Reliability Assessment and Enhancement of Electric Power Distribution:

(A Case Study of Ashebeka Distribution System)

By

Erko Biru Solena

A Thesis Submitted to the Department of Electrical Power and Control Engineering in School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Electrical Power Engineering

Office of Graduate Studies

Adama Science and Technology University

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Adama, Ethiopia

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Approval Page

We, the undersigned, members of the Board of Examiners of the final open defense by **Erko Biru Solena** have read and evaluated his thesis entitled "***Reliability Assessment and Enhancement of Electric Power Distribution: A Case Study of Ashebeka Distribution System***" and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of science in electrical power engineering.

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DECLARATION

I, the undersigned, declare that this MSc thesis is my own original work, has not been presented for partial fulfillment of a degree in this or any other university, and all sources and materials used for the thesis have been duly acknowledged.

Name: Erko Biru

Signature: _______________

Place: **Adama**, **Ethiopia.**

Date of submission: July 2020 G.C.

This thesis work has been submitted for examination with my approval as thesis Advisor.

Dr. Tafesse Asrat _________________

Advisor's Name Signature

Advisor's approval sheet

To: Electrical Power and Control Engineering Department

Subject: Thesis Submission

This is to certify that the thesis entitled "**Reliability Assessment and Enhancement of Electric Power Distribution: A Case Study of Ashebeka Distribution System**" submitted in partial fulfillment of the requirements for the degree of Master's in Electrical Power Engineering, the Graduate program of the department of Electrical Power and Control Engineering, and has been carried out by **Erko Biru Solena** Id. No. **A/PE16404/10**, under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

Dr. Tafesse Asrat	________________________	____________________
Name of major Advisor	Signature	Date

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First and foremost, I praise Lord the Almighty God, for giving me perfect health, strength and patience to overcome all hardships and temptations to complete the entire work. Without his help, I couldn’t really finalize this work. Glory to God forever Amen!!!

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LISTS OF ABBREVIATIONS

AAC	All Aluminum Conductor
AC	Alternating Current
ANSI	American National Standards Institute
ASAI	Average Service Availability Index
ASUI	Average service unavailability Index
ATWSP	Assela Town Water Supply Project
CAIDI	Customer Average Interruption Duration Index
CB	Circuit Breaker
CIC	Customer Interruption Cost
CKT	Circuit
CSA	Central Statics Agency
CT	Current Transformer
DA	Distribution Automation
DLOL	Distribution Line Overload
DPEF	Distribution Permanent Earth Fault
DPSC	Distribution Permanent Short Circuit
DS	Distribution System
DTEF	Distribution Temporary Earth Fault
DTSC	Distribution Temporary Short Circuit
EEA	Ethiopian Electric Agency
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility

EENS	Expected Energy Not Supplied
ETAP	Electrical Transient Analysis Program.
ETB	Ethiopian Birr
FDISR	Fault Detection Isolation and Service Restoration
FSR	Fast Speed Runner
GUP	Generating Unit Problem
HL	Hierarchical Level
HRC	High Rupturing Capacity
HV	High Voltage
IEEE	International Electrical and Electronics Engineers
KM	Kilo Meter
KV	Kilo Volt
KVA	Kilo Volt Ampere
LV	Low Voltage
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
MVA	Mega Volt Ampere
MW	Mega Watt
OCB	Oil Circuit Breaker
OP	Operational
PF	Power Factor
PLL	Phase Locked Loop
PT	Potential Transformer

PTOL	Power Transformer Overload
PVA	Photovoltaic Array
REC	Recloser
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SF6	Sulfur hexafluoride
SM	Smart Grid
SOL	System Overload
T	Transformer
TLP	Transmission Line Problem
TRAFO	Transformer
USD	United State Dollar

ABSTRACT

Electric power distribution reliability is an essential issue that could help to generate key ideas in solving problems related to interruptions, longer time the interruptions last and unavailability of power in a system to benefit electric utilities and electrical consumers at all levels of usage. Because of different power failure factors in electric power distribution system, power interrupts frequently and outage of it takes longer time to be restored the service to its normal state. In power distribution system, which lacks fault detection, isolation and service restoration technology, even the temporary faults became permanent and increase equipment replacement and maintenance costs causing crisis in economy, safety and life of utilizers and also deducts revenue & quality of service delivery of utilities. In Ashebeka distribution system (the case study area), the frequency of interruptions and duration of power outage are too far below the requirements set by EEA and IEEE guides in reliability performance point of view, as SAIFI is 338.4121 interruptions per customer per year and SAIDI is 328.5535 hours per customer per year for the existing system. Hence, the consequence of these power failure difficulties upset utilities & consumers' daily activities predominantly in continuous production process areas like water treatment plant of drinking water supply, resulting severe interruptions of water in Assela town. Interruptions of water due to these distribution power problems intern causes reduction in revenue on the water supply utility and at the same time decreases the quality of serving the society (customers) due to scarcity of water. These unreliable and extreme power interruptions complications also disturbing power customers of private industrial sectors & mostly troubling economy of electric power utilities. This thesis has conducted assessment & investigations on reliability performance of the proposed distribution system, by identifying the main causes of interruptions and power outage. Different study case scenarios were applied using ETAP 16.0.0 simulation tool to solve the existing problems and as a result of these solution options, the reliability performance of the system has been improved & hence, SAIFI was reduced by 83.63%, SAIDI was reduced by 74.33%, and EENS was also minimized by 76.2% as compared with that of the existing system. The improved system has saved revenue of ***884,173.01*** *ETB per year for Ethiopian electric utility &* ***542,464.14*** *ETB per year for a single customer (Assela town water supply).*

KEYWORDS: Power distribution reliability, Mitigation techniques, Power failure factors, ETAP.

CHAPTER ONE

INTRODUCTION

1.1 Background

The electric power distribution system is the supply system between the substation fed by the transmission system and the consumer's meters. Since the distribution system of a power supply system is the closest one to the consumers, its failures affect customer service more directly than failures on the transmission and generating systems. Furthermore, the amount of capital investment and total operation & maintenance expenses of distribution system stands next to expenditures for generating facilities. Therefore, the economic importance of the distribution system is very high, and the amount of investment involved dictates careful planning, design, construction and operation [1].

Power distribution systems, ideally should provide their consumers with uninterrupted flow of energy in adequate and safe manner. However in practice, power systems, especially the distribution systems, have numerous problems, which significantly affect customers' economy & comfort in every sector at different operational time.

The increased sensitivity of the vast majority of processes (industrial services and even residential) to reliability problems turns to availability of electric power with safe & protected way is a crucial factors for competitiveness in every activity sector. The most critical areas are the continuous process industry and the information technology services. Faults at distribution level may cause interruption and outage in the entire system or a large part of it. These effects can incur a lot of expense from the customer and cause equipment damage, imposing influential factor on demand of electric consumers. So, in order to provide uninterrupted power to the service sectors as well as others for economic growth and prevent equipment damage with frequent interruptions, undoubtedly power reliability improvement is utmost important.

This thesis work concentrates on power distribution system reliability assessment and investigations specified to case study area, that is Ashebeka distribution system, which is one of the outgoing feeder-05 in Assela town power distribution substation.

Assela town is found in Oromia Regional State, situated in Arsi Zone, being the zonal capital, at a road distance of 175km from South East of Addis Ababa which is the capital city of Ethiopia. It is accessed through asphalt road running from Addis Ababa via Adama to Bale Robe. It is 75km far from Adama city.

The Town is bounded by Geographical coordinates between UTM/Adinan 510881E to 518022E longitude and 874337N to 885532N latitude [Long term feasibility study of ATWSP].

The distribution network topology for Assela town substation is a radial grid. The primary distribution system takes 132KV from the transmission line and converts it to 15KV and 33KV by using two power transformers of capacity 25MVA of each as shown in figure 1.1. Where the final arrows indicate the power flow from feeders to load points.

Assela town Electric power substation provides totally nine (9) radial distribution lines (MV feeders) of four 33KV, and another five 15KV distribution lines, among which Ashebeka distribution system is 15KV line runs from this substation and feeds the loads of different type in Assela, Chebi, Sagure, and Digelu towns in addition to rural areas around & nearer to its distribution path beside drinking water supply projects, for example; Assela town water supply project and Sagure town water pumping station currently. As the name indicates Ashebeka feeder-05 formerly installed & commissioned for Assela town water project known as Ashebeka water supply project. Different types of loads are added as consumers based on the increased demand of electric supply from time to time in locality of the proposed line.

The current status of this feeder indicates that, the residential, commercial & industrial loads those all on the line (its distribution system) are facing challenging situations due to sustained power interruptions and longer outage durations due to frequent short circuit and earth faults.

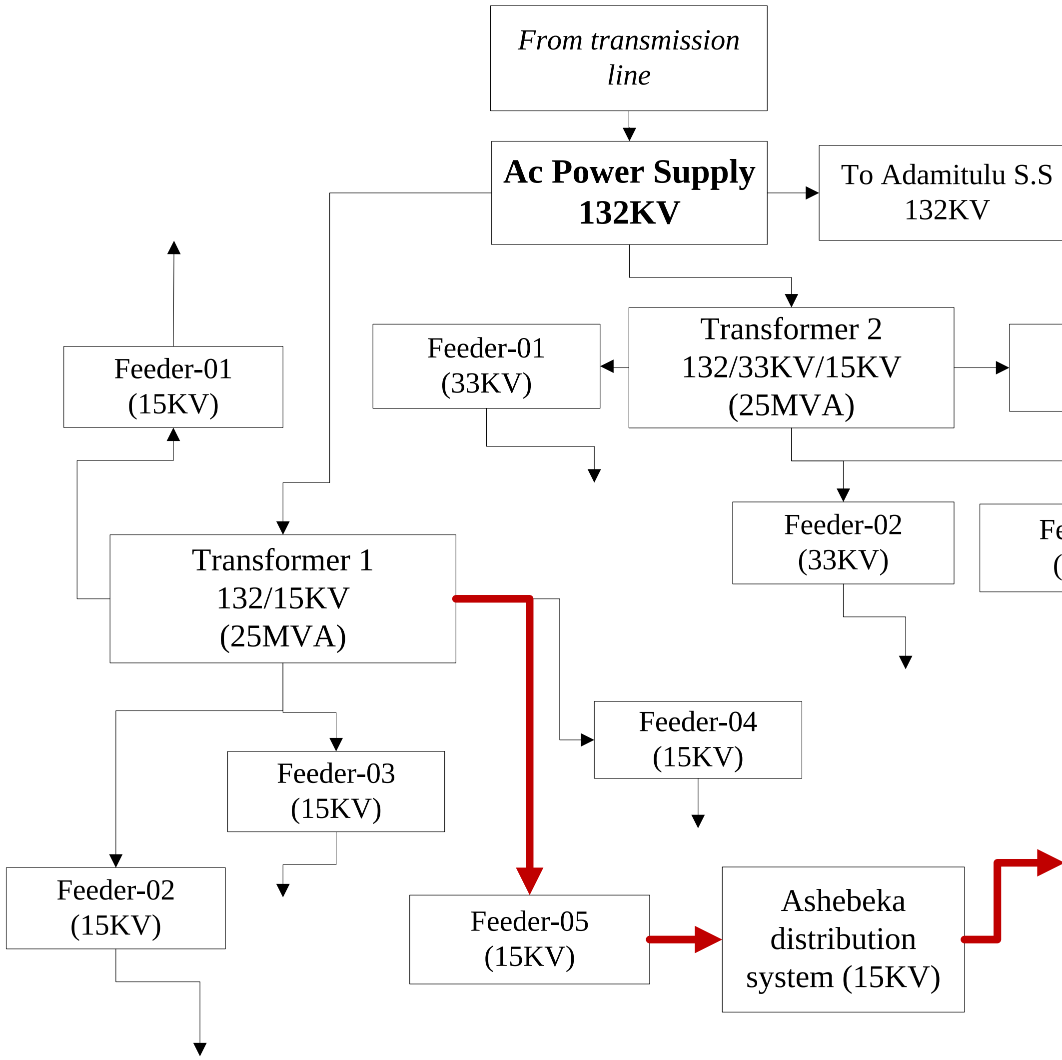

FIGURE 1.1: BLOCK DIAGRAM FOR ASSELA TOWN SUBSTATION

There are several aspects of power reliability problems due to which the other loads on Ashebeka distribution system and water pumping units in water utilities like, Assela & Sagure towns water supply utilities malfunction, fail prematurely or not operate at all. Some of the most common power supply reliability problems associated with the supply distribution line and their likely effect on different loads of the water pumping units on the stations are: voltage fluctuations, under voltage, long time power outages & recurrent interruptions, faults due to trees, wind, & animals, wooden pole aging and bare conductor problems.

The existence of these extreme power distribution system reliability problems make consumers' activities difficult and reduce quality of services especially in drinking water of the towns.

Interruptions in water due to interruptions of electrical power make life of towns' society more serious of these fundamental facilities. Service sectors like Assela hospital & the others health organizations, public and private universities and colleges, hotels and different commercial sectors are unable to perform their task due to lack of water.

The problem became more serious in water case for Assela town, because the town gets drinking water supply from only one directional source that is, Ashebeka River in Arsi Zone, Digelu and Tijo Wereda, which is about 35KM from raw water treatment plant which is found in Assela town particularly in Helila kebele, 'Dosha'. The water source scheme consists of two stations on one route, the gravitational and pump both dam are 'weir' intakes structure in the same river 6.1KM apart from each other & provide raw water together and in a separate way based on seasonal weather conditions. During rainy seasons, the gravity main is enough to supply raw water up to the treatment plant capacity so that there is less need of pump source at this time, since under or less water production capacity of the synoptic water treatment plant. But, at dry seasons specially starting from months of *October* to *May* the gravity main extremely minimizes to water amount of less than $100m^3$ per hour, because of seasonal factors. Hence, during this period of time the pump station takes over to boost and supply the raw water to the town water treatment plant [2]. So that, at this time the distribution system power unreliability & instability problems stated above create great disturbance to sustainability of water supply to the town.

The same is true for another water supply utility, which is Sagure town drinking water service "the water pumping station", it is spring water capped inside a hilly area known as Guggesa. In this area, there are submersible water pumps installed to drive drinking water from this source to Sagure town to fulfil water facility of the town. This water supply activity is not seasonal dependent, but always has to be continuous. Due to geographical nature of the water source location, it doesn't support gravity to drive water. Therefore, every time the system is electric power dependent. Hence, this water source is extremely victim of electric power unreliability problem in Ashebeka distribution system.

Figure 1.2 below indicated to show drinking water interruption problems in Assela town water supply system.

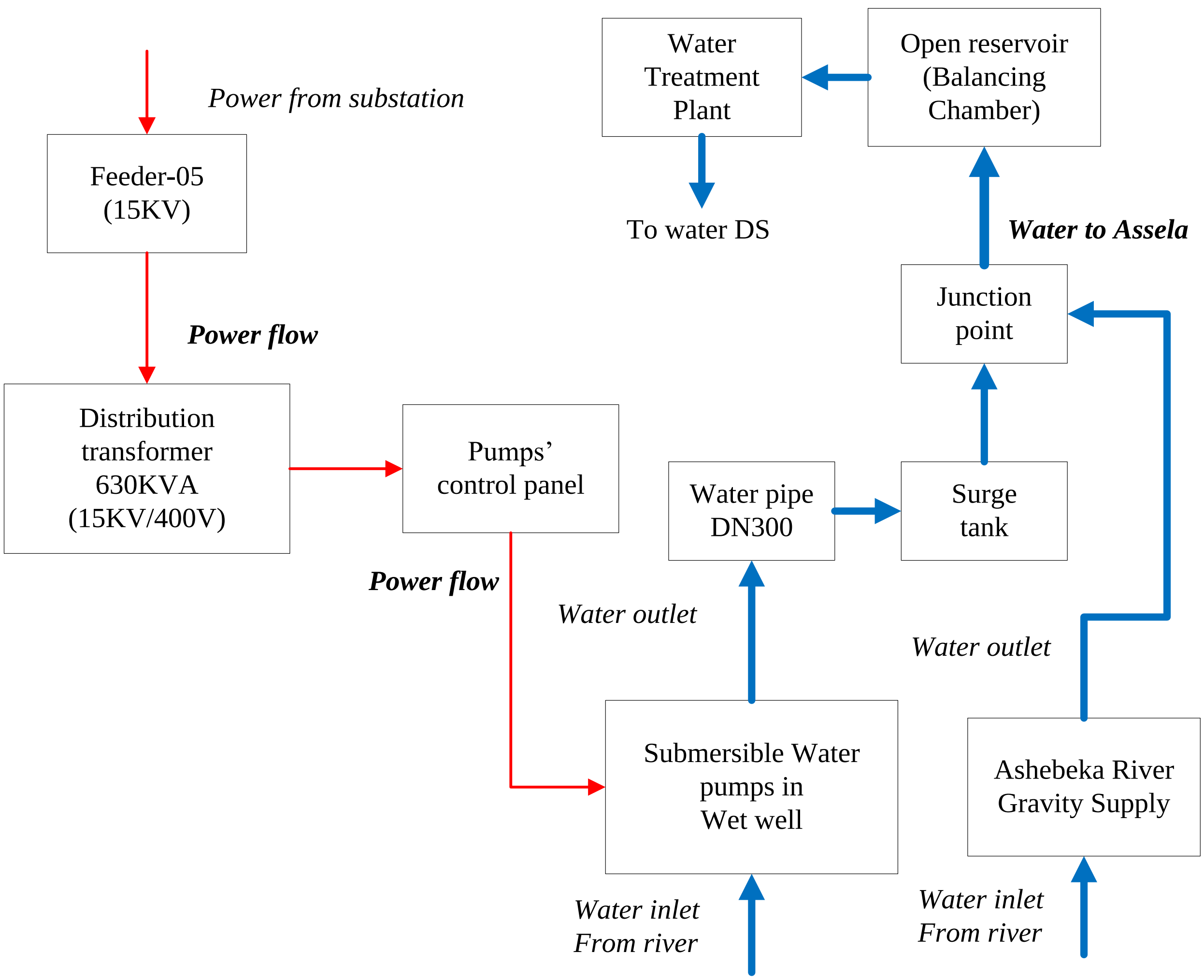

FIGURE 1.2: BLOCK DIAGRAM FOR ASHEBEKA WATER SUPPLY SYSTEM

1.2 Statement of the Problem

The fundamental concern of power supply system is to provide an abundant and safe electrical power supply to all consumers getting services from it in safe & economical way.

The power interruptions and instability become serious problems in the case study area of this thesis work. Currently the frequent interruptions of power and outage impacts are disturbing economy, safety and life of the society obtaining the power from Ashebeka distribution system.

These reliability problems of electric power supply from Ashebeka feeder or (15KV) distribution line in Assela town water supply utility especially for raw water pumping station cause:-

- ✓ Interruptions of water to water treatment plant and then to the town community, resulting in drinking water service delivering problem, even to most critical sectors in the town such as, Assela Hospital & the others health organizations, universities and colleges, hotels, restaurants etc..

Commonly, about more than 67,269 society of Assela town are facing extreme problems in shortage of water. The same is true for interruptions in Sagure town drinking water supply or pumping station resulting:-

- ✓ Reduction to the income that could be generated by water supply and electric utilities.
- ✓ Increases the equipment replacement and maintenance costs due to frequent failures for both utilities (Water supply & Electric).
- ✓ Increases the fuel cost of diesel generators in water pumping stations & water treatment plant.
- ✓ Owners of different factories such as Arsi Ketar food complex, Assela Concrete pole factory, Rong Chang manufacturing PLC, China wood processing factory, etc. are also complaining due to interruptions of power supply which has negative impacts on their production process and economic benefits.

In general, customers in the line are unable to perform their daily activities because of frequent interruptions and longer outage of power.

Therefore; these social, political, and economical problems has to be mitigated to satisfy social & utilities' benefits as well as customers' demand by investigating the causes of problems in the proposed electric distribution system.

This thesis conducts assessment on power distribution reliability performance, by examining & identifying the main causes of interruptions and power outage to come up with suitable solutions for the problems to achieve significant improvement at reasonable percentage on reliability of Ashebeka distribution system.

1.3 The Objective of this thesis

1.3.1 General Objective

The main objective of this thesis work is to investigate reliability problems and improve performance & reliability for existing Ashebeka electric power distribution system, by examining and identifying the possible problems that affect the performance of the network.

1.3.2 Specific Objectives

The specific objectives of this research are as follow:-

- To carry out reliability evaluation of current state of Ashebeka distribution system.
- To improve reliability and performance of the distribution system by more than sixty percent in average with implementation of reclosers & PV power supply.
- To simulate the results of reliability improvements for the distribution system using available software that outfit to the case of the problem.
- To draw relevant conclusions and recommendations based on the results obtained.

1.4 Methodology

The following methodology was accomplished for achieving the objectives in this thesis:

- **Literature reviews**

In this thesis, the literatures from a number of journals articles, reports, conference papers and books on power distribution system reliability assessment and study has been reviewed.

The literatures comprise reviews of:-

1. From the past and recent published and unpublished documents regarding theoretical back ground of power system, reliability analysis, role of protection system, and DG benefits in distribution system and
2. Reliability assessment & improvement related works on electric power distribution system.

- **Data collection**

The primary data like:

- The feeder length indicated in table 3.4 was collected from the existing sites through measurement.
- The physical distribution power network information, and component problems (insulators plugging out from poles, conductor & pole aging, problems of manual sectioning switches etc.) along the route of Ashebeka line were acquired through observation by site visit.
- The data and information associated with main causes of interruptions, fault managing strategy, and reason of prolonged outage are obtained by performing interviews,

discussions, and questionnaires with substation, and with the two stated utilities' managers, employees and technical workers.

The secondary data indicated below were collected from Assela & Sagure towns' electric utility offices and Assela substation.

- The substation topology, number, capacity, and type of power transformers, types of circuit breakers, numbers, types, & voltage level of feeders, types of faults were obtained from Assela substation.
- The type and size of conductors, the number, type, and capacity of distribution transformers, and manual sectionalizing switches etc. has been collected by the researcher from utilities and substation.
- The fault rates, frequency of interruptions and duration of interruption frequencies for the base years 2006 to 2010 E.C or (2013/14 to 2017/18G.C), & substation feeders' data has been taken from Assela substation.
- Capacities of distribution transformers & their corresponding number of customers were collected from Assela and Sagure electric utility offices.

❖ **Data Analysis, Distribution system Modelling and Simulation**

After the data have been collected, the numerical analysis was performed to interpret it into meaning full form that could represent the physical existing system under assessment. The distribution system was modelled and then represented by single line diagram using ETAP 16.0.0 reliability analysis tool. The failure rate and mean time to repair were calculated for the line using base year data of frequency of interruptions & duration of interruption frequencies. Reliability indices of the present system was calculated, evaluated, and compared with the standards.

The solution options were selected to mitigate the reliability problems in the existing system of the proposed feeder. PV array was selected as one alternative to solve the power interruption problems for Ashebeka water pumping station based on investigation result of load sensitivity and criticality in terms of demanded drinking water facility in Assela town and it was designed per the load requirement.

Six different study case scenarios were applied by simulations for reliability improvement; the improvements obtained in the consecutive simulation results were compared with that of the existing, and the best improved system was selected & finally accepted as a future modified distribution system of Ashebeka.

1.5 Organization of the thesis

The thesis is organized into five chapters which are briefly summarized below.

Chapter one presents the general introduction and background of the proposed distribution system, statement of the problem, objectives of the thesis and methodology followed in the thesis work. In addition, it provides the outline of the thesis.

The second chapter discusses about the literature reviews of the study topic, theoretical background, mainly on reliability analysis of electric power distribution system, protection system and literature reviews of related works.

Chapter three deals with performance evaluation and analysis of existing distribution system.

In this chapter; introduction, site description, data collection, causes of power interruptions, data analysis and system modeling are presented in detail.

Chapter four deals with simulation of power distribution reliability with ETAP 16.0.0 software, it includes introduction, simulation of six different study case scenarios and their corresponding result discussions, cost analysis and recommendations based on its results.

Conclusions, recommendations, and suggestions on future work are included under chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical Background

2.1.1 Power System Overview

The general outline of the power system shows, the electricity delivered to residential and industrial or commercial customers is generated in large power plants. The electricity is then transmitted from the power plants via high voltage transmission lines, which are interconnected in a network configuration to distribution substations. From these substations, the power is then distributed via low voltage distribution feeders to different load points (customers) through transformers located at close proximity to the load points. The distribution feeders are made up of overhead and underground cables. The voltage is stepped up or down by transformers appropriately along the transmission and distribution networks [3].

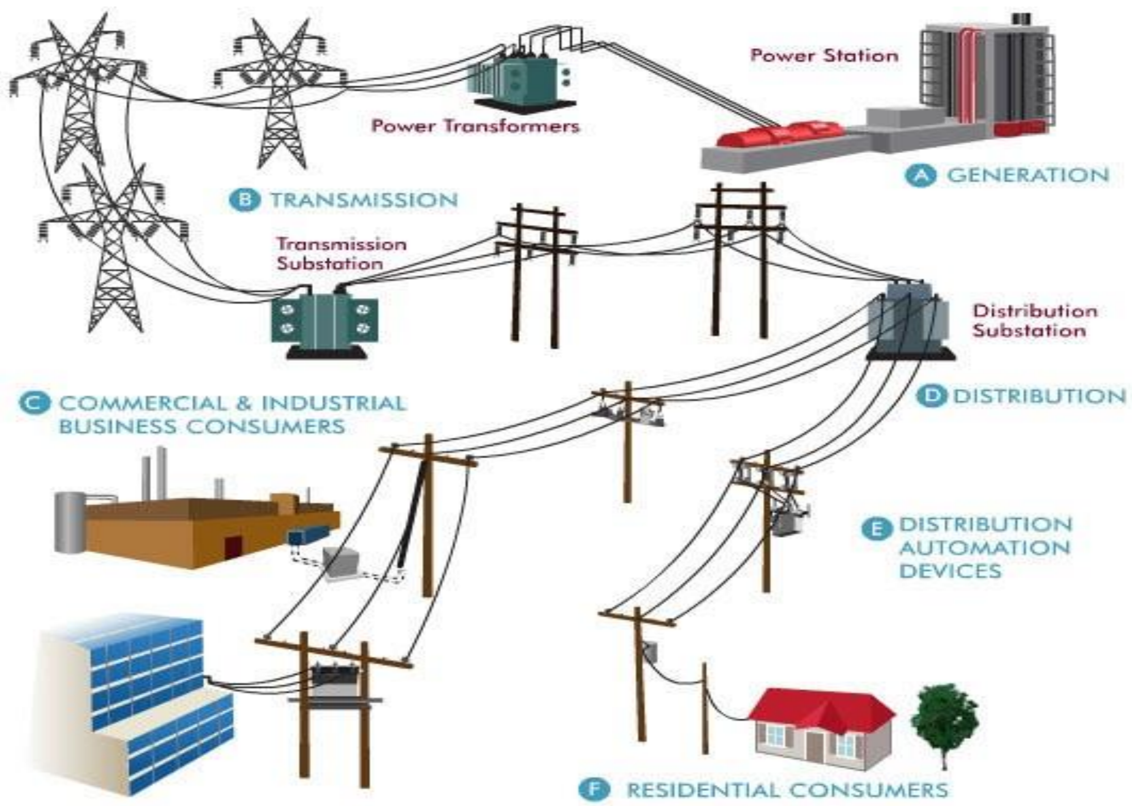

FIGURE 2.1: ELECTRIC POWER SYSTEM [4]

2.1.2 Power Generation

The generator is a machine that converts mechanical energy into electric power. The main prime movers such as engines and turbines convert thermal or hydraulic energy into mechanical power. Thermal energy is derived from the fission of nuclear fuel or the burning of common fuels such as oil, gas, or coal. The alternating current generating units of electric power utilities generally consist of steam turbine generators, gas combustion turbine generators, hydro (water) generators, and internal-combustion engine generators.

2.1.3 Alternating Current Power Transmission System

The transmission system transfers power between the power generation station and the distribution station from which power is carried to the customer delivery point. It includes step up and step down transformers at the generating and distribution stations respectively. Power transmission systems may include sub-transmission stages to supply intermediate voltage levels. Sub-transmission stages are used to enable a more practical or economic transition between transmission and distribution systems [3].

2.1.4 Transmission Lines

Transmission lines supply distribution substations equipped with transformers which step the high voltages down to medium levels e.g. 132KV to 45KV, 33KV or15KV. The transmission of large quantities of power over long distances is more economical at higher voltages. Power transmission at high voltage can be accomplished with lower currents which lower the I^2R power losses and reduce the voltage drop. The consequent use of smaller conductors requires a lower investment. Standard power transmission systems are 3-phase, 3-conductor, overhead lines with or without a ground conductor. Transmission lines are classed as unregulated because the voltage at the generating station is controlled only to keep the lines operating within normal voltage limits and to facilitate power flow [15].

2.1.5 Primary Distribution Systems

The distribution system is commonly broken down into three components: distribution substation, primary and secondary distribution. The transmission system voltage is stepped down to lower levels by distribution substation transformers. The primary distribution system is that portion of the power network between the distribution substation and the utilization transformers. The primary distribution system consists of circuits, referred to as primary or distribution feeders that originate at the secondary bus of the distribution substation. The distribution substation is usually the delivery point of electric power in large industrial or commercial applications. A typical Ethiopian primary distribution system voltage range can be anywhere from 132 kV down to 45KV, 33 KV or 15KV.

2.1.6 Distribution Substations

Distribution substations supply MV power to the distribution system. Have step-down power transformers, a few incoming high voltage sub-transmission lines and several outgoing medium voltage overhead lines or underground cables. Step down power transformers in the substation step down sub-transmission voltage levels to primary distribution levels. First, the distribution substations step down the voltage from 132 kV to 15 kV [8].

2.1.7 Distribution Feeders

The most common equipment found on primary distribution feeders are fuses, distribution transformers, reclosers, load break switches, tri-switches and voltage regulators. Most common distribution feeder configurations include feeder splitting, loop, radial and parallel. These configurations may be implemented closer to the substation side or downstream depending on what constraints are present when designing the feeder to meet customers' needs and embedding the required level of reliability [15].

Tie Feeder

The main function of a tie feeder is to connect two sources. It may join two substation buses in parallel to provide service continuity for the load supplied from each bus.

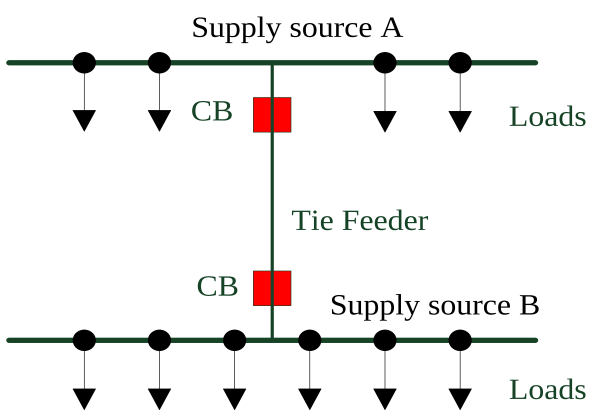

FIGURE 2.2: TIE FEEDER

Loop Feeder

A loop feeder has its ends connected to a source (usually a single source), but its main function is to supply two or more load points in between. Each load point can be supplied from either direction; so it is possible to remove any section of the loop from service without causing an outage at other load points. The loop can be operated normally closed or normally open. Most loop systems are, however, operated normally open at some point by means of a switch. The operation is very similar to that of two radial feeders [15].

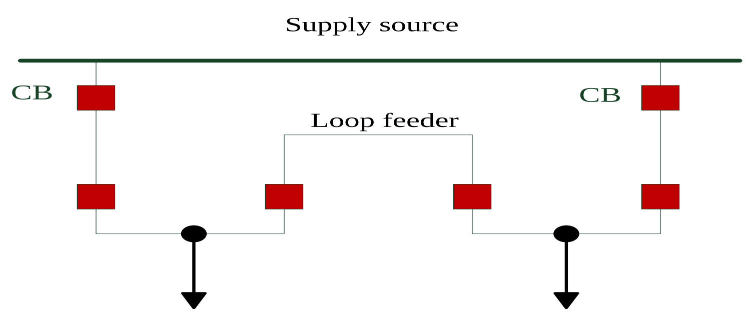

FIGURE 2.3: LOOP FEEDER [3]

Radial Feeder

Radial configuration of distribution system is the simplest and typically used arrangement for the electric utility company. This type of system requires the lowest capital cost and it also has the lowest reliability, since any faults in the feeders will cause service interruptions at all points downstream [8].

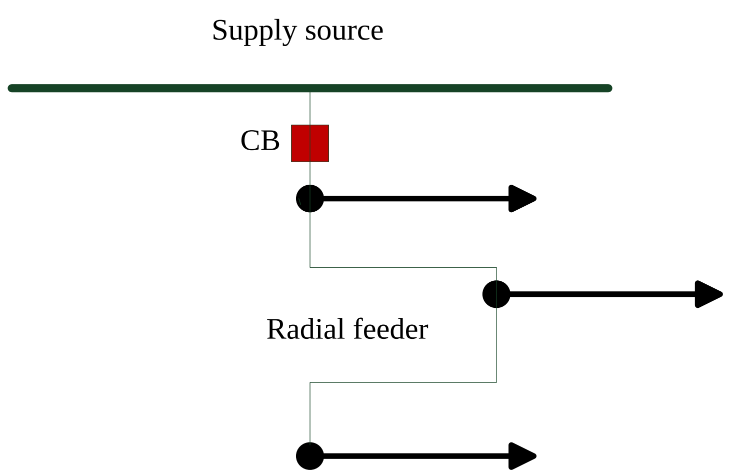

FIGURE 2.4: RADIAL FEEDER [3]

Parallel Feeder

Parallel feeders join the source and a load which 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 quick restoration of service when one of the feeders fails [15].

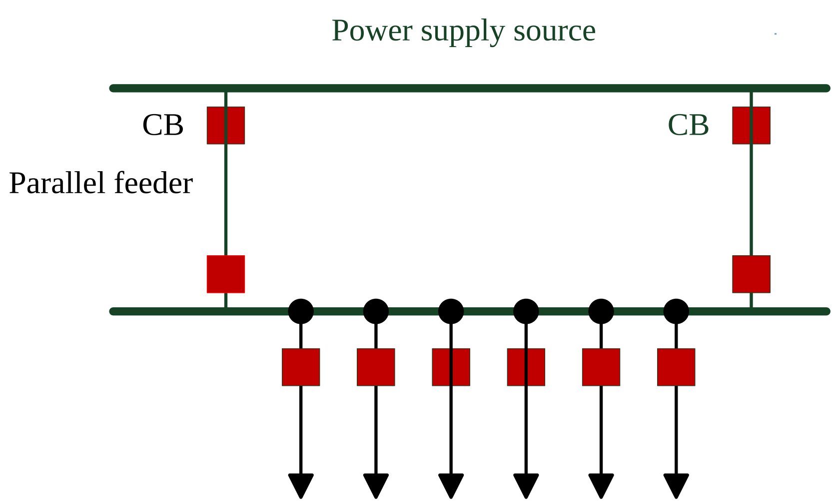

FIGURE 2.5: PARALLEL FEEDER [3]

Secondary Distribution Systems

The secondary distribution system is that section of the network between the primary feeders and utilization equipment. The secondary system consists of step-down transformers and secondary circuits at utilization voltage levels. Residential secondary systems are mainly single-phase, but commercial and industrial systems generally use three-phase power. The voltage levels for a particular secondary system are determined by the loads to be served. The utilization voltages are generally in the range of 230V to 400V.

2.2 Reliability Analysis of an Electric Power Distribution System

Reliability evaluation of a distribution system is concerned with the continuity of supply of energy from the supply points to the individual customer load points. The basic parameters used to evaluate the reliability of a distribution system can be categorized as load point indices and system indices. The load point failure rate, the average outage time and the average annual outage time are the basic load point indices. The system indices can be obtained from these three load point indices and information on the number of customers and load connected at each load point in the system. The set of system reliability indices can be further classified into customer-oriented indices and load-oriented indices. Customer-oriented indices include the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Index of Reliability (IOR), Customers Experiencing Multiple Interruptions (CEMI), and Customers Experiencing Longest Interruption Duration (CELID). Load-oriented indices include Average System Interruption Frequency Index (ASIFI) and Average System Interruption Duration Index (ASIDI) [17].

Most of the power interruptions of Ashebeka distribution system are due to the result of faults in the primary distribution system. A highly reliable generation and transmission system may still result in poor energy supply to the customers if the distribution system is unreliable. Therefore, distribution system reliability evaluation is important to ensure appropriate system reliability levels and to provide effective information for regulatory bodies to set proper benchmarks.

Analysis of past performance and prediction of future performance are two crucial factors of distribution system reliability evaluation.

Most distribution systems are radial in nature because of their low cost and simple design. Most low voltage distribution systems are operated radially. A radial system consists of a series of components between the substation and the load points. Failure of any of these components may result in outage at the load point(s). The duration of the outage depends on the protection and sectionalizing schemes used in the distribution system. The research work presented in this thesis is focused on analyzing a radial distribution system.

2.2.1 Reliability Evaluation

The techniques used in distribution system reliability evaluation can be divided into two basic categories - analytical and simulation methods. The difference between these methods is in the way the methodology uses the input data in which the reliability indices are evaluated. Analytical techniques represent the system by simplified mathematical models derived from mathematical equations and evaluate the reliability indices using direct mathematical solutions. Simulation techniques, estimate the reliability indices by simulating the actual process and stochastic behavior of the system. Therefore, the method treats the problem as a series of real experiments conducted in simulated time. It estimates probability of the events and other indices by counting the number of times an event occurs. Earlier day's reliability assessment was based on deterministic criteria for system failures like thumb rules like fixed values based on their experience in system operation. Nowadays, probabilistic methods are used to analyze the more complex distribution system. Reliability assessment of distribution system is usually concerned with the system performance at the customer end, i.e. at the load points [23].

The two main approaches applied to reliability evaluation of distribution systems are [16]:

- Simulation methods based on drawings from statistical distributions (Monte Carlo)
- Analytical methods based on solution of mathematical models.

The Monte Carlo techniques are normally very "time" consuming due to large number of drawings necessary in order to obtain accurate results. The fault contribution from each component is given by a statistical distribution of failure rates and outage times [16].

2.2.2 Reliability Indices

The reliability of a distribution system can be described using two sets of reliability parameters.

These are the load point reliability indices and the system reliability indices.

2.2.2.1 Load Point Indices

A distribution system provides power supply from a substation to individual customer load points. Three basic reliability indices can be used to describe the degree of service continuity. These are the load point average failure rate (λ), average outage time (r) and the average annual unavailability or average annual outage time (U). The average failure frequency is approximately equal to the average failure rate and indicates the number of failures a load point will experience during a given period of time. The average outage time is the average duration of failure at the load point. The average annual outage time is the average total duration of outage in a year experienced at the load point. It is the product of the average frequency of failure and the average outage time. These reliability indices are expected values and represent the long-run average values [17].

Failure Rates, λ

Failure rate (**λ**) refers to the number of failure that the component or the system has occurred during the studied period. Distribution feeders are radial systems consisting of a set of series components. A feeder includes lines, cables, interruption devices, fuses, reclosers, etc. Each component of the series system has its failure rate λ, which is defined as [17]:-

$$\lambda = \frac{Number\ of\ failures\ per\ unit\ time}{Number\ of\ components\ exposed\ to\ failure} \quad \text{---} \ (2.1)$$

For distribution feeders, this failure rate λ is directly related to the constructive aspects and the physical environment where the component is placed. This means that for improving the failure rate (λ) it is necessary to use more reliable components (lower λ) or modify the physical environment where the feeder is found, which is the equivalent to changing the line.

There is a design (acceptable) number of faults that one can expect on a network. It depends on the following [18]:

- The count of components (line length, structure count, transformer count etc.)
- Acceptable failure rate per component for that specific network
- Environment (condition)
- Equipment specification, quality (manufacture) and application
- Quality of construction
- Quality of maintenance

Mean Time To Repair (r)

Another important index of distribution system reliability is the Mean Time To Repair (r) of a component. This index is directly related to the duration of supply interruptions and, therefore, to how the distribution firm is to face failures in the network. This means that, in order to decrease the duration of an interruption, it is necessary to be better prepared for restoring such interruptions [27].

Mean Time To Repair (r) is the average time taken to repair the component.

$$r = \frac{Total\ time\ to\ recover}{Number\ of\ failures} \quad \text{---} \ (2.2)$$

Availability

The final and also important index of distribution system reliability is availability. Availability is the probability of something being energized. It is the most basic aspect of reliability and is typically measured in percent or per-unit. The complement of availability is unavailability [19]. Unavailability is the probability of not being energized.

2.2.2.2 System Reliability Indices

Systems reliability indices indicate the annual average performance of the network in terms of interruption frequency and duration. They are weighted by the number of customers or energy supplied. Quantitative reliability evaluation of a distribution system can be divided into two basic segments; measuring of the past performance and predicting the future performance [20].

Some of the basic indices that have been used to assess the past performance are:

1. System Average Interruption Frequency Index (SAIFI)

SAIFI indicates how often an average customer is subjected to sustained interruption over a predefine time interval. This index is average number of interruptions per customer served per year. It is determined by dividing the accumulated number of customer interruptions in a year by the number of customers served. A customer interruption is considered to be one interruption to one customer [15], [29].

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customer\ served} = \frac{\sum \lambda i Ni}{\sum Nt} \text{ ------------------------------------ } (2.3)$$

Where:

N_i = Total number of customers interrupted

N_t = Total number of customers served

λ_i = No of interruptions

2. System Average Interruption Duration Index (SAIDI)

SAIDI indicates the total duration of interruption an average customer is subjected for a predefined time interval. This index is the average interruption duration for customers served during a year. It is determined by dividing the sum of all customer interruption duration during a year by the number of customers served during the year [3].

$$SAIDI = \frac{Sum\ of\ customers\ interruption\ duration}{Total\ number\ of\ customers\ served} = \frac{\sum riNi}{\sum Nt} \quad ----------\quad (2.4)$$

Where: ri = Restoration time, minutes or hours

3. Customer Average Interruption Duration Index (CAIDI)

CAIDI indicates the average time required to restore the service. This index is the average interruption duration for customers interrupted during a year. It is determined by dividing the sum of all customer sustained interruption duration by the number of sustained customer interruptions over a one year period [14], [29].

$$CAIDI = \frac{Sum\ of\ customer\ interruptions\ duration}{Total\ number\ of\ customer\ interruptions} = \frac{SAIDI}{SAIFI} \quad ------------- \quad (2.5)$$

4. The Average Service Availability (Unavailability) Index (ASAI) or (ASUI)

ASAI specifies the fraction of time that a customer has received the power during the predefine interval of time and is vice versa for ASUI. This is the ratio of the total number of customer hours that service was available during a given time period to the total customer hours demanded. This is sometimes known as the "Service Reliability Index". ASAI is usually calculated on either a monthly basis (730 hours) or a yearly basis (8,760 hours), but can be calculated for any time period [14]. The ASAI is found as:

$$ASAI = \frac{Customers\ hours\ available\ service}{Customers'hours\ demanded} * 100\% \quad --------------- \quad (2.6)$$

The complementary value to this index i.e. the Average Service Unavailability Index may also be used. This is the ratio of the total number of customer hours that service was unavailable during a year to the total customer hours demanded.

$$ASUI = (100 - ASAI) * \% \quad ------------------------- \quad (2.7)$$

5. Momentary Average Interruption Frequency Index (MAIFI)

$$MAIFI = \frac{\text{Total number of customer momentary interruption}}{\text{Total number of customer served}} = \frac{\sum \mu Ni}{\sum Ni} \quad ------- \quad (2.8)$$

6. Energy not supplied (ENS)

ENS specifies the average energy the customer has not received in the predefined time.

Past performance statistics provide valuable reliability profile of the existing system. However, distribution planning involves the analysis of future systems and evaluation of system reliability when there are changes in configuration, operation conditions or in protection schemes. This estimates the future performance of the system based on system topology and failure data of the components. Due to stochastic nature of failure occurrence and outage duration, it is generally based on probabilistic models. The basic indices associated with system load points are: failure rate, average outage duration and annual unavailability [20].

2.2.3 Reliability Cost/Worth

Reliability is an inherent characteristics and a specific measure that describes the ability of any system to perform its intended function. The primary technical function of a power system is to supply electrical energy to its end customers. This has always been an important system issue and power system personnel have always strive to ensure that customers receive adequate and secure supplies within reasonable economic constraints [19]. The system adequacy basically means the availability of enough generation, transmission and distribution capacities to meet the customer demand. While on the other hand security is considered to relate to the ability of the system to respond to disturbances arising within the system. Therefore, adequacy assessment represents the static conditions, whereas security assessment pertains to the dynamic conditions of the power system [20].

Utilities, in a venture to supply power at an economic price with an adequate level of reliability, often faces challenges to balance the high level of reliability at relatively low cost, since these two aspects counters each other. Direct evaluation of reliability worth is a difficult task, therefore, a practical alternative, which is being widely used is to evaluate the impacts and monetary losses incurred by customers due to power failures. When an interruption is experienced by a customer, there is an amount of money that the customer is willing to pay to avoid the interruptions and this amount is referred to as the ‘customer cost of reliability’. These costs include both tangible and intangible cost and also the opportunity cost. As such, to maximize the reliability, utility should balance their reinforcement cost for reliability improvement and the customer cost for poor reliability. Therefore, the optimal level of reliability is said to be achieved when the sum of utility cost and the customer cost is at minimum [21].

2.3 Power distribution system protection

Protection of the power system is an important part of electrical power engineering. Electric power protection system is concerned with protection of the power generation, transmission, and distribution system for the purpose of system safety, reduction of power outage time and frequency of interruptions, decreasing customers complain due to frequent power failures & soon.

The purpose of protective relaying is to ensure stability of the system and to prevent harmful operating conditions. If a relay or fuse detects an abnormal system condition, it is important that a corrective action is taken as fast as possible. However, it is preferable that it causes a minimum of black out area. At lower system levels, where the cost and consequences of a disconnected line is lower, it is usually cheaper protective devices [26].

The main objectives of distribution system protection are:

To minimize the duration of a fault and to minimize the number of consumers affected by the fault.

The secondary objectives of distribution system protection are [1]:

- To eliminate safety hazards as fast as possible
- To limit service outages to the smallest possible segment of the system
- To protect the consumers' apparatus
- To protect the system from unnecessary service interruptions and disturbances, and
- To disconnect faulted lines, transformers, or other apparatus.

The overhead distribution systems are subject to two types of electric faults, namely, transient (or temporary) faults and permanent faults. Depending on the nature of the system involved, approximately 75%–90% of the total number of faults are temporary in nature [26].

Usually, transient faults occur when phase conductors electrically contact other phase conductors or ground momentarily due to trees, birds or other animals, high winds, lightning, flashovers, etc.

Transient faults are cleared by a service interruption of sufficient length of time to extinguish the power arc. Here, the fault duration is minimized, and unnecessary fuse blowing is prevented by using instantaneous or high-speed tripping and automatic reclosing of a relay-controlled power circuit breaker or the automatic tripping and reclosing of a circuit recloser. The breaker speed, relay settings, and recloser characteristics are selected in a manner to interrupt the fault current before a series fuse (i.e., the nearest source-side fuse) is blown, which would cause the transient fault to become permanent [1].

Permanent faults are those that require repairs by a repair crew in terms of [1]:

- ✓ Replacing burned down conductors, blown fuses, or any other damaged apparatus
- ✓ Removing tree limbs from the line, and

- ✓ Manually reclosing a circuit breaker or recloser to restore service.

Here, the number of customers affected by a fault is minimized by properly selecting and locating the protective apparatus on the feeder main, at the tap point of each branch, and at critical locations on branch circuits. Permanent faults on overhead distribution systems are usually sectionalized by means of fuses. For example, permanent faults are cleared by fuse cutouts installed at submain and lateral tap points. This practice limits the number of customers affected by a permanent fault and helps locate the fault point by reducing the area involved. In general, the only part of the distribution circuit not protected by fuses is the main feeder and feeder tie line. The substation is protected from faults on feeder and tie lines by circuit breakers and/or reclosers located inside the substation. Faults occurring on the feeder are cleared by tripping and lockout of the feeder breaker [1].

A wide variety of equipment is used to protect distribution networks. The particular type of protection used depends on the system element being protected and the system voltage level, and, even though there are no specific standards for the overall protection of distribution networks, there are some general indication of how these systems work can be made [35].

The devices mostly used for distribution system protection are [35]: Overcurrent Relays, Circuit breakers, Reclosers, Sectionalizing switches, Fuses etc.

Circuit Breakers

Circuit breakers are automatic interrupting devices that are capable of breaking and reclosing a circuit under all conditions, that is, faulted or normal operating conditions. The primary task of a circuit breaker is to extinguish the arc that develops due to the separation of its contacts in an arc extinguishing medium, for example, in air, as is the case for air circuit breakers; in oil, as is the case for oil circuit breakers (OCBs); in SF6 (sulfur hexafluoride); or in vacuum. In some types, the arc is extinguished by a blast of compressed air, as is the case for magnetic blowout circuit breakers. The circuit breakers used at distribution system voltages are of the air circuit breaker or OCB type. For low-voltage applications, molded-case circuit breakers are available [1].

Reclosers

A recloser is a device with the ability to detect phase and phase to ground overcurrent conditions, to interrupt the circuit if the overcurrent persists after a predetermined time, and then to automatically reclose to energize the line. If the fault that originated the operation still exists, then the recloser will stay open after a preset number of operations, thus isolating the faulted section from the rest of the system. In an overhead distribution system between 75 to 95 percent of the faults are of a temporary nature and last, at the most, for a few cycles or seconds. Thus, the recloser, with its opening/closing characteristic, prevents a distribution circuit being left out of service for temporary faults [10]. Typically, reclosers are designed to have up to three open/close operations and, after these, a final open operation to lock out the sequence. One further closing operation by manual means is usually allowed [27].

The counting mechanisms register operations of the phase or ground fault units which can also be initiated by externally controlled devices when appropriate communication means are available. The operating time/current characteristic curves of reclosers normally incorporate three curves, one fast and two delayed, designated as A, B and C respectively [30].

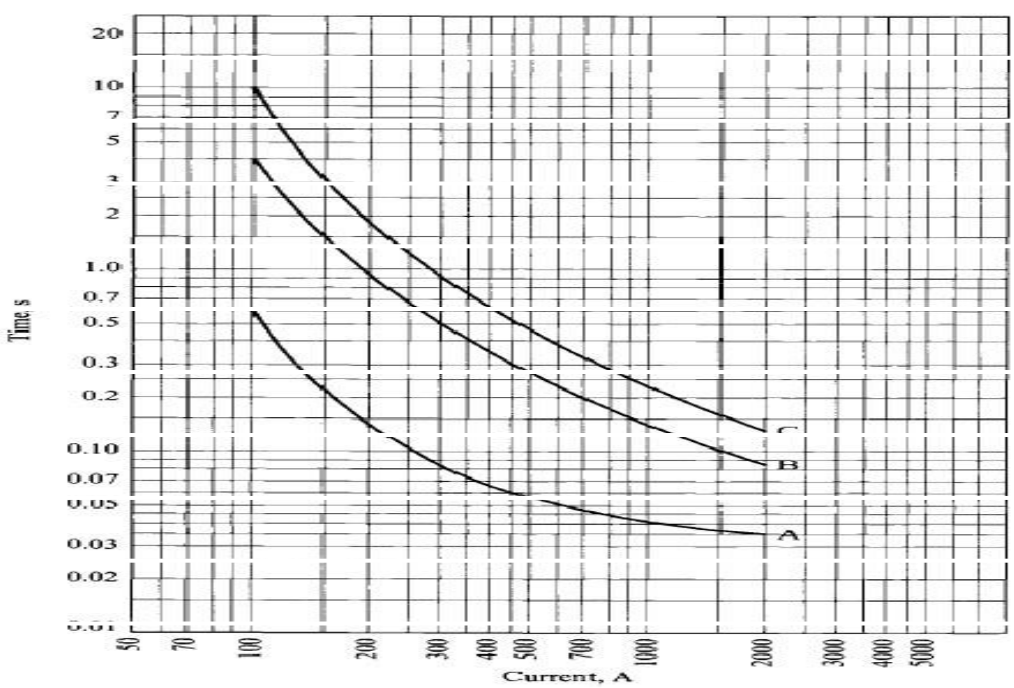

FIGURE 2.6: TIME/CURRENT CURVES FOR RECLOSERS [30]

Coordination with other protection devices is important to ensure that, when a fault occurs, the smallest section of the circuit is disconnected to minimize disruption of supplies to customers. Generally, the time characteristic and the sequence of operation of the recloser are selected to coordinate with mechanisms upstream towards the source. After selecting the size and sequence of operation of the recloser, the devices downstream are adjusted in order to achieve correct coordination.

A typical sequence of a recloser operation for a permanent fault is shown in Figure 2.7. The first shot is carried out in instantaneous mode to clear temporary faults before they cause damage to the lines. The three later ones operate in a timed manner with predetermined time settings. If the fault is permanent, the time delay operation allows other protection devices nearer to the fault to open, limiting the amount of the network being disconnected.

Ground faults are less severe than phase faults and, therefore, it is important that the recloser has an appropriate sensitivity to detect them. One method is to use CTs connected residually so that the resultant residual current under normal conditions is approximately zero. The recloser should operate when the residual current exceeds the setting value, as would occur during ground faults [35].

Reclosers can be classified as follows [35]:

I. Single phase and three phase;
II. Mechanisms with hydraulic or electronic operation;
III. Oil, vacuum or SF6.

Single phase reclosers are used when the load is predominantly single phase. In such a case, when a single phase fault occurs the recloser should permanently disconnect the faulted phase so that supplies are maintained on the other phases.

Three phase reclosers are used when it is necessary to disconnect all three phases in order to prevent unbalanced loading on the system. Reclosers with hydraulic operating mechanisms have a disconnecting coil in series with the line. When the current exceeds the setting value, the coil attracts a piston that opens the recloser main contacts and interrupts the circuit. The time characteristic and operating sequence of the recloser are dependent on the flow of oil in different chamber.

The electronic type of control mechanism is normally located outside the recloser and receives current signals from a CT type bushing. When the current exceeds the predetermined setting, a delayed shot is initiated that finally results in a tripping signal being transmitted to the recloser control mechanism. The control circuit determines the subsequent opening and closing of the mechanism, depending on its setting. Reclosers with electronic operating mechanisms use a coil or motor mechanism to close the contacts. Oil reclosers use the oil to extinguish the arc and also to act as the basic insulation. The same oil can be used in the control mechanism [30].

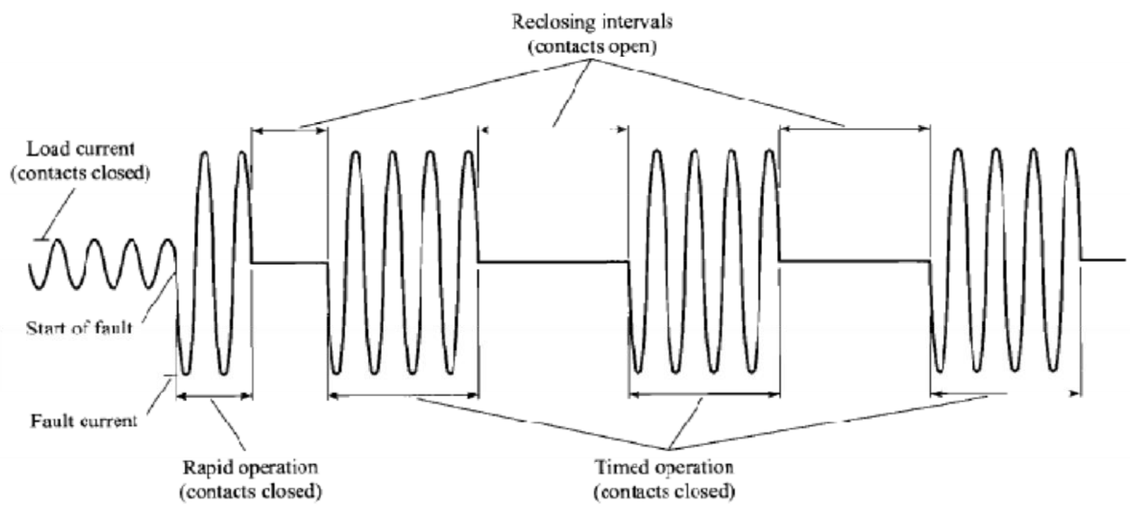

FIGURE 2.7: TYPICAL SEQUENCE FOR RECLOSER OPERATION [35]

Reclosers are used at the following points on a distribution network [27]:

- ✓ In substations, to provide primary protection for a circuit;
- ✓ In main feeder circuits, in order to permit the sectioning of long lines and thus prevent the loss of a complete circuit due to a fault towards the end of the circuit;
- ✓ In branches or spurs, to prevent the tripping of the main circuit due to faults on the spur. When installing reclosers it is necessary to take into account the following factors:

- System voltage.
- Short-circuit level.
- Maximum load current.

- Minimum short-circuit current within the zone to be protected by the recloser.
- Coordination with other mechanisms located upstream towards the source, and downs tream towards the load.
- Sensitivity of operation for ground faults.

The voltage rating and the short circuit capacity of the recloser should be equal to, or greater than, the values that exist at the point of installation. The same criteria should be applied to the current capability of the recloser in respect of the maximum load current to be carried by the circuit. It is also necessary to ensure that the fault current at the end of the line being protected is high enough to cause operation of the recloser [27].

Sectionalizers

A sectionalizer is a device that automatically isolates faulted sections of a distribution circuit once an upstream breaker or recloser has interrupted the fault current and is usually installed downstream of a recloser. Since sectionalizers have no capacity to break fault current, they must be used with a backup device that has fault current breaking capacity. Sectionalizers count the number of operations of the recloser during fault conditions. After a preselected number of recloser openings, and while the recloser is open, the sectionalizer opens and isolates the faulty section of line. This permits the recloser to close and re-establish supplies to those areas free of faults. If the fault is temporary, the operating mechanism of the sectionalizer is reset. Sectionalizers are constructed in single phase (three phase) arrangements with hydraulic or electronic operating mechanisms. A sectionalizer does not have a time/current operating characteristic, and can be used between two protective devices whose operating curves are very close and where an additional step in coordination is not practicable [35].

Sectionalizers with hydraulic operating mechanisms have an operating coil in series with the line. Each time an overcurrent occurs the coil drives a piston that activates a counting mechanism when the circuit is opened and the current is zero by the displacement of oil across the chambers of the sectionalizer. After a prearranged number of circuit openings, the sectionalizer contacts are opened by means of pretension springs. This type of sectionalizer can be closed manually.

Sectionalizers with electronic operating mechanisms are more flexible in operation and easier to set. The load current is measured by means of CTs and the secondary current is fed to a control circuit which counts the number of operations of the recloser or the associated interrupter and then sends a tripping signal to the opening mechanism.

The nominal voltage and current of a sectionalizer should be equal to or greater than the maximum values of voltage or load at the point of installation. The short circuit capacity (momentary rating) of a sectionalizer should be equal to or greater than the fault level at the point of installation. The maximum clearance time of the associated interrupter should not be permitted to exceed the short circuit rating of the sectionalizer. Coordination factors that need to be taken into account include the starting current setting and the number of operations of the associated interrupter before opening [35].

Fuses

A fuse is an overcurrent protection device; it possesses an element that is directly heated by the passage of current and is destroyed when the current exceeds a predetermined value. A suitably selected fuse should open the circuit by the destruction of the fuse element, eliminate the arc established during the destruction of the element and then maintain circuit conditions open with nominal voltage applied to its terminals, (i.e. no arcing across the fuse element).

The majority of fuses used in distribution systems operate on the expulsion principle, i.e. they have a tube to confine the arc, with the interior covered with deionizing fiber, and a fusible element. In the presence of a fault, the interior fiber is heated up when the fusible element melts and produces deionizing gases which accumulate in the tube. The arc is compressed and expelled out of the tube; in addition, the escape of gas from the ends of the tube causes the particles that sustain the arc to be expelled. In this way, the arc is extinguished when current zero is reached.

The presence of deionizing gases, and the turbulence within the tube, ensure that the fault current is not re-established after the current passes through zero point. The zone of operation is limited by two factors; the lower limit based on the minimum time required for the fusing of the element (minimum melting time) with the upper limit determined by the maximum total time that the fuse takes to clear the fault.

There are a number of standards to classify fuses according to the rated voltages, rated currents, time/current characteristics, manufacturing features and other considerations [35].

2.3.1 Protection coordination of Time/Current Devices in Distribution System

The process of selecting overcurrent protection devices with certain time–current settings and their appropriate arrangement in series along a distribution circuit in order to clear faults from the lines and apparatus according to a preset sequence of operation is known as coordination. When two protective apparatus installed in series have characteristics that provide a specified operating sequence, they are said to be coordinated or selective. Here, the device that is set to operate first to isolate the fault (or interrupt the fault current) is defined as the protecting device. It is usually the apparatus closer to the fault. The apparatus that furnishes backup protection but operates only when the protecting device fails to operate to clear the fault is defined as the protected device [1]. Properly coordinated protective devices help [1]:

- To eliminate service interruptions due to temporary faults.
- To minimize the extent of faults in order to reduce the number of customers affected, and
- To locate the fault, thereby minimizing the duration of service outages.

The following basic criteria should be employed when coordinating time/current devices in distribution systems [26]:

1. The main protection should clear a permanent or temporary fault before the backup protection operates, or continue to operate until the circuit is disconnected. However, if the main protection is a fuse and the backup protection is a recloser, it is normally acceptable to coordinate the fast operating curve or curves of the recloser to operate first, followed by the fuse, if the fault is not cleared.
2. Loss of supply caused by permanent faults should be restricted to the smallest part of the system for the shortest time possible.

2.3.1.1 Fuse -Fuse Coordination

The essential criterion when using fuses is that the maximum clearance time for a main fuse should not exceed 75 percent of the minimum melting time of the backup fuse, for the same current level. This ensures that the main fuse interrupts and clears the fault before the backup fuse is affected in any way. The factor of 75 percent compensates for effects such as load current and ambient temperature, or fatigue in the fuse element caused by the heating effect of fault currents that have passed through the fuse to a fault downstream but were not sufficiently large enough to melt the fuse.

The coordination between two or more consecutive fuses can be achieved by drawing their time current characteristics, normally on log/log paper as for overcurrent relays [35].

2.3.1.2 Recloser-Fuse Coordination

The criteria for determining recloser/fuse coordination depend on the relative locations of these devices, i.e. whether the fuse is at the source side and then backs up the operation of the recloser that is at the load side, or vice versa. These possibilities are treated in the following paragraphs. When the fuse is at the source side, all the recloser operations should be faster than the minimum melting time of the fuse. This can be achieved through the use of multiplying factors on the recloser time/current curve to compensate for the fatigue of the fuse link produced by the cumulative heating effect generated by successive recloser operations.

The recloser opening curve modified by the appropriate factor then becomes slower but, even so,

Should be faster than the fuse curve.

The procedure to coordinate a recloser and a fuse, when the latter is at the load side, is carried out with the following rules:

1) The minimum melting time of the fuse must be greater than the fast curve of the recloser times the multiplying factor.
2) The maximum clearing time of the fuse must be smaller than the delayed curve of the recloser without any multiplying factor; the recloser should have at least two or more delayed operations to prevent loss of service in case the recloser trips when the fuse operates. Better coordination between a recloser and fuses is obtained by setting the recloser to give two instantaneous operations followed by two timed operations. In general, the first opening of a recloser will clear 80 percent of the temporary faults, while the second will clear a further 10 percent. The load fuses are set to operate before the third opening, clearing permanent faults.

A less effective coordination is obtained using one instantaneous operation followed by three timed operations [35].

2.3.1.3 Recloser to Recloser Coordination

The coordination between reclosers is obtained by appropriately selecting the amperes setting of the trip coil in the hydraulic reclosers, or of the pick-ups in electronic reclosers.

Hydraulic Reclosers

The coordination margins with hydraulic reclosers depend upon the type of equipment used.
In small reclosers, where the current coil and its piston produce the opening of the contacts, the following criteria must be taken into account [35]:

- ❖ Separation of the curves by less than two cycles always results in simultaneous operation;
- ❖ Separation of the curves by between two and 12 cycles could result in simultaneous operation;
- ❖ Separation greater than 12 cycles ensures non-simultaneous operation.

With large capacity reclosers, the piston associated with the current coil only actuates the opening mechanism. In such cases the coordination margins are as follows:

- ✓ Separation of the curves by less than two cycles always results in simultaneous operation;
- ✓ A separation of more than eight cycles guarantees non-simultaneous operation.

The principle of coordination between two large units in series is based on the time of separation between the operating characteristics, in the same way as for small units.

Electronically-Controlled Reclosers

Adjacent reclosers of this type can be coordinated more closely since there are no inherent errors such as those that exist with electromechanical mechanisms (due to over speed, inertia, etc.). The downstream recloser must be faster than the upstream recloser, and the clearance time of the downstream recloser plus its tolerance should be lower than the upstream recloser clearance time less its tolerance. Normally, the setting of the recloser at the substation is used to achieve at least one fast recloser, in order to clear temporary faults on the line between the substation and the load recloser. The latter should be set with the same, or a larger, number of rapid operations as the recloser at the substation. It should be noted that the criteria of spacing between the time/current characteristics of electronically controlled reclosers are different to those used for hydraulically controlled reclosers [35].

2.3.1.4 Recloser to Relay Coordination

Two factors should be taken into account for the coordination of these devices; the interrupter opens the circuit some cycles after the associated relay trips, and the relay has to integrate the clearance time of the recloser. The reset time of the relay is normally long and, if the fault current is re-applied before the relay has completely reset, the relay will move towards its operating point from this partially reset position [35].

2.3.1.5 Recloser to Sectionalizer coordination

Since the sectionalizers have no time/current operating characteristic, their coordination doesn't require an analysis of these curves.

The coordination criteria in this case are based upon the number of operations of the backup recloser. These operations can be any combination of rapid or timed shots as mentioned previously, for instance two fast and two delayed. The sectionalizer should be set for one shot less than those of the recloser, for example three disconnections in this case. If a permanent fault occurs beyond the sectionalizer, the sectionalizer will open and isolate the fault after the third opening of the recloser. The recloser will then re-energize the section to restore the circuit. If additional sectionalizers are installed in series, the furthest recloser should be adjusted for a smaller number of counts. A fault beyond the last sectionalizer results in the operation of the recloser and the start of the counters in all the sectionalizers [35].

2.3.1.6 Recloser-Sectionalizer-Fuse Coordination

Each one of the devices should be adjusted in order to coordinate with the recloser. In turn, the sequence of operation of the recloser should be adjusted in order to obtain the appropriate coordination for faults beyond the fuse by following the criteria already mentioned [26].

By using power system protection it is possible to detach the faulty section from the system to make the rest of the portion work without any disturbance. In addition to this, it is used for the protection of power system and prevent the flow of fault current. It can help in preventing the continuation of flow by quickly disconnecting the short circuit [24].

Protection relays, on the other hand, are the important characteristic of power system protection helps to isolate the faulty part of the electrical system. However, it is important for this relay to possess certain qualities that are mentioned below [26]:

- **Dependability:** This is an important aspect of the relay to possess, as it remains out of action for a long time before the fault occurs. However, if the fault occurs, the relay should respond correctly.
- **Selectivity:** The property by which only the faulty element of the system is isolated and the remaining healthy sections are left intact.
- **Speed:** Protective relays are required to be quick acting due to the following reasons:

(a) Critical clearing time should not be exceeded.

(b) Electrical apparatus may be damaged, if they are made to carry fault currents for a long time.

(c) A persistent fault will lower the voltage resulting in crawling and overloading of industrial drives.

The relays should not be extremely fast; otherwise the relay will operate for transient conditions. It is important for the protective relays to operate at a required speed. Moreover, there should be correct coordination in various power system protection relays so that it should not disturb the healthy portion. The fault current flows through a healthy portion as it is electrically connected and associated with the healthy portion. Also, if relay associated with the faulty portion does not operate in the given time, then next relay associated with healthy portion should be worked upon to isolate the fault [26].

2.4 Distribution Generation and its benefits on distribution system reliability

Distributed Generation is a generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distribution level voltages. The technologies include biomass-based generators, combustion turbines, small (and micro) turbines, fuel cells, and photovoltaic systems, wind turbines, engines/generator sets etc. Distributed generation is the integrated or stand-alone use of small, modular electricity generation resources by utilities, utility customers, and/or third parties in applications that benefit the electric system, specific end-user customers, or both. Introduction of DG to distribution system has significant benefited impacts, and includes: loss reduction, improved utility system reliability, voltage support and improved power quality, transmission and distribution capacity release, deferments of new or upgraded transmission and distribution infrastructure, easy and quicker installation on account of prefabricated standardized components, lowering of cost by avoiding long distance high voltage transmission, environment friendly where renewable sources are used and reduction in the maintenance and operational costs of the electric network etc. [5].

2.5 Reviews of Related Works

A lot of literature reviews have been done regarding power reliability problems related ideas, in different areas, and 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 [4].

In [3], it is aimed to investigate alternative, more reliable and cost effective ways of improving the reliability performance of medium voltage networks. It deals in paying particular attention on customers interruptions mainly caused by faults on the distribution MV network. The literature focuses on improving the network management by increasing the level of network automation and control which improves the operating efficiency of medium voltage distribution networks. Steps are shown how to equip the network according to progressive investment capability, from Fault Path Indicators (FPIs) and remote control Pulse closing technologies to automatic Fuse Savers and Trip savers used in a feeder automation scheme to minimize the number of disturbances and the outage durations experienced when they occur.

The results of a study analyzing the impact of different intelligent automation solutions on the reliability performance of Medium Voltage distribution networks are presented in this dissertation. The respective system topologies are modelled and the resulting system reliability performance is determined by reliability calculations such as the SAIDI and SAIFI values. The results show that the distribution automation technologies can have a very significant impact on both the SAIDI and SAIFI performance of the system.

Based on investigation of the results, the use of different distribution automation technologies improved reliability performance by reducing the duration of interruptions but not the frequency of interruption i.e. it improves the SAIDI but not SAIFI. It appears clear that implementation of automatic technologies, remote control and fault detection are the key solutions to improving network reliability.

[27]: This research work focuses on Studies of power distribution system reliability assessment and improvement (a case study of Jimma town distribution system). According to this thesis report, the distribution system suffered with large number of interruptions and longer power outage time due to different factors (system overload, tree contact, windy rain, equipment failure etc.).

Evaluation and analysis of the existing performance of this distribution system using interruption data of base years showed that, the average frequency of interruptions and the average durations of interruptions were far below the standards. Based on these evaluation results, different mitigation alternatives using installment of auto reclosers and feeder reconfiguration has been used to improve the system reliability at reasonable cost. Five different alternatives or cases were outlined for improving the reliability of the study area with low SAIDI, SAIFI and EENS at a reasonable cost was selected & summary of each reliability indices reduction benefits and cost effectiveness analysis was applied. SAIFI, SAIDI and EENS were used as the main driver for evaluating of each alternative. Cost-effectiveness was considered as the main constraint of any analysis in this paper and as it was defined as the ratio of the cost of implementing an alternative using a recloser versus its corresponding reliability indices improvement. After overall analysis of the these alternatives, it was determined and concluded that the most effective alternative for improving the reliability of the study area was finalized by installing one tie switch, two auto reclosers at critically selected locations and permanently isolating the long and expected faulty line goes to rural 'Dedo woreda' from the existing feeder and chooses another non-loaded line for the loads of this faulty line.

[33]: This thesis deals on Reliability of Distribution systems using Markov Process and ETAP. The paper applies assessment of testing a system designed by Roy Billinton. The intention is to examine the consequences of distributed generation (DG) on the network. The analysis being carried out on third hierarchical level (HLIII) and the improvement in system reliability is studied using various indices. Additionally, system response in terms of overall reliability is observed and

analyzed after penetration of single DG and multiple DG near the load point. Later, the relation between system reliability and the distance of the installed DG is analyzed.

Recollecting the importance of system reliability for distribution companies from an investment point of view is also one of the objective of this study. Studies and analysis are supported and are verified using ETAP software.

Reliability analysis on modified bus 2 of the test system depicted the effect of DG insertion on overall system reliability. A total of four cases were considered and the system behavior in each of these cases was observed and tabulated. The customer oriented indices and the system reliability indices clearly indicate that system reliability is increased after DG placement near to the load or far away from the feeder. From analysis it was also observed that when multiple DGs are placed near to the load, the system reliability decreases, indicating that system reliability is highly sensitive to the location of the DG.

Based on the results obtained, it was recommended that the system designers and planners can identify the weak points and take necessary actions to improve overall system reliability. Additionally, one could also benchmark the system performance and compare it after system expansion. One major advantage of this analysis is as indicated that supply interruption cost can be reduced drastically by investing more on one of the load points during system planning.

CHAPTER THREE

PERFORMANCE EVALUATION AND ANALYSIS OF EXISTING ASHEBEKA DISTRIBUTION SYSTEM

3.1 Introduction

This chapter deals with the performance evaluation and analysis of existing Ashebeka distribution system based on primary & secondary data collected from proposed site. The section contains methods of data collection, analysis and modeling to briefly describe the problems and their causes in the stated problem area.

3.2 Problem Site Description

Assela is a town of the study's conducted area located in East Arsi Zone of Oromia Regional state about 175KM far from Addis Ababa; the Capital City of Ethiopia. Assela is found at the west foot of Chilalo Mountain, which is one of the known mountain in the country. It is the place where famous Ethiopian runners are emerging. The city has Geographical location of latitude and longitude between $7^{0}54'55''$N to $8^{0}00'05''$N, $39^{0}06'10''$E to $39^{0}10'00''$E, with an elevation of (2100-2430M) [Assela town profile]. It is the capital town of East Arsi Zone and Tiyo 'woreda' of Oromia regional state. It retains some administrative functions as the current seat of Arsi Zone [30]. The total population of Assela is about 67,269 as indicated from CSA 2007E.C (2015G.C).

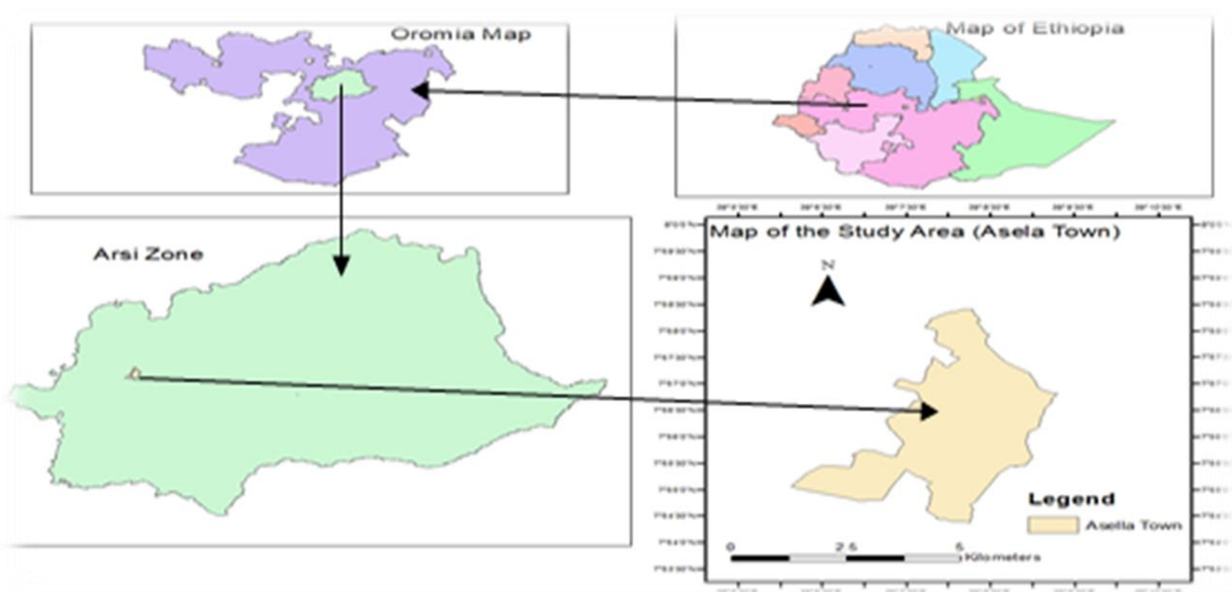

FIGURE 3.1: GEOGRAPHICAL MAP OF ASSELA TOWN [Assela town profile 2018], [30]

3.2.1 Assela Substation

Assela substation receives an AC electric power supply as an input from the transmission line that comes from Awash II (Two) with 132KV/45MW to the two power transformers and to Adami Tulu substation after connection to the first bus bar of the substation through the transmission tower. The first transformer (132/15KV, 25MVA) is the older one which takes 132KV from first bus bar and has output of 15KV to the five outgoing feeder lines through next bus bar. These lines are: Eteya (Line-1), Sagure (Line-2), Industry (Line-3), Assela (Line-4), and ***Ashebeka (Line-5)***. The second power transformer (132/33KV/15KV, 25MVA) is the newly installed one in 2002 E.C or 2009/10 G.C and has three winding to give two different medium voltage levels (33KV &15KV) at its secondary side. But, at time of this thesis only the 33KV is under service to supply electric power to Assela Malt Factory (Line-3) and other Arsi zonal districts such as Amude (Line-1), Cochebore (Line-2), and Gumuguma (Line-4). These 33KV feeders supply Arsi zonal towns and districts or 'weredas' those are rural areas far from Assela town which has to be extended farther in order to cover all the rural electrification activities, whereas the towns & rural areas nearer to Assela town are served by 15KV medium voltage line from the first transformer. These towns are: Eteya, kulumsa, Abura, Arata, Buru-jawi, Gonde, & a few number of Assela customers feed from Eteya (Line -1). Eteya, Abura, Arata and Buru-jawi have their own utility other than Assela utility [30].

Sagure (Line-2) feeds a few number of Assela town customers, and mostly serves customers in Sagure, Kersa, Lemmu, Tijjo, & Golja towns, & also rural villages such as Beriti, and Bulchana, which have their own utilities.

Industry (Line -3) gives service to factories around Assela and few number of residential customers in Assela.

Assela (Line -4) serves mostly Assela town commercial and residential customers, the customers in the nearer towns and some rural areas around Assela town, and a few number of industrial loads in the town.

The high voltage AC power that comes from Awash Two hydroelectric power plant enters the substation through transmission tower and also transmitted to Adami Tulu substation after terminating the first bus bar (132KV) of the substation.

FIGURE 3.2: PHOTO OF ASSELA SUBSTATION SHOWING ITS HV SYSTEM

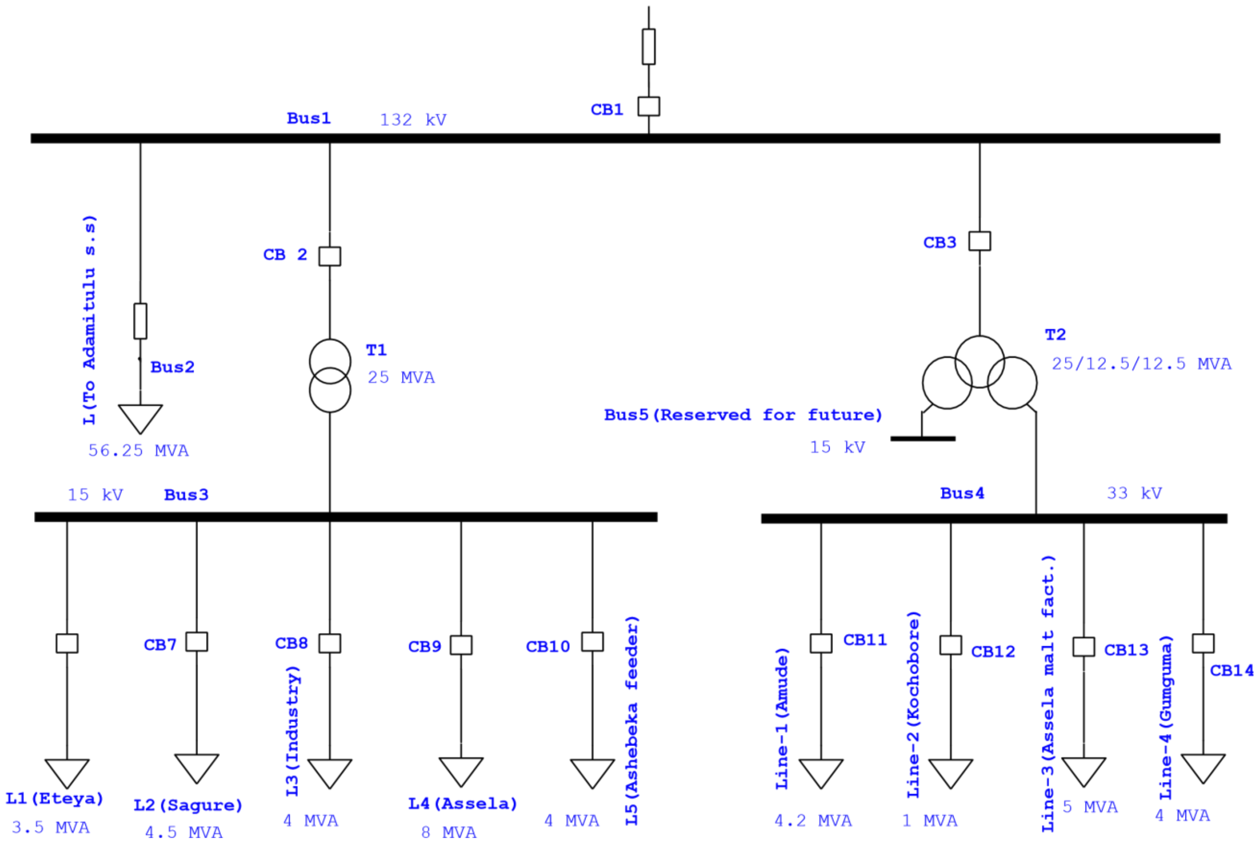

FIGURE 3.3: SINGLE LINE DIAGRAM FOR ASSELA SUBSTATION

3.2.2 Ashebeka Distribution System

Ashebeka feeder is one of the five outgoing feeder or secondary of older power transformer in Assela Electric power substation. It is a 15KV Distribution line that runs from this substation & feeds electrical loads of different type in different locations.

According to the feeder assessment accomplished by the researcher, information and data obtained from electric utilities under which this system is administered, Ashebeka distribution system currently serving different types of loads in Assela town and other towns and villages found in radius of 15 to 39 KM from Assela. These towns are: Chebi, Sagure, and Digelu as well as rural areas and villages such as Duna, Billallo, Beriti, Chere, & Shemege, in addition to Assela town Water supply project (Water treatment plant & raw water pumping station) and Sagure town drinking water pumping station.

Because of the way it is going through and also its longer distance, the operation and control of Ashebeka distribution system is administered by two utilities: Assela town electric utility & Sagure town electric utility.

3.3 Data collection

In order to achieve the goal of this thesis, the data and detail information necessary to perform the desired assessment work is very important. Based on this perception the primary and secondary data has been collected per schedule of the researcher adapting situation challenges that arise due to some overlapping with the institutional jobs especially in electric utility area.

The primary data, which is essential for the study such as distribution system topology & layout, the feeder length, number, type, & height of poles, types of insulators, number, type and rating of distribution transformers, size and type of the conductor, topography of line way/path areas, and etc. has been assessed and collected by the researcher using site survey, discussions, interviews, and questionnaires with Assela and Sagure towns electric utilities' technicians & workers.

And also the secondary data such as substation topology, number, capacity, and type of power transformers, types of circuit breakers, numbers, types, & voltage level of feeders, types of faults, frequency of interruptions, duration of interruptions, unsold energy, number of customers etc. has been obtained from Assela substation and electric utilities by site surveying and recorded documents.

Table 3.1: Name and Voltage levels of Assela substation outgoing feeders.

S/No	Feeder Name	Voltage Level (KV)	Type of Circuit Breaker	CT Ratio & Maximum Load (MVA)
1	Eteya (Line-1)	15	Minimum Oil CB	200/5A, (3.5MVA)
2	Sagure (Line-2)	15	Vacuum CB	400/5A, (4.5MVA)
3	Industry (Line-3)	15	Minimum Oil CB	600/5A, (4MVA)
4	Assela (Line-4)	15	Minimum Oil CB	400/5A, (8MVA)
5	Ashebeka (Line-5)	15	Minimum Oil CB	200/5A, (4MVA)
6	Amude (Line-1)	33	vacuum CB	75-150/1/1A, (4.2MVA)
7	Cochebore (Line-2)	33	Vacuum CB	75-150/1/1A, (1MVA)
8	Assela Malt factory (Line-3)	33	Vacuum CB	75-150/1/1A, (5MVA)
9	Gumguma (Line-4)	33	Vacuum CB	75-150/1/1A, (4MVA)

As shown from the above table, the types of circuit breakers of all 15KV feeders are minimum oil circuit breakers except for Sagure (Line-2), which is recently changed from minimum oil to vacuum type due to its extreme faults on the line that has been happening before, which was uneconomical, time taking, and tiresome work of frequent oil changing that is due to the formation of carbon for arc quenching/extinguishing purpose & sparks formed by repeatedly tripping action as stated by the substation operators.

The rest four 33KV medium voltage feeders have equipped with the vacuum type circuit breakers, which are more efficient and effective than that of oil type.

Table 3.2: Distribution transformers and customers' data of Ashebeka line.

S/No	**Name (Specific locations/area) of transformers**	**Transformer capacity (KVA)**	**No. of customers served**	**Manufacturer, year**
1	Around Mariam Church (Assela)	315	662	Ethio. (Metec)
2	At.Kenenisa Poly Technique College	1200	1	Ethio. (Metec)
3	Ardu Ber Garage (Ardu Ber)	100	85	Italy
4	Sheleko area (near Ardu Ber traffic control)	200	26	Ethio. (Metec)
5	Micro Enterprise/Cluster (Sheleko)	200	5	Ethio. (Metec)
6	Arsi Ketar Food Complex 1 (Gebriel church)	315	11	Ethio. (Metec)
7	Arsi Ketar Food Complex 2 (Gebriel church)	800	1	Ethiopia ('')
8	Water Treatment plant	315	1	Italy,1995
9	Bio park area (Pista road to Duna)	100	33	India
10	Rong chung manufacturing P.L.C	315	1	Ethiopia
11	Concrete pole factory (near water t/plant)	315	1	Ethiopia
12	Duna rural village	100	43	India
13	Chebi rural town 1	100	67	India
14	Chebi rural town 2 (Dabdo)	100	25	India
15	Hewi flour factory (Dosha)	200	1	Ethiopia
16	China wood processing factory (Billallo)	630	1	Ethiopia

17	Alemu Bati (near Bilalo)	50	4	Italy
18	Bilalo rural village	100	27	Ethiopia, (Metec)
19	Billallo Tele tower	50	1	
20	Beriti rural village	50	6	
21	Sagure town area (‘Agelglot’)	100	35	India
22	Sagure town 1	200	360	India
23	Sagure town 2	315	210	
24	Sagure town 3	315	157	Ethiopia, (Metec)
25	Chere rural village	100	26	
26	Ashebeka water pumping station	630	1	Italy, 1995
27	Shemege rural village 1	50	15	
28	Shemege rural village 2	100	25	India
29	Sagure water pumping station (Gugessa)	50	1	
30	Digelu 1 (Heath Center)	50	2	
31	Digelu 2 (primary school)	200	254	India
32	Digelu 3 (Tele tower)	25	1	
33	Digelu 4 (Bus station)	315	239	
34	Digelu 5 (central town)	100	53	India
35	Digelu 6	50	7	
36	Digelu 7 (Gebriel Church)	50	42	
	Total	**8205**	**2430**	

The distribution transformers and the loads

The second data required for ETAP 16.0.0 for distribution system analysis is distribution transformer ratings, capacity and the load of the transformer. The total number of transformers with their total loads has been collected for Ashebeka line-05 as indicated below.

Table 3.3: Data of distribution transformers and their loads that has been fed to ETAP

Trafo №	Primary Bus	Secondary Bus	Capacity (KVA)	Primary voltage (KV)	Secondary voltage (KV)	Load in (KVA)	% Trafo loaded
T1	Bus2	Bus3	315	15	0.38	228.16	72.43
T2	Bus4	Bus5	1200	15	0.38	812.99	67.75
T3	Bus6	Bus7	100	15	0.38	78.57	78.57
T4	Bus8	Bus9	200	15	0.38	144.25	72.12
T5	Bus10	Bus11	200	15	0.38	142.01	71
T6	Bus12	Bus13	315	15	0.38	227.76	72.3
T7	Bus14	Bus15	800	15	0.38	639.35	79.92
T8	Bus16	Bus17	315	15	0.38	221.27	70.24
T9	Bus18	Bus19	100	15	0.38	74.75	74.75
T10	Bus20	Bus21	315	15	0.38	222.7	70.7
T11	Bus22	Bus23	315	15	0.38	225.27	71.51
T12	Bus24	Bus25	100	15	0.38	70.64	70.64
T13	Bus26	Bus27	100	15	0.38	69.84	69.84
T14	Bus28	Bus29	100	15	0.38	71.75	71.75
T15	Bus30	Bus31	200	15	0.38	138.09	69.04
T16	Bus32	Bus33	630	15	0.38	431.94	68.56
T17	Bus34	Bus35	50	15	0.38	31.67	63.37
T18	Bus36	Bus37	100	15	0.38	69.4	69.4
T19	Bus38	Bus39	50	15	0.38	30.78	61.55
T20	Bus40	Bus41	50	15	0.38	31.86	63.71
T21	Bus42	Bus43	100	15	0.38	69.51	69.51
T22	Bus44	Bus45	200	15	0.38	141.15	70.57
T23	Bus46	Bus47	315	15	0.38	227.12	72.1
T24	Bus48	Bus49	315	15	0.38	225.51	71.59
T25	Bus50	Bus51	100	15	0.38	72.2	72.2

T26	Bus52	Bus53	630	15	0.38	443.09	70.33
T27	Bus54	Bus55	50	15	0.38	31.44	62.89
T28	Bus56	Bus57	100	15	0.38	69.9	69.9
T29	Bus58	Bus59	50	15	0.38	33.43	66.86
T30	Bus60	Bus61	50	15	0.38	31.84	63.68
T31	Bus62	Bus63	200	15	0.38	144.42	72.21
T32	Bus64	Bus65	25	15	0.38	19.13	76.52
T33	Bus66	Bus67	315	15	0.38	227.11	72.1
T34	Bus68	Bus69	100	15	0.38	67.45	67.4
T35	Bus70	Bus71	50	15	0.38	22.49	44.98
T36	Bus72	Bus73	50	15	0.38	31.5	63.01
Total			***8205***			***5820.34***	

Data of the Line

Ashebeka feeder or line is 15KV radial distribution system that has a conductor type AAC (all aluminum conductor) of size 50mm^2 with seven stranded, stretched from the substation to its load sites in three-phase three-wire system through overhead wooden poles of thickness ranged from 16 to 24 centimeters, height from 8 to 12meters, mostly equipped/supported with pin type insulators, with few of suspension type.

Based on data of conductor/line length and problems assessment made by the researcher, there are seven manual sectionalizers without including those at the primary of distribution transformers, out of which three are malfunctioned & shorted (jumped) with conductor. And also, there are six manual sectionalizers on distribution transformers those were failed and shorted. Assessment shows, there is no fuse or any other protecting device which is normally functions throughout the line to be observed, during the site visiting time of proposed system for the purpose of performance evaluation work.

According to data and information obtained from substation & utilities, Ashebeka distribution system was commissioned and started giving service during Ashebeka water supply project implementation and startup time that is 1998G.C [2]. Therefore, based on this information the overall system infrastructure & wooden pole age is estimated to be more than 20 (twenty) years.

During site visiting time, it was observed that there are poles those tilted from 5 to 45 degrees from the vertical position, and in addition there are poles totally failed and only supported by successive poles & their conductors, especially in Chebi way and in many places most of them are failed & maintained/repaired, hence, their heights are shorten from the original status and so on. Therefore, this is an evidence that shows the aging of poles infrastructure and is one of the great influential factor on the distribution system reliability of Ashebeka feeder.

The line travels through many farm lands, trees and homes throughout its way. This situation makes the distribution system problems to be more pronounced & since the conductors are also bare there is a frequent probability of fault happening during bad weather conditions.

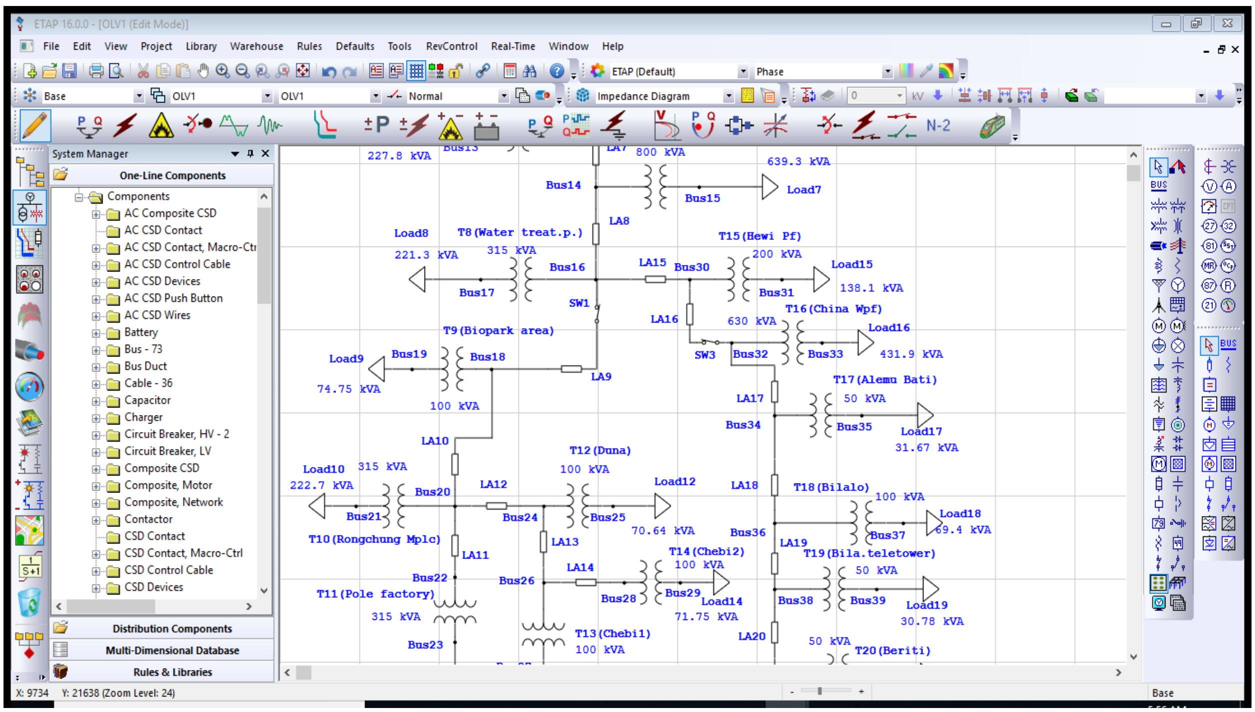

FIGURE 3.4: SINGLE LINE REPRESENTATION OF EXISTING ASSHEBEKA DS

After data of the proposed system was collected from the substation, survey of physical site, & utilities, the system has been represented by one line diagram as shown in the figure 3.5 on page 56, which is a complete one line diagram of a model indicated on window of ETAP 16.0.0 in figure 3.4.

In this study, to make the analysis more convenient, the line has been divided into a number of segments based on load centers or distribution transformers.

Table 3.4 shows the divisions of the line and their respective nodes to know the feeder estimated total length.

Where LA1 to LA36 are divisions of the line, Bus1 to Bus72 are consecutive nodes, 'A' stands for 'Ashebeka', and 'L' stands for 'line'.

Table 3.4: Data showing length of Ashebeka feeder

	Length of the line		
Name of a line	**From node**	**To node**	**Unit (KM)**
LA1	Bus1	Bus2	4.73
LA2	Bus2	Bus4	0.87
LA3	Bus4	Bus6	0.865
LA4	Bus6	Bus8	0.32
LA5	Bus8	Bus10	0.05
LA6	Bus10	Bus12	0.35
LA7	Bus12	Bus14	0.15
LA8	Bus14	Bus16	0.81
LA9	Bus16	Bus18	0.615
LA10	Bus18	Bus20	0.39
LA11	Bus20	Bus22	0.3
LA12	Bus20	Bus24	2.36
LA13	Bus24	Bus26	7.3
LA14	Bus26	Bus28	1.44
LA15	Bus16	Bus30	0.125
LA16	Bus30	Bus32	2.86
LA17	Bus32	Bus34	0.41
LA18	Bus34	Bus36	3.92
LA19	Bus36	Bus38	4.445
LA20	Bus38	Bus40	2.78
LA21	Bus40	Bus42	6.32
LA22	Bus42	Bus44	1.63

LA23	Bus44	Bus46	0.747
LA24	Bus46	Bus48	0.53
LA25	Bus48	Bus50	13.14
LA26	Bus50	Bus52	0.49
LA27	Bus52	Bus54	2.27
LA28	Bus54	Bus56	2.35
LA29	Bus56	Bus58	5.23
LA30	Bus58	Bus60	0.06
LA31	Bus60	Bus62	0.36
LA32	Bus62	Bus64	0.28
LA33	Bus64	Bus66	0.3
LA34	Bus66	Bus68	0.6
LA35	Bus68	Bus70	0.18
LA36	Bus70	Bus72	2.77
Total			***72.347***

As indicated on the above table the total length of Ashebeka line is estimated to be 72.347km.

Table 3.5: Summary in frequency of interruptions and durations of interruption frequencies for Ashebeka distribution system of base years from 2006-2010 E.C or 2013/14 to 2017/18 G.C

	Base years	**2013/14**	**2014/15**	**2015/16**	**2016/17**	**2017/18**
Frequency of Interruptions (*Inter./cust.yr*.)	Planned	118	86	92	139	103
	Non-temporary	349	225	164	168	237
	Total	467	311	256	307	340
	Average			**336.2**		
Durations of interruption frequencies (*Hrs/cust.yr*.)	Planned	68.868	53.455	190.596	99.732	110.803
	Non-temporary	353.79	467.005	256.044	187.239	331.775
	Total	422.658	520.46	447	286.971	442.578
	Average			**423.9334**		

As shown from the table, summary of frequency of interruptions and durations of interruption are calculated from every monthly summary of data for each base year obtained from Assela substation, and the average interruption frequencies and average durations of interruptions are found to be ***336.2*** *(Inter./year) &* ***423.93*** *(hrs/year)* respectively.

As it is too bulky to show all interruptions data, only detail interruption data of one base year 2010 E.C (2017/18 G.C) & summary of interruption data for five years (2006-2010 E.C. or. 2013/14-2017/18 G.C.) are shown in appendix A.

3.4 Main causes of Power interruptions in Ashebeka distribution system

There are various factors that cause interruptions in Ashebeka electric distribution system. Equipment failures, animals, human errors, natural disasters, trees are some of the frequently occurring factors leading to power interruptions. The distribution line is vulnerable to these failure factors and its reliability is always a question. A brief discussions on each of these failure factors and their effects on reliability of the proposed distribution system are presented in this section.

A number of discussions, interviews and questionnaires have been performed between the author and Assela substation operators, as well as workers of Assela & Sagure electric utilities, regarding main causes of power interruptions in Ashebeka distribution system. Based on the response of substation operators, the data like, interruption frequencies, durations of interruption frequencies, unsold energy, types of faults such as: distribution permanent earth fault (DPEF), distribution permanent short circuit (DPSC), distribution temporary earth fault (DTEF), distribution temporary short circuit (DTSC), generation unit problem (GUP), distribution line over load (DLOL) etc. has been recorded, but what makes these faults is not identified and documented, known/recorded by the substation workers except getting information from the maintenance crews and customers call about power outage events. The maintenance personnel mostly talking about failing trees on the line both naturally or by human errors, & unknown causes also are the major causes of power interruptions in the case of Ashebeka distribution system as stated by those questioned workers.

In the responses of utility technical managers, technical workers, & maintenance crews, the following failure factors are indicated as the main causes of power interruptions in the proposed system.

3.4.1 Aging of Infrastructure

As stated by the workers, the data of the system shows that Ashebeka distribution system has too aged equipment throughout its whole system. These aging of the overall system makes the interruption problems more serious. Infrastructures that are exposed to aging status are: the wooden poles, the conductors, the insulators, the manual sectionalizing switches etc.

According to data and information obtained from substation, & electric utilities, Ashebeka distribution system commissioned and started giving service during Ashebeka water supply project implementation & startup period of time that is 1998G.C. Therefore, based on this information the overall system structure & wooden pole age is estimated to be more than 20 (twenty) years. During site visiting time also, it was observed that there are numerous poles through the line way are tilted/leaned from 5 to 45 degrees from their vertical position, and also there are poles in many places totally failed and only supported by successive poles & the conductors: especially in Chebi, Sagure, and Digelu ways. In many places most of them are failed & re-maintained, hence, their heights are shorten from the original status and so on. These situations are mainly observed around Yohanis Church before crossing Welkessa River in Assela on the line way from substation, on the line path to Chebi, on the line way to Sagure, and Digelu towns.

The insulators are also cracked, broken, plugged out from the poles and hanged down by conductors in some areas especially in Duna, Chebi, Bilalo, Beriti, Chere, & Guggessa.

Most of manual sectionalizers are malfunctions and jumped/shorted by conductors, and only few are normally working both on the line and on load centers, and also HRC fuses in the line specifically at secondary of distribution transformers throughout the system are not functional.

Due to aging of the grounding conductor in many places earthing protection lines became inhibited to conduct the earthing fault hence cause equipment damage.

Another serious problem that is a cause of interruption in the proposed distribution system is loose connections occurs in the line specifically at connection points which is, extremely time consuming job to trouble shoot the problem as described during discussion time with maintenance workers.

Therefore, these are evidences that obtained during physical assessment of the sites to prove what is said by the site workers/ maintenance men indicating the aging of infrastructures and it is one of the great influential factor on the distribution system reliability of Ashebeka feeder.

3.4.2 Trees

Trees are the major contributors for the interruptions of power supply to customers in Ashebeka distribution system. During site visiting time, it was observed that in the path where the proposed line is passing through there is almost no way where trees are unavailable throughout the system, except in places like in Assela town: from around Mariam Church to Ardu Ber, from Sheleko to water treatment plant, & in central areas of Sagure and Digelu towns only. Except those areas the rest of line way are filled with trees at some intervals of consecutive poles, this makes the system unreliable as observed by the author, and also the responses obtained by the maintenance workers during interviews about causes of power interruptions reveals this is true.

In some areas the line totally passes through grown trees and in some of the areas their branches are growing and approaching to the line. In this situation, with in small movements of those trees due to external factors, the fault may be happened and became cause of power interruptions. Because of these situations, trees momentary faults are more common phenomena in Ashebeka distribution system. This makes the breaker tripping frequently, causing repeatedly oil changing of which is time taking job and uneconomical to tolerate, since much carbon formation of tripping action to extinguish the arc, due to presence of only one breaker at substation for controlling the whole operation of the system.

As discussions and interviews with utilities' maintenance crews and experienced workers' response, there is no practical periodically tree trimming schedule settings made by utilities and the society or dwellers around the line path are also do not have awareness of the problem so that they have negative response of tree trimming activities that is why the problems are more harmful.

3.4.3 Human errors

In Ashebeka distribution system, human errors have great contributions on interruptions of power to customers. As most of the line route is passing through rural areas and awareness of the people dwelling there is less and some personnel cut trees & tree branches on the line resulting short circuit problems, damage to supporting structures, conductors & poles. In addition to this, in many areas Ashebeka line is passing through farming lands, as a result of this the farmers plough their land without leaving any portion rounding wooden poles erection point, hence, the ploughed soil became wet during rainy time and made the pole part inside the soil to be decayed resulting of poles failing on another time. Those problems are mostly common in line way to Duna, Chebi, Sagure, Digelu, and Guggessa.

On other hand, there are residential homes built on the way of the line, those are not follow the master plan of the respective area and create big problems and uncomfortable situations during problem happening and maintenance time. Even, it may cause hazardous situations on residents during extreme weather conditions. Those problems are mostly seen in Assela town around Welkessa River on the line way from substation, on the line way to Sagure town in Billallo, Beriti, and near Sagure area.

3.4.4 Bad Weather

Bad weather is also one of the cause for power interruptions in the proposed distribution system. Weather conditions like wind, rain, windy rain, etc. are commonly happening phenomena and cause power outage. During these conditions it is easy for interruptions to be occur because of the presence of trees on the line way, which makes contact of one line to another resulting line to line faults, or three phase faults. The aging of system equipment also sensitive to this phenomenon. The wind causes these problems as the workers briefly explained it.

The lightning may strike the line, and trees near the line causing it to fail on the line resulting severe damage to the system during these extreme weather conditions. Ground cables and surge arrestors has to be mounted on top of poles in order to protect the distribution system from similar problems.

3.4.5 Animals

Animals are another causes of power interruptions in Ashebeka distribution system. Animals, like, squirrels, large birds, snakes, monkeys, apes, and rats can cause power outage especially in river crossing forests by climbing on the power lines creating short circuits and hence, impact the reliability of the distribution system. Squirrels are the most common reliability concern for these areas. Squirrels bring grounded equipment in contact with phase conductors causing faults. Special plastic guards are required to ensure protection of conductors.

Large birds are another cause of faults in the Ashebeka distribution system. They cause faults in system by bridging the conductors with their wings.

Snakes, being cold blooded animals, tend to squeeze through holes and stay in warm places like cabinets. Snakes cause problems by bridging two conductors.

Electrical cabinets should be sealed and food remains should be removed. Large animals like cows, oxen, horses and donkeys can cause damage to poles by rubbing on guy wires. A lot of cattle lean on or rub on poles or guy wires making poles lean and this reduces the reliability as the chances of collapsing poles increase. Fences has to be built around the poles in order to protect it as to increase the distribution system reliability.

3.4.6 Vehicle Accidents

In some areas, the proposed distribution system is closest to road side, because of this vehicles running with high speed strike the poles and cause mechanical & electrical damage to the system hence it is one of the cause of power interruptions and blackout to this system which is common on line way to Sagure asphalt road where drivers' of 'highroof' car and 'FSR' truck are not securely drive instead they drive with fast speed that is not allowed, beside this some of them perform this action with chewing 'Chat' causing the problem more severe, since traffic control in this area also less. Destructions happening in this case is too severe that makes the power outage time became longer since it takes time to get & replace all malfunctioned equipment.

3.4.7 Planned Interruptions

All interruption causes described above are unplanned power distribution system problems those result customer interruptions and power outage basically obtained by interviews, discussions, and questionnaires results with the workers & managers of the utilities.

Planned interruptions are also common in Ashebeka distribution system for the purpose of institutional jobs like maintenance, system upgrading, replacement etc. During these tasks the customers downstream of these areas experience interruptions, since the system is radial & no more alternative power supply has been implemented to energize them.

3.5 Data Analysis

Based on the data collected from the proposed distribution system, the existing performance of the system has been investigated by interpreting the obtained data into meaningful format that can represent the real situation of a case study site. Hence, the data gathered and shown above has been found from physical site of Ashebeka distribution system, Assela town distribution substation, & Assela and Sagure towns' electric utilities by direct involvement of the investigator.

To know reliability indices of power distribution system, calculating the values of ***failure rates*** and ***mean time to repair*** for each component of the system are necessary. To estimate the failure rate of the line per kilometer, the average number of outage frequencies should be divided by the feeder length (Kilo meters) as indicated in equation (3.1) [27], [30], [44]. The mean time to repair of each failure of the line is also computed using equation (3.2).

$$\lambda_A = \frac{Sum\ of interruptions\ of\ base\ years}{feeder\ length(km) * Number\ of\ years}\ (Interruptions/km.year) \text{ ----------------------- } (3.1)$$

$$MTTR = \frac{Total\ time\ to\ recover}{Total\ number\ of\ interruptions}\left(\frac{hours}{interruptions}\right) - - - - - - - - - - - - - - - (3.2)$$

Where: λ_A is active failure rate

MTTR is mean time to repair

The total length of Ashebeka line was indicated in the data of table 3.4 and estimated as to be ***72.347*** KM.

Applying these equations as shown:-

$$\lambda_A = \frac{(467+311+256+307+340)}{72.347*5} = \frac{336.2}{72.347} = 4.65 \qquad \left(\frac{interruptions}{km*year}\right)$$

$$MTTR = \frac{Total\ time\ to\ recover}{Total\ number\ of\ interruptions} = \frac{423.93}{336.2} = 1.26 \qquad \left(\frac{hours}{interruptions}\right)$$

Using the data of table 3.5 and these equations, the computed results of the active failure rate and mean time to repair of the proposed feeder are found to be ***4.65*** (*interruptions/km.year*) and ***1.26*** (*hrs/interruption*) respectively as shown.

ETAP 16.0.0 software uses λ_A and MTTR equations to predict the basic reliability parameters for reliability analysis. To estimate the failure rate of a component ETAP 16.0.0 uses combination of active λ_A and passive λp failure rates together. λ_A, the active failure rate is number of failures per year per unit length. The active failure rate is associated with the component failure mode that causes the operation of the primary protection zone around the failed component and can therefore cause the removal of the other healthy components and branches from service, after the actively failed component is isolated, and the protection breakers are reclosed. This leads to service being restored to some or all of the load points. It should be noted, however, that the failed component itself and those components that are directly connected to this failed component could be restored to service only after repair or replacement. While λp, the passive failure rate is number of failures per year per unit length. The passive failure rate is associated with the component failure mode that does not cause the operation of protection breakers and therefore does not have an impact on the remaining healthy components. Repairing or replacing the failed component will restore service. As there is no means of isolating a specific faulty areas in the system, λp is assumed as zero in the model [27], [Software Library].

The following table shows the active failure rate and mean time to repair of the components in the distribution system under study & that has been used in reliability analysis of this system. The rest data of distribution components excluding the line data are obtained from different literatures and [42].

Table 3.6: Failure inputs for distribution system components

Name of Component	**Voltage Level (KV)**	**Active Failure Rate (Inter./yr.)**	**MTTR (hrs.)**
Line	15	4.65	1.26
Transformer	15/0.4	0.015	200
Breaker	15	0.003	50
Bus-bar	15	0.001	2

3.6 Existing system modeling and problem identification

As explained in the software help index, Electrical Transient Analysis Program (ETAP) is a fully graphical enterprise package that runs on different Microsoft Windows operating systems. ETAP is the most comprehensive analysis tool for the design and testing of power systems available. Using its standard offline simulation modules, ETAP can utilize real-time operating data for advanced monitoring, real-time simulation, optimization, energy management systems, and high speed intelligent load shedding. ETAP allows someone to easily create and edit graphical one-line diagrams, underground cable raceway systems, three-dimensional cable systems, advanced time current coordination and selectivity plots, geographic information system schematics, as well as three-dimensional ground grid systems. The program operation emulates real electrical system operation as closely as possible. ETAP incorporates innovative concepts for determining protective device coordination directly from the one-line diagram. ETAP combines the electrical, logical, mechanical, and physical attributes of system elements in the same database. The software uses to analyze different electrical analysis, like reliability, short circuit, load flow, arc flash, protection coordination and others.

In this thesis, ETAP 16.0.0 has been used as a design, simulation and reliability assessment analysis tool.

Using every useful collected data from Assela substation, electric utilities under which Ashebeka distribution system is administered, and those obtained by survey of physical site, its existing system has been represented by single line diagram & its reliability indices were also indicated applying ETAP 16.0.0 software (reliability analysis tool) as shown below.

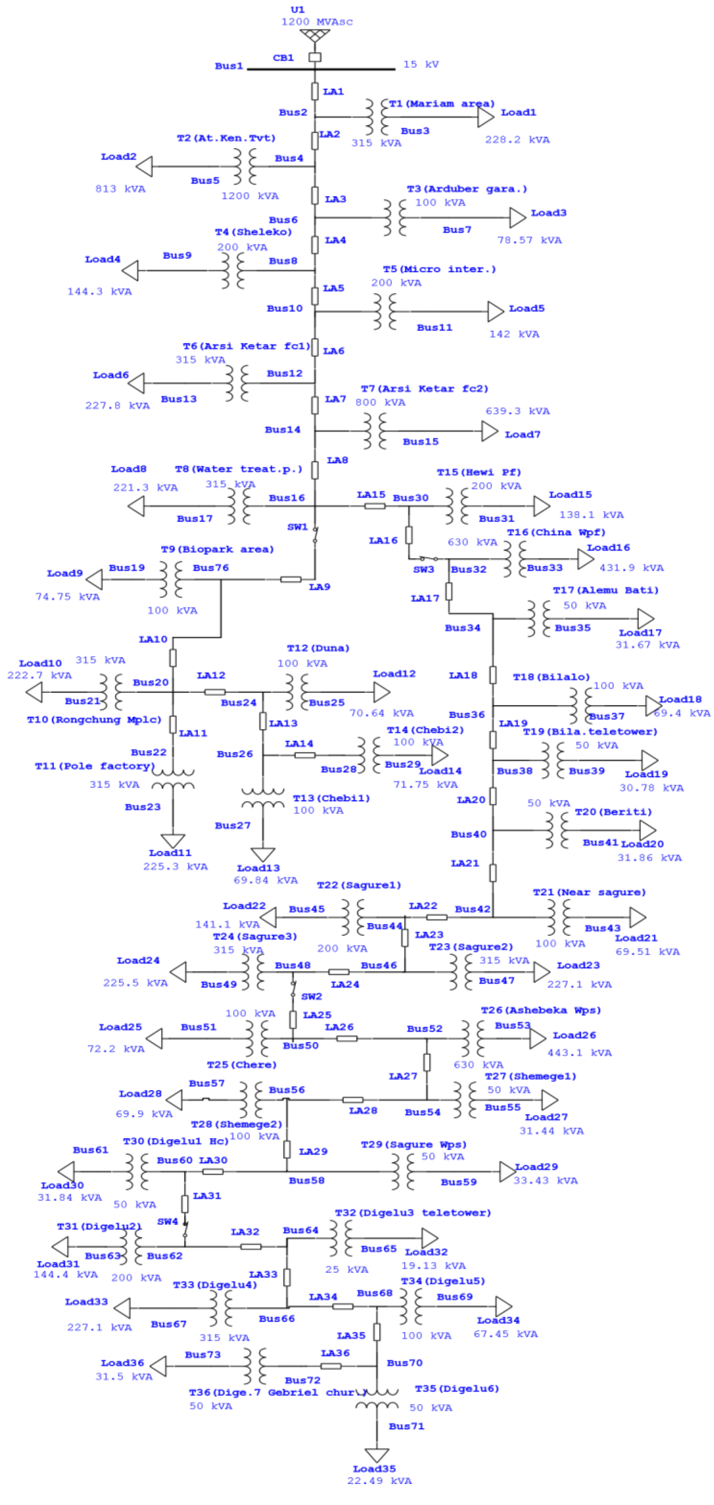

FIGURE 3.5: SINGLE LINE DIAGRAM FOR EXISTING ASHEBEKA DS

Table 3.7: Computed summary results of reliability indices for existing system

Project: DS Reliability Assessment	**ETAP**	Page: 1
Location: Arsi Assela	16.0.0C	Date: 11-28-2019
Contract:		SN: 4359168
Engineer: Erko Biru	Study Case: Existing DS RA	Revision: Base
Filename: Ashebeka distribution system		Config.: Normal

SUMMARY

System Indexes

AENS	34.6460 MW hr / customer.yr
ASAI	0.9625 pu
ASUI	0.03751 pu
CAIDI	0.971 hr / customer interruption
EENS	1247.256 MW hr / yr
SAIDI	328.5535 hr / customer.yr
SAIFI	338.4121 f / customer.yr

AENS	Average Energy Not Supplied
ASAI	Average service Availability Index
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
EENS	Expected Energy Not Supplied
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

According to this summary, as also based on the raw data collected and analysis results of reliability indices for existing Ashebeka distribution system obtained by ETAP 16.0.0 software, the following conclusions can be drawn.

- The basic reliability indices that could describe a power distribution system reliability performance and also indicated above to justify the status of existing Ashebeka distribution system are not within the standard ranges set by the regulatory body that is EEA (Ethiopian Electric Agency).

- The reliability of Ashebeka distribution is too far above as compared with the international standards or reliability benchmarks set by IEEE (International electrical and electronics engineers) guide.
- There is highly unavailable electric power supply in Ashebeka distribution network as can be seen from calculated results.
- There is also much amount of unsold energy or EENS (expected energy not supplied) because of frequent interruptions & longer power outage time.

The comparison of this study's results (existing reliability performance of Ashebeka feeder) with the reliability benchmark indices are shown in table 3.8 [34, 36].

Table 3.8: Reliability indices benchmark compared with existing Ashebeka DS

Country	**SAIDI** **(***hrs/year***)**	**SAIFI** **(***inter./cust***.)**	**CAIDI** **(***hrs/outage***)**	**ASAI** *(%)*
United States	4	1.5	2.05	99.91
United Kingdom	1.5	0.8	1.667	99.964
Italy	0.967	2.2	1.767	99.9991
Spain	1.733	2.2	1.9	99.968
Austria	1.2	0.9	1.867	99.97
Netherlands	0.55	0.3	1.25	99.97
Denmark	0.4	0.5	1.167	99.981
France	1.033	1	0.967	99.97
Ethiopia	25	20	1.25	
Ashebeka feeder	***328.5535***	***338.4121***	***0.971***	***96.25***

The standard with which reliability of a distribution system is measured against is known as reliability benchmarks [36]. These standards are given in order to provide a justification and acceptable margin for reliability performances of distribution networks. According to IEEE guide and the standards of EEA referenced by [34] & [36], the benchmarks for power distribution reliability of the above listed countries has been computed. While the author included the results in reliability performance of existing Ashebeka distribution system in the table 3.8 as shown.

Based on comparison, annual average customer-oriented reliability indices that can show the performance of a distribution system, such as SAIDI, SAIFI, CAIDI, and ASAI for Ashebeka feeder are ***328.5535***, ***338.4121, 0.971 & 96.25*** sequentially as indicated in the table. Therefore, Ashebeka feeder has worse reliability performance currently, so that it needs to be mitigated to come to its improved values of reliability indices.

In order to improve the huge reliability performance gap of Ashebeka feeder, the reliability improvement solutions that could suit the problem are discussed in the next section.

3.7 Reliability enhancement Options and selection criteria

Distribution reliability primarily relates to equipment outages and customer interruptions. In normal operating conditions, all equipment (except standby) is energized and all customers are energized. Schedule and unscheduled events disrupt normal operating conditions and can lead to outages and interruptions. The unscheduled events are caused either due to human error or due to equipment failures. The schedule events are meant for periodic maintenance of the equipment and shall be notified in advance to the customers [21].

According to reliability assessment conducted in Ashebeka distribution system, forced (unscheduled) outages are due to short circuits and earth fault that happened mostly because of trees, bad weather conditions, equipment aging, animals, human errors etc. As a result, most probably the temporary faults have changed to permanent and prolonged the outage time; that is why the cost effective & efficient overcurrent protective devices (the reclosers) are selected to solve these problems among different solutions of mitigating the poor performance of the system. The recloser senses and interrupts fault currents and automatically restores service after momentary outage. If a fault is permanent, the recloser locks open after a preset number of operations (usually three or four), isolating the faulted section from the main part of the system. The alternative which is technically feasible and economically viable has been considered and placement (integration) of PV array (DG) as additive supply was carefully chosen considering abundant availability of the resource and sufficient land for ground mounting of PV array implementation for socially & politically critical and sensitive load point (Ashebeka water pumping station), in addition to recloser as the alternative to improve reliability of the distribution system.

3.8 Design of PV array for Ashebeka Water Pumping Station

This section deals with the design of PV array and the corresponding three phase inverter that could form the sub-system of solar PV power which is selected as an alternative solution for the power interruptions problems in Ashebeka water pumping station from its distribution system. The desired solar PV power system of the proposed site is indicated in block diagram of figure 3.6 below.

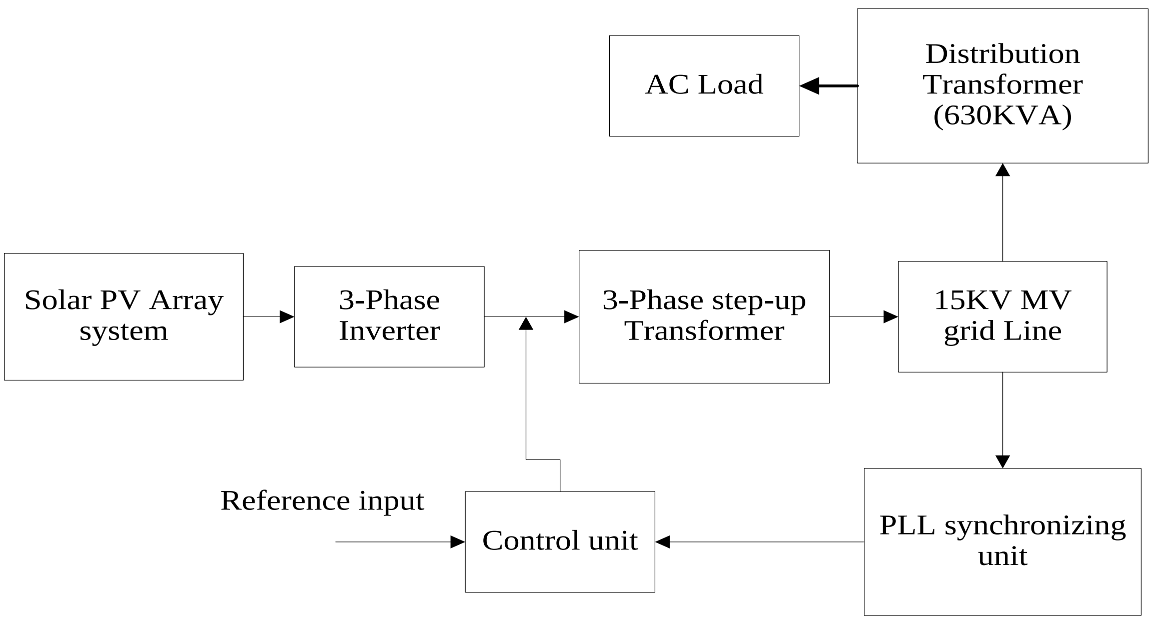

FIGURE 3.6: BLOCK DIAGRAM OF PROPOSED PV POWER SUPPLY SYSTEM

The following steps were considered for the actualization of the design; Data collected on load demand, weather conditions of the study area and synchronization in order to control the disturbances on the lines.

For consideration of metrological data, the irradiance and temperature are calculated at time of peak sun hours with ETAP 16.0.0 software by using the geographical latitude and longitude of the proposed site for which solar PV system is to be designed for maximum power point tracking.

The power of one module is not enough to meet the power requirement of the study area. Some of the modules in a PV array are connected in series to obtain the desired voltage while some are connected in parallel to produce current that made up the required power [45].

For designing this PV array, the following requirement has been taken into consideration.

- ✓ Load demand of a sensitive load area
- ✓ Accounting losses
- ✓ Equivalent sun hours

After the PV array was designed, the next is sizing & selecting or deciding the market available inverter.

Table 3.9: Load requirement data of Ashebeka water Pumping station

S/No	**Load Item**	**Quantity**	**AC Power/ Item(Watt)**	**Total AC Power/ Item(Watt)**	**Time of use(hrs/day)**	**Total energy (Watt.hr/day)**
1	LED lamp	10	9	90	12	1080
2	CF lamp	11	18	198	12	2376
3	Fluorescent lamp	8	40	320	12	3840
4	Mercury lamp	5	250	1250	12	15000
5	Stove	2	2000	4000	6	24000
6	Refrigerator (200litres)	1	110	110	12	1320
7	Desktop PC	1	100	100	9	900
8	Printer	1	60	60	7	420
9	Television	1	100	100	10	1000
10	Water Pump1	1	55000	55000	12	660000
11	Water Pump2	1	68000	68000	12	816000
12	Water Pump3	1	75000	75000	8	600000
13	Water Pump4	1	110000	110000	8	880000
	Total			**314,228**		**3,005,936**

The total number of photovoltaic (PV) modules required for the grid connected solar system is calculated using the equations given as follows [45]:

$$\text{Required Energy (Er)} = \frac{\text{Daily average consumption demand}}{product\ of\ components\ efficiency} = \frac{\text{E}}{\eta\ \text{Overall}} -------- (3.3)$$

Where:-

Er= Required energy

E= Daily energy or demand in Watt-hours

η= Component efficiency

The daily average consumption demand of the study area is shown in the table 3.9 and is equals to *3,005,936Watt.hour*.

Taking efficiency of components included (cable and inverter), 95% and 98% respectively and equation (3.3)

$$\text{Required Energy (Er)} = \frac{\text{Daily average consumption demand}}{product\ of\ components\ efficiency} = \frac{\text{E}}{\eta\ \text{overall}} = \frac{3{,}005{,}936}{0.98 * 0.95}$$

$$= \mathbf{3{,}228{,}717.51\textit{Watt.hour}}.$$

The peak power (Pp) is equal to the required energy (Er) divided by the average sun hours (Tmin) per day for a particular geographical location [45]. The equation (3.4) computes the Pp.

$$Peak\ power\ (Pp) = \frac{Daily\ Energy\ requirement}{Minimm\ sun\ peak\ hours\ per\ day} = \frac{Er}{Tmin} ---------- (3.4)$$

Where; Er =Required energy, Pp= peak power, Tmin= period of minimum sun peak hours or equivalent sun hours.

The minimum sun peak hours per day for the proposed site is estimated to be seven (7) hours.

Using result of equation (3.3) and inserting it in equation (3.4);

$$Peak\ power\ (Pp) = \frac{Daily\ Energy\ requirement}{Minimm\ sun\ peak\ hours\ per\ day} = \frac{Er}{Tmin}$$

$$= \frac{\mathbf{3{,}228{,}717.51\textit{Watt.hour}}}{\mathbf{7\textit{hour}}} = \mathbf{461{,}245.36\textit{Watt}}.$$

In this design, PV Monocrystalline module (SunPower SPR-415E-WHT-D manufactured by SunPower Company) [46] is selected to be used due to its specification for minimizing the required number of modules and space or place of implementation. It is consist of 128 cells with maximum power (Pmax) of 415W, open circuit voltage (Voc) is 85.3 V, short circuit current (Isc) is 6.09A, while the maximum power point voltage (Vmpp) and current (Impp) are 72.9 V and 5.69 A, respectively [46]. In order to accomplish the proposed PV system which is designed to generate a peak power of $\mathbf{461,245.36}\boldsymbol{Watt\ or}\ \mathbf{461.24}\boldsymbol{KW}$, the needed numbers of modules can be obtained by the following equation [46].

$$\text{Required numbers of modules} = \frac{\text{Peak power(Pp)}}{\text{Maximum power of the panel}} - - - - - - - - - - - -(3.5)$$

Hence, $\text{Required numbers of modules} = \frac{\text{Peak power(Pp)}}{\text{Maximum power of the panel}} = \frac{\mathbf{461{,}245.36}\boldsymbol{Watt}}{\mathbf{415}\boldsymbol{Watt}} =$

$\mathbf{1111.43} \cong \mathbf{1112}\ \boldsymbol{modules}$

In this design, the system DC-link rated at 650 VDC to reduce the output current ripple and regulate the voltage at the dc side of the inverter, therefore the number of necessary PV modules in series (Npvs) is obtained as [46]:

$$\text{Numbers of modules in series(Npvs)} = \frac{\text{Dc nominal voltage}}{\text{Maximum power point voltage}} - - - - - - -(3.6)$$

$$\text{Numbers of modules in series(Npvs)} = \frac{\text{Dc nominal voltage}}{\text{Maximum power point voltage}} = \frac{650V}{72.9V}$$
$$= 9\ modules$$

The number of strings of the photovoltaic array can be obtained according to the following relation [46]:

$$\text{Numbers of strings(Npvst)} = \frac{\text{Number of array modules}}{\text{Number of PV series modules}} - - - - - - - - - - - - -\ (3.7)$$

$$\text{Numbers of strings(Npvst)} = \frac{1112}{9} = 123.556 \cong 124\ strings$$

Therefore, the power generated by proposed solar PV Array

$$= \text{Total number of modules} * \text{ Maximum power of a module} = 9 * 124 * 415$$

$$= 1116\text{module} * \frac{415\text{W}}{\text{module}} = 463{,}140 W or\ 463.14 KW.$$

As a result, to generate $\mathbf{463,140}\boldsymbol{Watt\ or}\ \mathbf{463.14}\boldsymbol{KW}$ of power at Ashebeka water pumping station, 1116 modules with maximum power of 415W of each module has been used and distributed as 9 series modules and 124 parallel strings, as can be shown in Fig. 3.7.

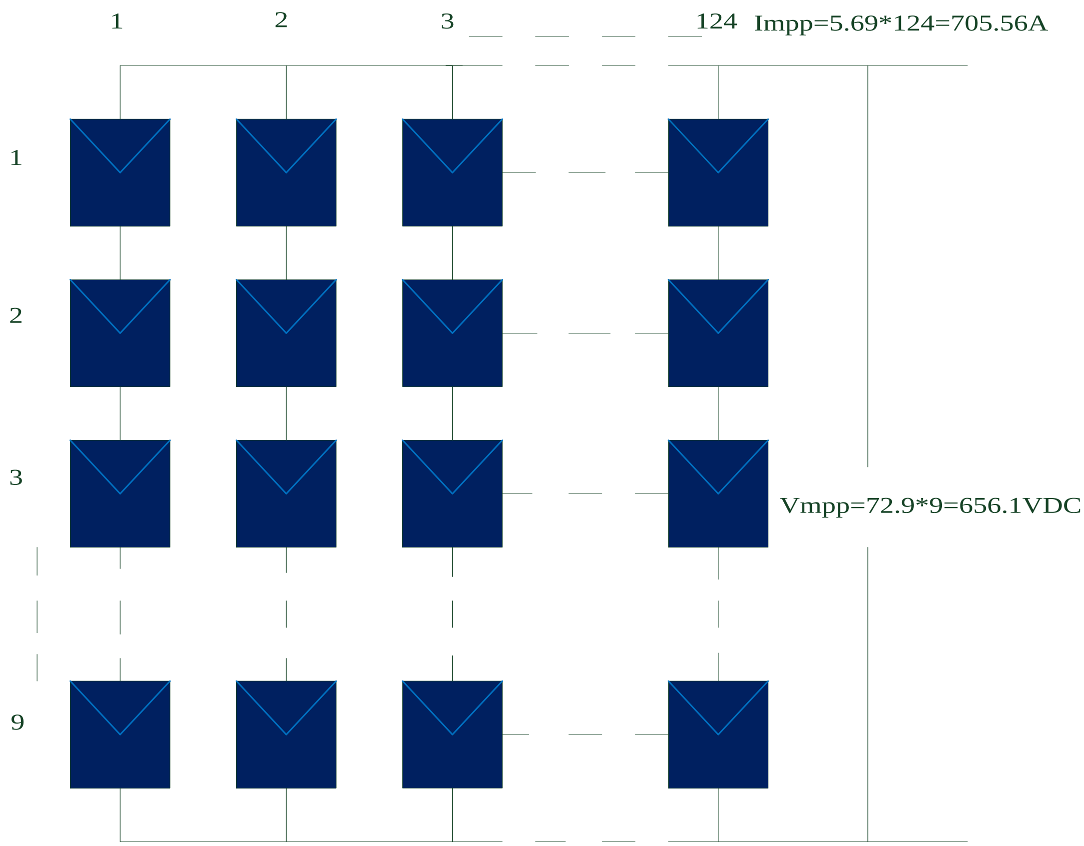

FIGURE 3.7: THE PV ARRAY CONFIGURATION OF THE DESIGN

The actual maximum voltage (V_{mpv}) and the actual maximum current (I_{mpv}) of the PV array can be obtained by (3.8) and (3.9), respectively:

$$Vmpv = Number\ of\ series\ modules * Maximum\ power\ point\ voltage --------- (3.8)$$

$$Vmpv = Number\ of\ series\ modules * Maximum\ power\ point\ voltage = 9 * 72.9 = 656.1 VDC$$

$$Impv = Number\ of\ Parallel\ strings * Maximum\ power\ point\ current ----- (3.9)$$

$$= 124 * 5.69 = 705.56A.$$

On the other hand, the actual maximum output power of the PV array can be calculated according to (3.10):

$$Pdc = Vmpv * Impv ----------------------------(3.10)$$

$$Pdc = 656.1 * 705.56 = 462{,}917.92Watt = 462.92KW.$$

The array maximum open circuit voltage (Voc) and its maximum short circuit current (Isc) can be calculated based on (3.11) and (3.12) respectively.

$$Voc = Number\ of\ series\ modules * Open\ circuit\ voltage ----------- (3.11)$$

$$= 9 * 85.3 = 767.7V\ DC.$$

$$Isc = Number\ of\ parallel\ strings * Short\ circuit\ current ----------(3.12)$$

$=124 * 6.09 = 755.16A$

Considering losses in PV power system, the total yield is the net output after the reduction of the losses in the DC cable loss (97%), the inverter (98.6%), and AC cable loss (99%). The mismatch losses due radiation and temperature changes can be reduced by using maximum power point tracking (MPPT) in inverter [32].

Hence, the output power of the PV array after losses can be obtained as follows:

$$The\ output\ power\ of\ PV = 462.92KW * 0.97 * 0.986 * 0.99 = \mathbf{438.32KW}.$$

Inverter Sizing

For grid tie systems or grid connected systems, the input rating of the inverter should be same as PV array rating to allow for safe and efficient operation [41].

Hence, the input power rating of the inverter is required to be 438.32KW. So that, the nearest available inverter selected for this design is needed to be 500KW three phase inverter from ABB central inverters due to its compatibility and capability of carrying high power starting [32].

The traditional low-voltage (288–690V) converter-based system requires a step-up transformer and a line filter to interconnect a solar PV power plant with medium-voltage grids [9]. A traditional solar PV power plant consists mainly of the solar PV modules, the power electronic converters (which is the heart and/or energy manager of a plant, that converts dc power into ac power), the medium-voltage transformer (generally 6–36 kV to step-up low ac voltage into a medium ac voltage to feed power into a medium-voltage power transmission line), the switchgear and the protection equipment [9].

In this system, the step-up transformer with capacity 800KVA is used for converting 300V to 15KV and interconnecting the designed PV system with MV line and a PLL is also applied to synchronize the inverter output voltage, frequency and phase to that of corresponding grid parameters.

Table 3.10: Type of selected inverter and its technical data [25]

Inverter type designation (PVS800-57)	-0500KW-A 500KW
Input (DC)	
Maximum input power ($P_{pv,max}$)	600KWp
DC voltage range, mpp ($U_{DC,mpp}$)	450 to 825V
Maximum DC voltage ($U_{max,DC}$)	1100V
Maximum DC current ($I_{max,DC}$)	1145A
Number of protected DC inputs	4 to 15(+/-)
Output (AC) and Efficiency	
Nominal power ($P_{N/AC}$)	500KW
Maximum output power	600KW
Power at pf=0.95	475KW
Nominal AC current ($I_{N/AC}$)	965A
Nominal output voltage ($U_{N/AC}$)	300V
Output frequency	50/60HZ
Harmonic distortion, current	< 3%
Distribution network type	TN and IT
Maximum efficiency	98.6%
Power consumption, Dimensions and Weight	
Own consumption in operation	490W
Standby operation consumption	65W
External auxiliary voltage	230V, 50HZ
Width/Height/Depth, mm (W/H/D)	2630/2130/708
Weight	1800kg

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, the reliability improvement strategy will be applied in the modeling of the proposed distribution system using reliability analysis and simulation software. Predictive reliability analysis software models the distribution circuit topology, probability and impact of outages, protective equipment response, post-fault switching, and time to restore service.

Predictive reliability analysis software can be thought of as a “load flow program for system reliability.” That is, instead of simulating the electrical conditions of the system, the software simulates the expected reliability performance of the system. The model included system topology, line segment lengths, protective & switching device locations and main feeder capacity limitations [21].

Ashebeka feeder-05 is protected by a circuit breaker of CT 200/5A rated at the outgoing of the transformer in the substation. The feeder is an old distribution system that has no any protective devices other than substation circuit breaker and manual sectionalizing switches to isolate the loads downstream of the line during fault finding & maintenance time as indicated in single line diagram of the existing system on figure 3.5. When a fault occurs at one point far from substation or in one lateral line, the total system will be interrupted. All customers on this feeder experience power interruptions and an interruption lasts for long duration of time until the lateral faulty line found, identified and isolated manually. Hence fault location and isolation mechanism is based on try and error tracing of the system & it takes from several hours to days based on type of happening event to restore power to the customers.

According to the existing system reliability analysis results and problem categories of Ashebeka distribution system, solution options to tackle limitations in the system reliability performance is required to be implementing auto reclosers at potentially selected locations and integrating a distribution generation (DG) for victims of the problem & expected critical load point. The reason behind for this, the line is longer and encountered by frequent fault that could occur due to broken branches of trees, & bad weather, system aging etc. as main factors.

The types of reclosers decided to be used for this study are three-phase electronic controlled with ANSI standard, Cooper/NOVA-TS-15(400A) with specification of 15KV, 400A, 8KA, which is available in software library. The specification setting for the recloser is based on the proposed distribution system design engineering point of view. The reason of choosing the recloser is its suitability to root causes of the problem and for pole mounting.

The distributed generation (DG) selected for this study is solar PV power system due to the abundant resource availability during critically required period of time for the sensitive loads of Ashebeka river water pumping station.

Placement and number of automatic reclosers are chosen by considering number of customers, feeder length, sensitivity of the load for interruption and economic benefits. The results of values of reliability indices SAIFI, SAIDI, EENS, and cost benefits obtained during consecutive scenarios of simulations would be the main aides for comparisons of different alternatives.

4.2 Simulation results and discussions by applying different study case scenarios

4.2.1 Scenario A: The effect of presence of one recloser at potentially selected location

This scenario is designed to assess the impact of one recloser on the reliability indices, by inserting it on the line segment LA6. In this placement of a recloser sensitivity of loads and economic benefits are taken into account. The single line diagram of figure C-1 in Appendix C shows the location configuration of recloser1 "REC1" and also summary results of this simulation is indicated as follows in the table 4.1.

Table 4.1: Computed summary results of reliability indices for scenario A.

Project:	**ETAP**	Page: 1
Location:	16.0.0C	Date: 11-29-2019
Contract:		SN: 4359168
Engineer:	Study Case scenario A: RA	Revision: Base
Filename: Ashebeka distribution system		Config.: Normal

SUMMARY

System Indexes

AENS	31.2320 MW hr / customer.yr
ASAI	0.9643 pu
ASUI	0.03567 pu
CAIDI	1.056 hr / customer interruption
EENS	1124.352 MW hr / yr
SAIDI	312.4524 hr / customer.yr
SAIFI	295.9468 f / customer.yr

AENS	Average Energy Not Supplied
ASAI	Average service Availability Index
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
EENS	Expected Energy Not Supplied
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

Table 4.1 (scenario A), illustrates the effect of one recloser in the system. As can be seen from the table, there is a variation in reliability indices of simulation results from that of original system. SAIFI was reduced from 338.4121 to 295.9468 interruption per customer per year, SAIDI was lowered from 328.5535 to 312.4524 hours per customer per year and EENS also reduced from 1247.256 to 1124.352 MWh per year as compared with the reliability indices of the existing system that has been shown before.

4.2.2 Scenario B: The effect of presence of two reclosers at potentially selected locations

In this scenario, the effects of inserting additional recloser at about midpoint of the feeder has been presented. The recloser is placed at line segment LA21 after Beriti village between Beriti and Sagure town considering the length of the feeder with respect to the first recloser implemented on scenario A. The location is shown "REC2" in figure C-2 of single line diagram on appendix C. The result is summarized as following in the table 4.2.

Table 4.2: Computed summary results of reliability indices for scenario B.

Project:	**ETAP**	Page: 1
Location:	16.0.0C	Date: 11-29-2019
Contract:		SN: 4359168
Engineer:	Study Case scenario B: RA	Revision: Base
Filename: Ashebeka distribution system		Config.: Normal

SUMMARY

System Indexes

AENS	27.8205 MW hr / customer.yr
ASAI	0.9675 pu
ASUI	0.03251 pu
CAIDI	1.274 hr / customer interruption
EENS	1001.538 MW hr / yr
SAIDI	284.7755 hr / customer.yr
SAIFI	223.5159 f / customer.yr

As can be shown from the summary result of table 4.2, the values of reliability indices has been changed from the existing system result due to insertion of additional recloser at indicated location. From the tabulated results, SAIFI was reduced from 338.4121 to 223.5159 interruption per customer per year, SAIDI was deducted from 328.5535 to 284.7755 hours per customer per year, and EENS also reduced from 1247.256 to 1001.538MWh per year as compared to that of existing or original system results.

4.2.3 Scenario C: The effect of presence of three reclosers at potentially selected locations

This scenario includes the impacts obtained by inserting additionally one recloser "REC3"at LA29 (the line segment between Shemege 2 and Sagure water pump station) as shown in single line diagram of figure C-3 on appendix C. It is the presence of totally three reclosers beside to that of the previous scenarios. The summary results of this scenario is indicated on table 4.3.

Table 4.3: Computed summary results of reliability indices for scenario C.

Project:		**ETAP**	Page:	1
Location:		16.0.0C	Date:	11-29-2019
Contract:			SN:	4359168
Engineer:		Study Case scenario C: RA	Revision:	Base
Filename:	Ashebeka distribution system		Config.:	Normal

SUMMARY

System Indexes

AENS	26.7140 MW hr / customer.yr
ASAI	0.9685 pu
ASUI	0.03149 pu
CAIDI	1.293 hr / customer interruption
EENS	961.705 MW hr / yr
SAIDI	275.8391 hr / customer.yr
SAIFI	213.3454 f / customer.yr

The results of scenario C presented in this summary table clearly shows that, implementation of third recloser as reliability improvement option at potentially selected site of loads significantly enhanced the reliability in comparison to the existing state, by reducing SAIFI from 338.4121 to 213.3454 interruption per customer per year, SAIDI from 328.5535 to 275.8391 hours per customer per year, and EENS from 1247.256 to 961.705MWh per year sequentially.

4.2.4 Scenario D: The effect of presence of DG and three reclosers at potentially selected locations

The results achieved by implementing DG with respect to the three reclosers inserted in previous successive scenarios is presented in this study case scenario. It is an insertion of photovoltaic array (PV) at most sensitive & critical load area after synchronization of phase, magnitude, and frequency of this supply with that of existing one (grid) for the purpose of supplying electric power to these loads during the regular grid supply interruption time. The location of implementation is at end point of LA26 as indicated in one line diagram of figure C-4 in appendix C. The summary is also as shown in table 4.4.

Table 4.4: Computed summary results of reliability indices for scenario D

Project:	**ETAP**	Page: 1
Location:	16.0.0C	Date: 06-12-2019
Contract:		SN: 4359168
Engineer:	Study Case scenario D: RA	Revision: Base
Filename: Ashebeka distribution system		Config.: Normal

SUMMARY

System Indexes

AENS	13.2746 MW hr / customer.yr
ASAI	0.9849 pu
ASUI	0.01513 pu
CAIDI	1.048 hr / customer interruption
EENS	477.885 MW hr / yr
SAIDI	132.5297 hr / customer.yr
SAIFI	126.5178 f / customer.yr

The results of scenario D presented in this table clearly shows that, implementation of selected DG at desired configuration significantly improved the reliability in comparison to its existing state, changing SAIFI from 338.4121 to 126.5178 interruption per customer per year, SAIDI from

328.5535 to 132.5297 hours per customer per year, and EENS from 1247.256 to 477.885MWh per year in comparison with existing system results.

4.2.5 Scenario E: The effect of presence of fuses at lateral segments keeping, DG and three reclosers at hypothetically selected locations

This scenario contains the results obtained by inserting four power fuses at line segments (LA9, LA18, LA21, & LA30) the configurations of the previous scenarios kept unchanged as indicated in one line diagram in figure C-5 of appendix C. The summary results are also shown in table 4.5 as follows.

Table 4.5: Computed summary results of reliability indices for scenario E

Project:	**ETAP**	Page:	1
Location:	16.0.0C	Date:	06-12-2019
Contract:		SN:	4359168
Engineer:	Study Case scenario E: RA	Revision:	Base
Filename: Ashebeka distribution system		Config.:	Normal

SUMMARY

System Indexes

AENS	11.2305 MW hr / customer.yr
ASAI	0.9865 pu
ASUI	0.01349 pu
CAIDI	1.274 hr / customer interruption
EENS	404.297 MW hr / yr
SAIDI	118.1662 hr / customer.yr
SAIFI	92.7715 f / customer.yr

As can be seen from the summary results of scenario E in table 4.5, the calculated values of reliability indices show significant variations from that of original system results. The comparison of the results of this scenario with that of indicated in its existing system shows that, SAIFI was reduced from 338.4121 to 92.7715 interruption per customer per year, SAIDI was decreased from

328.5535 to 118.1662hours per customer per year, & EENS also reduced from 1247.256 to 404.297MWh per year.

4.2.6 Scenario F: The effect of presence of interconnecting components between DG and MV line, and changing placement position for a recloser "REC2" to more sensitive load site

In this scenario, the effect of inserting interconnecting & protective components after DG circuit to connect it to the existing medium voltage line and changing the previous location of recloser2 "REC2" to a more sensitive load area is presented. One sectionalizer, a fuse, and two MV circuit breakers are implemented after application of photovoltaic power system & "REC2" has been changed in position from its original configuration of location LA21 to new location LA17 for the purpose of better system reliability improvement, taking load sensitivity into consideration. This implementation is indicated in one line diagram on figure C-6 of appendix C and summary of the results achieved by implementing this scenario is as follows.

Table 4.6: Computed summary results of reliability indices for scenario F

Project:	**ETAP**	Page:	1
Location:	16.0.0C	Date:	06-11-2020
Contract:		SN:	4359168
Engineer:	Study Case scenario F: RA	Revision:	Base
Filename: Ashebeka distribution system		Config.:	Normal

SUMMARY

System Indexes

AENS	8.2470 MW hr / customer.yr
ASAI	0.9904 pu
ASUI	0.00963 pu
CAIDI	1.522 hr / customer interruption
EENS	296.890 MW hr / yr
SAIDI	84.3388 hr / customer.yr
SAIFI	55.4083 f / customer.yr

As can be seen from the summary results achieved by implementation of scenario F in table 4.6, the calculated values of reliability indices show significant improvement of reliability as compared with that of original system results. The comparison of the results of this scenario with that of indicated in its existing system shows that, SAIFI has been reduced from 338.4121 to 55.4083 interruption per customer per year (83.63%), SAIDI has been decreased from 328.5535 to 84.3388 hours per customer per year (74.33%), & EENS also has been reduced from 1247.256 to 296.89 MWh per year (76.2% reduction).

Table 4.7: Summary of reliability indices for overall study case scenarios

Study Case Scenarios	**SAIFI (Int./cu./yr.)**	**SAIDI (hr./cu./yr.)**	**EENS (MWh/yr.)**	**Reduction of SAIFI (%)**	**Reduction of SAIDI (%)**	**Reduction of EENS (%)**
Existing	338.4121	328.5535	1247.256	0	0	0
A	295.9468	312.4524	1124.352	12.55	4.9	9.85
B	223.5159	284.7755	1001.538	33.95	13.32	19.7
C	213.3454	275.8391	961.705	36.96	16.04	22.89
D	126.5178	132.5297	477.885	62.61	59.66	61.69
E	92.7715	118.1662	404.297	72.58	64.03	67.59
F	55.4083	84.3388	296.89	83.63	74.33	76.2

As can be seen from the above summary of all study case scenarios, different study results are achieved by implementation of few alternatives as solution options to improve reliability of the existing distribution system and hence significant reductions in SAIFI, SAIDI, & EENS (expected energy not supplied) are obtained. The reductions in values of these indices clearly justify that the reliability of the existing distribution system is enhanced. This enhancement (improvement) is due to integration of overcurrent protective equipment and insertion of a feasible and suitable distributed generation (DG) as indicated in successive study case scenarios. For this particular thesis among scenarios used, the most preferred one is the last (scenario F) because of best result in improvement of the system reliability is achieved in it. Of course, this may not be the final option since reliability can be enhanced as the number of reclosers and DG increased in the distribution system. But, optimizing the cost of investment to improve the reliability should be the main issue and has to be taken into consideration.

4.3 Cost analysis of the study

After identifying these alternatives which are technically feasible, it is important to evaluate the cost of all the alternatives chosen including investment cost, cost of losses in the system, outage cost (cost of energy not supplied), operation and maintenance cost throughout the period of analysis. After evaluation of the cost, it is important to formulate a plan of development (i.e. size, type and time of investments), minimizing the total costs and maximizing social benefits [21]. In this particular study, both the utilities and customers of electricity are affected by problems arise due interruptions & longer interruption duration in terms of cost expended for reliability enhancement, revenue losses due to unsold energy, equipment failures, production losses etc. Simulation results achieved by application of the above different alternatives help us to make the decision to choose the solution among the number of alternatives and to recommend for the best future system that has to be practically implemented.

Among the loads in the distribution system under assessment, small industrials loads are mostly victimized to the interruptions problems, since there are sensitive loads due to societal services & revenue losses they have faced, also there are sensitive loads those suffered with problem of interruptions due to their production loss they do encountered. And also the utilities under which the system is administered are under huge amount of revenue loss due to expected energy not supplied and have many dollars of investments they could have made to improve reliability. Therefore, the total outage cost can be easily determined. But, due to lack of obtaining the accurate data, the cost analysis in this thesis is only specified to the investment cost rather than operation and maintenance costs. To do this the current tariff (the rate at which electrical energy to be sold) by electric utilities to their customers is important and has shown in the table below.

Table 4.8: Ethiopian electricity tariff since December 2018 G.C [Sagure Town EU Office].

S/N	Tariff category & block identification	Monthly Consumption	December 2018 Onward	December 2019 Onward	December 2020 Onward	December 2021 Onward
		(kWh/month)	Price Rate ETB/kWh	Price Rate ETB/kWh	Price Rate ETB/kWh	Price Rate ETB/kWh
1	***Residential***					
1.1	1st Block	Up to 50	0.2730	0.2730	0.2730	0.2730
1.2	2nd Block	Up to 100	0.4591	0.5617	0.6644	0.7670
1.3	3rd Block	Up to 200	0.7807	1.0622	1.3436	1.6250
1.4	4th Block	Up to 300	0.9125	1.2750	1.6375	2.0000
1.5	5th Block	Up to 400	0.9750	1.3833	1.7917	2.2000
1.6	6th Block	Up to 500	1.0423	1.4965	1.9508	2.4050
1.7	7th Block	Above 500	1.1410	1.5877	2.0343	2.4810
2	***General Tariff***					
2.1	Flat Rate		1.0352	1.3982	1.7611	2.1240
3	***Low Voltage Industry Tariff***					
3.1	Flat Rate		0.8161	1.0544	1.2927	1.5310
3.2	Demand Charge rate		50.0000	100.0000	150.0000	200.0000
4	***Medium Voltage Industry Tariff, 15kv & 33kv***					
4.1	Flat Rate		0.6047	0.8008	0.9969	1.1930
4.2	Demand Charge rate		36.8850	73.7700	110.6550	147.5400

5	***High Voltage Industry tariff Above 66KV***					
5.1	Flat Rate		0.5174	0.6540	0.7911	0.9280
5.2	Demand Charge rate		21.9100	43.8200	65.7300	87.6400
6	***Street Light Tariff***					
6.1	Flat Rate		1.0352	1.3982	1.7611	2.1240
7	***Bulk Supply Tariff***					
7.1	Demand Charge rate per kw		39.2908	78.5815	117.8723	157.1600
7.2	Generation Tariff, Monthly per kw		0.2218	0.4435	0.6653	0.8870

4.3.1 Electric utility and its customer based cost analysis for the existing system

As shown previously in table 3.7 and 4.7 of computed summary results of reliability indices for existing system, the EENS is 1247.256MWh per year. Based on this information and tariff amendment of December 2019 onward shown in the table 4.8, the annual revenue loss due to unsupplied energy of the existing system for electric utilities can be calculated as follows.

$$Revenue\ loss\ due\ to\ EENS$$

$$= \left(0.273\ to\ 1.5877\ (\frac{ETB}{KWh})\right) * 1{,}247{,}256\ \left(\frac{KWh}{year}\right) ----------(4.1)$$

$$= 340{,}500.89\ to\ 1{,}980{,}268.35\ (\frac{ETB}{year}).$$

Therefore, the average annual revenue loss of the existing system is ***1,160,384.62 ETB***.

Based on the currency exchange of December 23, 2019G.C, 1USD is 31.9873 ETB and hence the annual revenue loss is ***36,276.42 USD***.

Taking only one & the most critical load point customer per the data obtained from this respective customer for the purpose of rough comparison, the following calculations are performed to obtain the revenue loss due to stoppage of production as a result of electric power interruptions and outage.

Loss of revenue for Assela town water supply and Sewerage Enterprise

Assela town water supply & sewerage enterprise is a governmental organization that provides the town with drinking water & sewerage removal. This service sector is the customer of Assela and Sagure electric utilities which has encountered annually significant revenue loss due to unproduced water from its water treatment plant. Per information and data obtained from this town drinking water service provider, the most critical period of time in which the impact of electric power interruptions problem on water production is for total of eight (8) months from the beginning days of **October** to the end of **May** and an average water production loss is estimated to be 185m^3/hr. (that is the total production minus (due to gravity supply plus due to generator supply)). In another words, the total production is 350m^3/hr. and the average gravity & average supply due to generator are 65 and 100m^3/hr. respectively.

Using SAIDI of existing system for eight (8) months, estimated water interruption hours will be:

$$Average\ water\ interruption\ hours\ per\ year = \frac{328.5535*8}{12} = 219.04hr\ ------\ (4.2)$$

$$\text{And } Average\ water\ interruption\ per\ month = \frac{219.04}{8} = 27.38hr\ --------\ (4.3)$$

The water supply source of water pumping station has a diesel generator of reduced performance with capacity of 200KVA and it works for twelve (12) hours per month and it works totally 96 hours per eight (8) months or a year. Hence, water production per year due to this generator operation and performance is 96*100=9600m^3.

The fuel consumption of the generator is twenty (20) liters per hours and the fuel cost of the generator is as follows.

The total fuel consumption of the generator per eight (8) months or a year = 96*20 = 1920 liters.

The total fuel cost of the generator per eight months or a year = 1920*18.72 = 35,942.4 ETB.

Using result of (4.2) and average water production loss:

$The\ total\ water\ loss\ per\ year\ due\ to\ stoppage\ of\ production = 219.04 * 185 =$ $40{,}522.4m^3$.

The net water production loss per year due to stoppage $= 40{,}522.4 - 9600 = 30{,}922.4m^3$.

The average revenue loss per year due to unproduced drinking water from Assela town water treatment plant $= 30{,}922.4m3 * 20.75(\frac{ETB}{m3}) = \boldsymbol{641{,}639.8\ ETB}$ and it is ***20,059.21 USD.***

The average cost of $1m^3$ water is 20.75ETB [Assela Town Water Supply Office]

4.2.2 Electric utility and its customer based cost analysis after reliability improvement

After improvement of the system performance, the reliability indices have been reduced as shown from the summary results indicated previously. Based on this hypothesis, the cost analysis for both the utility and a customer is as follows. From the results summarized in table 4.7, the best preferable achievement obtained for SAIDI and EENS are 84.3388 h/customer/year & 296.89 MWh per year respectively. Using equation (4.1):

$$The\ revenue\ loss\ after\ this\ enhancement\ per\ year\ due\ to\ EENS = \left(0.273\ to\ 1.5877\left(\frac{ETB}{KWh}\right)\right) * 296{,}890KWh = 81{,}050.97\ to\ 471{,}372.25\ ETB.$$

Hence, the average revenue loss after reliability improvement per year due to unsupplied energy is equals to ***276,211.61ETB*** or ***8,635.04USD***.

Therefore, the average saved revenue per year as a result of reliability improvement is the difference between the results in the existing and that of obtained after improvement.

$Average\ annual\ saved\ revenue = 1{,}160{,}384.62 - 276{,}211.61 = \boldsymbol{884{,}173.01ETB}$. And it is ***27,641.38USD***.

The investment cost can be manipulated by considering the cost of total installed reclosers used to reform the improved system. The average cost of one recloser is 15,000 USD [27] and also from other sites (5,000-15,000 USD); hence, taking maximum cost, the cost of three reclosers is 45,000 USD or (1,439,428.5 ETB).

The payback period of recloser investment is the length of the time to recover or repay the cost of an investment and it can be computed as follows [29].

$$\text{Payback period} = \frac{Investment\ cost(ETB)}{Annual\ saving(\frac{ETB}{year})} ------------------------ (4.4)$$

Using this equation, the payback period of the improved system will be:

$$\text{Payback period} = 1{,}439{,}428.5\ ETB \Big/ \frac{884{,}173.01\ ETB}{year} = 1.63\ years$$

Therefore, the payback period indicates that it takes 1.63 years that is one year and seven months and sixteen days. Hence the implementation of reclosers for the existing distribution system of Ashebeka feeder is cost effective solution to mitigate the root causes of the problem.

Using SAIDI of the system after reliability improvement for eight (8) months, estimated water interruption hours also will be as shown:

$$\text{Average water interruption hours per year} = \frac{84.3388*8}{12} = 56.23\ hrs\ ----------- (4.5)$$

$$\text{And water interruption per month} = \frac{56.23}{8} = 7.03\ hrs ----------------- (4.6)$$

A diesel generator in water source pumping station can operate the same performance as that of existing system and it works for twelve (12) hours per month and it works totally 96 hours per eight (8) months or a year. Hence, it covers all interruption hours, but due to its less capacity & poor performance, water production due to this generator operation and performance is only 100m^3/hr. as stated before. Therefore, water production per year due to its operations is 56.23*100=5623m^3.

The fuel consumption of the generator is twenty (20) liters per hours and the fuel cost of the generator is as follows.

The total fuel consumption of the generator per eight (8) months or a year = 56.23*20 = 1124.6 liters.

The total fuel cost of the generator per eight months or a year = 1124.6liters*18.72ETB/liters = 21,052.51 ETB.

The total water loss per year due to stoppage of production after improvement $= 56.23 * 185 = 10{,}402.55$m^3.

$The\ net\ water\ production\ loss\ per\ year\ due\ to\ stoppage = 10{,}402.55 - 5623 = 4779.55$m^3.

$$The\ average\ revenue\ loss\ per\ year\ due\ to\ unproduced\ water = 4779.55m3 * 20.75\left(\frac{ETB}{m3}\right) = 99{,}175.66ETB.$$

Therefore, the average annual saved revenue as a result of reliability improvement for drinking water production process is also the difference between the results in the existing and that of obtained after distribution system reliability improvement.

Hence, the average annual savings for water supply utility$= 641{,}639.8 - 99{,}175.66 =$ $\mathbf{542,464.14ETB = 16,958.73USD}$.

Let's compare the investment cost of preferred DG (solar power) with this average annual savings of the water supply utility because of the electric distribution system reliability enhancement work.

The cost of solar power is 0.55 USD/Watt in 2016 G.C [40]. And also there is another information regarding costs of the solar power.

Solar PV module prices have fallen by 80% since the end of 2009, and PV increasingly offers an economic solution for new electricity generation and for meeting energy service demands, both on-grid and off-grid [39].

Solar PV module prices have fallen rapidly since the end of 2009, to between USD 0.52 and USD 0.72/watt (W) in 2015. At the same time, balance of system costs also have declined. As a result, the global weighted average cost of utility-scale solar PV fell by 62% between 2009 and 2015 and could decline by 57% from 2015 levels by 2025 GC [39].

Based on this information, the average cost of solar PV module in 2015 is 0.62 USD per watt. It could decrease by 57% from 2015 for next ten years, hence it could be 0.35USD per watt in 2025. Therefore, assuming equal decreasing rate, the expected cost per watt in 2019 will be:

$$0.62 - \left(57\% * 0.62 * \frac{4}{10}\right) = 0.62 - 0.14 = 0.48USD.$$

Taking this price, the investment cost of the selected DG is as follows.

The capacity of PV power system that has been used for this distribution system for improving the system performance especially in a critical load sector is 438.32KW or 0.438MW.

Hence, the investment cost of this solar power= $0.48\left(\frac{USD}{W}\right) * 0.438MW = \mathbf{210{,}240}\ \boldsymbol{USD} = \mathbf{6{,}725{,}009.95}\ \boldsymbol{ETB}$.

Using equation (4.4), payback period = $\frac{6{,}725{,}009.95\ ETB}{542{,}464.14\ \frac{ETB}{year}} = 12.4\ years$.

As indicated from this result, the payback period in investment of the intended solar power for this distribution system when compared with annual saving of water supply utility is 12.4 years and that is about twelve years and four month and twenty four days.

Based on this analysis, the investigator can suggest that the problem of unreliable power supply happening in Ashebeka distribution system can be mitigated & tackled by using the PV power supply system with bilateral investment of the water supply utility and electric utilities. This idea is used to help in reducing the payback period of investment that could be made by only electric utility. Even by sharing this investment cost 50% for these utilities, the payback period also could be reduced to minimize the burden that would be arise for one utility. As a result, the reliability of the distribution system can be improved easily, since unreliable power distribution can harm the revenues and quality service providing activities of the electric and water supply utilities, provided that joint agreement regarding happening problem of the loss in their revenue and their customer dissatisfaction has to be taken into account.

CHAPTER FIVE

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

Based on the results obtained from the reliability analysis of Ashebeka distribution system and the simulations conducted with reclosers and a selected DG for enhancement of its reduced existing reliability performance, the following conclusions and recommendations have been made and the possible future works are also proposed.

5.1 Conclusions

Based on the study results of this thesis, the reliability of Ashebeka distribution system does not meet the requirements set by Ethiopian Electric Agency (EEA). The system average interruption frequency index (SAIFI) of the existing system is 338.4121 interruptions per customer per year and the system average interruption duration index (SAIDI) is 328.5535 hours per customer per year. There is high unavailability of electric power in the distribution network. There is huge loss of unsupplied energy due to planned and forced (unplanned) outages as indicated. The average annual unsupplied (unsold) energy is 1247.256 MWh. This results in loss of around ***1,160,384.62 ETB*** per year for Ethiopian electric utility and it also causes an average revenue loss estimation of **641,639.8 ETB p**er year for a single customer (Assela town water supply utility) due to unproduced drinking water from water treatment plant. This shows that the system is under huge amount of economic crisis for both the electric utilities and their customers beside highly reduced quality of serving the society & their respective customers.

Six different study case scenarios were applied to improve the unfortunate existing reliability performance of the distribution system. Reclosers were implemented for the system in load locations where economic and social benefits were the most essential. And also a suitable DG (the PV array) with 0.438MW power has been designed to be used as an additional and alternative power supply for the expected most critical & sensitive society issued load center. The scenario with the best reliability performance achievement result was selected as finally enhanced reform of the improved version (future) for the distribution system under the study, taking into account of economic impacts for placement configurations and number of reclosers as well as number and sizing of a DG. Three reclosers and one DG with interconnecting & protective devices are configured in the improved status of the distribution system in economic and social benefited load points. Based on this applications, SAIFI has been reduced by 83.63% as it compared with that of the result in existing system. SAIDI and EENS are also reduced by 74.33% and 76.2% respectively. The annual revenue savings obtained for electric utility from the improved system by implementation of the reclosers is compared with investment made due to it and a DG investment is also compared with the savings gained by water production of water supply utility. The cost analysis results guide the author to conclude that, co-joint bilateral investments of the electric utilities & their customer especially for DG case, is an essential and recommended idea to tackle the problem of reduced & poor reliability performance of the distribution system studied, since the implementation benefits both and it is also profitable.

5.2 Recommendations

The distribution system reliability problems can be improved through different alternative options. Hence, in this studied distribution system an investigator recommends the concrete electric poles for expected better system reliability enhancement due to aging of existing wooden poles. And also there must be replacement of the present three-phase three-wire overhead bare all aluminum conductors by cost effective equivalent sized insulated conductors to reduce pronounced short circuits and earth faults which are more common in this system.

The line near to road sides has to be protected by pole guards to minimize the damages that can be caused by speedy driving and animals attack.

There must be awareness giving program by utility experts for rural dwellers especially for those nearer to the overhead line about the endangerment of the line to avoid the human errors and hazard encountered on the system & on the society of rural areas.

Another critical point which forced the researcher to be recommended is that, the electric utility office managers and the town administrative bodies have to come together to deal with solutions for illegally built residential homes under overhead existing line to reduce the hazard that is happening.

There must be periodical tree trimming program that has to be practiced by the electric utilities since it has great contribution on the reliability improvement of Ashebeka distribution system.

The preventive maintenances has to be planned and done within some intervals of times to minimize unreliability due to outages specially for wooden poles since many poles are largely tilted and left failed only supported by successive poles and the conductors.

The data recording culture has to be the main focus area of the jobs & must be practiced for both substation and utility offices, since there are a lot of gaps in data recording activities.

The performance of diesel generator in water source of Assela town water supply in Ashebeka water pumping station must be improved to solve the existing drinking water interruption problems that could happen due to power interruptions.

The open reservoir (Balancing chamber) in water treatment plant of Assela town water supply has to be increased in volume for further raw water storage to reduce water supply interruptions to water treatment plant during night and rain cloud time of power interruptions. Because, there is excess overflow of raw water in this reservoir due to water production capacity limitation of water treatment plant during pump operational & gravity supply water available time.

5.3 Future Work

The future works that could be performed regarding power distribution system reliability assessment are as follow:

- The reliability assessment and its corresponding alternative solutions has to be investigated for the substation (Assela distribution substation) as this thesis was specified for only one of the MV feeder.
- The investigator suggests that the power factor assessment and investigation for the same feeder has to be one of the next future works to mitigate unnecessary power loss due to industrial inductive loads.
- It is essential to deal with power quality related problems for the feeder under study to address and satisfy customers' needs & to assure economic benefits of the utilities.

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APPENDIX

Appendix A: Detail interruption data of base year 2010 E.C (2017/18 G.C) and Summary of interruption data for years 2006 to 2010 E.C (2013/14-2017/18 G.C.) for 15 kV Ashebeka Feeder -05

Table A-1: Detail interruption data of base year 2010 E.C (2017/18 G.C)

Date: DD/MM/YY		***Inter.time (hr:min.)***	***Reco.time (hr: min.)***	***Dur.time (hrs)***	***Type of fault relay acted***
E.C.	***G.C.***				
2/1/2010	12/9/2017	11:02	11:38	0.6	op
5/1/2010	15/9/2017	16:24	16:29	0.083	short ckt
6/1/2010	16/9/2017	18:37	18:52	0.25	op
7/1/2010	17/9/2017	14:09	14:18	0.15	short ckt
8/1/2010	18/9/2017	8:42	8:58	0.267	op
11/1/2010	21/9/2017	11:25	11:50	0.416	op
12/1/2010	22/9/2017	15:25	15:28	0.05	short ckt
>>	22/9/2017	18:28	18:56	0.467	op
13/1/2010	23/9/2017	9:19	9:33	0.233	op
14/1/2010	24/9/2017	13:15	13:20	0.083	short ckt
16/1/2010	26/9/2017	16:57	17:19	0.367	short ckt
17/1/2010	27/9/2017	17:23	17:42	0.317	op
19/1/2010	29/9/2017	8:01	9:03	1.033	short ckt
>>	29/9/2017	11:50	13:25	1.416	>>
>>	29/9/2017	18:13	18:18	0.083	>>
20/1/2010	30/9/2017	6:56	7:06	0.167	short ckt
21/1/2010	1/10/2017	6:02	8:02	2	short ckt
>>	1/10/2017	9:58	10:05	0.117	>>
>>	1/10/2017	11:58	12:10	0.2	op
22/1/2010	2/10/2017	13:25	13:35	0.167	op
>>	2/10/2017	17:20	17:56	0.6	>>
23/1/2010	3/10/2017	8:43	8:47	0.066	>>
>>	3/10/2017	12:03	1:.10	0.116	>>
24/1/2010	4/10/2017	4:20	7:50	3.5	Short ckt
25/1/2010	5/10/2017	20.08	20:20	0.2	op
26/1/2010	6/10/2017	11:19	11:27	0.133	Op
27/1/2010	7/10/2017	10:03	10:06	0.05	Short ckt
28/1/2010	8/10/2017	15:30	15:40	0.167	>>
2/2/2010	12/10/2017	14:00	14:20	0.333	Short ckt
3/2/2010	13/10/2017	7:07	7:22	0.25	Short ckt
>>	13/10/2017	7:55	9:01	1.1	>>
4/2/2010	14/10/2017	12:16	12:24	0.133	Op
5/2/2010	15/10/2017	12:20	12:25	0.083	Short ckt
>>	15/10/2017	14:33	14:53	0.333	Op
7/2/2010	17/10/2017	12:42	12:49	0.117	Op
9/2/2010	19/10/2017	14:10	14:15	0.083	Short ckt
14/2/2010	24/10/2017	14:07	12:24	0.1	Op
16/2/2010	26/10/2017	10:50	10:54	0.0667	Op
>>	26/10/2017	12:10	12:17	0.117	Short ckt
17/2/2010	27/10/2017	11:40	11:50	0.166	Short ckt
>>	27/10/2017	14:45	16:10	1.25	Op
19/2/2010	29/10/2017	10:13	10:18	0.0833	Short ckt
20/2/2010	30/10/2017	10:51	12:54	2.05	Op

23/2/2010	2/11/22017	21:05	21:13	0.133	Short ckt
26/2/2010	5/11/2017	2:20	9:40	7.333	op
29/2/2010	8/11/2017	11:47	11:50	0.05	Short ckt
1/3/2010	10/11/2017	10:28	10:40	0.2	Op
>>	10/11/2017	15:55	16:32	0.617	Earth fault
2/3/2010	11/11/2017	12:53	13:08	0.25	Op
3/3/2010	12/11/2017	9:50	12:52	3.033	Short ckt
4/3/2010	13/11/2017	9:53	9:57	0.067	Short ckt
>>	13/11/2017	16:20	16:25	0.083	Earth fault
>>	13/11/2017	16:58	17:04	0.1	Short ckt
5/3/2010	14/11/2017	12:48	12:53	0.083	Short ckt
6/3/2010	15/11/2017	11:11	11:17	0.1	Op
>>	15/11/2017	15:40	16:06	0.433	Short ckt
7/3/2010	16/11/2017	10:52	12:18	1.433	Earth fault
8/3/2010	17/11/2017	15:33	15:40	1.117	Op
9/3/2010	18/11/2017	16:13	18:54	2.683	Short ckt
10/3/2010	19/11/2017	6:15	8:30	2.25	Earth fault
>>	19/11/2017	10:50	11:05	0.25	Short ckt
11/3/2010	20/11/2017	6:25	6:34	0.15	Op
>>	20/11/2017	9:18	16:20	7.0333	Op
>>	20/11/2017	11:27	12:01	0.567	Op
14/3/2010	23/11/2017	7:57	8:02	0.083	Short ckt
>>	23/11/2017	8:51	9:49	0.967	Op
>>	23/11/2017	14:44	15:51	1.1	Op
16/3/2010	25/11/2017	12:40	13:10	1.167	Op
>>	25/11/2017	17:17	17:52	0.583	Op
>>	25/11/2017	19:57	20:07	0.167	Short ckt
17/3/2010	26/11/2017	12:05	12:09	0.067	Short ckt
>>	26/11/2017	12:20	14:28	2.133	Short ckt
18/3/2010	27/11/2017	14:22	14:53	0.517	Earth fault
20/3/2010	29/11/2017	14:07	14:11	0.067	Short ckt
21/3/2010	30/11/2017	13:05	13:10	0.083	Short ckt
22/3/2010	1/12/2017	2:40	8:57	6.2833	op
>>	1/12/2017	11:20	16:50	5.5	Short ckt
>>	1/12/2017	21:30	22:45	1.25	Short ckt
25/3/2010	4/12/2017	16:10	17:30	1.333	Short ckt
26/3/2010	5/12/2017	3:20	5:30	2.167	Short ckt
>>	5/12/2017	10:30	12:50	2.333	Short ckt
>>	5/12/2017	20:18	21:40	1.367	Short ckt
28/3/2010	7/12/2017	20:15	21:47	1.533	op
>>	7/12/2017	12:26	12:56	0.5	Short ckt
>>	7/12/2017	17:35	18:05	0.5	Short ckt
3/4/2010	12/12/2017	7:34	7:58	0.4	op
>>	12/12/2017	13:39	17:37	3.967	Earth fault
>>	12/12/2017	19:32	19:40	0.133	>>
>>	12/12/2017	22:10	22:50	0.667	Short ckt
4/4/2010	13/12/2017	3:12	4:23	1.1833	>>
5/4/2010	14/12/2017	1:28	1:46	0.3	>>
>>	14/12/2017	5:36	7:43	2.117	Earth fault
>>	14/12/2017	15:15	16:18	1.05	Short ckt
7/4/2010	16/12/2017	3:38	6:39	3.0167	op
8/4/2010	17/12/2017	17:34	19:29	1.9167	Short ckt
9/4/2010	18/12/2017	8:20	9:39	1.3167	Short ckt

>>	18/12/2017	2:42	2:54	0.2	Earth fault
>>	18/12/2017	8:23	9:54	1.5167	Short ckt
>>	18/12/2017	19:37	20:28	0.85	Short ckt
10/4/2010	19/12/2017	16:41	17:27	0.767	Short ckt
11/4/2010	20/12/2017	6:39	8:34	1.9167	op
>>	20/12/2017	14:27	15:31	1.067	Short ckt
12/4/2010	21/12/2017	1:55	3:41	1.767	Short ckt
>>	21/12/2017	13:27	14:45	1.3	Earth fault
>>	21/12/2017	16:42	16:54	0.2	Short ckt
14/4/2010	23/12/2017	5:32	15:43	10.1833	Short ckt
15/4/2010	24/12/2017	2:40	4:18	1.367	Short ckt
>>	24/12/2017	6:25	7:54	1.4833	Short ckt
>>	24/12/2017	11:29	14:42	3.2167	Short ckt
>>	24/12/2017	16:32	22:39	6.117	Short ckt
16/4/2010	25/12/2017	6:42	6:57	0.25	Earth fault
17/4/2010	26/12/2017	4:43	6:58	2.25	Earth fault
19/4/2010	28/12/2017	2:37	5:47	3.167	op
>>	28/12/2017	7:28	7:39	0.1833	Short ckt
>>	28/12/2017	11:33	11:55	0.367	Short ckt
>>	28/12/2017	13:26	16:38	3.2	Short ckt
20/4/210	29/12/2017	12:39	13:37	0.967	Short ckt
>>	29/12/2017	17:04	21:29	4.4167	Short ckt
22/4/2010	31/12/2017	17:05	17:26	0.35	>>
23/4/2010	1/1/2018	16:22	16:26	0.067	>>
25/4/2010	3/1/2018	18:30	10:35	0.0833	Op
>>	3/1/2018	11:42	11:47	0.083	Short ckt
>>	3/1/2018	12:24	12:30	0.1	Short ckt
>>	3/1/2018	12:35	13:50	1.416	Short ckt
>>	3/1/2018	15:40	17:10	1.5	Short ckt
26/4/2010	4/1/2018	7:20	7:37	0.283	Op
>>	4/1/2018	11:16	11:36	0.333	Op
>>	4/1/2018	16:41	16:46	0.083	Short ckt
27/4/2010	5/1/2018	8:10	10:20	2.167	Op
27/4/2010	5/1/2018	11:12	15:15	4.05	Short ckt
>>	5/1/2018	15:57	17:11	1.233	Short ckt
28/4/2010	6/1/2018	12:55	15:36	2.683	Short ckt
>>	6/1/2018	13:10	13:15	0.083	Short ckt
>>	6/1/2018	16:04	19:07	3.05	Short ckt
30/4/2010	8/1/2018	13:54	13:55	0.067	Short ckt
1/5/2010	9/1/2018	15:04	15:12	0.133	Op
2/5/2010	10/1/2018	15:38	15:53	0.25	Op
3/5/2010	11/1/2018	10:30	10:34	0.15	Short ckt
>>	11/1/2018	11:05	11:08	0.05	Short ckt
>>	11/1/2018	11:10	11:30	0.333	Short ckt
>>	11/1/2018	11:22	11:26	0.067	op
>>	11/1/2018	11:34	14:34	3	Short ckt
>>	11/1/2018	14:48	14:51	0.216	>>
>>	11/1/2018	15:30	17:10	1.667	>>
4/5/2010	12/1/2018	10:06	10:14	0.133	Op
>>	12/1/2018	10:47	10:55	0.133	Short ckt
>>	12/1/2018	13:10	14:21	1.183	>>
>>	12/1/2018	14:35	15:29	0.9	>>
>>	12/1/2018	15:40	17:04	1.4	Short ckt

5/5/2010	13/1/2018	9:00	9:05	0.083	Op
6/5/2010	14/1/2018	9:30	10:20	0.083	op
>>	14/1/2018	12:30	12:45	0.25	Earth fault
7/5/2010	15/1/2018	10:48	10:55	0.116	Short ckt
8/5/2010	16/1/2018	9:55	10:05	0.167	Op
>>	16/1/2018	10:56	11:12	0.267	Op
14/5/2010	22/1/2018	10:36	10:50	0.233	Op
15/5/2010	23/1/2018	5:30	15:50	10.33	Short ckt
16/5/2010	24/1/2018	8:30	12:22	3.867	Short ckt
>>	24/1/2018	14:50	14:55	0.083	Op
17/5/2010	25/1/2018	9:15	12:05	2.833	Op
>>	25/1/2018	16:10	17:16	1.1	Op
>>	25/1/2018	19:10	19:30	0.333	Op
23/5/2010	31/1/2018	10:30	12:30	2	op
25/5/2010	2/2/2018	9:41	10:49	1.133	Op
28/5/2010	5/2/2018	12:30	17:02	4.533	Short ckt
2/6/2010	9/2/2018	15:36	15:40	0.067	Short ckt
>>	9/2/2018	18:00	18:08	0.133	Earth fault
9/6/2010	16/2/2018	10:30	10:40	0.167	Short ckt
13/6/2010	20/2/2018	7:30	7:50	0.333	Short ckt
>>	20/2/2018	19:29	19:45	0.4	Op
14/6/2010	21/2/2018	14:20	14:38	0.333	Short ckt
>>	21/2/2018	18:45	19:00	0.25	Op
15/6/2010	22/2/2018	5:17	15:20	10.05	Short ckt
16/6/2010	23/2/2018	10:15	11:58	0.716	op
>>	23/2/2018	17:38	17:42	0.067	Short ckt
17/6/2010	24/2/2018	8:30	8:50	0.333	Short ckt
18/6/2010	25/2/2018	7:50	8:30	0.66	Short ckt
>>	25/2/2018	12:28	12:30	0.033	Short ckt
>>	25/2/2018	12:55	13:00	0.083	Short ckt
>>	25/2/2018	13:03	13:18	0.25	Short ckt
19/6/2010	26/2/2018	9:49	10:43	0.9	Short ckt
22/6/2010	1/3/2018	18:35	1:34	6.15	sol
23/6/2010	2/3/2018	9:21	9:26	0.083	Short ckt
>>	2/3/2018	10:10	13:13	3.05	Short ckt
>>	2/3/2018	14:26	16:05	1.65	Short ckt
>>	2/3/2018	16:55	19:07	2.2	Short ckt
24/6/2010	3/3/2018	9:10	9:25	0.25	Short ckt
>>	3/3/2018	9:50	9:58	0.133	Short ckt
>>	3/3/2018	10:20	11:10	0.833	Short ckt
>>	3/3/2018	19:15	19:23	0.133	Short ckt
25/6/2010	4/3/2018	21:37	21:47	0.167	Short ckt
>>	4/3/2018	21:49	9:35	11.767	Short ckt
26/6/2010	5/3/2018	10:22	12:15	1.833	Short ckt
>>	5/3/2018	14:42	15:17	0.583	Short ckt
>>	5/3/2018	17:23	17:55	0.533	Short ckt
29/6/2010	8/3/2018	22:30	22:36	0.1	Short ckt
1/7/2010	10/3/2018	16:47	16:51	0.067	Op
2/7/2010	11/3/2018	16:30	16:39	0.15	Op
3/7/2010	12/3/2018	10:45	10:50	0.083	Short ckt
>>	12/3/2018	11:25	11:29	0.067	Short ckt
>>	12/3/2018	11:49	11:52	0.05	>>
>>	12/3/2018	13:00	14:43	1.717	>>

>>	12/3/2018	16:02	16:15	0.217	>>
5/7/2010	14/3/2018	8:37	8:41	0.067	>>
>>	14/3/2018	9:22	9:57	0.583	>>
6/7/2010	15/3/2018	11:41	11:48	0.117	>>
9/7/2010	18/3/2018	10:05	10:20	0.25	op
10/7/2010	19/3/2018	11:10	11:16	0.1	Short ckt
>>	19/3/2018	11:23	12:10	0.783	>>
>>	19/3/2018	16:14	16:19	0.083	>>
>>	19/3/2018	18:50	18:55	0.083	>>
11/7/2010	20/3/2018	9:55	11:55	2	>>
>>	20//2018	14:30	14:40	0.167	op
>>	20/3/2018	19:41	20:20	0.65	Short ckt
14/7/2010	23/3/2018	13:21	17:11	3.833	Short ckt
>>	23/3/2018	18:28	18:33	0.083	Short ckt
16/7/2010	25/3/2018	15:26	15:36	0.167	Short ckt
>>	25/3/2018	18:35	18:40	0.083	Short ckt
17/7/2010	26/3/2018	15:38	16:04	0.433	Short ckt
>>	26/3/2018	16:50	18:22	1.533	Short ckt
22/7/2010	31/3/2018	6:40	6:50	0.167	op
5/8/2010	13/4/2018	4:20	7:30	3.167	Short ckt
>>	13/4/2018	10:10	10:20	0.167	op
>>	13/4/2018	10:50	10:55	0.083	Short ckt
>>	13/4/2018	11:30	14:05	2.583	Short ckt
7/8/2010	15/4/2018	3:28	15:39	12.1833	Short ckt
8/8/2010	16/4/2018	7:20	9:20	2	Short ckt
11/8/2010	19/4/2018	15:58	18:51	2.883	Short ckt
13/8/2010	21/4/2018	9:50	10:10	0.334	Short ckt
>>	21/4/2018	17:40	17:47	0.117	Short ckt
15/8/2010	23/4/2018	11:44	11:56	0.2	op
>>	23/4/2018	17:05	17:10	0.083	Short ckt
16/8/2010	24/4/2018	17:11	17:13	0.0334	Short ckt
17/8/2010	25/4/2018	15:17	15:32	0.25	op
18/8/2010	26/4/2018	9:48	10:20	0.533	Short ckt
>>	26/4/2018	10:30	11:45	0.25	Short ckt
>>	26/4/2018	11:59	13:30	1.516	Short ckt
>>	26/4/2018	18:55	19:22	0.45	Short ckt
22/8/2010	30/4/2018	12:50	13:50	1	Short ckt
24/8/2010	2/5/2018	6:06	12:20	6.233	Op
25/8/2010	3/5/2018	6:38	6:45	0.117	op
>>	3/5/2018	15:20	15:25	0.083	Short ckt
>>	3/5/2018	15:28	16:40	1.2	Short ckt
26/8/2010	4/5/2018	12:56	13:13	0.283	Short ckt
>>	4/5/2018	15:05	15:34	0.316	Short ckt
27/8/2010	5/5/2018	3:19	12:39	9.333	Short ckt
29/8/2010	7/5/2018	15:30	17:48	2.3	Short ckt
30/8/2010	8/5/2018	11:19	11:26	0.117	op
>>	8/5/2018	15:15	15:21	0.1	Short ckt
>>	8/5/2018	15:35	15:58	0.383	Short ckt
2/9/2010	10/5/2018	6:02	6:12	0.167	Short ckt
3/9/2010	11/5/2018	14:53	14:58	0.083	Short ckt
>>	11/5/2018	16:18	16:25	0.117	Short ckt
>>	11/5/2018	17:42	17:48	0.1	Short ckt
5/9/2010	13/5/2018	9:50	10:00	0.167	Short ckt

>>	13/5/2018	13:20	14:00	0.667	Earth fault
>>	13/5/2018	21:45	21:50	0.083	Earth fault
6/9/2010	14/5/2018	13:50	13:55	0.083	Short ckt
>>	14/5/2018	15:30	16:10	0.667	Short ckt
>>	14/5/2018	19:20	19:30	0.167	Op
>>	14/5/2018	23:05	9:05	10	Short ckt
8/9/2010	16/5/2018	10:07	10:40	0.55	Op
8/9/2010	16/5/2018	10:45	10:50	0.083	Short ckt
>>	16/5/2018	14:23	14:38	0.25	Op
11/9/2010	19/5/2018	19:55	20:20	0.416	Op
13/9/2010	21/5/2018	20:45	8:50	12.083	Op
14/9/2010	22/5/2018	9:25	9:29	0.067	Short ckt
>>	22/5/2018	9:58	10:28	0.5	Short ckt
16/9/2010	24/5/2018	9:13	9:36	0.382	Op
20/9/2010	28/5/2018	6:40	7:36	0.933	Short ckt
>>	28/5/2018	1:.08	12:14	0.1	Short ckt
>>	28/5/2018	12:35	11:32	4.95	Short ckt
>>	28/5/2018	13:40	13:55	0.25	op
>>	28/5/2018	18:18	18:23	0.083	Short ckt
21/9/2010	29/5/2018	16:28	16:38	0.167	Op
22/9/2010	30/5/2018	13:30	12:20	22.833	Short ckt
23/9/2010	31/5/2018	14:18	14:25	0.117	Short ckt
30/9/2010	7/6/2018	11:38	11:43	0.083	Short ckt
2/10/2010	9/6/2018	8:01	8:06	0.083	Op
3/10/2010	10/6/2018	3:50	7:50	4	Short ckt
6/10/2010	13/6/2018	13:45	14:00	0.25	Op
7/10/2010	14/6/2018	6:20	15:16	8.933	Short ckt
8/10/2010	15/6/2018	11:30	11:38	0.113	Op
>>	15/6/2018	15:02	15:05	0.083	Short ckt
9/10/2010	16/62018	10:50	10:55	0.083	Short ckt
>>	16/6/2018	11:06	11:33	0.45	Op
11/10/2010	18/6/2018	12:38	14:14	1.6	Op
12/10/2010	19/6/2018	5:57	16:05	10.113	Short ckt
13/10/2010	20/6/2018	9:30	10:10	0.65	Short ckt
>>	20/6/2018	17:40	17:49	0.15	Op
17/10/2010	24/6/2018	6:40	7:55	1.25	Short ckt
>>	24/6/2018	8:15	9:02	0.783	Short ckt
18/10/2010	25/6/2018	14:15	16:09	1.9	Op
20/10/2010	27/6/2018	18:10	18:41	0.516	Op
>>	27/6/2018	19:30	19:38	0.133	Op
25/10/2010	2/7/2018	6:50	7:02	0.117	Short ckt
28/10/2010	5/7/2018	7:20	7:30	0.167	Short ckt
>>	5/7/2018	17:50	17:55	0.083	Op
29/10/2010	6/7/2018	12:40	12:50	0.167	Short ckt
30/10/2010	7/7/2018	19:48	20:00	0.2	Op
1/11/2010	8/7/2018	6:10	6:30	0.333	Short ckt
>>	8/7/2018	11:22	11:30	0.133	Short ckt
9/11/2010	16/7/2018	13:47	14:22	0.583	Op
10/11/2010	17/7/2018	13:52	14:29	0.616	Op
>>	17/7/2018	10:37	15:58	5.35	Short ckt
12/11/2010	19/7/2018	10:20	10:29	0.15	Short ckt
13/11/2010	20/7/2018	12:08	12:17	0.15	Short ckt
>>	20/7/2018	16:45	16:50	0.083	Short ckt

14/11/2010	21/7/2018	18:35	19:20	0.75	op
15/11/2010	22/7/2018	8:20	9:13	0.883	Short ckt
24/11/2010	31/7/2018	16:47	16:57	0.167	Short ckt
26/11/2010	2/8/2018	13:16	13:54	0.633	Op
2/12/2010	8/8/2018	10:16	10:40	0.4	Op
4/12/2010	10/8/2018	16:51	17:19	0.467	Op
8/12/2010	14/8/2018	7:25	7:34	0.15	Op
>>	14/8/2018	11:50	17:52	6.033	Op
10/12/2010	16/8/2018	6:10	8:05	1.916	Short ckt
13/12/2010	19/8/2018	9:10	12:41	2.516	Op
15/12/2010	21/8/2018	2:40	3:50	1.167	Short ckt
>>	21/8/2018	15:58	16:02	0.067	Short ckt
16/12/2010	22/8/2018	8:26	10:28	2.033	Short ckt
>>	22/8/2018	12:40	12:49	0.15	Short ckt
>>	22/8/2018	14:05	14:09	0.067	Short ckt
>>	22/8/2018	14:20	15:20	1	Short ckt
17/12/2010	23/8/2018	7:50	8:15	0.416	Short ckt
>>	23/82018	8:50	15:06	6.267	Short ckt
18/12/2010	24/82018	13:50	14:47	0.95	Short ckt
>>	24/82018	16:30	16:50	0.333	Op
19/12/2010	25/8/2018	9:35	10:56	1.35	Op
20/12/2010	26/8/2018	4:02	14:05	9.467	Short ckt
>>	26/8/2018	14:50	17:11	2.35	Op
22/12/2010	28/8/2018	8:57	9:05	0.133	Short ckt
>>	28/8/2018	11:15	11:25	0.167	Short ckt
27/12/2010	2/9/2018	5:15	5:35	0.333	Op
>>	2/9/2018	7:45	9:10	1.416	Short ckt
>>	2/9/2018	15:51	16:12	0.35	Short ckt
28/12/2010	3/9/2018	15:50	16:08	0.3	Op
1/13/2010	6/9/2018	7:45	10:15	2.5	Short ckt
4/13/2010	9/9/2018	6:45	8:15	1.5	Short ckt
5/13/2010	10/9/2018	17:14	17:26	0.2	Op
Total = 340			***Total =***	***442.578***	

Table A-2: Summary of interruption data for base year 2006 E.C. (2013/14 G.C)

S/N	*Name of feeder*	*Year*	*Month*	*Frequency of interruption (inter./cust.)*		*Duration of interruption (hr.)*		*Total inter.freq. (iner./cust.)*	*Total Inter. Dura.(hr.)*
				Planned	**Non-temp.**	**Planned**	**Non-temp.**		
1	Ashebeka	2013/14	Sept.	22	29	13.035	11.722	51	24.757
2	Ashebeka	2013/14	Oct.	7	13	2.15	15.615	20	17.765
3	Ashebeka	2013/14	Nov.	11	24	5.01	12.676	35	17.686
4	Ashebeka	2013/14	Dec.	5	35	4.89	30.661	40	35.551
5	Ashebeka	2013/14	January	3	16	1.22	14.773	19	15.993
6	Ashebeka	2013/14	Feb.	5	22	3.9	24.086	27	27.986
7	Ashebeka	2013/14	March	8	28	5.232	33.183	36	38.415
8	Ashebeka	2013/14	April	10	32	4.683	31.295	42	35.978
9	Ashebeka	2013/14	May	13	52	2.535	54.318	65	56.853
10	Ashebeka	2013/14	June	18	46	19.954	52.434	64	72.388
11	Ashebeka	2013/14	July	8	30	3.44	49.53	38	52.97
12	Ashebeka	2013/14	August	8	22	2.819	23.497	30	26.316
	Overall (Total)			**118**	**349**	**68.868**	**353.79**	**467**	**422.658**

Table A-3: Summary of interruption data for base year 2007 E.C. (2014/15 G.C)

S/N	*Name of feeder*	*Year*	*Month*	*Frequency of interruption (inter./cust.)*		*Duration of interruption (hr.)*		*Total inter.freq. (iner./cust.)*	*Total Inter. Dura.(hr.)*
				Planned	*Non-temp.*	*Planned*	*Non-temp.*		
1	Ashebeka	2014/15	Sept.	14	13	2.87	28.05	27	30.92
2	Ashebeka	2014/15	Oct.	4	22	1.7	39.4	26	41.1
3	Ashebeka	2014/15	Nov.	10	18	1.93	28.18	28	30.11
4	Ashebeka	2014/15	Dec.	5	24	4.316	33.684	29	38
5	Ashebeka	2014/15	January	5	21	1.609	8.721	26	10.33
6	Ashebeka	2014/15	Feb.	13	27	1.913	32.087	40	34
7	Ashebeka	2014/15	March	8	33	26.27	80.73	41	107
8	Ashebeka	2014/15	April	4	25	2.516	64.484	29	67
9	Ashebeka	2014/15	May	7	11	2.535	42.465	18	45
10	Ashebeka	2014/15	June	8	4	3.917	19.083	12	23
11	Ashebeka	2014/15	July	6	13	0.88	36.12	19	37
12	Ashebeka	2014/15	August	2	14	2.999	54.001	16	57
	Overall (Total)			**86**	**225**	**53.455**	**467.005**	**311**	**520.46**

Table A-4: Summary of interruption data for base year 2008 E.C. (2015/16 G.C)

S/N	Name of feeder	Year	Month	Frequency of interruption (inter./cust.)		Duration of interruption (hr.)		Total inter.freq. (iner./cust.)	Total Inter. Dura.(hr.)
				Planned	Non-temp.	Planned	Non-temp.		
1	Ashebeka	2015/16	Sept.	3	12	2.53	12.683	15	15.213
2	Ashebeka	2015/16	Oct.	14	4	3.24	16.76	18	20
3	Ashebeka	2015/16	Nov.	10	12	12.51	59.49	22	72
4	Ashebeka	2015/16	Dec.	5	29	1.68	61.32	34	63
5	Ashebeka	2015/16	January	3	13	0.3	11.7	16	12
6	Ashebeka	2015/16	Feb.	18	14	4.282	17.718	32	22
7	Ashebeka	2015/16	March	12	19	2.333	8.667	31	11
8	Ashebeka	2015/16	April	8	28	0.682	14.318	36	15
9	Ashebeka	2015/16	May	3	17	2.039	25.388	20	27.427
10	Ashebeka	2015/16	June	16	16	161	28	32	189
11	Ashebeka	2015/16	July						
12	Ashebeka	2015/16	August						
	Overall (Total)			**92**	**164**	**190.596**	**256.044**	**256**	**447**

Table A-5: Summary of interruption data for base year 2009 E.C. (2016/17 G.C)

S/N	Name of feeder	Year	Month	Frequency of interruption (inter./cust.)		Duration of interruption (hr.)		Total inter.freq. (iner./cust.)	Total Inter. Dura.(hr.)
				Planned	Non-temp.	Planned	Non-temp.		
1	Ashebeka	2016/17	Sept.	8	2	1.97	0.313	10	2.283
2	Ashebeka	2016/17	Oct.	11	8	5.78	2.884	19	8.664
3	Ashebeka	2016/17	Nov.	15	16	11.3	15.16	31	26.46
4	Ashebeka	2016/17	Dec.						
5	Ashebeka	2016/17	January	21	62	13.66	11.9	83	25.56
6	Ashebeka	2016/17	Feb.	10	23	11.885	56.789	33	68.674
7	Ashebeka	2016/17	March	8	19	21.3	8.7	27	30
8	Ashebeka	2016/17	April	19	2	12.754	6.576	21	19.33
9	Ashebeka	2016/17	May	12	4	3.25	53.75	16	57
10	Ashebeka	2016/17	June	7	12	5.062	4.938	19	10
11	Ashebeka	2016/17	July	11	11	7.435	13.565	22	21
12	Ashebeka	2016/17	August	17	9	5.336	12.664	26	18
	Overall (Total)			**139**	**168**	**99.732**	**187.239**	**307**	**286.971**

Table A-6: Summary of interruption data for base year 2010 E.C. (2017/18 G.C)

S/N	***Name of feeder***	***Year***	***Month***	***Frequency of interruption (inter./cust.)***		***Duration of interruption (hr.)***		***Total inter.freq. (inter./cust.)***	***Total Inter. Dura.(hr.)***
				Planned	***Non-temp.***	***Planned***	***Non-temp.***		
1	Ashebeka	2017/18	Sept.	14	14	4.032	9.266	28	13.298
2	Ashebeka	2017/18	Oct.	8	10	11.383	2.398	18	13.781
3	Ashebeka	2017/18	Nov.	12	26	21.051	29.099	38	50.150
4	Ashebeka	2017/18	Dec.	8	42	11.367	69.084	50	80.451
5	Ashebeka	2017/18	January	15	15	8.898	28.128	30	37.026
6	Ashebeka	2017/18	Feb.	3	28	1.366	42.874	31	44.240
7	Ashebeka	2017/18	March	5	20	0.801	12.732	25	13.533
8	Ashebeka	2017/18	April	6	23	7.084	41.214	29	48.298
9	Ashebeka	2017/18	May	9	20	14.265	41.883	29	56.148
10	Ashebeka	2017/18	June	8	14	13.542	18.282	22	31.824
11	Ashebeka	2017/18	July	4	8	2.582	7.249	12	9.831
12	Ashebeka	2017/18	August	11	17	14.432	29.566	28	43.998
	Overall (Total)			**103**	**237**	**110.803**	**331.775**	**340**	**442.578**

Appendix B:

Questionnaires aimed for survey of main causes of power interruptions in Ashebeka power distribution system.

Dear Participant,

The purpose of this document is to provide an outline of preliminary information that will be used by the thesis work in the School of Electrical Engineering and Computing in Adama Science and Technology University. This study is a part of partial fulfillment of the requirements for the Degree of Masters of Science in Electrical power and Control Engineering. The area of the research is selected on "**Reliability Assessment and Enhancement of Electric Power Distribution: A Case Study of Ashebeka Distribution System.**" The aim of this questionnaire is for gathering relevant data in relation to assessment of power interruptions in Ashebeka distribution system for the purpose of identifying the main causes of power interruptions and to find out proper & possible mitigation options as a solutions for those hypothetically identified problems and to suggest recommendations to the concerning bodies. Through this participation, your answers will be helpful in contribution of enhancing the reliability performance of Ashebeka distribution system. Your response will be only used for the research analysis purpose and the researcher hopes your response is all-encompassing.

Thank you very much for sharing your precious time and appreciated suggestions!!

Questionnaires contents for Assela & Sagure Electric utilities' and Assela substation staff employees.

I. Personnel information

1. In which areas of responsibility you involved? ---

2. What is your educational level? --

3. How many years of experience on the current responsibility of work you involved? -----------------------

II. General information

1. What is the total capacity of Ashebeka distribution system (feeder) in MW? -------------------------
2. What type of topology exists in Ashebeka distribution? Circle your choices.
    a) Radial system
    b) Open loop system
    c) Closed loop arrangement
    d) Link arrangement
    e) If any other specify it --

III. Information related to causes of power interruptions

1. What are the main causes of power interruptions on Ashebeka distribution system? Please list.

a) ---------------------b) ---------------------- c) ---------------------- d) ----------------------- e) ----------------

f) ---------------------------- g) ----------------------------------- h) ------------------------------------- i) --------------------- ------------ j) ----------------------------------- k) -----------------------------------

2. How do you rank or level the contributions of the following causes of power interruptions in Ashebeka distribution system?

Tick or circle your choice of ranking for each interruption causes indicated from number 2.1 to 2.10 (N.B: only one choice is recommended for one cause of interruption!).

Where: Level A= the highest contributor, Level B= higher contributor, Level C= medium contributor, Level D= lower contributor, Level E= the lowest contributor.

2.1 Vehicles accidents

a) Level A b) Level B c) Level C d) Level D e) Level E

2.2 Animals

a) Level A b) Level B c) Level C d) Level D e) Level E

2.3 Failures of equipment

a) Level A b) Level B c) Level C d) Level D e) Level E

2.4 Human errors

a) Level A b) Level B c) Level C d) Level D e) Level E

2.5 Bad weather

a) Level A b) Level B c) Level C d) Level D e) Level E

2.6 Operational interruptions

a) Level A b) Level B c) Level C d) Level D e) Level E

2.7 Tree contacts

a) Level A b) Level B c) Level C d) Level D e) Level E

2.8 Workers' skill gap

a) Level A b) Level B c) Level C d) Level D e) Level E

2.9 System overload

a) Level A b) Level B c) Level C d) Level D e) Level E

2.10 Unknown causes

a) Level A b) Level B c) Level C d) Level D e) Level E

3. What method the maintenance crews use for fault managing activities? This is a question of system problem tracing strategy to search faults and repair the system. --
----
----

4. What are your reasons for prolonged time of the power outage? ---
----
----

5. What solutions could you suggest for longer interruption outage time? --
----
----

6. If you have any suggestion about the solutions of the power interruption problems in Ashebeka distribution system, please specify it.---
----

7. If you have any comment regarding problems in Ashebeka distribution system, please write. -------------------------
----

Thanks a lot for your excellent ideas!!!

Table B-1: Summary of questionnaires' results about main causes of power interruptions which indicate their degree of contributions in ranking level.

S/N	Causes of Interruptions	Interruption factor judgement result (level=point)*number of respondent					Total result	Ranking level
		(A=6)*	(B=5)*	(C=4)*	(D=3)*	(E=1)*		
1	Trees contact	54	45	28	12	0	139	1st
2	Equipment failures	36	35	20	18	6	115	2nd
3	Bad weather	42	20	28	9	10	109	3rd
4	Animals	36	25	12	12	7	92	4th
5	Human errors	36	25	20	0	5	86	5th
6	System overload	30	20	8	9	7	74	6th
7	Operational interruptions	36	15	12	9	0	72	7th
8	Vehicle accidents	24	5	20	12	7	68	8th
9	Workers skill gap	18	25	0	12	6	61	9th
10	Unknown	18	10	16	9	0	53	10th

Appendix C: ***Location configurations implemented in each study case scenarios***

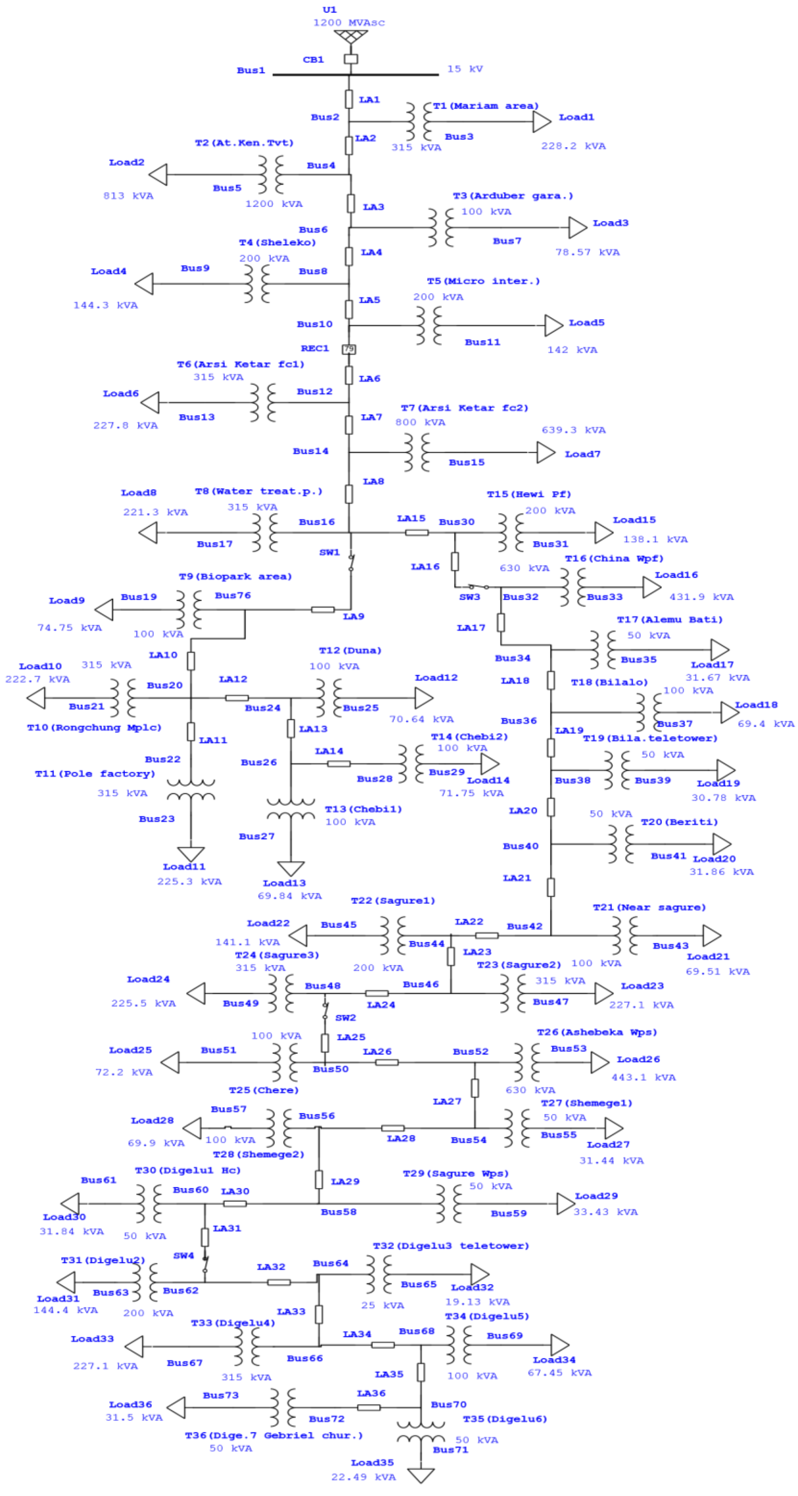

FIGURE C-1: SINGLE LINE DIAGRAM FOR STUDY CASE SCENARIO A.

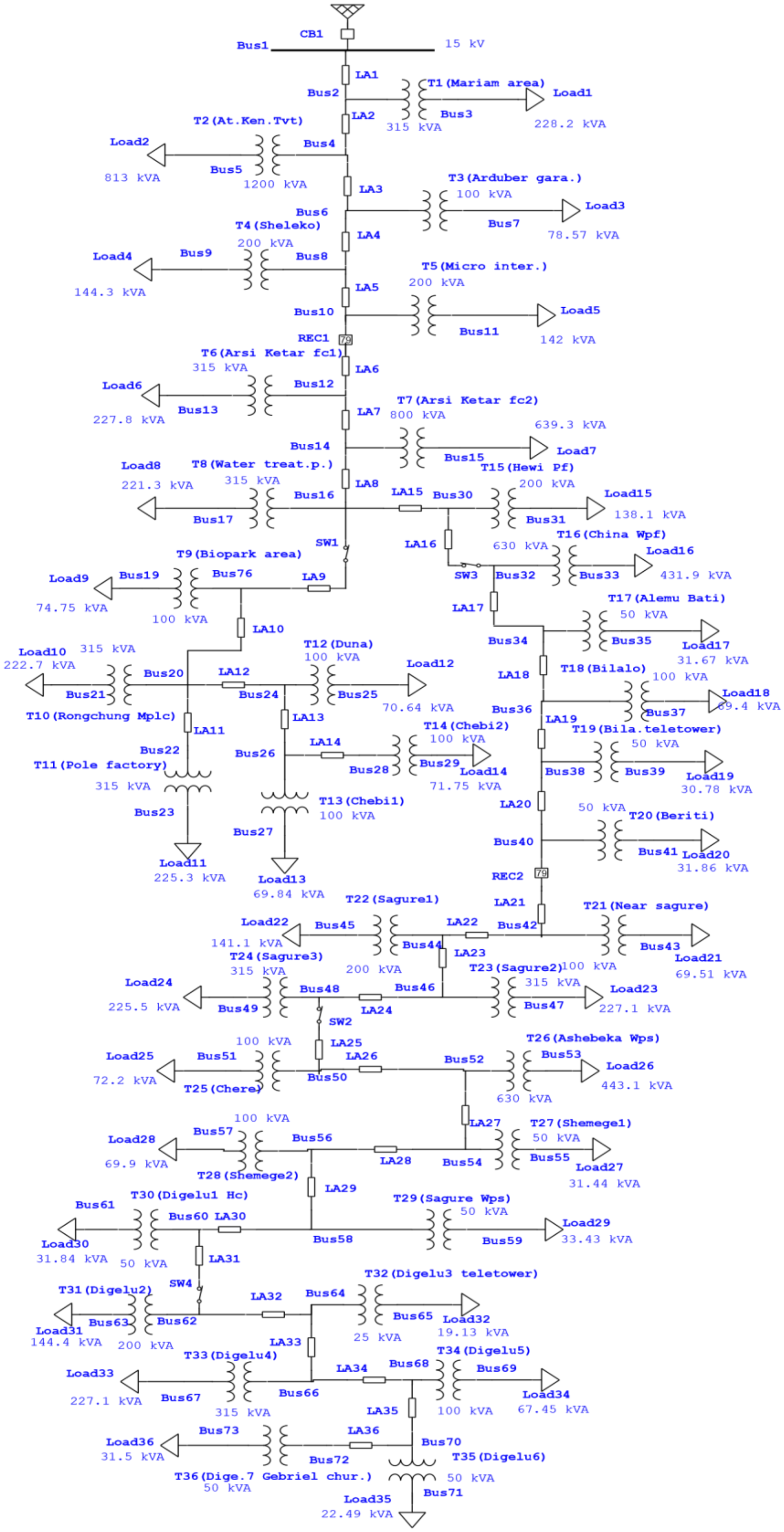

FIGURE C-2: THE COMPLETE ONE LINE DIAGRAM FOR SCENARIO B

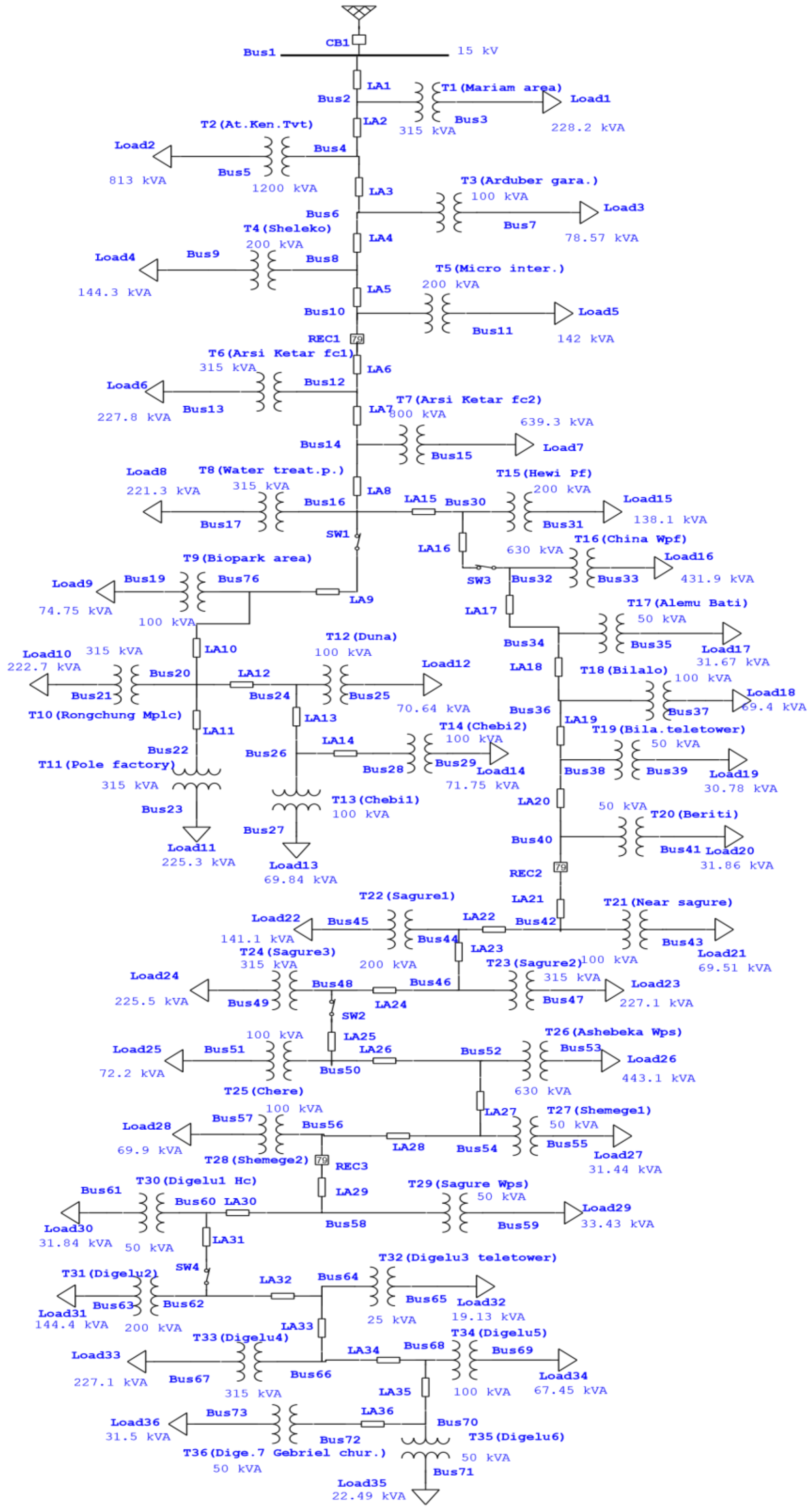

FIGURE C-3: THE COMPLETE ONE LINE DIAGRAM FOR SCENARIO C

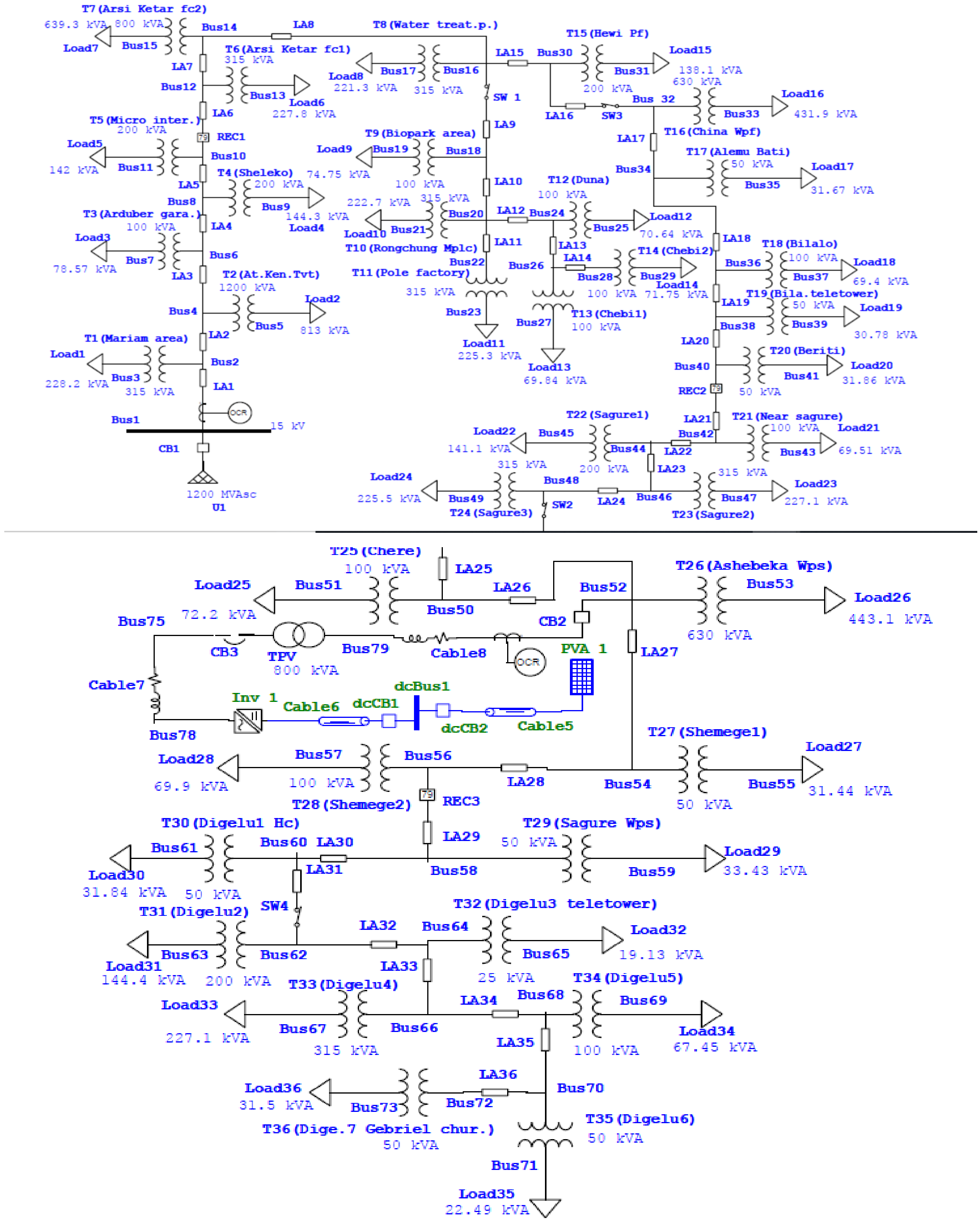

FIGURE C-4: THE COMPLETE ONE LINE DIAGRAM FOR SCENARIO D

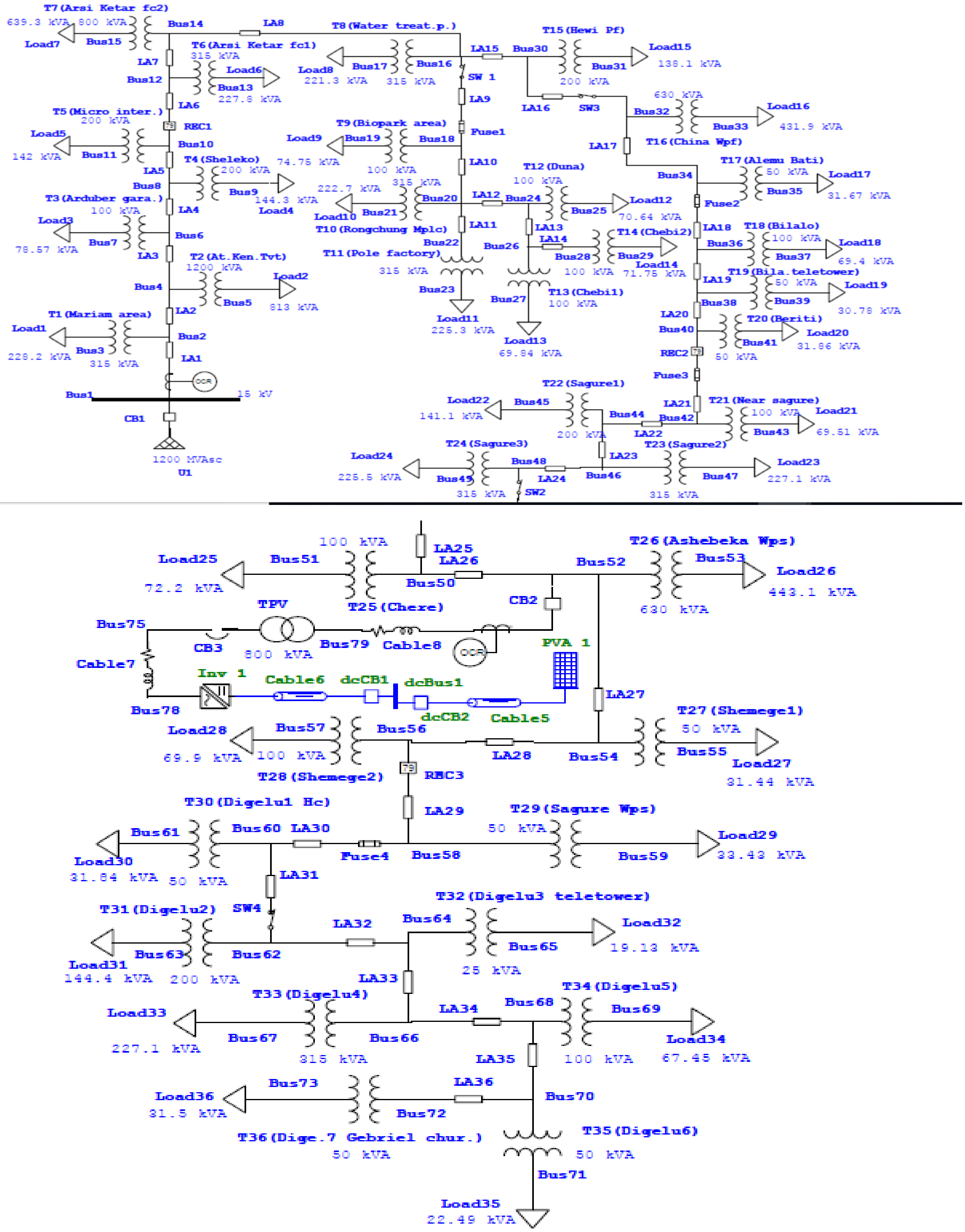

FIGURE C-5: THE COMPLETE ONE LINE DIAGRAM FOR SCENARIO E

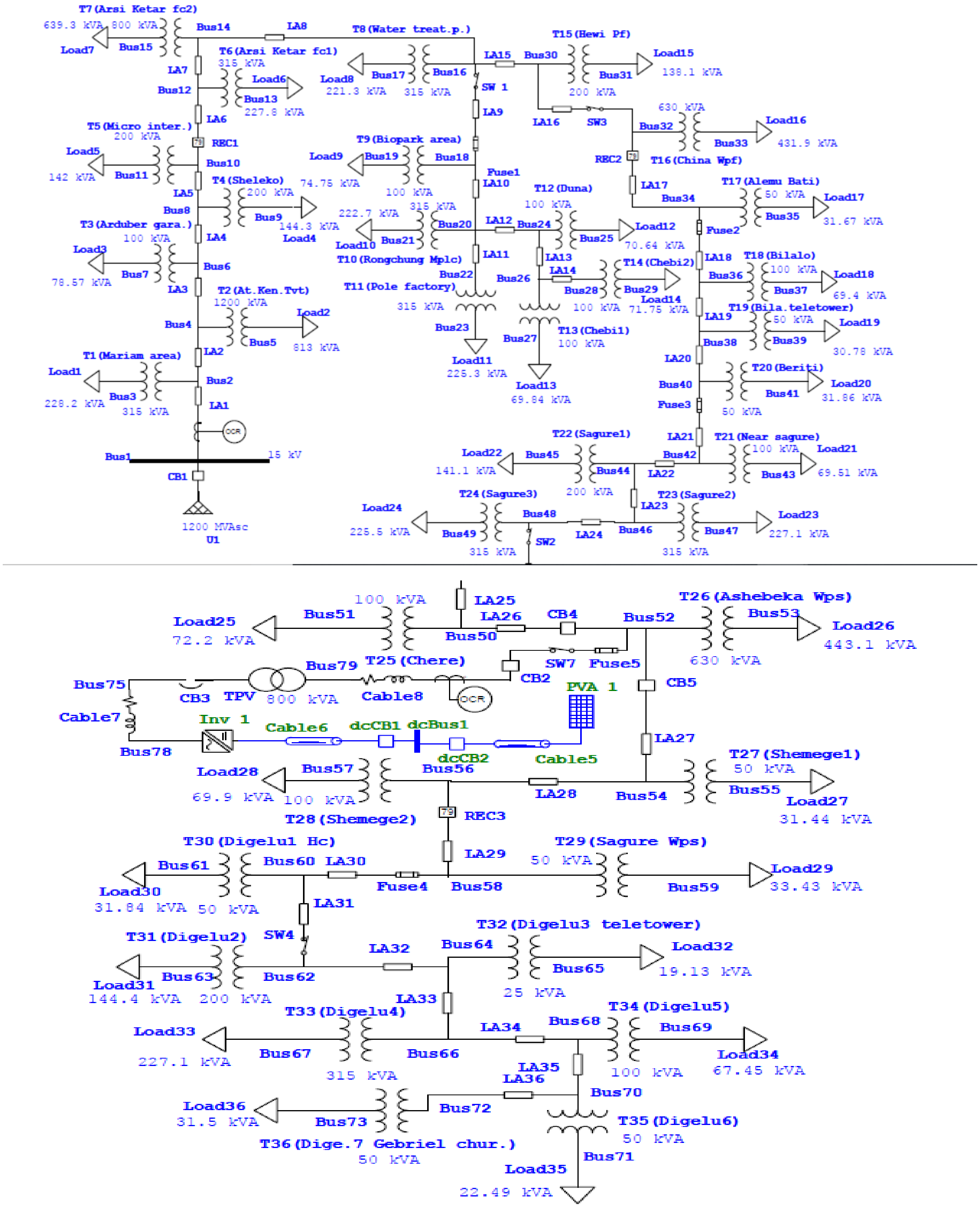

FIGURE C-6: THE COMPLETE SINGLE LINE DIAGRAM FOR SCENARIO F