angles could enter any of the worst conditions. The analysis is

considering a one-time worst disturbance that would happen. But this disturbance could happen many times per year. Thus, the effect will be higher than the value identified.

4.2.1 Decay of distribution poles

Because of the progressive cross-sectional loss due to fungal decay, the strength of poles decreases with time. The decay depth of the distribution pole is also studied through TimberLife software. The TimberLife Educational Software provides a means of estimating timber's service life performance for [9]:

- Decay in ground contact
- Decay above ground exposed to weather
- Corrosion within building envelope, and
- Termite management

Considering the parameter of EEU wooden poles and the weather condition of the selected region, its decay characteristics are simulated. Both the surface and Centre decay of in-ground poles part is indicated by the software.

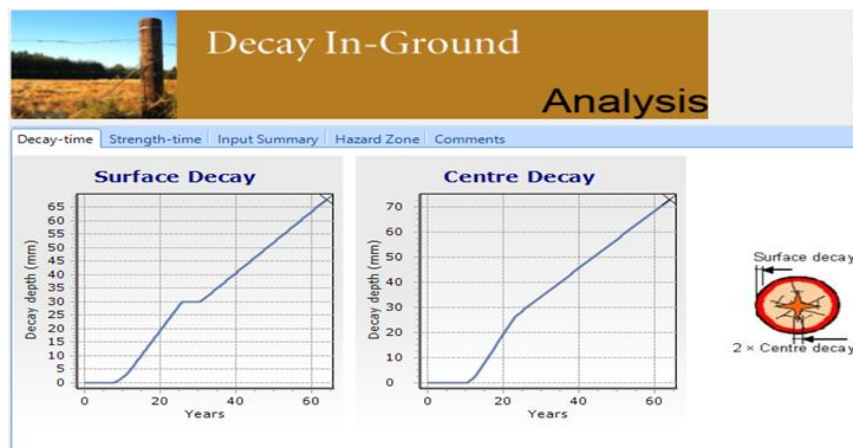


Figure 4.6: Surface and Centre decay of the inground distribution poles

The simulation result for surface decay of the inground distribution poles has similar results with the previously calculated value (see on chapter three sub-subsection 3.4.1.3). So wind effect for the failure of these poles is considered and simulated using COMSOL. The effect of Centre decay of poles is similar to the characteristics of outer surface decay shown above. After 15 and 20 years, the Centre decay is about 10mm and 20mm, respectively. Using the standards indicated in table 3.8, the life of wooden poles will be below 15 years considering both surface and Centre decay.

The surface decay of above-ground distribution poles is relatively slower. The result indicates that poles need service after 33 years and need replacements after 68 years of their installation. Its effect for failure is relatively low and not considered during simulation.

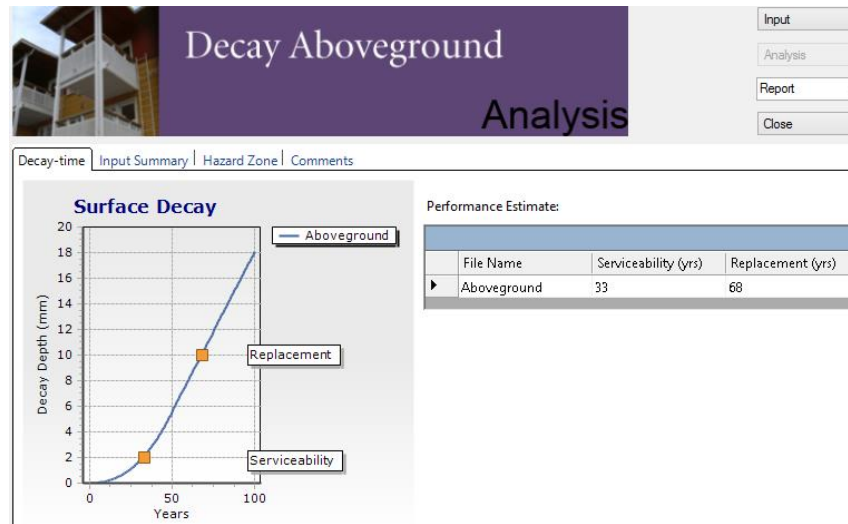


Figure 4.7: Surface decay of distribution pole above ground

4.2.2 Effect of weather influence on decayed distribution poles

Decayed poles are vulnerable to failure with simple disturbance. The effect of weather and other factors for decayed poles is high. Summary of the simulation result for deflection of normal and tilted distribution poles considering decay is indicated below.

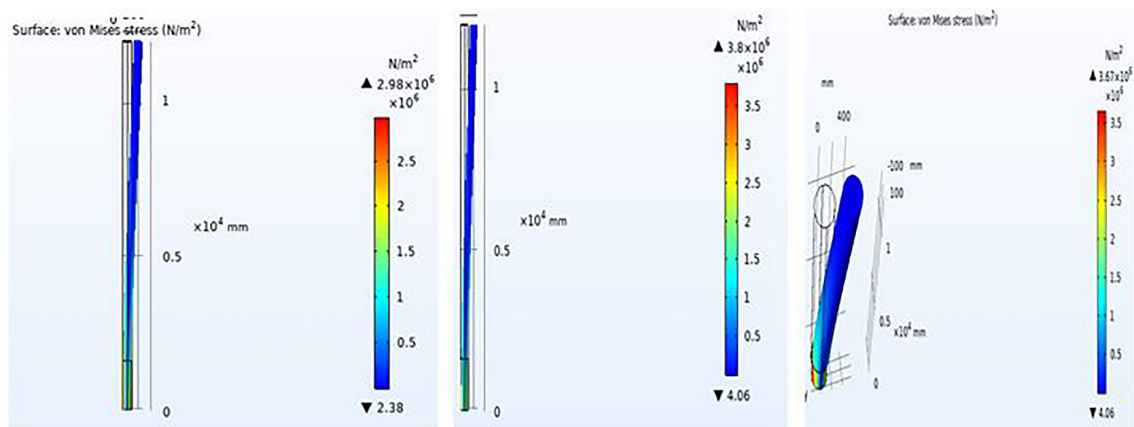


Figure 4.8: Weather influence on decayed wooden distribution poles of 5, 10 and 15 years age ($\theta = 0^\circ$)

As its age increase, the decay depth, deflection due to weather and other influences increases. The simulation is performed for a certain time effect of weather influence. The deflection is continuous as the weather effect is available. Thus, the effect will become high, and the distribution system will be vulnerable to failure.

The results are samples to show the stress and deflection displacement characteristics. The results for deflection up to 20 years age considering different deflection angle is simulated and summarized as shown in table 4.3 below.

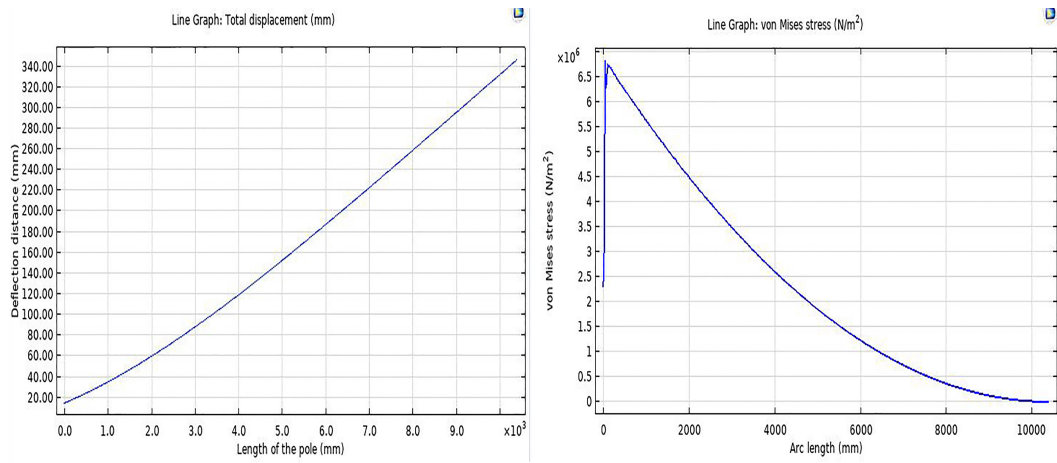


Figure 4.9: Deflection (left side) and stress (right side) of 15 years aged decayed poles ($\theta = 0^\circ$)

Table 4.3: Summary of the simulation result for deflection of decayed poles

Age of poles	Maximum deflection for selected tilted angle of decayed poles										
	0 ⁰	5 ⁰		10 ⁰		15 ⁰		20 ⁰		25 ⁰	
	DF.	DF.	Total DF.	DF.	Total DF.	DF.	Total DF.	DF.	Total DF.	DF.	Total DF.
5	1.25	1.45	6.45	1.61	11.61	1.75	16.75	1.90	21.90	2.03	27.03
6	1.27	1.48	6.48	1.63	11.63	1.78	16.78	1.93	21.93	2.06	27.06
7	1.30	1.50	6.50	1.66	11.66	1.81	16.81	1.96	21.96	2.10	27.10
8	1.32	1.53	6.53	1.69	11.69	1.84	16.84	1.99	21.99	2.13	27.13
9	1.34	1.55	6.55	1.72	11.72	1.88	16.88	2.03	22.03	2.17	27.17
10	1.37	1.59	6.59	1.76	11.76	1.91	16.91	2.07	22.07	2.21	27.21
11	1.39	1.62	6.62	1.79	11.79	1.95	16.95	2.11	22.11	2.25	27.25
12	1.45	1.65	6.65	1.82	11.82	1.99	16.99	2.15	22.15	2.30	27.30
13	1.51	1.69	6.69	1.86	11.86	2.03	17.03	2.19	22.19	2.35	27.35
14	1.54	1.72	6.72	1.89	11.89	2.07	17.07	2.24	22.24	2.39	27.39
15	1.58	1.76	6.76	1.93	11.93	2.11	17.11	2.28	22.28	2.45	27.45
16	1.62	1.79	6.79	1.98	11.98	2.16	17.16	2.33	22.33	2.50	27.50
17	1.65	1.84	6.84	2.02	12.02	2.21	17.21	2.39	22.39	2.56	27.56
18	1.70	1.87	6.87	2.07	12.07	2.26	17.26	2.44	22.44	2.62	27.62
19	1.74	1.92	6.92	2.12	12.12	2.31	17.31	2.50	22.50	2.68	27.68
20	1.78	1.96	6.96	2.17	12.17	2.37	17.37	2.56	22.56	2.75	27.75
21	1.83	2.02	7.02	2.23	12.23	2.43	17.43	2.63	22.63	2.82	27.82
22	1.88	2.07	7.07	2.29	12.29	2.50	17.50	2.70	22.70	2.89	27.89
23	1.91	2.12	7.12	2.35	12.35	2.56	17.56	2.77	22.77	2.97	27.97
24	1.93	2.18	7.18	2.41	12.41	2.64	17.64	2.85	22.85	3.05	28.05

Where, DF stands for deflection angle

From the result, the deflection of poles increases with their aging. More tilted poles will

deflect more with a single disturbance. It could enter the worst resilience condition with continuous disturbances. Thus, appropriate maintenance is needed.

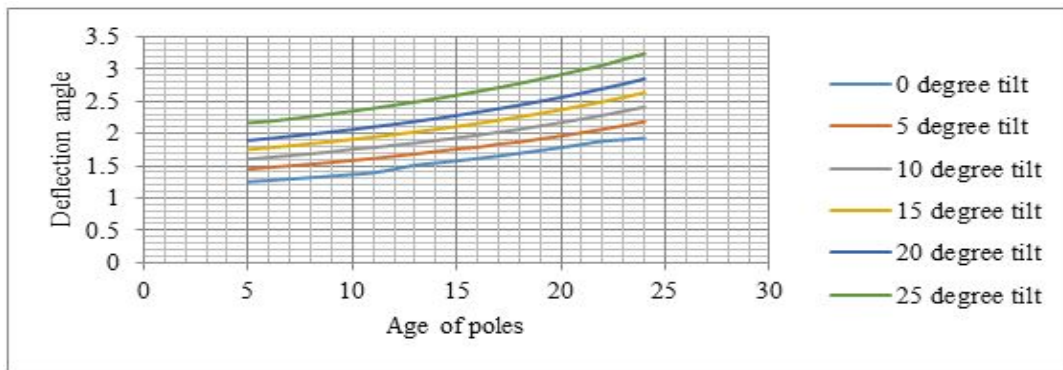


Figure 4.10: Deflection of poles with increased ageing

Considering the stress due to the above factors for distribution poles vulnerability study is an important indicator. The simulation results of the stress for different tilt angles are shown below.

Table 4.4: Stress developed at different tilt angle of decayed poles

Years	Stress for selected tilted angles of decayed poles ($\times 10^7 \text{ N/m}^2$)					
	0^0	5^0	10^0	15^0	20^0	25^0
1	9.7	14.9	11.9	13.9	13.9	15.2
2	12.4	12.0	15.1	16.9	14.3	15.4
3	10.9	12.5	14.4	14.1	15.3	15.2
4	11.4	13.0	15.4	14.3	15.5	16.5
5	12.9	15.0	15.7	17.0	18.6	16.9
6	11.4	15.5	17.3	18.2	16.6	19.7
7	11.6	15.1	16.9	15.4	16.7	17.4
8	15.1	16.3	18.2	19.9	21.2	22.6
9	13.6	16.6	16.4	18.7	20.3	21.7
10	12.9	17.4	16.0	17.3	19.1	20.0
11	12.9	19.0	14.9	16.2	17.5	20.2
12	12.4	14.9	16.5	17.8	19.2	20.5
13	13.6	15.2	16.6	18.4	19.7	21.0
14	14.1	14.8	16.2	19.1	19.1	20.5
15	14.5	16.0	17.9	18.7	19.8	22.6
16	14.7	15.6	18.2	19.7	21.6	23.2
17	15.2	17.4	19.1	21.3	22.4	24.1
18	15.5	16.7	19.4	21.3	23.0	24.9
19	15.4	18.1	20.2	20.8	23.9	25.8
20	16.9	18.6	20.4	22.8	23.2	25.9

The stress above 2/3 of the maximum strength of the distribution poles can result in its failure [36]. The standard of the utility wooden pole's maximum strength is 31.026MPa. Thus, the stress above 20.684MPa from the simulation result table is indicators of poles that are vulnerable to failure. It can be shown that more aged and tilted poles are more vulnerable.

4.3 Effect of lightning on distribution transformers

The consequence of lightning is one of the major factors for the distribution components failure. Its effect on the transformers is frequent and needs greater attention [24]. The improper grounding of lightning rods during installation is the common problem identified at the utility. Thus, its effect for vulnerability of transformers is also considered.

If lightning hits an overhead line, the injected current into the conductor will be divided at the strike point, gives rise to two voltage waves that propagate in opposite directions [39]. The magnitude of these voltages can be determined by multiplying the current that flows in each direction and the characteristic impedance of the line (i.e., half of the stroke current by the characteristic impedance). The value of surge impedance for overhead lines is 400Ω, whereas the impedance value for underground cable is around 40Ω [38]. Studies indicate that lightning current magnitude can range from 5kA to 200kA [27]. It also shows that there is a 90% probability of lightning strike magnitude to be approximately 10 kA and 50% of 30 kA. For the study, 10kA of lightning level is used. Therefore, for a line characteristic impedance of 400Ω and a stroke current of 10 kA, the corresponding surge magnitude will be 2000 kV, which is far beyond the Basic Insulation Level (BIL).

Table 4.5: Standard probability of lightning level [27]

Lightning current distribution			
Percent of lightning distribution	90%	50%	5%
Lightning magnitude (kA)	10	30	80

The lightning surge model developed in Simulink is shown below to simulate impulsive transient caused by lightning at the distribution network. The lightning block is connected to the feeder line to induce the lightning transient. A controlled voltage source with a resistive and inductive network is used to couple the generated lightning impulse to a given phase of the power system line. The lightning impulse applied to the voltage-controlled source input is computed using the equation below [40].

$$V(t) = Ae^{-\alpha(|t-t_1|)}.u(t-t_1) \quad (4.1)$$

Where,

A: is the impulse magnitude

α : is the damping factor

t_1 : is the time when the impulse starts

t: is the time function

u: is the impulse rise step function

The lightning impulse model is implemented using MATLAB function block, ramp block, constant block, and step-function block. The ramp block is used for the time function t , constant block for impulse magnitude A and impulse start time t_1 , and step-function block u for step rising. The equation is coded in the MATLAB function block. The standard lightning impulse characteristic is $1.2/50\mu\text{S}$, where the impulse rises to a peak of $1.2\mu\text{S}$ and decays to 50% at $50\mu\text{S}$ time as defined by IEEE 1159.1, 2009 and IEEE C62-41.2, 2002 standards [22]. Lightning impulse waveform model computed by the equation above with damping factor of α is 14,000 in the MATLAB function block.

The lightning effect on distribution transformers that have surge arresters and no surge arresters is analyzed. To visualize the lightning effect easily, four distribution transformers with 50, 100, 200, and 315kVA ratings at equal distance from sending to receiving end of the line are considered. The distribution load is modeled on each transformer using the actual data records. The line parameters are used from EEU data.

The model consists of three phase source, Y- Δ substation transformer, distribution lines, distribution transformers, surge arrester and lightning block.

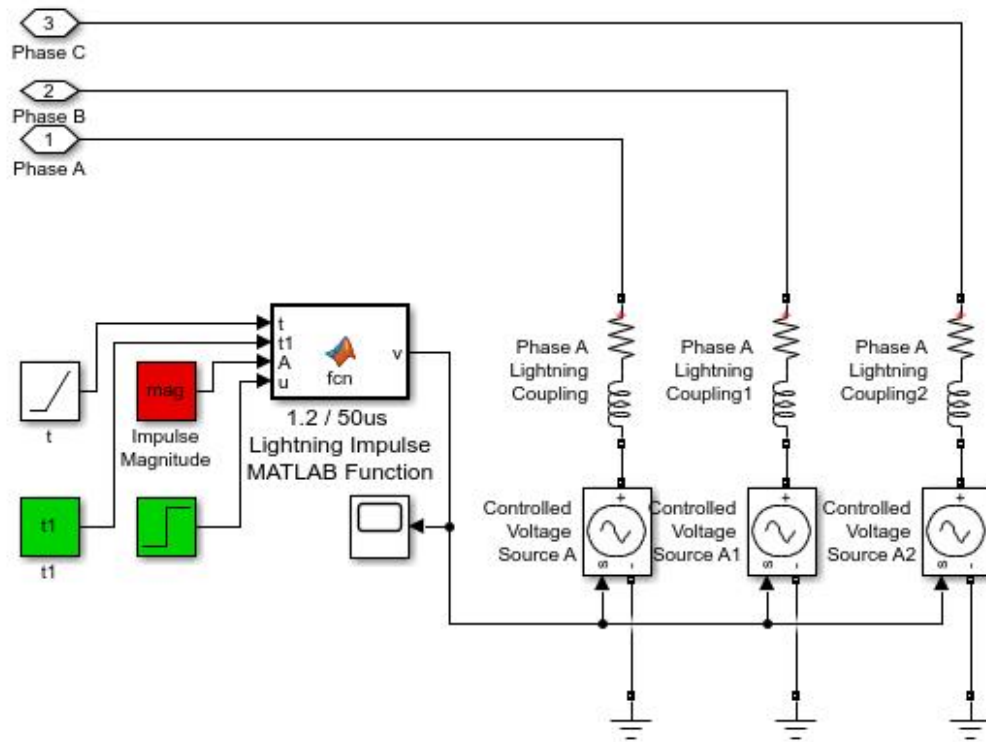


Figure 4.11: Lightning block of the Matlab/Simulink

Lightning can happen anywhere on the 24km length distribution line. But to visualize the effect clearly, it's simulated by considering at sending, and receiving end. The lightning surge characteristics based on the specified standards is shown in figure 4.12 below [22].

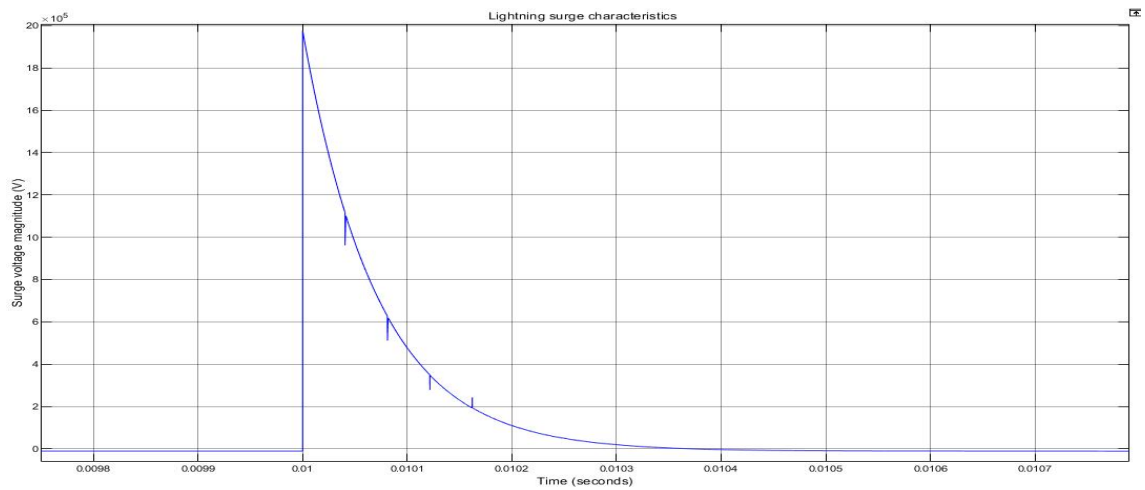


Figure 4.12: Lightning characteristics for 10kA magnitude

Conditions were considered based on the actual problems during the study. Those considerations are:

- Effect of lightning for transformers with no surge arrester
- Effect of soil resistivity for transformers having surge arrester
- Surge voltage at different terminals of transformers as the length of line increase

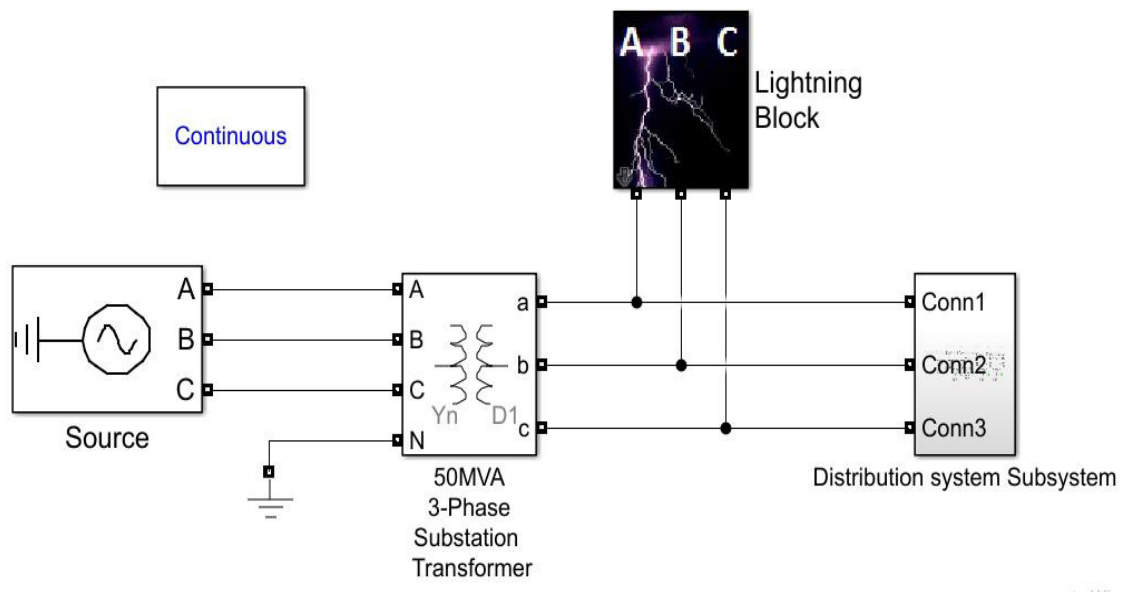


Figure 4.13: Overall model of the Matlab/Simulink lightning model

Case 1: lightning effect for transformers without surge arrester

If there is no surge arrester, there is no lightning protection. Lightning that strikes the distribution system directly introduces thousands of kilovolts to the transformers and other devices. It can cause severe damage to transformers and other electrical or electronic devices.

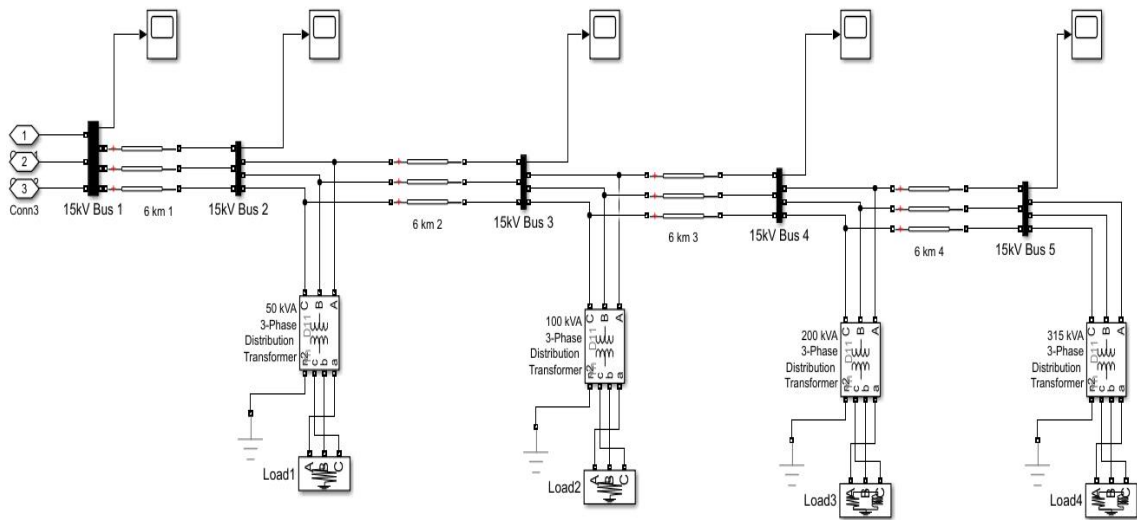


Figure 4.14: The distribution subsystem model of figure 4.13 (transformers without surge arrester)

For the sake of visualizing the system easily, lightning that can occur at sending and receiving end of the line is simulated. The surging output at bus 1 of the transformer without surge arrester is as shown in figure 4.15 below.

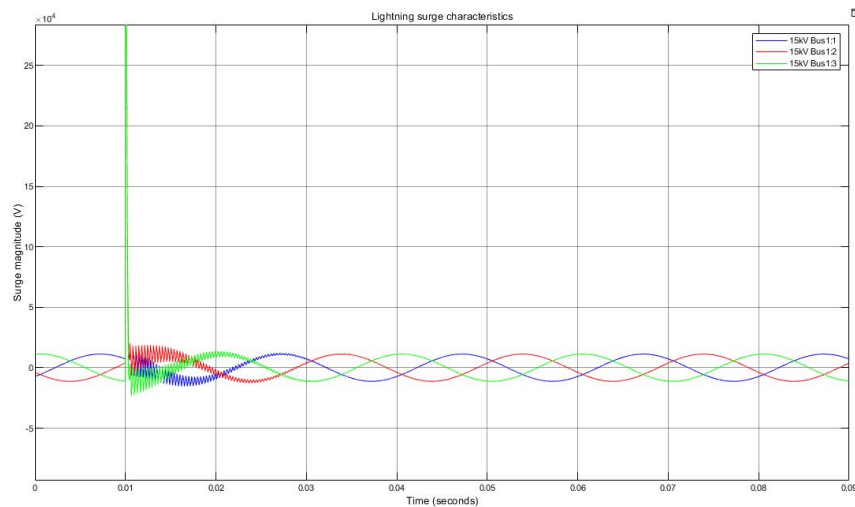


Figure 4.15: Surge voltage at bus 1 when lightning occur at bus 1 of the transformer

As shown from the result, when lightning happens at bus one of the distribution transformers having no surge arrester, the voltage magnitude at all buses exceeds the BIL. The surge magnitude range from 98.18kV to 350.2kV at the sending and receiving end buses of the line, respectively. Also, the surge at the other terminal of bus 2, bus 3, and bus 4 is 202.2kV, 262.7kV, and 305.2kV, respectively. The result at the different buses of the transformers without surge arrester is as shown in figure 4.16.

The voltage waveforms at the other buses of the transformers have similar characteristics except their magnitude.

The surge characteristics when lightning happens at receiving end are similar to the result indicated above. But, its magnitude is higher at receiving end and decreases to a lower value at sending end. The surge at bus 1 when lightning happens at sending end is similar

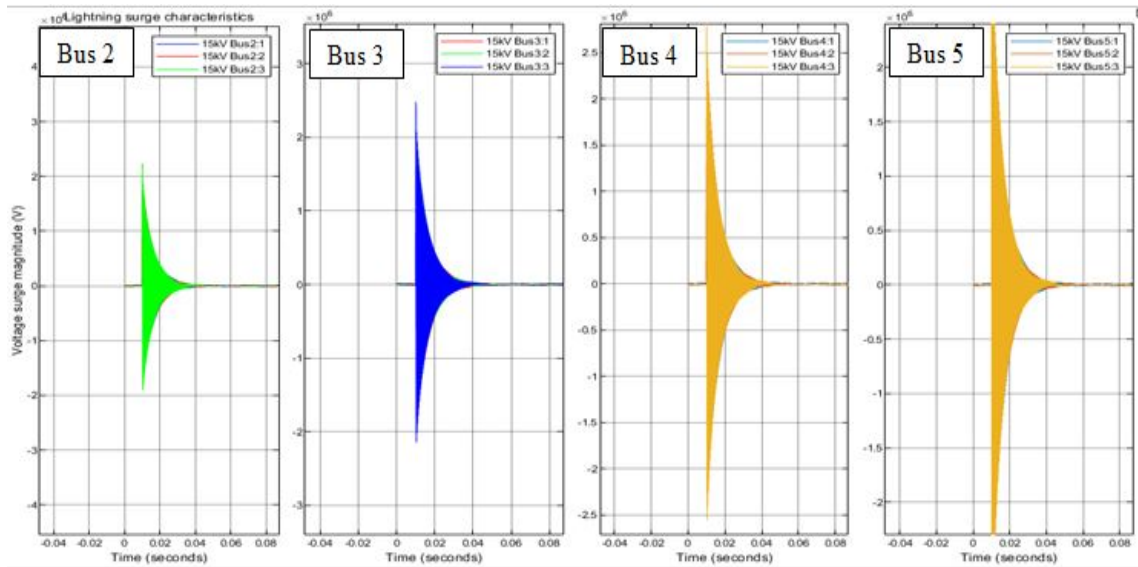


Figure 4.16: Surge voltage at bus 2 to 5 of the transformers when lightning occur at bus 1 of the transformer

to the lightning surge characteristics at the entrance. Since all transformers are considered to have no surge arrester, the surge magnitude increases as the length of the line increase. The surge voltage decays faster with time. But its magnitude is high and the energy that will dissipate is too high that could result in damage to transformers.

Case 2: lightning effect for transformers with surge arrester considering soil resistivity

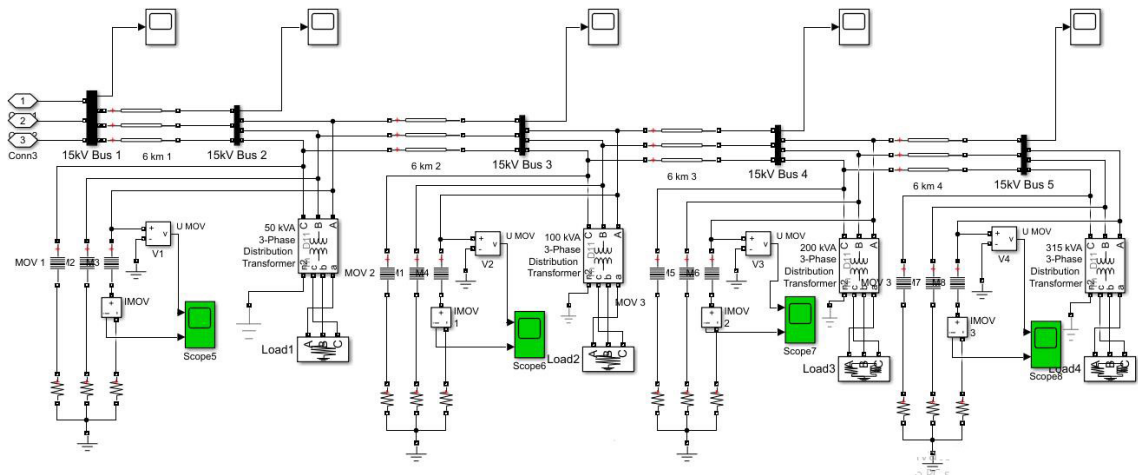


Figure 4.17: The distribution subsystem model of transformers having surge arrester

For those transformers having lightning arresters, properly grounding copper rods with the required standard size is the common problem in the utility. Study the soil resistivity before grounding has no attention. This has a higher effect on both the transformers and the surge arresters. The typical surge arrester applicable for the utility is MOV. The arresters should have a current discharge capability of at least half of its standard distribution class [41]. From the nameplate data, the Basic Insulation Level (BIL) of the EEU distribution transformers is 36kV. The transformers are protected by the MOV

block of 20 columns and reference current of 500 A/column(i.e., 10kA total current). By modelling the distribution system and using the MOV standards, the effect of soil resistivity and rod size for the surge level is simulated on Matlab/Simulink. The soil electrical resistivity is taken from the IEEE standard. The soil type of the study area is identified through previous literature studies. The utility installation practice of using any rod without considering its size is also taken under consideration.

Table 4.6: IEEE standards of soil type and its resistivity [42]

Type of soil	Average soil resistivity ($\Omega.m$)
Wet organic soil	10
Moist soil	100
Dry soil	1000
Bedrock	10000

The common types of soil in Addis Ababa are leptosols and nitisol soil types [43]. The characteristics of such type of soil are dry, well-drained, and red in color. Thus, the resistivity of dry soil type is used for the study. The grounding resistance is determined by considering the actual practice of using rods in EEU. In actual practice, there are many transformers without surge arresters (from the inspection data). Also, the ground rods used for transformers having surge arresters are not based on the standard size. The rod length used is 2 meter. But the actual practice is, any rod size found nearby during the installation of transformers is buried to the ground. Improper lying such as placing horizontally rather than installing rods vertically is the other problem. During the study, the effect of rod size used for installation and resistivity of the soil are considered.

Table 4.7: Grounding resistance considering standards of soil resistivity and rod size

Rod size		Resistance (Ω)
Rod length (mm)	Radius (mm)	
1200	12.5	656.60
1500	16.0	522.76
2100	20.0	381.99
3000	25.0	274.48

The National Electrical Code (NEC) targets minimum required grounding resistance 25Ω [16]. However, a grounding resistance of 5Ω or less is preferred [44]. Since the performance of any surge arrester is enhanced by a highly conductive path to earth ground, lightning currents will divert from seeking other sensitive industrial equipment paths.

The RMS value is recorded from the resulting waveform signal statics. Similar approaches are used for the effect without lightning arrester indicated above. Characteristics of lightning at different buses when it occurs at the sending end are indicated as shown below.

- Surge magnitude for soil grounding resistance of 25Ω

The surge at the point of strike (bus 1) has a higher magnitude and similar characteristics to the lightning surge of the entrance. The surges at the other buses have similar wave characteristics except their magnitude. The surge voltage magnitude at bus 1, bus 2, bus 3, bus 4, and bus 5 is 34.52kV, 26.39kV, 19.45kV, 18.72kV, and 18.09kV, respectively. The surge magnitude at the different length of the line is indicated by the figure 4.18

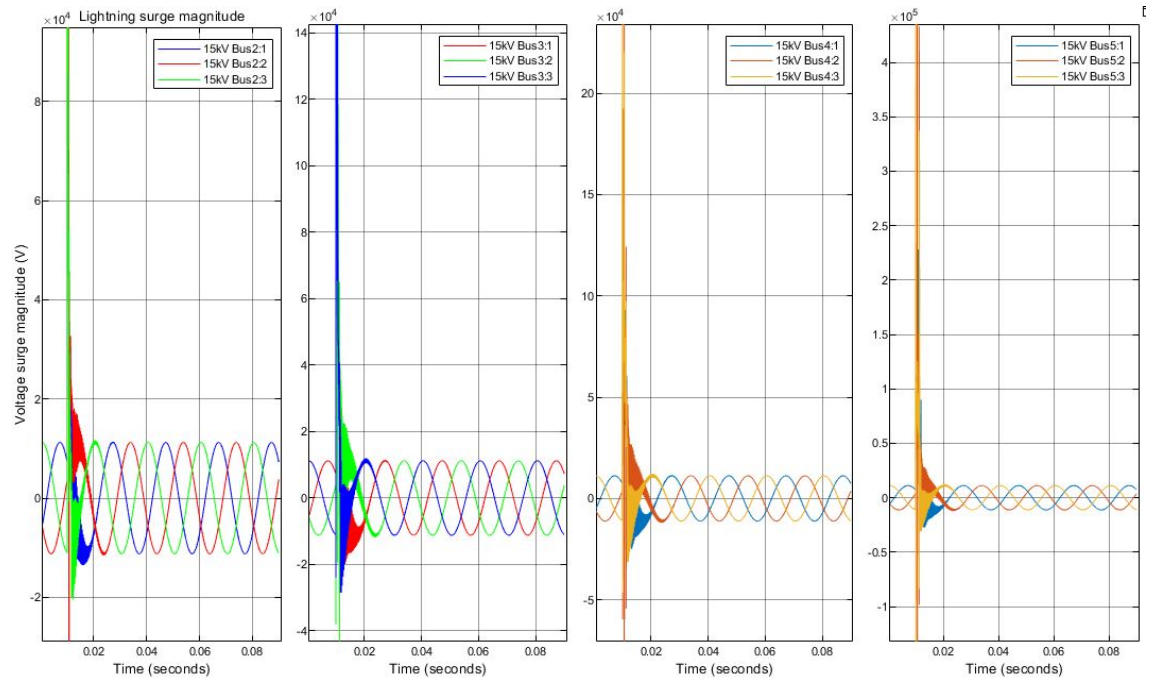


Figure 4.18: Surge voltage at different bus of transformers with 25Ω grounding resistance

From the result, it can be shown that grounding with the required standard helps to reduce the surge magnitude. Since all transformers are considered as having surge arresters, voltage magnitude decrease as the length of the line increases. Thus, the effect at the farthest distance will be lower.

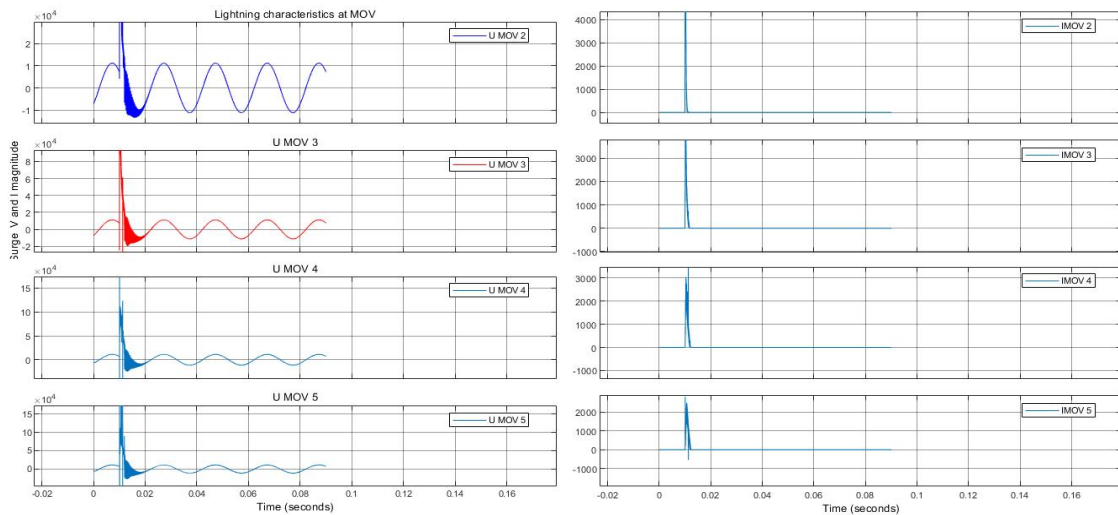


Figure 4.19: MOV surge arrester current and voltage waveform at different buses

The surge arresters conduct while the surge voltage is above the rated basic insulation level (BIL). Otherwise, it does not conduct, and the current will be zero since the arresters become a high resistance insulator at rated voltage. The surge magnitude will be lower as the distance from the lightning strike is farther. As shown, its magnitude at the receiving end is lower. The voltage and the current through the MOV surge arrester when lightning happens is as shown figure 4.19.

- **Surge magnitude for grounding resistance of soil 274Ω**

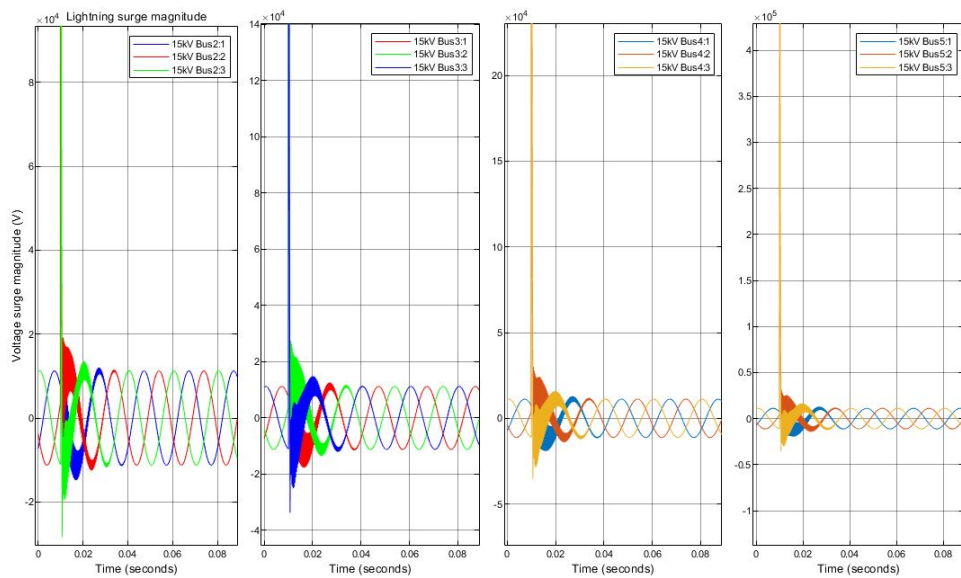


Figure 4.20: Surge voltage at different terminal of transformers for 274Ω

The surge voltage at 274Ω is higher than 25Ω resistance. The surge magnitude at bus 1, bus 2, bus 3, bus 4, and bus 5 is 72.43kV, 52.74kV, 41.09kV, 34.96kV, and 28.41kV, respectively. This indicates that the surge magnitude is higher for higher soil resistivity. This can result in damage to both surge arresters and transformers. Once a surge arrester fails, any surge can easily damage transformers.

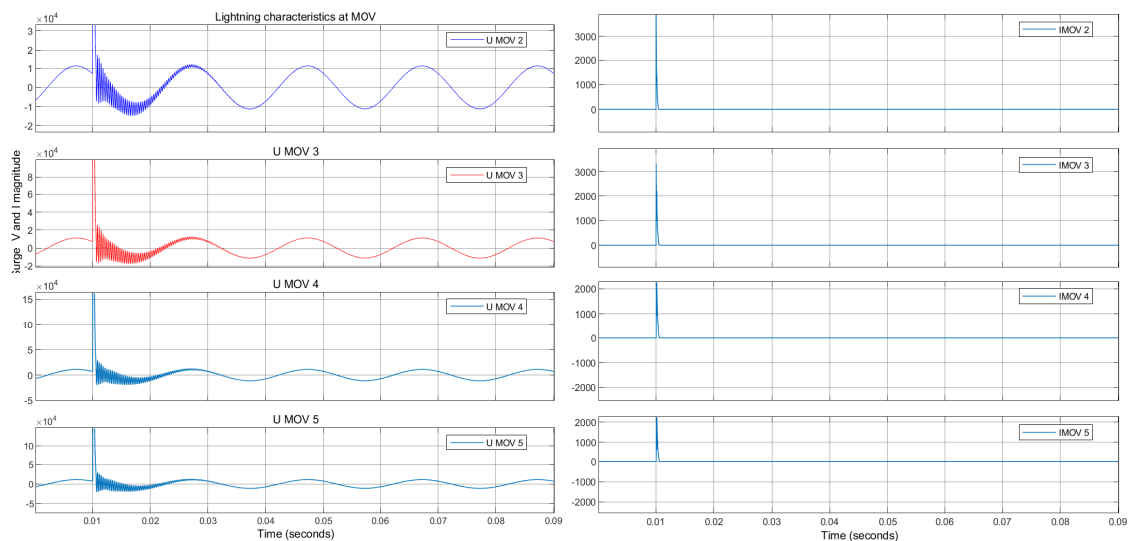


Figure 4.21: MOV surge arrester current and voltage waveform from bus 2 to 5

The surge current at MOV arresters is lower relative to the above 25Ω resistance. The resistivity of the soil and the rod size limits the capability of surge arresters to surge the current to the ground. The MOV current and voltage at the other buses hold similar characteristics to the indicated buses.

- Surge magnitude for grounding resistance of 382Ω

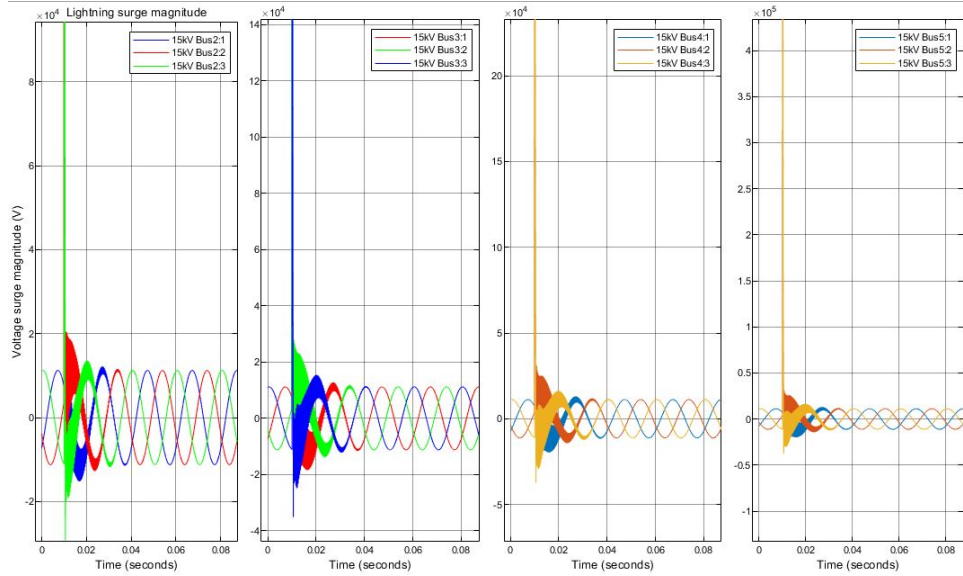


Figure 4.22: Surge voltage at different buses of transformers for 382Ω grounding resistance

Surge voltage magnitude for grounding resistance of 382Ω at bus 1, 2, 3, 4, and 5 is 74.42kV, 58.32kV, 49.78kV, 41.08kV, and 35.05kV, respectively. Its magnitude is higher than 25Ω and 274Ω . The surge magnitude is higher than the BIL value except at the receiving end of the line. The MOV arrester voltage and current during the surge are shown in figure 4.23.

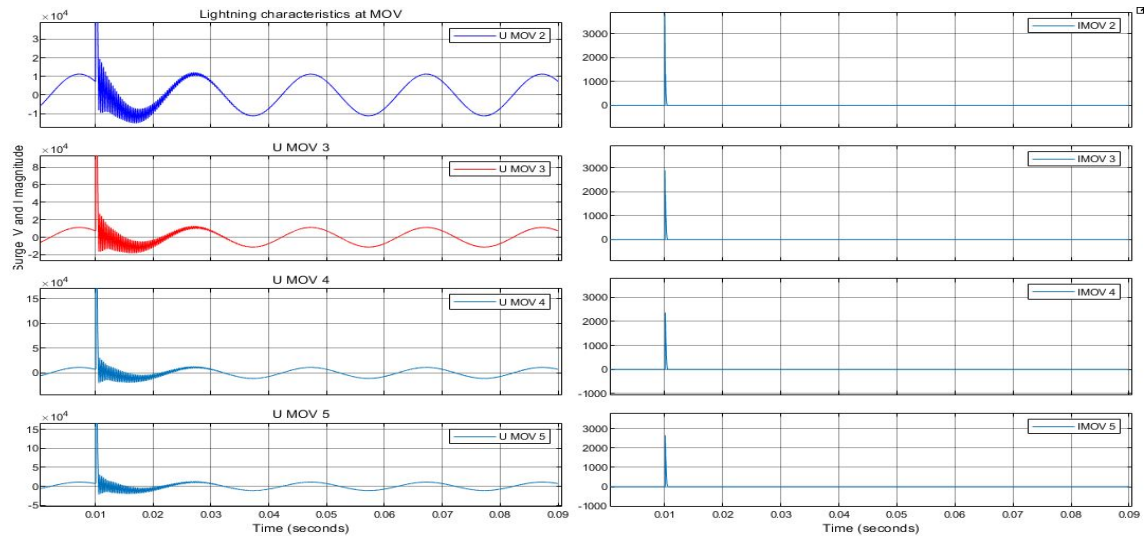


Figure 4.23: MOV surge arrester current and voltage waveform for 382Ω grounding resistance

The current through the MOV is very low as the soil resistivity is high. The surge properties discussed above for 274Ω hold for this also.

- **Surge magnitude for grounding resistance of 523Ω**

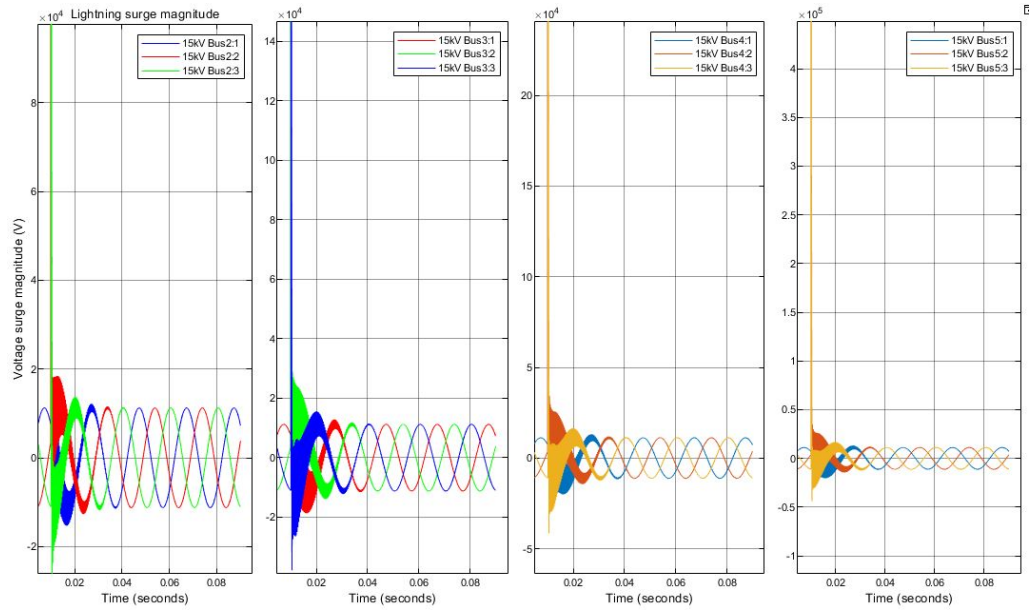


Figure 4.24: Surge voltage at bus 2, 3, 4 and 5 terminals of 523Ω grounding resistance

The lightning surge considering 523Ω and 657Ω grounding resistance shows similar characteristics with different values of the previous grounding resistance except its magnitude. The surge magnitude for 523Ω is higher than the indicated lower grounding resistances, which holds for 657Ω grounding resistance.

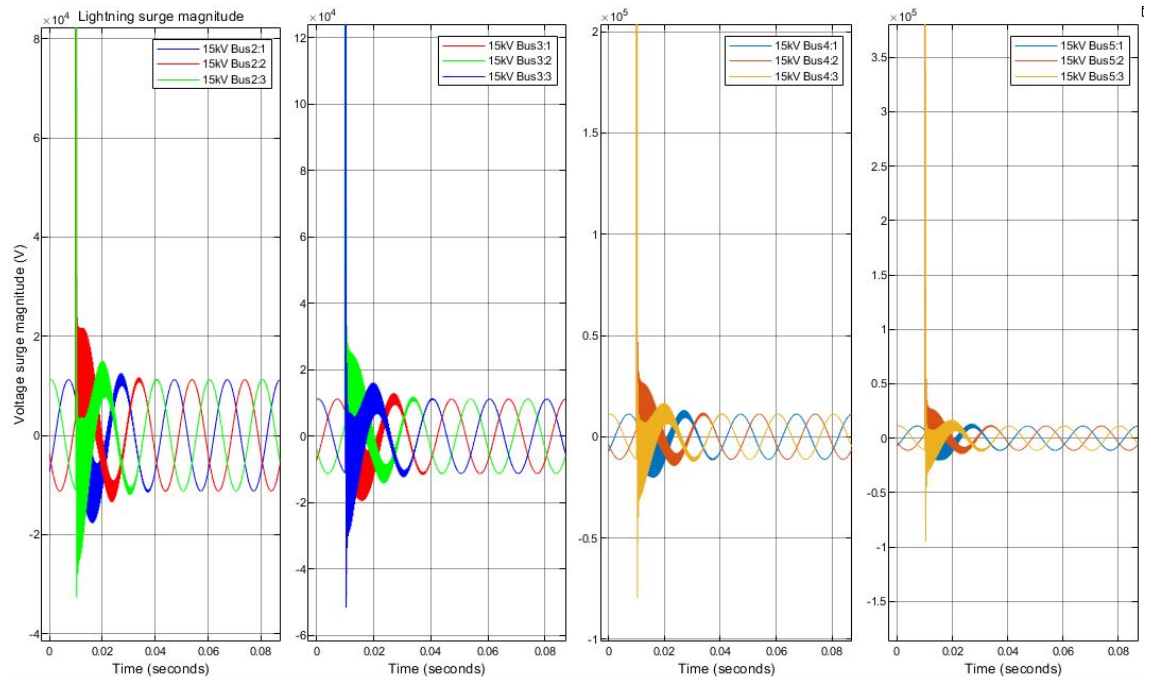


Figure 4.25: Surge voltage from bus 2 to 5 terminals of 657Ω grounding resistance

The surge magnitude at different buses of the distribution transformers is summarized as shown in the table below.

Table 4.8: Surge magnitude when lightning happens at sending end bus of the line

Resistance of the soil	Surge voltage (kV) at each bus				
	Vbus 1	Vbus 2	Vbus 3	Vbus 4	Vbus 5
25 Ω	34.52	26.39	19.45	18.72	18.90
274 Ω	72.43	52.74	41.09	34.96	28.41
382 Ω	74.42	58.32	49.78	41.08	35.05
523 Ω	74.88	57.98	47.54	35.04	31.83
657 Ω	77.85	68.01	53.38	38.02	34.19
No lightning arrester	98.18	202.2	262.7	305.2	350.2

As shown above, the surge magnitude of having surge arresters decreases as the length of the line from the fault location increase. The surge magnitude increases as the length of the line increase for transformers having no surge arrester. A transformer having surge arresters with the required grounding resistance helps to reduce its surge magnitude within the allowable BIL. It also helps to reduce the surge for the cascaded transformers. If there are no other transformers having surge arresters after the place of lightning strikes, those having no surge arrester will be more vulnerable.

Table 4.9: Surge magnitude when lightning happens at receiving end of the line

Resistance of the soil	Surge voltage (kV) at each bus				
	Vbus 1	Vbus 2	Vbus 3	Vbus 4	Vbus 5
25 Ω	11.24	13.72	19.56	28.81	35.21
274 Ω	16.81	36.10	47.93	60.52	75.25
382 Ω	18.13	36.01	49.05	60.06	73.75
523 Ω	21.38	35.61	59.80	67.93	78.44
657 Ω	24.04	40.27	64.22	76.85	81.47
No lightning arrester	352.1	303.6	263.8	198.4	84.45

When lightning happens at sending end, the surge magnitude is higher around sending bus and decreases at the receiving end. When it occurs at the receiving end, the surge around the strike is higher and decreases to lower values at the sending end.

In general, the surge magnitude for transformers having surge arresters is higher around the strike point and decreases to lower values for the distant buses. The surge magnitude at different buses of the line is shown graphically in figure 4.26.

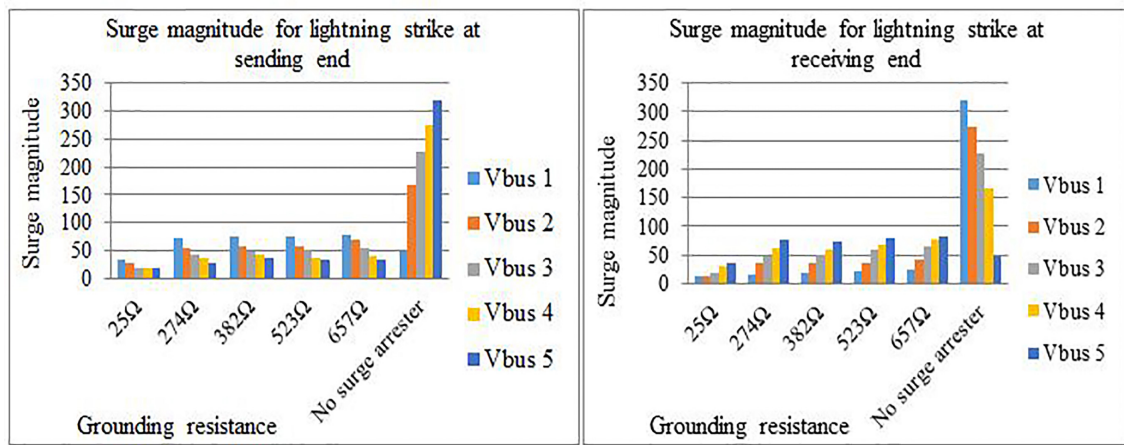


Figure 4.26: Surge magnitude at different buses for a lightning strike at sending and receiving end

4.3.1 Methods to reduce grounding resistance

The grounding resistance is needed to satisfy the minimum standard during installation. Otherwise, the effect will be higher, which may damage transformers and surge arresters. It can be achieved through several methods:

- **Increase the rod size**

Driving a longer rod deep into the earth decreases grounding resistance. Doubling the rod length reduces resistance by about 40 percent [45]. Increasing the rod diameter would lower the resistance but only a little. For the same depth, doubling the rod's diameter reduces the resistance by only about 10 percent.

- **Use of multiple rods**

Two well-spaced rods driven into the earth provide parallel paths. In effect, they are resistances in parallel. The rule for resistances in parallel does not apply exactly [45]. The reduction for two equal resistance rods is about 40 percent. If three rods are used, the reduction will be 60

- **Soil treatment**

Different methods can be used to reduce soil resistivity. Common types are water retention, chemical salts, bentonite, chemical-type electrodes, and ground enhancement materials.

- * **Water retention**

Soil loses moisture when it receives direct sunlight. The sun heats the ground and causes the water contained in it to rise to the surface and vaporize, dispersing in the atmosphere. Excessive drainage can also quickly leach away the salts in the soil and dry out the deeper layers. This condition directly impacts both the distribution of ionizable salts content and the formation of the electrolyte. Improving the soil's ability to retain moisture is an effective way to decrease its resistivity. Without moisture, an electrical connection to the earth is not possible. In addition, an infrequent but effective way to maintain soil moisture is to plant vegetables around the grounding electrodes. Vegetables retard runoff

and retain irrigation water and salts in the soil, helping to keep the area moist and the salts dissolved [45].

*** Chemical treatments**

The use of ion-producing chemical compounds like sodium chloride, magnesium sulfate, copper sulfate, and calcium chloride around the grounding electrodes decreases the soil resistivity and grounding resistance. It indirectly increases the diameter of the electrode by modifying the surrounding soil.

*** Bentonite**

Bentonite is fine-grained plastic clay formed by volcanic action. It is chemically hydrated, innately stable, and retains its properties over time [45]. It absorbs moisture from the surrounding soil and swells up to several times its dry volume. Bentonite adheres to the surface of the grounding rods and cables lay in trenches, reducing the contact resistance and increasing their diameter artificially.

*** Chemical rods**

Chemical rods are suitable for high resistivity areas. This type of rod is a tube filled with mineral salts distributed evenly. It has holes along its length, allowing the entry of soil moisture. The moisture combines with the salts and dissolves them. The saline solution then seeps out through the holes and soaks into the surrounding soil, continuously conditioning a large volume around it.

*** Grounding enhancement fill**

Replacing all or part of the soil around an electrode with a low resistivity filler will facilitate the achievement of low ground resistance. The higher the percentage of earth swapped, the lower the ground resistance.

4.4 Proposed solutions for failure reduction

• Distribution poles failure reduction

Wooden poles need to be treated to reduce the effect of climate, fungi, and other factors before being installed. Three approaches can be used to protect timber poles from attack by these factors [46].

- Addition of chemicals to timber
- Modification of the timber to change the chemical structure of the wood components for making them resistant to degradation by fungi attacks
- Appropriate structural design; selecting timber of the required durability to carry out specific functions, construction detailing, and the use of physical barriers

To reduce the vulnerability of decayed wooden poles, regular maintenance, repair, or periodic replacement can be employed [47]. Delaying maintenance could lead to a higher probability of poles failure, higher corrective costs, and lower system performance [10]. Various adaptation measures like alterations to design or maintenance practices using

larger poles installation and more frequent inspections can be employed [31].

Another potential strategy is the use of fiber-reinforced polymers (FRP) to repair and strengthen decayed poles [48]. FRP are strands of carbon-fiber reinforcement arranged in parallel and cast into an epoxy coating and applied to the exterior of structural elements. It has an exceptional tensile capacity, so the application of FRP to the extreme tension fiber of a structural cross-section can increase the bending capacity of the structural element.

There are tilted, cracked, poor foundation poles. Each weak point makes the distribution feeder vulnerable to failure. Therefore, proper rehabilitation is required to minimize the problems. During visual inspection, some wooden poles are replaced with concrete. But still, there are many wooden poles of MV which are highly vulnerable.

In addition, poles with poor foundations are identified during the inspection. This could make the poles unstable and could cause failure. Thus, replacing or relocation is need for minimizing the risk of hazard from falling over humans and livestock. Also, it helps to limit power outages and maintenance or repair costs to the utility.

Maintenance has a higher impact on system reliability. A quality maintenance program can play a significant role in restoring or improving the reliability of infrastructure components. A quality maintenance program includes several actions that need to be carried out at regular intervals to maintain the required system performance. The actions are minimal repair, overhauling, and replacement. Replacement enables the system to be brought back to a fully restored state. The minimal repair for wooden poles is the insertion of the pole saver rod into the decaying pole.

Most wood poles condemn because of the degradation of strength from decay at the ground line. When this degradation strength is far beyond treatment, mechanical reinstatement or quick pole reinstatement is the last action to extend the life of poles. Reinstatement can provide an additional ten to fifteen years of service life for a cost of around 20-30 percent of the initial cost [4].

- **Distribution transformers failure reduction**

The first and foremost important thing for distribution transformer and other components failure reduction is periodic inspection and maintenance. Problems that could be solved easily would evolve to more complex conditions and result in higher costs.

Every inspection or maintenance has its own stages. A higher frequency of sophisticated inspection and maintenance can improve the system reliability at an increased maintenance cost. However, it can reduce the cost of downtime. On the other hand, low frequency or conventional inspection and replacement during failure can reduce the inspection and maintenance cost. But it can increase downtime costs and the risks associated with the failure. Maintenance is worthwhile if its additional cost is less than the saving from the reduced failure costs. Therefore, a tradeoff is required between no inspection and repair/replacement during failure vs over or unnecessary replacements.

From the study, many of the transformers are working overloading. Thus, it is clear that expansion planning is required. For the appropriate expansion plan, investigating the actual load demand and the future load growth is needed.

Some transformers are operating with lightly loading. Thus, it less costly option to shift loads from loaded to under load transformers. Transformers without protection devices like silica jell, surge arrester, spark arc, and other components need frequent solutions.

Chapter 5

Conclusions, Recommendations and Future Works

5.1 Conclusions

Distribution system failure is a common problem in Ethiopian Electric utility network. In the capital, Addis Ababa, power interruption is frequent phenomena. Identification and coming up with the causes of interruptions helps to take appropriate action for maintenance and repair works.

In this thesis, the causes of interruption and vulnerability of the existing components of the Kotebe distribution system are studied. The causes are identified using the data collected from the utility East Addis Ababa Region (EAAR) maintenance offices. The most common identified causes of interruption are weather-related factors like rain, wind, and lightning. Old conductors breaking, trees falling on lines, accidents, and others are also identified. There are also overloaded distribution transformers. Many of the distribution networks are in a poor state of repair. From visual inspection, there are not only interruption problems but also higher safety risks to the customers.

For the component-wise study, one feeder is selected based on the frequency of interruption. Feeder 6 of the substation is the most frequently interrupted line. The existing conditions of the components on this feeder are inspected. Distribution poles, conductors, insulators, transformers, and protection devices are assessed.

The selected feeder covers over 24km distance. During the inspection, 705 poles are observed. Cracked, poor foundation and tilted wooden poles are identified. The exact location of these poles is depicted using 3D map (section 3.4.1.1), which helps maintenance workers to give attention to maintenance and replacement. The in-ground wooden pole's outer surface decay characteristic is modeled using weather data collected from NMA. The vulnerability of these distribution poles due to the weather influence is studied using COMSOL and timber life software. The result indicates that poles above 20 years of age in the utility distribution are at risk of failure and need immediate replacement or exigent maintenance. In addition, the Centre and outer surface decay characteristics indicate that wooden poles need replacement or quick maintenance below 15 years.

The vulnerability of wooden poles due to wind and gravitational force of tilted poles is also studied through COMSOL software. The resilience condition is studied using deflection

angles. The deflection angle with single disturbance can range from 1.117 to 1.749° for poles tilted by 0° to 25° respectively. The effect will be severe for continuous disturbance. Thus, poles could enter from resilience to moderately resilience condition and from moderately resilience to non-resilience condition. The effect of wind considering decay is also simulated. The deflection angle could range from 1.25° to 3.05° for poles tilted by 0° to 25° respectively. Higher deflection makes the distribution more vulnerable to failure.

The distribution transformers are the other important component considered for the study. About 157 transformers are identified on the selected feeder. From a specific time loading records data for three days, many of the transformers are working overloaded. The effect of loading on the life of transformers is analyzed using the IEEE guide. Only 74 of 157 transformers could sustain the standard 20.55 years. Also, 95 transformers are expected to sustain above one year. The remaining transformers will lose their life within one year. But, the most appropriate investigation needs 24 hours records for many days. As the duration of records increase, the accuracy of the result will be higher. Here, the study is to emphasize the vulnerability of distribution transformers with overloading.

The effect of lightning at different terminals of the distribution transformers is simulated using Matlab/Simulink by considering the effect of both the soil resistivity and size of rods used for grounding. The results indicate that the surge level becomes higher as the rod sizes are below the required standard. When lightning block is placed at bus 1 of transformers having surge arrester, the surge magnitude is higher around this bus and decreases with increasing distance of the receiving end. When it placed at the receiving end, the surge around the strike will be higher and decrease to a lower value at sending end. Thus, the surge magnitude for transformers having surge arresters is higher around the strike point and decreases to a lower value for distant buses. The emphasis is required to reduce the utility conventional practice of surge arresters installation without soil resistivity study. The solutions that needed to be taken are also recommended.

The problems identified in the study area are usually experienced in other areas of the country as well. Thus, the utility is needed to pay attention to those measures to reduce the problems.

5.2 Recommendations

The reliable power supply is a determinant factor for once country development. For every interruption, both the utility and customer would lose money, which is a higher crisis for a developing country like Ethiopia. Thus, the EEU needs to pay attention to the losses due to the interruption.

The utility needs to improve the distribution system infrastructure. Many of the distribution poles, conductors, and insulators are vulnerable to failure with simpler disturbance. Thus, rehabilitation is essential to reduce the problems. It should be based on the study of the existing as well as proper planning future demand forecast.

Many of the transformers are working overloaded. Thus, expansion planning is required. Load unbalances, protection device problems, and other control components can be easily maintained or replaced with proper periodic inspection and maintenance. More emphasis should be on pre-maintenance (inspection) than maintenance after fault happens.

5.3 Suggestions for future work

Due to the broad scope of the study, the following topics are not covered by the thesis and recommended for the future work.

1. The effect of improper expansion planning and rehabilitation study for the failure of distribution system is recommended.
2. The analysis of thermal characteristics of distribution transformers during lightning using COMSOL could be carried out to analyze its severe effect and suggested as future work.
3. Lightning effect on the distribution system failure analysis using Electromagnetic Transient Program (EMTP) software is also recommended for future work.

Bibliography

- [1] Lou van der Sluis, "Transients in power systems," KEMA high power laboratory facilities Netherlands , 2001
- [2] Li Wang, "The fault causes of overhead lines in distribution network," MATEC web of conferences, 2017
- [3] Richard E. Brown, "Electric power distribution reliability," CRC Press, North Carolina, 2017
- [4] United States department of agriculture, "Wood pole inspection and maintenance," Transmission branch, Electric staff division, April 15, 1996
- [5] IEC 60050-191, "Dependability and quality of service," International electro-technical vocabulary, 1990
- [6] Edvard, "The most common failure modes of electrical equipment in distribution systems," Electrical engineering portal, May 2021
- [7] Yakup K, Martijn W, Robert E. K, Frances M.T. B, "Structural vulnerability assessment of electric power grids," IEEE International Conference on Networking, Sensing and Control, Miami, FL, USA, 7-9 April 2014
- [8] Reza T. "Application of polymer based composites: Polymer based composite insulators," Shahrood university of technology, Shahrood, Iran, 2019
- [9] Timber service life design guide 5, Australia, 2016
- [10] E. D. Gezer, A. Temiz, T. Yüksek, "Inspection of wooden poles in electrical power distribution networks in Artvin," Advances in materials science and engineering, Turkey 2015
- [11] Loading guide for oil-immersed power transformers, IEC publication 354, 1991
- [12] Md. M. Alam, B. E. Tokgoz, S. Hwang, "Framework for measuring the resilience of utility poles of an electric power distribution network," Springer publisher, 24 May 2019
- [13] Radomír G, Michal K, Stanislav R, "Analysis of failures in electrical distribution system," Electric power engineering conference, January 2009
- [14] O. Quiroga, J. Meléndez, S. Herraiz, "Fault causes analysis for feeders of power distribution networks," International conference on renewable energies and power quality (ICREPQ), Las Palmas Spain, 13 to 15th April 2011

- [15] Brischke, C. and Rapp, A. O, "Influence of wood moisture content and wood temperature on fungal decay in the field," Georg august universität göttingen, Wood science and technology, December 2008
- [16] Chi-hsiang Wang, "Vulnerability of timber in ground contact to fungal decay under climate change," CSIRO ecosystem sciences, Highett, Victoria, Australia, 2012
- [17] Jad El Najjar, Samir Mustapha, "Condition assessment of timber utility poles using ultrasonic guided waves," Mechanical Engineering, American University of Beirut, Beirut, Lebanon, 2020
- [18] A. M. Salmana, Y. Lia, E. B.Arteagab, "Maintenance optimization for power distribution systems subjected to hurricane hazard," Reliability engineering, March 2017
- [19] Alam, M.M, B. E. Tokgoz, M. Safa and S. Hwang, "Evaluation of effects of wind speed on resilience of electric pole," 2018 IISE Annual conference, Orlando, Florida, USA, May 2018.
- [20] Emilia Hamed, "Electrical connection for aluminum conductors in automotive applications," KTH Skolan for industrial teknik och management, Stockholm, Sverige, 2017
- [21] Ilya G., Petro G., Taras G., "Power distribution system conductor sizing as viewed from thermodynamics principles," American society for engineering education annual conference and exposition, 2002
- [22] Shahriarkhan, "Failure characterization of distribution insulators and new method of predictive maintenance," PHD dissertation graduate studies of Texas A and M university December, 1997
- [23] P.K. Sen, S. Pansuwan, K. Malmedal, O. Martinoo, M. G. Simoes, "Transformer overloading and assessment of loss of life for liquid filled transformers," Final project report, Colorado school of mines, PSERC publication, February 2011
- [24] Ayalsew T, Getachew B, "Distribution transformer failure study and solution proposal in Ethiopia," 2020 IEEE PES/IAS PowerAfrica, Kenya, Nairobi, October 2020
- [25] IEEE guide for loading mineral-oil-immersed transformers, IEEE C57.91-1995
- [26] Swiss quality weather forecasting, accessed June 2021, <https://meteologix.com/et>
- [27] C.M. Chu, J.F. Moon, H.T. Lee, J.C. Kim, "Extraction of time-varying failure rates on power distribution system equipment considering failure modes and regional effects," Electrical Power and Energy Systems, www. elsevier.com, 2010
- [28] William F. Horton and Curt A. Volkmann, "The failure rates of overhead distribution system components," IEEE, 1991
- [29] Mills E. "Extreme grid disruptions and extreme weather," Lawrence berkeley national laboratory, U.S. disaster reanalysis workshop; May 3, 2012

- [30] Wilson A. Vasquez, Jesús Játiva-Ibarra, "Advanced aging failure model for overhead conductors," IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT- Europe), 26-29 Sept. 2017
- [31] Paraic C. Ryan, Mark G. Stewart, "Cost-benefit analysis of climate change adaptation for power pole networks," US department of agriculture, 2017
- [32] J. Zheng, L. Xie, X. Tan, W. Fang, X. Qiao, "Failure Analysis and Suggestions of Composite Insulators," IOP Conference Series: Earth and Environmental Science, Hohhot 010020, China, 2019
- [33] Pydikondala G, Senthilkumar A, "Cause and impact of protection failure due to power distribution system," International journal in physical and applied sciences, Vol.03, July 2016
- [34] Carl Johan Wallnerström, and Patrik Hilber, "Vulnerability analysis of power distribution systems for cost-effective resource allocation," transactions on power system, Vol. 27, February 2012
- [35] U.S. department of energy office of energy assurance, "Vulnerability assessment methodology electric power infrastructure," September 30, 2002
- [36] Md. M. Alam, B. E. Tokgoz, S. Hwang, "Framework for measuring the resilience of utility poles of an electric power distribution network," May 24, 2019
- [37] "COMSOL Multiphysics reference manual," COMSOL AB, Stockholm, Sweden, 2019
- [38] A. Piantini, "Lightning protection of overhead power distribution lines," 29th International conference on lightning protection, Uppsala, Sweden, 2008
- [39] Akansha S, Jyotsna B, Debabrata D, "Vulnerability analysis of power grid network against failures by state classification," www.researchgate.com, August 2013
- [40] Rodney H.G. Tan and Vigna K. Ramachandaramurthy, "A Comprehensive modeling and simulation of power quality disturbances using Matlab/Simulink," Power quality issues in distributed generation, 2015
- [41] Amin A, Ludovic G, Franco R, "Review of major approaches to analyze vulnerability in power system," Reliability engineering and system safety, November 2018
- [42] IEEE Std 80-2000, "Guide for range of soil resistivity," New York, USA, August 4, 2000
- [43] Aschalew Lakew Haile, EAIR-NFALRC, Otto Moog, "Top-down operative stream classification system (typology) for Ethiopian," Australian development corporation, June 2016
- [44] IEC 354:1991, IEC 354:1991/Corr.1:1992, "Loading guide for oil-immersed transformers"
- [45] Edvard, "Ways to improve earth electrode resistance," Electrical engineering portal, November 25, 2016

- [46] Eaton R. A. and Hale, M. D. C., "Wood decay pests and protection," Chapman and hall, London 1993
- [47] Ryan, Paraic C, Stewart, Mark G, "Probabilistic analysis of climate change impacts on timber power pole networks," 6th International symposium on reliability engineering and risk management, Singapore, May 31, 2018
- [48] N. F. Grace, G. A. Sayed, A. K. Soliman and K. R. Saleh, "Strengthening reinforced concrete beams using fiber reinforced polymer (FRP) laminates," ACI agricultural journal, October 1999

Appendix A

Causes of Kotebe Distribution System Failure

Table A.1: Causes of Kotebe distribution system failure in each month

Month	Rain	Line and transformer Overloading	Wind	Tree	Phase Reversal	Phase Unbalance	Cable noise sound	Car Accident	UF	Operation	Lighting	Unknown
January	1	4	25	6	8	4	2	2	0	74	4	78
February	6	9	12	16	6	7	3	7	1	59	17	60
March	4	5	22	11	31	12	1	6	0	89	9	47
April	6	11	30	12	2	9	3	6	0	79	5	66
May	12	20	8	20	0	12	2	5	0	199	19	47
June	31	14	17	33	1	18	3	4	0	211	18	71
July	28	27	25	23	2	13	2	4	0	41	27	46
August	39	12	8	21	1	17	3	4	4	87	24	67
September	16	3	8	17	0	10	0	5	0	56	15	85
October	13	4	34	15	0	8	3	10	0	64	17	88
November	11	2	21	19	0	16	2	3	0	59	14	87
December	7	20	18	10	1	12	2	3	0	87	11	96
Total	174	131	228	203	52	138	26	59	5	1105	180	838

Appendix B

Kotebe Distribution System

Transformers Loading

Table B.1: Loading of the distribution transformers on feeder 6 of Kotebe substation

No.	Capacity (kVA)	Total load current (A)	Rated current (A)	Loading (in %)
1	630	586.25	909.35	64.44
2	1250	545.40	1804.27	30.21
3	630	649.35	909.35	71.37
4	630	480.22	909.35	52.78
5	630	579.54	909.35	63.67
6	315	386.23	454.68	84.90
7	100	144.34	144.34	99.76
8	200	150.13	288.68	51.96
9	100	153.43	144.34	105.99
10	50	161.22	72.17	223.08
11	100	164.43	144.34	113.61
12	315	396.49	454.68	87.095
13	315	585.65	454.68	128.66
14	315	633.67	454.68	139.22
15	315	495.17	454.68	108.87
16	50	108.21	72.17	149.64
17	200	275.55	288.68	95.26
18	100	337.87	144.34	233.47
19	315	436.19	454.68	95.89
20	200	388.17	288.68	134.40
21	200	306.13	288.68	106.00
22	630	783.41	909.35	86.11
23	100	205.11	144.34	142.02
24	630	717.29	909.35	78.85
25	315	547.10	454.68	120.30
26	200	100.43	288.68	34.64

Table B.1 – *Continued from previous page*

27	315	376.78	454.68	82.70
28	315	747.24	454.68	164.29
29	315	847.87	454.68	186.29
30	315	469.56	454.68	103.15
31	200	303.08	288.68	104.96
32	100	198.38	144.34	137.17
33	315	488.28	454.68	107.33
34	315	770.09	454.68	169.35
35	800	894.29	1154.73	77.42
36	100	218.11	144.34	151.03
37	800	806.48	1154.73	69.80
38	315	470.23	454.68	103.37
39	200	447.27	288.68	154.84
40	100	224.11	144.34	155.19
41	25	163.43	36.09	451.71
42	50	189.27	72.17	261.88
43	100	229.84	144.34	158.65
44	200	195.45	288.68	67.55
45	100	163.37	144.34	112.93
46	100	168.29	144.34	116.39
47	315	373.21	454.68	82.04
48	200	132.03	288.68	45.72
49	315	559.01	454.68	122.94
50	25	149.67	36.09	412.91
51	800	197.57	1154.73	17.06
52	200	374.38	288.68	129.55
53	315	430.48	454.68	94.57
54	315	468.12	454.68	102.93
55	200	130.72	288.68	45.03
56	315	667.26	454.68	146.70
57	315	242.56	454.68	53.22
58	315	361.26	454.68	79.40
59	315	335.10	454.68	73.68
60	200	165.67	288.68	57.16
61	25	69.38	36.09	191.21
62	25	90.20	36.09	249.41
63	200	1150.21	288.68	398.36
64	200	1168.10	288.68	404.60
65	100	365.23	144.34	252.87
66	200	427.11	288.68	147.91
67	200	196.19	288.68	67.90
68	50	150.47	72.17	207.84

Table B.1 – *Continued from previous page*

69	315	530.01	454.68	116.57
70	315	505.21	454.68	111.07
71	800	530.32	1154.73	45.90
72	100	120.38	144.34	83.14
73	630	598.19	909.35	65.76
74	630	725.38	909.35	79.73
75	100	247.22	144.34	171.12
76	100	253.84	144.34	175.28
77	25	83.67	36.09	230.01
78	630	497.20	909.35	54.65
79	630	598.33	909.35	65.76
80	25	78.11	36.09	216.15
81	100	244.05	144.34	169.04
82	200	552.23	288.68	191.21
83	200	479.74	288.68	165.92
84	200	515.78	288.68	178.40
85	25	73.33	36.09	202.30
86	315	433.06	454.68	95.23
87	25	63.23	36.09	174.59
88	25	57.80	36.09	157.96
89	315	441.22	454.68	96.99
90	315	424.13	454.68	93.2531
91	100	245.28	144.34	169.7360
92	25	230.89	36.09	637.3760
93	315	278.80	454.68	61.1423
94	200	305.23	288.68	105.6520
95	25	74.12	36.09	205.0688
96	200	518.07	288.68	179.4352
97	200	510.23	288.68	176.6640
98	200	477.11	288.68	165.2328
99	200	459.22	288.68	158.9976
100	200	435.39	288.68	150.6840
101	200	413.67	288.68	143.0632
102	200	320.55	288.68	110.8480
103	200	295.25	288.68	102.1880
104	100	199.45	144.34	137.8672
105	315	290.12	454.68	63.7816
106	315	242.89	454.68	53.2246
107	200	252.23	288.68	87.2928
108	25	72.54	36.09	199.5264
109	50	74.12	72.17	102.5344
110	200	351.11	288.68	121.5864

Table B.1 – *Continued from previous page*

111	630	615.43	909.35	67.6305
112	200	274.12	288.68	94.9136
113	50	74.43	72.17	102.5344
114	200	317.17	288.68	109.8088
115	50	93.54	72.17	128.8608
116	100	311.11	144.34	215.4608
117	200	404.13	288.68	139.9456
118	200	430.44	288.68	148.9520
119	315	524.13	454.68	115.2467
120	200	454.87	288.68	157.2656
121	200	489.34	288.68	169.3896
122	200	435.45	288.68	150.6840
123	200	310.10	288.68	107.3840
124	315	288.08	454.68	63.3417
125	200	187.78	288.68	64.7768
126	50	189.56	72.17	261.8784
127	200	184.23	288.68	63.7376
128	315	386.33	454.68	84.8955
129	315	406.56	454.68	89.2942
130	200	319.07	288.68	110.5016
131	200	399.56	288.68	138.2136
132	200	421.36	288.68	145.8344
133	200	327.63	288.68	113.2728
134	200	265.12	288.68	91.7960
135	200	390.78	288.68	135.0960
136	200	221.43	288.68	76.5544
137	200	299.25	288.68	103.5736
138	200	363.17	288.68	125.7432
139	200	351.13	288.68	121.5864
140	200	383.47	288.68	132.6712
141	400	395.38	577.37	68.4140
142	200	327.14	288.68	113.2728
143	200	336.43	288.68	116.3904
144	200	413.24	288.68	143.0632
145	200	304.37	288.68	105.3056
146	200	322.22	288.68	111.5408
147	200	395.34	288.68	136.8280
148	200	548.53	288.68	189.8272
149	315	480.07	454.68	105.5695
150	200	166.14	288.68	57.5024
151	200	144.82	288.68	49.8816
152	200	263.25	288.68	91.1032

Table B.1 – *Continued from previous page*

153	200	517.57	288.68	179.0888
154	200	513.28	288.68	177.7032
155	200	540.24	288.68	187.0560
156	200	238.83	288.68	82.4432
157	100	207.56	144.34	143.4096

Appendix C

Transformers Hotspot Temperature and Loss of Life

Table C.1: Summary of hotspot temperature (T_{HS}), ageing acceleration factor (F_{AA}) and % of loss of life transformers

Number of transformers	Ambient temperature(T_A)	K (actual to rated load ratio)	ΔT_{TO}	ΔT_H	Hot spot temperature (T_{HS} in $^{\circ}C$)	F_{AA} (Aging acceleration factor)	% of loss of life (L)
1	17.55	0.644414	38.0908	7.426	63.0668	0.0042134	5.6179E-05
2	17.55	0.302061	20.9397	2.20924	40.6989	0.00017477	2.3302E-06
3	17.55	0.713694	42.6836	8.74401	68.9776	0.00911324	0.00012151
4	17.55	0.527848	31.1575	5.39641	54.104	0.00124019	1.6536E-05
5	17.55	0.636716	37.6016	7.28458	62.4362	0.00387426	5.1657E-05
6	17.55	0.848955	52.5862	11.5427	81.6789	0.04383682	0.00058449
7	17.55	0.997632	64.7949	14.9432	97.2881	0.26066933	0.00347559
8	17.55	0.5196	30.7068	5.26213	53.519	0.00114237	1.5232E-05
9	17.55	1.059984	70.3015	16.4653	104.317	0.55438574	0.00739181
10	17.55	2.230816	209.315	54.1543	281.019	178013.723	2373.51631
11	17.55	1.136192	77.3276	18.3998	113.277	1.39417223	0.01858896
12	17.55	0.870949	54.3076	12.0248	83.8824	0.05691733	0.0007589
13	17.55	1.286629	92.113	22.45	132.113	8.48061822	0.11307491
14	17.55	1.392198	103.183	25.4691	146.202	29.4369948	0.39249326

Table C.1 – *Continued from previous page*

15	17.55	1.088686	72.9101	17.1844	107.645	0.78477638	0.01046369
16	17.55	1.496448	114.654	28.5884	160.792	98.0743246	1.30765766
17	17.55	0.9526	60.9574	13.8787	92.3861	0.15137838	0.00201838
18	17.55	2.334736	224.527	58.2468	300.324	442967.784	5906.23712
19	17.55	0.958923	61.4891	14.0264	93.0655	0.16336204	0.00217816
20	17.55	1.344032	98.0632	24.0739	139.687	16.7323519	0.22309803
21	17.55	1.059984	70.3015	16.4653	104.317	0.55438574	0.00739181
22	17.55	0.861051	53.5293	11.807	82.8862	0.05059956	0.00067466
23	17.55	1.42024	106.217	26.2948	150.062	40.7996022	0.5439947
24	17.55	0.788472	48.0103	10.2553	75.8156	0.02153292	0.00028711
25	17.55	1.203053	83.7518	20.1626	121.464	3.12128533	0.04161714
26	17.55	0.3464	22.5778	2.75053	42.8783	0.00024307	3.241E-06
27	17.55	0.826961	50.8952	11.068	79.5132	0.03380629	0.00045075
28	17.55	1.642926	131.641	33.1956	182.387	505.449902	6.73933202
29	17.55	1.862862	158.974	40.5864	217.11	5214.11808	69.5215744
30	17.55	1.031502	67.7587	15.7632	101.072	0.39268244	0.00523577
31	17.55	1.049592	69.3684	16.2078	103.126	0.48883226	0.00651776
32	17.55	1.371744	100.995	24.873	143.418	23.1730928	0.30897457
33	17.55	1.07329	71.5051	16.7973	105.852	0.65131427	0.00868419
34	17.55	1.693511	137.737	34.8459	190.133	876.885382	11.6918051
35	17.55	0.774204	46.9652	9.96001	74.4752	0.01824149	0.00024322
36	17.55	1.510304	116.218	29.0131	162.781	114.83742	1.5311656
37	17.55	0.697996	41.6135	8.43832	67.6018	0.00763353	0.00010178
38	17.55	1.033702	67.9534	15.817	101.32	0.40327768	0.00537704
39	17.55	1.548408	120.565	30.1931	168.308	176.73389	2.35645187
40	17.55	1.551872	120.964	30.3013	168.815	183.760049	2.45013398
41	17.55	2.517056	252.229	65.6931	335.472	2007869.02	26771.5869
42	17.55	2.618784	268.235	69.9924	355.777	4451108.2	59348.1093
43	17.55	1.586512	124.981	31.3907	173.921	270.841593	3.61122123
44	17.55	0.67548	40.1085	8.00703	65.6655	0.00593433	7.9124E-05
45	17.55	1.129264	76.6757	18.2207	112.446	1.28219238	0.0170959
46	17.55	1.163904	79.9612	19.1231	116.634	1.94810836	0.02597478
47	17.55	0.820363	50.3939	10.927	78.8709	0.03127993	0.00041707
48	17.55	0.457248	27.4797	4.28878	49.3184	0.00062777	8.3703E-06
49	17.55	1.229445	86.3529	20.875	124.778	4.28450216	0.0571267
50	17.55	2.129088	194.84	50.2575	262.648	70334.2872	937.790496
51	17.55	0.170602	17.2821	0.88566	35.7177	8.0796E-05	1.0773E-06
52	17.55	1.295536	93.0254	22.6992	133.275	9.42763052	0.12570174
53	17.55	0.945727	60.3822	13.7188	91.651	0.13935538	0.00185807
54	17.55	1.029303	67.5643	15.7094	100.824	0.38236615	0.00509822
55	17.55	0.45032	27.1412	4.18529	48.8765	0.00058891	7.8522E-06
56	17.55	1.466977	111.358	27.6929	156.601	69.9903366	0.93320449

Table C.1 – *Continued from previous page*

57	17.55	0.532246	31.4002	5.46854	54.4187	0.00129608	1.7281E-05
58	17.55	0.793971	48.4166	10.37	76.3365	0.022959	0.00030612
59	17.55	0.736787	44.2886	9.20108	71.0397	0.01185349	0.00015805
60	17.55	0.57156	33.6362	6.12901	57.3152	0.00193686	2.5825E-05
61	17.55	1.912128	165.386	42.3173	225.253	8598.39115	114.645215
62	17.55	2.49408	248.668	64.7363	330.954	1669734.38	22263.1251
63	17.55	2.9836	328.755	86.2335	432.539	59658430.5	795445.74
64	17.45	2.045952	183.323	47.1546	247.928	31878.9242	425.052323
65	17.45	2.52872	254.045	66.1809	337.675	2194630.8	29261.7441
66	17.45	1.479128	112.712	28.0608	158.223	79.8123508	1.06416468
67	17.45	0.678944	40.3377	8.07283	65.8605	0.00608755	8.1167E-05
68	17.45	2.0784	187.784	48.3568	253.591	43451.5221	579.353628
69	17.45	1.165663	80.1298	19.1694	116.749	1.97034068	0.02627121
70	17.45	1.110679	74.9399	17.7433	110.133	1.01369928	0.01351599
71	17.45	0.45898	27.5649	4.31481	49.3297	0.00062879	8.3839E-06
72	17.45	0.83136	51.231	11.1623	79.8433	0.03517922	0.00046906
73	17.45	0.65761	38.9395	7.6708	64.0603	0.00480578	6.4077E-05
74	17.45	0.79727	48.6613	10.439	76.5503	0.02356979	0.00031426
75	17.45	1.711216	139.898	35.4306	192.778	1053.9845	14.0531266
76	17.45	1.752784	145.026	36.8177	199.294	1643.50983	21.9134644
77	17.45	2.300096	219.409	56.8702	293.729	326706.544	4356.08725
78	17.45	0.546542	32.1992	5.70544	55.3547	0.00147689	1.9692E-05
79	17.45	0.65761	38.9395	7.6708	64.0603	0.00480578	6.4077E-05
80	17.45	2.161536	199.412	51.4886	268.351	94467.6304	1259.56841
81	17.45	1.690432	137.363	34.7446	189.557	842.242567	11.2299009
82	17.45	1.912128	165.386	42.3173	225.153	8546.58476	113.954463
83	17.45	1.659256	133.596	33.7251	184.771	600.067297	8.00089729
84	17.45	1.78396	148.922	37.8711	204.243	2284.70138	30.4626851
85	17.45	2.022976	180.19	46.3102	243.95	25544.1672	340.588896
86	17.45	0.952325	60.9344	13.8723	92.2566	0.14919153	0.00198922
87	17.45	1.74585	6 144.166	36.5851	198.201	1526.82505	20.3576673
88	17.45	1.579584	124.173	31.1716	172.794	248.811156	3.31748208
89	17.45	0.96992	62.4193	14.2846	94.154	0.18446328	0.00245951
90	17.45	0.932531	59.2857	13.4138	90.1495	0.11755953	0.00156746
91	17.45	1.69736	138.205	34.9727	190.628	907.759887	12.1034652
92	17.45	2.37376	230.348	59.8123	307.611	615152.728	8202.03638
93	17.45	0.611423	36.0247	6.82714	60.3018	0.00290953	3.8794E-05
94	17.45	1.05652	69.9898	16.3793	103.819	0.52602656	0.00701369
95	17.45	2.050688	183.971	47.3294	248.751	33360.7124	444.809498
96	17.45	1.794352	150.231	38.2246	205.905	2547.99273	33.9732364
97	17.45	1.76664	146.752	37.2845	201.487	1903.39433	25.378591
98	17.45	1.652328	132.765	33.5	183.715	556.284044	7.41712059

Table C.1 – *Continued from previous page*

99	17.45	1.589976	125.385	31.5004	174.336	279.396631	3.72528841
100	17.45	1.50684	115.826	28.9067	162.183	109.530269	1.46040358
101	17.45	1.430632	107.351	26.6033	151.404	45.641941	0.60855921
102	17.45	1.10848	74.7357	17.6871	109.873	0.98706744	0.0131609
103	17.45	1.02188	66.91	15.5286	99.8886	0.3457636	0.00461018
104	17.45	1.378672	101.734	25.0743	144.258	24.9163769	0.33221836
105	17.45	0.637816	37.6712	7.30472	62.426	0.00386898	5.1586E-05
106	17.45	0.532246	31.4002	5.46854	54.3187	0.00127807	1.7041E-05
107	17.45	0.872928	54.464	12.0686	83.9826	0.05759248	0.0007679
108	17.45	1.995264	176.441	45.2993	239.19	19506.273	260.08364
109	17.45	1.025344	67.215	15.6129	100.278	0.36057493	0.00480767
110	17.45	1.215864	85.0099	20.5072	122.967	3.60584186	0.04807789
111	17.45	0.676305	40.163	8.02267	65.6356	0.00591121	7.8816E-05
112	17.45	0.949136	60.6672	13.798	91.9152	0.14356747	0.00191423
113	17.45	1.025344	67.215	15.6129	100.278	0.36057493	0.00480767
114	17.45	1.098088	73.7745	17.4225	108.647	0.87036784	0.0116049
115	17.45	1.288608	92.3154	22.5053	132.271	8.6036798	0.11471573
116	17.45	2.154608	198.432	51.2248	267.107	88629.524	1181.72699
117	17.45	1.399456	103.965	25.6818	147.097	31.7667582	0.42355678
118	17.45	1.48952	113.875	28.3769	159.702	89.8930928	1.19857457
119	17.45	1.152467	78.8693	18.8234	115.143	1.68019375	0.02240258
120	17.45	1.572656	123.367	30.9532	171.77	230.262806	3.07017075
121	17.45	1.693896	137.784	34.8586	190.092	874.404888	11.6587318
122	17.45	1.50684	115.826	28.9067	162.183	109.530269	1.46040358
123	17.45	1.07384	71.5551	16.811	105.816	0.64884914	0.00865132
124	17.45	0.633417	37.3933	7.22429	62.0676	0.00368826	4.9177E-05
125	17.45	0.647768	38.3053	7.48794	63.2433	0.00431324	5.751E-05
126	17.45	2.618784	268.235	69.9924	355.677	4434250	59123.3333
127	17.45	0.637376	37.6434	7.29666	62.3901	0.00385049	5.134E-05
128	17.45	0.848955	52.5862	11.5427	81.5789	0.04331707	0.00057756
129	17.45	0.892942	56.059	12.5144	86.0233	0.07312932	0.00097506
130	17.45	1.105016	74.4146	17.5987	109.463	0.94652978	0.0126204
131	17.45	1.382136	102.104	25.1752	144.729	25.9475533	0.34596738
132	17.45	1.458344	110.4	27.4326	155.283	62.8607911	0.83814388
133	17.45	1.132728	77.0013	18.3102	112.762	1.32361003	0.01764813
134	17.45	0.91796	58.0871	13.08	88.6171	0.09868248	0.00131577
135	17.45	1.35096	98.7926	24.2728	140.515	17.995858	0.23994477
136	17.45	0.765544	46.3374	9.78236	73.5698	0.01629599	0.00021728
137	17.45	1.035736	68.1338	15.8668	101.451	0.40893604	0.00545248
138	17.45	1.257432	89.1509	21.6405	128.241	5.93288731	0.07910516
139	17.45	1.215864	85.0099	20.5072	122.967	3.60584186	0.04807789
140	17.45	1.326712	96.2504	23.5795	137.28	13.5187604	0.18025014

Table C.1 – *Continued from previous page*

141	17.45	0.68414	40.6831	8.1719	66.305	0.006451	8.6013E-05
142	17.45	1.132728	77.0013	18.3102	112.762	1.32361003	0.01764813
143	17.45	1.163904	79.9612	19.1231	116.534	1.92895006	0.02571933
144	17.45	1.430632	107.351	26.6033	151.404	45.641941	0.60855921
145	17.45	1.053056	69.6788	16.2935	103.422	0.50440634	0.00672542
146	17.45	1.115408	75.3797	17.8643	110.694	1.07340776	0.0143121
147	17.45	1.36828	100.626	24.7726	142.849	22.058675	0.29411567
148	17.45	1.898272	163.572	41.8278	222.85	7430.89034	99.0785378
149	17.45	1.055695	69.9157	16.3589	103.725	0.52079625	0.00694395
150	17.45	0.575024	33.8389	6.18855	57.4775	0.00198055	2.6407E-05
151	17.45	0.498816	29.5954	4.92942	51.9748	0.00091835	1.2245E-05
152	17.45	0.911032	57.5216	12.9225	87.8941	0.09081322	0.00121084
153	17.45	1.790888	149.794	38.1066	205.351	2457.11958	32.7615943
154	17.45	1.777032	148.053	37.636	203.139	2124.03655	28.3204873
155	17.45	1.87056	159.969	40.8551	218.274	5606.17446	74.7489928
156	17.45	0.824432	50.7027	11.0138	79.1666	0.0324197	0.00043226
157	17.45	1.434096	107.73	26.7065	151.887	47.5102841	0.63347046

Appendix D

Transformers Greater Percentage of Loss of Life than the Standards

Table D.1: Transformers having above the standard T_{HS} , F_{AA} and % loss of life

No.	Number of transformers	Ambient temperature (T_A)	K (actual to rated load ratio)	ΔT_{TO}	ΔT_H	Hot spot temperature (T_{HS} in $^{\circ}C$)	F_{AA} (Aging acceleration factor)	% of loss of life (L)
1	10	17.55	2.230816	209.315	54.1543	281.019	178013.723	2373.51631
2	11	17.55	1.136192	77.3276	18.3998	113.277	1.39417223	0.01858896
3	13	17.55	1.286629	92.113	22.45	132.113	8.48061822	0.11307491
4	14	17.55	1.392198	103.183	25.4691	146.202	29.4369948	0.39249326
5	16	17.55	1.496448	114.654	28.5884	160.792	98.0743246	1.30765766
6	18	17.55	2.334736	224.527	58.2468	300.324	442967.784	5906.23712
7	20	17.55	1.344032	98.0632	24.0739	139.687	16.7323519	0.22309803
8	23	17.55	1.42024	106.217	26.2948	150.062	40.7996022	0.5439947
9	25	17.55	1.203053	83.7518	20.1626	121.464	3.12128533	0.04161714
10	28	17.55	1.642926	131.641	33.1956	182.387	505.449902	6.73933202
11	29	17.55	1.862862	158.974	40.5864	217.11	5214.11808	69.5215744
12	32	17.55	1.371744	100.995	24.873	143.418	23.1730928	0.30897457
13	34	17.55	1.693511	137.737	34.8459	190.133	876.885382	11.6918051
14	36	17.55	1.510304	116.218	29.0131	162.781	114.83742	1.5311656
15	38	17.55	1.033702	67.9534	15.817	101.32	0.40327768	0.00537704
16	39	17.55	1.548408	120.565	30.1931	168.308	176.73389	2.35645187

Table D.1 – *Continued from previous page*

17	40	17.55	1.551872	120.964	30.3013	168.815	183.760049	2.45013398
18	41	17.55	2.517056	252.229	65.6931	335.472	2007869.02	26771.5869
19	42	17.55	2.618784	268.235	69.9924	355.777	4451108.2	59348.1093
20	43	17.55	1.586512	124.981	31.3907	173.921	270.841593	3.61122123
21	45	17.55	1.129264	76.6757	18.2207	112.446	1.28219238	0.0170959
22	46	17.55	1.163904	79.9612	19.1231	116.634	1.94810836	0.02597478
23	49	17.55	1.229445	86.3529	20.875	124.778	4.28450216	0.0571267
24	50	17.55	2.129088	194.84	50.2575	262.648	70334.2872	937.790496
25	52	17.55	1.295536	93.0254	22.6992	133.275	9.42763052	0.12570174
26	56	17.55	1.466977	111.358	27.6929	156.601	69.9903366	0.93320449
27	61	17.55	1.912128	165.386	42.3173	225.253	8598.39115	114.645215
28	62	17.55	2.49408	248.668	64.7363	330.954	1669734.38	22263.1251
29	63	17.55	2.9836	328.755	86.2335	432.539	59658430.5	795445.74
30	64	17.45	2.045952	183.323	47.1546	247.928	31878.9242	425.052323
31	65	17.45	2.52872	254.045	66.1809	337.675	2194630.8	29261.7441
32	66	17.45	1.479128	112.712	28.0608	158.223	79.8123508	1.06416468
33	68	17.45	2.0784	187.784	48.3568	253.591	43451.5221	579.353628
34	69	17.45	1.165663	80.1298	19.1694	116.749	1.97034068	0.02627121
35	75	17.45	1.711216	139.898	35.4306	192.778	1053.9845	14.0531266
36	76	17.45	1.752784	145.026	36.8177	199.294	1643.50983	21.9134644
37	77	17.45	2.300096	219.409	56.8702	293.729	326706.544	4356.08725
38	80	17.45	2.161536	199.412	51.4886	268.351	94467.6304	1259.56841
39	81	17.45	1.690432	137.363	34.7446	189.557	842.242567	11.2299009
40	82	17.45	1.912128	165.386	42.3173	225.153	8546.58476	113.954463
41	83	17.45	1.659256	133.596	33.7251	184.771	600.067297	8.00089729
42	84	17.45	1.78396	148.922	37.8711	204.243	2284.70138	30.4626851
43	85	17.45	2.022976	180.19	46.3102	243.95	25544.1672	340.588896
44	87	17.45	1.74585	6 144.166	36.5851	198.201	1526.82505	20.3576673
45	88	17.45	1.579584	124.173	31.1716	172.794	248.811156	3.31748208
46	91	17.45	1.69736	138.205	34.9727	190.628	907.759887	12.1034652
47	92	17.45	2.37376	230.348	59.8123	307.611	615152.728	8202.03638
48	95	17.45	2.050688	183.971	47.3294	248.751	33360.7124	444.809498
49	96	17.45	1.794352	150.231	38.2246	205.905	2547.99273	33.9732364
50	97	17.45	1.76664	146.752	37.2845	201.487	1903.39433	25.378591
51	98	17.45	1.652328	132.765	33.5	183.715	556.284044	7.41712059
52	99	17.45	1.589976	125.385	31.5004	174.336	279.396631	3.72528841
53	100	17.45	1.50684	115.826	28.9067	162.183	109.530269	1.46040358
54	101	17.45	1.430632	107.351	26.6033	151.404	45.641941	0.60855921
55	104	17.45	1.378672	101.734	25.0743	144.258	24.9163769	0.33221836
56	108	17.45	1.995264	176.441	45.2993	239.19	19506.273	260.08364
57	110	17.45	1.215864	85.0099	20.5072	122.967	3.60584186	0.04807789
58	115	17.45	1.288608	92.3154	22.5053	132.271	8.6036798	0.11471573

Table D.1 – *Continued from previous page*

59	116	17.45	2.154608	198.432	51.2248	267.107	88629.524	1181.72699
60	117	17.45	1.399456	103.965	25.6818	147.097	31.7667582	0.42355678
61	118	17.45	1.48952	113.875	28.3769	159.702	89.8930928	1.19857457
62	119	17.45	1.152467	78.8693	18.8234	115.143	1.68019375	0.02240258
63	120	17.45	1.572656	123.367	30.9532	171.77	230.262806	3.07017075
64	121	17.45	1.693896	137.784	34.8586	190.092	874.404888	11.6587318
65	122	17.45	1.50684	115.826	28.9067	162.183	109.530269	1.46040358
66	126	17.45	2.618784	268.235	69.9924	355.677	4434250	59123.3333
67	131	17.45	1.382136	102.104	25.1752	144.729	25.9475533	0.34596738
68	132	17.45	1.458344	110.4	27.4326	155.283	62.8607911	0.83814388
69	133	17.45	1.132728	77.0013	18.3102	112.762	1.32361003	0.01764813
70	135	17.45	1.35096	98.7926	24.2728	140.515	17.995858	0.23994477
71	138	17.45	1.257432	89.1509	21.6405	128.241	5.93288731	0.07910516
72	139	17.45	1.215864	85.0099	20.5072	122.967	3.60584186	0.04807789
73	140	17.45	1.326712	96.2504	23.5795	137.28	13.5187604	0.18025014
74	142	17.45	1.132728	77.0013	18.3102	112.762	1.32361003	0.01764813
75	143	17.45	1.163904	79.9612	19.1231	116.534	1.92895006	0.02571933
76	144	17.45	1.430632	107.351	26.6033	151.404	45.641941	0.60855921
77	147	17.45	1.36828	100.626	24.7726	142.849	22.058675	0.29411567
78	148	17.45	1.898272	163.572	41.8278	222.85	7430.89034	99.0785378
79	153	17.45	1.790888	149.794	38.1066	205.351	2457.11958	32.7615943
80	154	17.45	1.777032	148.053	37.636	203.139	2124.03655	28.3204873
81	155	17.45	1.87056	159.969	40.8551	218.274	5606.17446	74.7489928
82	157	17.45	1.434096	107.73	26.7065	151.887	47.5102841	0.63347046

Appendix E

EEU Overhead Medium Voltage Distribution Conductors Size

Table E.1: EEU overhead medium voltage distribution conductors specifications

Nominal Area (mm^2)	Stranding No. *mm	Overall Diameter (mm)	GMR (mm)	Resistance Ω/km	Inductance Ω/km	Rated current (A)
500	61/3.2	37	14.2857	0.0722	0.2461	752
400	61/2.85	33.5	12.934	0.09651	0.253	616
300	61/2.52	29.5	11.3899	0.1191	0.261	530
250	61/2.25	26.5	10.232	0.1587	0.2674	471
200	37/2.52	23.5	8.8803	0.196	0.2763	412
150	37/2.25	15.8	6.066	0.2256	0.30024	309
120	19/2.8	14	5.304	0.2831	0.3087	269
95	19/2.5	12.5	1.89	0.3551	0.374	234
50	7/3.0	9	3.27	0.666	0.3391	158
35	7/2.5	7.5	2.72	0.9591	0.3506	126
25	7/2.1	6.3	2.286	1.3591	0.362	102