Enhancement of Distribution System Reliability with Distributed Generation

(Case Study: Mojo Distribution Substation)

Karu Elemo Fole

A thesis submitted to the Department of Electrical Power and Control Engineering
College of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of Master's in Electrical Power and Control Engineering
(Power System Engineering)

Office of Graduate Studies
Adama Science and Technology University

September, 2025
Adama Ethiopia

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DECLARATION

I declare that this thesis, **“Enhancement of Distribution System Reliability with Distributed Generation,”** is my work and has not been submitted to any university for a similar purpose. Proper citations duly recognize the references used in this proposal.

Karu Elemo Fole	____________________	____________________
Name of student	Signature	Date

RECOMMENDATION

I, this thesis's major advisor/supervisor, certify that I closely advised/supervised the student while developing this thesis entitled "Enhancement of Distribution System Reliability with Distributed Generation," Prepared under my Guidance by Karu Elemo Fole. Therefore, I recommend submitting the thesis to the department for further review and evaluation.

Dr.CS.Reddy	B. chandra sekhar Reddy	
Advisor	Signature	Date

APPROVAL PAGE

I/we hereby certify that the recommendations and suggestions given by the thesis review committee are appropriately incorporated into the final thesis entitled "Enhancement of Distribution System Reliability with Distributed Generation" by Karu Elemo Fole.

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Advisor	Signature	Date

APPROVAL PAGE OF MSc THESIS

I, the advisor of the thesis entitled **“Enhancement of Distribution System Reliability with Distributed Generation”** and developed by Karu Elemo Fole, hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr.CS.Reddy B chandra sekhar Reddy ________________ ________________

Advisor Signature Date

We, the undersigned, members of the Board of Reviewers of the thesis open defense by Karu Elemo Fole, have read and evaluated the thesis proposal entitled **“Enhancement of Distribution System Reliability with Distributed Generation”** and assessed the understanding of the candidate about the thesis. This is, therefore, to certify that the thesis is accepted, and we recommend the implementation of the thesis.

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Dr.Yeshitela Shiferaw ______________ ______________

External Examiner Signature Date

The thesis proposal's final approval and acceptance are contingent upon its submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and College Graduate Committee (CGC).

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ACRONYMS

Abbreviations	**Description**
AENS	Average Energy Not Supplied
ASAI	Average Service Availability Index
ASUI	Average Service Unavailability Index
BETB/yr	Billion Ethiopian Birr per year
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
DER	Distributed Energy Resource
DG	Distributed Generation
Dig SILENT	Digital Simulation and Electrical Network
DPEF	Distribution Permanent Earth Fault
DPSC	Distribution Permanent Short Circuit
EEA	Ethiopian Electric Agency
EENS	Expected Energy Not Supplied
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
ENS	Energy Not Supplied
IEEE	Institute of Electrical and Electronics Engineers
Int	Interruption
KVA	Kilovolt Ampere
Kwh	Kilowatt hour
METB	Million Ethiopian Birr
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MV	Medium Voltage
MVA	Mega Volt Ampere
MVAR	Mega Volt Ampere Reactive
MWh/yr.	Mega Watt hour per year
OPR	Operational

P	Active power
Pf	Power factor
PV	Photo Voltaic
Q	Reactive power
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
Syst.	System
TEF	Temporary Earth Fault
TSC	Temporary Short Circuit

ABSTRACT

This study examines how reliable the Mojo new distribution substation is and suggests ways to improve it. The main causes of the current system's reliability issues include short circuits, earth faults, overloads, aging equipment, and poor maintenance and operation practices. In this study, we used ETAP 19.0.1 software to simulate the existing system and incorporate solar distribution generators. The reliability indicators of the current system do not meet Ethiopian standards based on the results. By adding distributed generators, the reliability indices improved significantly, reducing interruption duration and the number of interruptions per customer per year while increasing availability. According to the simulation results, installing distributed generators at selected feeders improved the SAIFI value by 61.7%, the SAIDI value by 87.15%, and the ENS value by 87.08%. Additionally, the ECOST decreased from 6.3 BETB/year to 105 METB/year, with an average revenue saving of 6.25 BETB/year. The study recommends connecting distributed generators to the existing system, and pre-maintenance (replace aging equipment and tree trimming) enhances the overall reliability of the network

Key Words: Distributed Generator, SAIDI, SAIFI, Distribution System reliability, ETAP

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Given that an electric supply is vital to an industry's operation, the economy, and even an extended family's daily life, the power systems must be reliable. Each utility company is responsible for providing its consumers with a certain level of service continuity and quality, which could include restrictions on load, voltage, and frequency within specified levels. Therefore, there should be a good balance between providence and trustworthiness (security) when making a functional decision regarding unit commitment. The term "reliability of power system" refers to a customer's ongoing demand for electricity. The dependability of its power structure constrains a state's ability to function economically, politically, and technologically. That is why in this research work, the main project question is what the distribution system reliability in terms of electricity delivery dependability and safety to the customer.

Reliability in a distribution power system can be studied in two ways: system security and system acceptability. Adequacy concerns the System's availability of enough facilities, including subsystems and components capable of fulfilling coverage and meeting requirements, and fulfilling as per the demand, and at any instant satisfying the customers. Security, in this case, means the capacity to accept unexpected disruptions, like Changes in load conditions, short circuits, and any fault that the system may develop. With the growing demand for electric power, it is important to provide electric power with an optimum level of dependability, quality, and security at all times and at a reasonable cost.

Mojo City is one of the rapidly growing cities in our country in all sectors, such as the manufacturing industry, agriculture, and horticulture. The city's need for both social and economic growth creates a huge electricity demand. However, a daily warning in the area is an electric power outage. In fact, there are instances when multiple daily power outages happen, impacting distribution systems with low and medium voltages. The thesis's study area is Mojo, which is in the East Shewa Zone of Ethiopia's central Oromia Region, 22 kilometers from Adama and southeast of Addis Ababa, the country's capital.

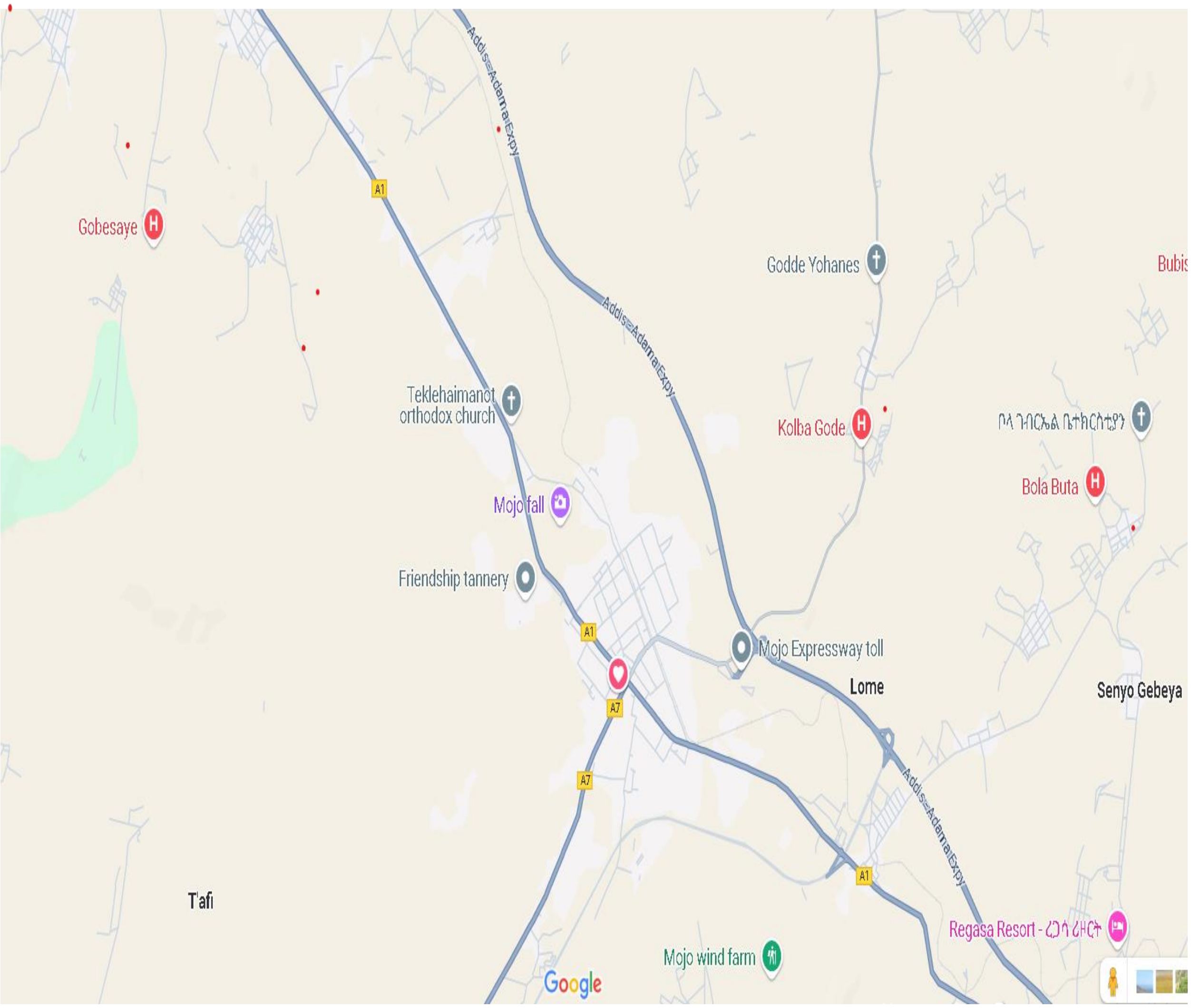


Figure 1.1: Location of Mojo Ethiopia (www.maps.com)

Mojo's New substation is connected to a 230 kV incoming feeder from Bishoftu generation II. Three transformers with capacities of two (50MVA) and twenty-five (25MVA) step down the incoming voltage to 15kV and 33kV, respectively. On the feeders, three transformers run separately. To supply the customer loads, the distribution transformer further steps down the distribution feeder voltage. Ten outgoing feeders are available at the Mojo New substation to supply electricity to residential, commercial, and industrial loads (Report, 2013-2015).

The feeder lines for the Power Transformer 230/15kV are as follows:

- ✓ L1, Mojo Town.
- ✓ L2, Bishoftu Airforce
- ✓ L3, Bishoftu Town

- ✓ L8, Mojo Tannery
- ✓ L10 Adama Water

The feeder lines for the Power Transformer 230/33kV are as follows:

- ✓ L1, Ejere
- ✓ L2, Anbesa Bira
- ✓ L3, Arerti Industry Park
- ✓ L4, Arerti Town

Figure 1.2 Overview of the Mojo New distribution substation taken during a site visit

1.2. Statement of the problem

The issue of reliability is of great concern in our daily lives. Since Mojo is the rapidly growing city of the country and a preferred location for most of the industries, a considerable share of the electric power supply is directed towards the city. Due to this fact, Mojo's new substation is one of the substations found in that face distribution inefficiency, repetitive and sporadic power interruptions, and power quality problems.

The people in the city and different towns in Ethiopia are facing problems because it is associated with their livelihood. All residential, commercial, and industrial customers are victims of the problem. Especially for factories and industries, it is really challenging to tolerate a power interruption since it causes much revenue loss within hours of interruption. So the root cause of this problem should first be identified, and the possible solution should be investigated.

1.3. Objectives of the study

1.3.1. General objective

To evaluate the reliability performance of the Mojo New Distribution Substation and investigate how distributed generation can enhance the reliability of the power distribution system.

1.3.2. Specific objectives

- To identify the main causes of reliability problems in the Mojo New Distribution Substation.
- To determine the existing system's reliability indices (SAIFI, SAIDI, CAIDI, and ENS).
- To simulate and analyze the impact of distributed generation on system reliability using ETAP software.
- To compare the reliability performance before and after DG integration.
- To propose practical recommendations for reducing unreliability in the power distribution network.

1.4. Significance of the Study

Ethiopia is currently producing a lot of electricity. One of the economic centers of our country is Mojo City. However, there are frequent and prolonged power outages. The lack of contemporary protection devices along the feeder and the difficulty in identifying the fault section are the causes of this. Enhancing the power distribution system's dependability is crucial to obtaining a steady supply of electricity.

1.5. Scope of Work

This thesis will explore the existing power system's reliability problems, their underlying causes, and the proportion of improvements that can be achieved by integrating distributed generators into the existing Mojo New Distribution substation.

1.6. Organizations of the Thesis

The thesis contains five chapters, and these are summarized briefly as follows: Background, problem statement, objectives, scope, significance, reason for DG, and study area description are included in Chapter 1. Chapter 2 provides the theoretical background and literature survey of power system reliability and distributed generation (DG). Chapter 3 presents substation data that were gathered and reliability index results that were obtained; Chapter 4 explains the simulation and compares before and after changes; and the Overall conclusion, recommendations, and future research of the thesis are explained in Chapter 5.

CHAPTER TWO

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Definition of Reliability

The main definition of distribution reliability is the uninterrupted continuation of the power supply. The probability that a system will function as it is supposed to for some period of time under given operating conditions is termed reliability. The measurement of power interruption duration and equipment outage rates is known as reliability. Power outages result from a variety of events that interfere with the distribution system's regular operation (Brown, 2017).

2.2 Literature Review

There are various reliability issues, such as the duration and frequency of interruptions. The need to measure a distribution system's performance has arisen as a result of growing awareness of power quality and reliability. Several researchers have gone beyond just studying and addressing reliability as a power quality issue in several fields.

(Azami & Fard, 2008) Power Distribution Network Reliability Analysis. The main technologies for creating a smart grid were described in this paper. However, the absence of a cause for the disruption does not explain.

(Kim & Kim, 2011) suggested a method for assessing distribution reliability that makes use of the location of the superconducting fault current limiter in a network, which affects the higher failure rate of all protective devices. As a result, these changes are investigated, and it is expected that the SFCL will improve the reliability of adjacent equipment on an existing network. This study defined distribution reliability indices and considered the impact of renewable energy sources' alternating output. Case studies demonstrate the SFCL's ability to reduce fault currents and enhance distribution reliability. These effects are analyzed in connection with the SFCL's location in a case study system.

Adegboyega, Gabriel A. (2014): This paper estimates system designs for three feeders and analyzes outage data to study power distribution system reliability. This study compares the frequency, duration, and basic reliability and customer location indicators of outages for each distribution feeder over the course of the study. However, a reliability improvement method is not included in the paper.

Thompson, Stan. (2018): The Auto recloser case was used to investigate ways to increase the reliability of the power distribution system. It described the relationship between dependability and cost as well as the recloser's performance in the distribution system. However, the reliability indexes' mathematical analysis is not explained by the writers.

2.3 Distribution Systems

Electric power systems consist of various components, including generating plants, distribution substations, transmission systems, sub-transmissions, and generating substations. Distribution systems connect the customer and the distribution substation. Electric energy can be safely and reliably transferred to different guests throughout the service home thanks to this system. Conventional distribution systems begin as a medium-voltage, three-phase circuit, usually between 11 and 66 kV, and end at a lower secondary, three- or single-phase voltage, usually below 1 kV, at the customer's location, usually at the meter (Prakash et al., 2014). Generally, Distribution feeder circuits, both overhead and underground circuits, connect branching laterals from the station to the different customers. When connecting two (2) or more feeder components, these different branching laterals can be used in a radial or spiral configuration, typically through an open distribution switch. A typical general configuration for an electric power system is shown in Figure 2.1 (Short, 2018).

2.4 Distributed generator

Generation Through Dispersion The traditional centralized power generation concept, in which electricity is produced in massive power plants and delivered to final consumers via transmission and distribution lines, is not like the DG theory. Even though central power systems are still essential to the world's energy supply, they are limited in their capacity to adapt to changing energy demands. Central power consists of transmission and distribution (T&D) grids and large capital-intensive plants. Using renewable energy reduces emissions and helps avoid the construction of large power plants and new transmission lines. Improved voltage profiles, lower power losses, and less network congestion are just a few ways that DG units can improve power quality and dependability. The power flows in conventional centralized power generation (the current system) and DG connected to the system (the proposed power flow with DG interfaced) are depicted in the figure below, respectively (Maya & Jasmin, 2015).

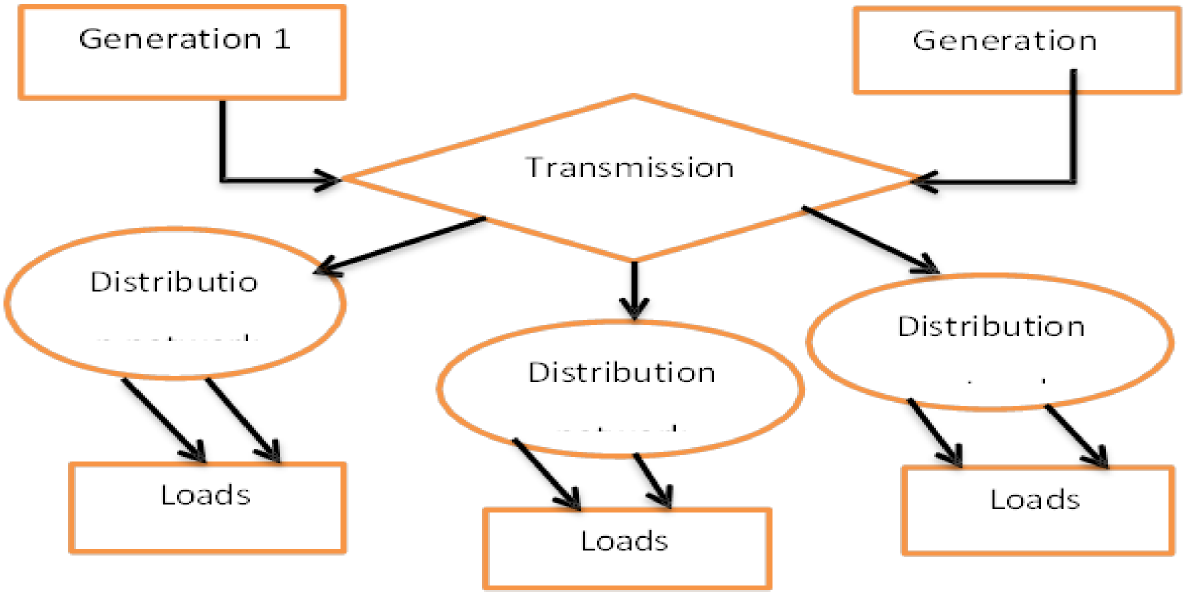


Figure 2.1: Existing power flows without DG.

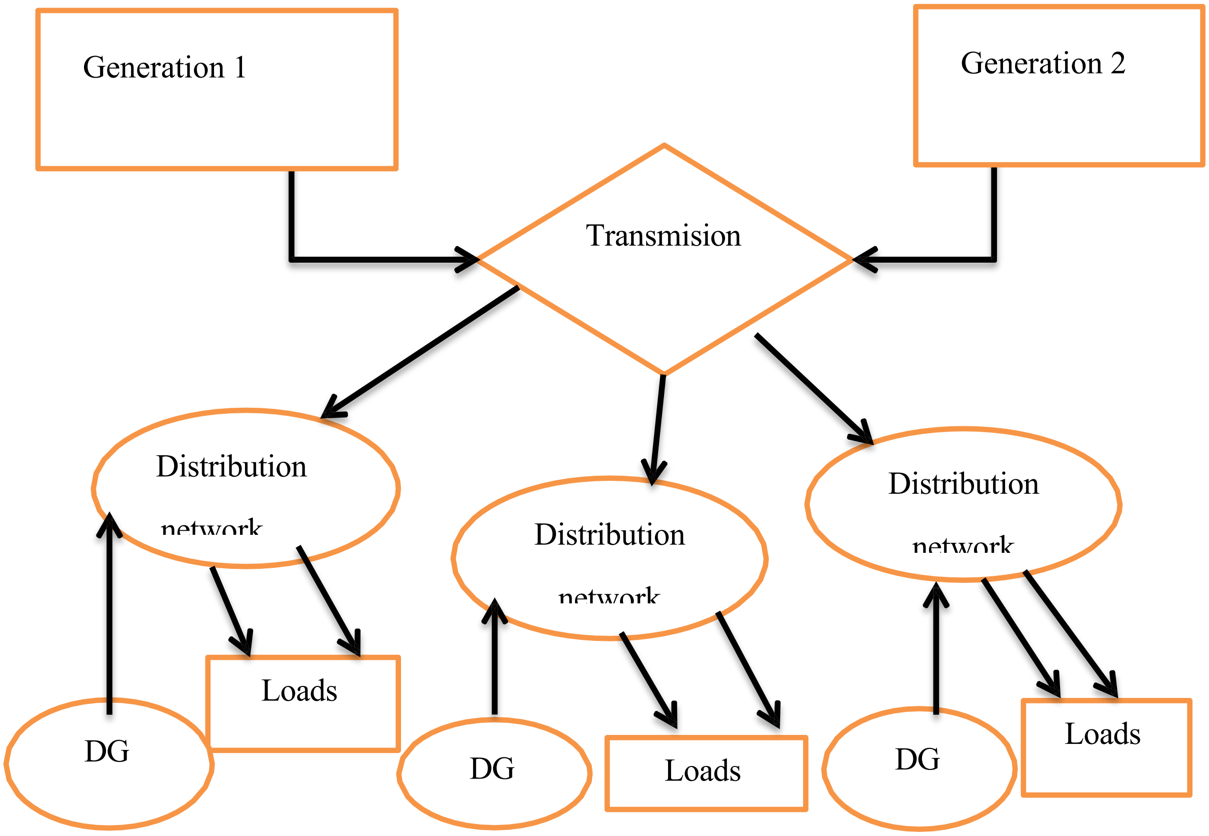


Figure 2.2: Power flow with DG connected (Gupta et al., 2014

Distributed generator technologies are based on photovoltaic, fuel cell, combustion gas turbine, micro turbine, reciprocating engine, and wind turbine technologies. According to Gupta et al. (2014), Alternative energy systems are another name for this technology. The electrical network's dependability is increased, and the system's power demand can be met by connecting dispersed generators to the distribution system. To help explain the DG concept, the following list includes some categories that define the size of the generating units. DGs are determined by the following sources (Gupta et al., 2014; Sarabia, 2011):

Unit capacity and unit technology are the two primary DG classifications. According to unit capacity, the first classification is as follows:

- Micro distributed generation ranges from 1W to 5kW,
- Small distributed generation ranges from 5 kW to 5 MW, and
- Medium distributed generation ranges from 5 MW to -50 MW.
- Large-scale distributed generation ranging from 50 to 300 megawatts.

This thesis concentrates on small distributed generation based on the aforementioned classification.

2.4.1 Categories of Distributed Generation Technologies

Distributed generation makes use of a wide range of technologies and resources. It can be categorized as either renewable or conventional DG technology. Fuel cells, micro turbines, gas turbines, wind turbines, photovoltaic (PV) systems, and other renewable resources are a few examples (Zhu, 2003).

Photovoltaic system

Light energy from the sun's radiation is transformed into electrical energy by a photovoltaic (PV) system. It is a proven technology for powering locations in a way that makes the power produced by PV-based DG units and the distribution substation intrinsically intermittent, less variable, and much more predictable. Regarding small-, medium-, and large-scale DG, its integration into the distribution system is presently being contemplated. According to Ghosh et al. (2013), photovoltaic (PV) panels are frequently offered for both residential and commercial use. The materials used in photovoltaic systems include bismuth indium selenite, cadmium telluride, mono-liquid silicon, polycrystalline silicon, and microcrystalline silicon. The PV cell, which can be assembled into panels or modules, is the basic building block of a photovoltaic power system. In addition, the panels are arranged to form a large photovoltaic array that is connected in series or parallel. The solar cells generate photovoltaic energy when they are exposed to direct sunlight. Every cell produces less than one watt of DC power at the lowest voltage, which is about 0.5 V. The junction potential or voltage is created when photons from the sun strike a semiconductor diode in a solar cell, creating electron-hole pairs that split at the diode junction. The potential drop in the forward direction at the semiconductor p-n junction sets a constraint on the voltage developed. The amount of current produced depends on the solar power radiation's density and surface area (Ng, 2012). Solar irradiance, cell temperature, and PV module voltage output influence a PV module's voltage output characteristics. They can be very expensive, though. The economic obstacles currently preventing the widespread use of PV systems must be removed through the development of less costly components and improvements in the manufacturing process. The PV system is depicted in Figure 2.3 below, and Table 2.1 below lists the advantages and disadvantages of photovoltaic.

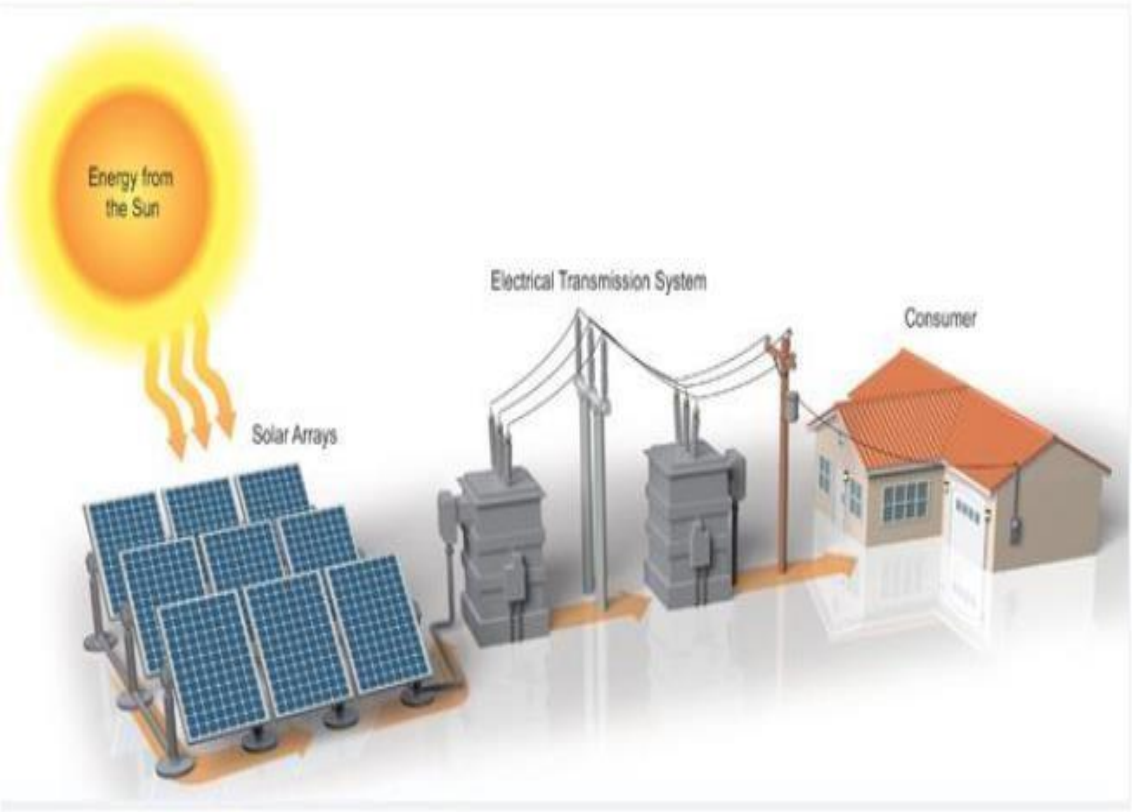


Figure 2.3 Photovoltaic systems (Ng,2012)

Table 2.1: Advantages and Disadvantages of Photovoltaic

Advantages	Disadvantage
Effective in remote areas	-The PV system's potential is directly impacted by local sun and weather patterns. - --Solar energy won't be available in some places. -The use of hazardous materials in cadmium telluride solar cells, such as cadmium.
doesn't need a fuel supply	
It needs very little upkeep.	
Completely silent	High cost
Long shelf life	
No emission (environmentally friendly)	
Low maintenance	

Using inverters, the system converts DC voltage to AC. These kinds of systems can be designed with or without battery storage. Since there are no emissions or pollutants, this system is safe for the environment. I like PV systems in my thesis analysis because they are easy to use, have a straightforward design, and run solely on solar light. This is one way to illustrate the accretive growth in installed solar capacity worldwide.

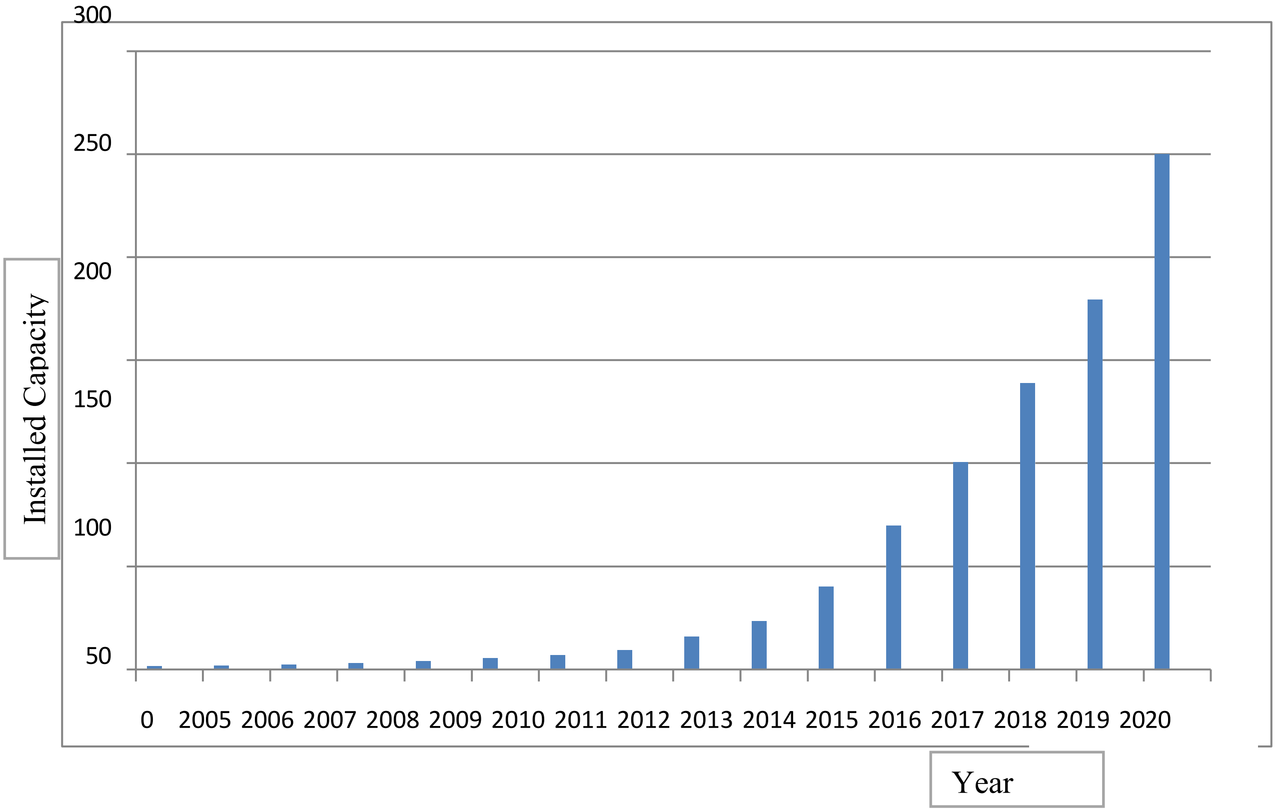


Figure 2.4: Global cumulative solar power installation. (Ng, 2012)

Wind power generation-based DG system

Currently, there are about 433 GW installed, with roughly 63 GW installed in the last two or three years (Ng, 2012). Electricity can be produced from wind energy using wind turbines. Wind turbines come in a variety of sizes, from 5 to more than 1,000 kW, and are currently offered by many manufacturers. Wind turbines have two ways of converting their kinetic energy: the rotor first transforms it into mechanical torque in the shaft, which the generator system then transforms into electrical power.

The main output voltage of the creator system is an AC voltage that is affected by wind speed. Inverters are necessary to change the generated voltage from DC to AC and back again because wind speed fluctuates. However, it is possible to directly connect fixed wind turbines to the grid. The rotor slice swept area and the wind speed cell that cuts through the same slice decide the power output of a wind turbine. Furthermore, the normal of the energy that the turbine rotor extracts from the wind is expressed by a power measure that is entangled with the air density (Adeuyi & Liang, 2016). The wind speed is the most crucial of these factors because of its cubical effect. Figure 2.5 depicts a wind turbine's general layout along with its key components.

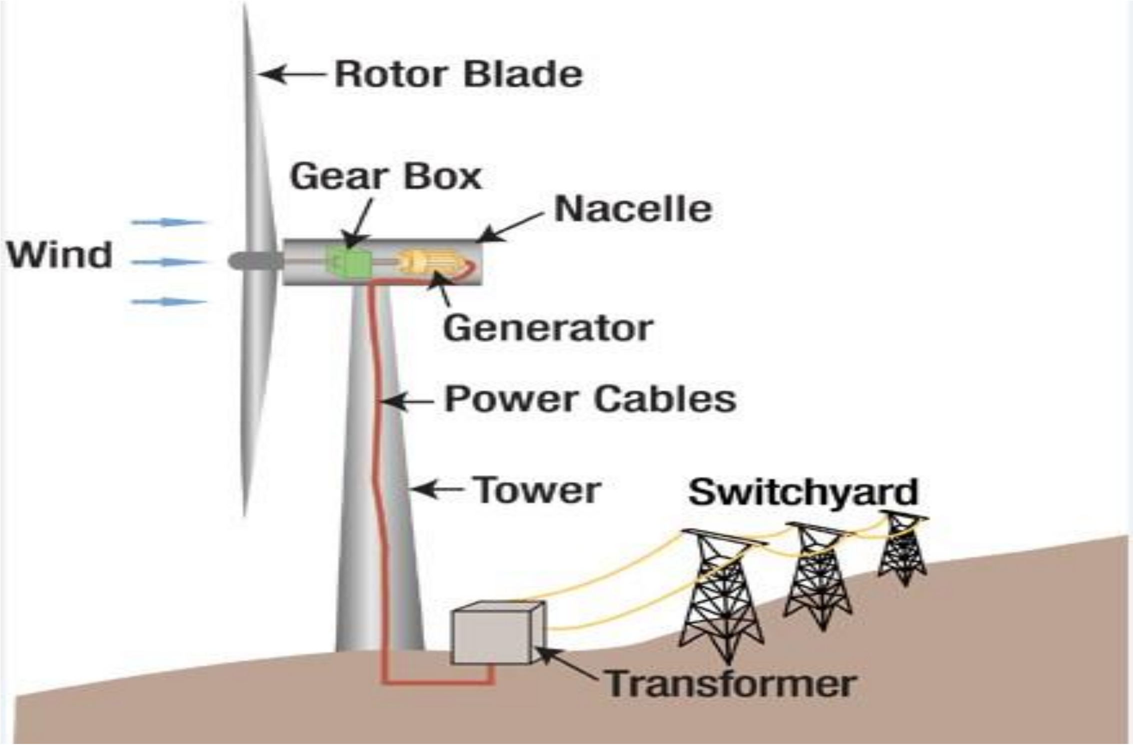


Figure 2.5: Essential elements of a DG system powered by wind power (Ng, 2012).

Table 2.2: Advantages and Disadvantages of Wind Turbines

Advantages	Disadvantage
A wind farm can generate electricity at a relatively low cost.	Variable power output due to the wind speed fluctuations at the site
Low cost of energy	Location
Requires no fuel	The visual impact and aesthetic issue of situating them in areas with a higher population density
Minimal land—farming or animal grazing are possible uses for the land beneath each turbine.	Mortality of birds
No harmful emissions	Commercial wind turbine noise pollution can occasionally be compared to that of a tiny jet engine.

Fuel Cell System

A fuel cell uses an electrochemical process rather than combustion to combine hydrogen and oxygen to produce electricity. However, the fuel cell is continuously supplied with fuel and an oxidant to ensure that the electrical power generation continues, whereas the battery is a device that stores energy that eventually runs out and needs to be recharged (Jahangiri & Fotuhi-Firuzabad, 2008).

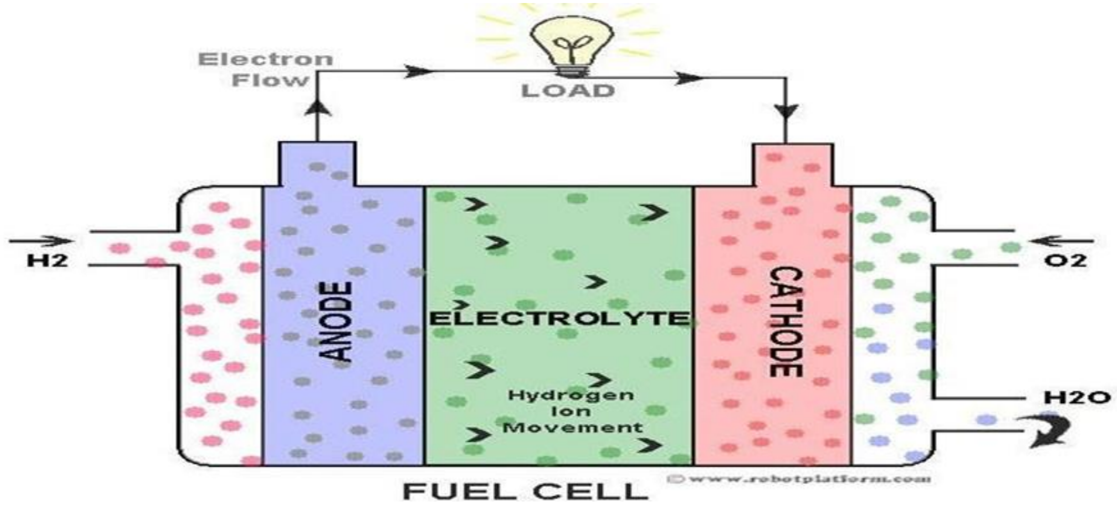


Figure 2.6 Fuel cell systems (Rahman et al., 2008)

Types of Fuel Cells

Fuel cell classification is based on the type of electrolyte used. The development stages of various fuel cell types vary. The various types of fuel cells are listed below based on their operating temperature (Rahman et al., 2008).

- The PEMFC-175 F is a proton exchange membrane fuel cell.
- Fuel cell with phosphoric acid (PAFC-400 °F)
- Molten carbonate fuel cell (MCFC-1250 °F)
- Fuel cell made of solid oxide (SOFC-1800 ^{0} F)

Table 2.3: Advantages and Disadvantages of Fuel Cells

	PAFC	**MCFC**	**SOFC**	**PEMFC**
Advantages	Quiet	Quiet	Quiet	Quiet
	low emissions	minimal emissions	minimal emissions	minimal emissions
	Great effectiveness	Great effectiveness	Great effectiveness	Great effectiveness
	Proven reliability	Reforming itself	Reforming itself	
Disadvantages	High cost	Long-term dependability must be shown.	Although planar SOFCs are still in the research and development phase, recent advancements show promise when operating at low temperatures.	Waste heat at low temperatures has many limitations, including cogeneration potential.
	Low density of energy	Expensive	Expensive	Insufficient experience with field testing
				High cost

Micro Turbine

Micro turbines are presently only available from a small number of manufacturers, a novel and developing technology. As their name implies, micro turbines are tiny combustion turbines that have been available for purchase for over a decade. They use gas or liquid fuels to power an electrical generator. A micro-turbine is a machine that lets gas in and converts thermal energy into mechanical energy. Micro turbines come in two varieties: Mended MT and UN mended MT (Zareipour et al., 2004). Although they have lower initial costs, UN-repaired micro turbines are less competitive (Zhu, 2003).

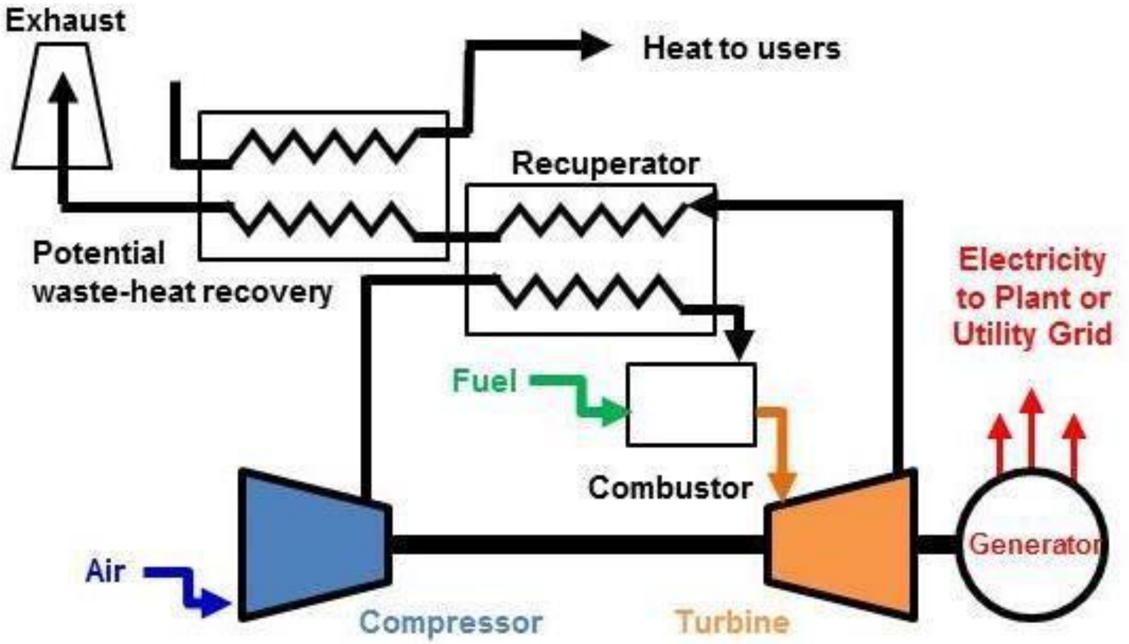


Figure 2.7 Micro turbine systems. (Zhu, 2003)

Table 2.4: Advantages and Disadvantages of Micro turbines

Advantage	Disadvantage
minimal number of moving components	Low fuel-to-electricity efficiencies
Compact in size & Good efficiencies in cogeneration	Power generation and effectiveness decrease with increasing elevation and temperature
Lightweight and capable of using waste fuels	Efficiency and minimal system costs were.
Long maintenance intervals	High maintenance cost

2.4.2 Profits of utilizing DG units

In numerous DG technologies, applications can offer significant advantages to electric distribution systems as well as consumers. DG units' compact size and modular design promote their use in a variety of applications (Rahman et al., 2008). Utilizing DG has many advantages if it is incorporated into the distribution grid in the best possible way, both in terms of size and location. In particular, DG can: Enhance an electric network's voltage profile.

- Minimize the system's losses.
- Reduce the feeders' overloads.
- Reduce expenses by postponing the distribution system upgrade.
- Boost power quality and system dependability.
- Increase the electrification of rural areas, where transmission and distribution expenses are substantial.
- Since they lower CO2 emissions in the atmosphere, they lower healthcare costs.
- Greenhouse gas emissions are significantly decreased by DG powered by renewable energy sources like photovoltaic and wind turbines.

Drawbacks of DG

However, several problems could occur if the distribution of DG is incompatible with the characteristics and the grid topology's technical constraints, including:

- Over voltages
- Increased power losses
- Flickers of Voltage
- Bidirectional power flows cause protective relay malfunctions

2.5 Reliability of power systems and some associated terminology

Power system reliability is the capacity of the power system to provide electricity to all points of application within predetermined parameters, in the requested quantity, for the necessary duration, under normal operating conditions.

There are two ways to define the connected bulk power system's reliability. Derbie (2014).

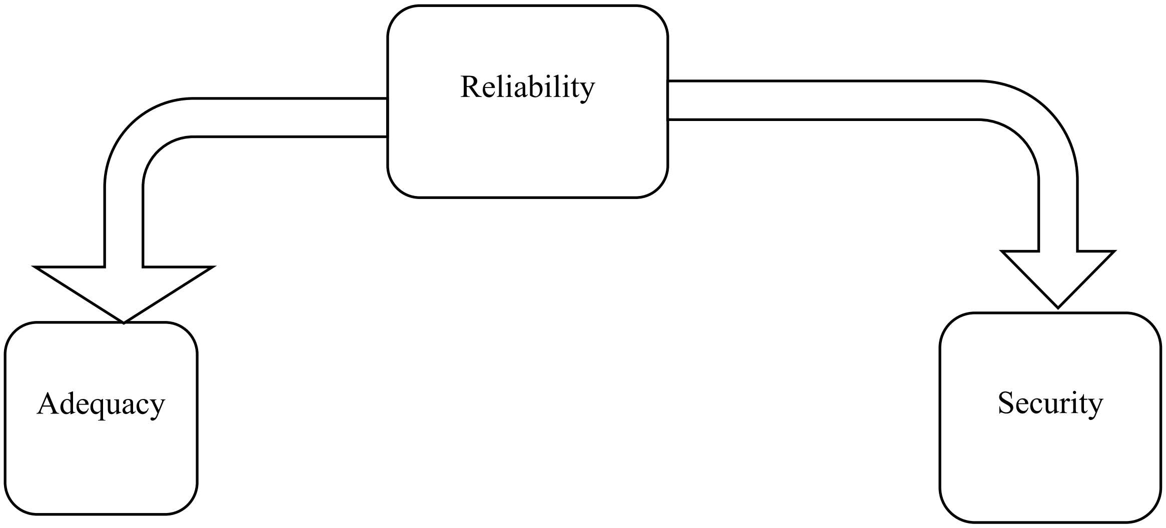


Figure 2.8 Reliability evaluation elements.

1. Adequacy: A measurement of the power system's ability to provide all of its customers' electric power and energy needs within element conditions and voltage restrictions, keeping in mind both scheduled and unforeseen system factor outages. Assuming standard conditions, acceptability gauges the power system's capacity to supply the cargo in all stable nations where it may function (Kim, 2011).

2. Security: An evaluation of the resilience of a power system to unanticipated disruptions, including cargo conditions, unexpected system component losses, or electric short circuits, in addition to operational limitations. System integrity, or the capacity to continue connected operation, is another facet of security. In the face of certain severe disturbances, integrity refers to preventing uncontrolled separation or maintaining the functioning of a connected system. Adequacy assessment is at the heart of the majority of probabilistic methods for reliability assessment (Kim, 2010). Assessing reliability entails calculating the total number of electric outages for loads in a power system over the course of an operating period, usually using statistical techniques. Several indices describe the interruptions. Similar features are naturally reflected in reliability indices (Manohar, 2009).

- ➢ The number of customers [N].
- ➢ Typically, the connected load is stated in [kW].
- ➢ The disruptions' duration, usually expressed in [h] = "hours."

- The power outage is expressed in [kW].
- The standard expression for the frequency of interruptions is [1/a] = "per annum."
- The standard format for repair times is [h] = "hours."
- Probabilities or expectations are expressed as fractions or as time of year ([h/a], [min/a]).

Annual interruption costs and the anticipated frequency of interruptions are calculated using network reliability assessment, which also compares various network designs. A probabilistic and automated extension of contingency evaluation is reliability analysis. Pre-defining outage events is not necessary for this type of analysis; instead, the tool can select the outages to take into account automatically (Kim, 2010). The program models the protection system and the response of the network operator to re-supply interrupted customers by automatically calculating the effect of each outage. The outcome is quantifiable in terms of probability since statistical information regarding the frequency of occurrence of such events is available. The frequency, duration, and severity of negative impacts on the electrical supply can be used to gauge the degree of dependability (Brown, 2017).

Note: Reliability assessment tools are often employed to quantify the economic impact of the unavailability of power system equipment. Reliability assessment study results can be utilized to justify investments in new remote-control switches, lines, or transformers, or to measure the effectiveness of under-voltage load shedding schemes.

Reliability engineering uses a wide range of terms and definitions. Below are some definitions and terms that are commonly used (Brown, 2017).

Reliability (R (t)): This is the likelihood that, in typical circumstances, an item will transmit its designated mission satisfactorily for the allotted amount of time.

Availability(A): The possibility that an item will be available for use or application when needed is known as availability, or the likelihood that a component is normal at any given time t, given that it was good at time zero. (Brown, 2017).

$$A=\frac{MTTF}{MTTF+MTTR} \qquad 2.1$$

Where: MTTF = mean time to failure

MTTR = mean time to repair

Unavailability (U): The possibility of a component going down at any random time and not being able to function is known as unavailability. (Brown, 2017).

Unavailability,

$$U = \frac{MTTR}{MTTF+MTTR} \qquad = \frac{f*MTTR}{8760} \qquad 2.2$$

Where: MTTF = mean time to failure

MTTR = mean time to repair

f = frequency

Since MTTR is measured in hours based on the description of availability and unavailability, the 8760 hours in the right section represent the total hours of a year (Kim, 2010).

The concepts of availability and unavailability, and reliability and failure probability are almost the same. Whether or not component maintenance is considered is what separates them. Although it is also reliable, it is unavailable if a healthy component is being maintained to assess its quality (Makarov & Moharari,1999). Mean Time to Failure (MTTF): The average amount of time, measured from t=0, that it takes for a component or system to fail.

- The average time required to identify and fix a failure is known as the mean time to repair, or MTTR.

$$MTTR = \frac{Total\ duration\ time}{Total\ number\ of\ Interruption} \qquad 2.3$$

Where MTTR = means mean time to repair

Failure: the failure of a product to operate in accordance with the original specifications.

$$\mu A = \frac{\text{Total number of Interruption}}{\text{Length of feeder}} \qquad 2.4$$

Where μA=Failure Rate

Failure Frequency (f): The total number of potential failures over time is the failure frequency. The number of failures per year is the failure frequency dimension in this study.

$$f = \frac{Number\ of\ Failure}{Studied\ period} \qquad 2.5$$

Failure Probability (F (t)): The possibility that a system or component will malfunction within a given time frame under specific conditions is known as the failure probability. Unreliability, represented by the symbol (F (t)), is the same as this.

Maintainability: The likelihood that a broken item will be fixed to a desirable degree of operation.

2.6 The Structure of the Electrical Power System

Generating, transmission, and distribution systems make up the power system, which is a network. Energy is used and transformed into electrical energy.

2.6.1. Generation Plants

Central power plants, also known as generating stations, transform mechanical energy into electrical energy to produce electricity. To transfer mechanical power to a generator for the production of electricity, prime movers, like Steam, wind, and hydraulic turbines, are examples of thermal or non-thermal sources that are transformed by engines and turbines. At generation substations, which serve as the connecting points between transmission lines and generating plants, electricity is stepped up to a higher voltage (usually between 230 kV and 500 kV) for long-distance transportation.

2.6.2. Transmission

Transmission and sub-transmission systems make up the two components of the transmission system. Through generating substations, electricity is moved in large quantities from a generating plant to a sub-transmission system at advanced 66, 132, and 230 kV voltage levels. Typically, the electrical power grid includes the transmission system. Additionally, the sub-transmission system sends electrical power to the distribution substation and then to the distribution networks at voltage levels ranging from 66 kV to 132 kV. Higher voltages are more effective for transmitting large amounts of power over long distances. Lower currents can be used to transmit power at high voltages, reducing voltage drop and power losses. As a result, a smaller investment is needed to use lower operators. Typical power transmission systems consist of overhead lines with three conductors, three phases, and either a ground conductor or not. Transmission lines are categorized as limited since the generating station's voltage is only controlled to maintain the lines' typical operating voltage limits and to manage power flow (Gonen, 2019). The purpose of sub-transmission stages is to make the transition between transmission and distribution systems for the production of electricity more feasible or profitable. An advanced voltage, typically between 132 kV and 500 kV, is achieved by stepping up electric power for long-distance transportation on generation substations, which are connection nodes between generation plants and transmission lines (Gonen, 2019; Huang et al., 2019).

2.6.3. Distribution Substations

MV power is supplied to the distribution system by distribution substations. The substation is equipped with switchgear, bus bars, voltage and current regulating devices, and one or more power transformers. Because a substation is one of the most crucial pieces of infrastructure in the electric power system and has a big influence on the reliability of the distribution system, this thesis may be of interest in evaluating the substation's reliability and how it affects the reliability of the distribution system. One of the crucial components of the power system for providing customers with adequate and dependable electricity transfer is the substation. Additionally, it serves as a conduit for the conversion of voltages between sub-transmission systems and distribution systems, transmission systems and sub-transmission systems, or between generating and transmission systems. One important factor in calculating the overall system reliability is how frequently and for how long substation equipment outage events happen that are not consistent with the requirements of the system's reliability, e.g., equipment overload or inexcusably high voltages. There have been several outgoing medium voltage overhead lines or underground cables, step-down power transformers, and some incoming high voltage sub-transmission lines. Substation step-down power transformers step down sub-transmission voltage levels to primary distribution levels. Distribution substations initially step down the voltage from 132 kV or 66 kV to 33 kV or 15 kV. Electric power is then transferred from the substation to the distribution transformers via the primary distribution system. The primary distribution serves a portion of its industrial customers directly. The distribution transformers reduce the voltage once more to the levels of utilization, which are 380/400 V for three phases and 220/230 V for single phases. Finally, power is distributed to the customers' service entrance equipment by the secondary distribution systems. Subterranean cables or overhead lines make up the distribution networks (Hunt et al., 2012).

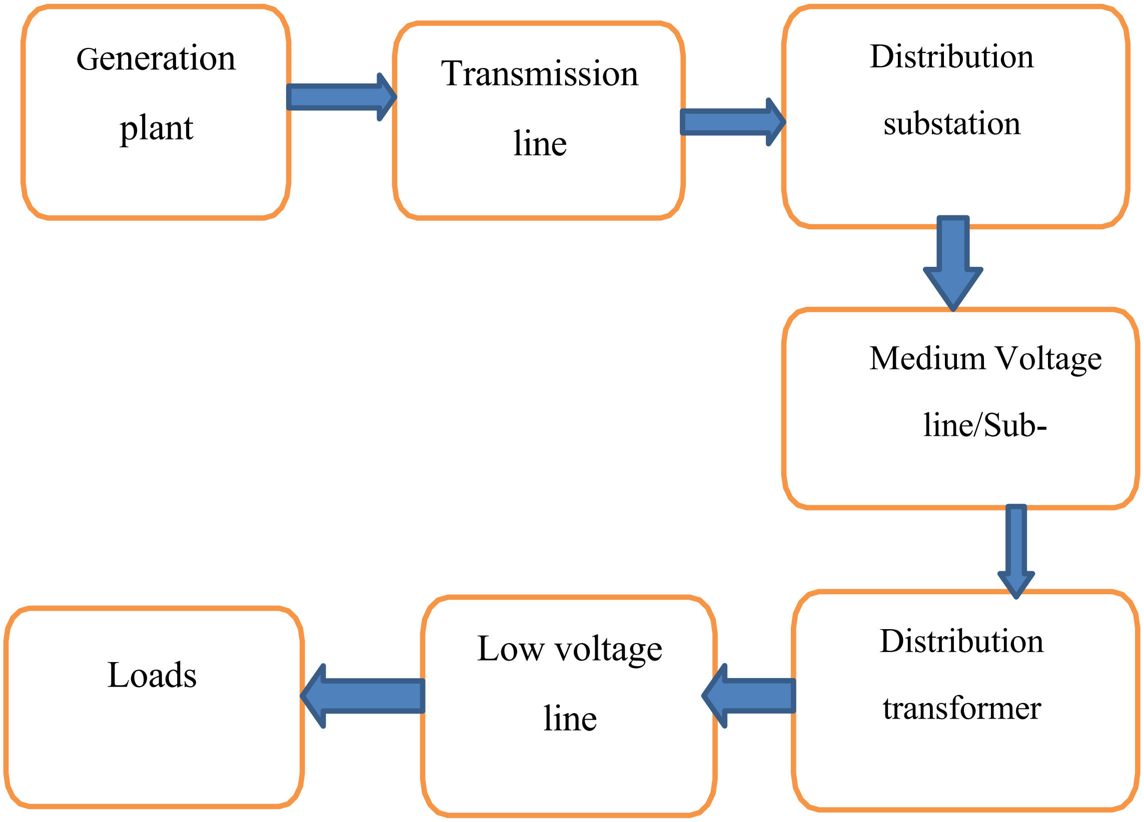


Figure 2.10: functional zones power system (Gonen, 2019)

2.7 Power System Reliability Indices

The electric utility sector developed several reliability metrics to assess system performance. These reliability indices take into account response time, system availability, outage frequency, and duration. Reliability can be measured by the frequency, duration, and intensity of adverse effects on the electrical supply. There are many different reliability indices available. (SECUI & BENDEA).

2.7.1 System Indices

System Average Interruption Frequency Index (SAIFI):

In units of [1/C/a], the System Average Interruption Frequency Index (SAIFI) indicates the average number of times a customer experiences a prolonged interruption during the calculation period. One way to calculate it is to divide the total number of customer interruptions by the total number of customers served. (John D. Kueck and Brendan J. Kirby, 2004)

$$\mathrm{SAIFI}=\frac{\Sigma\lambda iNi}{\Sigma NT} \tag{2.6}$$

Where: $\lambda_i\ is\ the\ failure\ rate\ at\ load\ point\ i$

N_i is the total number of customers interrupted at load point *i.*

N_T is the total number of customers at load point *i.*

Another way to calculate SAIFI is to divide the SAIDI value by the CAIDI value:

$$\text{SAIFI}=\frac{SAIDI}{CAIDI} \qquad 2.7$$

Customer Average Interruption Frequency Index (CAIFI):

For customers who experience sustained interruptions, the mean frequency of these interruptions is represented by the [1/A/a] units of the Customer Average Interruption Frequency Index. Regardless of how many times they are interrupted, each customer is counted once for this calculation. The CAIFI calculates the average annual number of interruptions per customer. (Makarov & Moharari, 1999).

The CAIFI is expressed as;

$$\text{CAIFI}=\frac{\Sigma\overline{No}}{\Sigma Ni} \qquad 2.8$$

Where: N_o = Total number of interruptions

N*i* = Total number of consumers who were interrupted

System Average Interruption Duration Index (SAIDI):

System Average Interruption Duration Index shows the average customer interruption duration over the calculation period, expressed in [h/C/a] units. It is often measured in customer hours or customer minutes of interruption. SAIDI is usually calculated monthly or annually, but it can be calculated daily or for any other time period. (SECUI & BENDEA).

The calculation involves dividing the total number of consumers by the total number of customers who were interrupted for each interruption event and restoration durations for every instance of disruption (Larson, 2024).

$$\text{SAIDI}=\frac{\Sigma riNi}{\Sigma NT} \qquad 2.9$$

Where: ri = recovery duration, in minutes

Ni = Total number of consumers who were interrupted

NT = The total number of clients

Customer Average Interruption Duration Index (CAIDI):

The Customer Average Interruption Duration Index, which is quoted in [h] units, calculates the average duration of service restoration. CAIDI, like SAIDI, is calculated by dividing the ratio of all utility customers by customers who experienced interruptions. (BENDEA AND SECUI).

$$\text{CAIDI}=\frac{\Sigma U*Ni}{\Sigma\lambda i*Ni}=\frac{SAIDI}{SAIFI} \qquad 2.10$$

Where: λ_i= Rate of failure at load point I

Ui = Outage duration per year at load point I

Ni = Total number of consumers who were interrupted

Average Service Availability Index (ASAI):

Average Service Availability Index indicates the proportion of time a customer receives electricity supplied within the defined reporting period or one year, or the proportion of time a customer is connected within the stated calculation period (most likely presented as a percentage). It is computed by taking the total number of customer hours that service was available during a given time period and dividing that number by the total number of customer hours that were requested. Another name for this is the service reliability index. The ASAI may be determined for any time period, but is typically determined on a monthly (730 hours) or annual basis (8,760 hours) (Makarov & Moharari, 1999). The ASAI is determined by:

$$\text{ASAI} =1-\frac{ri*Ni}{\Sigma NT*T}*100 \qquad 2.11$$

Where: T = Study period, expressed in hours

ri = restoration duration, expressed in hours

Ni = The total number of customers who were interrupted at load point I.

NT = Total number of customers served.

Average Service Unavailability Index (ASUI):

The average service availability index (ASAI) is supplemented by the average service unavailability index (ASUI), which determines the probability of loads going unsupplied.

$$\text{ASUI}=1-\text{ASUI}=\frac{\Sigma Ui*Ni}{\Sigma Ni*8760} \qquad 2.12$$

Where: Ui = Annual outage time at load point i

Ni = Total number of customers interrupted

2.7.2 Load Point Indices

Energy Not Supplied Index (ENS): Energy Not Supplied is the total amount of energy that is typically not delivered, expressed in [MWh/a].

Where: -L_a =is the peak load demand

L_f = is the load factor

E_d =is the total energy demanded in the period of interest t.

Average Energy Not Supplied Index (AENS):

[MWh/Ca] units are used to represent the average energy not supplied for all customers or the index that displays the average energy not supplied by the system. (Makarov and Moharari, 1999).

$$\text{AENS} =\frac{Total\ Energy\ not\ Supplied}{total\ number\ of\ customer\ affected}$$

$$=\frac{\Sigma La(i)-Ux}{\Sigma No} \qquad 2.13$$

Where: La = is the average load

U_i = is the annual outage time

N_O = is the total number of interruptions

2.8 Relationship of economics and reliability

Cost-benefit analysis is frequently used in the economic evaluation of power systems to determine and contrast the costs and advantages of a specific service area, and lifecycle energy cost models can be used to assess how sensitive power systems are to cost changes in relation to Component reliability variation. Reliability usually improves with increased investment in system reliability, although this relationship is not linear (Gezer, 2009). A reliability cost-benefit analysis evaluates the reliability and costs of various system configurations. By including economic considerations in the reliability evaluation decision-making process, reliability cost-benefit analyses can be carried out.

2.8.1. Outage Cost Evaluation

Development and economic expansion now depend on having access to affordable, high-quality electricity supplies. The costs of interruptions in the electricity supply for small businesses are closely linked to both production losses and the expenses of resuming production. Additionally, interruptions result in revenue losses and property damage for businesses, private citizens, and industries. The residual electricity or interruption cost is projected based on the latest Ethiopian Electric Power Corporation's marketing and sales process estimation guide.

$$Interruption\ Cost\ = \frac{1}{4}*(\mathrm{EENS})*1000*(\mathrm{SAIDI})\mathrm{x}\ 0.8\ \mathrm{x}0.767)\ \mathrm{ETB} \qquad 2.14$$

To find the average interruption power (kilowatt), interrupted energy is multiplied by the power factor (0.8) and then divided by a quarter (1/4). The average load drawn from the transformer's capacity during the interruption period is shown by the fourth. The cost of unsold energy or interruption is calculated by multiplying the load (KW) by the hour and SAIDI, and after that, by the cost per kWh (0.767 Ethiopian Birr). Since most Ethiopian electricity users are assumed to be domestic and commercial customers, the 0.767 tariff is derived from their average tariff.

CHAPTER THREE

METHODOLOGY

This thesis's primary goal is to examine consistency issues and assess the current distribution system's dependability. The most potent reliability indices are then calculated by gathering and evaluating data from the Mojo New substation. Then, these reliability indices are contrasted with international standards and the EEP standard. One of the measures to overcome the problems of the existing distribution system is integrating DG into the substation. Time, frequency, number of customers served, interrupted customers, connected loads, and others are required for reliability analysis. The current level of reliability of the substation is then ascertained by analyzing these data

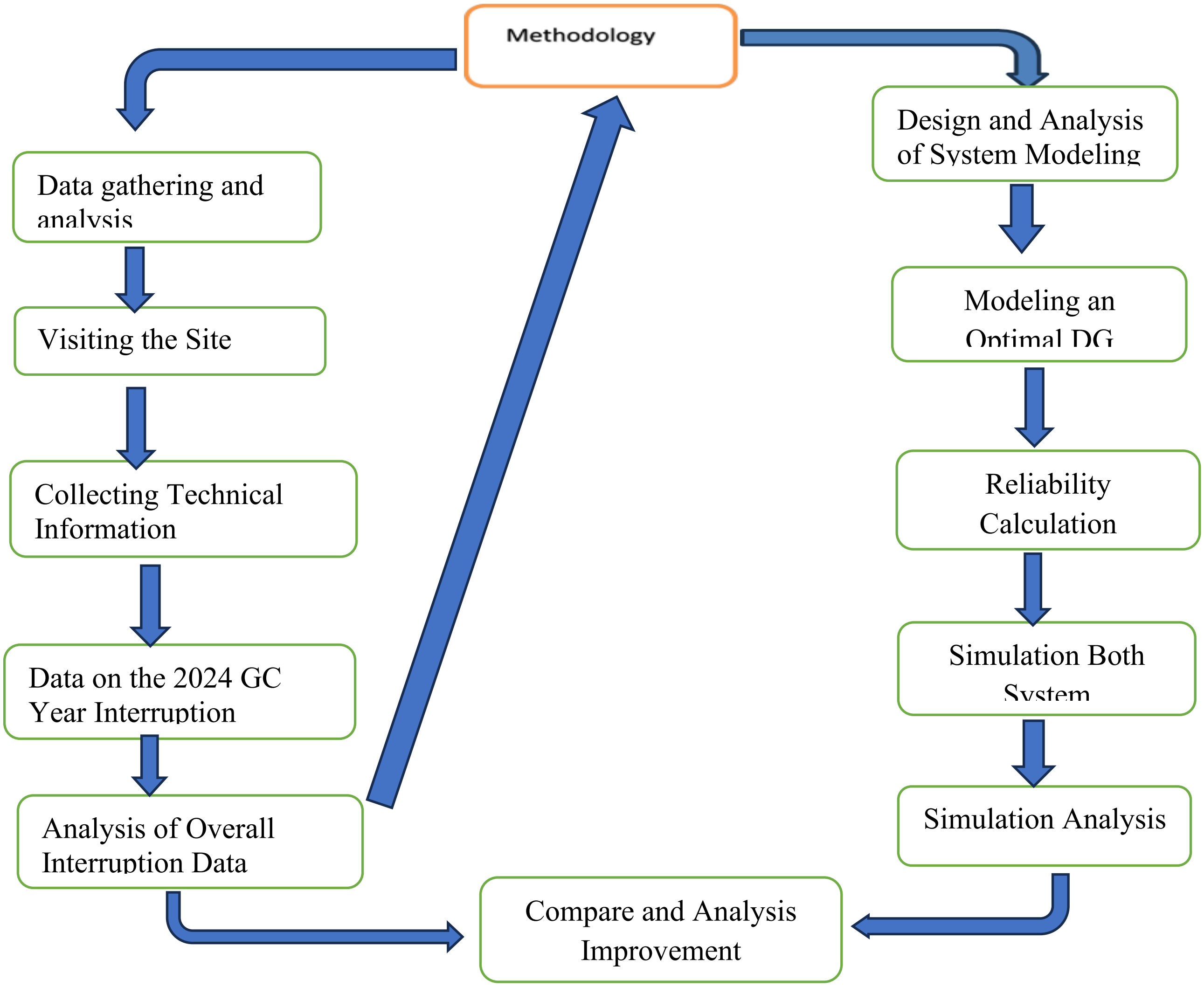


Figure 3.1: Block diagram of the methodology

3.1 Data Source

The necessary data for this thesis has been gathered from Mojo New distribution substation, Mojo customer service center, the Adama district Ethiopian electric utility (EEU), and the Engineering office of Ethiopian electric power (EEP). The secondary data have been gathered from records of feeders from both institutions.

- loading (peak load) data of the substation,
- interruption data of the feeder,
- Route of the feeder and rating of the distribution transformer.

Mojo New substation has only one 230 kV incoming feeder, from Bishoftu III, and five 15 kV and four 33 kV outgoing feeders. There are three power transformers, with capacities of 2(50) MVA and 25 MVA, which step down into 15kV and 33 kV feeders, respectively.

- L1, supply 15kV to the Mojo Town.
- L2, supply 15kV to the Bishoftu Air Force
- L3, supply 15kV to the Bishoftu Town
- L8, supply 15 kV to The Mojo Tannery
- L10, supply 15 kV to Adama water
- L1, supply 33kV to the rural area of Mojo Town, Ejere, Shara, Dibandiba, Tafi Abok, Daka Bora, Zone Misoma, Tade & etc, a small city.
- L2, supply 33kV to the Anbese Bira.
- L3, supply 33kV to the Ararti industry park.
- L4, supply 33kV to the Arerti Town.

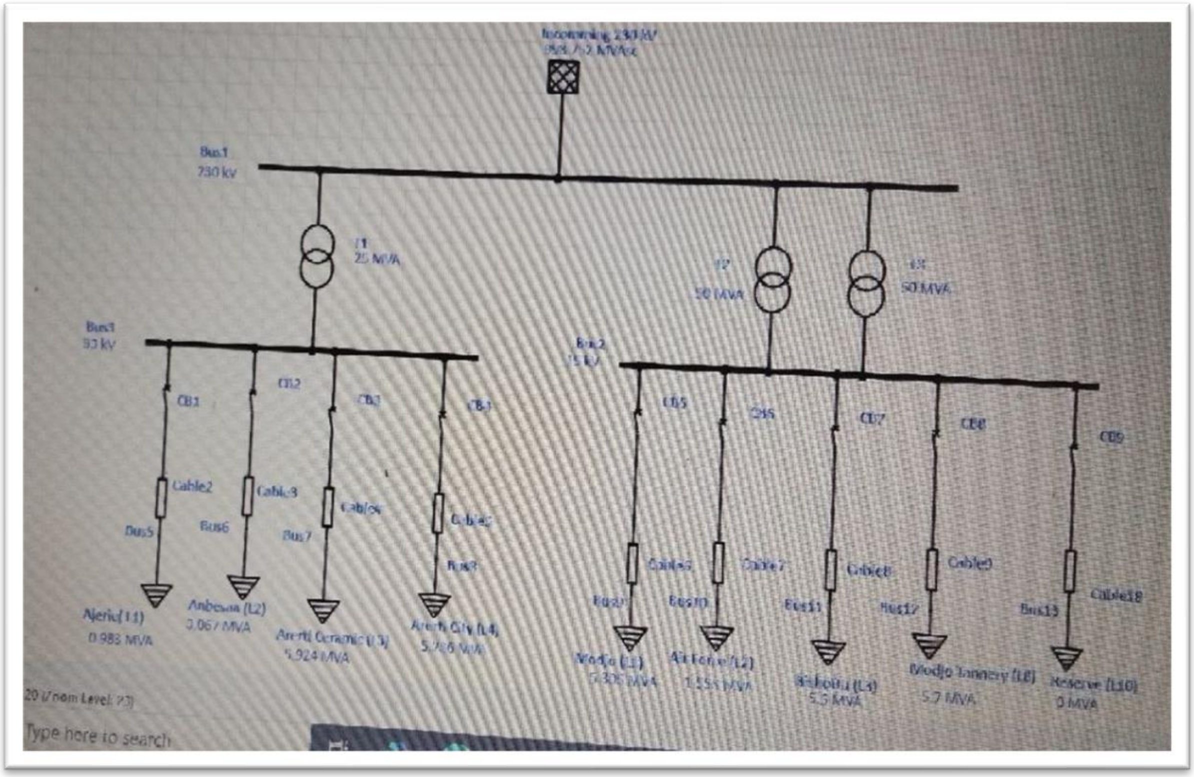


Figure 3.2: Existing single-line diagram of Mojo New distribution substation

3.1.1 Basic data of Mojo New Substation

One of the nation's electric power service providers is Ethiopian Electric Power (EEP).

Table 3.1 The power transformers' number & capacity:

No of Transformers.	Type of winding	Voltage level in kV
Transformer 1	2 winding	132/33
Transformer 2	2 winding	132/15
Transformer 3	2 winding	132/15

Both power transformers of the Mojo New distribution substation are 2-winding transformers, which means their outputs are only either 15kV or 33kV, but 3-winding power transformers give both 15kV and 33kV or any other.

Table 3.2 Mojo New substation feeder name, length, no of transformers, no of customers, and their capacity

Name of Feeder	Level of Voltage	Peak load in MW	Feeder Length in KM	No of Transformer	No of Customer
L1	15	4.69	13.5	51	3120
L2	15	1.47	21	1	1
L3	15	4.84	40	35	3174
L8	15	5.13	10	29	2512
L10	15		25	2	2
L1/33KV	33	0.87	40	61	3550
L2/33KV	33	2.77	9	2	2
L3/33KV	33	5.38	70	15	10
L4/33KV	33	4.78	194	174	13454
TOTAL NUMBER OF CUSTOMERS					25825

Table 3.3: In a substation, the average, maximum, and minimum loads for each feeder are as follows:

(Typical monthly load: April/2024).

Feeders	Minimum Load (MW)	Maximum load (MW)	Average load (MW)
(L1)/15	0.074043	1.604265	0.25112
(L2)/15	0.148086	1.085964	0.443033
(L3)/15	0.024681	4.289535	0.982851
(L8)/15	0.098724	5.577906	2.450948
(L1)/33	0.108471	4.778242	0.540032
(L2)/33	0.108596	1.031666	0.555688
(L3)/33	0.108596	4.018067	1.317219
(L3)/33	0.271491	4.018067	1.754128

3.2 Major causes of power interruption at the Mojo New distribution substation

Short circuits, earth faults, and overloading are the main faults that commonly occur in the Mojo New substation. For operational and maintenance reasons, there is a planned outage in addition to this unplanned one. The main issues that arise may be either transient or irreversible. Permanent or sustained interruptions are those that continue for more than five minutes. On the other hand, brief interruptions, less than five minutes, are referred to as momentary. As is customary, the regulatory body receives only information about prolonged disruptions (Hunt et al., 2012). Tree, animal, and weather contact are the primary causes of many of the transient distribution issues. With minimal system intervention, they can be answered fluently. Additionally, the system can be reenergized by simply closing it again. However, merely re-energizing won't fix a permanent flaw. Equipment failure, cable failure, down line, or ongoing tree contact can all result in permanent faults. Planned and unplanned interruptions are two categories for persistent or permanent disruptions. Preventive maintenance, repair, and construction are the main reasons for planned interruptions, also known as operational outages. The guests have been informed in advance of the planned interruption, which takes place at a time that is less inconvenient for them. On the other hand, the interruption is unplanned if the time has not been selected. Unplanned interruptions can happen as a result of fault clearing, unintentional protection system operation, or human error when the switching device is opened (Makarov & Moharari, 1999).

3.3 Power interruption data of the Mojo New substation

Interruption data from January 2024 to December 2024

Numerous types of power system failures frequently happen at the Mojo New substation. These typically include distribution earth faults, distribution short circuit faults, operation/maintenance interruptions, power transformer overloads, and system overloads. The various power system fault types are listed in this table along with their frequency and duration: Distribution Permanent Earth Fault (DPEF), Distribution Permanent Short Circuit Fault (DPSC), Distribution Transient Earth Fault (DTEF), Distribution Transient Short Circuit Fault (DTSC), and System over Load (SOL), Power Transformer over Load (PTOL), and Operational.

Table 3.4: Interruption duration and frequency of various faults from April 2024

Feeder	DPEF		DPSC		DTEF		DTSC		DLOL		EEUO	
	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)		Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)
L1/15	94	168.81	13	23.966	8	1.05	1	0.1	0	0	5	3.15
L2/15	1	1.8666	0	0	0	0	0	0	0	0	0	0
L3/15	59	164.08	1	0.9666	2	0.316	0	0	0	0	4	3.75
L8/15	74	141.81	1	1.0833	9	1.416	0	0	0	0	9	4.8333
L1/33	12	7.8333	7	6.5666	5	0.666	0	0	0	0	5	3.5666
L2/33	7	7.8166	9	11.55	0	0	0	0	0	0	3	1.2333
L3/33	3	2.25	2	1.0666	1	0.066	3	0.233	0	0	7	7.8833
L4/33	14	18.9	13	13.45	2	0.283	0	0	0	0	0	0
Total	**264**	**513.33**	**46**	**58.64**	**27**	**3.797**	**4**	**0.333**	**0**	**0**	**34**	**27.4162**

Table 3.5: Interruption duration and frequency of various faults from June 2024

Feeder	DPEF		DPSC		DTEF		DTSC		DLOL		EEUO	
	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)		Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)
L1/15	83	174.7333	14	22.0333	3	0.4333	0	0	0	0	6	4.9
L2/15	0	0	0	0	0	0	0	0	0	0	0	0
L3/15	74	197.25	2	20.15	2	0.25	0	0	0	0	4	1.95
L8/15	89	210.15	11	32.45	4	0.5	0	0	0	0	13	45.01667
L1/33	2	4.183333	15	28.4333	1	0.1	0	0	0	0	4	3.733333
L2/33	2	7.53333	5	7.88333	1	0.1666	2	0.3	0	0	6	7.033333
L3/33	1	1.18333	3	5.33333	1	0.0833	0	0	0	0	4	1.9
L4/33	5	4.81666	8	9.33333	3	0.3666	1	0.0666	0	0	8	29.01667
Total	**256**	**599.74**	**58**	**125.6**	**16**	**1.8992**	**3**	**0.0666**	**0**	**0**	**45**	**93.5499**

Table 3.6: Interruption duration and frequency of various faults from September 2024

Feeder	**DPEF**		**DPSC**		**DTEF**		**DTSC**		**DLOL**		**EEUO**	
	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)		Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)
L1/15	64	124.2167	9	28.75	5	0.45	0	0	0	0	7	5.466667
L2/15	0	0	0	0	0	0	0	0	0	0	3	2.716667
L3/15	90	146.1333	0	0	5	0.583333	0	0	0	0	8	6.183333
L8/15	61	153.3667	0	0	0	0	0	0	0	0	4	3.683333
L1/33	11	6.266667	14	40.23333	3	0.266667	1	0.083333	0	0	13	8.35
L2/33	7	8.983333	13	8.45	1	0.083333	2	0.2833	0	0	2	0.283333
L3/33	2	4.9	0	0	2	0.2	0	0	0	0	4	3.533333
L4/33	5	2.65	6	4.033333	0	0	1	0.133	0	0	8	5
Total	**240**	**446.51**	**42**	**81.466**	**16**	**1.5833**	**4**	**0.4996**	**0**	**0**	**49**	**35.219**

Table 3.7: Interruption duration and frequency of various faults from December 2024

	DPEF		**DPSC**		**DTEF**		**DTSC**		**DLOL**		**EEUO**	
	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)		Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)
L1/15	54	58.98333	3	2.266667	6	0.8	0	0	0	0	2	1.566667
L2/15	1	0.6	0	0	0	0	0	0	0	0	0	0
L3/15	79	73.38333	2	5.783333	6	0.75	0	0	0	0	6	12.53333
L8/15	54	82.9	5	21.48333	3	0.35	0	0	0	0	4	9.883333
L1/33	5	9.916667	2	1.7	0	0	0	0	0	0	8	21.7
L2/33	6	3.083333	1	0.316667	1	0.083333	0	0	0	0	3	0.9
L3/33	10	65.81667	2	0.483333	4	0.516667	0	0	0	0	7	32.56667
L4/33	0	0	0	0	0	0	1	0.116667	0	0	2	0.9
Total	**209**	**301.68**	**15**	**32.033**	**20**	**3.499**	**1**	**0.1166**	**0**	**0**	**32**	**80.049**

Table 3.8: Planned and Unplanned interruption duration (Hr.) from January 1, 2024, up to April 30, 2024

Feeder	**January**		**February**		**March**		**April**		**Tot**
	Planned	**Unplanned**	**Planned**	**Unplanned**	**Planned**	**Unplanned**	**Planned**	**Unplanned**	
L1/33	0	0	0	0	0	0	3.15	193.9	**197.05**
L2/33	0	19.45	0	0.25	0	3.82	0	1.87	**25.39**
L3/33	7.82	109.09	19	71.88	45.6	165.7	3.75	165.3	**588.14**
L4/33	11.7	154.18	8.55	257.1	7.72	242.8	4.83	144.3	**831.18**
L1/15	7.53	49.12	26.3	22.85	10.4	30.09	3.57	15.07	**164.93**
L2/15	1.07	0.13	1.42	9.5	1.13	6.2	1.23	19.37	**40.05**
L3/15	27.3	3.87	5.93	11.03	2.67	18.03	7.88	3.62	**80.33**
L8/15	9.98	3.45	6.77	3.31	8.27	16.26	0	32.63	**80.67**

Table 3.9: Planned and Unplanned interruption duration (Hr.) from May 1, 2024, up to August 30, 2024

Feeder	**May**		**June**		**July**		**August**		**Tot**
	Planned	**Unplanned**	**Planned**	**Unplanned**	**Planned**	**Unplanned**	**Planned**	**Unplanned**	
L1/33	193.9	33.02	588.8	4.9	32.7	217.4	3.4	222.5	**1296.62**
L2/33	1.87	0	0	0	0	7.73	0	8.83	**18.43**
L3/33	165.3	1.03	37.79	1.95	37.3	139.8	27.1	145.4	**555.67**
L4/33	144.3	2.25	138.2	45.02	37.3	258.7	17.8	292	**935.57**
L1/15	15.07	1.58	45.74	3.73	14.4	63.77	1320	37.88	**1502.17**
L2/15	19.37	6.33	16.3	7.03	9.2	18.02	16.1	59.32	**151.67**
L3/15	3.62	15.2	5	1.9	24.8	8.1	8.3	11.13	**78.05**
L8/15	32.63	0	41.25	29.02	11.6	12.58	3.4	28.72	**159.2**

Table 3.10: Planned and Unplanned interruption duration (Hr.) from September 1, 2024, up to December 30, 2024

Feeder	September		October		November		December		Tot
	Planned	Unplanned	Planned	Unplanned	Planned	Unplanned	Planned	Unplanned	
L1/33	5.47	153.4	3.33	397.6	22.5	115.3	1.57	62.1	**761.27**
L2/33	2.72	0	0	0.7	0	18.98	0	0.6	**23**
L3/33	6.18	146.7	3.63	95.8	10.8	71.43	12.5	79.9	**426.94**
L4/33	3.68	153.3	2.93	62.4	13	93.18	9.88	109.6	**447.97**
L1/15	8.35	46.85	4.87	15.4	22.5	30.33	21.7	11.6	**161.6**
L2/15	0.28	17.8	5.08	39.6	1.98	22.67	0.9	3.5	**91.81**
L3/15	3.53	5.1	25.2	4.2	0.75	0.97	32.5	66.8	**139.05**
L8/15	5	6.82	11.3	2.6	16.8	5.07	0.9	0.1	**48.59**

Table 3.11: Planned and Unplanned interruption frequency (Int/yr.) from January 1, 2024, up to April 30, 2024

Feeder	January		February		March		April		Tot
	Planned	Unplanned	Planned	Unplanned	Planned	Unplanned	planned	Unplanned	
L1/33	0	0	0	0	0	0	5	116	**121**
L2/33	0	3	0	1	0	4	0	1	**9**
L3/33	9	101	5	23	10	120	4	62	**334**
L4/33	12	99	23	138	15	109	9	85	**490**
L1/15	4	12	4	10	7	11	5	24	**77**
L2/15	2	1	3	4	3	12	3	16	**44**
L3/15	18	10	10	17	10	22	7	9	**103**
L8/15	9	8	5	6	8	9	0	34	**79**

Table 3.12: Planned and Unplanned interruption frequency (Int/yr.) from May 1, 2024, up to August 30, 2024

Feeder	May		June		July		August		Tot
	Planned	Unplanned	Planned	Unplanned	Planned	Unplanned	Planned	unplanned	
L1/33	5	90	6	101	9	87	4	85	**387**
L2/33	0	0	0	3	0	5	0	2	**10**
L3/33	1	25	4	79	14	95	11	92	**321**
L4/33	8	123	13	105	8	90	6	83	**436**
L1/15	3	20	4	22	9	22	7	16	**103**
L2/15	9	17	6	10	7	19	11	30	**109**
L3/15	3	5	4	7	8	3	7	4	**41**
L8/15	0	29	8	21	7	13	3	15	**96**

Table 3.13: Planned and Unplanned interruption frequency (Int/yr.) from September 1, 2024, up to December 30, 2024

Feeder	September		October		November		December		Tot
	Planned	Unplanned	Planned	Unplanned	Planned	Unplanned	Planned	unplanned	
L1/33	7	63	5	82	10	74	2	63	**306**
L2/33	0	1	0	1	0	2	0	1	**5**
L3/33	6	87	4	109	8	92	6	87	**399**
L4/33	4	67	3	55	6	59	4	67	**265**
L1/15	8	7	6	9	11	11	8	7	**67**
L2/15	3	8	11	31	4	13	3	8	**81**
L3/15	7	16	9	2	3	3	7	16	**63**
L8/15	2	1	6	8	9	8	2	1	**37**

NB: System overload (SOL), power transformer overload (PTOL), distribution transient earth faults (DTEF), distribution transient short circuit faults (DTSC), distribution permanent earth faults (DPEF), and distribution permanent short circuit faults (DPSC) are examples of unplanned outages. Planned outages are power outages that occur for operational purposes.

Table 3.14: Average interruption frequency and duration per year (2024 GC):

Feeder	**Frequency Of Interruption (int/yr)**			**Outage Duration (Hr./yr)**		
	Planned	Unplanned	**Total**	Planned	Unplanned	**Total**
L1/33	53	761	**814**	854.82	1400.12	**2254.94**
L2/33	0	24	**24**	4.59	62.23	**66.82**
L3/33	82	972	**1054**	376.77	1193.98	**1570.75**
L4/33	111	1080	**1191**	399.89	1814.83	**2214.72**
L1/15	76	171	**247**	1500.43	328.27	**1828.7**
L2/15	65	169	**234**	74.06	209.47	**283.53**
L3/15	93	114	**207**	147.48	149.95	**297.43**
L8/15	59	153	**212**	147.9	140.56	**288.46**

I deduce that the feeders on 33kV are experiencing longer interruption duration and frequency based on Table 3.14 above, which shows the average interruption frequency and duration annually. As a result, placing the DG unit at these feeders is preferable.

3.4 Reliability Indices Calculation

Equations from (2.1) to (2.13), provided in Chapter Two, are used to determine the reliability indices of the current substation. We can compute some of the reliability indices up to 3.15 using the information in Table 3.5.

Table 3.15: Calculated system reliability indices

Feeders	SAIFI	SAIDI	CAIDI	ASAI	ASUI	Peak Load	ENS
L1/33	814	2254.94	2.74	0.932842	0.067158	0.87	2634.29
L2/33	24	66.82	2.90	0.816932	0.183068	2.77	198.76
L3/33	1054	1570.75	1.51	0.940456	0.059544	5.38	8628.23
L4/33	1191	2214.72	2.08	0.88013	0.11987	4.78	10422.38
L1/15	247	1828.7	7.58	0.985475	0.014525	4.69	10748.28
L2/15	234	283.53	1.21	0.242625	0.757375	1.47	529.57
L3/15	207	297.43	2.33	0.297169	0.702831	4.48	1597.76
L8/15	212	288.46	1.34	0.999481	0.000519	5.13	1698.33
System average	**497.875**	**1094.4**	**2.711**	**0.76188**	**0.23811**	**3.69**	**4557.19**

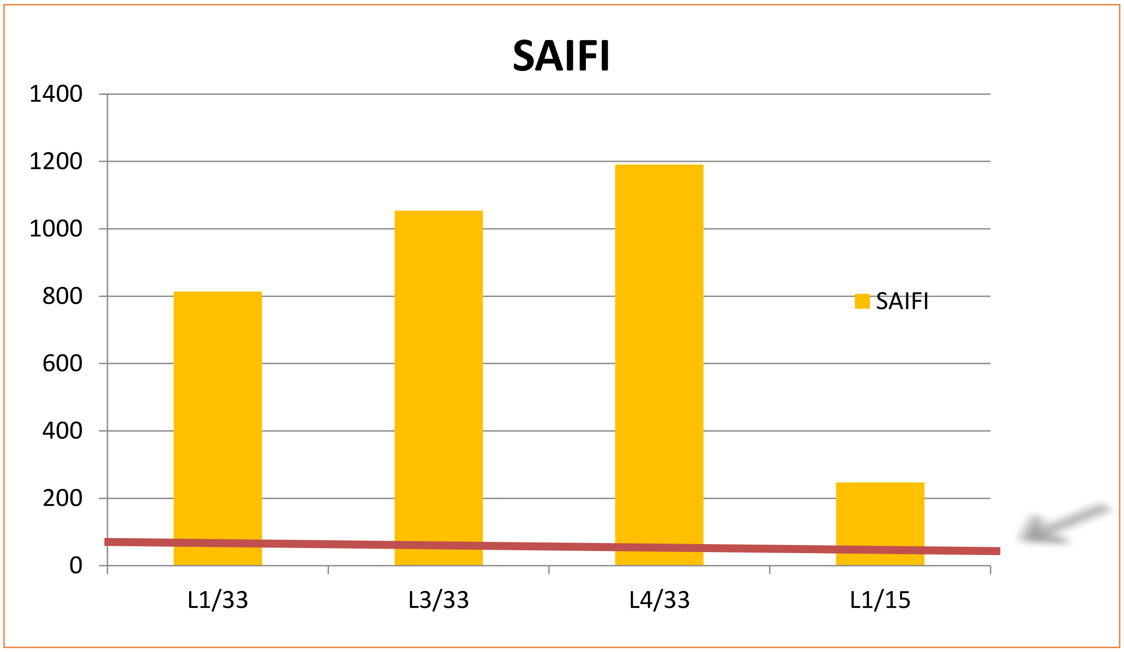
3.5 Comparison of the determined reliability indices with the Ethiopian Electric Agency's benchmarks and international standards

The calculated reliability indices should be compared with the network's benchmark values to ascertain whether or not the Mojo New distribution substation is a reliable part of the system (in this case, the calculated reliability index results are compared with the benchmark value set by the Ethiopian Electric Power Agency). These calculated reliability indices should also be compared to international standards.

Table 3.16 below compares the most popular reliability indices (SAIFI, SAIDI, and CAIDI) with different network standards and benchmarks.

Table 3.16: Comparing the computed reliability indices with various standards

Country		SAIFI(int/yr./ Ca)	SAIDI (hr./yr./Ca)	CAIDI (hr./yr./Ca)
United Kingdom		0.8	1.1	2.3
Canada		3.4	6.9	0
USA		1.5	2.3	1.4
Germany		0.5	0.383	0
Netherland		0.3	0.55	0
Ethiopia		20	25	5
Mojo New Substation	L1/33 (Ajerie)	814	2254.94	2.74
	L2/33 (Anbesa)	24	66.82	2.90
	L3/33 (Arerti Ceremic)	1054	1570.75	1.51
	L4/33(Arerti Town)	1191	2214.72	2.08
	L1/15 (Mojo Town)	247	1828.7	7.58
	L2/15(AirForce)	234	283.53	1.21
	L3/15(BishoftuTown)	207	297.43	2.33
	L8/15 (mojo Tannery)	212	288.46	1.34

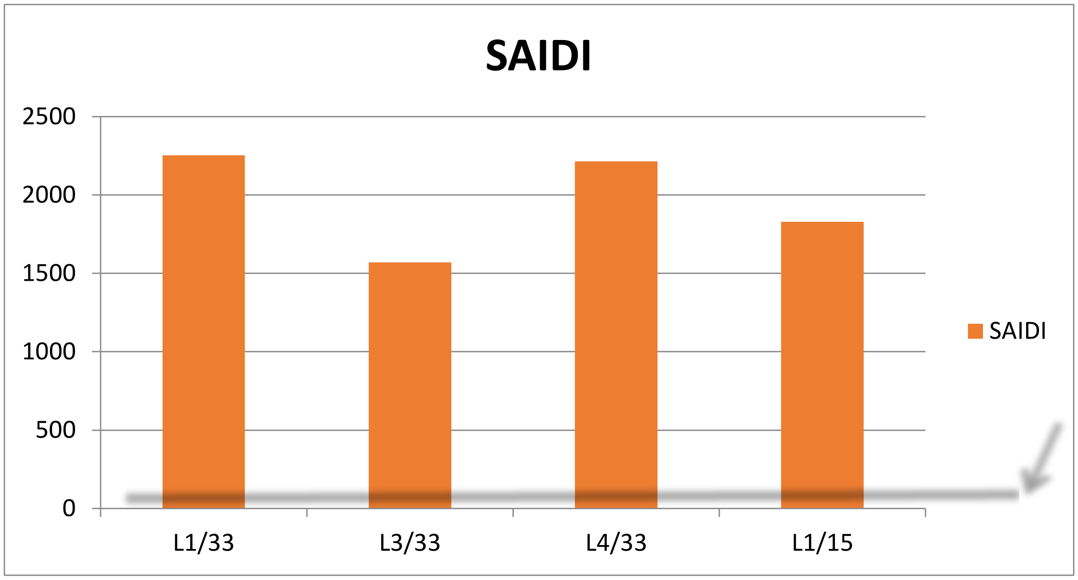


20/int/yr

Benchmark

Figure 3.3: Average calculated SAIFI values of the selected feeders

According to the above bar chart figure, the feeders L1/33 (Ajerie), L3/33 (Ararti Ceramic), L4/33 (Arerti Town), and L1/15 (Mojo tannery) have SAIFI values of 814 int./yr./Ca, 1054 int./yr./Ca, and 1191 int./yr./Ca, respectively. The Ethiopian Electric Agency's (EEA) standard, however, states that SAIFI cannot disrupt more than 20 customers annually. The current Mojo new distribution substation has a major reliability issue since the calculated SAIFI value is significantly higher than the acceptable value.



benchmark.25hr/ayrBmark

Figure 3.4: Average calculated SAIDI values of the selected feeders

According to Figure 3.3, the feeders L1/33 (Ajerie), L3/33 (Arerti Ceremic), L4/33 (Arert Town), and L1/15 (Mojo Town) have SAIDI values of 2254.94 hours/year/Ca, 1570.75 hours/year/Ca, 2214.72 hours/year/Ca, and 1828.7 hours/year/Ca, respectively. However, in compliance with the Ethiopian Electric Agency's (EEA) standard, SAIDI should not exceed 25 hours per customer per year. Because the calculated value of SAIDI is much higher than the acceptable benchmark, there is a serious reliability problem with the current Mojo new distribution substation.

CHAPTER FOUR

SIMULATION RESULT AND DISCUSSION

4.1 System Modeling

PSCAD, ETAP, and Dig SILENT are just a few of the many software programs available today that can model DG systems. The software program selected for this analysis is ETAP.

Several Microsoft Windows operating systems are compatible with the fully graphical Enterprise package Electrical Transient Analysis Program (ETAP). ETAP is the most comprehensive analysis tool for designing and testing power systems. ETAP can use real-time operating data for monitoring, real-time simulation, optimization, energy operation systems, and fast intelligent load shifting through its standard offline simulation modules. With ETAP, you can easily create and modify graphical one-line diagrams, three-dimensional ground grid systems, time-current collaboration and selectivity plots, underground cable raceway systems, and graphical one-line diagrams. The program operates as closely as possible to a real electrical system. For example, when you open or close a circuit breaker, put an element out of service, or change the operating status of the motors, the de-energized elements and sub-systems are displayed in gray on the one-line diagram. ETAP determines defensive device coordination based on the one-line diagram using cutting-edge concepts. The logical, mechanical, electrical, and physical components of system fundamentals are all combined into one database by ETAP. One of the most integrated databases for electrical systems, ETAP, allows engineers to have multiple presentations of a system for different analysis or design purposes. The software analyzes arc flash, load flow, reliability, short circuit, protection coordination, and other electrical analyses. Failure rate and mean time to repair values for each component are required to forecast a distribution system's reliability indices. As shown in equation (2.4), the total number of outages should be divided by the feeder length (kilometers) to determine the line failure rate per kilometer. Equation (2.3) is used to calculate the average mean time to repair for each failure. The introductory reliability parameters used in the reliability analysis of ETAP software are computed using equations 2.3 and 2.4.

$$UA = \frac{8805.35}{422.5} = 20.84$$

$$MTTR = \frac{8805.35}{3983} = 2$$

ETAP 19.0.1 has been utilized as a design, simulation, and reliability assessment analysis tool in this thesis.

4.2 Simulation of the Existing System

ETAP19.1.0 software is used to model the current system, which is depicted in Figure 4.1 below. To provide the system reliability indices and load point reliability indices as outputs, the software requires the one-line diagram, the voltage and power levels for each component, the active failure rate, and the mean time to repair for each component as inputs. The current system of the chosen feeder in this study is designed either directly or indirectly using the primary and secondary data that were gathered. Every parameter required for the system design is computed and entered appropriately.

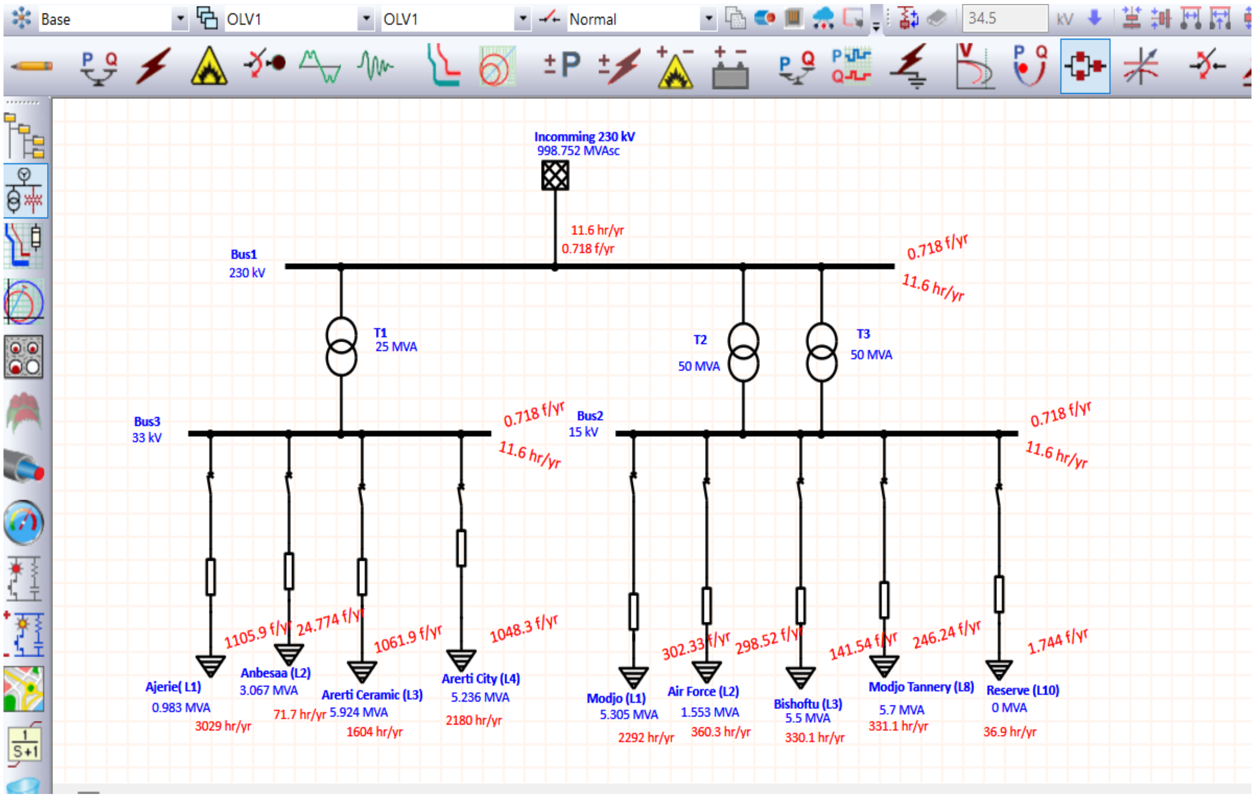


Figure 4.1: Simulated existing system distribution substation

Table 4.1: Result of Reliability indices of existing system

Project: Reliability Of Distribution Substation
ETAP
Page: 1

Location: Mojo
19.0.1C
Date: 19-05-2025
SN:
Contract:
Engineer: Karu Elemo
Study Case: RA
Revision: Base
Filename: Mojo Substation
Config.: Normal

SUMMARY

System Indexes

AENS	4050.8460 MW hr / customer
ASAI	0.8702 pu
ASUI	0.12982 pu
CAIDI	2.419 hr/customer interruption
ECOST	108,677,400.00 $ / yr
EENS	36457.610 MW hr / yr
SAIDI	1137.2580 hr/customer.yr
SAIFI	470.1548 f / customer.yr

The simulated base case system reliability indices yielded a value for SAIFI of 470.15 f/ca, SAIDI of 1137.25 hrs/ca, and energy not supplied of 36457.61 MWh/ca, as shown in Table 4.1 above. Additionally, the substation has a high rate of service unavailability, with an average service availability of 96.5%.

4.3 Simulation and Result Discussion of the Modified System

The objective of this case study is to design an upgraded system that would make the Mojo New distribution system a near-net-zero consumer interruption. Now, Small MW DG (PV) units are connected at low voltage sides 1kV bus bars of the feeders (Ajeri, Arerti Ceramic, Arerti Town, and Mojo Town), and simulation is conducted as shown in the single line diagram below.

The table from the simulation's output window shows the improvement in overall reliability indices following DG connection.

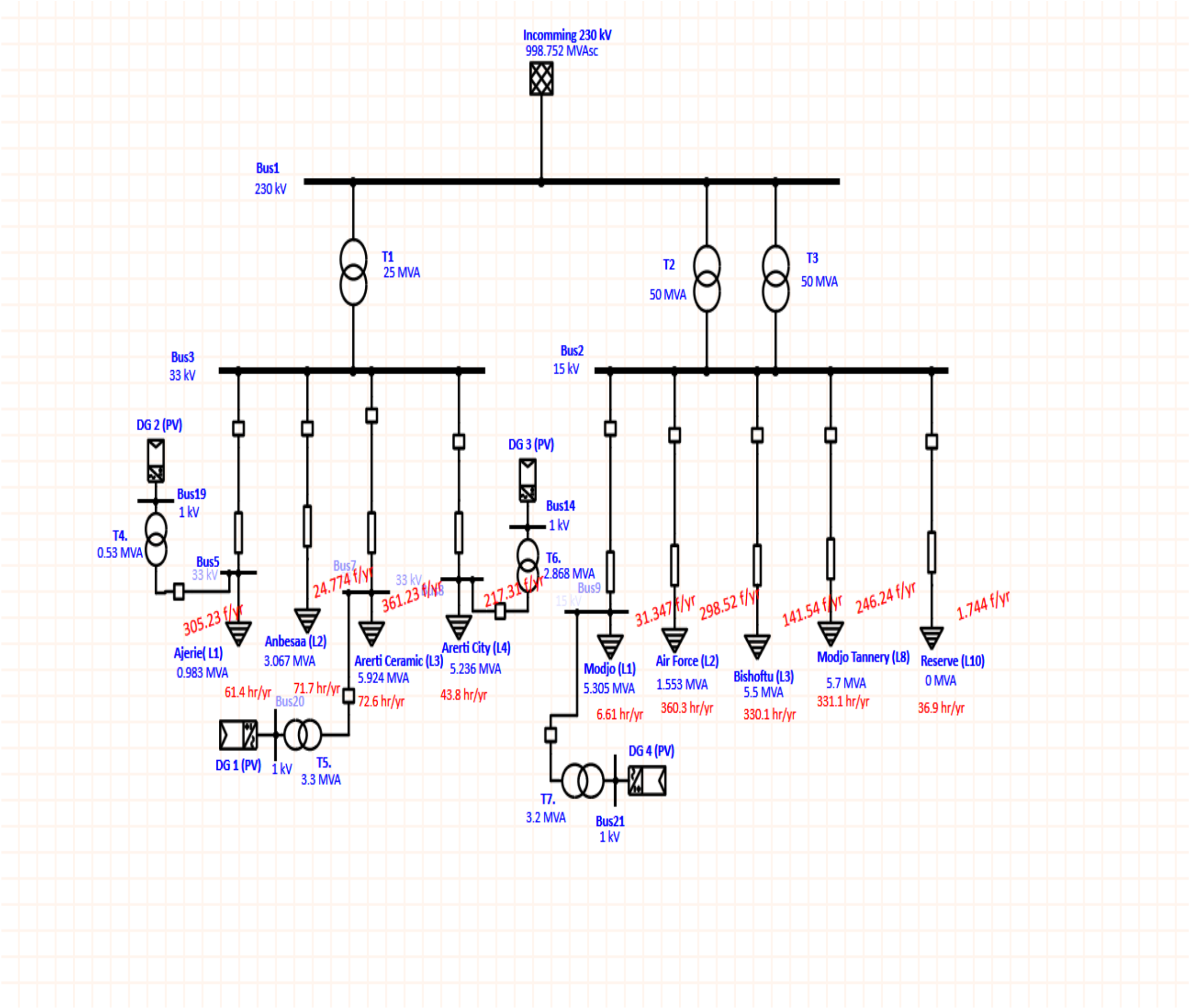
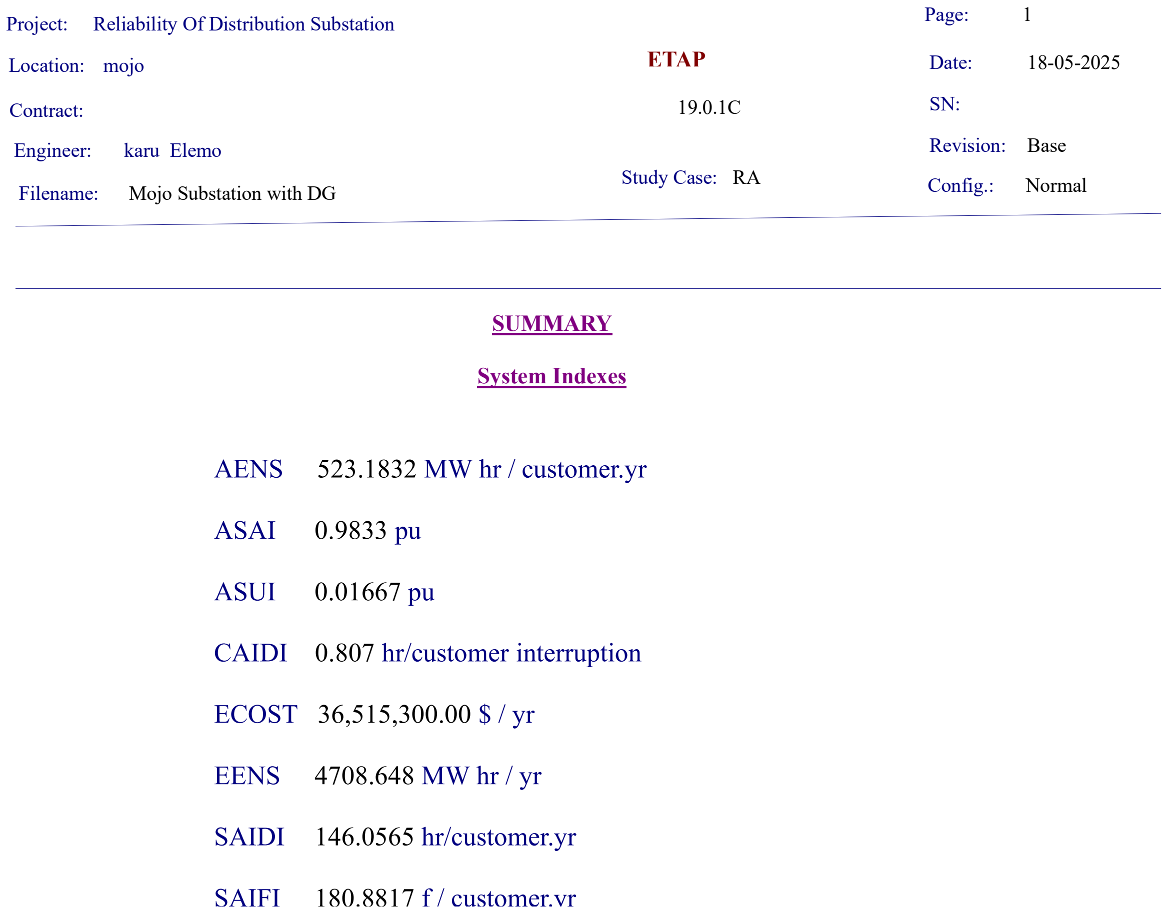


Figure 4.2: The simulated modified distribution substation

Table 4.2: Simulation output of system reliability indices with DG at 1kV selected feeders.



Project: Reliability Of Distribution Substation
Location: mojo
Contract:
Engineer: karu Elemo
Filename: Mojo Substation with DG

ETAP
19.0.1C
Study Case: RA

Page: 1
Date: 18-05-2025
SN:
Revision: Base
Config.: Normal

SUMMARY

System Indexes

AENS	523.1832 MW hr / customer.yr
ASAI	0.9833 pu
ASUI	0.01667 pu
CAIDI	0.807 hr/customer interruption
ECOST	36,515,300.00 $ / yr
EENS	4708.648 MW hr / yr
SAIDI	146.0565 hr/customer.yr
SAIFI	180.8817 f / customer.vr

According to the above table, the overall improvement in the indices SAIFI, SAIDI, and ENS is 84.95%, 83.34%, and 87.08%, respectively, when the simulation is run and the Small MW DG unit is connected to the LV side bus bar of the feeders (Ajerie, Arerti ceramic, Arerti Town, and Mojo Town). This demonstrates that greater reliability improvement is achieved when DG units of the same magnitude are connected at various bus bars. As a result, where the DG is installed, reliability indices (SAIDI, CAIDI, and ENS) improve. Thus, it can be inferred from the simulation that the greatest improvement in reliability indices occurs upon installation of the DG unit.

4.4 Comparison of simulated results of the existing system with the modified case system

Table 4.3: Simulated results

System Indices	existing system (without DG)	modified system (with 3MW DG)
SAIFI	470.15	180.88
SAIDI	1137.25	146.05
CAIDI	2.419	0.807
ASAI	0.8702	0.9833
ASUI	0.12982	0.01667
EENS	36457.61	4708.64.64
AEN	4050.84	523.18

Table 4.3 shows that the current system's reliability is extremely low due to its extremely high index value. The system reliability increases by a larger percentage with the installation of small MW DG units. As a result, 88.13%, 84.95%, and 83.34%, respectively, represent the percentage improvement in energy not supplied, system average interruption frequency, and system average interruption duration. Table 4.3 shows that the system's average service availability has also improved significantly. The cost before and after improvement is computed using equation (2.14).

- **Interruption cost before improvement**

$$-\quad \frac{1}{4} * \text{EENS} * (\text{SAIDI}) \text{x } 0.8 \text{ x } 0.767) \text{ ETB} = \frac{1}{4} * 36457.61*1000*1137.25*0.8*0.767 \text{ ETB}$$

$$= 6{,}360{,}181{,}364 \text{ ETB}$$

- **Interruption cost after improvement**

$$-\quad \frac{1}{4} * \text{EENS} * (\text{SAIDI}) \text{x } 0.8 \text{ x} 0.767) \text{ ETB} = \frac{1}{4} * 4708.64*1000*146.05*0.8*0.767 \text{ ETB}$$

$$= 105{,}492{,}700 \text{ ETB}$$

Saved revenue cost = Int cost before improvement – int cost before improvement

6,360,181,364 ETB- 105,492,700 ETB = 6,254,688,664ETB

Therefore, the cost saved by connecting DG on selected feeder is about 6.25, and the percentage improvement in ECOST is 88.34 %.

CHAPTER FIVE

CONCLUSION, RECOMMENDATION, AND FUTURE WORK

The following conclusions and suggestions have been made in light of the findings of this study on the reliability issues of the Mojo New distribution substation and the simulation done using distributed generation to mitigate the overloading and reliability issues. Additionally, potential future research projects are suggested.

5.1 Conclusion

This study demonstrates that the Mojo New substation's dependability falls short of the standards established by the Ethiopian Electric Agency (EEA), the regulatory body. In the current system, the average duration of interruptions (SAIDI) is 1137.25 hours per customer annually, and the average frequency of interruptions (SAIFI) at the substation is 470.15 interruptions per customer annually. Both planned and unplanned outages cause a significant loss of unsupplied energy in the current system study. As a result, the substation has a greater reliability vulnerability of ENS (36457.61 MWh/yr), which causes revenue losses of about 6.3 BETB/yr.

The four feeders, Ajerie, Arerti ceramic, Arerti town, and Mojo town, that encounter more disruptions were linked to DGs. These DGs improve the system's overall dependability. Therefore, DGs ought to be situated on a load point where a large portion of the load is supplied, where there are the most interruptions, and where customers are. The installation of DG at the chosen feeders improved the SAIFI value by 61.7.95%, the SAIDI value by 87.15%, and the ENS value by 87.08%, according to the simulation results. With an average revenue savings of roughly 6.25 BETB annually, the ENS is decreased from 36457.61 MWh/year to 4708.64 MWh/year, and the ECOST is decreased from 6.3 BETB/year to 105METB/year.

5.2 Recommendations

The research's conclusions allow for the formulation of the following significant recommendations:

In the vicinity of the Mojo area, the EEU ought to endeavor to enhance the reliability of the electrical grid. The power provider should encourage DG options based on renewable energy, both for urban electrification as a backup and for rural electrification. Substation automation technologies should be implemented by EEP to increase power supply reliability. A planned tree trimming and clearance program can significantly reduce the failure rate of overhead lines and improve the reliability of the distribution system.

5.3 Future Work

The upcoming projects in the field of DG-assisted reliability enhancement are discussed.

- DG can be utilized for peak load sharing or as a backup. Therefore, a control system between the DG and the current grid should be modeled for each of these purposes.
- The distribution system can be modeled by treating it as a radial network.

In the future, other distribution system types, like mesh networks, might be taken into account for reliability assessment.

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APPENDIX: A

Table 1A: Procedures in the ETAP19.1.0 software simulation.

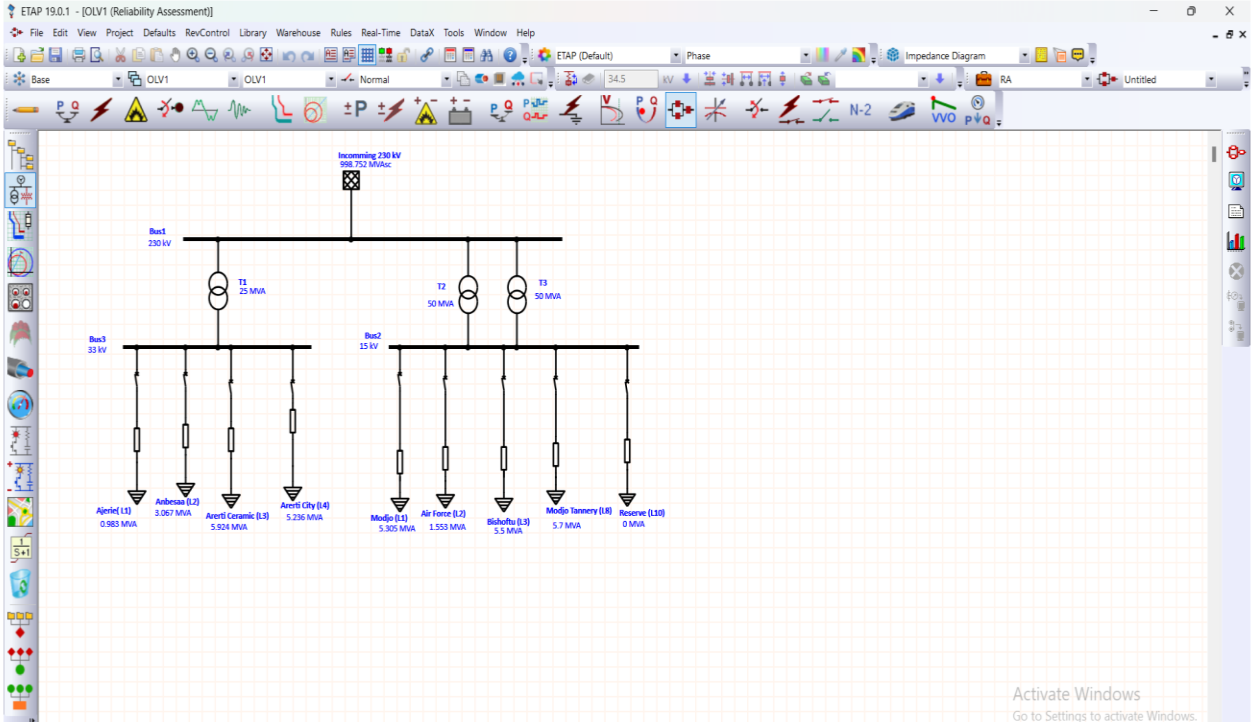

Figure 1A Procedures in the ETAP19.1.0 software simulation.

APPENDIX: B

Table 1B: EEU electricity tariff (Birr/kWh).

Residential	Range (KWh)	Price Rate (ETB/KWh)
	0-50	0.2730
	51-100	0.7670
	101-200	1.6250
	201-300	2.000
	301-400	2.200
	401-500	2.405
	Above 500	2.48
Commercial	0-50	1.930
	Above 50	2.124
Industrial (@15&33KV)	Peak	1.531
	Off-Peak	1.486

APPENDIX: C

Table 1C: Hourly load (MW) of each feeder of the substation (typical: 29-April-2024)

APPENDIX: C

Table 1C: Hourly load (MW) of each feeder of the substation (typical: 29-April-2024)

Hr	Feeder							
	L1/15	L2/15	L3/15	L8/33	L1/33	L2/33	L3/33	L4/33
1	0.123405	0.296172	0.074043	1.97448	0.162895	0.325789	1.683244	0.923069
2	0.123405	0.271491	0.074043	1.826394	0.162895	0.325789	1.683244	0.868771
3	0.123405	0.24681	0.074043	1.801713	0.162895	0.380087	1.628946	0.760175
4	0.123405	0.222129	0.074043	1.702989	0.162895	0.325789	1.52035	0.705877
5	0.123405	0.222129	0.074043	1.875756	0.162895	0.325789	1.683244	0.868771
6	0.222129	0.444258	0.296172	2.418738	0.162895	0.434386	1.683244	0.923069
7	0.296172	0.617025	0.444258	2.912358	0.271491	0.380087	1.52035	2.443419
8	0.271491	0.789792	0.197448	4.146408	0.271491	0.488684	1.19456	2.389121
9	0.296172	0.913197	0.197448	4.738752	0.108596	0.380087	1.248859	2.171928
10	0.24681	0.863835	0.197448	4.738752	0.271491	0.380087	1.303157	2.280524
11	0.271491	0.814473	0.222129	4.44258	0.325789	0.380087	1.411753	2.226226
12	0.222129	0.765111	0.296172	3.183849	0.434386	0.162895	1.411753	2.171928
13	0.24681	0.715749	0.172767	3.307254	0.325789	0.434386	1.52035	1.900437
14	0.24681	0.691068	0.148086	4.072365	0.380087	0.59728	1.357455	1.791841
15	0.24681	0.691068	0.172767	3.183849	0.325789	0.651578	1.411753	1.791841
16	0.320853	0.592344	0.172767	2.937039	0.325789	0.651578	1.357455	1.900437
17	0.24681	0.345534	0.24681	2.320014	0.271491	0.542982	1.248859	2.226226
18	0.345534	0.394896	0.24681	1.900437	0.380087	0.59728	1.19456	2.334823
19	0.296172	0.444258	0.345534	2.147247	0.434386	0.542982	1.085964	2.226226
20	0.345534	0.419577	0.345534	1.97448	0.542982	0.651578	1.846139	2.606314
21	0.24681	0.370215	0.172767	1.777032	0.434386	0.542982	1.52035	2.009033
22	0.24681	0.296172	0.197448	1.72767	0.380087	0.542982	1.357455	1.900437
23	0.197448	0.271491	0.123405	1.604265	0.271491	0.542982	1.085964	1.628946
24	0.148086	0.296172	0.074043	1.48086	0.325789	0.760175	1.466051	0.868771

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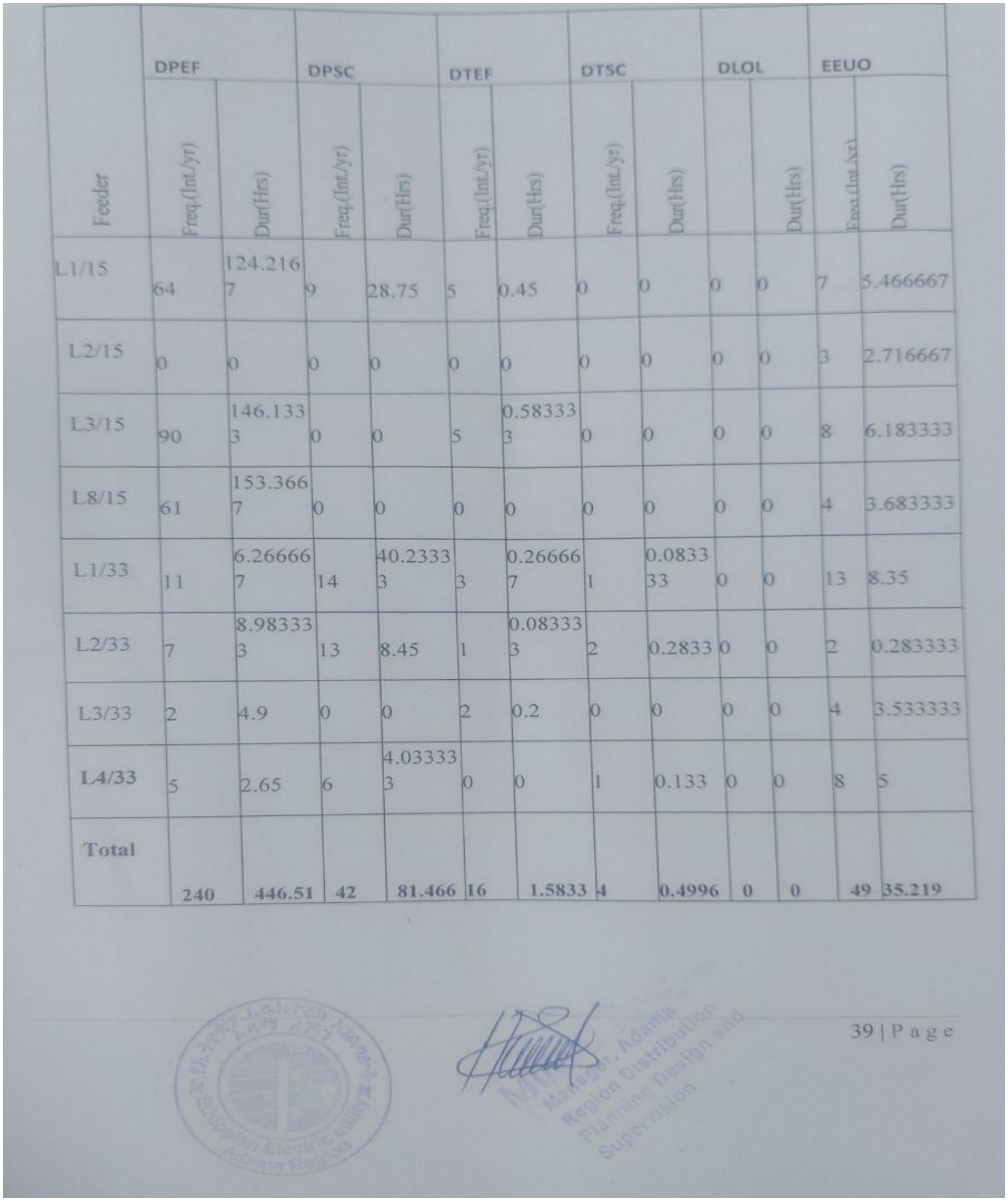
Table 2C: Interruption duration and Frequency of Various faults from September 2024



Feeder	DPEF		DPSC		DTEF		DTSC		DLOL		EEUO	
	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)		Dur(Hrs)	Freq.(Int./yr)	Dur(Hrs)
L1/15	64	124.2167	9	28.75	5	0.45	0	0	0	0	7	5.466667
L2/15	0	0	0	0	0	0	0	0	0	0	3	2.716667
L3/15	90	146.1333	0	0	5	0.583333	0	0	0	0	8	6.183333
L8/15	61	153.3667	0	0	0	0	0	0	0	0	4	3.683333
L1/33	11	6.266667	14	40.23333	3	0.266667	1	0.083333	0	0	13	8.35
L2/33	7	8.983333	13	8.45	1	0.083333	2	0.2833	0	0	2	0.283333
L3/33	2	4.9	0	0	2	0.2	0	0	0	0	4	3.533333
L4/33	5	2.65	6	4.033333	0	0	1	0.133	0	0	8	5
Total	**240**	**446.51**	**42**	**81.466**	**16**	**1.5833**	**4**	**0.4996**	**0**	**0**	**49**	**35.219**

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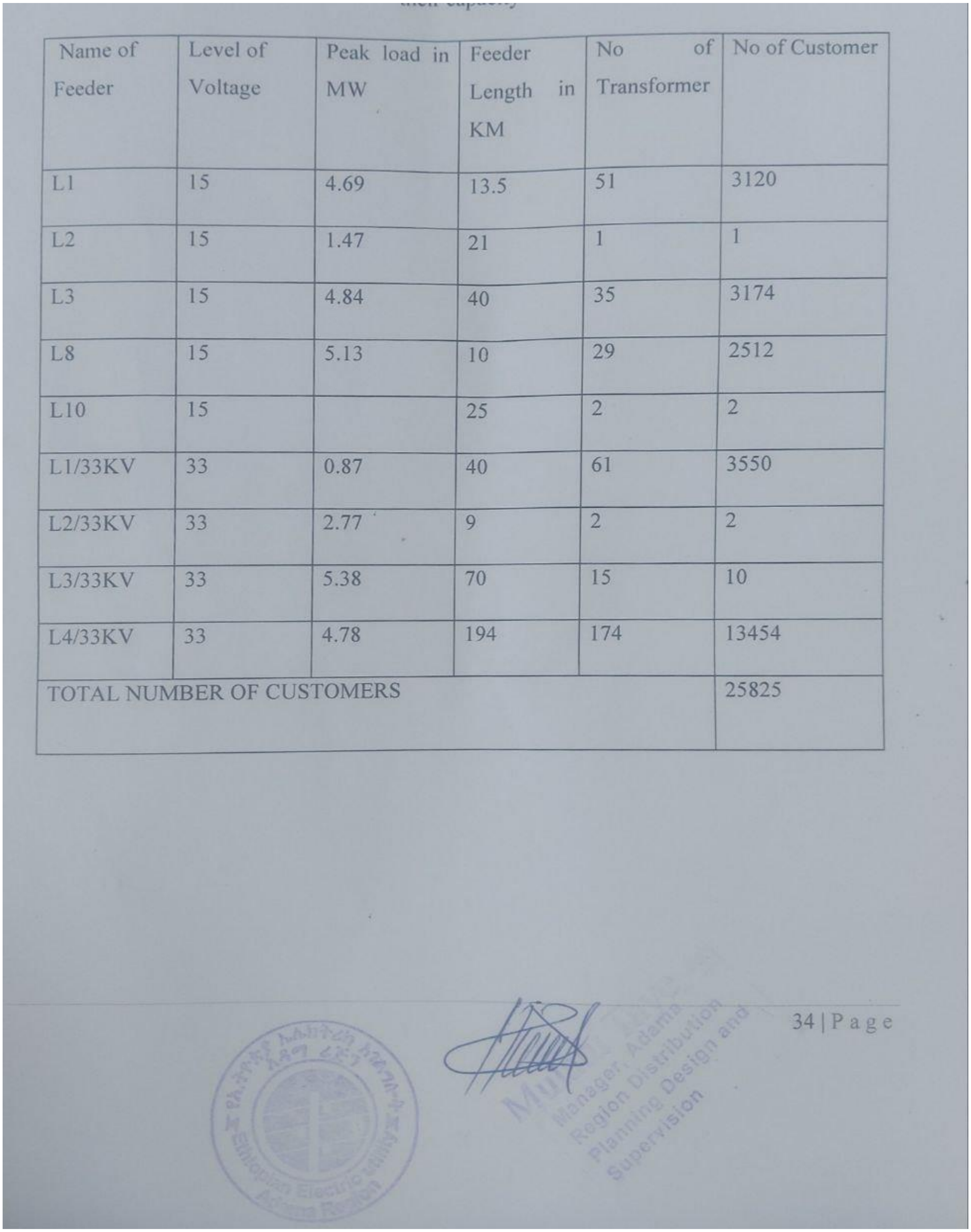
Table 3C: Substation Feeder No of Transformer, Their Capacity, and No of Customer



Name of Feeder	Level of Voltage	Peak load in MW	Feeder Length in KM	No of Transformer	No of Customer
L1	15	4.69	13.5	51	3120
L2	15	1.47	21	1	1
L3	15	4.84	40	35	3174
L8	15	5.13	10	29	2512
L10	15		25	2	2
L1/33KV	33	0.87	40	61	3550
L2/33KV	33	2.77	9	2	2
L3/33KV	33	5.38	70	15	10
L4/33KV	33	4.78	194	174	13454
TOTAL NUMBER OF CUSTOMERS					25825

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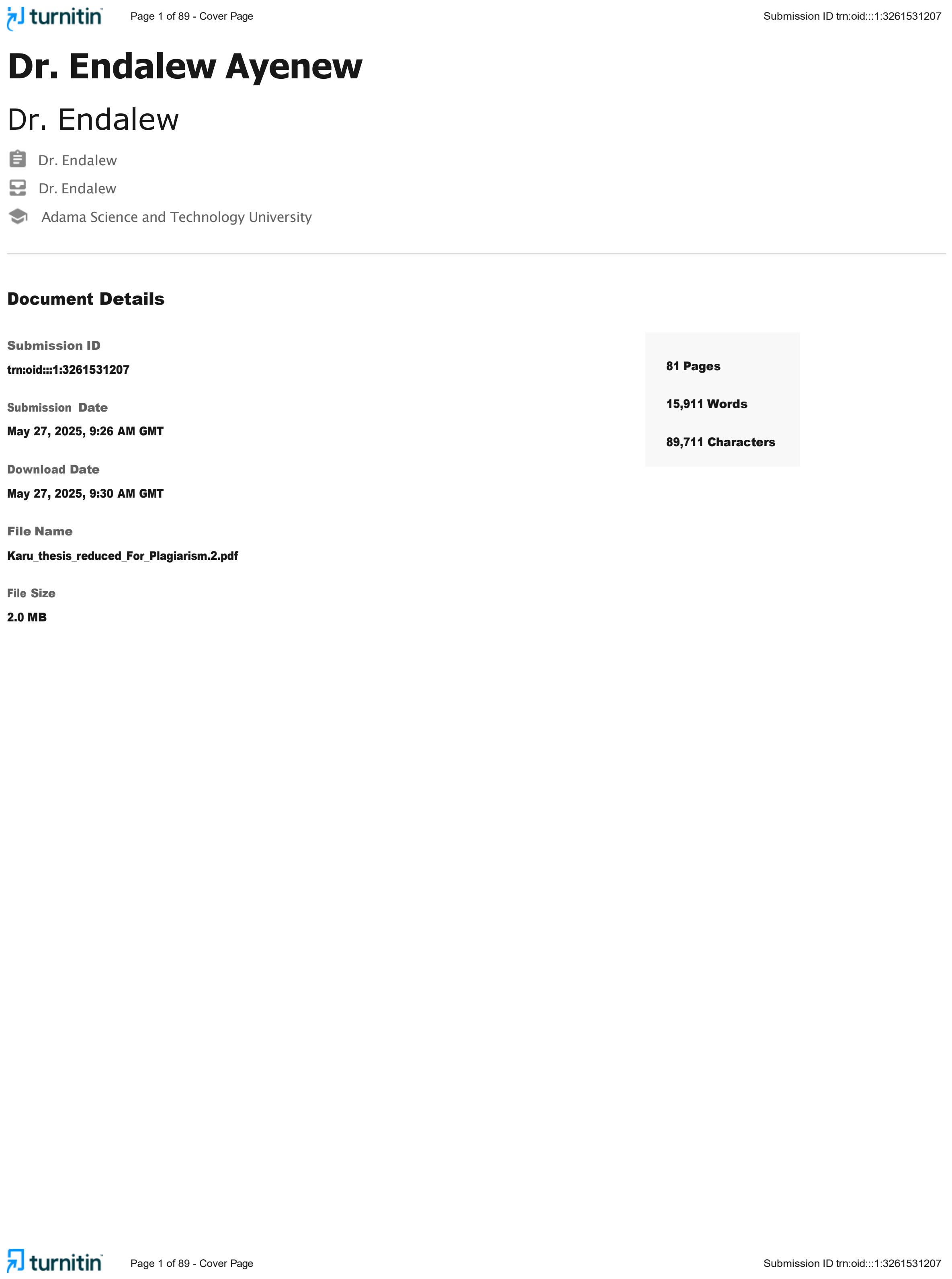
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