ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

RELIABILITY ANALYSIS OF 15kV DISTRIBUTION SYSTEM NETWORK

(CASE STUDY: ADDIS ALEM SUBSTATION NETWORK)

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BY

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RELIABILITY ANALYSIS OF 15kV DISTRIBUTION SYSTEM NETWORK (CASE STUDY: ADDIS ALEM SUBSTATION NETWORK)

By

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DECLARATION

I hereby declare that this thesis, entitled **"RELIABILITY ANALYSIS OF 15kV DISTRIBUTION SYSTEM NETWORK" (CASE STUDY: ADDIS ALEM SUBSTATION NETWORK)** is original work of my own, has not been presented for a degree in any other university and all sources and materials used for the thesis is acknowledged in this document.

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Reliability engineering with regard to distribution systems involves gathering outage data and evaluating system designs. The great majority of service interruptions that affect customers are caused by problems on the distribution system.

For the analysis, data has been collected from Addis Alem electric distribution system. The collected data are a recorded data that includes types of faults, frequency and duration of interruption of 15kV outgoing feeders' of the distribution system.

Currently customer served from Addis Alem substation are affected by frequent power interruptions and power quality problems. The interruptions are caused mostly by earth fault and short circuit. There also planned outage for operation purposes. The substation's System Average Interruption Frequency Index (SAIFI) is 178.37 Interruption per customer per year, System Average Interruption Duration Index (SAIDI) is 152.22 Hour per customer per year. The substation is not reliable by the standard of Ethiopian Electric Agency (EEA) which set (SAIDI = 25 and SAIFI = 20). This reliability disparity requires finding the best solution for improving the reliability of distribution system. Therefore, the best solutions to distribution system reliability problems, integrating Distribution Generation (DG) to the existing network as backup, which is evaluated in this thesis.

For best placement of DG on the distribution system at different load point, reliability improvement with DG has been investigated. The size of a single DG is 4MW and fed to the grid as backup when there is power interruption. Reliability analysis based on simulation studies carry out by DIgSILENT Power Factory Software.

Holeta feeder was studied to investigate the effect of DG at the end line to reliability. From the simulation, SAIFI and SAIDI of this feeder without of DG are 291.99 interruption per customer per year and 195.63 Hour per customer per year respectively. With DG option at the end of the line, the simulation result shows that the SAIFI and SAIDI of this feeder improved to 91.16% and 91.16% respectively.

Key Words: Distribution Network, Distribution System, Distribution Generation (DG), Availability, Feeders, Distribution Faults & Others, Reliability Analysis

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LIST OF ABBREVIATIONS

ASAI	Average service Availability Index
APPA	American Public Power Association
Avg.freq	Average frequency
Avg.Hr	Average Duration in hour
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
Cust.	Customer
D	Duration
DG	Distributed Generation
EEA	Ethiopia Electric Agency
EELPA	Ethiopian Electric Light and Power Authority
EEP	Ethiopian Electric Power
EEPCO’s	Ethiopian Electric Power Corporation’s
EEU	Ethiopian Electric Utility
Fr	Frequency
Hr	Hour
Hr/yr	Duration of Hour per Year
IEEE	International Electric and Electronic Engineering
Int.	Interruption
kV	Kilo Volt
LV	Low Voltage lines
MTBF	Average Mean Time Between Failures
MTTR	Average Mean Time To Repair

MVA	Mega Volt Ampere's
MVAr	Mega Var
MW	Mega Watt
MWh	Mega Watt Hour
NT	Total number of customers
PCG	Centralized Active Power
PDG	Active power generated by distributed generation
PEF	Permanent Earth Fault
PL.Maximam	Peak load of the feeder
PSC	Permanent Short Circuit
p.u	Per unit
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Super Control and Data Acquisition
SOL	System over Load
TD	Total Duration in Hour
TEF	Temporary Earth Fault
TFR	Total frequency
TSC	Temporary Short Circuit
yr	Year
λ	Failure rate

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

It is now universally accepted that the social and economic factors which define the level of prosperity, are highly correlated with the level of demand for electric power. In Ethiopia power development was introduced as early as 1950s. During these times, three landmark stages (Operation, Engineering, Finance and Administration) have passed to reach at the current status of the sector.

Ethiopian Electric Power Corporation was formed in 1956 as the Ethiopian Electric Light and Power Authority (EELPA), which bundled all Ethiopian activities around electricity in a single organization. A general manager leading five departments, namely Operations, Engineering, Planning, Finance and Administration, and Services, managed it.

In 1996, Ethiopian Electric Light and power Authority (EELPA) has split into the Ethiopian Electric Authority (EEA), taking overall regulating activities and a company, Ethiopian Electric Power Corporation (EEPCO) building activities from power generation to household delivery.

In 2013, Ethiopian Electric Power Corporation (EEPCO's) was split into two companies, Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU). Ethiopian Electric Power (EEP) is responsible for generation, transmission and system operation while Ethiopian Electric Utility (EEU) is responsible for power distribution to the end user's.

Generally, the above corporation consists of 500kV (where it is under construction), 400kV, 230kV, 132kV primary transmission systems and 66kV, 45kV as sub transmission system and 33kV and 15kV as distribution system. The power distribution system is made up of sub-transmission lines, power transformers, 33kV lines, 15kV lines, distribution transformers, LV lines, etc. Distribution substations are situated at convenient locations close to the center of gravity of some components of load. The main role of distribution substation is to monitor and adjust circuits within the system. At all the 66 or 45kV substations power transformers of various rating likes 25/12/6.3/3MVA are installed for step down of voltage to 15kV for feeding to distribution transformers. The outgoing feeders are connected in radial system. The voltage is then further reduced by distribution transformers to the utilization voltages of 380 volts three-phase or 220 volts single-phase supply required by most users. Once the voltage has been lowered at the distribution substation, the electricity flows to industrial, commercial, and residential centers through the distribution system. Conductors called feeders reach out from the distribution substation to carry electricity to customers. At key locations along the distribution system, voltage is lowered by distribution transformers to the voltage needed by end-users [1].

Electric Power distribution system in Addis Alem is something of a major poor state of electric power distribution concern. Most of a time the substation is interrupted by internal and external causes which affects the availability and reliability of distribution network. Reliability, availability together with maintainability is analyzed to determine the ability of system to accomplish an intended task. Reliability of an electric power system is defined as the probability that the power system will perform the function of delivering electric energy to customers on a continuous basis and with acceptable service quality [2].

1.2 Scope of the Research

The purpose of this research is to analyze the reliability of distribution system network using 15kV outgoing feeders from distribution substation as a case study. This analysis will help the power system planners and utilities to identify the sensitive components of the distribution system that need more attention for better improvement. In this Thesis, DG units are used to improved system reliability. The results are explained using simulation on Power Factory DIgSILENT Software.

1.3 Statement of the Problem

There are many factors that contribute to the failure of distribution network. Reliability is very important issue in dealing with planning and operation of the networks. In distribution system planning, reliability aspects are an important part of the decision base. Thus, to be able to assess and evaluate, reliability is needed in the operational process.

The main problem facing in the Addis Alem distribution substation is there are number of power interruptions which was affects the reliability and availability of distribution network. Enhance knowledge in reliability analysis of distribution network will contribute to the measurement of how far the system meets the performance criteria, to help quantify comparison between various options [3].

The analysis carrying out by using powerful digital software “DIgSILENT Power Factory for simulation. It has powerful to calculate reliability indices like SAIFI, SAIDI, CAIDI and ASAI, and it also, Non Delivered Energy based upon input data in the existing network. This software helps us to find the best location of line equipment like switches either automated or manual, based on long- term approach rather than short- term approaches. The results of the computer- generated solution depend on the quality of input data or the data available with the user.

Therefore, it is very important for the utilities to maintain and update the data recording systems for future use. This would enhance to improve the system studies in future, overall reliability in the system could be improved and the need of the regulators and customers are met.

1.4 Objectives of the Study

- **General Objectives**

The main objective of this thesis is to conduct reliability analysis of 15kV distribution system network for Addis Alem substation and study potential improvement methods.

- **Specific Objectives**

The specific objectives of this research are:

- ✓ To create a database of interruption for consecutive of two years period (2017 and 2018) to determine the availability of substation.
- ✓ Perform reliability analysis of 15kV Addis Alem substation based on database of interruption consecutive of two years period (2017 and 2018) using Analytical Method.
- ✓ Analyze the reliability of Addis Alem Substation without and with DG using the DIgSILENT Power Factory Software.
- ✓ Draw relevant conclusions and recommendations from the result of the investigation.

1.5 Organization of the Thesis

Chapter One: In this chapter, power distribution system concepts related to the background of the study is described. And also, the aim and objectives of the research is given.

Chapter Two: This chapter, introduced about electrical distribution network, reliability, Distributed Generation and types of DG technology is defined. And also, factors that affect the reliability of power distribution system were discussed.

Distribution reliability evaluation is divided into two aspect and the two main methods used to carry out reliability evaluation are discussed. The later part of this chapter gives a critical review of published current research papers on reliability evaluation.

Chapter Three: This chapter presents the result obtained from the reliability evaluation carried out on the distribution substation. The result is discusses and interprets so as to identify the feeder contributing the most to interruption of the system and also the overall reliability of the substation.

Chapter Four: This chapter discusses the effect of integrating DG system at different load points of distribution substation using DIgSILENT Power Factory Software. It analyzes that connecting DG at a distance far away from the supply point gives better improvements of the feeders.

Chapter Five: This chapter is concludes the overall reliability of distribution system and recommends the Ethiopian electric utility; it describes the work requires for the future who need to work on this substation.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Electric Power Distribution Network

Electrical distribution network provides consumers with electric power in a way that the quality of service and high quality and that the importance of the reliability of electrical distribution network as a factor of development and economic growth [4]. As the studies have shown which confirmed that 80% of interruptions in the supply of electric power resulting from the problems and breakdowns in the electrical distribution networks [5].

Electrical distribution systems are usually radial so exposed to the rates of interruption because of system components of transformers and breakers and switching devices, the growing demand for customers to provide high quality service make requirements for improvements in the electrical distribution network.

The electric distribution networks are means by which the electric energy generated at the power stations are delivered to the consumers. The electric network can be subdivided into two, namely: the transmission and distribution system. The distribution system connects all the individual loads in a given locality to the transmission lines via switchgear equipment.

Currently, the Ethiopian electric distribution system may be sub-divided into three, based on the voltage level as follows

- ✓ Primary distribution (66kV or 45kV)
- ✓ Secondary distribution (15kV)
- ✓ Tertiary distribution (380V for three phases and 220V for single phase).

Hence, Factors, individual, small and large consumers around this area survived from this distribution network. Therefore, there is the need to improve the reliability of distribution network due to the increasing dependability of human existence on electricity. However, In accordance with the National Electricity rules in 6.5.7 (e), understanding that it would be difficult and extremely expensive to re-design a full network to withstand all causes of poor reliability.

2.2 Distribution System

Distribution system is portion of an electric system that delivers electric energy from transformation points on the transmission system to the customer. It generally considered being anything from the distribution substation fence to the customer meter and often the initial overcurrent protection and voltage regulators are within the substation fence and are considered part of the distribution system. The distribution network typical located at every nook and corner to provide the electric power supply for all the individual customers. It contains sub-transmission, distribution substations, primary feeder, distribution transformers, secondary circuit and service lines.

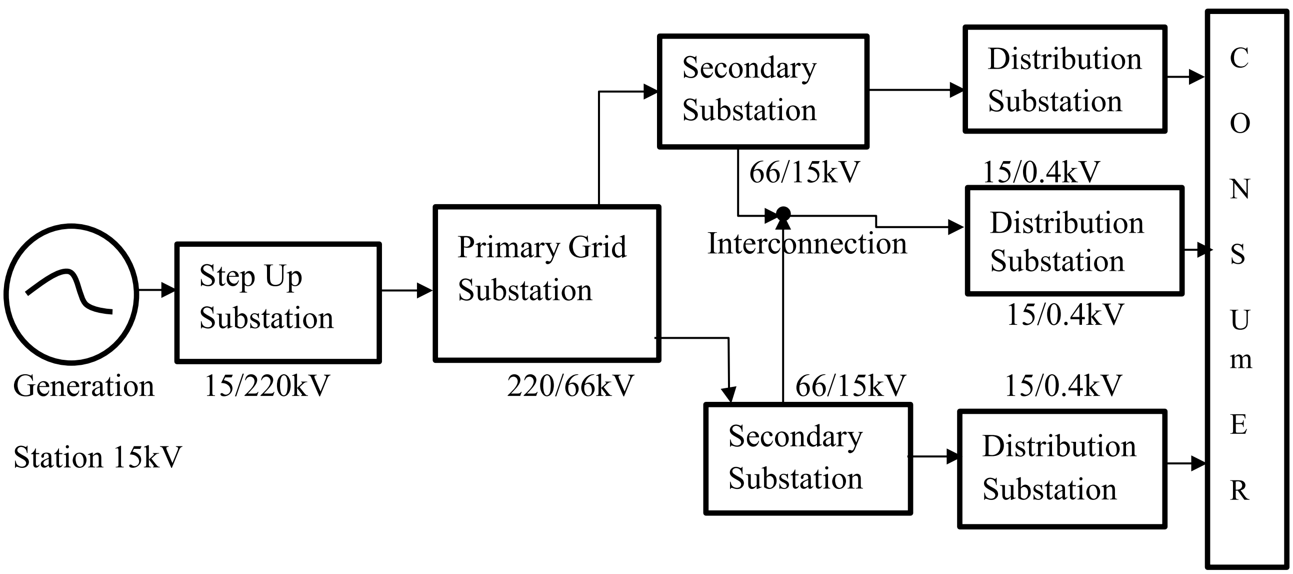


Figure 2.1: Key network elements –focusing on 15kV distribution network [7]

Distribution substations convert energy to lower primary system voltage for local distribution and usually provide facilities for low voltage regulation of the primary voltage. Primary feeder usually operate in the range of 15kV to 66kV and supply the load in well-defined geographical areas.

Distribution transformers are often installed on poles or near the customer sites and transformer the primary voltage to the secondary voltage carry energy from the distribution transformer at service voltage. Service line/tertiary lines deliver energy to consumer premises at the required voltage level. There are two basic of distribution system configuration

Radial System

A radial system is connected to only one source of supply and is exposed to many interruption possibilities. The most important of which are those due to feeders/overhead lines failures and transformer failures. Each event may be accompanied by a long Interruption. This make radial feeders tend to have lower reliability. Feeders and Transformers have finite failure rates and interruptions are expected and statistically predictable.

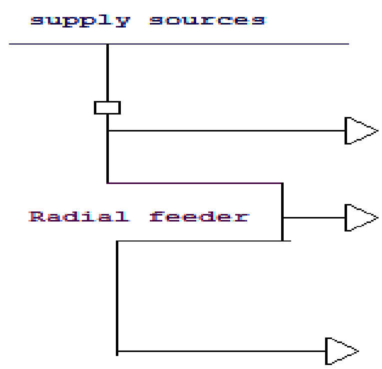


Figure 2.2: Radial System [7, 13, 16]

Primary Loop System

A big improvement over a radial system is obtained by providing a primary loop, which can provide power from two sources and open ring system don't exposed with many interruption which mean that feeders connected with this system have high reliability. Obviously, the distribution system is the most suitable system to meet the individual consumer requirements such as the electricity demand and reliability i.e. certain load centers need high level of reliability and different load centers have different demand growth. The reliability analysis of distribution system is a matter of practical interest.

A power system engineer must know the information about the number, capacity/size, location and type of the network elements in order to analyze the distribution system and although the majority of distribution systems are operated radially. The main role of distribution substation transform voltage from high to low as necessary. Substations also dispatch electric power from generating stations to consumption centers. Electric power may flow through several substations between the generating plant and the consumers, and the voltage may be changed in several steps.

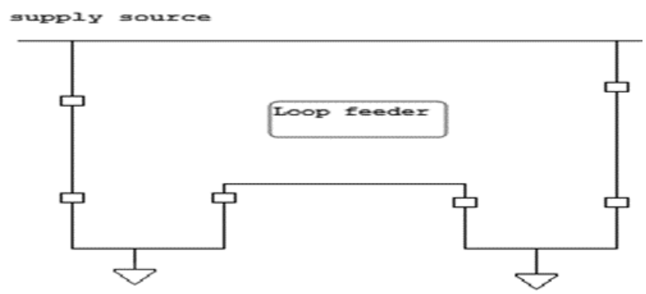


Figure 2.3: Primary Loop System [7, 13, 16]

Parallel System

Parallel feeders join the source and a load that provides the capability of supplying power to the load through one or any number of the parallel feeders. Parallel feeders provide for maintenance of feeders without interrupting service to loads and restoration of service when one of the feeders fails [6].

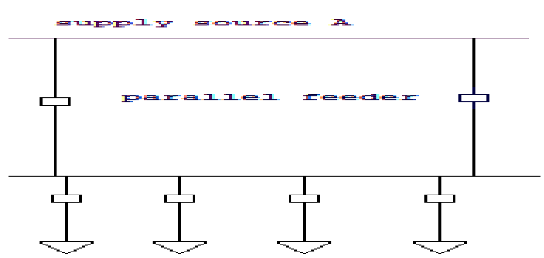


Figure 2.4: Parallel System [6, 14,16]

2.3 Distribution System Operation

Distribution system operation is comprised of the dispatch centers, operators, and crew. The dispatch centers are ran by operators who engage in real-time control and operation using Supervisory Control and Data Acquisition (SCADA). SCADA offers the ability to monitor such things as feeder loading or equipment trouble, which is sounded by a device alarm or by customer's interruptions [1, 17]. When there is a contingency (fault) in the system operator can either perform a remote reconfiguration or send a crew to perform corrective measures such as a switching action or repairing damaged equipment.

The crew is also responsible for performing routine maintenance. All equipment requires inspections, testing and maintenance to ensure proper operations and to minimize probability of failure.

2.4 Power Quality, Reliability and Availability of Distribution System

A power quality problem might be defined as any electric supply that causes to malfunction or prevents their use or the degree to which the utility voltage not approaches the ideal case of stable, uninterrupted, zero-distortion and disturbance free source [7].

In fact, power is equal to the instantaneous product of current and voltage, and formulating a meaningful definition of power quality is difficult.

Perfect power quality is a perfect sinusoidal with constant frequency and amplitude. Less than perfect power quality occurs when transient distorts a voltage waveform or harmonics, changes its amplitude, or deviated in frequency. According to this definition, customer interruptions are power quality problem concerns since they are a reduction in voltage magnitude to zero.

A best utility can do is to supply customers a perfect sinusoidal voltage source. Load current can affect voltage as it interacts with system impedances, but voltage is the ultimate measure of power quality [8].

Reliability is primarily concerned with customer interruptions and is therefore, a subset of power quality. Though there is general agreement that power quality includes reliability, the boundary that separates the two is not well defined.

Sustained interruptions (more than a 5 minutes) have always been categorized as a reliability issue, but many utility have classified momentary interruptions(less than a 5 minutes) as a power quality issue.

The reasons are

- Momentary interruptions are the result of intentional operating practices
- They did not generate a large number of customer complaints.
- They are difficult to measure. Today, both interruptions are an important customer issue and most distribution engineers consider them a reliability issue.
- Availability deal strictly with interruptions, they are classified as a subset of reliability. There is the hierarchy of power quality, reliability, and availability is shown below.

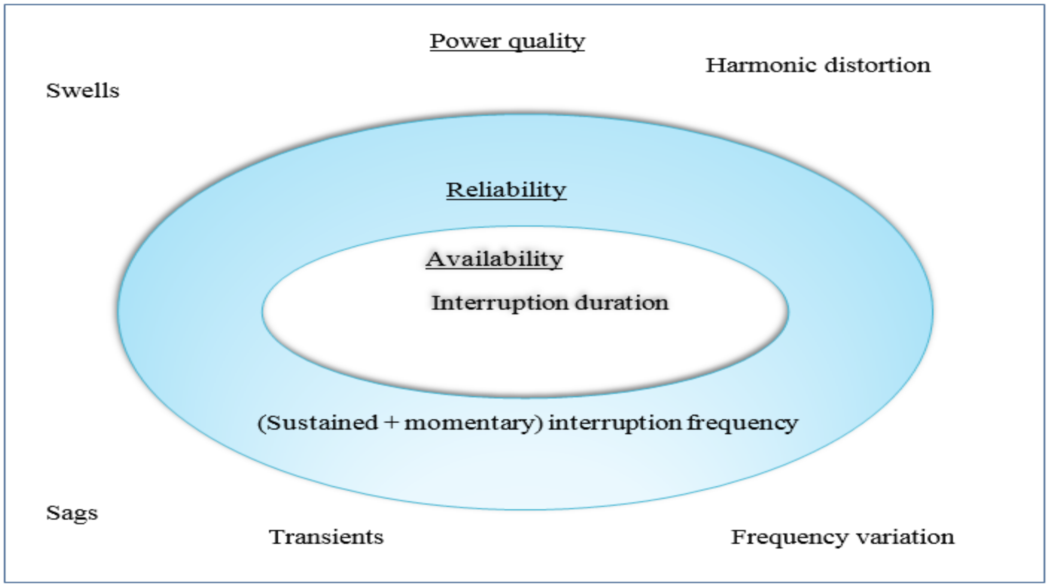


Figure 2.5: Hierarchy of Power Quality, Reliability and Availability [19]

2.4.1 Power Quality

Perfect power quality is characterized by a perfect sinusoidal voltage source without waveform distortion, variation in amplitude or variation in frequency. To attain near perfect quality, a utility could spend vast amounts of money and accommodate equipment with higher power quality needs. On the other hand, a utility could spend little and require customer s to compensate for the resulting power quality problems.

Neither of extreme is desirable, utilities must find a balance between cost and power quality provided to the customer. Power quality concerns are becoming more frequent with the proliferation of sensitive electronic equipment and automated process. Power quality problems are divided into many categories such as interruptions, sags, swells, transients, noise, flicker, harmonic distortion and frequency variations.

2.4.2 Reliability of Distribution System

Reliability is a measure of the ability of the power system to deliver electricity to all points of utilization within accepted standards and in the amount desired, for the period of time intended, under the operating conditions [9].

In statistics, reliability is often denoted by the survival function calculated using the cumulative distribution function of the failure probabilities or Reliability of an electric power system is defined as the probability that the power system will perform the function of delivering electric energy to customers on a continuous basis and with acceptable service quality.

Reliability Analysis of Distribution System

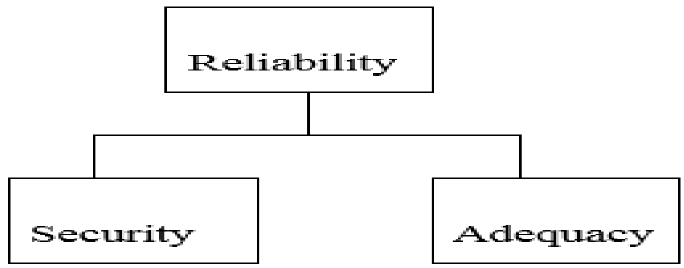


Figure 2.6: Block Diagram of Reliability Analysis Power System [11].

There are two main types of the reliability analysis of power system.

Security: Ability of the electric systems to respond to sudden disturbances arising within that system, such as electric short circuits. It is assessed using dynamic calculation [10].

Adequacy: Relates to the existence of sufficient facilities within the system to satisfy the consumers load demand at all times; taking into account scheduled or unscheduled outages. It is assessed using the power flow solution

Scheduled and unscheduled events disrupt normal operating conditions and can lead interruption to power supply. The unscheduled events may be as a result of oversights during installation or maintenance operations and faults. The scheduled events are usually as a result of the need to carry out maintenance operations on the equipment, consumer request, and usually consumers do get notice of interruption of supply in advance. From this, both scheduled and unscheduled events lead to operational interruptions.

2.4.2.1 Different Types of Interruption

There are different types of interruption and they are discussed below

Momentary Interruption

This is a situation where a customer is without electricity supply from the utility for less than a few minutes. When power supply is interrupted and restored in less than 5 minutes, then the customer is said to have experienced momentary interruption according to IEEE 1366-2003 standard. The operation of circuit breaker or tripping of the feeders, which opens the circuit momentarily to clear faults and closed back, brings about this interruption. Momentary interruptions sometimes affect power quality and lead to voltage sags [12].

Temporary Interruption

This usually categorized as interruption that last a few hours. It is usually less in duration than a sustained interruption and higher than momentary interruption. This interruption usually requires an operator to put the system back to perform the switching on by manual operation. The interruption is expected to last for less than two hours. Both momentary and temporary interruptions can be as a result of faults due to two conductors in contact when there is wind [13].

Sustained Interruption

This is a loss of supply to customer, which is usually more than many hours and can sometimes last for days. A temporary fault can lead to sustained interruption if it is not taken care of as soon as possible. However, sustained interruption could be as a result of transformer failure, insulator failure and damaged wires.

Planned Interruption

This happens when deliberate action is taken on a component by removing it from service in order to carry out maintenance work or construction. This interruption usually accompanies scheduled outage.it is usually planned and the customers are aware of the loss of supply that ensues.

Unplanned Interruption

These types of interruption is as a result of faults which makes a component to be unavailable perform its function. It is usually considered as unscheduled outage.

Faults are one of the major factors that can affect the reliability of power distribution system. Faults occur when there is short circuit between phases, or phase to ground faults to unintended opening of circuit breakers used for protection within a power distribution system. A fault means that an accidental electrical connection is made between an energized component and something at a different potential to short circuit [14].

2.4.3 Availability of Distribution System

Availability is the measure of the duration for which the component is in operation at any time. It deals with the duration for which the system is fully operational for its specific function.

These parameters are essential to producing realistic and valid results. Both averages values and probability distribution have been used, however average values fail to reflect the reliability of a component entirely leaving margin for overestimating the reliability of a customer that is actually experiencing adverse conditions [18].

Power equipment and power systems are vulnerable to failures occurred due to internal or external sources. The failure of a component is the inability of a component to perform its intended function at a particular time under specified operating conditions. Reliability, availability together with maintainability is analyzed to determine the ability of system to accomplish an intended task [15].

Generally, reliability means of the capacity of a system to accomplish the function it is designed for under the operating conditions trips upon during its anticipated lifetime.

It can be seen from above Figure 2.5[19]

- Both reliability and availability are a subset of power quality.
- Power quality deals with any deviation from a perfect sinusoidal voltage source while reliability deals with interruption.
- Availability deals with the probability of being in an interrupted state.

Ideally, reliability of a power system from consumer’s viewpoint means uninterrupted supply of power from the generation to the consumer.

In action, the important elements of a power system’s reliability for consumers are frequency and duration of interruptions at consumption point.

One of the main encounters for electric utilities is to increase the price of their services, availability and reliability and to provide customers with lower electricity rates.

A radial system consists of a series of components between the substation and the end points. Failure of any of these components may result in outage at the end point. Reliability analysis of distribution network is usually concerned with the system performance at the customer end such that at the end points.

2.5 Distributed Generation

Distributed generation (DG) is one of the new trends in power systems used to support the increased energy demand, peak shaving and to use as a backup generator and the advantages include voltage support, energy loss reduction, and improvement in reliability [17]. And is generally defined as generating units sufficiently smaller than the central generating plants.

The term is used differently in some countries by using notations such as "dispersed generation", embedded generation" or "decentralized generation" [18] . Different professional bodies such as the International Energy Agency (IEA) and Institute of Electrical and Electronic Engineers (IEEE) had proposed numerous definitions for DG. Most DG definitions are generally based on the size and location of the generating unit with respect to centralized generating plants.

IEA defines DG as generating plants supplying a customer on-site, or providing support to the network, and are integrated to the grid at distribution voltage levels [18].

The IEEE on the other hand, defines DG as electricity generation by units that are smaller than the centralized generating plants such that interconnection at nearly any point in a network is possible [20]. Distributed Generation (DG) are units of limited size that are connected directly to the distribution network or on the customer site [21].

Typically, the units used are gas turbines powered by synchronous generators, wind turbines, fuel cells, hydro, and photovoltaic [11].

2.5.1 Distributed Generation Technology

Various DG technologies are involved in power systems. Some of these technologies have been in use for a long time while others are newly emerging. In spite of that, the features that all DG technologies have in common are to increase efficiency, to improve the system reliability and decrease costs related to installation, running and maintenance.

DG technologies are packaged together categorized into two types: renewable technologies (e.g., photovoltaic and wind turbine) and non-renewable technologies (e.g., mini and micro-turbines, combustion turbines and fuel cells).

DG technologies have a significant impact on the selection of the appropriate capacity and place of a DG unit to be connected to a grid or customer side.

The DG units are classified based on their rated power given in reference [22]. To clarify about the DG concept, DG units are classified into three main categories based on their rated power.

These categories are presented as follows:

- Category A includes DGs with rated power in the range of 0 to 1 MVA
- Category B includes DGs with the rated power in the range equal to 1MVA but less than 20MVA
- Category C includes any DG unit with power rating equal to or greater than 20MVA.

2.5.2 Types of Distributed Generation Technologies

There are many resources of distributed generations. Some of them are Micro-turbine, Fuel cells, Wind turbines, Photovoltaic system and other renewable resources.

1. Micro-Turbine

Micro-Turbines are small electricity generators that burn fuel such as natural gas, propane, and fuel oil to create a high-speed rotation that is transferred to an electrical generator via a main shaft. Micro-turbines consists of three basic components: a compressor, a turbine generator, and recuperates [23].

In present energy markets, Micro-turbines generators are the most improved and most attractive devices in distributed power generation equipment. Their capacity ranges from 20 kW to 500 kW and their efficiency is more than 80% when the CHP application is used in the system. Also, the NOx emissions of Micro-turbines are very low compared to large-scale turbines.

2. Photovoltaic system

A photovoltaic system (PV), converts the light energy received from the sun radiation to electric energy. Semi conducting materials are used to construct solar cells, which are capable of transforming self-contained energy of photons into electricity when they are exposed to solar radiation. The cells are placed in an array that is either fixed or moving to keep tracking the sun to generate the maximum power [23]. PV systems are comfortable to environment since they are not associated with emissions, easy to use, are simple in designs and it does not need any other fuel than solar light.

3. Fuel Cells

Fuel Cells (FC) are classified as non- convention generators. They are electrochemical devices that convert chemical energy from a fuel directly into electrical energy by combining oxygen, as an oxidant, and hydrogen, as a fuel, without combustion [24]. The hydrogen is usually obtained from a fossil fuel "natural gas" while air is used as a source of oxygen. The result of this electrochemical process is high-current/low-voltage DC power. To connect the fuel cell to the grid, a DC/AC converter and filter system current are used to convert the output to AC power. Water (H2O) and heat are by-products of the process. This heat, often reach 1800 ºF, converts the water to steam, which can then be used to perform other work. Regardless of the auxiliary systems, FCs have no moving parts and no combustion, making them silent devices.

4. Wind turbines

Wind turbines are capable of converting wind energy into electricity. The wind has high stochastic nature, which cannot be stored, thus, it must be handled according to this characteristic. There are two conversion steps in wind turbines. First, the rotor takes the kinetic energy of the wind; convert it into mechanical torque in the shaft; and then the generator system converts this mechanical torque into electricity. Mostly, the generator system gives an AC output voltage, which is dependent on the wind speed. As wind speed is not constant, the voltage generated must be transferred to DC and back again to AC with the aid of inverters. However, turbines with fixed wind speed can directly be connected to grid [25].

2.5.3 DG Sizing

Distributed generation (DG) unit is one of the new trends in power systems used to support the peak shaving and to use as a backup generator. DG units are classified into renewable DGs and non-renewable DG. Renewable DGs are preferred due to cleanness of their technology and high availability in most geographic locations.

There are no general rule on selecting the size and number of DG units to be installed in the network. However, some factors can be ruling the selection of DG unit size selection

- ✓ For reliability purposes in case of islanding, the DG size must be greater than double the required island load to avoid a shortage of power. The DG unit size can affect system protection coordination schemes and devices as it affects the value of the short-circuit current during a fault. Therefore, as the DG size increases, the protection devices; fuses, re-closers and relays settings have to be upgraded.
- ✓ To improve the system voltage profile and reduce power losses, it is sufficient to use DG units of total capacity in the range of 10-60% of the capacity (MW) of the substation or the maximum load of the feeder [26].

According to the reference [26], the DG penetration level in distribution system is given in the following equations.

$$\%\ \text{DG penentraction} = \frac{\text{PDG}}{\text{PL. Max}} \text{x } 100\% \tag{2.1}$$

$$\%\ \text{DG penetration } = \frac{\text{PDG}}{\text{PDG} - \text{PCG}} \text{ X}100\% \tag{2.2}$$

Where PDG and PCG represent the amount of total active power generated by DG unit and centralized generation respectively and $PL.max$ is the maximum load of the feeder

Drawback of Distributed Generation

Inserting of a Distributed Generation to the existing distribution system has its own challenges [27].

- When DG unit is inserted to the network, system protection coordination schemes and devices are affected as it affects the value of the short-circuit current during a fault. As a result, system protection coordination schemes setting should be changed and when DG unit disconnecting, the system protection coordination schemes setting should be changed to its original state
- We need DC/AC converters to connect DG unit with the grid, which are capable of injecting harmonics into the system.
- The connection of DG unit might cause power quality problems (such as Over-voltage, fluctuation, etc.) if coordination with the utility supply is not properly achieved.

2.6 Reliability Assessment, Metrics and Indices

Distribution substation system serves as the interface between utility companies and the customers served. Hence, its assessment helps to determine how reliable the system is and to what extent customers are being served. The ability of a distribution system to perform its function under stated conditions for a given period of time with little or no interruptions to service delivery is known as distribution reliability.

Distribution reliability usually involves critical analytical handling of well-defined metrics also known as units of measurement. Across the world, reliability indices are being used by utility companies to monitor the performance of their distribution region, and or the substation. Most utilities owned by investors are usually required by regulation to report their reliability performance as enumerated by reliability parameters.

Some commercial and industrial customers request for reliability indices from utility companies when planning to find a site for their firms. In addition, one thing that makes distribution system reliability very important is that, carrying out individual physical assessment on all installed equipment in the system would usually be physically tasking, expensive and time consuming.

2.6.1 Reliability Analysis Methods

As stated previously, reliability is the expectation that a given system will perform its intended function given normal operation conditions for a specific amount of time. The topic of reliability and its relation to the power system is not new and research in the area continues to grow every year. As the demand from customers for more secure and adequate, as deregulation policies are enforced, and as reliability standards are developed, reliability in the power system remains a hot topic [9].

Reliability analysis addresses the need to quantify the quality and availability of power for each customer by predicting the interruption profile of a given distribution system in relations to the system, specific topology and reliability data [4, 8]. Reliability analysis methods are divided into two areas, analytical and simulations [1, 4, 8].

2.6.1.1 Analytical Methods

The analytical method uses mathematical solutions to evaluate mathematical models; this technique has been used for many years. In this approach, the impact to all load points due to each component failure will be considered as well as the average failure rate of the component.

Then, the interruption frequency and duration at each load point is calculated to eventually calculate the system reliability indices such as SAIFI and SAIDI [4, 10].

When calculations are performed, the mean values are the results produced and they represent the reliability indices, which prove to be very useful however, that does not give a realistic picture. The reliability indices are in fact variable [36]; therefore, it is beneficial to be able to look at its distribution. The probability distribution offers a way for the variations in the reliability indices to be shown; therefore, Monte Carlo simulation is a more popular choice [2].

2.6.1.1.1 Network Modelling

An electrical system can usually be viewed as a network of its components connected together either in series, parallel, meshed or a combination of these. The structural relationships between a system and its components are considered in this technique. Modelling the failure behavior of the system is one of the major challenges in reliability analysis. Hence, failure mode and effect analysis (FMEA) has become the widely accepted means for reliability evaluation of distribution systems. This method determines at least those components within a system that result in an interruption of service at the load-point of interest. A radial system consists of set of series components such as breakers, lines, switches, transformers and at the end "Customers''

2.6.1.1.2 Series System

From reliability viewpoint, all the components in a series system must be working together to ensure system success or the failure of one leads to entire system failure. This therefore implies that a series system is a non- redundant system.

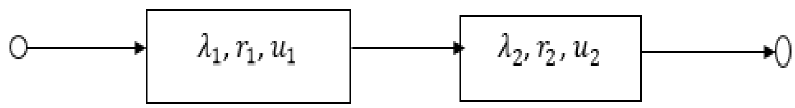


Figure 2.7: Typical Diagram of Series System [28]

Provide the formulae used in the calculations involved in series system shown in the Figure 2.7 above and are given in equations (2.3) to (2.5);

Where,

λ = the expected failure rate

u = the annual outage time

r = the average outage time

$$\lambda_s = \lambda_1 + \lambda_2 = \sum_{i=1}^{2} \lambda_i \,(fr/yr) \qquad (2.3)$$

$$u_s = \lambda_1 r_1 + \lambda_2 r_2 = \sum_{i=1}^{2} \lambda_i r_i (Hr/yr) \qquad (2.4)$$

$$r_s = \frac{u_s}{\lambda_s} \; (Hr) \qquad (2.5)$$

2.6.1.1.3 Parallel System

The components in a set are said to be in parallel from a reliability point of view if only one needs to be working for system success or all must fail for system failure.

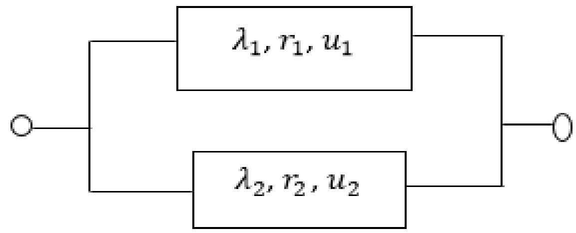


Figure 2.8: Typical Diagram of Parallel System [29]

The calculations involved in the parallel system shown in the Figure 2.8 above are given in equations (2.6) to (2.8);

$$\lambda_p = \lambda_1 \lambda_2 (r_1 + r_2) \quad (fr/yr) \tag{2.6}$$

$$u_p = \lambda_1 \lambda_2 r_1 r_2 \, (Hr/yr) \tag{2.7}$$

$$r_p = \frac{u_p}{\lambda_p} \quad (Hr) \tag{2.8}$$

The above equations (2.3) to (2.8) are sufficient for simple radial systems and more indices are computed for general distribution systems. Network technique using the series system is used in calculating the failure rates of all components making up the distribution system.

2.6.1.2 Monte Carlo Simulation Methods

Monte Carlo simulation method is the most commonly utilized numerical method. In this method, simulation of physical relationship is used to analyze the random behavior of the system. The possible outcomes of this technique are not only average values like that of analytical methods, but also the expected probability distributions of reliability indices. The method provides the possibility to be applied to a more complicated component models. e.g. including effects of component aging. However, this has its own side effect .i.e. increased computation time, which makes the Markov models to be utilized much more often.

In addition to the analytical techniques, the simulation methods may also be used to estimate the output power and evaluate the reliability of a renewable generation system. Monte Carlo simulation consists of randomly sampling system states, testing them for acceptability and aggregating the contribution of loss of load states to the reliability till the coefficients of variation of these indices drop below pre-specified tolerances.

By means of mathematical modeling and evaluation of the reliability indices using the analytical technique, direct mathematical solutions were obtained. Due to low computation cost, short time solution in evaluating the reliability indices of the power system network of distribution, the analytical technique was selected. Adequacy in performance and reliability of the system is obtained as result from application of this technique.

2.7 Reliability Indices under DIgSILENT Power Factory

DIgSILENT is a graphical environment based software for building single line diagrams of power system models. The most element used in DIgSILENT Power Factory to design the distribution system are; external grid, bus bar, line, transformer, circuit breaker, load, DG and so on.

The reliability of the power system carry out by DIgSILENT Power Factory since it has powerful for reliability analysis. Reliability analysis involves determining, generally using statistical methods, the total electric interruptions for loads within a power system during an operating period.

Reliability indices typically consider such aspects as:

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

Network reliability assessment is used to calculate expected interruption frequencies and annual interruptions costs, and to compare alternative network designs. Reliability analysis is an automation and probabilistic extension of contingency evaluation. For such analysis, it is not required to pre-define outage events; instead, the tool can automatically choose the outages to consider.

The relevance of each outage is considered using statistical data about the expected frequency and duration of outages according to component type. The effect of each outage is analyzed automatically such that the software simulates the protection system and the network operator’s actions to re-supply interrupted customers. Because statistical data regarding the frequency of such events is available, the results can be formulated in probabilistic terms.

The generation of reliability indices, using the Reliability Assessment tool also known as ’Reliability Analysis’, consists of the following:

- ✓ Failure modelling
- ✓ Load modelling
- ✓ System state creation
- ✓ Failure Effect Analysis (FEA)
- ✓ Statistical analysis
- ✓ Reporting.

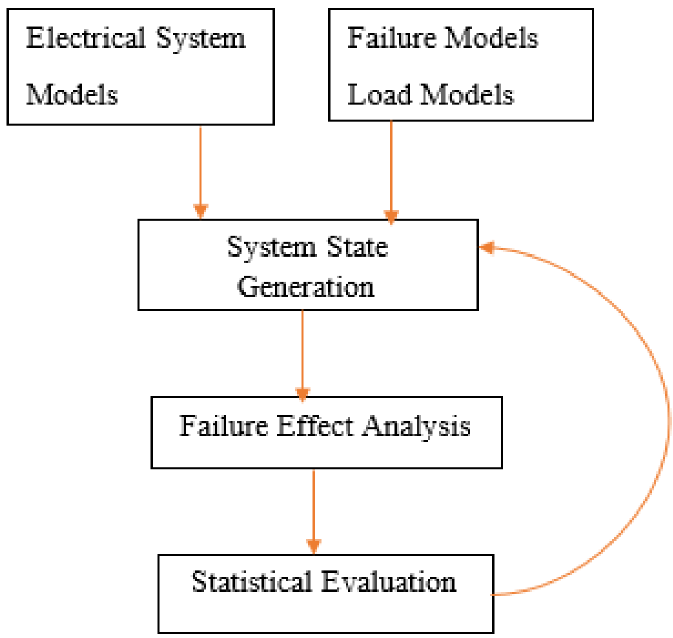


Figure 2.9: Basic Flow Diagram of Reliability Analysis using DIgSILENT Power Factory[30].

The combination of one or more simultaneous faults and a specific load condition is called a ’system state’. Internally, DIgSILENT Power Factory 15.1 version system state generation engine uses the failure models and load models to build a list of relevant system states.

Subsequently, the Failure Effect Analysis (FEA) module analyzes the faulted system states by simulating the system reactions to these faults.

The FEA takes the power system through a number of post-fault operational states that can include:

- Fault clearance by tripping of protection breakers or fuses
- Fault separation by opening separating switches
- Power restoration by closing normally open switches

The objective of the FEA function is to determine if system faults will lead to load interruptions and if so, which loads will be interrupted and for how long.

The results of the FEA are combined with the data that is provided by the system state generation module to create the reliability statistics including indices such as SAIFI, CAIFI and SAIDI. The system state data describes the expected frequency of occurrence of the system state and its expected duration. The indices have traditionally only included long duration interruption (interruptions longer than 5 minutes).

Reliability indices are numerical parameters that reflect the capacity of the system to provide its customers can acceptable level of electricity supply [31].

By providing quantitative measures at different individual system points or feeders and for the whole system, these indices approximate system reliability. The most important of all the indices used in evaluation of power systems reliability are the duration of interruption and frequency of interruption; this is due to the fact that they indicate the expected frequency and the expected duration of interruption of power supply.

2.8 The Algorithm Flow Chart for Calculation of Reliability Indices

The logic describing the relation between the components and their fault contribution to different load points-the reliability topology is generated before starting the reliability calculations.

The next step is to generate expected values from the statistical distribution of failure rates, repair times and sectioning times for all components in the system. The algorithm then accumulates reliability indices for each load point from each component giving outages to the load point. Finally, when all the fault contribution is found, the total accumulated indices are available.

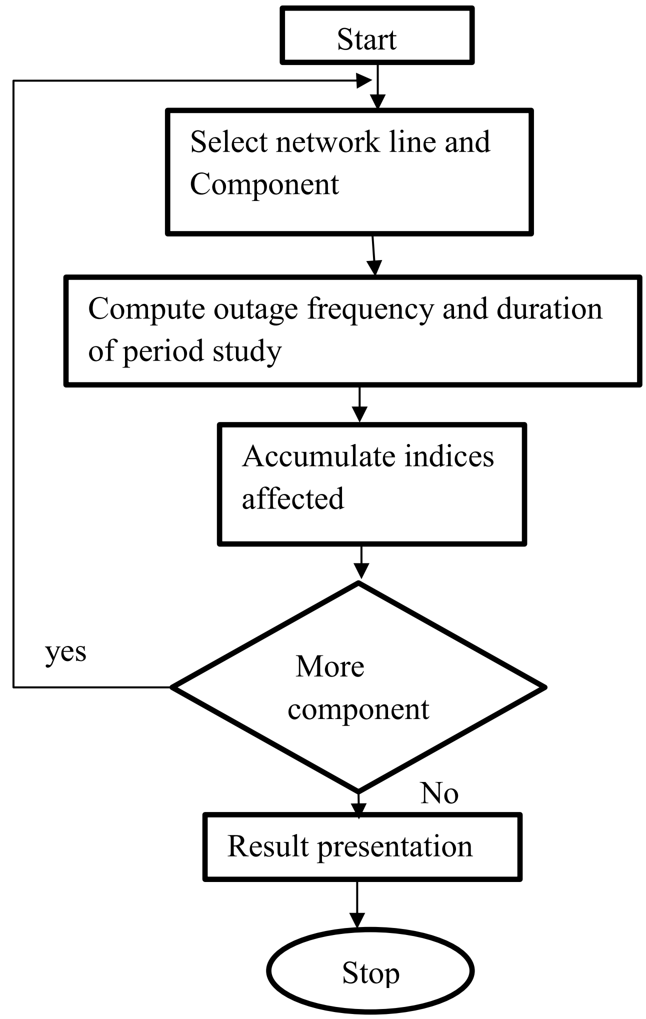


Figure 2.10: Flow chart for calculation of reliability indices [32]

A system state with a single feeder on outage (i.e. due to a short circuit), will have a duration equal to the time needed to repair that feeder. This is no more a problem in the case of a double feeder where no loads may suffer any interruption. In the case that loads are interrupted by the outage, the power may be restored by network reconfiguration (i.e. by fault separation and closing a backstop switch). The interruption duration will then equal the restoration time, and not the repair duration (system state duration).

A common way of defining reliability is in terms of customer-oriented indices and Energy or load-oriented indices.

A. Customer-Oriented Indices

These indices are directly related to customers. Some of these indices are listed below.

1. System Average Interruption Duration Index (SAIDI)

The index indicates the average time a customer has an interruption during a time cycle (one year). It is usually specified in customer minutes or customer hours of interruption/year.

SAIDI is the average interruption duration per customer served as given equation (2.9). It is determined by dividing the sum of all customer interruption durations during a year by the number of customers served.

$$\text{SAIDI} = \frac{\text{Sum of all customer interruption duration}}{\text{Total number of customers served}} = \frac{\sum(U_i * N_i)}{NT} \tag{2.9}$$

2. System Average Interruption Frequency Index (SAIFI)

The index represents the average number of interruptions/outages experienced by a customer in a unit time (generally one year). The definition of service area is flexible in the sense that the number of customers and the interruptions experienced by them changes with the definition of the enclosed area. For instance, a feeder SAIFI indicates the average number interruptions a customer serviced by the particular feeder would experience in a year and for a substation or a distribution system encloses the total customers in the service area. SAIFI is the average interruption frequency per customer served as given in equation (2.10).

$$\text{SAIFI} = \frac{\text{Total number of customer interrupted}}{\text{Total number of customers served}} = \frac{\sum(\lambda_i N_i)}{NT} \tag{2.10}$$

In order to calculate the index, data of individual frequency of outages in a year are required. For each of these interruptions/outages the number of customers affected comprises the customer interruption for the particular outage. The denominator is the total number of customers in the service area under consideration. The method to improve on the SAIFI levels of a system is by reducing the number of sustained interruptions that occur. This can be achieved by improved protective equipment that sense faults and attempt to clear the same before it turns into a permanent outage.

3. **Customer Average Interruption Duration Index (CAIDI)**

It is the average interruption duration for those customers interrupted during a year. It is determined by dividing the sum of all customer interruption durations by the numbers of customers experiencing one or more interruptions over a one-year period. It represents the average time taken to restore service to the customers when a sustained interruption occurs as given in equation (2.11).

$$\mathrm{CAIDI} = \frac{\text{Sum of all customer interruption duration}}{\text{Total number of customers interrupted}} = \frac{\mathrm{SAIDI}}{\mathrm{SAIFI}} \qquad (2.11)$$

4. **Customer Average Interruption Frequency Index (CAIFI)**

The CAIFI indicates the average frequency of sustained interruptions for those customers experiencing sustained interruptions.

$$\mathrm{CAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customer interrupted}} = \frac{\sum N_o}{\sum N_i} \qquad (2.12)$$

5. **Average Service Availability Index (ASAI)**

The average service availability index (ASAI) gives the fraction of time the customer has power during the reporting time. The higher ASAI values reflect levels of reliability. This is the ratio of total number of customer hours that service was available during a given time period to the consumer hours service demand.

The equation (2.13) is used to calculate the value of ASAI for a given service area [33].

It is usually represented either in percentages or per unit.

$$\mathrm{ASAI} = \frac{\text{Consumer hours service availability}}{\text{consumer hours service demand}} = \frac{8760-\mathrm{SAIDI}}{8760} \qquad (2.13)$$

6. **Average Service Unavailability Index (ASUI)**

It provides the fraction of time customers are without electricity throughout the predefined interval of time. The equation (2.14) is used to calculate the value of ASUI for a given service area.

$$\mathrm{ASUI} = 1 - \mathrm{ASAI} = \frac{SAIDI}{8760} \qquad (2.14)$$

Where, λi is failure rate, Ui is hour lost, Ni is total number of customers interrupted, NT is total number of customer served, N0 is total number of interruptions.

B. Load or Energy-Oriented Indices

1. Energy Not Supplied Index (ENS): This index represents the total energy not supplied by the system. And it is given by

$$\text{ENS} = \sum_i L_a(i)U_i \tag{2.15}$$

Where, $L_a(i)$ is the average load given by:

$$L_a(i) = L_P(i) * L_F(i) = \frac{E_d\ (i)}{t} \tag{2.16}$$

L_P is peak load demand, L_F is the load factor, and Ed is the total energy demanded in the period of interest t.

2. Average Energy Not Supplied Index (AENS): This index represents the average energy not supplied by the system.

$$\text{AENS} = \frac{Total\ energy\ not\ supplied}{Total\ number\ of\ customers\ served} = \frac{\sum_i L_a(i)U_i}{\sum_i N_i} \tag{2.17}$$

In this thesis, SAIDI, SAIFI and ENS are taken for comparison of reliability indices.

2.9 Literature Review of Current Research Papers

Our technological world has become deeply dependent upon the continuous availability of electrical power. Any interruption in availability of electricity causes major disruption in people lives. The level of disruption is a function of dependency of people on electricity, which can be very high for a developed country and not as much for developing countries [16].

The primary function of any utilities provides a reliable and economic supply of electrical energy to their customers. An analysis throughout the world shows that around 90% of all customer reliability problems are due to the problem in distribution system, hence, improving distribution reliability is the key to improving customer reliability. The availability of a reliable power supply at a reasonable cost is crucial for the economic growth and development of a country. The main role of electric utility throughout the world is endeavoring to meet customer demands as economic as possible at a reasonable service of reliability. To meet customer demands, the power utility has to evolve and the distribution system have to be upgraded, operated and maintained accordingly [33].

To evaluate the reliability of distribution systems basic reliability evaluation techniques needed which are applied in distribution system planning and operation [34]. These papers considered seven different alternatives, examined on distribution system, and predict the impact of adding new components to the system.

A.S. Pabla in [35], evaluates various analytical and simulation techniques which incorporate varying degrees of complexity and data to evaluate the expected customer costs at the system and load level of radial distribution system. A computer program based on time sequential Monte Carlo simulation has been developed. The results show that certain analytical techniques provide as accurate results as using a Monte Carlo simulation technique.

As transmission and distribution systems equipment continue to age and gradually deteriorate the probability of service interruption due to component failure increases. To minimize the failures of a system, an effective maintenance strategy framework (condition-based, cost effective maintenance optimization program) is essential in delivering safe and reliable electric power to customers economically [16, 36].

Bhargava in [37], Focus on reliability analysis of distribution network using Dynamic Bayesian network, which is a time extension of the static Bayesian network, consists of the initial network and transfer network. Based on Dynamic Bayesian networks, the actual value of the components failure rates and repair rates can be accurately reflected and failure frequency and duration of distribution system can be calculated. This method permits not only computing the reliability indices of a distribution system but also presenting the effect of each component or some component on the system reliability.

In [38], Reliability analysis of distribution system was made with DG connection to a network. This paper show that connecting DG to distribution network; improve the reliability of the distribution system but it can causes power quality problems (over voltage on the circuit, interrupt protection, upset voltage regulation).

In [39, 40], proposed a method to analyze and evaluate the reliability of the transmission equipment in the electrical system when installing the generator to a distributed system as a case study. The value of the Failure Rates is calculated in [40], which analyzes and compares the reliability of the power system in the different case studies.

In [41], power system analysis was made without and with DGs in terms of total power loss and voltage profile of all the buses. The voltage profile of all the buses remained stable within the tolerable limits. In this paper, ENS is reduced by about 29 %.

The paper analyzed the system with and without DG for different case studies and the following result was obtained for the corresponding SAIFI and SAIDI. SAIFI with DG was reduced by 50% and SAIDI by 50% [42].

In [43], Reliability worth assessment is undertaken. The installations of DG at supply point will barely improve system reliability. From this paper, I understand that, DG at further point will increase their role of reliability improvement. As far the location is from the substation, the reliability system indices increase. The best location for the placement of the DG is at the end of the line where much improvement is achieved.

CHAPTER THREE

DATA COLLECTION AND ANALYSIS

3.1 Data Collected from Addis Alem Distribution Substation

For the analysis, data has been collected from EEU. The collected data are a recorded data that includes types of faults, frequency and duration of interruption of 15kV outgoing feeders of the distribution system. The collected data is recorded for two years (2017 and 2018). In case of my study, Addis Alem distribution substation is found in the west part of Ethiopia, which is service as secondary distribution (15kV) and has five outgoing feeders, namely;

- Holeta feeder
- Flower feeder
- Addis Alem feeder
- Ehude gebia feeder
- Cement feeder

And has only one 45kV radial incoming feeder from Gefersa substation. There is one power transformer 45/15kV rating.

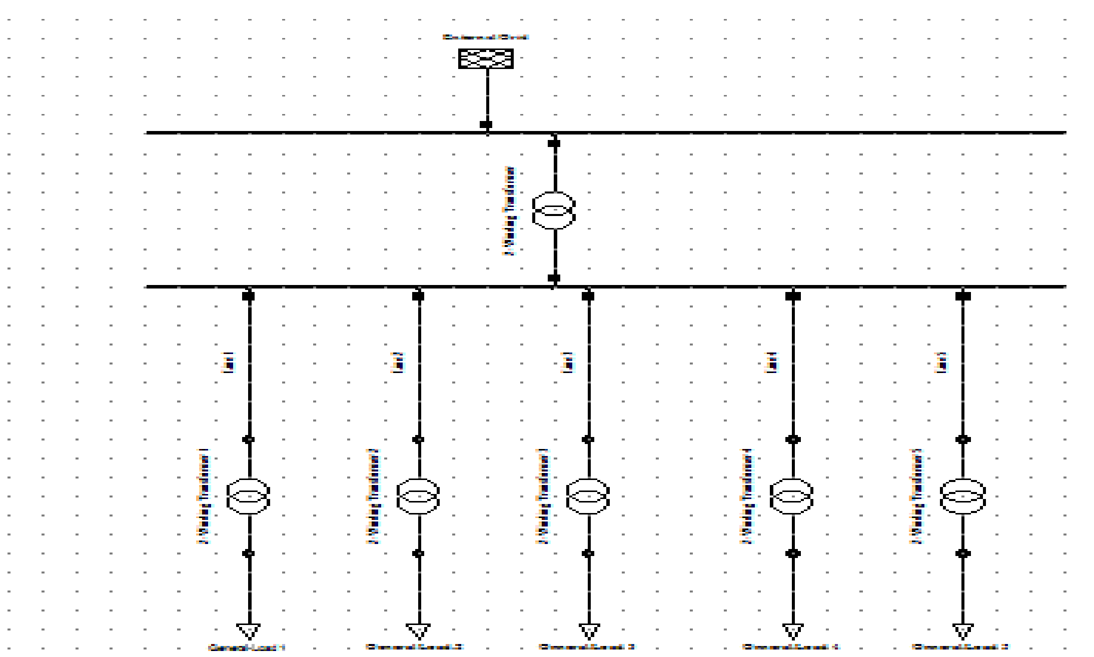


Figure 3.1: Single line diagram of Addis Alem substation

The collected data for Addis Alem distribution substation are shown in Table 3.1, 3.2 and 3.3, and the frequency of interruption and duration of interruption for Addis Alem distribution system for two consecutive years are analyzed and interpreted as in Tables 3.4, 3.5, and Figures 3.2, 3.3, 3.4 and 3.5.

Table 3.1: Overview on Addis Alem Substation

Name of Substation	Voltage Level (kV)	Transformer Quantity	Transformer Capacity (MVA)	Total Substation Capacity (MVA)	Incoming Feeder
Addis Alem	45/15	1	12	12	Gefersa

Table 3.2: Feeder Capacity in Addis Alem Substation:

Substation Name	Feeder Name	Voltage Level (kV)	Average Active Power (MW)	Feeder Load (A)	Average Reactive Power (MVAr)	Average Apparent Power (MVA)	Peak Load (MW)
Addis Alem	Holeta	15/0.4	4.35	143	1.366	4.559	6.67
Addis Alem	Flower	15/0.4	3.81	138	1.212	3.998	5.76
Addis Alem	Addis Alem	15/0.4	2.87	105	0.731	2.962	4.35
Addis Alem	Ehude gebia	15/0.4	1.98	75	0.688	2.096	2.89
Addis Alem	Cement	15/0.4	3.36	132	1.527	3.691	5.36

Table 3.3 contains the data of five feeders of the distribution network such as total numbers of distribution transformers, total capacity of transformers on each feeders and estimated number of customers.

Table 3.3: Feeder transformer and number of customers

No	Substation Name	Feeder Name	Total number of Distribution Transformers	Total Capacity of Transformers (kVA)	Estimated number of Customers
1	Addis Alem	Holeta	46	10650	7976
2	Addis Alem	Flower	16	6820	3325
3	Addis Alem	Addis Alem	41	8165	3603
4	Addis Alem	Ehude gebia	` 13	4125	1996
5	Addis Alem	Cement	11	2495	1341
Total			127	32255	18241

3.2 Causes for Power Interruption in the Addis Alem Distribution Networks

In Addis Alem substation, major faults occurring frequently are earth fault, short circuit, blackout, system over load, overload. And there are planned outages for operational and maintenance purpose. The major faults occurring can either be of momentary and sustained type. Momentary (Temporary) interruptions with duration of less than 5 minutes interruptions whereas Permanent (Sustained) interruptions are long-duration interruptions which last longer than 5 minutes [28]. Usually, only data on sustained interruptions is reported to the regulatory authority. Many of the distribution problems are momentary and mainly caused by animal contact, Tree and whether condition. They can easily be solved with little or no intervention from the system. Then by simply reclosing, the system will be re-energized. But, sustained faults can't be restored by simple re-energizing. Sustained faults can be caused by Equipment malfunction, cable failure, down line or persistent tree contact [29].

Sustained interruptions can be classified as Planned and Unplanned Interruptions [28]. Planned interruptions (operational outages) occur mainly for the purpose of construction, preventative maintenance or repair. A planned interruption occurs at a selected time less inconvenient for the customers and the customers have been notified beforehand of the interruption. On the other hand, if the occurrence time of the interruption has not been selected, then the interruption is unplanned.

Unplanned interruption occurs, for example, due to fault clearing, unwanted operation of the protection system or due to inadvertent initiation of opening operation of a switching device by a human.

Sustained interruption: are the results of the following faults

Distribution Earth fault

This fault occurs when there is a conducting connection between any electric conductor and any conducting material that is grounded or that may become grounded. Electricity always wants to find a path to the ground. In a ground fault, electricity has found a path to ground, but it is a path the electricity was never intended to be on, such as through a person's body [23].

The earth fault, caused by an insulation loss between a live conductor and an exposed conductive part, represents a plant engineering problem, which may cause damage.

Distribution Short Circuit

Short circuit is the most commonly used term to describe the cause of a power failure. It occurs when an electric current travels along a path that is different from the intended one in an electrical circuit. When this happens, there is an excessive electric current which can lead to circuit damage, fire, and explosion. In fact, short circuits are one of the primary causes of electrical fires throughout the world [19]. It also occurs when the insulation of the wiring used breaks down. It can also occur due to the presence of an external conducting material (such as water) that is introduced accidently into the circuit. Electrical batteries can explode if they are subjected to a large current. Short circuits can even occur when electric motors are forced to operate when the moving parts are jammed. This can result in abnormal buildup of current, ultimately leading to a short circuit.

Water can lead to short circuits and power failure. Because water is conductive, so the current easily flows through it. Current will always take the easiest path. Since there is little resistance in water, the current will flow from positive to negative (or vice-versa) through the water causing the short circuit. The damage caused due to water in electrical circuits can be very expensive so it makes sense to ensure that you are well protected from it. Electrical switchboards, wires, and circuits should be protected from exposure to water.

Distribution Line Overload

Increasing demands for electric power have caused existing power grids to become overloaded. Overloading is a common cause of line voltage fluctuations. Inadequate power generation and inadequate distribution systems are also causes of line voltage problems. Improper or poorly designed power regulating devices may create voltage fluctuations. Loose or corroded connections at the electric service user end can create voltage irregularities. The same conditions on the distribution power lines may also affect voltage. Many voltage fluctuation problems can be traced back to inadequate infrastructure [19].

Blackout

Blackout is a total loss of the electric service in one area. It can be caused by catastrophic equipment failure or severe weather. It can also be caused by the utility itself for peak shaving purpose.

System overload

System overload is a total loss of electric service in all area. It can be happen when the generating capacity less than the load demand.

Table 3.4: Summary of total frequency and duration of interruption for 2017 year.

Feeder Name	Frequency and Duration of interruption												Frequency of interruption (No)	Duration of interruption (Hr)
	EARTH FAULT		SHORT CIRCUIT		BLACKOUT		OVERLOAD		SOL		OPERATION			
	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)
Holeta	66	57.64	67	62.37	21	14.43	1	4.71	42	49.12	61	36.33	258	229.81
Flower	29	22.48	97	56.67	17	17.52	5	4.42	55	54.57	59	51.03	220	184.08
Addis Alem	1	0.63	13	11.48	36	24.76	3	1.01	33	35.83	49	40.38	122	107.53
Ehude gebia	1	6.07	30	29.84	18	21.05	4	2.81	25	26.14	14	8.33	80	97.53
Cement	10	6.67	19	30.18	7	10.07	8	1.48	0	0	16	19.88	60	55.39

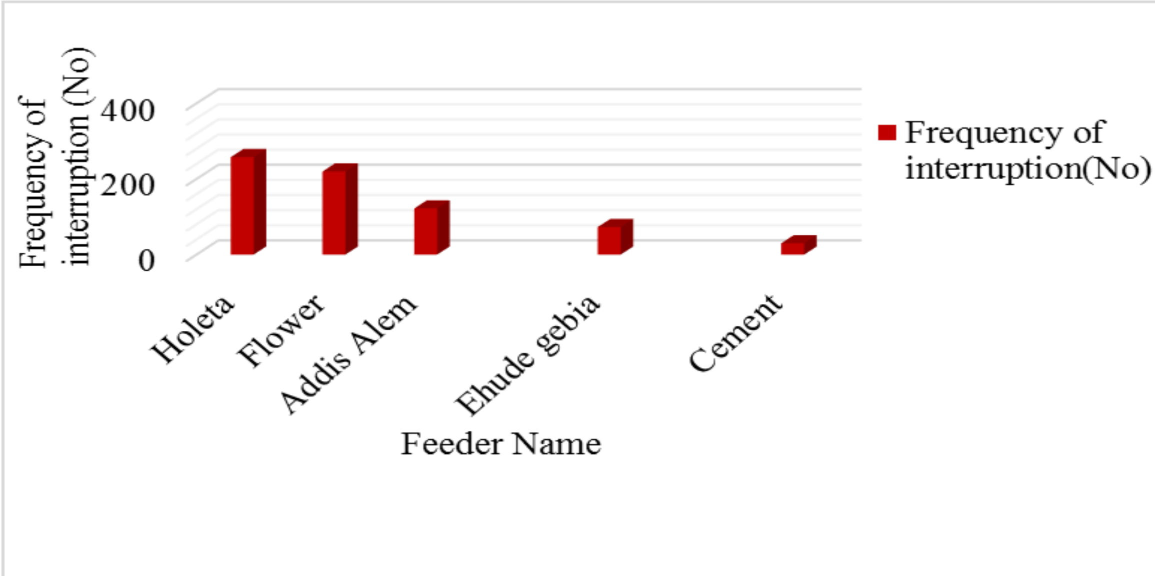


Figure 3.2: Summary of the total frequency interruption for 2017 year

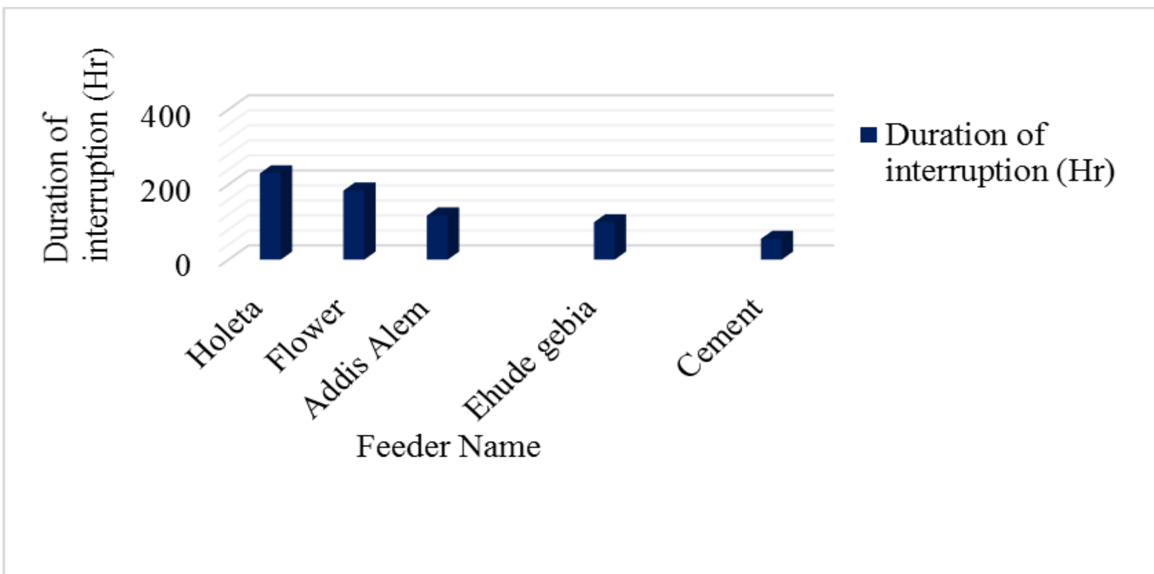


Figure 3.3: Summary of the total duration interruption for 2017 year

In Figure 3.2 and 3.3, the frequency and duration interruption for both Ehude gebia and Cement feeders is low as compares to other feeders because in both feeders there is good tree management system, maintenance activities and shorter response time.

Table 3.5: Summary of total frequency and duration of interruption for 2018 year

Feeder Name	Frequency and Duration of interruption												Frequency of interruption (No)	Duration of interruption (Hr)
	EARTH FAULT		SHORT CIRCUIT		BLACKOUT		OVERLOAD		SOL		OPERATION			
	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)	F	D(Hr)
Holeta	75	59.72	96	82.69	24	19.54	7	9.27	34	39.02	61	60.6	299	286.25
Flower	87	51.15	145	152.18	16	19.47	10	8.5	23	20.49	62	79.65	276	266.58
Addis Alem	0	0	8	12.46	37	45.05	13	9.91	72	57.69	54	37.37	188	170.48
Ehude gebia	24	16.57	47	18.57	12	17.32	12	6.71	4	1.81	19	15.71	108	97.88
Cement	12	17.77	24	37.75	12	17.32	12	6.73	1	1.81	16	15.81	85	79.72

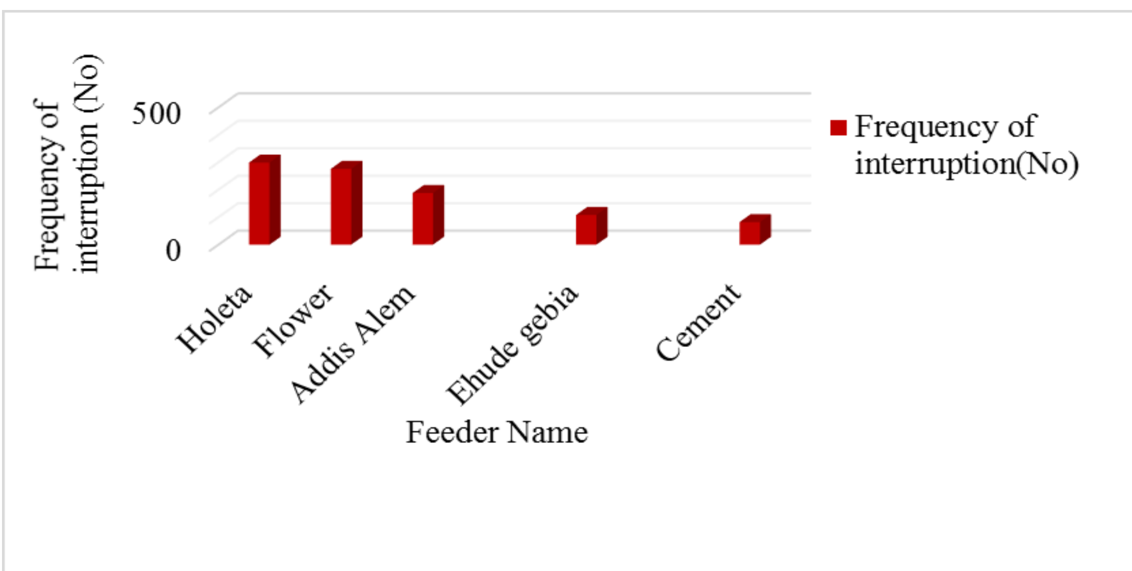


Figure 3.4: Summary of the total frequency interruption for 2018 year

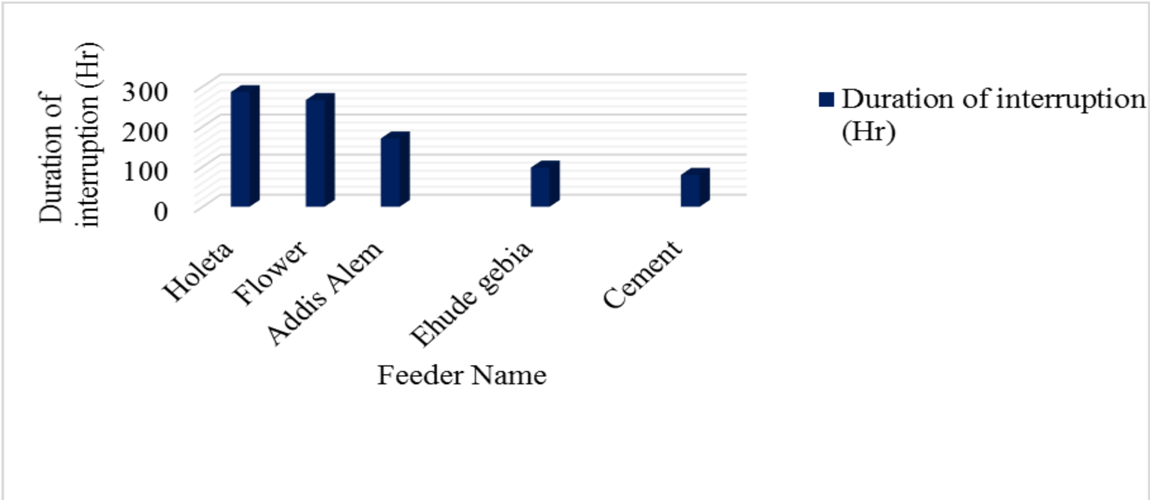
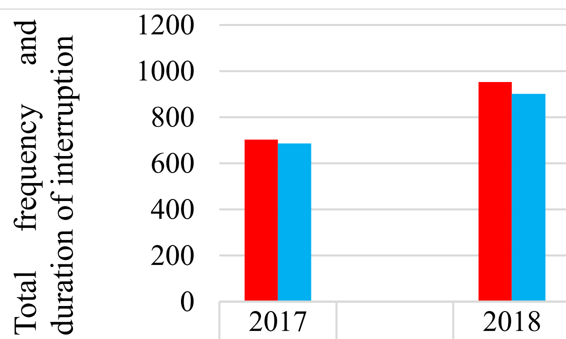


Figure 3.5: Summary of the total duration interruption for 2018 year

From Figure 3.2 and 3.4, we analyzed that 31%, 37% the total number of frequency of interruption per year occurred on Holeta feeder in the years of 2017 and 2018 respectively whereas 4%, 9% the total number of frequency of interruption per year occurred on Cement feeder in the years of 2017 and 2018 respectively. This show that Holeta feeder was the greatest number of frequency of interruption compare to others while Cement was the extent one.



	2017	2018
Frequency of Interruption(No)	703	953
Duration of Interruption(Hr)	686.25	900.91

Figure 3.6: Summary of the total frequency and duration of interruption for 2017 and 2018 years

Figure 3.6 shown that the frequency of interruption over all the 15kV feeders for the consecutive of the two years would be increased which was affect availability of distribution substation and the duration of interruption almost increased during the years of 2017 and 2018. This shown that the utilities took less maintenance activities over the consequences of two years.

3.3 Types of Faults in Addis Alem outgoing Feeders

Addis Alem outgoing feeders consists of different types of faults, which interrupt the power supply to the user end. Some of the faults were explained according to their average frequency and duration of interruptions for the 2017 to 2018 years in the next Tables with their graphs.

Table 3.6: Average frequency of interruption for 2017 year based on types of faults

No	Type of faults and others	Feeders Name				
		Holeta	Flower	Addis Alem	Ehude gebia	Cement
1	Earth Fault	66	29	1	1	3
2	Short Circuit	67	97	13	30	8
3	Black out	1	17	36	18	7
4	SOL	42	5	3	4	2
5	Over Load	42	55	33	25	1
6	Operation	61	59	49	14	10

SOL = System over Load (when generated power is below the total demand)

Where, Short circuit, Earth Fault and over Load are distribution faults while SOL, Black out and operation are a types of other faults.

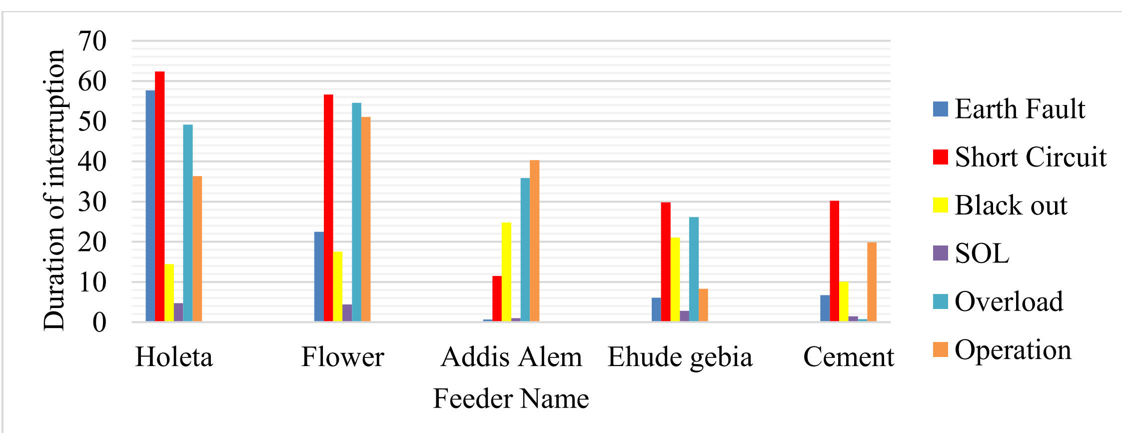


Figure 3.7: Average frequency of interruption for 2017 year based on types of faults

Table 3.7: Average frequency of interruption for 2018 year based on types of faults

No	Types of faults and others	Feeders Name				
		Holeta	Flower	Addis Alem	Ehude gebia	Cement
1	Earth Fault	75	87	1	24	12
2	Short Circuit	96	145	8	47	24
3	Black out	24	16	37	12	12
4	SOL	7	10	13	12	12
5	Overload	34	23	72	4	1
6	Operation	61	62	54	19	16

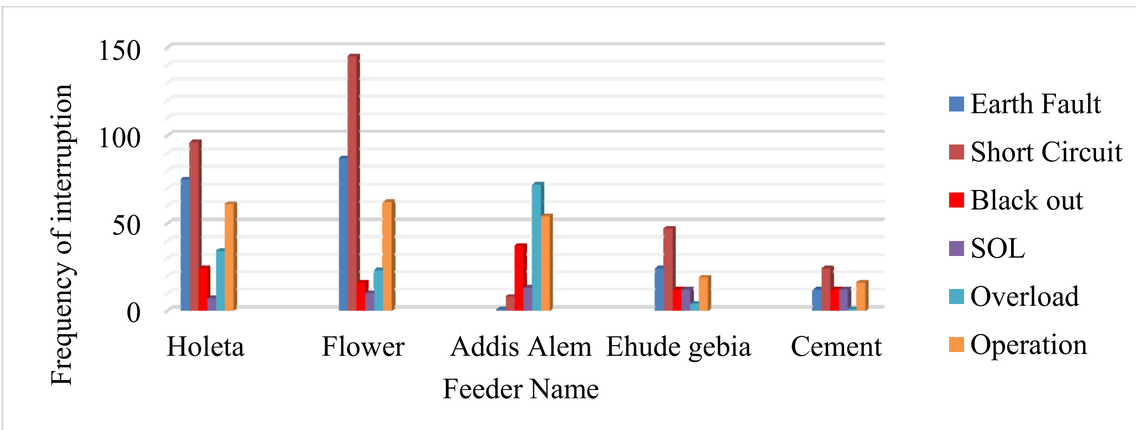


Figure 3.8: Average frequency of interruption for 2018 year based on types of faults

Figure 3.7 and 3.8 shows the average frequency of interruptions due to the distribution faults and others faults for the years of 2017 and 2018 for the five feeders of Addis Alem distribution substation. Types of the faults typically subdivided into distribution faults and others faults. Among the cases short circuit took greatest contribution of the interruption in Addis Alem substation. A power interruption due to short circuits in Addis Alem substation in 2017 year is 27.17 % and in 2018 year is 31.08%.

Table 3.8: Average Duration of interruption for 2017 year based on type's faults

No	Types of faults and others	Feeders Name				
		Holeta	Flower	Addis Alem	Ehude gebia	Cement
1	Earth Fault	57.64	22.48	0.63	6.07	6.678
2	Short Circuit	62.37	56.67	11.48	29.84	30.18
3	Black out	14.43	17.52	24.76	21.05	10.07
4	SOL	4.71	4.42	1.01	2.81	1.48
5	Overload	49.12	54.57	35.83	26.14	0.73
6	Operation	36.33	51.03	40.35	8.33	19.88

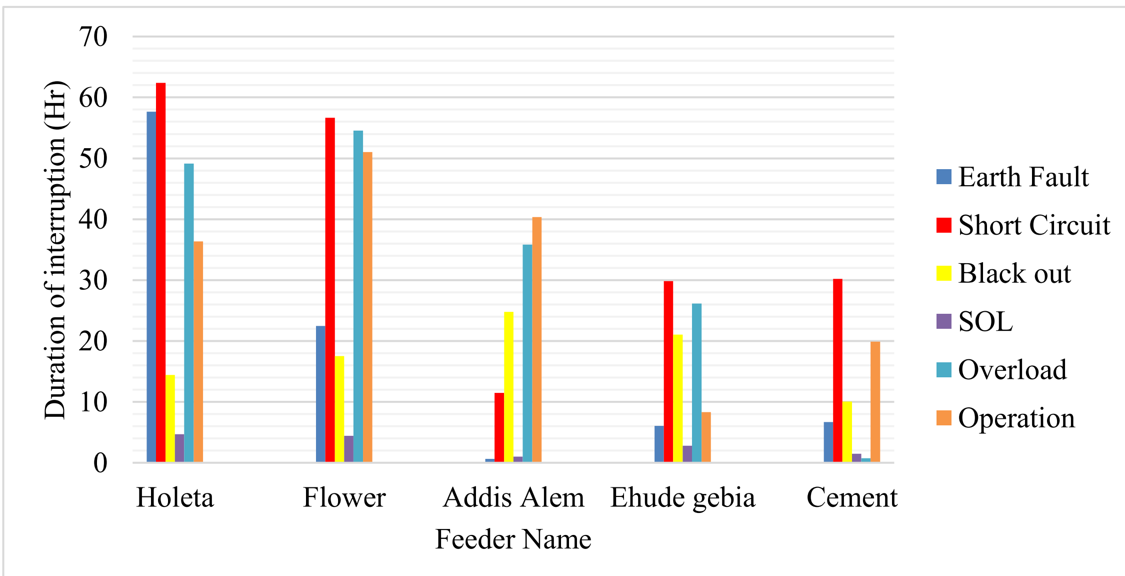


Figure 3.9: Average duration of interruption for 2017 year based on types of faults

Table 3.9: Average duration of interruption for 2018 year based on types of faults

No	Type of faults and others	Feeders Name				
		Holeta	Flower	Addis Alem	Ehude gebia	Cement
1	Earth Fault	59.72	51.15	0	16.57	17.77
2	Short Circuit	82.69	152.16	12.46	18.57	37.35
3	Black out	19.54	19.47	45.05	17.32	17.32
4	SOL	9.27	8.5	9.91	6.71	6.73
5	Overload	39.02	20.49	57.69	1.81	1.81
6	Operation	60.6	79.65	37.37	15.71	15.81

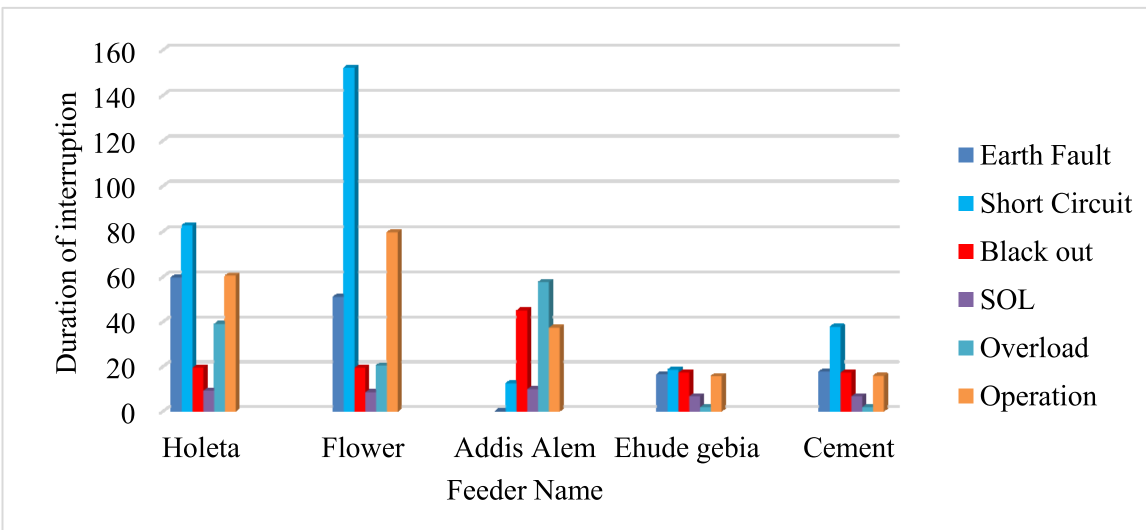


Figure 3.10: Average duration of interruption for 2018 year based on types of faults

Figure 3.9 and 3.10 shows the average duration of interruption in hours due to Earth fault, Short Circuit, Black out, System over Load, Overload and Operation for 2017 and 2018 years of the five feeders of Addis Alem substation.

Table 3.10: Percentage contribution in frequency and duration of faults over two years

Faults	Fault frequency (Avg.Freq.)	Fault duration (Avg.Hr)	Contribution in Int.frequency (%)	Contribution in Int.Duration (%)
Earth fault	150	119.354	16	15
Short circuit	269	247.095	29	30
Overload	90	103.265	10	13
Blackout	60	27.775	7	3
SOL	145	143.605	16	17
Operation	203	182.530	22	22
Total	917	823.624	-------	----------

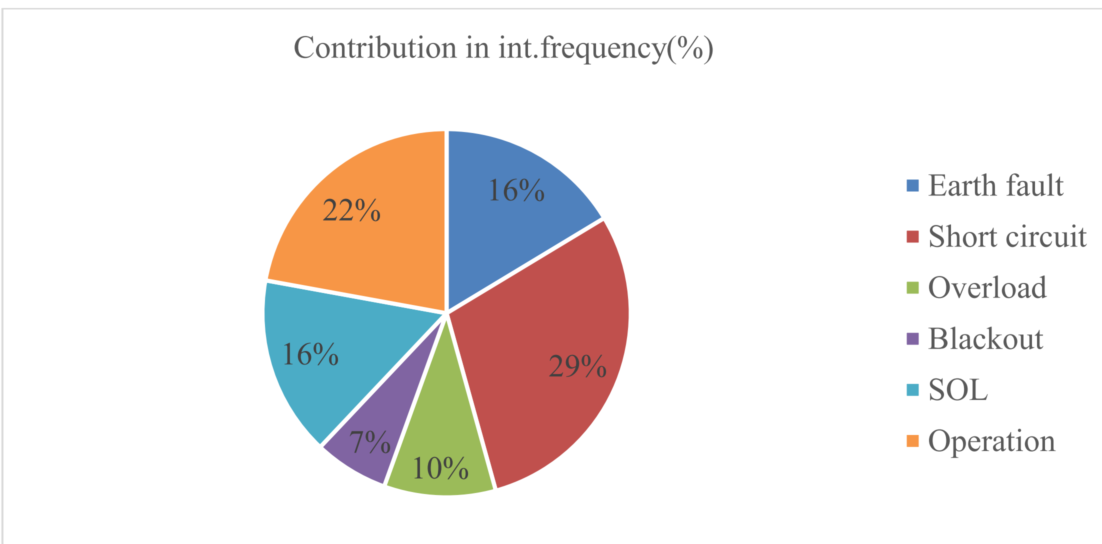


Figure 3.11: Percentage contribution in frequency of faults over two years

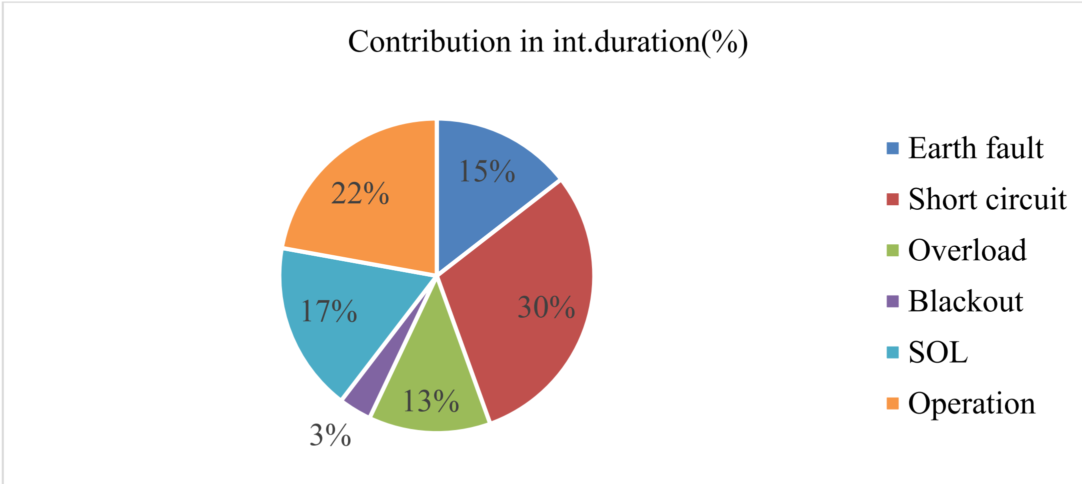


Figure 3.12: Percentage contribution in duration of faults over two years

From Table 3.10 and Figure 3.11, 3.12 we analyzed that a short circuit took a greater percentage contribution of average frequency and duration over two years. This fault would be interpreted as percentage 29% and 30% average frequency and duration respectively. In other terms short circuit the most contribution for frequent causes of failures of a system. While Blackout took less contribution in frequency and duration when compared with other types of faults.

3.4 Reliability Analysis of 15kV Addis Alem Distribution System Network

Those reliability analyses such as failure rate, mean time between failure and mean time to repair are used to determine the availability of individual feeders and overall performance of the substation.

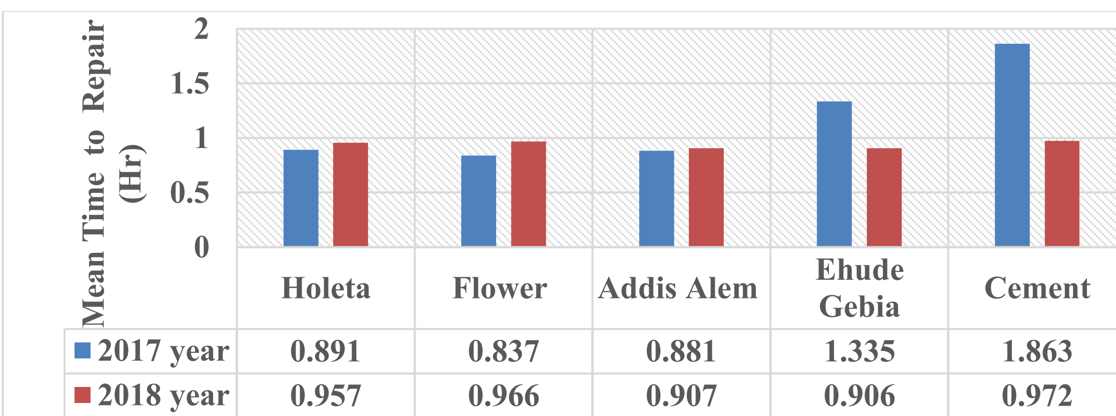


Figure 3.13: Summary of the MTTR of the feeders over the two years

Table 3.11: Summary of the MTBF of the feeders over two years.

No	Feeders Name	2017	2018
1	Holeta	33.56	28.34
2	Flower	38.98	30.77
3	Addis Alem	70.92	45.69
4	Ehude Gebia	118.66	80.21
5	Cement	290.154	105.86

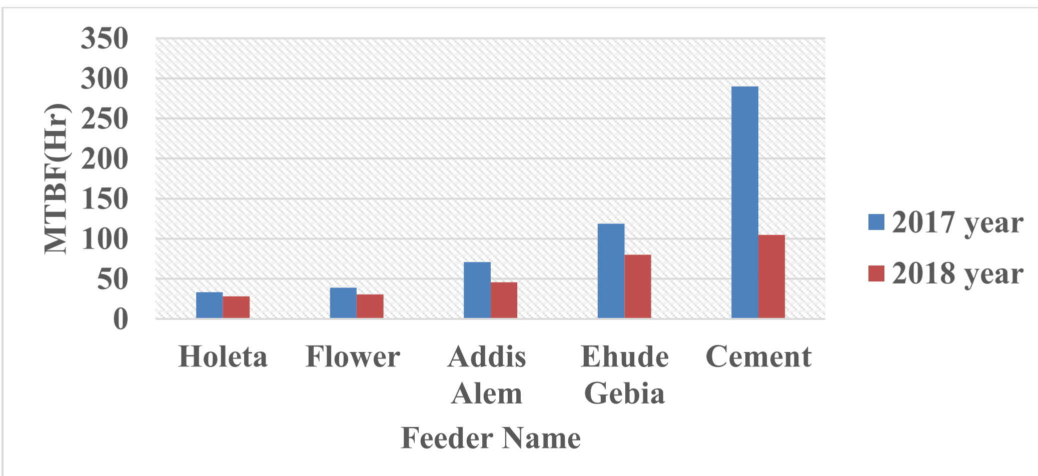


Figure 3.14: Summary of the MTBF of the feeders over two years.

Reliability analysis was made based on the extraction of the data from the daily spreadsheet report of five 15kV outgoing feeders from Addis Alem distribution substation. The outage data for 2017 and 2018 years were available at the station at the time of research. From Figures 3.13 and 3.14 the feeder with shorter MTTR and larger MTBF has the highest availability and is the most reliable. It was observed that 15kV Holeta feeder has highest MTTR due to their frequent outages occurrences. This indicate that the outage of these feeder bring about the highest loss of energy, as well as the highest momentary worth of loss to the EEU management compared to the other feeders. On the other hand, 15kV Flower feeder, Addis Alem feeder, Ehude gebia feeder and Cement feeder respectively have the least outages occurrence. This implies that customers served by these feeders experienced least interruption of power supply for that period of study and justifies the highest amount of preventives maintenance.

Table 3.12: The main feeder availability indices of existing distribution system

No	Feeder Name	2017	2018	Ave. Availability(p.u)
1	Holeta	0.9735	0.9470	0.9603
2	Flower	0.9785	0.9686	0.9736
3	Addis Alem	0.9876	0.9662	0.9769
4	Ehude gebia	0.9899	0.9886	0.9886
5	Cement	0.9936	0.9908	0.9922
Ave. Availability at substation		0.9844	0.9792	0.9819

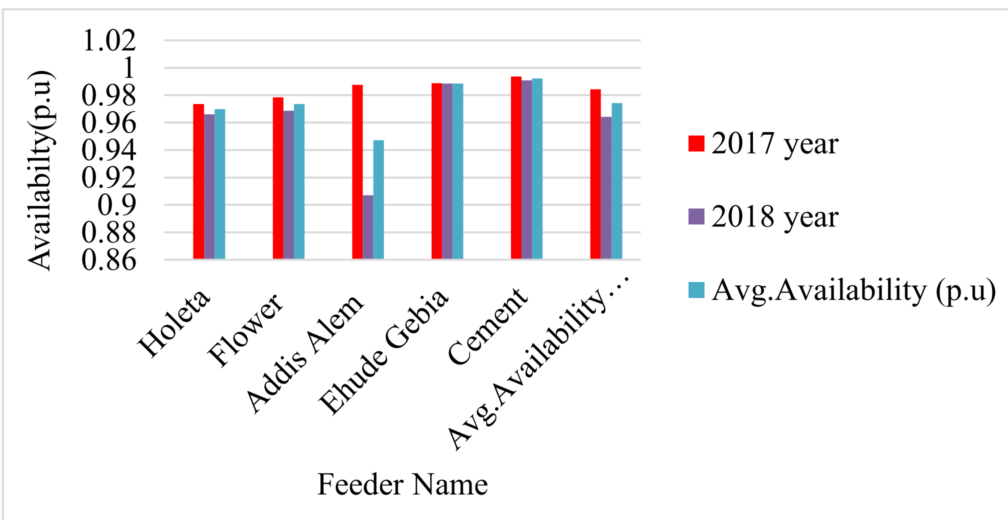


Figure 3.15: The main feeder availability indices of existing distribution system

From Table 3.12 and Figure 3.15 the available of supply delivered to customers decrease within the consecutive of two years, special the Holeta feeder is the least delivered of power supply to the customers served from this feeder while Cement feeder is the highest when compared with the extents.

From Figure 3.15, we observed that Holeta feeder has large power outage as compared to other feeders in the consecutive of two years. The reason that large power outage in Holeta feeder; there is less tree management system, maintenance activities and greater response of time.

Table 3.13: Duration (Hours) of interruptions of Addis Alem substation

No	Feeder Name	2017	2018	Grand total
1	Holeta	229.81	286.25	516.06
2	Flower	184.08	266.58	450.66
3	Addis Alem	107.53	170.48	278.01
4	Ehude gebia	97.44	97.88	195.32
5	Cement	55.39	79.72	135.11
Total Substation		674.25	900.91	1575.16

Table 3.14: Frequency of interruption of Addis Alem substation

No	Feeder Name	2017	2018	Grand total
1	Holeta	258	299	557
2	Flower	220	276	496
3	Addis Alem	122	188	310
4	Ehude gebia	80	108	181
5	Cement	60	85	112
Total Substation		740	956	1656

Table 3.13 and 3.14 Shows that both frequency and duration of interruption of Addis Alem substation are increased in 2018 with 58% and 57.2% respectively.

Table 3.15 Average value reliability over two years.

Event	2017	2018	Average value over two years
MTTR(Hr)	0.9416	1.1614	1.0515
MTBF(Hr)	110.456	58.1724	84.314
Availability(p.u)	0.9844	0.9792	0.9818

Traditionally, historical interruption events occurring at the distribution feeders over specific time periods can be used to calculate the reliability of system of the distribution feeders. Using historical data behavior of the distribution feeders can also be predicted by combining the reliability parameters values such as failure rates, mean time to repair and mean time between failures. The reliability of system varies from year to year because of the statistical variation in the duration of such outages.

Figure 3.15 shows that the availability of the 15kV distribution system decreased in the consecutive of two years because of the fact that there were less preventive maintenance activities on the distribution network of the area. A maintenance activities help to reduce the fault rate of the feeders. Reliability of the electric distribution system can be increased by either shortening the duration of the interruptions of the power supply or lowering the frequency by which interruptions occur [44].

From the analysis, average of power availability for Addis Alem distribution substation over two years is 98.19%. But in fact, consumers expected electric power to be available twenty- four (24) hours a day or 8760 hours a year without any interruption. According to APPA distribution system reliability and operations survey report, by Alex Hofmann, Nov 2012, utility will be able to make power available between 99.9 and 99.999 percent of the time.

3.5 Reliability Indices Calculation

The reliability indices of the existing substation can be calculated using equations (2.9) to (2.17), which are given in chapter two. Based on the data given in Table 3.4 and 3.5, the reliability indices for 2017 year, 2018 year, and the average reliability indices of the 2017 and 2018 years are calculated.

Table 3.16: Reliability indices of 2017 year.

Feeder	SAIDI (Hr/cust.yr)	SAIFI (Int/cust.yr)	CAIDI (Hr/cust.Int)	ASAI (p.u)	ASUI (p.u)	ENS (MWh/yr)	AENS (MWh.yr/cust)
Holeta	229.81	258	0.8907	0.9738	0.0262	1532.83	0.06323
Flower	184.08	220	0.8367	0.9789	0.0211	1060.30	0.05419
Addis Alem	107.53	122	0.8814	0.9877	0.0123	467.76	0.04368
Ehude gebia	97.44	80	1.2180	0.9889	0.0111	281.60	0.04831
Cement	55.39	60	0.9232	0.9937	0.0063	296.89	0.09412
Avg. value	134.85	148	0.9489	0.9846	0.0154	3639.38	0.30553

Table 3.17: Reliability indices of 2018 year.

Feeder	SAIDI (Hr/cust.yr)	SAIFI (Int/cust.yr)	CAIDI (Hr/cust.Int)	ASAI (p.u)	ASUI (p.u)	ENS (MWh/yr)	AENS (MWh.yr/cust.)
Holeta	286.25	299	0.9574	0.9673	0.0295	1909.28	0.07823
Flower	266.58	276	0.9658	0.9696	0.0258	1396.88	0.15372
Addis Alem	170.48	188	0.9068	0.9805	0.0159	657.59	0.06620
Ehude gebia	97.88	108	0.9063	0.9888	0.0112	281.89	0.04915
Cement	79.72	85	0.9722	0.9909	0.0077	399.39	0.09634
Avg.value	180.182	191.6	0.9379	0.9794	0.0181	4145.06	0.44314

From Table 3.16 and 3.17, it is being observed that Ehude gebia and Cement feeders gives the better results in terms of improvement of SAIDI and SAIFI, which in turn gives the minimum interrupted energy.

Table 3.18: Average reliability indices of the 2017 and 2018 years

Feeder	SAIDI (Hr/cust.yr)	SAIFI (Int/cust.yr)	CAIDI (Hr/cust.Int)	ASAI (p.u)	ASUI (p.u)	ENS (MWh/yr)	AENS (MWh.yr/cust.)
Holeta	258.03	279	0.9265	0.9706	0.0294	1721.06	0.0705
Flower	225.33	248	0.9086	0.9743	0.0257	1228.59	0.1035
Addis Alem	139.01	155	0.8968	0.9841	0.0159	562.68	0.0545
Ehude gebia	97.66	93.53	1.0389	0.9889	0.0111	281.74	0.0485
Cement	67.561	72.52	0.9318	0.9923	0.0077	348.14	0.0953
Avg.value	157.516	169.6134	0.9405	0.9819	0.0181	3892.22	0.3723

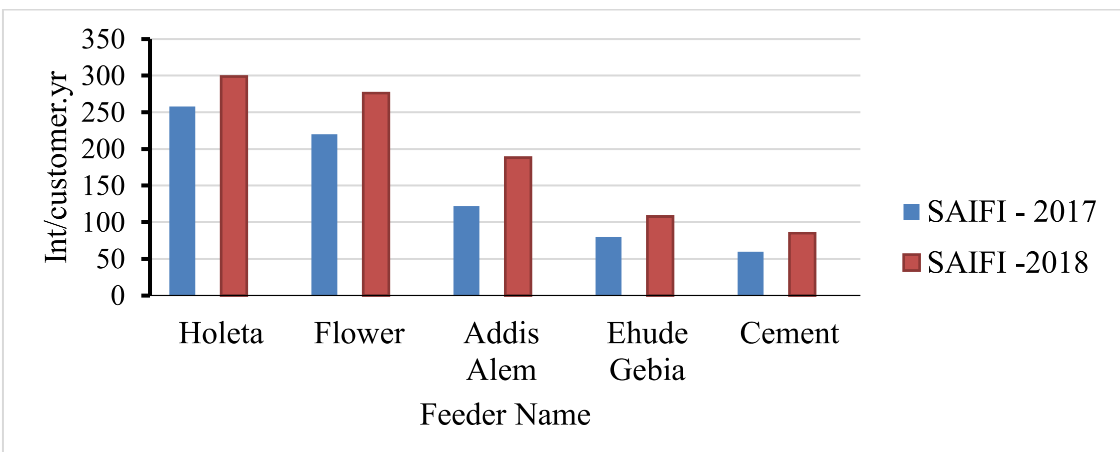


Figure 3.16: SAIFI Comparison

As shown in the Figure 3.16, the index SAIFI has increased from 2017 to 2018 year. The reason for this is ageing of conductors.

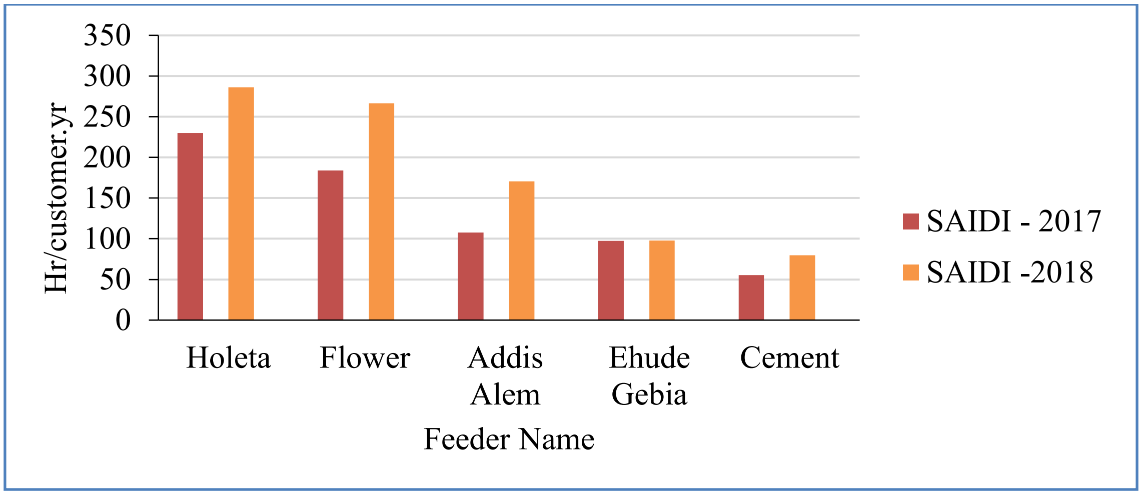


Figure 3.17: SAIDI Comparison

As shown in Figure 3.17, the maximum interruption duration in 2017 year was 229.81 Hr. while that of 2018 year is 286.25 Hr. it is seen from the Figure 3.17, SAIDI of system average interruption duration index has shown much increment from 2017 to 2018 year. The reason for this is ageing of conductors.

Summary of the Analysis

1. SAIDI of the overall system as shown in Table 3:18 is 157.516 hours per customer per year. This shows that every customer experiences 157.516 Hr/yr. This proves that there is great reliability problem in existing Addis Alem substation. As per Ethiopian Electric Agency's (EEA), the SAIDI value should not exceed 25 hours per customer per year [48]. The permissible SAIDI value in Germany is 0.383 hours per customer per year [45].
2. Table 3.18 SAIFI of the system are 169.6134 Int/customer.yr. As per Ethiopian electrical Agency's (EEA) standard, SAIFI should not exceed 20 interruption per customer per year, which indicates that the current value is above the acceptable value by large margin. And also, when we compare the calculated SAIFI value with German standard, it is much greater than the maximum limit [47]. This clearly indicates that there is serious reliability problem in present Addis Alem substation.
3. ASAI: It is the average service availability index, which shows the fraction of time that a customer has received power during the reporting period. The power supply of the overall system is 98.19% available as shown in Table 3.18. However, this value is not still good enough since the ASAI value should be greater than 99.98% as per EEA's standard [48].

4. ENS: It indicates the unsold energy of each feeder. For the overall system, the total unsold energy was 3892.2186 MWh as given in Table 3.18.
5. AENS: It is the average energy not supplied per customer by the system. The overall system has an AENS value of 0.3723 MWh per customer.

From the summary analysis above

1. The reliability of Addis Alem substation does not satisfy the requirements set by the Ethiopia Electric Agency.
2. The reliability of Addis Alem substation is not good enough as compared to the standard reliability benchmark of best-experienced countries.
3. There is much of unsold energy due to both planned and unplanned outages in Addis Alem substation.

3.6 Comparison of Reliability Indices with Benchmarks

Reliability benchmarks are the standard against which analyzed or measured reliability is judged. The purpose of reliability benchmarks are to define minimum average reliability performance, by feeder type, for a distribution network, for a substation based on summing the performance of the feeders and provide a basis against which a distribution network service provider's reliability performance can be assessed.

A benchmark of SAIFI and SAIDI, for nine countries is shown in Table 3.19. And comparing the average SAIFI and SAIDI, value of Addis Alem substation with the benchmarks shows that has worse performance.

Table 3.19: Benchmarks for reliability indices [47, 48].

No	Country	SAIFI (Int/cust.yr)	SAIDI (Hr/cust.yr)
1	France	0.5	1.033
2	Italy	2.2	0.967
3	Austria	0.9	1.200
4	United states	1.5	4.00
5	Germany	1	0.383
6	Spain	2.2	1.733
7	Netherland	0.3	0.55
8	Denmark	0.5	0.40
9	UK	0.8	1.50
10	Ethiopia	20	25
11	Addis Alem substation	169.6134	157.516

A typical customer expects to have a power at all times. In reality a utility will be able to make power available between 0.999 and 0.99999 per unit of the time. To put it in another way, the average customer may be dissatisfied if there is no electricity for more than for 53 minutes a year. (Source: APPA distribution system reliability and operations survey report, by Alex Hofmann, Nov 2012, published by American Public power association).

Due to all feeder of Addis Alem distribution substation a customers experienced life without electricity on average for about 315.034 hour per year.

3.7 Loss of Revenue due to Power Interruption in Addis Alem Substation

A common method used in evaluating the worth or benefit of electric service reliability is to appraise the customer costs related with power interruptions. The customer interruption cost when an electric supply failure occurs depend on many factors. Based on the average electric tariff category I got from the Ethiopia electric utility in Addis Alem due to power interruption, the thesis work to evaluate only cost lost by utility from outgoing feeders.

Table 3.20: EEU's Electricity tariff (Birr/kWh) [46]

	Active Energy Rate(kWh)	PriceRate(Birr/kWh)
Domestic	0-50	0.2730
	51-100	0.4591
	101-200	0.7807
	201-300	0.9125
	301-400	0.9750
	401-500	1.0423
	Above 500	1.4100
Commercial	0-50	0.6723
	Above 50	1.4100
Low voltage Time of day industry	Peak	0.7426
	Off peak	0.5453
Medium Voltage Time of day industry @ 15kV and 33kV	Equivalent Flat Rate	0.6047
High voltage Time of day industry above 66kV	Equivalent Flat Rate	0.5174

Based on EEU's tariff (Table 3.20), the cost of energy not supplied due to interruption for Addis Alem substation is calculated using the formula,

Cost of Energy = Power * time * tariff for electric (3.1)

By considering an average electric price of 0.8815 Birr/kWh, the average energy not supplied and the average cost of energy not supplied due to power interruption for one-year (2018) at Addis Alem outgoing feeders are calculated and tabulated in Table 3.21.

Table 3.21: Average energy not supplied and Cost of energy not supplied for outgoing Feeders

Item No	Feeder Name	Average Peak Load(MW)	Duration of Interruption(Hr.)	Energy not Supplied (MWh/yr)	Cost of Energy not Supplied (Birr/yr)
1	Holeta	6.67	286.25	1909.287	1683036.931
2	Flower	5.24	266.58	1396.879	123148.838
3	Addis Alem	4.37	150.48	657.597	579672.284
4	Ehude Gebia	2.88	97.88	281.894	248489.913
5	Cement	5.01	79.72	399.397	352068.632
Total.				4145.056	4094616.598

As shown in Table 3.21, the average energy not supplied due to power interruption 4145.056MWh/yr and average cost of energy not supplied due to this power interruption for one year at Addis Alem outgoing feeders is 4.095 Million Birr/yr. or 142421.447USD.

CHAPTER FOUR

SIMULATION RESULT AND DISCUSSION

4.1 Introduction

This chapter begins by describing the sizing of the proper DG unit for specific and continues to the reliability simulation of the current substation without and with DG. And analysis of the obtained result (SAIFI, SAIDI and ENS) is presented in the corresponding simulation.

For better reliability improvement in case of radial system network, feeder that has more frequency interruption, duration of interruption and more number of customers should be selected [43].

As discussed in chapter three, Holeta feeder has more values of SAIDI and SAIFI comparing with other feeders and has much duration of interruptions, frequency interruptions and more number of customers. So, it desirable to assess and enhance the reliability of Holeta feeder leading to improve the overall distribution reliability.

4.2 Sizing of DG Technology

When DG unit inserted in the network; it injects short circuit current value in the network. The size of DG unit inserted in the network is directly proportional to the injected short circuit current. If a short circuit current value in the network increases due to the size of DG some constraints (Protection devices i.e. fuses, relays setting changed, Voltage profiles out of the standard limit i.e. 0.95p.u – 1.05 p.u., Line overload, Transformer overload, Over voltage and over current) happens.

Therefore, to avoid the constraints the size of DG connected to the network should be in the standard range 10%-60% of the maximum peak load of feeder [26].

In this Thesis, the size of the selected DG is based on the peak load of Holeta feeder that is 6.67MW and 60% that is 4MW. Therefore, throughout the thesis, single DG refers to a capacity of 4MW.

4.3 Reliability Analysis using DIgSILENT Power Factory

The scheme under investigation is part of Addis Alem distribution system. DIgSILENT Power Factory is employed to simulate and analyses the reliability of distribution system without and with distributed generation (DG).

The electrical and failure inputs given to each equipment is shown in **APPEDIX C.** Every equipment has electrical and failure inputs. For example, a bus bar which is used in a distribution system shown in the below one line diagram is fed its ratings like, voltage and current ratings and the failure inputs are the interruption frequency and duration.

The distribution system shown in Figure 4.1 receives 45kV from Addis Alem substation feeds one transformer of 12MVA. This transformer step down the voltage from 45kV to 15kV and then customers will be supplied by their corresponding feeders.

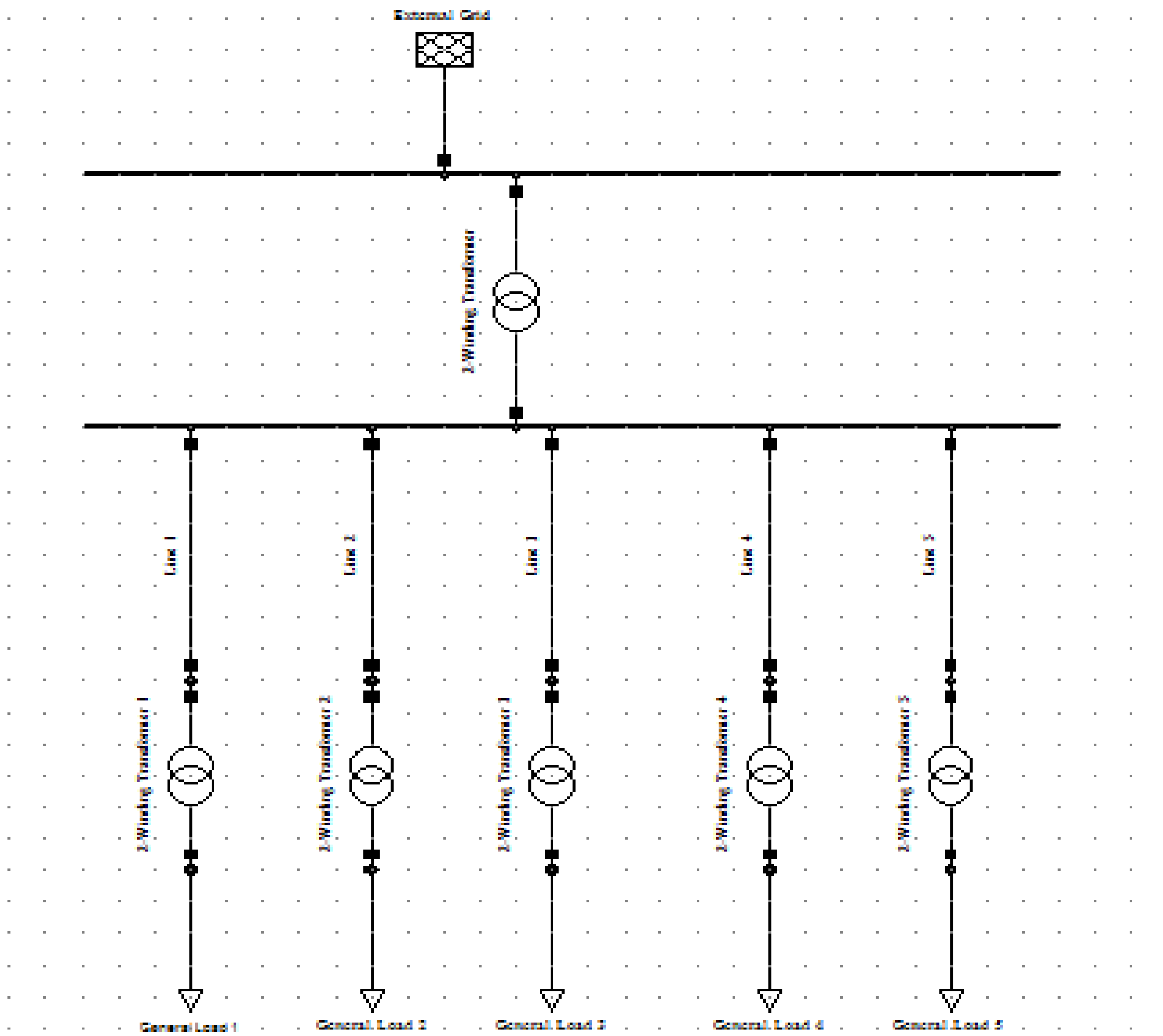


Figure 4.1: Single line diagram of Addis Alem substation

The reliability assessment in this Chapter has two main parts. These are connecting DG unit to the selected feeders of the substation then, evaluating the overall improvement and taking a single feeder (Holeta) and applying DG unit at one load point which far away from the supply point of that specific feeder.

4.4 Connecting DG at selected Feeders

The following case studies are undertaken to the overall substation shown in Figure 4.1

1. Base case reliability indices (without DG),

2. DG at Holeta Feeder

3. DG at Flower Feeder

3. DG at Holeta and Flower Feeder

4. DG to all Feeders

In radial network system, the impact of faults on the main feeders occurs at the substation or supply utility due to tripping of circuit breaker (BC). Tripping of circuit breaker at substation affect all number of customers connected to the substation. In fact, total number of customer served the same as the total number of customer affected if faults occurs on the main feeders of radial network system. From reliability point view, SAIFI values are the same with CAIFI values if a system is radial network system [51].

Table 4.1: Base case reliability indices (without DG)

Study Case: Study Case | Annex:

System Summary

System Average Interruption Frequency Index	: SAIFI	=	178.375008	1/Ca
Customer Average Interruption Frequency Index	: CAIFI	=	178.375008	1/Ca
System Average Interruption Duration Index	: SAIDI	=	152.216	h/Ca
Customer Average Interruption Duration Index	: CAIDI	=	0.853	h
Average Service Availability Index	: ASAI	=	0.9826237544	
Average Service Unavailability Index	: ASUI	=	0.0173762456	

Study Case: Study Case | Annex:

System Summary

Energy Not Supplied	: ENS	=	3732.828	MWh/a
Average Energy Not Supplied	: AENS	=	0.205	MWh/Ca
Average Customer Curtailment Index	: ACCI	=	0.000	MWh/Ca
Expected Interruption Cost	: EIC	=	0.000	M$/a
Interrupted Energy Assessment Rate	: IEAR	=	0.000	$/kWh
System energy shed	: SES	=	0.000	MWh/a

Case study 1: Integrating DG at Holeta Feeder

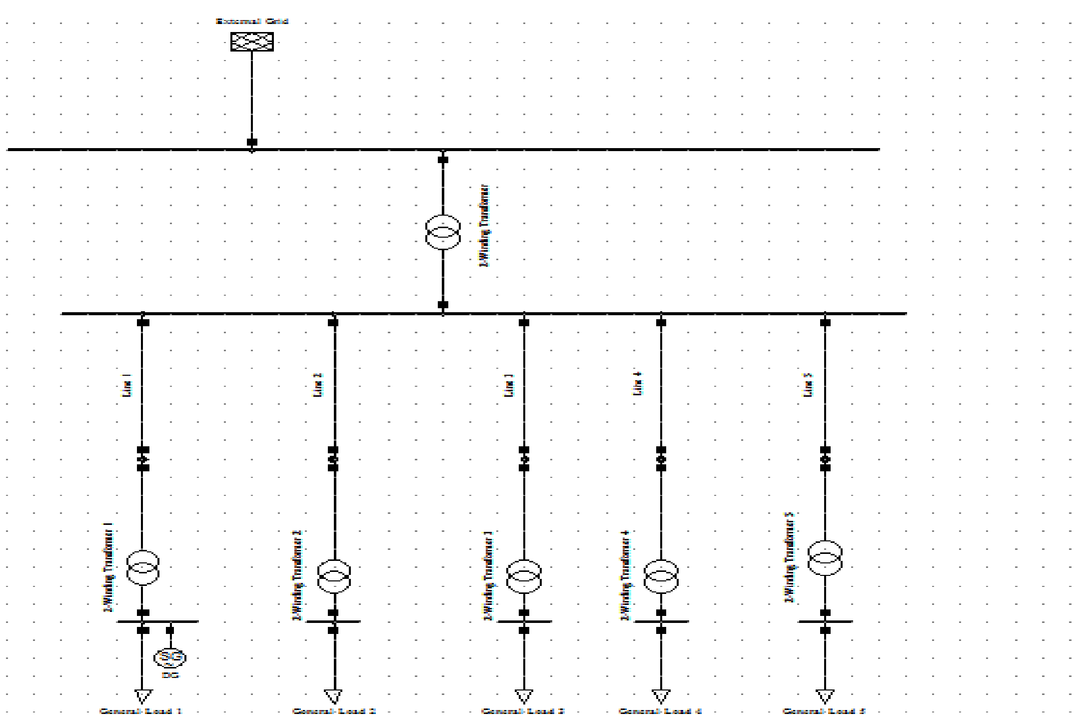


Figure 4.2: Integrating DG at Holeta Feeder

From the result in Table 4.2, the overall system has improved in SAIDI, SAIFI and ENS by 30.2%, 23.1% and 34.5%. In this case study, it is shown that the presence of DG on the substation has positive impact in the power system's reliability. That means that the indices are reduced by the integration of DG to the overall system.

Table 4.2: Reliability Indices with DG at Holeta Feeder

```
Study Case: System Summary                                                          | Annex:
---------------------------------------------------------------------------------------------
System Summary
---------------------------------------------------------------------------------------------
System Average Interruption Frequency Index      :  SAIFI  =  134.055411 1/Ca
Customer Average Interruption Frequency Index    :  CAIFI  =  134.055411 1/Ca
System Average Interruption Duration Index       :  SAIDI  =  110.651    h/Ca
Customer Average Interruption Duration Index     :  CAIDI  =    0.825    h
Average Service Availability Index               :  ASAI   =    0.9873685771
Average Service Unavailability Index             :  ASUI   =    0.0126314229
---------------------------------------------------------------------------------------------

---------------------------------------------------------------------------------------------
Study Case: System Summary                                                          | Annex:
---------------------------------------------------------------------------------------------
System Summary
---------------------------------------------------------------------------------------------
Energy Not Supplied                              :  ENS    = 2399.818    MWh/a
Average Energy Not Supplied                      :  AENS   =    0.177    MWh/Ca
Average Customer Curtailment Index               :  ACCI   =    0.000    MWh/Ca
Expected Interruption Cost                       :  EIC    =    0.000    M$/a
Interrupted Energy Assessment Rate               :  IEAR   =    0.000    $/kWh
System energy shed                               :  SES    =    0.000    MWh/a
```

Case study 2: Integrating DG at Flower Feeder

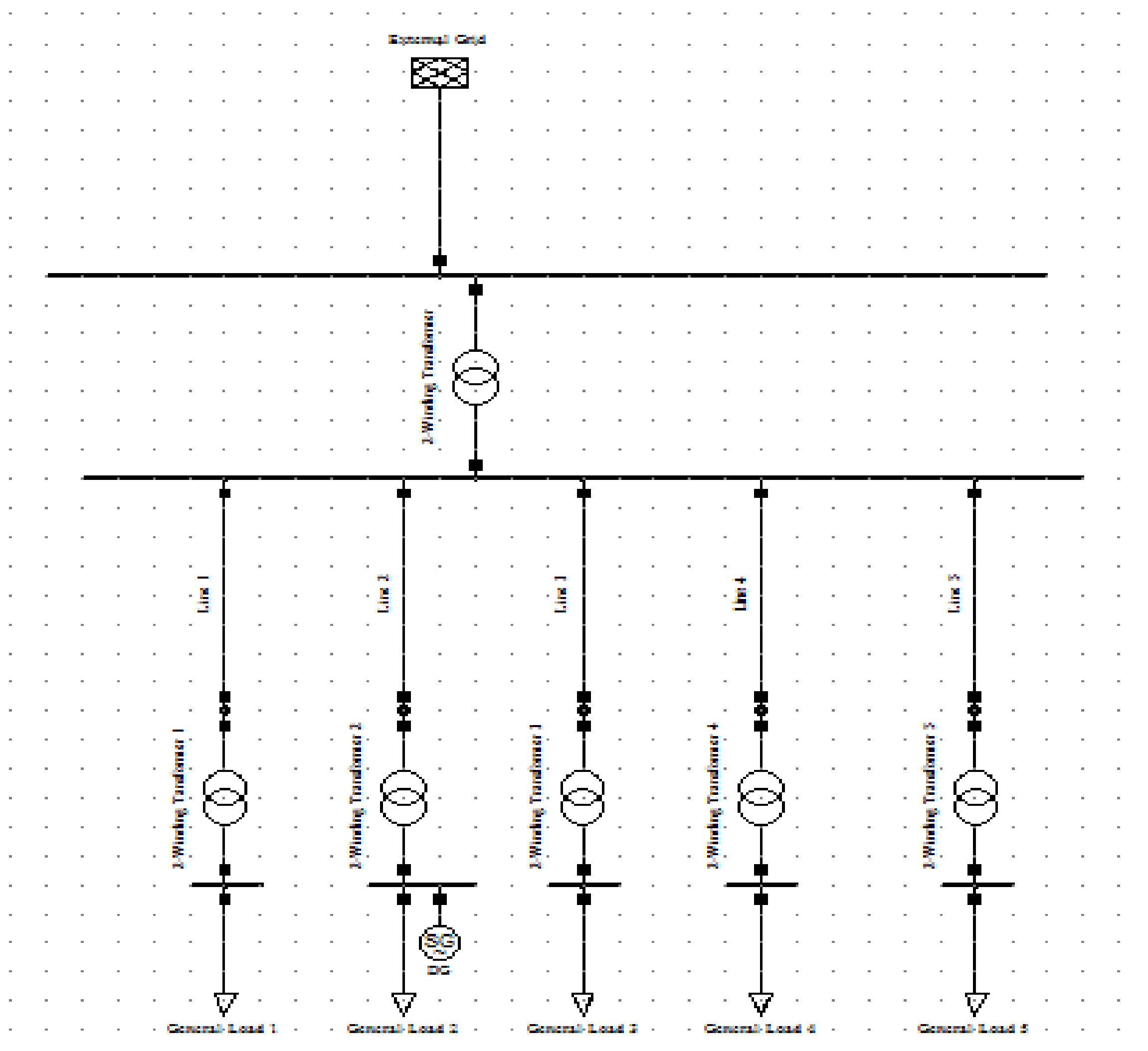


Figure 4.3: Integrating DG at Flower Feeder

From the result in Table 4.3, the overall system has improved in SAIDI, SAIFI and ENS by 38.0%, 28.2% and 56.9%. This shows the same magnitude of DG connected at Flower Feeder gave more improvement than at Holeta Feeder. This is because Flower Feeder is has less interruption duration and frequency.

Table 4.3: Reliability indices with DG at Flower Feeder

```
Study Case: Study Case                                                         | Annex:
-----------------------------------------------------------------------------------------
System Summary
-----------------------------------------------------------------------------------------
System Average Interruption Frequency Index       :  SAIFI  =  118.618304 1/Ca
Customer Average Interruption Frequency Index     :  CAIFI  =  118.618304 1/Ca
System Average Interruption Duration Index        :  SAIDI  =   98.536    h/Ca
Customer Average Interruption Duration Index      :  CAIDI  =    0.831    h
Average Service Availability Index                :  ASAI   =    0.9887516175
Average Service Unavailability Index              :  ASUI   =    0.0112483825
-----------------------------------------------------------------------------------------

-----------------------------------------------------------------------------------------
Study Case: Study Case                                                         | Annex:
-----------------------------------------------------------------------------------------
System Summary
-----------------------------------------------------------------------------------------
Energy Not Supplied                               :  ENS    = 1669.213    MWh/a
Average Energy Not Supplied                       :  AENS   =    0.073    MWh/Ca
Average Customer Curtailment Index                :  ACCI   =    0.000    MWh/Ca
Expected Interruption Cost                        :  EIC    =    0.000    M$/a
Interrupted Energy Assessment Rate                :  IEAR   =    0.000    $/kWh
System energy shed                                :  SES    =    0.000    MWh/a
```

Case study 3: Integrating DG at both Holeta and Flower Feeders

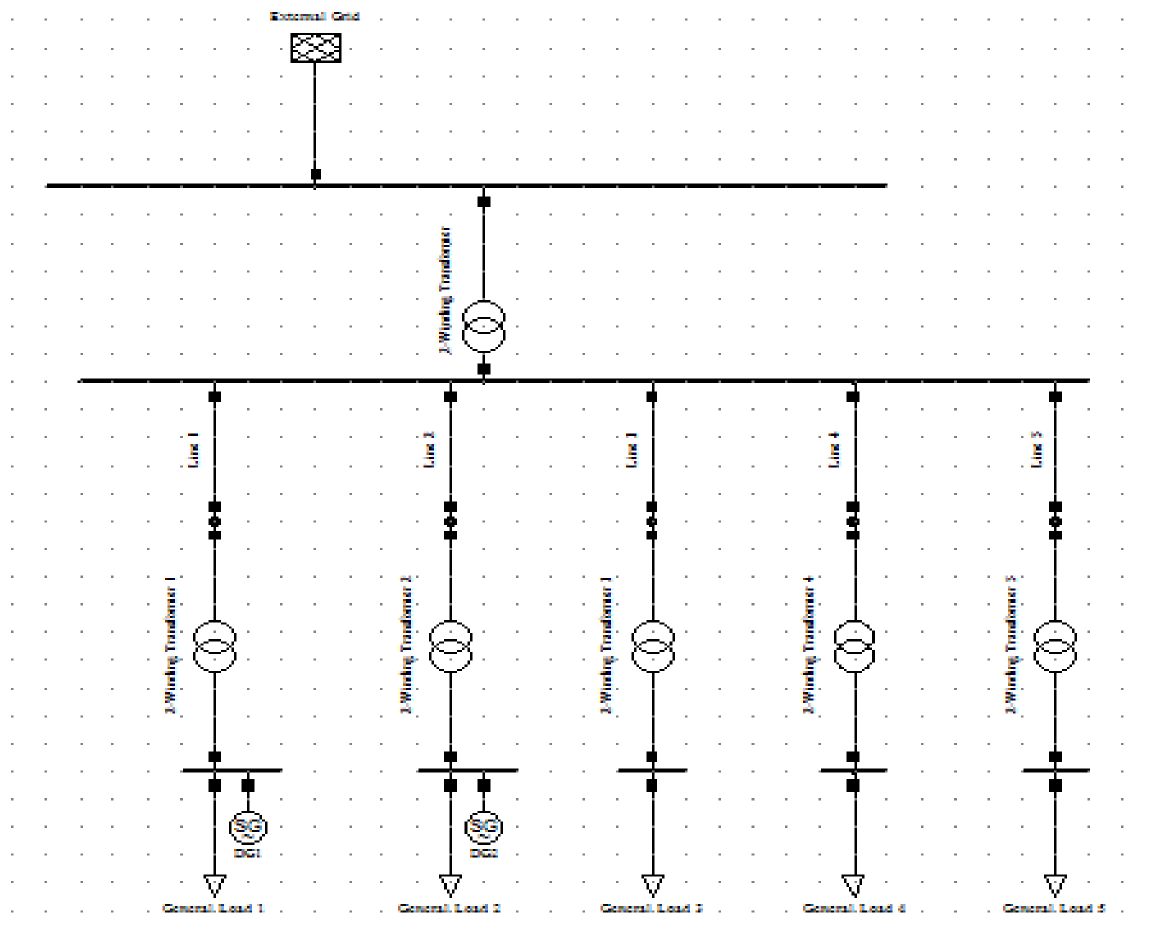


Figure 4.4: Integrating DG at both Holeta and Flower feeders

As shown below, when DG connected to both Holeta feeder and Flower feeder at the same time, the improvement is 53.3%, 48.0% and 72.1% respectively. This is large improvement because applying two DGs of 4MW resulted in almost 58% improvement.

Table 4.4: Reliability indices with DG at both Holeta and Flower Feeders

```
 Study Case: Study Case                                                                          | Annex:
-----------------------------------------------------------------------------------------------------------
 System Summary
-----------------------------------------------------------------------------------------------------------
 System Average Interruption Frequency Index        :  SAIFI  =   70.203415 1/Ca
 Customer Average Interruption Frequency Index      :  CAIFI  =   70.203415 1/Ca
 System Average Interruption Duration Index         :  SAIDI  =   58.243    h/Ca
 Customer Average Interruption Duration Index       :  CAIDI  =    0.830    h
 Average Service Availability Index                 :  ASAI   =    0.9933512009
 Average Service Unavailability Index               :  ASUI   =    0.0066487991
-----------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------
 Study Case: Study Case                                                                          | Annex:
-----------------------------------------------------------------------------------------------------------
 System Summary
-----------------------------------------------------------------------------------------------------------
 Energy Not Supplied                                :  ENS    = 1018.221    MWh/a
 Average Energy Not Supplied                        :  AENS   =    0.056    MWh/Ca
 Average Customer Curtailment Index                 :  ACCI   =    0.082    MWh/Ca
 Expected Interruption Cost                         :  EIC    =    0.000    M$/a
 Interrupted Energy Assessment Rate                 :  IEAR   =    0.000    $/kWh
 System energy shed                                 :  SES    =    0.000    MWh/a
```

Case study 4: Integrating DG to all Feeders.

In this case study, it is assumed that all protective devices and DGs are fully reliable. Based on these assumptions, connection of DG to all feeders as shown in Figure 4.5, show that the overall reliability of the system will be improved by 100%. This means average service availability index becomes one (ASAI=1) and the others zero. But locating DG to those five feeders requires high investment cost. So it is economical to locate the DG into feeders which experience more interruption than the rest.

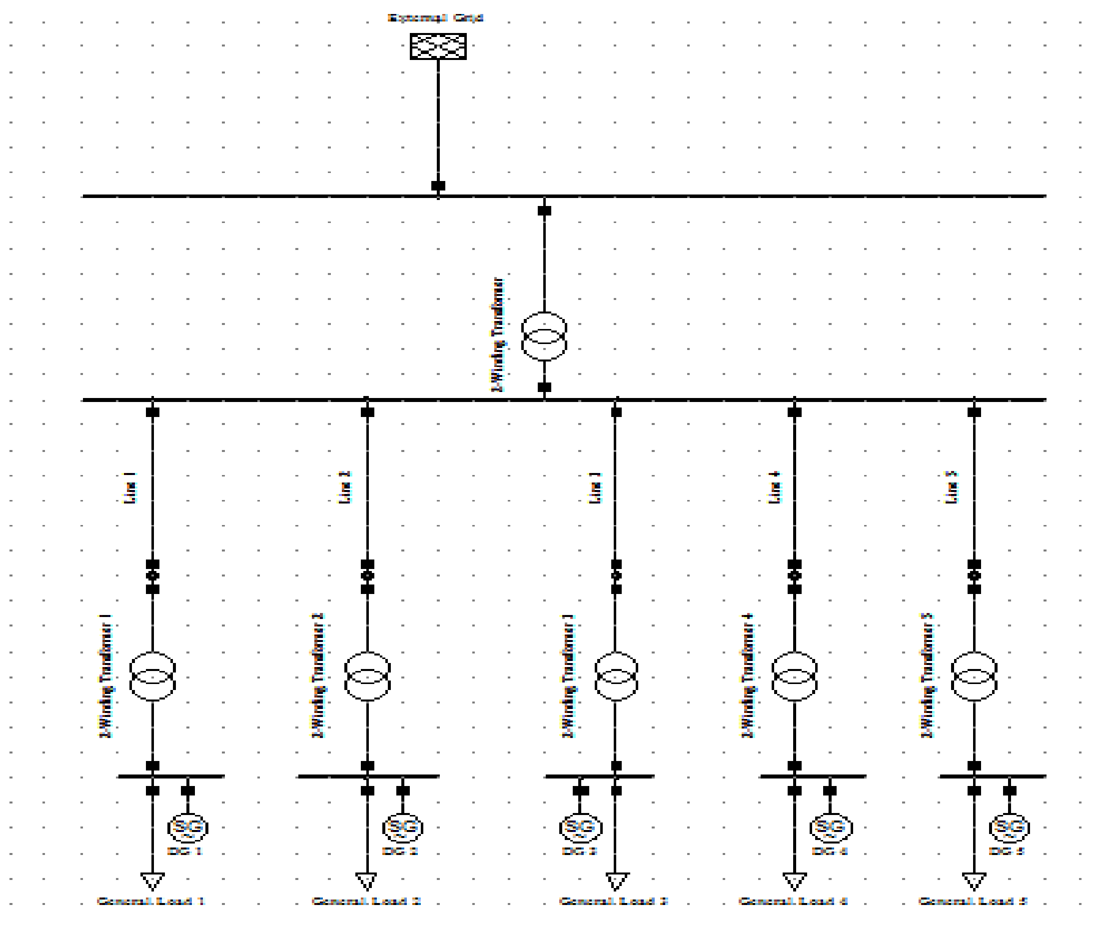


Figure 4.5: Integrating DG to all Feeders.

Table 4.5: Summaries of Reliability of overall System

Reliability Indices	Without DG	DG at Holeta Feeder	DG at Flower Feeder	DG at Holeta and Flower Feeder	DG at all Feeders
		23.1%	28.2%	58%	100%
SAIDI(Hr/cust.yr)	152.216	110.651	98.536	58.243	0
SAIFI(Int/cust.yr)	178.375	134.055	118.618	70.2034	0
ASAI(p.u)	0.9826	0.9874	0.98875	0.99335	1
ENS(MWh/yr)	3732.828	2399.818	1669.213	1018.221	0

4.5 Single Line Diagram of Holeta Feeder

Holeta feeder that has 46 distribution transformers with a total capacity of 10650kVA is selected for better improvement. The peak load for this feeder is 6.67MW. Hence, the peak load used for our analysis is only about 60% of the total capacity of transformers. Single line diagram of Holeta feeder drawn using DIgSILENT Power Factor 15.1 version.

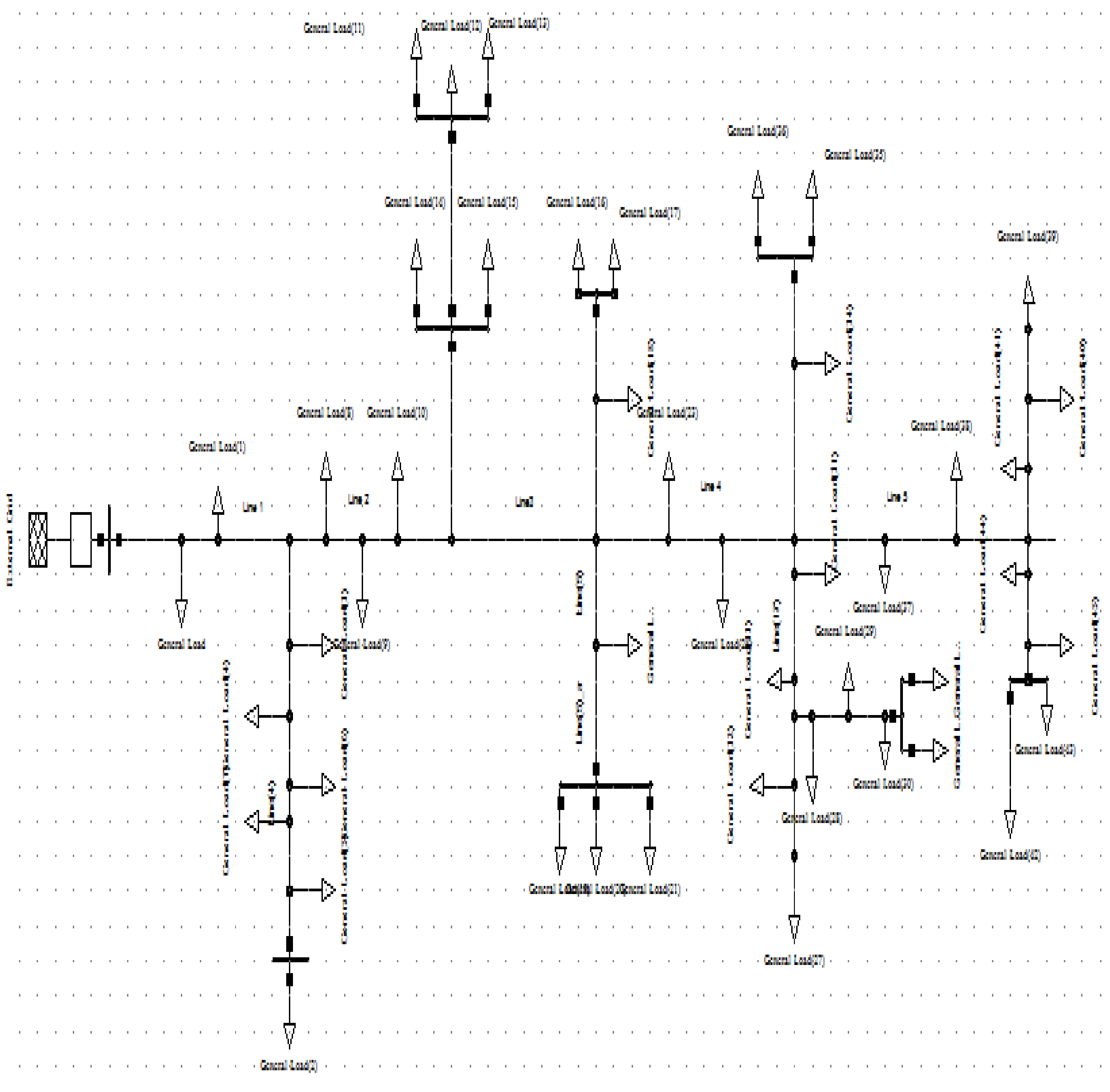


Figure 4.6: Single line diagram of Holeta feeder

4.6 Integrating DG on Simplified Line Diagram of Holeta Feeder

Until now, we have done four case studies on effect of integrating DG on reliability improvement to the overall substation. But now, we will study a single feeder, this feeder is Holeta Feeder.

For better of analyzing reliability, this one line diagram is lumped in to five load points as shown in Figure 4.7. In this analysis, each load point is not tested for best location of the DG in terms of distance from the supply point; only load point five is tested because of many researches shows that it is good to place DG far away from the supply point to improve the reliability of the system [52].

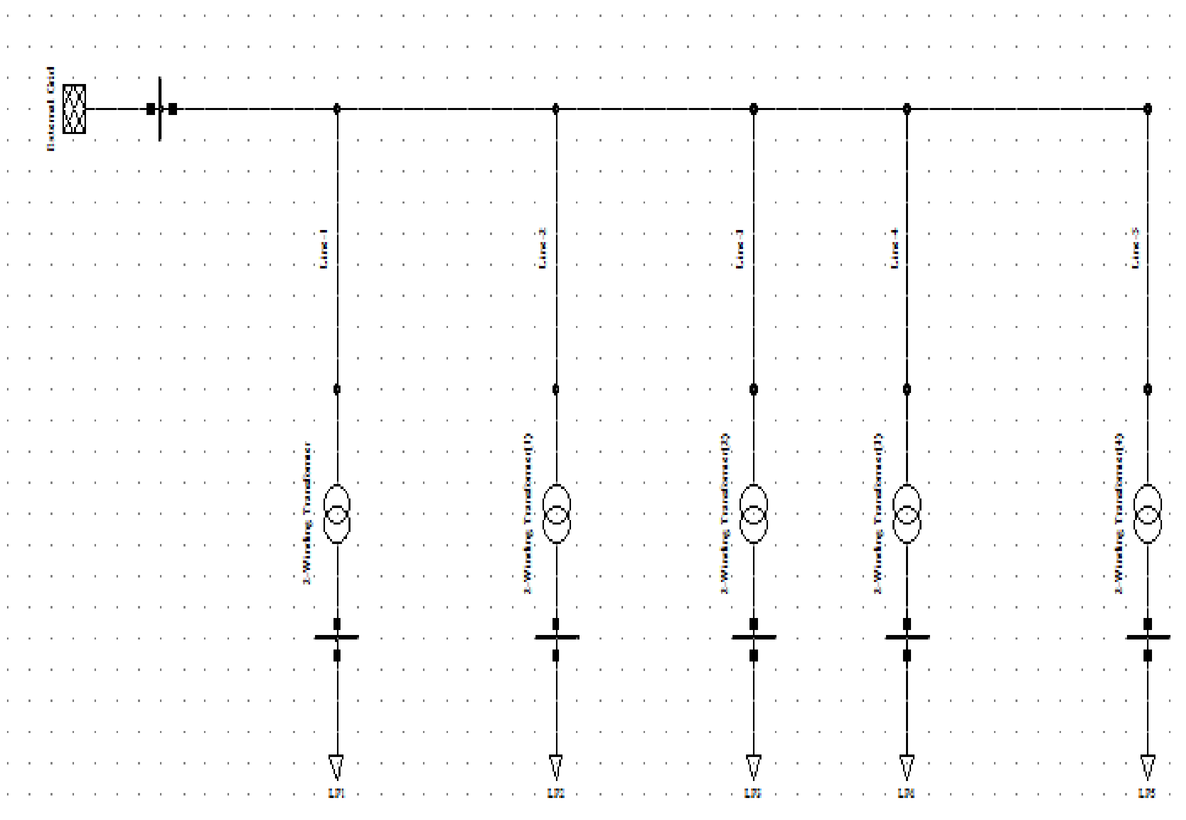


Figure 4.7: Simplified line diagram of Holeta feeder

Table 4.6: Base case Holeta reliability indices without DG.

```
Study Case: Study Case                                                                    | Annex:
------------------------------------------------------------------------------------------------
System Summary
------------------------------------------------------------------------------------------------
System Average Interruption Frequency Index          :  SAIFI  =  291.997026 1/Ca
Customer Average Interruption Frequency Index        :  CAIFI  =  291.997026 1/Ca
System Average Interruption Duration Index           :  SAIDI  =  195.633    h/Ca
Customer Average Interruption Duration Index         :  CAIDI  =    0.670    h
Average Service Availability Index                   :  ASAI   =    0.9776674907
Average Service Unavailability Index                 :  ASUI   =    0.0223325093
------------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------
Study Case: Study Case                                                                    | Annex:
------------------------------------------------------------------------------------------------
System Summary
------------------------------------------------------------------------------------------------
Energy Not Supplied                                  :  ENS    = 1357.690    MWh/a
Average Energy Not Supplied                          :  AENS   =    0.155    MWh/Ca
Average Customer Curtailment Index                   :  ACCI   =    0.001    MWh/Ca
Expected Interruption Cost                           :  EIC    =    0.000    M$/a
Interrupted Energy Assessment Rate                   :  IEAR   =    0.000    $/kWh
System energy shed                                   :  SES    =    0.000    MWh/a
```

Table 4.6: Shows that Base case reliability indices of the feeder and it shows SAIFI, SAIDI and ENS of 291.997, 195.633 and 1357.69 respectively.

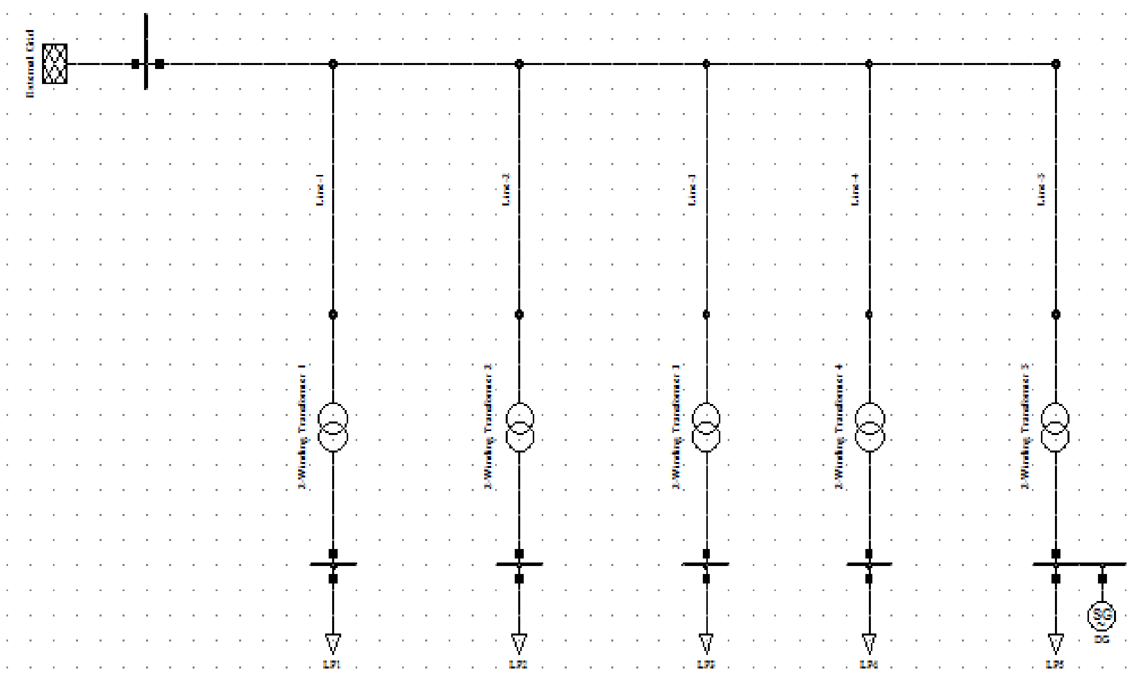


Figure 4.8: Integrating DG at end of load point (9.1037km from supply point)

Table 4.7: Reliability Indices with DG at load point 5 (9.1037km from supply point).

```
Study Case: Study Case                                                                  | Annex:
---------------------------------------------------------------------------------------------------
System Summary
---------------------------------------------------------------------------------------------------
System Average Interruption Frequency Index        :  SAIFI  =   26.319227 1/Ca
Customer Average Interruption Frequency Index      :  CAIFI  =   26.319227 1/Ca
System Average Interruption Duration Index         :  SAIDI  =   17.631    h/Ca
Customer Average Interruption Duration Index       :  CAIDI  =    0.670    h
Average Service Availability Index                 :  ASAI   =    0.9979872988
Average Service Unavailability Index               :  ASUI   =    0.0020127012
---------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------
Study Case: Study Case                                                                  | Annex:
---------------------------------------------------------------------------------------------------
System Summary
---------------------------------------------------------------------------------------------------
Energy Not Supplied                                :  ENS    =  868.617    MWh/a
Average Energy Not Supplied                        :  AENS   =    0.099    MWh/Ca
Average Customer Curtailment Index                 :  ACCI   =    0.000    MWh/Ca
Expected Interruption Cost                         :  EIC    =    0.000    M$/a
Interrupted Energy Assessment Rate                 :  IEAR   =    0.000    $/kWh
System energy shed                                 :  SES    =    0.000    MWh/a
```

When DG of 4 MW is applied at load point five (Lp5), which is 9.1037 km from the supply point, the improvements are SAIFI = 91.16% and SAIDI = 91.16 %. This case study has shown that, the reliability of the distribution system will be improved most, if the DG is applied at end of the supply line.

CHAPTER FIVE

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1 Conclusions

As studied in this thesis, the reliability of the Addis Alem substation does not meet the requirements set by Ethiopian Electric Agency (EEA). The average frequency of interruptions of the substation is 169.6134 interruptions per customer per year, the average duration of interruptions is 157.516 hours per customer per year and the average service availability Indices is 98.19%. There is high unavailability of electric power in the distribution network. There is huge loss of unsupplied energy due to power interruptions. The average energy not supplied is 4145.056MWh per year. Average cost of energy not supplied due to power interruptions is around 4.095 Million Birr per year from EEU.

DGs were connected to the two feeders (Holeta feeder and Flower feeder) which experience more interruptions. As a result of these DGs, the overall system's reliability is improved by 58%. Therefore, DGs should be located on a load point where there is most interruption and most customers are found and where much of the load is supplied.

The load point of Holeta feeder were studied for best placement of DG from supply point. And the best location for the DG is found to be at the end of the feeder where 91.16% improvement is achieved. This is because the faults anywhere on the main line can be isolated and the upstream customers can be supplied by the substation and the downstream by the DG.

5.2 Recommendations

Reliability analysis of distribution system requires number of customers served, total number of customers, number of customers interrupted, loads connected, number of transformers and their rating, and so on. Power system faults, power system devices likes; lines, transformers on each feeder, circuit breakers, bus bar and total number of customers served and interrupted should be correctly documented by EEU.

Nowadays the concept of DG integration into distribution system widely applicable to many other developing countries worldwide to solve the problem associated with the increase in energy demand and increase the reliability of distribution systems. But, We Ethiopian are mostly using hydroelectric power plant to meet our energy demand. Therefore, it is recommend that Ethiopian electric utility may apply the concept of DG integration into distribution system that mostly uses small-scale renewable energy technologies implemented to substation to solve the problem associated with the increase in energy demand and increase the reliability of distribution system.

5.3 Suggestion for Future Work

The costs of integrating distributed generation and the performance of control system are not assessed in this thesis. The detailed impact of DG on control system and its cost analysis benefits of integrating DG into the distribution network may be carried out as further extension of this work.

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APPENDIX A

Table 1: Summary of frequency and duration of interruptions due to types of faults for Addis Alem feeders for 2017 year.

PEF		PSC		TEF		TSC		Black out		SOL		Overload		Operation		F	D(HR)
FR	D(Hr)	FR	D(Hr)	FR	D(Hr)	FR	D(Hr	FR	D(Hr	FR	D(Hr	FR	D(Hr	FR	D(Hr)	TFR	TD(Hr
2017 JANUARY																	
6	5.46	4	3.58	1	0.01	4	0.11	1	2.13	1	1.48	2	20.5	3	1.63	22	34.91
3	7.23	3	1.25	1	0.01	2	0.06	1	0.73	2	1.48	3	20.8	4	6.18	19	37.74
0	0	2	2	0	0	0	0	3	1.03	2	1.48	6	5.81	3	1.13	16	11.45
0	0	2	2.76	0	0	0	0	1	0.41	2	1.48	3	3.88	1	0.5	9	9.03
0	0	0	0	0	0	0	0	0	0	2	1.48	0	0	0	0	2	1.48
2017 FEBRUARY																	
2	0.32	4	20.03	4	0.11	8	0.11	2	2.43	0	0	3	3.01	5	2.09	28	28.1
2	2.14	10	18.09	3	0.05	3	0.03	1	0.04	0	0	0	0	5	2.45	24	22.8
0	0	0	0	0	0	0	0	3	1.4	0	0	0	0	6	3.74	9	5.14
0	0	1	12.03	0	0	2	0.02	1	0.63	0	0	1	0.5	1	0.31	6	13.5
0	0	2	12.14	0	0	0	0	1	0.36	0	0	0	0	1	6.06	4	18.56
2017 MARCH																	
5	12.23	6	3.02	8	0.32	6	12.33	3	0.56	0	0	9	5.24	5	0.4	42	34.1
1	0.73	5	3.35	2	0.01	10	5.8	2	2.1	0	0	8	7.99	4	0.36	32	20.34
0	0	0	0	0	0	8	5.11	3	0.86	0	0	8	7.43	0	0	19	13.4
0	0	0	0	0	0	8	3.7	1	0.23	0	0	3	0.94	0	0	12	4.87
0	0	1	5.8	0	0	3	0.24	0	0	0	0	0	0	0	0	4	6.04
2017 APRILY																	
10	14.32	5	3.42	6	1.24	8	0.26	2	0.34	0	0	20	28.16	9	7.75	60	55.49
0	0	6	4.81	2	0.16	5	0.08	1	3.2	0	0	20	27.19	10	11.38	44	46.81
0	0	0	0	0	0	0	0	4	3.16	0	0	17	9.57	14	10	35	22.73
0	0	0	0	0	0	0	0	3	1.2	0	0	16	10.77	1	0.15	20	12.12
0	0	0	0	0	0	0	0	1	2.1	0	0	0	0	1	0.15	2	2.25
2017 MAY																	
7	11.71	6	2.14	4	0.2	5	0.05	3	1.51	0	0	7	8.35	11	5.35	43	29.31
0	0	5	14.39	1	0.01	7	0.11	1	2.35	0	0	3	0.29	8	3.34	25	20.49
0	0	0	0	0	0	0	0	2	2.19	0	0	3	2.11	4	3.49	9	7.79
0	0	5	5.45	0	0	2	0.03	1	4.15	0	0	2	1.72	1	0.13	11	11.48
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.47	1	0.47
2017 JUNE																	
7	21.4	4	2.1	11	0.2	3	0.04	1	0.23	0	0	12	29.1	9	4.93	47	58.01
0	0	7	7.21	2	0.02	9	0.3	3	0.4	0	0	10	27.15	5	6.64	36	41.72
0	0	0	0	0	0	0	0	4	4.15	0	0	7	5.51	3	5	14	14.66
0	0	3	3.45	0	0	3	0.06	3	2	0	0	5	2.67	1	0.13	15	8.31
0	0	0	0	0	0	0	0	1	2.89	0	0	0	0	1	0.15	2	3.04
2017 JULY																	
4	10.1	6	7.89	0	0	3	0.6	3	2.24	0	0	15	28.51	10	5.35	41	54.65
5	4.87	9	6.78	0	0	5	0.97	2	2.98	0	0	9	24.67	7	12.23	37	52.57
0	0	3	5.14	0	0	0	0	1	1.79	0	0	4	5.15	5	4.17	13	16.25
0	0	0	0	0	0	0	0	0	0	0	0	2	2.39	1	0.13	3	2.52
0	0	0	0	0	0	0	0	2	1.24	0	0	0	0	1	0.13	3	1.37
2017 AUGUST																	
6	2.28	12	18.99	3	0.07	5	0.12	1	0.75	0	0	11	6.49	9	2.62	47	31.12
3	4.77	2	0.85	1	0.02	4	0.09	0	0	0	0	0	0	7	3.14	17	18.87
0	0	0	0	0	0	0	0	3	2.41	0	0	0	0	6	3.63	9	6.04
1	6.07	0	0	0	0	0	0	2	2.55	0	0	0	0	0	0	3	8.62
0	0	1	7.85	0	0	0	0	0	0	0	0	0	0	0	0	1	7.85
2017 SEPTEMBER																	
3	11.7	0	0	4	0.08	2	0.05	3	1.87	0	0	5	1.22	4	0.13	21	15.05
0	0	1	0.75	0	0	2	0.05	4	1.76	0	0	6	8.27	5	2.15	18	12.98
0	0	0	0	0	0	0	0	6	2.35	0	0	3	1.92	3	0.93	12	5.2
0	0	2	0.75	0	0	1	0.03	0	0	0	0	1	0.33	2	0.43	6	1.54
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2017 OCTOBER																	
1	6.31	0	0	1	0.03	1	0.01	0	0	1	3.23	0	0	8	19.01	12	28.59
0	0	0	0	0	0	0	0	1	1.23	3	2.94	0		6	11.52	10	15.69
0	0	0	0	0	0	0	0	3	9.05	1	1	0	0	3	6.24	7	16.29
0	0	0	0	0	0	0	0	3	3.13	2	1.33	0	0	2	1.88	7	6.37
0	0	0	0	0	0	0	0	0	0	0	0			2	13.52	2	13.52
2017 NOVEMBER																	
5	7.47	7	2.36	0	0	1	0.02	1	1.8	0	0	8	14.37	7	3.57	29	29.59
0	0	2	0.48	0	0	0	0	1	2.73	0	0	10	11.25	4	2.33	17	16.79
0	0	0	0	0	0	0	0	1	2.1	0	0	5	4.02	3	3.22	9	9.34
0	0	2	0.55	0	0	0	0	1	3.56	0	0	3	1.36	1	1.27	7	6.7
0	0	1	9.15	0	0	0	0	0	0	0	0	0	0	1	1.09	2	10.24
2017 DECEMBER																	
4	0.98	5	11.06	4	0.1	3	0.08	1	2.37	0	0	15	15.4	6	1.9	38	31.89
2	2.45	13	16.78	1	0.01	6	0.26	0	0	0	0	8	8.96	2	0.31	31	28.77
1	0.63	8	10.23	0	0	0	0	3	1.27	0	0	7	6.31	6	3.8	25	22.24
0	0	1	1.01	0	0	0	0	2	3.19	0	0	2	1.58	3	3.4	16	12.38
3	6.78	0	0	0	0	0	0	2	3.48	0	0	0	0	2	8.31	7	18.57

APPENDIX B

Table 2: Summary of frequency and duration of interruptions due to types of faults for Addis Alem feeders for 2018 year.

PEF		PSC		TEF		TSC		Black out		SOL		Over load		Operatior		F	D(Hr)
FR	D(Hr)	FR	D(Hr)	FR	D(Hr)	FR	D(Hr)	FR	D(Hr)	FR	D(Hr)	FR	D(Hr)	FR	D(Hr)	TFR	TD(Hr)
2018 JANUARY																	
7	10.31	6	11.18	8	0.49	4	0.18	2	2.98	2	2.03	3	9.8	5	2.63	37	39.61
5	10.32	4	2.25	2	0.22	3	0.65	1	1.67	3	2.14	4	4.22	6	17.18	28	38.65
0	0	0	0	0	0	0	0	3	2.19	4	1.48	7	14.27	3	1.18	17	19.12
0	0	1	0.46	0	0	0	0	2	0.58	1	1.95	3	9.93	1	1.43	8	14.35
1	7.26	0	0	0	0	0	0	0	0	2	1.48	0	0	0	0	3	8.84
2018 FEBRUARY																	
4	1.51	5	21.15	6	0.05	6	0.26	3	3.15	0	0	4	4.68	7	7.23	35	38.03
5	5.45	8	12.61	5-ፐር	0.27	6	0.19	2	0.78	0	0	0	0	4	4.2	28	23.46
0	0	0	0	0	0	0	0	3	1.65	0	0	7	8.96	2	4.17	12	14.78
0	0	0	0	0	0	3	0.15	2	0.69	0	0	7	7.61	2	3.2	14	11.65
3	5.23	0	0	0	0	0	0	2	0.43	0	0	0	0	3	3.48	8	9.14
2018 MARCH																	
7	13.02	9	14.23	8	0.17	10	0.61	2	2.13	11	7.24	0	0	6	0.8	53	38.21
1	1.35	3	6.81	15	0.18	8	1.63	3	2.48	7	10.36	0	0	5	8.13	42	30.94
0	0	3	2.13	0	0	0	0	5	2.73	9	8.43	0	0	3	1.48	21	14.77
3	1.83	1	2.48	5	0.46	3	0.03	1	0.51	8	2.62	0	0	2	3.26	23	11.19
0	0	0	0	1	0.03	0	0	0	0	10	5.23	0	0	2	1.38	13	6.64
2018 APRIL																	
8	15.24	6	4.32	13	2.24	8	0.3	3	1.73	0	0	13	28.75	10	7.27	61	59.85
4	5.39	8	25.22	7	0.1	9	0.09	1	3.64	0	0	0	0	11	4.81	40	39.25
0	0	0	0	0	0	0	0	5	4.02	0	0	18	11.57	16	12.75	39	28.34
3	8.19	0	0	2	0.04	1	0.05	6	1.16	0	0	3	4.05	7	2.11	22	15.6
0	0	1	2.71	0	0	0	0	1	1.5	0	0	0	0	0	0	2	4.21
2018 MAY																	
3	12.61	8	3.75	5	0.29	7	0.5	1	1.98	0	0	1	8.48	13	5.85	38	33.46
0	0	6	14.72	3	0.02	4	0.13	2	3.01	0	0	0	0	9	3.42	24	21.03
0	0	0	0	0	0	0	0	2	4.63	0	0	3	1.57	5	1.84	10	8.04
3	7.06	0	0	1	2.01	3	1.03	1	0.05	0	0	1	0.83	3	1.65	12	12.63
1	2.86	0	0	0	0	0	0	0	0	0	0	0	0	1	1.97	2	4.83
2018 June																	
8	3.13	4	18.24	12	0.05	4	0.26	2	0.35	0	0	2	1.31	18	23.42	50	46.76
1	0.28	13	31.01	4	0.11	10	0.3	2	0.37	0	0	5	2.62	5	8.6	38	43.29
0	0	0	0	0	0	0	0	2	5.08	0	0	6	2.95	7	6.82	15	14.85
3	1.75	5	3.66	0	0	2	0.07	3	1.89	0	0	5	2.61	1	1.12	18	11.11
1	1.45	0	0	1	0.05	1	0.01	1	3.04	0	0	0	0	3	2.33	7	6.88
2018 July																	
6	29.95	4	4.36	4	0.017	3	0.87	1	2.45	0	0	12	0.9	12	17.99	42	56.15
3	5.45	8	20.57	5	0.07	7	0.26	2	2.79	0	0	1	0.73	12	9.24	38	39.11
0	0	2	6.47	0	0	0	0	2	1.89	0	0	8	6.04	3	3.2	15	17.66
0	0	0	0	0	0	4	0.22	0	0	0	0	4	1.55	1	0.61	9	2.38
0	0	1	0.85	1	0.01	0	0	1	2.19	0	0	0	0	2	2.47	5	5.52
2018 August																	
5	3.37	13	8.08	3	0.19	6	1.01	3	3.89	0	0	2	0.85	8	15.48	40	32.87
4	2.9	3	5.19	5	0.36	6	0.68	0	0	0	0	3	2.32	2	8.61	23	20.06
0	0	1	3.45	0	0	2	0.21	1	2.55	0	0	5	2.94	3	1.63	12	10.78
1	2.01	2	5.91	1	0.1	1	0.34	2	1.67	0	0	3	1.47	2	1.55	12	13.05
0	0	1	0.43	0	0	1	0.11	0	0	0	0	0	0	2	0.86	4	1.4
2018 September																	
4	2.86	8	6.19	5	0.43	4	0.4	2	1.97	0	0	3	2.31	1	3.97	27	18.13
3	3.28	5	6.54	1	0.04	2	0.13	1	0.63	0	0	2	2.31	5	2.6	19	15.53
0	0	0	0	0	0	0	0	6	3.45	0	0	3	2.01	4	1.28	13	6.74
1	1.01	2	3.71	0	0	1	0.01	0	0	0	0	1	1.96	3	0.67	9	7.36
1	0.36	2	6.59	0	0	1	0.1	1	2.01	0	0	0	0	1	1.84	6	10.9
2018 October																	
2	6.79	4	11.64	1	0.28	3	0.49	1	1.32	0	0	1	5.36	5	3.36	17	29.24
1	7.35	4	4.12	2	0.41	2	0.15	0	0	0	0	1	1.35	6-ፐር	5.38	16	18.76
0	0	0	0	0	0	0	0	3	14.01	0	0	2	0.98	3	4.03	8	19.02
0	0	1	0.27	1	0.11	2	0.01	1	4.58	0	0	2	1.56	2	0.7	9	7.23
0	0	0	0	0	0	2	10.02	0	0	0	0	1	1.81	2	1.38	5	13.21
2018 November																	
3	1.89	8	8.67	3	0.19	8	0.16	2	1.79	0	0	4	13.75	2	3.36	30	30.21
2	2.78	6	7.86	2	0.11	8	0.25	1	2.65	0	0	3	1.03	1	3.75	23	18.43
0	0	0	0	0	0	0	0	3	2.93	0	0	2	1.47	5	4.99	10	9.39
0	0	0	0	0	0	0	0	3	4.09	0	0	0	0	5	2.72	8	6.81
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2018 December																	
5	6.43	8	23.43	6	0.2	10	0.1	2	2.8	0	0	5	5.83	4	2.24	40	39.73
2	3.97	10	14.09	5	0.17	7	0.73	1	1.45	0	0	4	5.93	3	3.73	32	30.07
0	0	0	0	0	0	0	0	2	10.37	0	0	11	11.62	0	0	13	21.99
0	0	0	0	0	0	0	0	1	4.16	0	0	5	3.52	12	7.23	18	15.91
0	0	0	0	0	0	0	0	6	8.15	0	0	0	0	0	0	6	8.15

APPENDIX C

Table 3: Electrical equipment and failure inputs [47, 49]

Equipment Name	Failure rate λ	Mean time to repair (Hr/yr)	Voltage level (kV)
Main Transformer	0.015(fr/yr)	120	45
Distribution transformer	0.015(fr/yr)	200	15
Busbar	0.08(fr/yr)	25	45/15
Line	18(fr/yr*km)	0.8	15
Terminal	0.0046(fr/yr)	0.12	15/0.4
External grid	0.675(fr/yr)	0.12	45

APPENDIX D

Table 4: Basic data of Holeta feeder

Load points	Repair Duration (Hr)	Interruption Frequency (No)	Transformer Capacity (MVA)	Distance from supply point (km)
LP1	0.675	18.15	2.35	1.016
LP2	0.56129	22.03	2.045	1.184
LP3	0.8163	36.652	2.16	2.012
LP4	0.665	65.871	2.575	3.161
LP5	0.5453	74.133	1.76	9.1037