Addis Ababa University

Addis Ababa Institute of Technology (AAiT)

Department of Electrical and Computer Engineering

Analysis and Design of Medium and High Voltage Network of Sendafa Industry Zone for Improved Reliability and Quality

By: Tibebu Hailemariam

THESIS SUBMITTED TO ADDIS ABABA INSTITUTE OF TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

Advisor:

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Date: July 2016

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APPROVAL BY BOARD OF EXAMINERS

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Declaration

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

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

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Acknowledgement

First of all, I would like to thank the Almighty God for giving me the endurance to complete the entire work.

I would like to express my utmost gratitude to my advisor Dr. -Ing. Getachew Biru for his expert guidance, constructive comments, suggestions and encouragement without which this work could have not been completed.

My special gratitude also goes to Mr. Aboma Tesfa (EEU, Sendafa District), Mr. Tesfaye Getaneh (EEP, Cotebe substation operator), Mr. Ermias Bekele (EEP, Engineering Department) and Mr. Tesfaye Tsegaye (EEU, Engineering Department) for their kind cooperation on providing the necessary technical information.

Last but not least, I would like to thank my family and friends who always stood by my side.

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Abstract

Since recent years, the Government of Ethiopia has been striding to transform the nation's economy of currently predominantly agriculture lead to industrial economy. To facilitate and achieve this magnificent ambition, one of the tools at the center piece is the construction of industry zones. It is obvious that building industry zones would help the government to provide all the necessary infrastructures such as road, electricity, water, telecom services, etc. in a reliable and efficient manner. Despite these efforts by the government, as a matter of fact, electric power supply has been a source of despair and dissatisfaction both for the investors and the government due to the frequent power interruptions the industries are suffering.

The main reason among others for the lack of quality and reliability of the electric power supply for these industry zones is a deficient network which is not designed and equipped to meet reliability and quality requirements.

In this thesis, an assessment on the existing electricity network of Sendafa industry zone is undertaken. The performance of the existing network is quantitatively analyzed with standard reliability indicators like SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration) and the load flow of the network is also simulated for voltage drops and short circuit level analysis. The existing network is also observed qualitatively in terms of network configuration, contingency, and capacity to handle the increasing demand.

With due research on distribution network analysis and design, the industrial network is redesigned considering all the technical and security requirements. Protection coordination calculation, reliability and load flow analysis of the redesigned industrial network is also done including the financial aspects. As discussed in chapter four, the redesigned industrial network with the proposed open loop configuration employing intelligent reclosers, SAIFI is improved by 99.7% and SAIDI improved by 99.4% and the voltage profile in all the nodes is also shown to be within limits for different scenarios. The SAIFI and SAID values of the existing network are 622 interruption/yr.customer and 571 hrs/yr.customer respectively which is too far from the national standard set by Ethiopian Electric Agency as 20 int/yr.cust and 25 hrs/yr.cust respectively.
Key words: Network reconfiguration, Industry zone, DIgSILENT, Protection coordination, Distribution reliability

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List of Abbreviations

A	Ampere
AAC	All Aluminum Conductor
AAAC	All Aluminum Alloy Conductor
ACSR	Aluminum Conductor Steel Reinforced
CSPP	Customer Service Policy and Procedure
CB	Circuit Breaker
CT	Current Transformer
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
EEPCo	Ethiopian Electric Power Corporation
HRC	High Rupturing Capacity
IEC	International Electro technical commission
IEEE	International Electrical and Electronics Engineers
kVAR	Kilovolt Ampere Reactive
kVA	Kilovolt Ampere
kA	Kilo Ampere
kV	Kilo Volt
kWh	Kilo watt hour
kW	Kilo watt
LV	Low Voltage
MV	Medium Voltage
MVA	Mega volt ampere
MW	Mega watt
PSC	Permanent short circuit fault
PEF	Permanent earth fault
PDF	Permanent double fault (both earth fault and short circuit)
P	Active power
PF	Power factor
PT	Potential transformer
Q	Reactive power

RMS	Root-mean-square (effective value)
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SOP	Standard Operating Procedure
TCC	Time Current Characteristic curve
TEF	Temporary earth fault
TSC	Temporary short circuit fault
V	Volt
VAR	Volt ampere reactive

Chapter One

Introduction

1.1. Background

Sendafa industry zone is located about 48 km to the east of Addis Ababa adjacent to Sendafa town in Oromia regional state at a latitude 9.1496^{O} N, longitude 39.0242^{O} E and an altitude of 2555 m above sea level.

Currently, there are various small and medium industries in operation involved in the manufacturing of textile products, food processing, metallic products, furniture, packaging etc. and there are also many other industries under construction and in pipe line to start construction.

The industry area is being supplied on 33 kV radial feeder from the 132/33 kV, 16 MVA transformer in Cotebe substation. The substation is located about 30 km from the industry area. This outgoing feeder serves Sendafa town and other rural towns in addition to the industrial area with a total feeder length (sum of main and branch networks) of about 109 km and a total of 113 33/0.4 kV distribution transformers. In other words, the medium voltage network covers a very wide area which is one of the reasons for increase in interruption frequency and long time durations to locate faults and restore power. Some of the industries have also reported about problems of under voltage resulting from the long distance between the distribution substation and the loads.

The other but as important reasons for such unbearable frequency of power interruptions in addition to covering a very wide area is that it is not well equipped with protection devices and the network is not designed with contingency considerations.

The 33KV feeder from the 132/33 kV, 16 MVA transformer in the substation was initially planned to supply Sendafa town and the surrounding rural areas. With Sendafa industry zone as additional load, it is observed that the available capacity becomes insufficient to serve industrial customers which have already requested power let alone future requests.

This thesis aims at evaluating the current power reliability and adequacy problems and find an amicable solution to supply the industry zone taking into account all the necessary technical and security requirements.

1.2. Problem Statement and Motivation

The development of industries have been booming in the country since recent years. To facilitate this plan, special industry zones have been developed so that the industries would get better infrastructure and services in an efficient and cost effective way. Among the infrastructure requirements, electric power supply is the soul of the industries.

Despite the effort by the government to develop industry zones or parks, industries have been deprived of good quality and reliable electric power supply which is the issue that is being addressed in this thesis.

Industries in Sendafa industry zone have been suffering from unbearable frequent electric power interruption and sometimes power quality issues mainly voltage drops. The problem with the interruption is not only the frequency which is far beyond the standard, it is also the duration of interruption they face even for a number of days which is unacceptable by any standard.

With this in mind, this thesis focuses on identifying and analyzing the gaps in the existing network in terms of quality, reliability and security of electric power and hence redesign the system for high reliability while keeping the power quality requirements mainly the steady state voltage stability. The contingency of the network will also be discussed so that failure of a specific network element would not cause outage of power to the whole industrial network.

1.3. Research Objective

General Objectives

The general objective of this thesis work is to study the reliability and quality problems of Sendafa industrial network by analyzing the gaps in the existing network and redesign the network for improved reliability and quality. The distribution network shall be designed taking into account the high reliability and contingency requirement for industrial networks and improved power quality.

Specific Objectives

The specific objectives include:

- Gather relevant data of the existing network that will be useful for reliability and quality analysis.

- Investigate the drawbacks and strengths of the existing network.
- Model the existing network on DIgSILENT (Power Factory 14) distribution software and simulate for the network performance for different scenarios.
- Calculate and evaluate reliability indices of the existing network.
- Evaluate and compare different network configurations and select a suitable configuration for the industry area considering the required contingency and reliability issues.
- Redesign the distribution network with protection system for improved reliability and contingency.
- Draw relevant conclusions and recommendations based on the research result.

1.4. Methodology

Raw data of the existing network is collected from the respective work units of Ethiopian Electric Power or Ethiopian Electric Utility. For instance, data from Cotebe substation that include fault statistics (interruption), peak load, power transformer name plate and other equipments ratings. There are also feeder data from the distribution network such as conductor length, size and type, distribution transformers data, protection and sectionalizing equipments and types of industries.

The next and major part of the thesis is literature review related to distribution network reliability and quality. Particular focus was given to reliability measures, network configuration options, protection devices and protection coordination calculations, and network load flow simulations.

DIgSILENT (Power Factory 14) distribution software is used for load flow and short circuit simulations of the network. AutoCAD is used to locate distribution feeder lines and transformers with the respective latitude-longitude coordinates which helps to model the whole network on DIgSILENT. MATLAB is used to plot the TCC (Time Current Characteristic) curves of protection devices on log-log scale.

1.5. Report Outline

The thesis is organized into five chapters which are briefly summarized as follows.
The first chapter presents the introduction, background, motivation and statement of the problem, objectives of the study and methodology followed in the thesis work.

Chapter two comprises literature review and theoretical background regarding reliability of distribution networks, measures of distribution reliability, distribution protection equipments, protection coordination of distribution network, power quality issues, and distribution network configuration options.

Chapter Three is about raw data collected and existing network reliability analysis, calculations and load flow simulations like voltage drop and short circuits.

Chapter Four discusses the design of the industrial network in terms of configuration, protection coordination design or calculations, calculating reliability measures of the redesigned network, load flow and short circuit simulations of the redesigned network and financial analysis.

Finally, the conclusions, recommendations and future researches are discussed in the fifth chapter.

Chapter Two

Theoretical Background and Review of Literatures

2.1 Introduction to Distribution Systems

The distribution system typically starts with the distribution substation that is fed by one or more sub-transmission lines. In some cases the distribution substation is fed directly from a high-voltage transmission line, in which case there is likely no sub-transmission system. This varies from company to company. Each distribution substation will serve one or more primary feeders. With a rare exception, the feeders are radial, which means that there is only one path for power to flow from the distribution substation to the user [1].

Typical distribution systems begin as the medium-voltage three-phase circuit, typically about 11–60 kV, and terminate at a lower secondary three- or single-phase voltage typically below 1 kV at the customer's premise, usually at the meter. Distribution feeder circuits usually consist of overhead and underground circuits in a mix of branching laterals from the station to the various customers. The circuit is designed around various requirements such as required peak load, voltage, distance to customers, and other local conditions such as terrain, visual regulations, or customer requirements. These various branching laterals can be operated in a radial configuration or as a looped configuration, where two or more parts of the feeder are connected together usually through a normally open distribution switch [2].

There are several distribution devices used to improve the safety, reliability, and power quality of the system. Switches are used to disconnect various parts of the system from the feeder. Reclosers are a special type of breaker, typically deployed only on overhead lines and are designed to reduce the outage times caused by momentary faults. Many overhead distribution faults are successfully cleared and service is restored with this technique, significantly reducing outage times. Capacitors are designed to inject volt amp reactives (VARs) into the distribution circuit, typically to help improve power factor or support system voltage. Fuses are standard devices used to protect portions of the circuit when a breaker is too expensive or too large. Lightning arresters are designed to reduce the surge on the line when lightning strikes the circuit. Distribution automation sequences include fault detection, localization, isolation, and load restoration (FDIR). These sequences will detect a fault, localize it to a segment of feeder, open the switches around the fault, and restore un-faulted sources via the substation and alternative sources as available. These algorithms work to safely minimize the fault duration and extent, significantly improving the SAIDI (system average interruption duration index) and SAIFI (system average interruption frequency Index) performance metric for the customers on those feeders [2].

2.2 Basic Distribution Network Configurations

Primary distribution systems include three basic types of configurations [3] [4]:

1. Radial systems
2. Loop system, including both open and closed loops
3. Primary network or mesh

2.2.1 Radial System

The radial-type system is the simplest and the one most commonly used. It comprises separate feeders or circuits "radiating" out of the substation or source, each feeder usually serving a given area. The feeder may be considered as consisting of a main or trunk portion from which there radiate spurs or laterals to which distribution transformers are connected, as illustrated in Figure 2.1 [3].

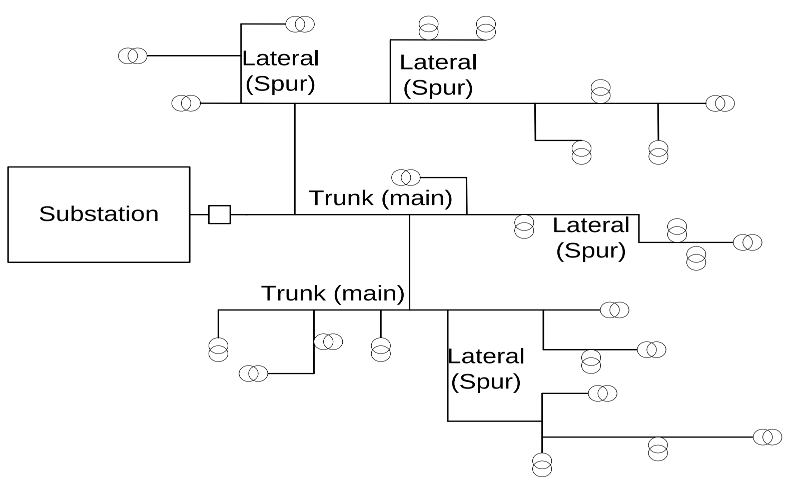


Fig 2.1 Radial distribution network

The spurs or laterals are usually connected to the primary main through fuses, so that a fault on the lateral will not cause an interruption to the entire feeder. Should the fuse fail to clear the line, or should a fault develop on the feeder main, the circuit breaker back at the substation or source will open and the entire feeder will be de-energized [3].

2.2.2 Loop System

Another means of restricting the duration of interruption employs feeders designed as loops, which essentially provide a two-way primary feed for critical consumers. Here, should the supply from one direction fail, the entire load of the feeder may be carried from the other end, but sufficient spare capacity must be provided in the feeder. This type of system may be operated with the loop normally open or with the loop normally closed [3].

Open Loop

In the open-loop system, the several sections of the feeder are connected together through disconnecting devices, with the loads connected to the several sections, and both ends of the feeder connected to the supply. At a predetermined point in the feeder, the disconnecting device is intentionally left open. Essentially, this constitutes two feeders whose ends are separated by a disconnecting device, which may be a fuse, switch, or circuit breaker [3].

In the event of a fault, the section of the primary on which the fault occurs can be disconnected at both its ends and service reestablished to the un-faulted portions by closing the loop at the point where it is normally left open, and reclosing the breaker at the substation (or supply source) on the other, un-faulted portion of the feeder [3].

Such loops are not normally closed, since a fault would cause the breakers (or fuses) at both ends to open, leaving the entire feeder de-energized and no knowledge of where the fault has occurred. The disconnecting devices between sections are manually operated and maybe relatively inexpensive fuses, cutouts, or switches [3].

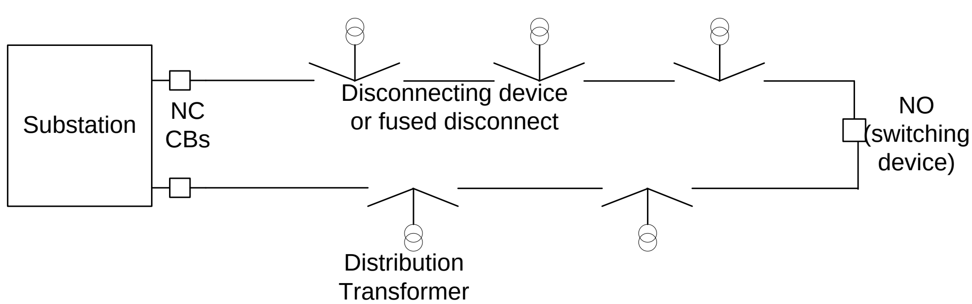


Fig 2.2 Open loop distribution network

Closed Loop

Where a greater degree of reliability is desired, the feeder may be operated as a closed loop. Here, the disconnecting devices are usually the more expensive circuit breakers. The breakers are actuated by relays, which operate to open only the circuit breakers on each end of the faulted section, leaving the remaining portion of the entire feeder energized. In many instances, proper relay operation can only be achieved by means of pilot wires which run from circuit breaker to circuit breaker and are costly to install and maintain; in some instances these pilot wires may be rented telephone circuits [3].

To hold down costs, circuit breakers may be installed only between certain sections of the feeder loop, and ordinary, less expensive disconnecting devices installed between the intermediate sections. A fault will then de-energize several sections of the loop; when the fault is located, the disconnecting devices on both ends of the faulted section may be opened and the un-faulted sections reenergized by closing the proper circuit breakers [3].

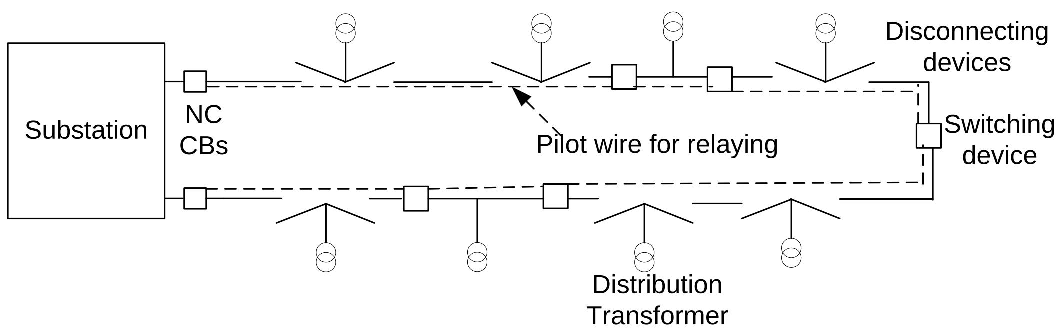


Fig 2.3 Closed Loop distribution network

2.2.3 Primary Network or Mesh system

Although economic studies indicated that under some conditions the primary network may be less expensive and more reliable than some variations of the radial system, relatively few primary network systems have been put into actual operation and only a few still remain in service.

This system is formed by tying together primary mains ordinarily found in radial systems to form a mesh or grid. The grid is supplied by a number of power transformers supplied in turn from sub-transmission and transmission lines at higher voltages. A circuit breaker between the transformer and grid, controlled by reverse-current and automatic reclosing relays, protects the primary network from feeding fault current through the transformer when faults occur on the supply sub-transmission or transmission lines. Faults on sections of the primaries constituting the grid are isolated by circuit breakers and fuses [3].

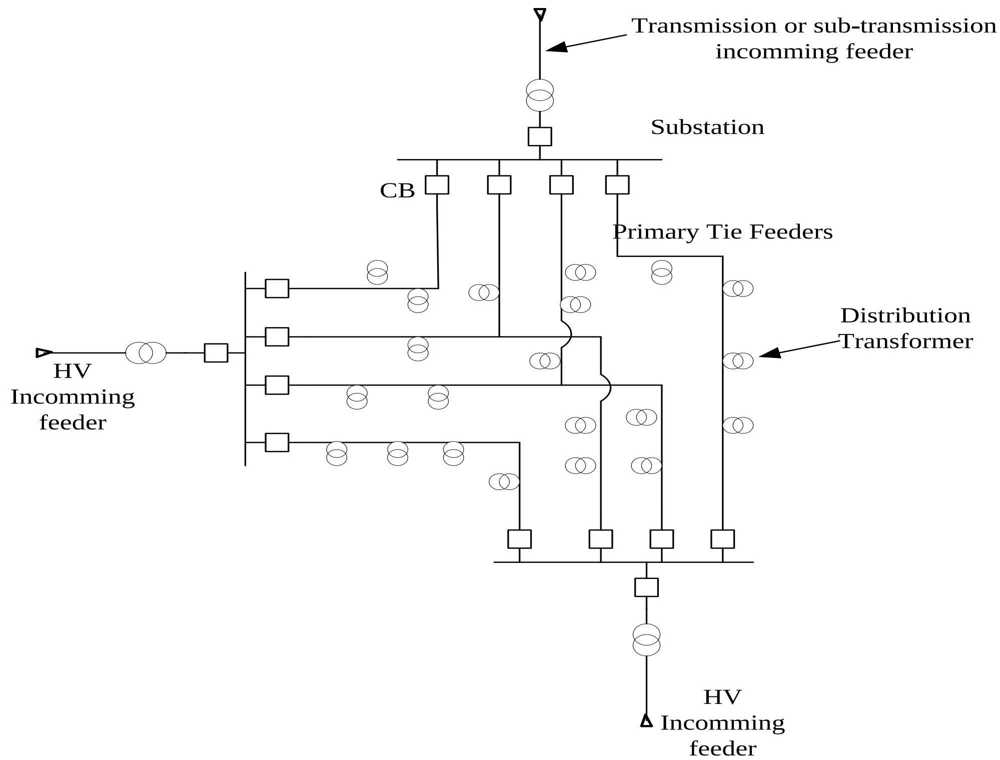


Fig 2.4 Primary Network or Mesh System, sectionalizing devices on feeders not shown

2.3 Distribution Network Protection and Control

2.3.1 Protection Devices

A wide variety of devices are used to protect distribution networks. The most important protective devices used on medium-voltage distribution systems are Reclosers, Sectionalizers, Manual Switches or Disconnectors, Fuses, and Overcurrent relays [5] [6].

2.3.1.1 Reclosers

A distribution recloser is designed to interrupt both load and fault current. Also, per its term, it is designed to “reclose” on the fault repeatedly in a predefined sequence in an attempt to clear the fault.

Reclosers have two basic functions on the system, reliability and over current protection. While one of the philosophies for the use of reclosers is to increase reliability, in the past their use for many utilities was determined primarily because the feeder breaker did not have protective reach to the end of the feeder. This was due to the fact that high load currents forced the minimum trip setting to a higher value than the fault level at the end of the feeder. Nowadays, reclosers are more frequently applied for reliability reasons, mainly due to three of their benefits: Reclosing capability, single phase reclosing, and automated loop capabilities.

The operation of a recloser depends on its time current curve (TCC). Each recloser has two TCCs: the fast and delayed curves. The recloser is on the fast tripping setting if it operates on the fast curve. Similarly, it is considered to be on the delayed setting if it operates on the delayed curve. Figure 2.5 shows a fault current on a typical TCC of a recloser. The recloser will interrupt within 0.04 s on the instantaneous setting or within 1.3 s if on the time-delay setting [5].

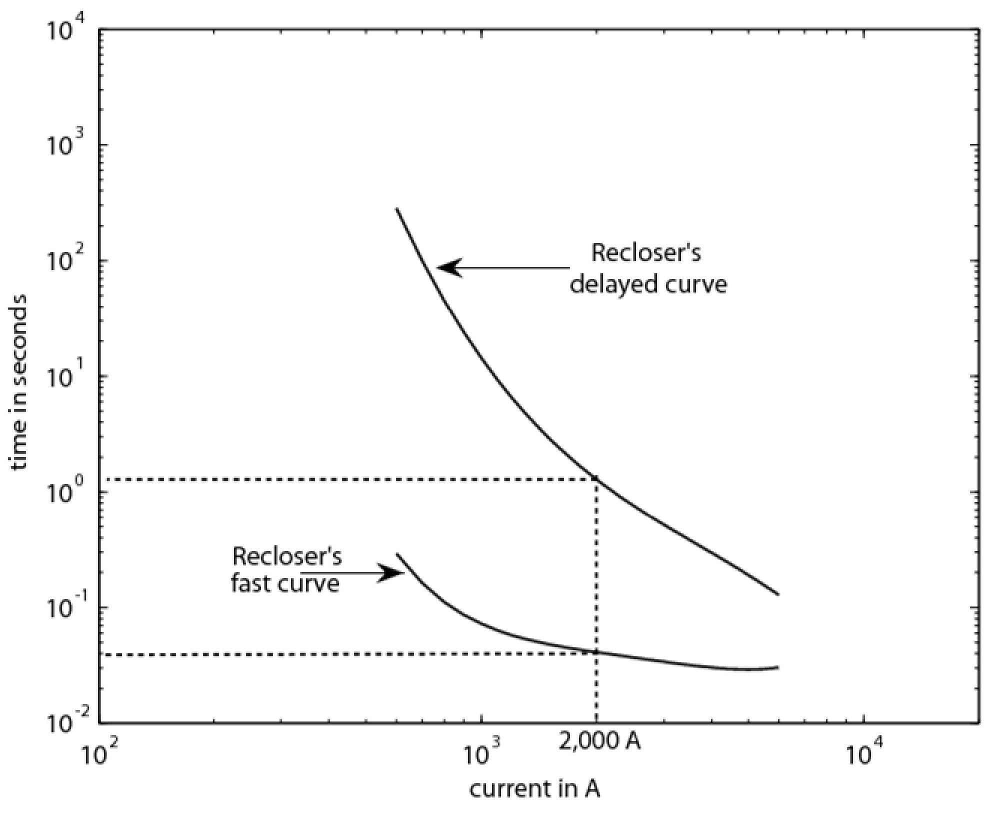


Fig 2.5 Time-current characteristics of a recloser: fast and delayed curves

Intelligent Loop Automation

State of the art recloser control units can provide, in addition to its traditional recloser functions, SCADA friendly interface for remote communication and distributed intelligence of reclosers for local automated operation [7].

Classic Loop Automation

The basic rules of Loop Automation (Classic Loop Automation Rules) are [7] [8]:

(1) Feeder devices trip when their source supply is lost.

(2) Mid-Point devices activate their alternative (or reverse) protection group when they lose source supply and, if the Mid-Point is an automatic recloser, it will also change to single-shot mode (auto-reclose off). After supply is restored, Mid-Points will have auto-reclose turned back on automatically.

(3) Tie devices close when they detect that supply from either load or source side is lost.

These simple rules disconnect, isolate and reconfigure the grid for all possible faults.

Intelligent Loop Automation

Intelligent Loop Automation adds additional functionality to Classic Loop Automation [7] [8].

(4) A Feeder or Mid-Point that goes to lockout (the locked out device) sends a trip request to its downstream device using peer-to-peer communication.

(5) A Feeder will also send a trip request to its downstream device if it trips to lockout after losing its source supply (Classic Loop Automation Rule 1).

(6) If Tie control mode is Message, the locked out device sends a close request to the ring Tie upon confirmation of a successful trip operation of its downstream device.

(6a) If this confirmation doesn't come (e.g. communications are unavailable), the locked out device will not send a close request to the Tie. Restoration of supply will not occur.

(7) If Tie control mode is Timer, a Tie will operate as per its basic Classic Loop Automation Rule 3 – regardless of receiving a close request or not. This mode maintains the availability of the scheme and enables an automatic attempt to restore supply regardless of the availability of the peer-to-peer communications.

(8) If Tie control mode is Message, a Tie will operate only if it receives a Loop Automation close request.

Pulse Reclosers: Today, a totally new type of device is available that significantly improves the whole distribution protection/automation landscape. It has a Pulse-Close / Pulse-Reclose feature that pulses and tests the line one phase at a time so it does not hard-close directly into a solid fault. This is why it is called a Pulse-Recloser [9].

2.3.1.2 Switches or Disconnectors

Manual and motor operated switches are the most basic type apparatus on the line. These are typically air break devices which are not typically designed for automatic operation and are for local (and occasionally remote) operation. These devices are useful for manual temporary restoration of faulted lines, where if several are used can be useful to reconfigure a line manually to regain as much of the segments as possible after a fault [2].

2.3.1.3 Sectionalizer

The function of a sectionalizer is not to interrupt a faulted line, but instead count the fault occurrences on the line and upon a predefined number of counts, and open up when the line is de-energized. The interrupting device, which allows the counting action, is either an upstream recloser or circuit breaker in the substation. Since sectionalizers have no capacity to break fault current, they must be used with a back-up device that has fault current breaking capacity. Following figure shows a simple radial feeder utilizing the functionality of an auto-mated sectionalizer together with the circuit breaker's auto-reclosing scheme [10].

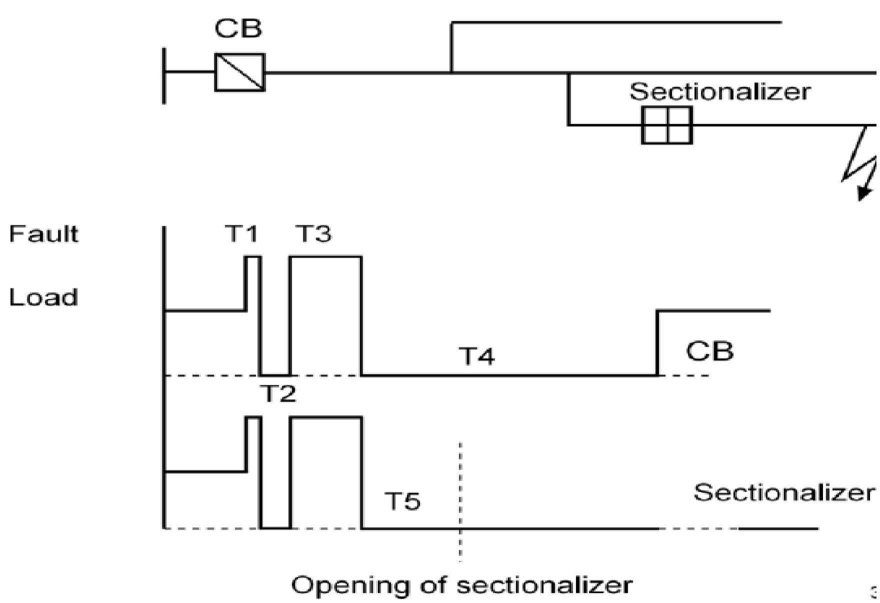


Fig 2.6 Example of utilizing sectionalizers

When the fault appears on the overhead line section beyond the sectionalizer, the protective relaying at the supplying substation and at the sectionalizer recognizes the case. The protective relaying at the substation starts the autoreclosing sequence by tripping the circuit breaker in time of T1. The sectionalizer acknowledges this action. After a preset time delay (T2), the circuit breaker recloses. Since the fault has not been cleared, the circuit breaker trips again after a preset time delay of T3. The sectionalizer commences its opening cycle during the feeder's de-energized period of T4. The actual sectionalizer opening command is issued after a preset time delay of T5. After the time delay of T4 of the autoreclosing scheme has elapsed, the sectionalizer is fully open and the circuit breaker recloses, energizing the healthy sections of the feeder.

2.3.1.4 Fuses

A fuse is an over-current 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. 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. In distribution systems, the use of fuse links designated K and T for fast and slow types, respectively. Two basic kinds of fuse used in power systems are [5]:

Expulsion vs. Current Limiting

Expulsion Fuse: An expulsion fuse is a vented fuse in which the expulsion effect of the gases produced by internal arcing, either alone or aided by other mechanisms, results in current interruption. Expulsion fuses are the more widely used protective devise on distribution systems due to their low-cost and maintenance-free operation. This fuse type is designed to carry a normal load current and interrupt the faulted part of the circuit. In general, the operating time of the fuse depends on its distinctive inverse time-current characteristic (TCC). The higher the fault current, the faster the fuse melts.

As shown in Figure 2.7, the TCC consist of two curves, the minimum melting curve and the maximum total clearing melting curve. The minimum melting curve is required for selecting the appropriate fuse. Whereas the maximum total clearing melting curve is required for coordination with upstream devices.

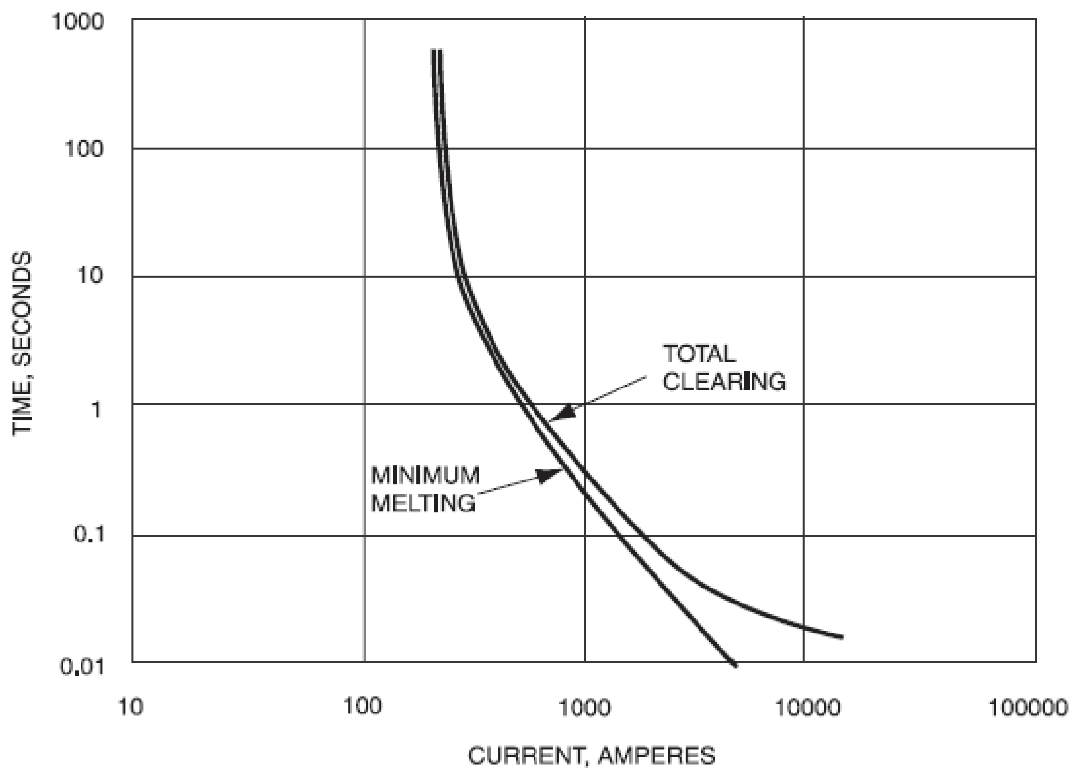


Fig 2.7 Typical TCC curves for an expulsion fuse

Current Limiting Fuse: A current limiting fuse is a fuse that when it's current responsive element is melted by a current within the fuse's specified current limiting range, abruptly introduces a high resistance to reduce current magnitude and duration, resulting in subsequent current interruption. Current limiting fuses are constructed with pure silver fuse elements, high purity silica sand filler, and a glass resin outer casing.

Fuse should withstand Inrush Current

Magnetizing-inrush current. When an unloaded distribution or power transformer is energized, there occurs a short-duration inrush of magnetizing current which the transformer-primary fuse must be capable of withstanding without operating. A conservative estimate of the integrated heating effect on the primary fuse as a result of this inrush current is roughly equivalent to a current having a magnitude of 12 times the primary full-load current of the transformer for a duration of 0.1 second. A current having a magnitude of 25 times the primary full-load current of the transformer for 0.01 second is also frequently used. The minimum melting time-current characteristic of the primary fuse should be such that the fuse will not operate as a result of this magnetizing-inrush current.

2.3.2 Protection Devices Coordination

In distribution systems, selectivity is normally expected between upstream and downstream devices. Selectivity of protection is essential in order to limit the supply interruption to the smallest area possible and to give a clear indication of the faulted part of the network. This makes it possible to direct the corrective action to the faulty part of the network and the supply to be restored as rapidly as possible [6].

2.3.2.1 Fuse-Fuse Coordination

The essential criterion when using fuses is that the maximum clearance time for a main fuse should not exceed 75 per cent 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 per cent 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 [6].

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

2.3.2.2 Recloser - 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 [6].

For Electronically-Controlled Reclosers, adjacent reclosers 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 [6].

For electronic reclosers, the TCC curve separation between upstream and downstream reclosers should be greater than 0.3 sec [12].

0.3 sec = 0.22 sec (CT saturation and errors) +0.08 sec (Breaker opening time)

2.3.2.3 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. The following graph shows typical recloser – fuse coordination curves.

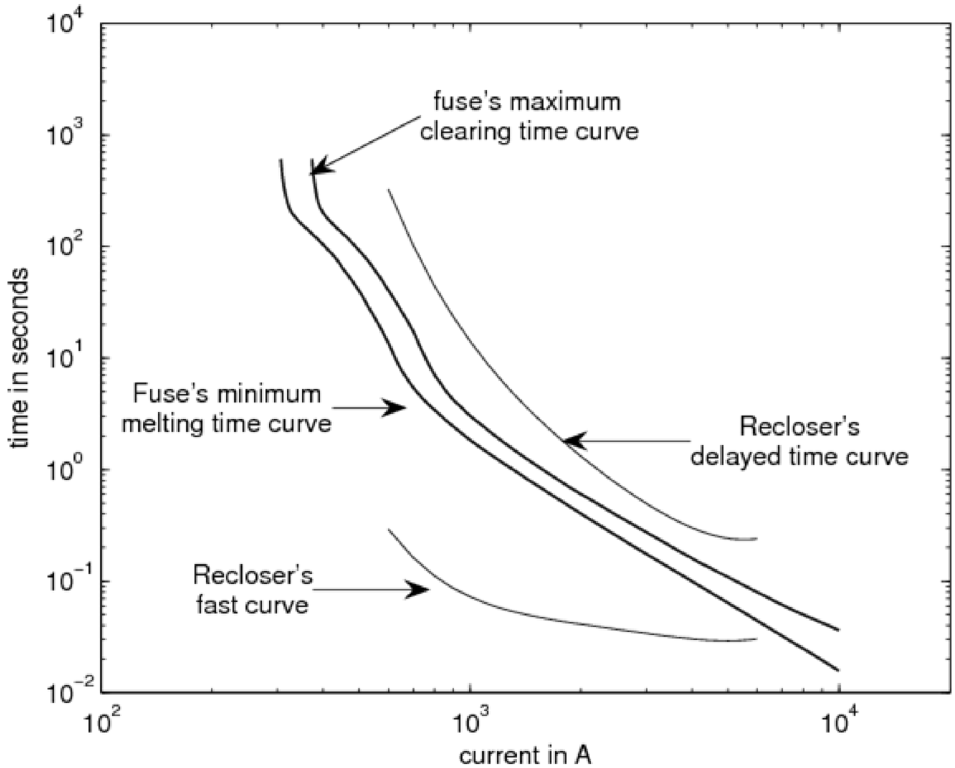


Fig 2.8 Time-current characteristic curves for recloser-fuse coordination

2.3.2.4 Recloser - Sectionalizer Coordination

Since the sectionalizers have no time/current operating characteristic, their coordination does not require an analysis of these curves. The coordination criteria in this case are based upon the number of operations of the back-up recloser. These operations can be any combination of rapid or timed shots as mentioned previously, for example two fast and two delayed. 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 [6].

2.3.2.5 Recloser – Sectionalizer - Fuse Coordination

Each one of the devices should be adjusted in order to co-ordinate 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 [6].

2.3.2.6 Over current Relays

Over current relays are used in the protection of distribution circuits. Over current relays use time current characteristics in their operations.

The relay at the far end is set with the shortest operating time. Relays further upstream have to be time graded against the next downstream relay in steps of about 0.3s. For lines where coordination with fuses or reclosers is necessary, strong or extremely inverse characteristic curve is selected. Strong inverse characteristics may be used with expulsion-type fuses (fuse cutouts), while extremely inverse versions adapt better to current limiting fuses [5].

Pick-up current [7]

Pickup is defined as that minimum current that starts an action and it is the minimum value of current that will cause the relay to close its contacts.

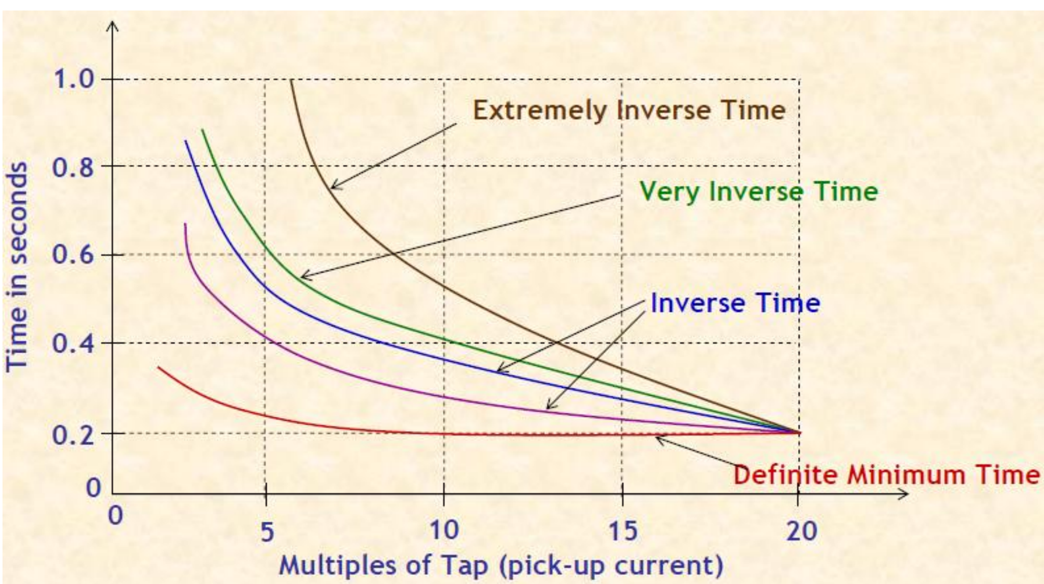


Fig 2.9 Multiples of Tap (pick-up current)

Pickup current should be above maximum load current seen by the feeder. This ensures that relay does not trip on load. Typical norm is to set $I_P > 1.25\ I_{Lmax}$ where I_P is relay pickup current and I_{Lmax} is the maximum load current on the relay. The pickup current should also be below the minimum fault current i.e.; $I_P < I_{fmin}$ where I_{fmin} is the minimum fault current on the relay. This ensures that protection system operates for low as well as high fault current. During this condition, in the utility least number of generators are in service. Hence, this coordination occurs at light load condition and at the remote end of the feeder of the respective devices. Pick up current should also be below the minimum fault current of the feeder that it has to backup. Otherwise, a relay's backup protection responsibility will not be fulfilled.

Time Multiplier Setting (TMS) or Time Dial Setting (TDS) [13]

Overcurrent relays have to play dual role of both primary and backup protection. For example, in a radial distribution system, there may be more feeders downstream. If the downstream fuse or relay or circuit breaker fails to detect the fault and/or isolate the equipment, upstream relays/CBs have to be opened.

The upstream relay action should be initiated if and only if downstream relay has failed. Thus, back up action requires a wait state. For this purpose, in an overcurrent relay, an additional feature of Time Multiplier Setting (TMS) is provided. The basic idea is that by increasing or decreasing the TMS, the relay operating time can be increased or decreased proportionately. TMS is also referred to as TDS (Time Dial Setting). It is means of adjusting the time taken by the relay to trip once the current exceeds the set value.

Formally T.M.S. is defined as,

$$\text{T.M.S.} = \frac{T}{Tm} \qquad (2.1)$$

where, for a given Plug Setting Multiplier (PSM),

T - is the required relay operating time

Tm - is the corresponding operating time at TMS of 1.0.

The ratio abs (I/I_P) is called the Plug Setting Multiplier (PSM) where I_P is the pickup current which is the reference or threshold for discriminating over current and I is measured device current. Since currents are measured through current transformer, both I_P and I should be referred to either primary or secondary of the CT. The value of PSM indicates the severity of the fault as seen by the relay. Trip the device, if PSM is above the threshold. The threshold should be strictly greater than 1, e.g. 1.5.

For relays which do not have co-ordination responsibility (e.g. relays at the leaf nodes), usually TMS can be set to the minimum. With the knowledge of PSM and TMS, the desired relay operating time is calculated. Strong Inverse time-current curve is chosen for the circuit breakers and reclosers since expulsion fuse types shall be used in the medium voltage network and supposed to be coordinated accordingly.

2.3.3 Voltage Regulation and Control

The voltage delivered to a customer must remain within certain limits. The source transformer that feeds a MV bus-bar is typically a 132/15 kV or 132/33KV in Ethiopia. On-load tap changing allows the transformer to be connected to the system during taps. Typical regulation range is ±20%. Reactive power or voltage at a certain point in the network may be controlled using the tap changer, depending on the point of installation of the transformer and its planned function in the system [14].

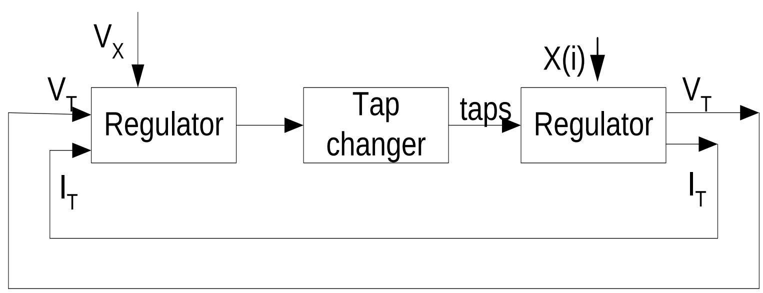


Fig. 2.10 Block diagram of a transformation ratio control

2.3.3.1 Voltage Control by the Distribution Transformer Tap Changer.

Distribution transformers up to a value of typically 1000 kVA can be fitted with a tap changer, although it is normally an off load device. Five taps, with ratios of –5%,–2.5%, nominal, +2.5% and +5%, are common. This tap changer is used to provide a basic control over the voltage on the LV side of the transformer, where the loads may still vary considerably over time, but where the on load tap changer would be too expensive [14].

2.3.3.2 Voltage Control by the In Line Voltage Regulator.

The inline voltage regulator, also known as a booster, is a small device that is commonly used on MV overhead lines. It is a transformer of, nominally, 1:1 ratio, fitted with an on load tap changer with five taps, each of 1.25%, which is used to boost or lower the voltage as load current increases and decreases. It can be controlled by a voltage regulating relay much the same as for the source substation transformer, but for reasons of economy, it usually responds to a simple current transformer in one or more phases of the network [14].

2.3.3.3 FACTS Devices

The term FACTS is an acronym for Flexible Alternating Current Transmission Systems. The FACTS concept is based on the incorporation of power electronic devices and methods into the high -voltage side of the network to make it electronically controllable.

Shunt capacitor

Shunt capacitors are relatively inexpensive to install and maintain. Installing shunt capacitors in the load area or at the point that they are needed will increase the voltage stability. However, shunt capacitors have the problem of poor voltage regulation and, beyond a certain level of compensation; a stable operating point is unattainable. Furthermore, the reactive power delivered by the shunt capacitor is proportional to the square of the terminal voltage; during low voltage conditions Var support drops, thus compounding the problem [15].

Static Var compensator (SVC)

SVC is a shunt connected static Var generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variable. Typically, the power system control variable is the terminal voltage. There are two popular configurations of SVC. One is a fixed capacitor (FC) and thyristor controlled reactor (TCR) configuration and the other one is a thyristor switched capacitor (TSC) and TCR figuration [15].

2.4 Medium Voltage Overhead Line Conductors

Most conductors are either aluminum or copper. Utilities use aluminum for almost all new overhead installations. Aluminum is lighter and less expensive for a given current-carrying capability. Aluminum starts to anneal (soften and lose strength) above 100°C. It has good corrosion resistance; when exposed to the atmosphere, aluminum oxidizes, and this thin, invisible film of aluminum oxide protects against most chemicals, weathering conditions, and even acids [16].

Several variations of aluminum conductors are available [16]:

- ❖ AAC — all-aluminum conductor — Aluminum grade 1350-H19 AAC has the highest conductivity-to-weight ratio of all overhead conductors.
- ❖ ACSR — aluminum conductor, steel reinforced — Because of its high mechanical strength-to-weight ratio, ACSR has equivalent or higher ampacity for the same size conductor size designation is determined by the cross-sectional area of the aluminum; the steel is neglected).
- ❖ AAAC — all-aluminum alloy conductor — this alloy of aluminum, the 6201-T81 alloy, has high strength and equivalent ampacity of AAC or ACSR.

For most urban and suburban applications, AAC has sufficient strength and has good thermal characteristics for a given weight. In rural areas, utilities can use smaller conductors and longer pole spans, so ACSR or another of the higher-strength conductors is more appropriate [28].

In comparison with all aluminum conductors AAC, AAAC conductors have the advantage of

- Higher breaking load allowing longer spans.

The dimensions of conductors of aluminum alloy AAAC, Al 59 compared to the corresponding ACSR and AAC conductors are shown in Table below [17].

Table 2.1: Comparison of conductor properties

Cross-section mm^2			DC Resistance Ω/km			Breaking Load kN			Weight kg/m		
AAC	AAAC	ACSR	AAC	AAAC	ACSR	AAC	AAAC	ACSR	AAC	AAAC	ACSR
70	70	70	0,452	0,470	0,535	10,5	15,6	19,0	0,170	0,170	0,216
100	95	95	0,275	0,296	0,336	16,0	22,8	29,8	0,291	0,271	0,343
150	150	150	0,194	0,193	0,314	23,3	39,7	50,2	0,415	0,436	0,545
240	240	240	0,123	0,127	0,143	35,8	55,5	72,9	0,654	0,663	0,812

Therefore, based on the merits of conductivity, breaking load capacity and weight, All Aluminum Alloy conductors (AAAC) are proposed for medium voltage overhead networks and moreover, covered All Aluminum Alloy conductors are preferred in dense populated, forests and windy areas [17].

2.4.1 Distinction between Insulated and Covered Conductors

Insulated conductors are generally designed as single conductors for direct burial or use in raceways, or as components for multiple-conductor cables, Temperature ratings of conductors range from 60^{o}c to 105^{o}c with some cables designed for higher ratings dependent on the type of insulation used.

Covered conductors, in contrast to insulated conductors, are used mostly by the utility industry under conditions where insulation is not required, and covering is applied for weather ability. Overhead line with covered conductors is designed as a conventional overhead line with conductors and the XLPE covered conductor is standardized to the same cross sections as normal bare AAAC conductors. By using covered conductors the fault rate could be expected to be decrease by 75% [18].

While covered wire helps with trees, it has some drawbacks compared with bare conductors. Covered wire is much more susceptible to burndowns caused by fault arcs. At the time of a lightning stroke on a line, the line is induced with an over voltage of magnitude of several hundred KV between phase and earth. Over voltage travel along the line to the nearest pole where it discharges by igniting an arc between cross arm and conductor. After the over voltage has discharged a power frequency short circuit current, the magnitude of which depends on the short circuit power of the network and distance to the substation, starts to flow through ionized air resulting a power arc between phases. Power arc magnitude is normally several kilo amps. A covered conductor is susceptible to burndowns because when a fault current arc develops, the covering prevents the arc from moving. On bare conductors, the arc is free to move, and the magnetic forces from the fault cause the arc to move. The covering constricts the arc to one location, so the heating and melting is concentrated on one part of the conductor resulting in burn downs [18] [19].

2.4.2 Arc Protection

Arc protection devices (APD) are responsible for protection of conductors and other network equipments against burning off. APDs are designed to direct the generated arc to a safer and sufficient distance from conductor and insulator. An APD with an arcing horn is used for pin and line post insulators. Figure 2.11 shows an arc horn arrangement for arc protection [19].

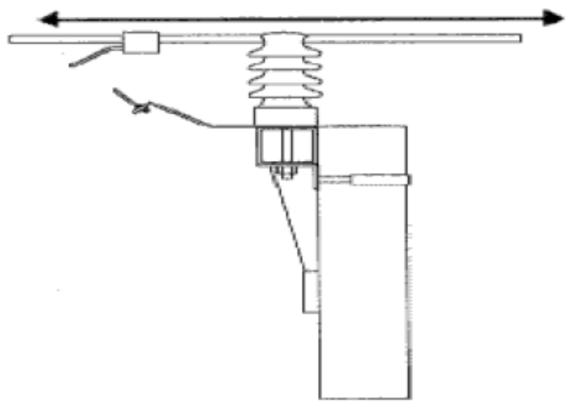


Fig 2.11 Arcing horn for arc protection

2.5 Distribution Network Reliability

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. Scheduled and unscheduled events disrupt normal operating conditions and can lead to outages and interruptions. Several key definitions relating to distribution reliability include [20] [21]:

Contingency — an unexpected event such as a fault or an open circuit. Another term for a contingency is an unscheduled event.

Open Circuit — a point in a circuit that interrupts load current without causing fault current to flow. An example of an open circuit is the false tripping of a circuit breaker.

Fault — a short circuit. Faults are caused by dielectric breakdown of insulation systems and can be categorized as self-clearing, temporary, and permanent.

Outage — an outage occurs when a piece of equipment is de-energized. Outages can be either scheduled or unscheduled.

Momentary Interruption — a momentary interruption occurs when a customer is de-energized for less than a few minutes. Most momentary interruptions result from reclosing or automated switching.

Sustained Interruption — a sustained interruption occurs when a customer is de-energized for more than a few minutes. Most sustained interruptions result from open circuits and faults.

The maximum duration of a momentary interruption varies from utility to utility, but is typically between one and five minutes. Results from utility survey indicate that 1 minute is the most commonly used value. Despite this, the IEEE has chosen define the maximum momentary interruption value as 5 minutes in its 1366 standard [21].

Disturbances in the electrical distribution system contribute most to the majority of customer outages per year compared to the generation and transmission systems [22], [23]. A way to reduce the duration of the customer outages is to increase the reliability and reserve capacity within the distribution network. An increase in reliability can be achieved by proper design of the distribution network taking into account reliability and quality of supply and increased maintenance of the components within the system and thereby lowering the probability of failure. The duration of outages for the customer can be reduced by adding redundancy and reserve capacity for the supply of electricity.

Reliability index targets are set internally or by state regulators and are based on historical index values and desired reliability trends. Once set, utilities act in good faith to achieve and maintain these targets. Targets are typically based on maintaining or improving recent SAIDI and SAIFI values. [21]

Table 2.2 shows the reliability indices (SAIFI and SAIDI) of best experienced countries including that of the Ethiopian Electric Agency (EEA) [24-26].

Table 2.2: Reliability indices of different countries

Country	**SAIFI (int/yr.cust)**	**SAIDI (h/yr.cust)**
United States	1.5	4.0
Australia	0.9	1.2
Denmark	0.5	0.4
France	1.0	1.03
German	0.5	0.383
Italy	2.2	0.967
Netherlands	0.3	0.55
Spain	2.2	1.73
United Kingdom	0.8	1.5
Ethiopia	20.0	25.0

2.5.1 Types of Faults

A fault can be between one phase conductor and earth (ground), in which case it is an earth (ground) fault, or it can be between two phases, in which case it is a phase-to-phase fault. Additional combinations exist; for example, a fault on a three-phase cable could be two phases to earth and one phase left completely healthy. There are also open circuit faults.

Two types of faults are encountered on an overhead distribution system: transient and permanent. A transient fault is one whose cause is transitory in nature. If the arc that results can be cleared quickly, before it burns into a permanent fault, the cause of the fault is gone, no equipment damage has occurred, and the circuit can be re-energized immediately, returning service to the entire system [27].

Examples of Transient Faults Include:

Wind blowing two conductors together temporarily. A tree branch that falls across two conductors and then falls clear. A bird or small animal that briefly causes an arc from a live terminal to ground, and then falls clear. On most distribution systems, the majority of faults (50 to 90%) are transient in nature [27].

Examples of Permanent Faults:

A permanent fault is one in which permanent damage has resulted from the cause of the fault. Examples would include a broken insulator, a broken conductor, an automobile knocking a pole down, etc. For permanent faults, the extent of the outage can be minimized by limiting the size and length of the affected line. The shorter line segment minimizes the number of customers affected and minimizes the time required to patrol the line and locate the fault [27].

2.5.2 Reliability Indices

The most widely used reliability indices are averages that weight each customer equally [21].

System average interruption duration index (SAIDI) is the average duration of all interruptions per utility customer during the period of analysis (usually annually).For each stage of each interruption, the product of the number of customers interrupted and the corresponding duration is calculated and is known as customer-minutes. For the total number of faults in the period under review, the total customer-minutes interrupted are added up and divided by the total number of customers served for the system or area of the system under evaluation.

$$\text{SAIDI} = \frac{Sum\ of\ duration\ of\ all\ customer\ interruption}{Total\ customers\ in\ system} \tag{2.2}$$

System average interruption frequency index (SAIFI) is the average number of interruptions (sustained) per utility customer during the period of analysis. Simply, this is the number of customer interruptions per year divided by the total customers on the system.

$$\text{SAIFI} = \frac{Number\ of\ customer\ interruption}{Total\ customers\ in\ system} \tag{2.3}$$

2.5.3 Load Characteristics

Demand Factor and Load Coincidence

Individual customers are often characterized by their total amount of connected kVA. A customer's peak demand is typically much lower than this value. It is unlikely that all appliances will be simultaneously turned on; some electrical appliances are rarely used and certain combinations are not used at the same time. The ratio of peak kVA to total connected kVA is called demand factor [20].

$$\text{Demand Factor} = \frac{\text{Peak KVA}}{\text{Total connected KVA}} \tag{2.4}$$

Because of this, the probability of all customers simultaneously experiencing peak demand is small and decreases as the number of customers increases. Because of this, distribution systems can be designed to supply less power than the sum of individual customer peak demands. The ratio of peak system demand to the sum of individual customer peak demands is called coincidence factor. The reciprocal of coincidence factor is diversity factor [20].

$$\text{Coincidence factor} = \frac{Peak\ System\ Demand}{\sum Individual\ Peak\ Demands} \tag{2.5}$$

$$\text{Diversity factor} = \frac{\sum Individual\ Peak\ Demands}{Peak\ System\ Demand} \tag{2.6}$$

Load coincidence and diversity are important to reliability because systems become less reliable as they become more heavily loaded. Heavily loaded equipment becomes hot and prone to failure. Heavily loaded systems are difficult to reconfigure to restore service to customers after a fault occurs. Increasing load diversity will reduce system peak load and result in higher reliability [20].

Loss Load Factor (LLF)

The Loss Load Factor (LLF) relates the annual energy losses to the peak power losses as follows:

Annual Variable Losses (kWh) = LLF x Peak Variable Losses (kW) x 8760 (2.7)

The loss load factor can be estimated from the load factor using the following empirical formulae:

$$LLF = 0.3\ LF + 0.7\ LF^2 \text{ (urban system)} \quad (2.8)$$

$$LLF = 0.2\ LF + 0.8\ LF2 \text{ (rural networks)} \quad (2.9)$$

Load Factor (LF)

The annual Load Factor is defined as the relationship between a consumer's average demand and his maximum demand over the period of one year and is given by [20]:

$$\text{Load Factor} = \frac{\text{Average Load}}{\text{Peak Load}} \quad (2.10)$$

where the number of hours in a year usually equal to 8760.

Thus if the maximum demand and the Load Factor are known then the average load can be calculated. This average load is the load which, when present for the whole duration of the defined period, results in the same energy as that supplied by the actual varying load for the same period.

2.6 Introduction to Power Quality

2.6.1 Voltage Fluctuations

Voltage fluctuations are described by the IEC as cyclical variations of the voltage envelope or a series of random voltage changes of up to 10% of the nominal.

Fluctuations resulting from industrial loads can affect many consumers, the main effect usually being flicker. Also step voltage changes due to the connection or disconnection of large loads or capacitor banks can fall into the category of voltage fluctuations. Equipment with significant time constants, such as heating elements, is largely unaffected, but some electronic and IT equipment can be seriously affected [27].

2.6.2 Short-term Interruptions and Voltage Dips and Peaks

Short interruptions (termed 'discontinuities' in some standards) to a consumer's supply, lasting not more than 1 minute (which for the purposes of power quality include short time voltage reductions to less than 0.1 pu) are typically caused by the operation of automatic reclosing systems. Voltage dips can be caused by any of a number of events including the starting current of large motors, inrush currents occurring on connection of certain reactive loads and system faults. Faults on the transmission system result in dips of relatively high retained voltage over a large area, while distribution system faults tend to cause dips of lower retained voltage and longer duration but effective over a smaller area [27].

The term 'sag' is also used, particularly in American usage; it is often a synonym for 'dip', but can sometimes be intended as a discriminatory term designating a longer-term reduction in voltage. Attempts have been made to standardize all these terms – but they are not universally applicable. For the IEC a voltage dip has amplitude drop more than 10% of the nominal voltage, and a short supply interruption is simply a dip with 100% amplitude [27].

2.6.3 Harmonics

Distortions in voltage and current wave shapes can upset end-use equipment and cause other problems. Harmonics are a particularly common type of distortion that repeats every cycle. Harmonically distorted waves contain components at integer multiples of the base or fundamental frequency 50Hz. Resistive loads like incandescent lights, capacitors, and motors do not create harmonics — these are passive elements — when applied to 50-Hz voltage; they draw 50-Hz current. Electronic loads, which create much of the harmonics, do not draw sinusoidal currents in response to sinusoidal voltage [27].

Chapter Three

Existing Network Data and Analysis

3.1 Description of the Network

Sendafa industry zone is currently supplied on 33 kV by a 132/33 kV 16 MVA power transformer from the 132/45/33/15 kV Cotebe substation. Cotebe substation is located at about 30 km from the industry zone and Legetafo substation is also located in between as shown in Figure 3.1 below.

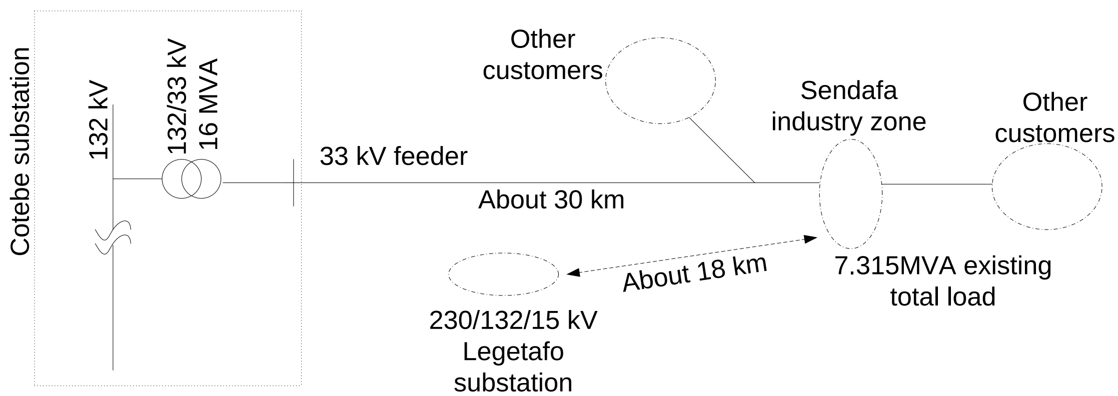


Fig 3.1 Simplified description of the network

As shown in figure 3.2, the 33 kV outgoing feeder supplies other loads like residential and domestic customers, water supply stations and quarry sites in different locations in addition to the industrial zone.

The existing network has the following major drawbacks:

- The 33 kV feeder covers a very wide area which makes it unsuitable to serve an industrial area as shown in Figure 3.2.
- The network is not well equipped with protection devices such as fuses and reclosers.
- The contingency of the network is not considered for instance, permanent fault on the 33 kV feeder could mean outage of power to the whole network.
- The on-load tap changer of the power transformer works only manually which means the response time of tap changing manually by the substation operators is not predictable leading to poor voltage regulation. There is one auto-recloser as shown in figure 3.2 but it is not operational since first installed.

- The substation is very far from the load center or the industrial zone leading to excessive voltage drops.
- The capacity of the power transformer in Cotebe substation is not sufficient to handle the rising demand as there are already big industrial power requests for example only one customer requests 7.5MVA in addition to various other requests while the available margin in the transformer is less than 8.5MVA.

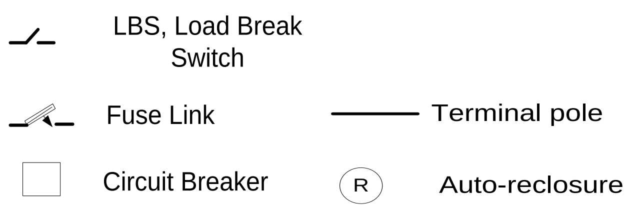
Currently industries in Sendafa industry zone are facing excessive power interruption which will be discussed later in detail. Long duration of interruption is also the feature of the network. Some customers also face voltage drops sometimes. For example, some industries register a voltage as low as 330 V which is about 14% voltage drop from 380 V LV standard value. As will be discussed, voltage drop will be an even bigger problem when the additional loads are connected.

Due to the poor performance of the network, industries incur the following additional costs:

1. Fuel cost to run with diesel standby generators which is nearly common to all industries.
2. Spoilage of materials in the manufacturing process during the interruptions (the case for some industries) and quality of final product is affected.
3. Costs for not meeting delivery time. Frequent interruptions mean reduced production volume. If they fail to meet the delivery time of contracts, it could mean a penalty.
4. Loss of trust by their customers is also a cost difficult to measure.

The total revenue loss to Ethiopian Electric Utility due to the unserved energy is also significant in addition to economic and social impacts as a whole which will be discussed in the later chapters.

The total 33 kV existing network single line diagram is shown in Figure 3.3. The different colors indicate types of customers. Blue is water supply stations network, rose is Sendafa industrial network, green for domestic and commercial customers and red is for quarry sites. Ti's indicate name of transformer. The symbols in the figure are described as follows:



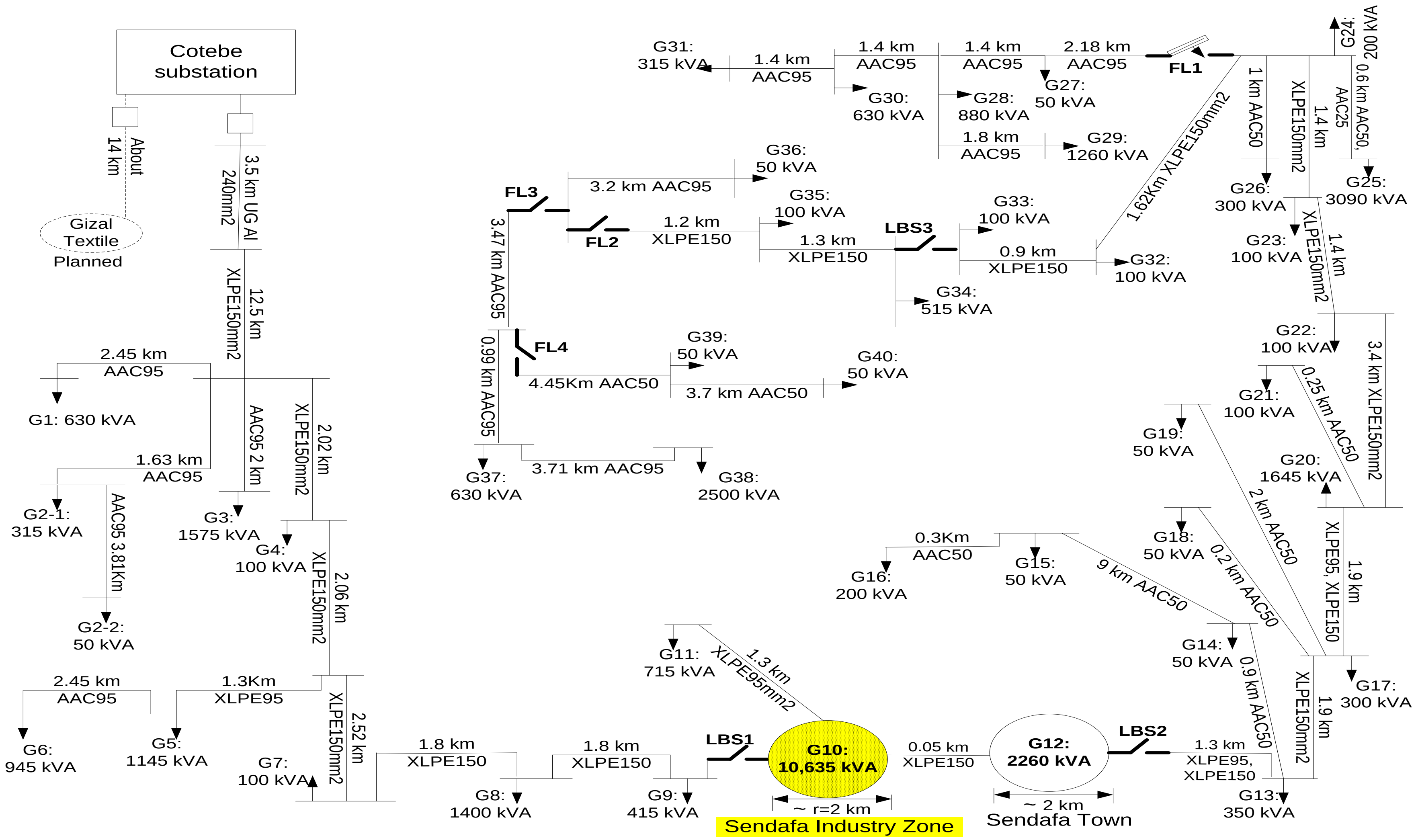
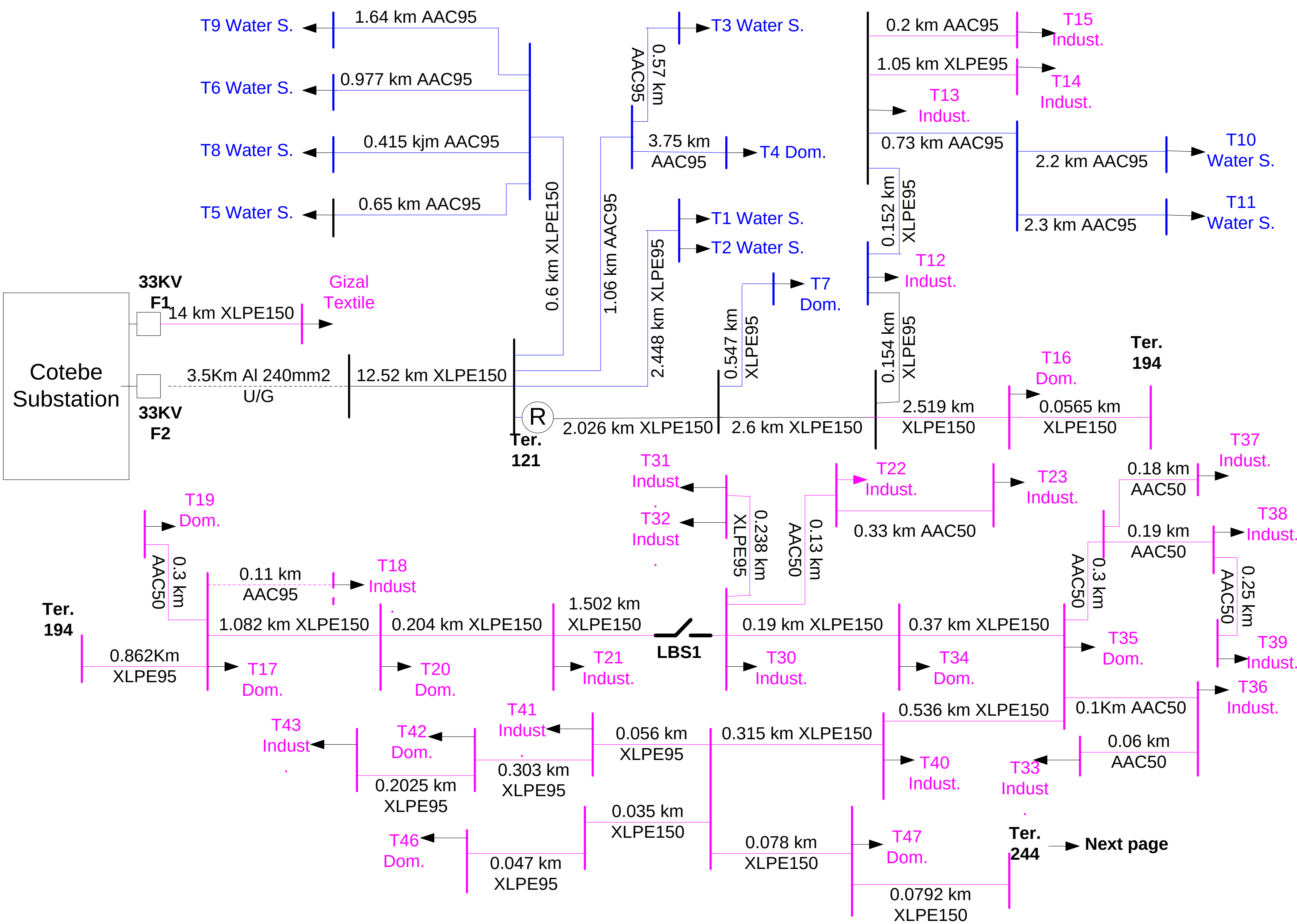


Fig 3.2 Simplified network diagram showing radial nature of the existing 33 kV network


T9 Water S.
1.64 km AAC95
T6 Water S.
0.977 km AAC95
T8 Water S.
0.415 kjm AAC95
T5 Water S.
0.65 km AAC95
0.6 km XLPE150
1.06 km AAC95
0.57 km AAC95
T3 Water S.
3.75 km AAC95
T4 Dom.
2.448 km XLPE95
T1 Water S.
T2 Water S.
0.547 km XLPE95
T7 Dom.
0.2 km AAC95
T15 Indust.
1.05 km XLPE95
T14 Indust.
T13 Indust.
0.73 km AAC95
2.2 km AAC95
T10 Water S.
2.3 km AAC95
T11 Water S.
0.152 km XLPE95
T12 Indust.
0.154 km XLPE95
Cotebe Substation
33KV F1
14 km XLPE150
Gizal Textile
33KV F2
3.5Km Al 240mm2 U/G
12.52 km XLPE150
R
Ter. 121
2.026 km XLPE150
2.6 km XLPE150
2.519 km XLPE150
T16 Dom.
0.0565 km XLPE150
Ter. 194
T31 Indust.
T32 Indust.
0.238 km XLPE95
0.13 km AAC50
T22 Indust.
0.33 km AAC50
T23 Indust.
0.18 km AAC50
T37 Indust.
0.19 km AAC50
T38 Indust.
0.3 km AAC50
0.25 km AAC50
T19 Dom.
0.3 km AAC50
0.11 km AAC95
T18 Indust
Ter. 194
0.862Km XLPE95
T17 Dom.
1.082 km XLPE150
0.204 km XLPE150
T20 Dom.
1.502 km XLPE150
T21 Indust.
LBS1
0.19 km XLPE150
T30 Indust.
0.37 km XLPE150
T34 Dom.
T35 Dom.
T39 Indust.
T36 Indust.
0.1Km AAC50
0.536 km XLPE150
T40 Indust.
0.06 km AAC50
T33 Indust
T43 Indust
T42 Dom.
0.2025 km XLPE95
T41 Indust
0.303 km XLPE95
0.056 km XLPE95
0.315 km XLPE150
T46 Dom.
0.047 km XLPE95
0.035 km XLPE150
0.078 km XLPE150
T47 Dom.
0.0792 km XLPE150
Ter. 244
Next page

existing 33 kV network(continued from previous page)

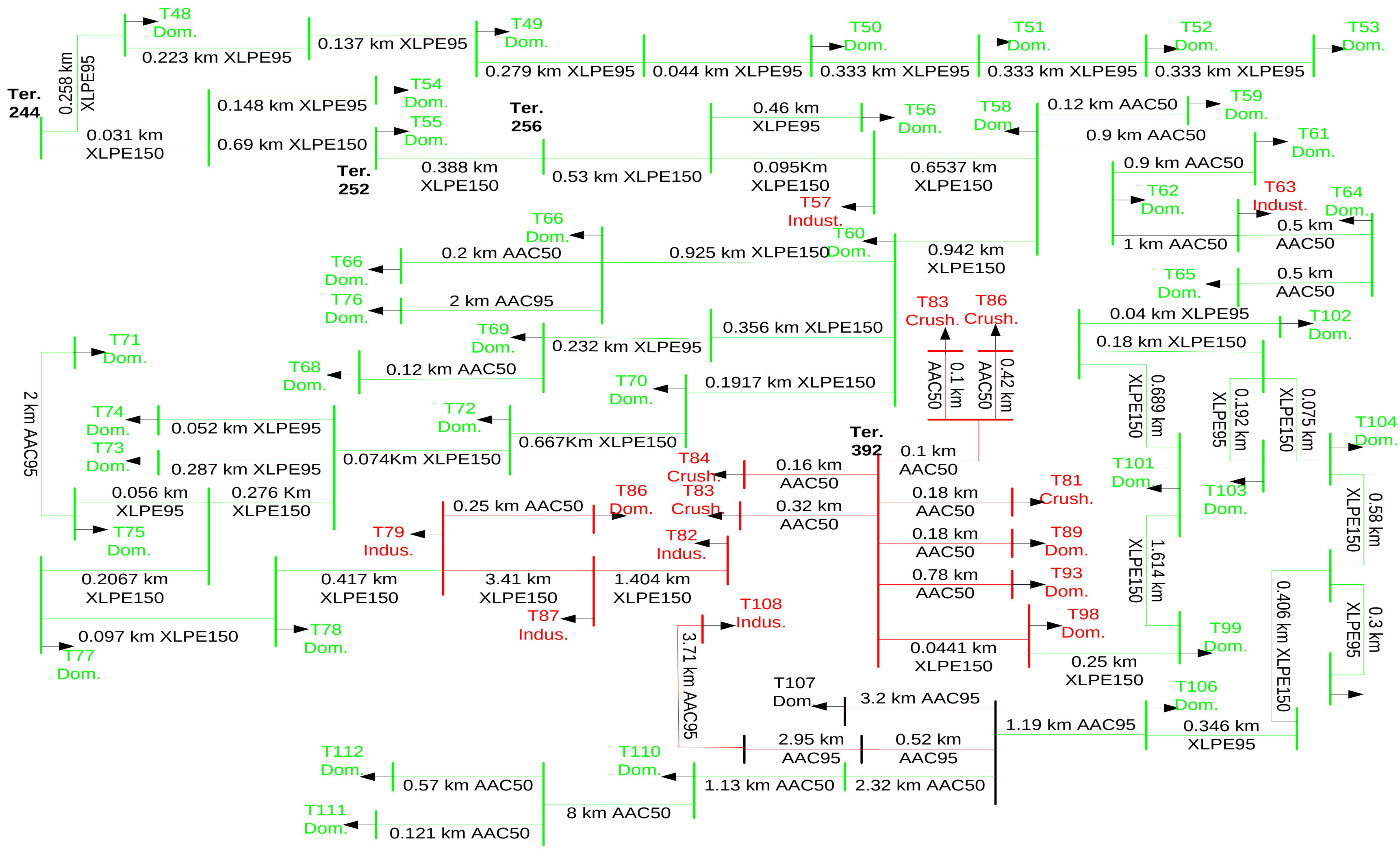


Fig 3.3 Total 33 kV Network diagram (continued from previous page)

3.2 Cotebe 132/45/33/15 kV Substation Data

3.2.1 Load Profile

The existing monthly peak load of the 132/33 kV, 16 MVA transformer is about 128 A which is equivalent to about 7.315 MVA. This means the transformer is about 46 % loaded. The 24 Hours Load Profile of the feeder is discussed as follows based on Table 3.1 below.

Table 3.1: 24 hours load profile of the existing 33KV outgoing feeder

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load (MVA)	3.09	2.74	2.74	3.20	3.72	4.06	4.34	4.63	6.06	7.14	7.32	6.17

Hour	13	14	15	16	17	18	19	20	21	22	23	24
Load (MVA)	5.72	5.37	5.72	6.06	6.40	5.60	5.37	5.49	5.14	4.46	3.77	3.83

As shown in Table 3.1, the hourly peak load of the feeder is 7.32 MVA and the 24 hours average load is 4.92 MVA. Therefore,

$$\text{Load Factor (LF)} = \frac{Average\ Load}{Peak\ Load} = \frac{4.92\ MVA}{7.32\ MVA} = 0.67$$

One reason for reduced load factor is that currently most of the industries operate during daytimes and it can be improved when the bigger industries which also operate in the evenings come into operation. It can also be improved by shifting some deferrable loads to off peak hours. Loss Load Factor (LLF) which is later used to calculate unserved energy is calculated as follows.

Loss Load Factor (LLF) = $0.3LF + 0.7LF^2 = 0.3*0.67 + 0.7*0.67^2 = 0.515$

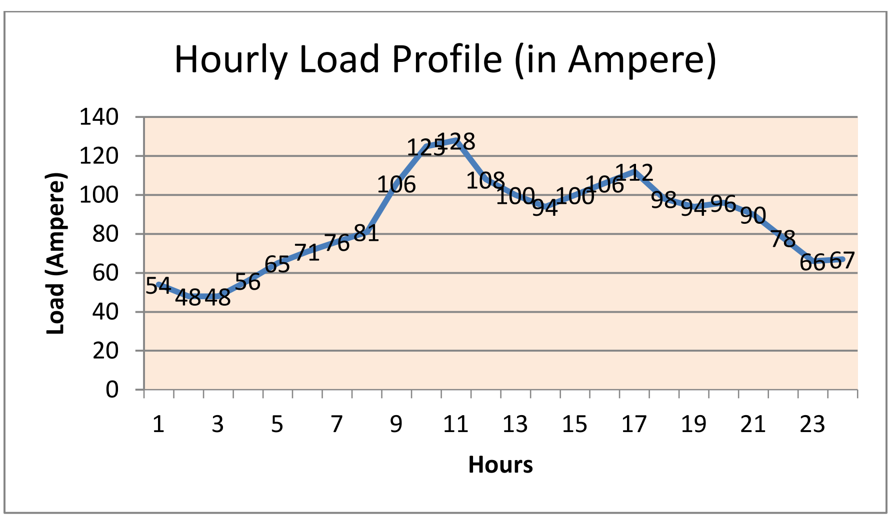


Fig 3.4 Hourly load profile (Load profile in March 2016)

3.2.2 Fault Statistics

The fault statistics of the substation is attached in Appendix A. Fault statistics data comprises the daily interruptions of power, duration and cause of each interruption. The data helps us to quantitatively describe the reliability of the network with standard performance indicators and compare with standard values. The fault statistics shows the reliability of the network is far behind standards as discussed in section 3.4.

3.3 Load Flow Analysis

A major consideration in the design of a distribution system is to ensure that it provides the required quality of service to the various loads. Load flow analysis of the distribution network is carried out to make sure that the voltage profile of the network is within limit while lines and transformers are not loaded beyond their ratings. A load flow is run on DIgSILENT (Power Factory 14) distribution software first with the existing peak load and then including the already requested loads to examine the voltage profile. The load flow result discussed in 3.3.2 shows that maintaining the automatic tap changer of the power transformer can make the voltage profile always within range but as the load rises under voltage will become a problem.

3.3.1 Line Parameters

The available overhead (OH) lines and underground (UG) cables data in the existing network is summarized in Table 3.2 [29].

Table 3.2: Technical data of conductors [29]

Code of conductor	**R**	**X**	**I_{sc}, Short circuit current (kA)**	**I_{Rated} (A)**	**Type of conductor**
AAC25	1.179	0.379	2.1	145	OH Bare
AAC50	0.578	0.36	4.3	225	OH Bare
AAC95	0.307	0.34	8.1	340	OH Bare
XLPE AAAC150	0.183	0.34	8.4	385	OH XLPE Covered
XLPE AAAC95	0.279	0.32	5.3	282	OH XLPE Covered
1/C UG AL 240mm^2	0.122	0.103	19.2	385	UG Cable

Where;

R: Positive sequence resistance of conductor (Ω/km)

X: positive sequence reactance of conductor (Ω/km)

Isc (kA): is short circuit capability

I_{Rated}: Thermal Limit (A)

3.3.2 Load Flow Result

A load flow is simulated on DIgSILENT with the existing peak load of 128 A to assess the medium voltage profile. With this scenario, the voltage profile during peak hour at different power transformer primary voltage levels (V_{prim}) is as shown in Figure 3.5 where the nodes represent selected MV supply points in the network. During operation, 132KV bus voltage varies ±5 % at substation level as per EEP standard and hence, the corresponding medium voltage of the power transformers in the substation varies until maintained by the on-load tap changer. This is why different high voltage values are taken in the load flow for MV profile.

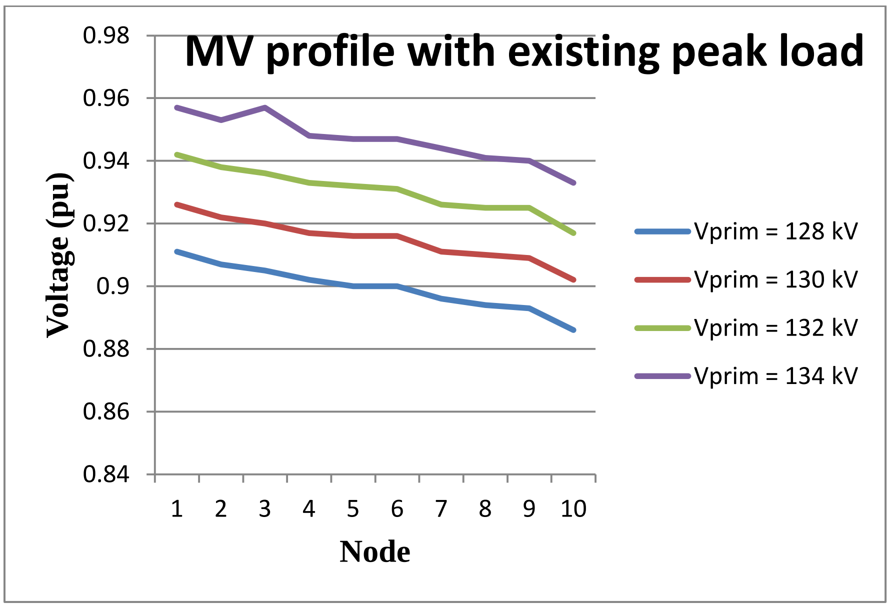


Fig 3.5 Voltage profile with existing peak load

As per measurement records at Cotebe substation, primary side (HV) voltage of the power transformer decreases from the nominal value of 132 kV to as low as 126 kV. With this scenario, voltage drop of some nodes observed at 128 kV would not have been a problem if the automatic on-load tap changer were repaired so that there will be predictable response time in a couple of seconds during high voltage variations. Thus, the complaint of some customers about under voltage problem is justifiable.

Next, a load flow is run on DIgSILENT with the expected peak load of 270.7 A or 15.5 MVA on the existing 33 kV feeder including the already requested loads.

The total installed capacity of distribution transformers on the existing 33 kV feeder shall be 34,380 kVA when the already requested loads are added. There is also a new customer with 7500 kVA transformer but to be supplied with a new feeder as per the plan in EEU. Hence, the load flow is run to assess the voltage profile of the 33 kV network with a maximum load the 16 MVA power transformer can serve and with an assumption that the power factor of all customers with transformers of 200 kVA and above is corrected.

Assuming a peak load of each customer is 80% of installed transformer capacity (as observed from their power requests), the sum of the maximum demand on each transformer is therefore;

0.8*34,380.00 kVA = 27,504.00 kVA.

Experience in distribution system shows that the coincident factor in the medium voltage network is 0.28 – 0.5. Hence, taking an average coincident factor of 0.4, the expected peak load on the existing 33 kV outgoing feeder will be:

0.4*27,504.00 kVA/1.732*33 kV = 192.00 A

Since the customer requesting 7500 kVA power has a dedicated feeder, a higher coincident factor of 0.6 is assumed. Thus, its contribution to the peak load on the power transformer shall be:

0.6*7500.00/1.732/33 kV = 78.7 A

Therefore, the total peak load on the transformer is expected to be: 78.7 + 192 = 270.7 A. i.e., a percentage loading of 97 %. This implies the transformer cannot serve all the waiting customers since the loading on the transformer will even be more than this considering the increase in reactive loading and the power losses. Figure 3.6 shows the voltage profile of the network with this operating condition.

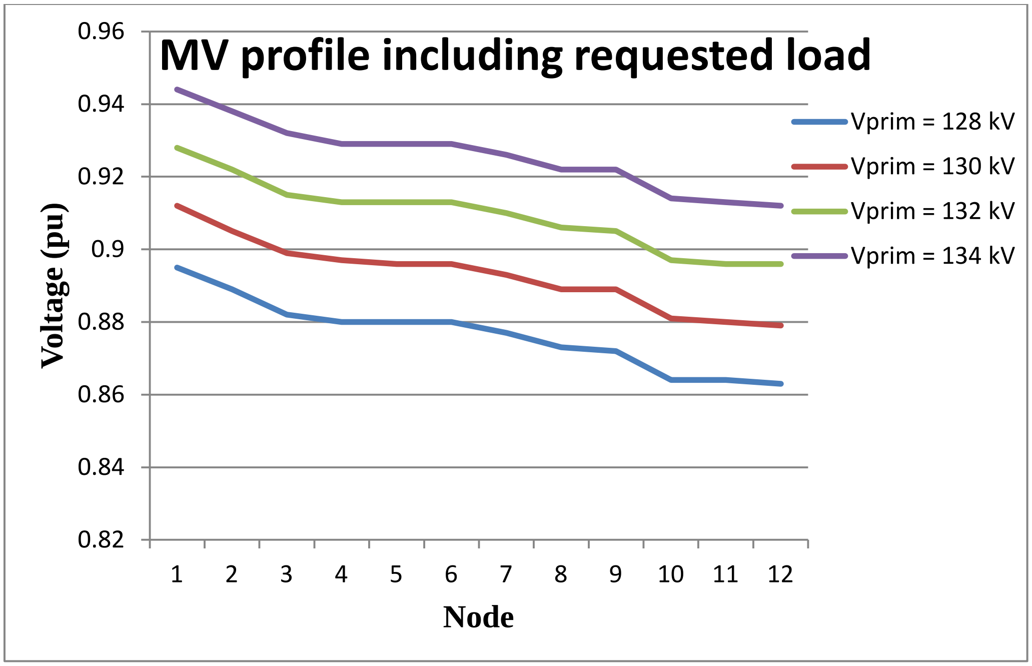


Fig 3.6 Voltage profile with expected peak load including the requested loads

The medium voltage profile in Figure 3.6 shows that some customers experience voltage drop even at the nominal 132KV value. The load flow is carried out with an assumption that the power factor of all customers with transformers of 200 kVA and above is corrected.

As discussed above, the expected peak load would be about 15.5 MVA when the already requested loads are incorporated. But, the load flow result shows that only 14.53 MVA load can be served by the system before the existing power transformer in Cotebe substation is overloaded. That means about 1.44 MVA of the industrial loads could not be served since the 16MVA transformer would otherwise be overloaded.

We can draw three main conclusions from the above discussion:

- The existing system has a major capacity constraint to serve the industrial customers which have already requested for electricity access and those under construction. Thus, the substation or the area needs substation capacity augmentation.

- The voltage profile of the 33 kV network will get worse as these loads are gradually connected with a power factor of 0.97 at substation level.

3.4 Reliability Calculation and Analysis

Reliability calculation of the network carried out to quantify with standard reliability indices SAIDI and SAIFI and compare with standard values and show the performance of the network. The monthly power interruption statistics of the existing 33 kV feeder is shown in Tables 3.3 and 3.4.

Table 3.3 Monthly fault statistics of existing 33 kV feeder of 2013 and 2014 [EEP]

Month	Total frequency	Total Duration (Hr)	Month	Total frequency	Total Duration (Hr)
Jan. 2015	46	20.17	Jan. 2014	32	20.47
Dec. 2014	54	41.57	Dec. 2013	32	31.45
Nov. 2014	33	17.27	Nov. 2013	32	27.3
Oct. 2014	18	10.73	Oct. 2013	43	40.12
Sept. 2014	26	19.05	Sept. 2013	41	58.37
Aug. 2014	51	45.72	Aug. 2013	28	45.82
Jul. 2014	27	67.47	Jul. 2013	23	33.81
June. 2014	42	23.47	June. 2013	45	44.75
May. 2014	34	21.37	May. 2013	22	9.15
Apr. 2014	53	56.6	Apr. 2013	12	28.52
Mar. 2014	30	23.31	Mar. 2013	30	33.63
Febr. 2014	45	31.98	Febr. 2013	23	24.81
	459	378.71		363	398.2

Table 3.4: Year 2015 monthly fault statistics summary of the existing 33 kV feeder [EEP]

Month	Operational		TSC		TEF		PSC		PEF		PDF		Blackout		Overload		Total	
	Duration (Hr)	Frequency	Duration (Hr)	Frequency	Duration (Hr)	Frequency	Duration (Hr)	Frequency	Duration (Hr)	Frequency	Duration (Hr)	Frequency	Duration (Hr)	Frequency	Duration (Hr)	Frequency	Duration (Hr)	Frequency
Jan. 2016	35.92	16			1.37	18	0.52	1	22.13	17	1.17	1	4.5	2			65.61	55
Dec. 2015	14.77	24	3.8	25	1.55	19	7.08	8	22.02	8	2.23	1	8.88	3			60.33	88
Nov. 2015	2.25	5	0.07	1	0.53	3	13.62	3							17.27	40	33.74	52
Oct. 2015	6.93	10	1.33	9	1.48	17	6.35	8	21.82	7							37.91	51
Sept. 2015	24.08	21	1.05	8	2.62	29	3.48	4	4.33	5							35.56	67
Aug. 2015	28.33	20	0.07	1	1.9	26	0.65	1	50.95	22			3.65	2			85.55	72
July. 2015	15.18	12			1.92	29	2.88	2	24.93	17							44.91	60
June. 2015	17.03	9			7.1	15	0.23	1	4.18	5			0.22	1			28.76	31
May. 2015	32.77	14	0.08	1	0.9	12			12.9	7			12.95	2			59.6	36
April. 2015	76.98	26			0.7	13			0.55	2							78.23	41
March. 2015	11.65	13			2.23	10			12.4	9			2.68	1			28.96	33
Febr. 2015	5.97	8			3.33	25	0.93	1	2.02	2							12.25	36
Yearly Total:	**271.9**	**178**	**6.4**	**45**	**25.6**	**216**	**35.7**	**29**	**178**	**101**	**3.4**	**2**	**32.9**	**11**	**17.3**	**40**	**571**	**622**

As per the fault statistics shown in Tables 3.3 and 3.4, the network performance indicators SAIFI and SAIDI of the existing network are shown in the Figures 3.7 and 3.8 with respect to a national standard (SAIFI = 25 and SAIDI = 20) of Ethiopian Electric Agency. Figures 3.7 and 3.8 show how low the performance of the distribution system is even with respect to standard set by Ethiopian Electric Agency let alone with other international standards shown in Table 2.2.

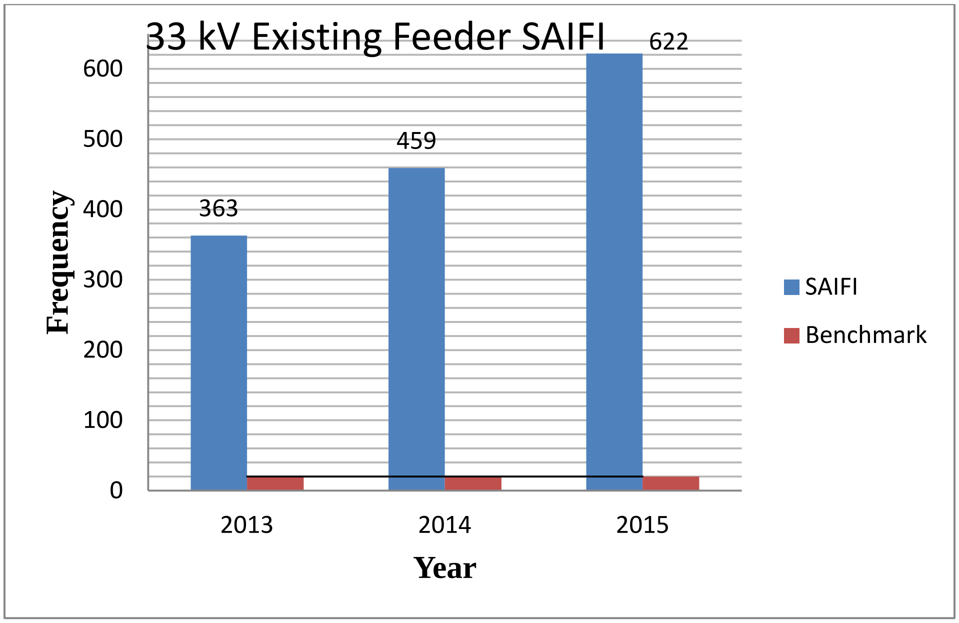


Fig 3.7 SAIFI of the existing 33 kV outgoing feeder

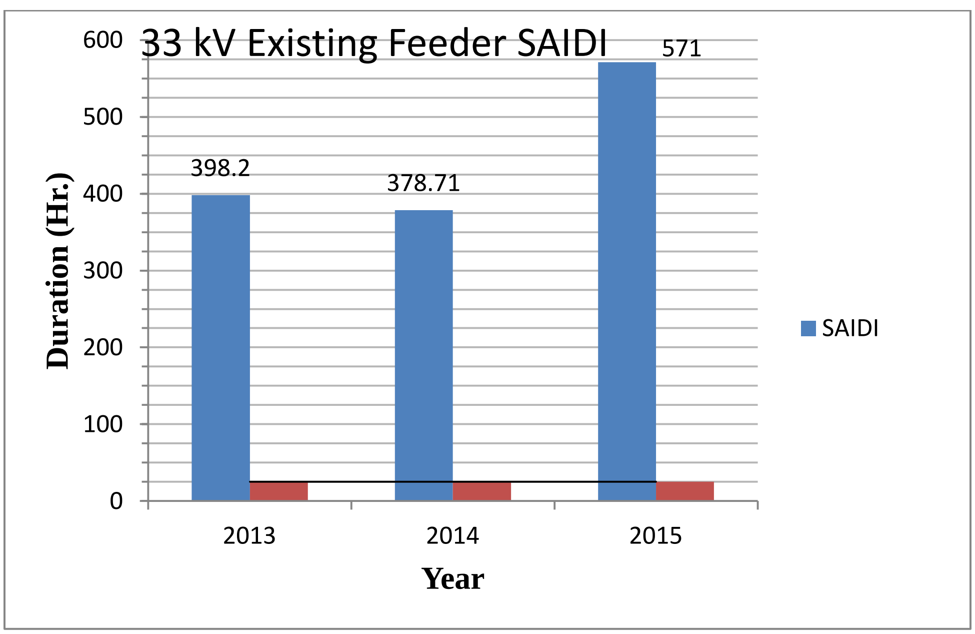


Fig 3.8 SAIDI of the existing 33 kV outgoing feeder

Chapter Four

Redesign and Analysis of the Industrial Network

4.1 Major Design Requirements

Industrial power supply systems call for a maximum level of operational reliability, economic efficiency and flexibility [15] [30]. In order to fulfill the high reliability and quality requirement of the industrial electric networks, utilities should adhere to standard design and operational procedures in a world where the competition is global.

The design of the industrial electric network is guided by the following major technical parameters [15] [30]:

i. The configuration of main substations and main supplies should be “intrinsically safe”. This means that if an HV / MV transformer or a MV feeding line should fail, the connected loads have to be switched to another main substation or other points of supply. Thus, the network contingency should satisfy at least N-1 criteria. N-1 criteria mean, given N network elements and in case one network element fails, the missing loads will be supplied with the N-1 network elements. This encompasses selecting appropriate network configuration.

ii. In order to limit the short-circuit power in the medium-voltage system, the transformers of the main substations should not be operated in parallel. It is better they are allocated to separate sub-networks. This needs the MV bus bar to have a sectionalizer breaker so that the transformers operate separately during normal conditions.

iii. Power system protection should limit the effects of a defect in a system element on the system operation and reduce the effects on parts that are directly affected as far as possible.

iv. The installation of main substations and main supplies should be close to load centers. This enables losses to be minimized, a simple and flexible network configuration as well as an economic network extension and ensures supply quality.

v. Distribution automation technology is taken into account for the operation of MV grids so that network faults are quickly detected and isolated and power is restored to fault free sections.

vi. The design of the electric network should also be cost effective and give attention for personal safety.

vii. The electric network elements should be designed to withstand the mechanical and electrical impacts of short circuit currents. There should also be protection against over voltages and equipments should withstand designed overvoltage levels.

viii. The capacity of the main substation should be decided considering anticipated load growths.

4.1.1 Substation Capacity Estimation

As discussed in section 4.1, one of the requirements for an industrial network design is that there should be sufficient capacity to cater the anticipated demands including load forecasts. Here, the capacity requirement to upgrade the substation to serve Sendafa industry zone is estimated.

Load Forecast

In a load forecast, it is normal to consider high and low cases as well as a reference (base) case. The high case should be a reflection of an optimistic but achievable social-economic-political future. Similarly the low forecast should be based upon a pessimistic view of the future, not a catastrophic one. Tables 4.1 and 4.2 are taken from a load forecast study by a consultant in EEP and used as a reference to take an average value [31].

Table 4.1: High Load Forecast [EEP]

	2012 – 2015	2016 - 2020	2021 - 2025	2026 – 2037
Agriculture	10.5%	8.3%	7.4%	5.9%
Industrial	25.0%	19.1%	17.4%	14.2%
Commercial	12.5%	9.9%	9.0%	7.5%
Services	12.5%	9.9%	9.0%	7.5%
Average	13.8%	11.4%	11.1%	10.2%

Table 4.2: Low Load Forecast [EEP]

	2012 – 2015	2016 - 2020	2021 - 2025	2026 – 2037
Agriculture	4.1%	3.8%	2.9%	1.7%
Industrial	9.8%	9.2%	7.5%	5.9%
Commercial	4.5%	4.2%	3.3%	2.1%
Services	4.5%	4.2%	3.3%	2.1%
Average	5.1%	4.9%	4.1%	3.0%

As shown in Tables 4.1 and 4.2, the average high load forecast is as high as 13.8% and the average low forecast is as low as 3%. Thus, a yearly average load forecast of about 7% is assumed to estimate the capacity requirement of the network.

- ❖ The current peak load is 128 A.
- ❖ The expected peak load including the industries under construction with a coincident factor of 0.4 is 332.5 A probably a year later.
- ❖ Assuming a yearly 7% load growth in the next 10 years, the expected peak load would be about 654.1 A (37.4 MVA).
- ❖ It is also assumed that the industrial area has limited capacity regarding the number of industries it will accommodate.

To satisfy N-1 criteria, it’s assumed that there shall be two transformers for the proposed substation each with a normal loading of 60% of their rated capacity assuming transformers emergency loading capacity of up to 120%. Hence, a substation total installed capacity of 37.4 MVA/0.6 = 62.3 MVA is required [14] [15].

Therefore, it is recommended to upgrade the existing 132/33 kV, 16 MVA transformer to 132/33 kV, 2 x 31.5 MVA based on 10 years demand forecast.

4.2 Substation Design Options

As discussed in section 3.3, one of the constraints of the existing network is insufficient substation capacity. As shown in Figure 3.1, there is Legetafo substation in between Cotebe substation and Sendafa industrial zone. Hence, the following three options for substation capacity augmentation should be considered:

- **Upgrading Cotebe substation** - which is about 30 kms from Sendafa industry zone
- **Upgrading Legetafo substation** - which is about 18 kms from Sendafa industry zone
- **New substation** - at Sendafa industry zone

But, upgrading Cotebe substation is not recommendable due to the following technical and economical constraints:

- It has a major constraint of right of way issue (access to over head line and underground cable routes) to take out three or more additional MV feeders since Cotebe substation is in a very developed part of the city whereas it will be much easier for Legetafo substation which is on the outskirts of Addis Ababa.

- It is very far from the load center (the industry zone) which is greater than 30 km and even much far from some of the customers which is about 50 km, leading to large voltage drops and maintenance costs.

- Additional load on Cotebe substation requires the 132 kV line from Legetafo substation to Cotebe substation be upgraded since it will be over loaded as shown in the PSS/E result in Appendix C.

Therefore, the following two viable options are to be compared for substation capacity augmentation and Figures 4.1 and 4.2 show the proposed substation configurations and medium voltage network block diagram is shown.

Option 1 - Upgrading of Legetafo Substation

With this option, the 132 kV busbar of Legetafo substation is extended with two 31.5 MVA transformer bays as shown in Figure 4.1. Legetafo substation is a 230 kV substation with two 230 kV incoming lines from Kaliti I substation and Combolcha II substation.

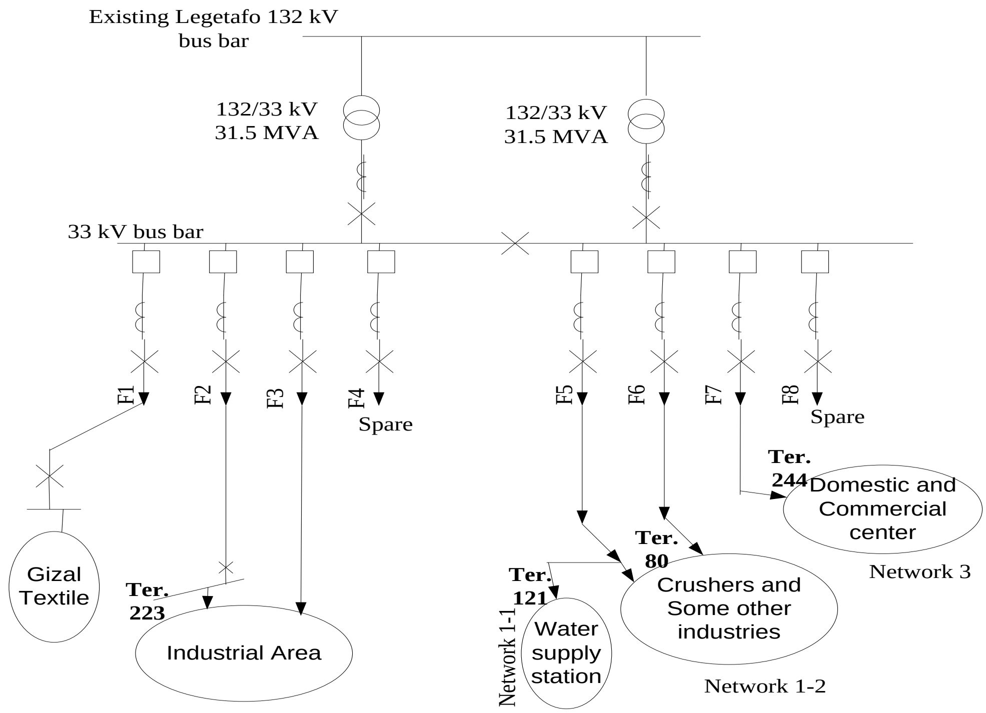


Fig 4.1 Option 1 - Upgrading Legetafo substation and MV network block diagram

Option 2 - New substation at Sendafa industry zone

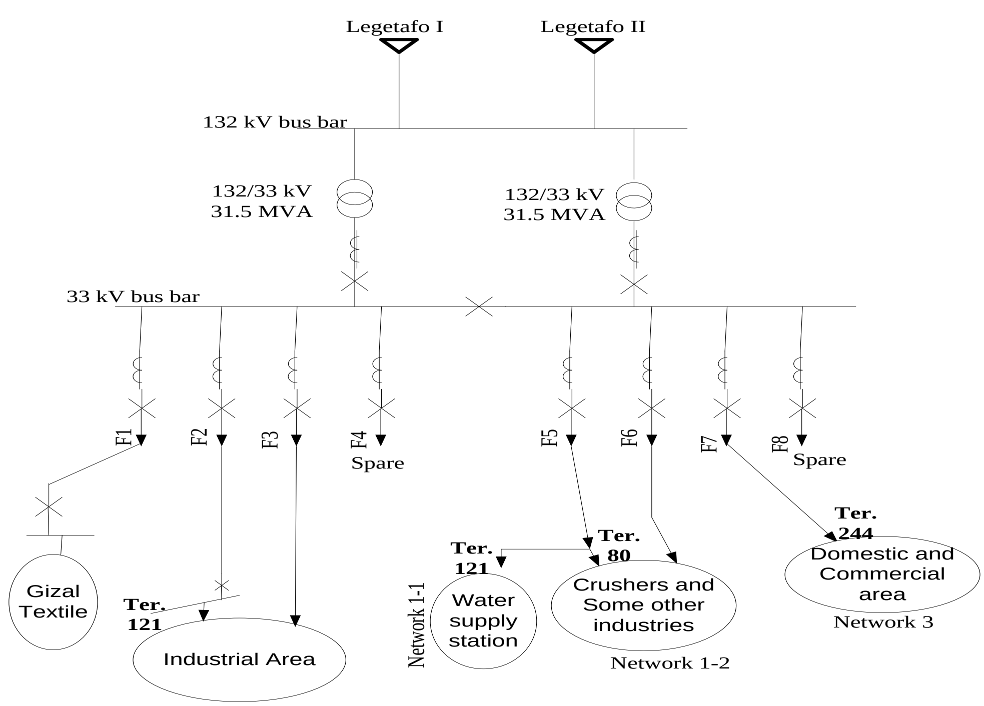


Fig 4.2 Option 2 - New industry zone substation and MV network block diagram

4.2.1 Analysis of the Substation Design Options

Upgrading Legetafo substation or Option 1 shown in Figure 4.1 is proposed by extending the 132 kV bus bar and installing 2 x 31.5 MVA power transformers whereas Option 2 or a new substation in the industry zone is proposed by constructing 2 x 132 kV lines from Legetafo substation and setup a substation in the industry zone with 2 x 31.5 MVA power transformers.

As per operational practices of Ethiopian Electric Utility (EEU) discussed in section 2.4 which was recommended by an international consultant, XLPE covered AAAC150 conductor is used for the backbone of Sendafa industry zone medium voltage network and that of XLPE covered AAAC95 conductor for the lateral circuits.

Standard 132KV level conductor types used by EEP are AAAC Ash (nominal area 150 mm^2), ACSR Ostrich (Nominal area 152.2 mm^2) and ACSR Tiger (Nominal area 125 mm^2) [31].
The two options are technically and financially analyzed in the following sections.

4.2.1.1 Technical Analysis of Option 1 and Option 2

The aim of the technical analysis is to discuss the reliability and quality issues associated with the two proposed options. Based on the design requirements stated in section 4.1, the following points are observed with the proposed options:

- The N-1 criterion of high voltage system of the two options is satisfied since both have at least two incoming lines. Legetafo substation has two 230 kV incoming lines one from Kaliti-I substation and the other from Combolcha-II substation. Similarly, the optional new Sendafa industry zone substation would have two 132KV incoming lines from Legetafo substation.

- Similarly, the arrangement of the power transformers and the medium voltage feeders for the industry zone in both options is taking same criteria into account as shown in Figures 4.1 and 4.2.

- New substation at Sendafa industry zone is within 2 km radius to the load center or the industrial area where as Legetafo substation is about 18 km from the industrial area. Hence, option 2 would have a better voltage profile but option 1 will also be checked for voltage profile to be within limits.

- The 230 kV Legetafo substation has higher short circuit level than a new Sendafa industry zone substation with a 132 kV line extension from Legetafo substation which implies a better voltage regulation delivered.

- The medium voltage network of both options is open loop configured equipped with intelligent reclosers for automated fault isolation and power restoration. Thus, both options are equally equipped in terms of distribution protection and automation.

4.2.1.2 Financial Comparison of the two Options

The two options of upgrading the network to meet the current and future demand with a consideration of reliability and power quality issues are compared with an estimated investment cost. The 132 kV conductor type of AAAC 150 mm^2 (Ash) is chosen for option 2. The initial cost of 132 kV AAAC Ash single circuit is taken as 191,000.00 $/km [31].

Table 4.3: Cost analysis of Options 1 and 2

Options	Cost Element	Unit	Qty.	Unit cost ($)	Total cost ($)	Total ($)
Option 1: Upgrading Legetafo substation	132 kV Transformer bay	Each	2	684,000	1,368,000	6,568,000
	132/33 kV, 31.5 MVA Transformer	Each	2	2,000,000	4,000,000	
	33 kV switchgear	Each	8	150,000	1,200,000	
Option 2: New Sendafa industry zone substation	132 kV Line bay	Each	4	684,000	2,736,000	13,042,000
	132 kV double line (AAAC Ash)	Km	14	267,000	3,738,000	
	132 kV Transformer bay	Each	2	684,000	1,368,000	
	132/33 kV, 31.5 MVA Transformer	Each	2	2,000,000	4,000,000	
	33 kV switchgear	Each	8	150,000	1,200,000	

As shown in Table 4.3, Option 2 or constructing a new substation at Sendafa industry area is costlier by 6,474,000.00 $ than option 1. i.e., option 2 is nearly twice costlier at substation level.

Now let's compare the estimated investment cost to upgrade the medium voltage distribution network of the two options.

Table 4.4: 33 kV feeders length and cost comparison of Options 1 and 2

Feeder Name	Length of feeder (Km)		[C] = [A] - [B] Km	$/Km of 33KV with AAAC XLPE150	Total cost difference ($)
	Option 1 = [A]	Option 2 = [B]			
F1	14	4.5	9.5	28,000.00	266,000.00
F2	18	1.8	9.5	28,000.00	266,000.00
F3	22	3.2	9.5	28,000.00	266,000.00
F5	33	15.6	9.5	28,000.00	266,000.00
F6	4	4.4	-0.4	28,000.00	(11,200.00)
				Total:	**1,052,800.00**

The cost of Option 1 at substation level is about USD 6,568,000.00 and that of Option 2 is USD 13,042,000. Option 2 would cost about 1,052,800.00 $ lesser at medium voltage level. This implies, the total cost of Option 2 is about 5,421,200.00 $ more than option 1.

Therefore, option 2 is much costlier than Option 1 and hence, Upgrading Legetafo substation (Option 1) which is about 18 km from Sendafa industry zone is the preferred option given that it also has the technical merits required as discussed in section 4.2.1.1.

4.3 Distribution Network Design

The distribution network starts from the HV/MV substation. It comprises of primary (MV) network and secondary (LV) network up to the customers' premises. The scope of the distribution network design under consideration is up to the MV supply point of the customers' transformers based on the design requirements discussed under section 4.1.

A distribution network design is aimed at realizing a system that will cost-effectively and safely supply electric service to both present and future probable loads while maintaining the power quality and maximum service continuity or reliability.

4.3.1 Selection of Medium Voltage Level

The medium voltage levels in the primary distribution network have been standardized by Ethiopian Electric Utility (EEU) as 15 kV or 33 kV.

33 kV voltage level is preferred for the network under consideration mainly for two reasons:-

a. Existing network equipments for instance, more than 100 distribution transformers, surge arresters, fuses, etc. are rated for 33 kV

b. Big customers like industrial loads are efficiently served by higher voltage and hence 33 kV is best option rather than 15 kV. In addition to that, the existing customer service policy of EEU states that customers requesting between 5 MVA and 10 MVA shall be served on 33 kV. Hence, the 33 kV voltage is justified as there is already a big textile company with a power demand of about 10 MVA.

4.3.2 Network Contingency

Security of supply is one important criterion to be considered. The contingency of the industrial network should satisfy a minimum of N-1 criteria and hence, the system under consideration is designed taking this into account [14].

Therefore, there shall be open loop configured two MV feeders as shown in Figure 4.3 for the industry zone network so that failure on one feeder does not lead to total power outage. Similarly, there are two power transformers in the substation with this criteria into consideration.

4.3.3 Layout of the Redesigned Industrial Network

Industrial zones require the highest level of service reliability and flexibility. Loop network configuration is recommended than simple radial network since it has the following advantages:

- The network segments that could be affected by permanent faults can be as minimized as needed with minimum number of customers and minimum power amount of power system disconnected whereas with simple radial networks as the fault location gets closer to the power source wider area of the network will be affected.

- Permanent failure on one of the feeders' breaker or outgoing cable and overhead lines does not lead to power outage of the whole network which is not the case with simple radial networks.
- Loop network is very flexible in case of preventive and emergency maintenance activities.

With this consideration, the open loop network configuration shown in Figure 4.3 is recommended for the industrial network to achieve the required standard performances which will be discussed in the later sections. The load points shown in the figure represent a load in a branch or lateral network consisting of a number of distribution transformers of different industries to simplify the network layout.

Intelligent reclosers and manual disconnectors are also employed in the proposed network with a feature for automatic isolation of faulty sections via preprogrammed sequence of operation and power is restored to the rest of the network. Therefore, minimum sections of network are affected by permanent faults and the duration of interruption of the faulty sections is reduced since the maintenance crew of the utility can easily locate the faults given that the fault location will now be much more localized. Loop Automation requires each device in the scheme to be configured as a particular type (Feeder device, Mid-point device or Tie device) depending on its position in the network and each with a particular logic of operation [8].

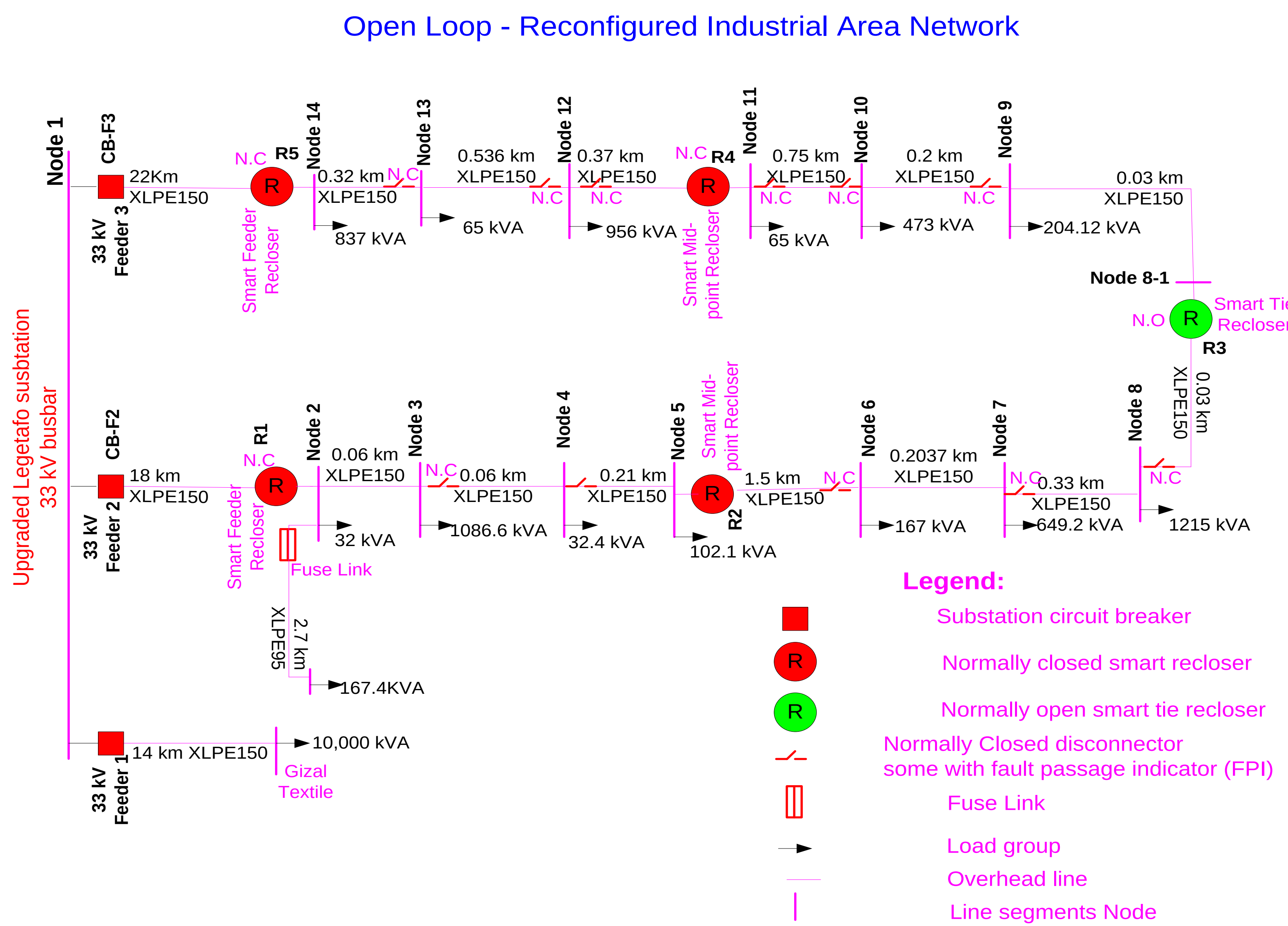


Fig 4.3 Open Loop – Reconfigured Industrial Area Network with intelligent reclosers

4.3.4 Protection Coordination Calculation

For protection coordination, minimum and maximum short circuit simulation on each protection device is done on DIgSILENT software shown in Tables 4.5. The CT ratio of the relays is chosen considering the expected loads including load growth. I_P/I_N (Relay current multiplier setting) shown in the Table is done for pickup values I_P be safely above maximum load current on each protection device. I_N is CT rated primary current. I_{prim} is the primary setting current corresponding to I_P/I_N.

Table 4.5: Normal configuration (Tie recloser, R3 Open)

Loop	Node	Protection Equipment	Max. load (A)	I_{sc}, max (A)	CT Ratio	I_P/ I_N	$I_{prim.}$ (A)	$I/I_p = I_{sc,max}/ I_{prim.}$
Via Feeder 2	1	CB-F2	62	4660	200 - 400/5	0.62	124	57.82
	2	R1	60.4	1870	200/5	0.39	78.52	23.82
	2	FuseLink	2.9	1870	-	-	-	-
	5	R2	35.6	1790	100/5	0.46	46.28	38.68
Via Feeder 3	1	CB-F3	45.3	4660	200 - 400/5	0.29	58.89	79.13
	14	R5	45.3	1640	100 - 200/5	0.59	56.4	29.08
	11	R4	12	1590	100/5	0.16	15.6	101.92

Table 4.6: Network Configuration with Tie Recloser (R3) Closed and R5 Open

Loop	Node	Protection Equipment	Max. Load (A)	I_{sc}, max (A)	CT Ratio	I_p/I_N	$I_{prim.}$ (A)	$I/I_p = I_{sc,max}/ I_{prim.}$
Via Feeder 2	1	CB-F2	108	4660	200 - 400/5	1.08	216	33.19
	2	R1	106.4	1870	200/5	0.69	138.3	13.52
	2	FuseLink	2.9	1870	-	-	-	-
	5	R2	80	1790	100/5	1	100	17.90
	14	R3	44.3	1680	100/5	0.58	57.59	29.17
	11	R4	32	1630	100/5	0.42	41.6	39.18

The Time Multiplier Setting (T.M.S.) is calculated as follows. For the time grading of inverse-time relays, the time grading is first calculated for the maximum fault level and then checked for lower current levels [15] [32].

Normal network configuration (R3 Open) – Via Feeder 2

Device at Node 5: Recloser 2 (R2)

Current multiples of relay setting = $\frac{Isc,max}{Iprim.} = \frac{1790}{46.28} = 38.68$

The IEC 60255 defines standard equation governing very inverse characteristic curve as follows [33]:

$$t = TMS * \frac{13.5}{(\frac{I}{Is}) - 1} \tag{4.1}$$

where t – is relay operating time

TMS is Time Multiplier Setting

I is measured device current

Is is setting current

and with TMS = 0.5, the operating time of recloser R2 will be:

t_{R2} = 0.5 * (13.5/37.68) = 0.18 sec

Recloser 1 (R1) at Node 2

Current multiples of relay setting, I/Ip = $\frac{1790}{78.52} = 22.8$

Let's take a coordination time interval (CTI) = 0.3 sec. Thus, for the maximum fault at Node 5, the relay operating time of R1 is:

t_{R2} + CTI = 0.3 + 0.18 = 0.48 sec

Therefore, the TMS of recloser 1 is derived using eq. (4.1):

$$0.48 = TMS * \frac{13.5}{22.8 - 1} \quad => TMS = 0.77$$

Device at Node 2: Recloser 1

Maximum fault

Current multiples of relay setting, I/Ip = $\frac{1870}{78.52} = 23.815$

Recloser relay operating time, t_{R1} = 0.77$*\frac{13.5}{23.815-1}$= 0.46 sec

For a fault at node 2 (say, at maximum fault), the relay operating time of feeder circuit breaker CB-F2 should be:

CTI + t_{R1}= 0.3 + 0.46 = 0.76 sec

Current multiples of relay setting (of CB-F2), I/Ip = $\frac{1870}{124}$= 15.08

Hence, the TMS of CB=F2 is obtained as: 0.76 = TMS $*\frac{13.5}{15.08-1}$=>TMS = 0.8

Device at Node 1: Substation circuit breaker CB-F2

Maximum fault

Current multiples of relay setting, I/Ip = $\frac{4660}{124}$= 37.58

Thus, relay operating time of CB-F2, t = 0.8 $*\frac{13.5}{37.58-1}$= 0.29 sec

Fuse type selection:

DBU (Distribution Boric acid fuse Unit) is applicable for protecting power transformers, feeder circuit sectionalizing, distribution transformers, metal clad switchgear and potential transformers. DBU expulsion fuses use the proven performance of boric acid to create the de-ionizing action needed to interrupt fault currents [34]. Fuse blow rather than fuse saving is employed so that fault on the lateral feeder does not affect the other network. The lateral tap fuse is selected based on a criteria that I = 2 x I_{load}= 2 x2.9 = 5.8 A [12]. The next higher fuse rating available is 6 A. The TCC curve separation rule for a digital relay with a fuse requires minimum time margin of 0.2 sec [12].

$I_{sc,max}$ = 1870 A and $I_{sc,min}$ = 1300 A at the fuse link. At 1870 A fault current, R1 operates in 0.46 sec. The fuse should operate in less than 0.26 sec at this fault current for proper coordination. At 1300 A fault current, R1 operates in 0.67 sec. Thus, the fuse link should operate before 0.47 sec at this fault level. Referring to the manufacturer's TCC of 6K DBU fuse link shown in Figure 4.4, it is observed that this condition is met [34].

The fuse should withstand transformer magnetizing inrush current. Rough approximation is 12*In for 0.1 sec and 25*In for 25 sec. The total nominal current of the transformers connected on the fuse link is 7.26 A on 33 kV side. Hence, the fuse must withstand a transformer magnetizing current of 87.12 A for 0.1 sec and 181.52 A for 0.01 sec. Observing on the manufacturers TCC, the selected fuse can withstand a current of 181.52 A for more than 0.05 sec and that of 87.12 A for about 0.13 sec. Hence, the selected fuse satisfies this requirement.

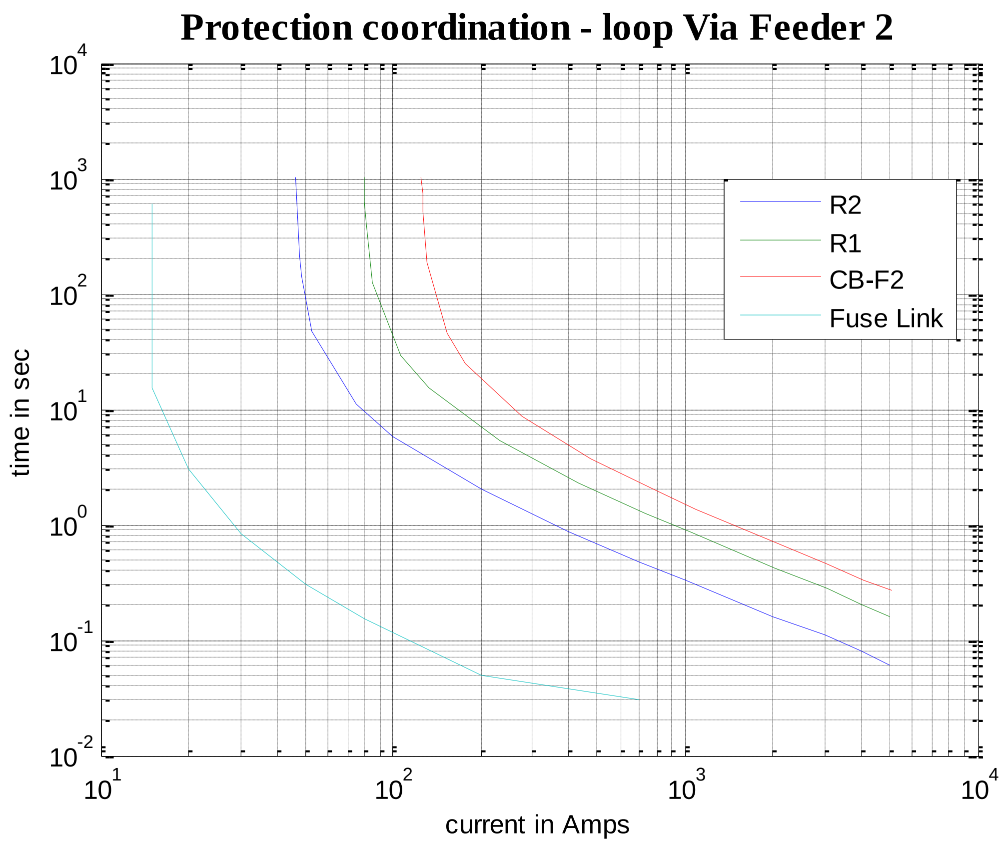


Fig 4.4 TCC of protective equipments in the loop section via Feeder 2

Using a similar procedure for normal network configuration (R3 Open) – Via Feeder 3, the characteristic values can be obtained:

R4 (Recloser 4): TMS = 1

R5 (Recloser 5): TMS = 0.83

CB-F3 (Feeder 3 breaker): TMS = 0.6

The TCC (time current characteristic curve) of the protection equipments as shown below also confirms the proper coordination of the devices.

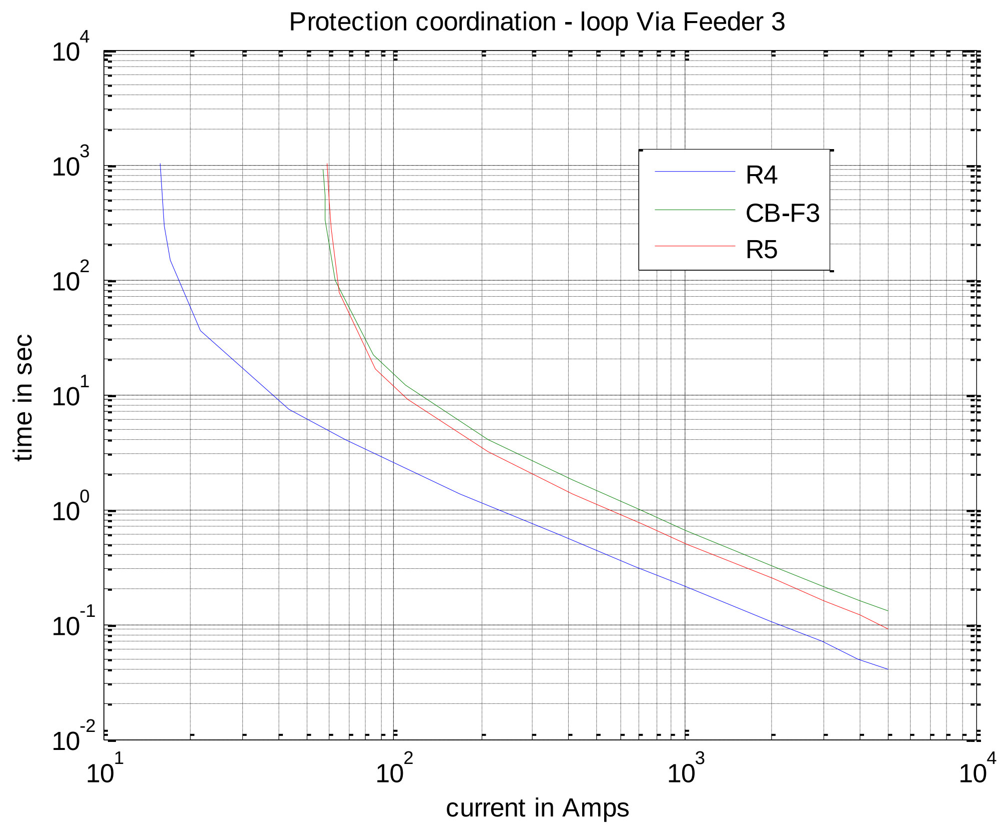


Fig 4.5 TCC of protective equipments in the loop section via Feeder 3

Using a similar procedure for Network configuration Via Feeder 2 with Tie recloser R3 closed and R5 open, the characteristic values can be obtained:

R4 (Recloser 4): TMS = 0.5

R3 (Recloser 3): TMS = 0.96

R2 (Recloser 2): TMS = 0.89

R1 (Recloser 1): TMS = 0.9

CB-F2 (Feeder 2 breaker): TMS = 0.7

The overall coordination of the protective devices is shown below with a plot of TCC curves of the devices.

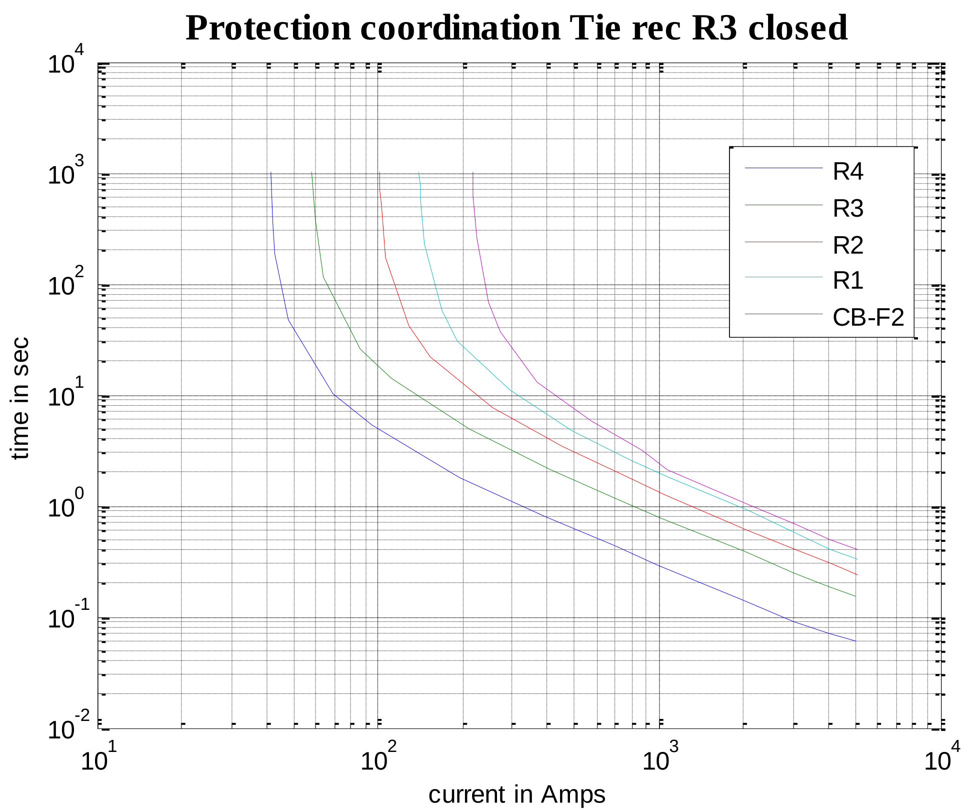


Fig 4.6 TCC of protective equipments with R3 closed and R5 open

4.3.5 Medium Voltage Equipments Selection and Specification

The selected of the 33 kV equipments is based on the following basic technical parameters [31] [35]:

- **Nominal or rated voltage:** The nominal voltage of equipment is selected based on the nominal voltage of the distribution network which in our case is 33 kV.

- **Maximum operating voltage:** Maximum operating voltage of the system is the highest value which occurs under normal operating conditions at any time and at any point in the system due to lightly loaded transmission lines and poor system regulation. Equipments are designed to withstand this value.

- **Rated frequency:** Rated frequency of the system (50Hz).

- **Rated Continuous Current:** The equipment should be rated considering the maximum load expected and future load growth.

- **Rated Symmetrical Interrupting Current:** The interrupting current rating of the equipment should be greater than the maximum fault current available in the specific location. Usually these values are standardized by utilities. For instance, for 33 kV level, 16 kA or 25 kA is applied for substation circuit breakers and 16 kA, 10 kA, or 8 kA for reclosers and other devices at the backbone and branch circuits based on the anticipated fault levels.

- **Maximum number of closing operations before locking out:** Applied for breakers, reclosers, and auto-sectionalizers.

- **Power Frequency withstand voltage and lightning Impulse Withstand Voltage:**

Rating the dielectric withstand of equipment is based on a combination of the expected dielectric stresses caused by power frequency continuous voltages (48 Hz – 62 Hz for 1 minute) resulting from normal operations e.g. capacitive charge of unloaded line and short term over voltages such as switching and lightning over voltages.

Altitude correction factor: Table 2 of IEC 60071-1 gives standard power frequency withstand voltage and lightning impulse withstand voltage values corresponding to the respective standard highest voltage for equipment. These standard rated withstand voltages are valid for the normal environmental conditions. Normal environmental conditions ambient air temperature does not exceed 40^{O}C, medium pollution level and the altitude does not exceed 1000 m a.s.l. Therefore, the medium voltage network is located at an average altitude of 2550 m a.s.l. needs an altitude correction.

For 36KV highest equipment voltage, considering the effect of altitude and taking the next higher values of withstand voltage values from Table 2 of IEC 60071-1, we can take:
Power frequency withstand voltage of 95 kV and lightning impulse withstand voltage of 170 kV.

As per the above discussed parameters, Table 4.7 summarizes the basic technical specification of the selected medium voltage equipments.

Table 4.7: Summary of 33 kV equipments technical specification

Technical parameters	33 kV Equipments specification				
	Circuit Breaker	**Recloser**	**Surge Arrester**	**Isolator**	**Fuse**
Rated voltage	33 kV	33 kV	36 kV	33 kV	33 kV
Maximum operating voltage	36 kV	36 kV	36 kV	36 kV	36 kV
Rated frequency	50 Hz	50 Hz	50 Hz	50 Hz	50 Hz
Rated current	800 A	400 A	-	800 A	6 A
Nominal discharge current	-	-	10 kA	-	-
Rated symetrical interrupting current	16 kA	12.5 kA	-	16 kA	10 kA
Lightning impulse withstand voltage, 1.2/50 μs	170 kV	170 kV	170 kV	170 kV	170 kV
Power frequency withstand voltage for 60 sec	95 kV	95 kV	95 kV	95 kV	95 kV
Min. interrupting time		0.05 sec	-	-	-
Power operating time (close)		0.1 sec	-	-	-
Rated operation sequence	O - 0.3s - CO - 3 min – CO		-	-	-

4.4 Load Flow of the Redesigned Industrial Network

The voltage profile of the medium voltage network at the maximum expected load of Sendafa Industry zone is shown in Figure 4.7. As shown in the Figure, the medium voltage profile of the redesigned industrial network is within acceptable range even for primary voltage (HV) of the power transformer in the substation as low as 126 kV and with the entire open loop network supplied only from one of the open loop configured feeders. In normal operations, the transformers on-load tap changer acts quickly when the HV side or primary voltage of the power transformer drops below the nominal value or 132KV and also the industrial network is supplied by two feeders sharing each half of the network. Hence, in normal operations the voltage profile is even much better.

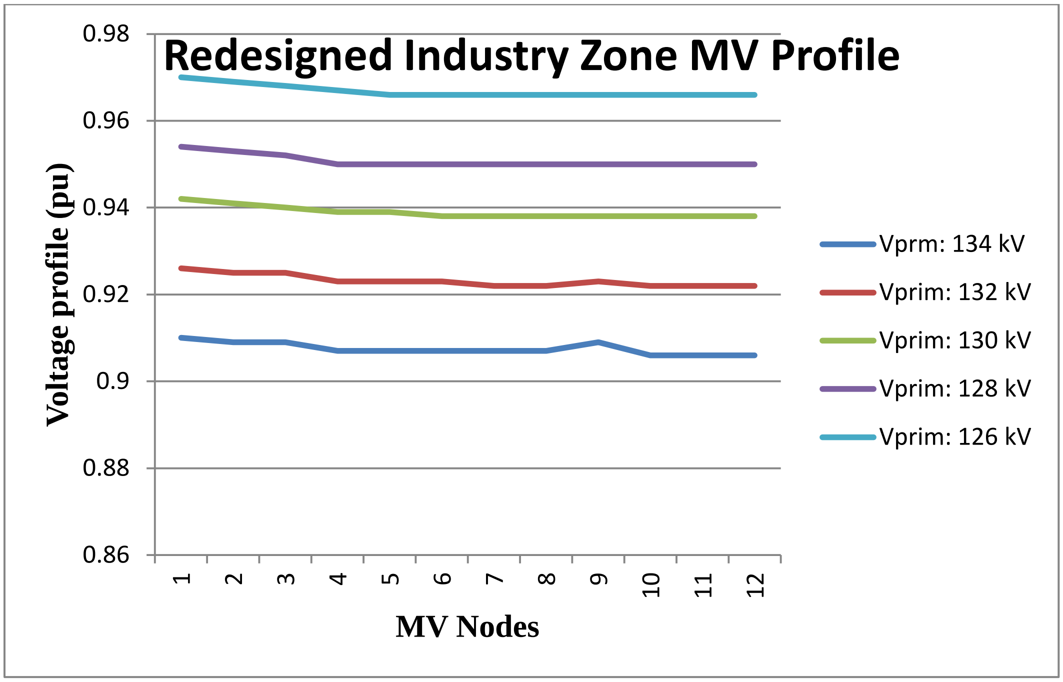


Fig 4.7 MV profile of redesigned industry zone network at expected peak load

4.5 Reliability Analysis of the Redesigned Industrial Network

Reliability analysis of the redesigned industrial network is performed to evaluate the improvement of the network with standard reliability indicators SAIFI and SADI.

The specific parameters for reliability analysis of the redesigned industrial network are as follows [28]:

Table 4.8: Redesigned industry zone network data

Feeder Section	Range of sub-network section	Length and types of conductor	No. of industries	Connected load (kVA)
1	CB-F2 to R1	18 km XLPE150	0	0
2	R1 to R2 including the lateral line	1.34 km XLPE150, 3.8 km XLPE95, 0.11 km AAC95 and 0.3 km AAC50	9	1420.5

3	R2 to R3	1.96 km XLPE150 0.24 km XLPE95, 0.25 km AAC50	8	2031.2
4	R3 to R4	1.01 km XLPE150, 0.42 km AAC50	6	742.12
5	R4 to R5	1.23 km XLPE150, 0.06 km XLPE95, 1.08 km AAC50	9	1858
6	R5 to CB-F3	22 km XLPE150	0	0

The following assumptions are also considered for reliability calculation:

- Faults are assumed distributed along all parts of the circuit.
- 1.9 hrs average permanent faults duration of the existing network calculated below is taken for reliability calculation
- As discussed in section 2.5, interruption durations 1 minute and above are considered as sustained interruption.

Now let us calculate the average fault rate per km of the existing network. The available conductors in the network is summarized in Table 4.9 below.

Table 4.9: Conductor types and total lengths in the existing 33 kV network

No.	Conductor type	Length (Km)	Remark
1	1/C 240 mm^2 Al UG cable	3.5	Underground cable
2	AAC50 17.27 km	50.15	Bare overhead line
3	AAC95 32.88 km		
2	XLPE95 10.22 km	55.66	XLPE Covered overhead line
3	XLPE150 45.44 km		

Total length of 33 kV lines is 105.81 km overhead lines and 3.5 km underground line. Considering the fault statistics, about 80 % of faults are temporary and 20 % of faults are permanent. Fault occurrence in XLPE covered overhead lines is about 35 % of that on bare overhead lines [12].

Based on the existing interruption data, the total duration of permanent faults is 217.1 Hrs/yr on 113.4 frequency/yr of permanent interruptions. This implies, the time taken to restore operation on permanent faults is 217.1/113.4 = 1.9 hrs/fault.

Given 113.4 permanent faults occurrence per year and total distribution network length of 105.81 km, the permanent fault rate is 113.4/105.81 faults/km/yr = 1.071 faults/km/yr. But this fault rate is the combined fault rate of bare and covered overhead lines. Thus, we need to calculate the fault rate of the bare and covered line sections using the assumption that fault rate of covered overhead line is 35 % of bare overhead line [35]. In the existing network, 47 % consists of bare overhead lines and 53 % consists of covered overhead lines. With these data, it is calculated that the permanent fault rate of bare overhead lines is 1.635 faults/km.yr and that of covered overhead lines is 0.572 faults/km.yr.

Given 453.6 temporary faults occurrence per year and total distribution network length of 105.81 km, the temporary fault rate is 453.6/105.81 faults/km/yr = 4.3 faults/km/yr. With a similar arithmetic procedure, the temporary fault rate of the covered overhead line section would be 2.3 faults/km.yr and that of the bare overhead lines section would be 6.57 faults/km.yr.

Permanent and temporary faults are assumed in each section of Figure 4.3 and calculated step by step based on the operating logic of the protection devices shown in Appendix D and the result of sustained frequency and duration of interruptions is summarized in Table 4.10 below:

Table 4.10: Summary of reliability calculations

Faults on	**No. of industries**	**Sustained Customer-hours (interruption duration)**	**Customer - Interruption**	**Load (kVA) affected**
Section 2	9	33.08	17.37	1420.5
Section 3	8	25.34	13.6	2031.2
Section 4	6	14.41	7.56	742.12
Section 5	9	42.8	22.5	1858

From Table 4.10, SAIDI and SAIFI are calculated as follows:

$$\text{SAIDI} = \frac{115.63\ customer\text{−}hrs\ /yr}{32\ customers} = 3.61 \text{ hrs/yr}$$

$$\text{SAIFI} = \frac{61.03\ cust\text{−}\ int/yr}{32\ customers} = 1.91 \text{ int/yr}$$

Therefore, with the proposed open loop configuration for the industry zone SAIFI is improved by 99.7% and SAIDI is improved by 99.4%. The result seems exaggerated. But it is due to the fact that the performance of the existing network is too far behind what can be achieved by implementing state of the art network design. For instance, if our objective were to improve SAIDI and SAIFI by 70%, it would mean achieving a SAIFI of 186.6/year and a SAIDI of 171.3Hrs/year which is still too far from the national standard SAIFI and SAIDI values of 20 and 25, respectively.

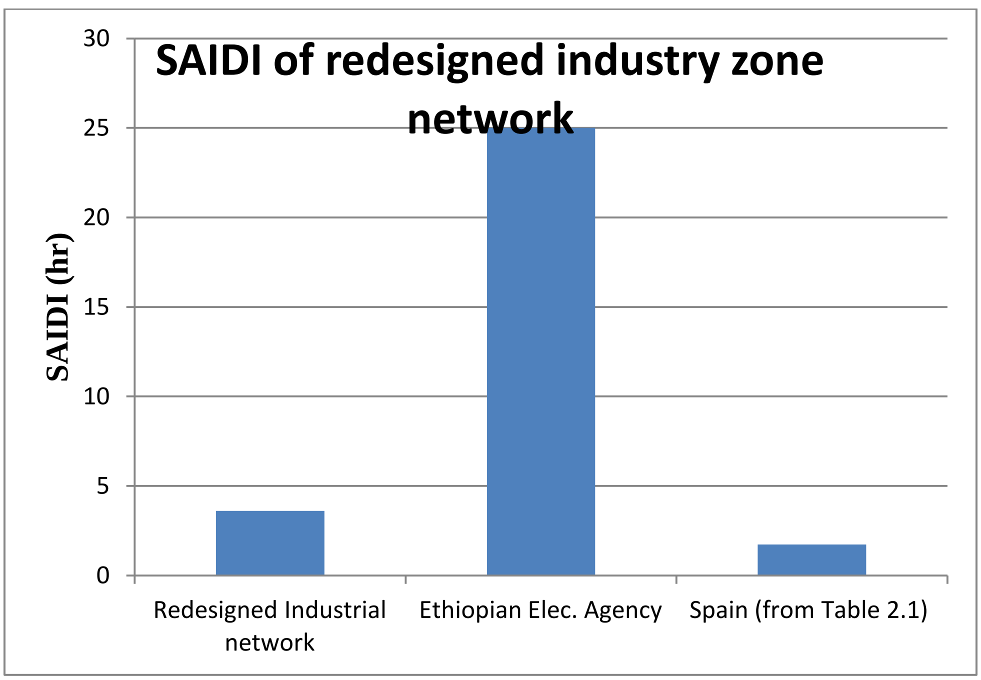


Fig 4.8 SAIDI of redesigned industry zone network with respect to benchmarks

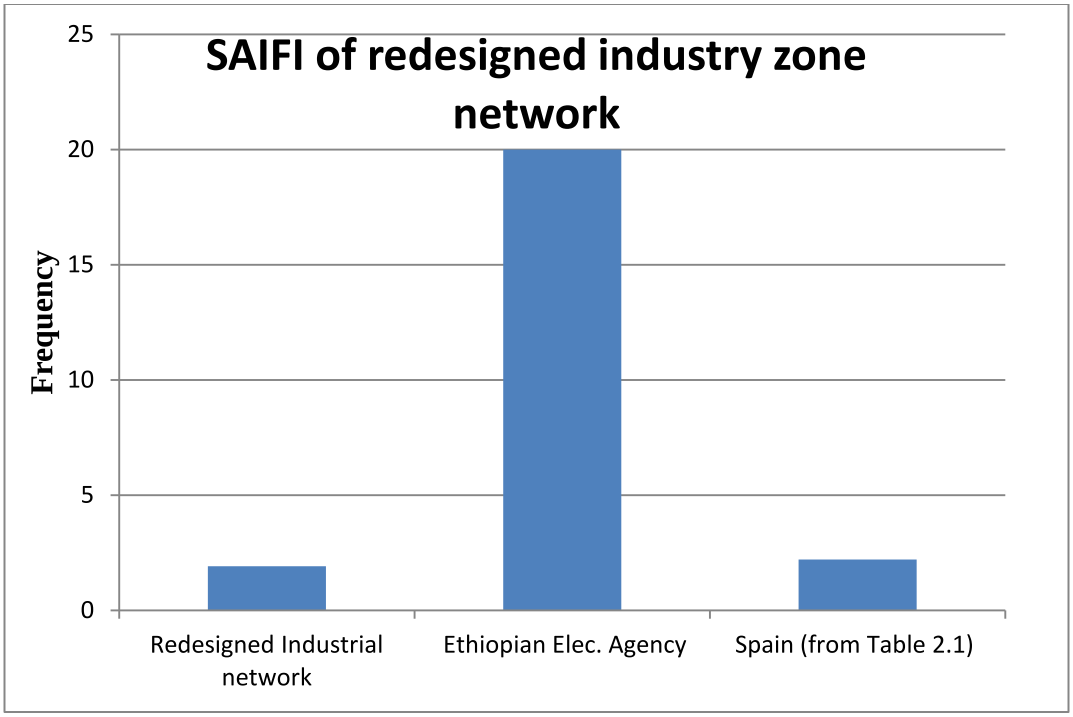


Fig 4.9 SAIFI of redesigned industry zone network with respect to benchmarks

The average duration of 1.9 hrs to restore power after permanent faults taken for the reliability calculations could be lower with the redesigned network since faulty sections are automatically localized which makes it easier to identify the faulty network element. Thus the reliability of the system could even be better.

4.6 Return on Investment

4.6.1 Utility Revenue Loss of Existing System

Frequent power interruptions and insufficient capacity to serve new customers have negative impact on return on investment due to loss of revenue to the utility and reduced economic benefits as a whole due to increased operational costs, reduced social benefits etc. whereas reliable and sufficient power supply increases the return on investment. Here, loss of revenue to the utility is discussed as follows.

Monthly energy not served due to interruptions in the existing network is summarized in the Table 4.11 from which yearly revenue loss can be calculated referring to the tariff rate mentioned in Table 4.12.

Table 4.11: Peak load of the 33 kV outgoing feeder and Energy Not Served (ENS) [EEP]

Month	Peak load (A)	Peak load (MVA)	Peak load (MW)	Interruption Duration (Hr)	Energy Not Served, ENS (KWh)
Jan. 2016	124	7.09	6.38	65.61	215,574.78
Dec. 2015	112	6.40	5.76	60.33	178,962.91
Nov. 2015	100	5.72	5.14	33.74	89,313.15
Oct. 2015	100	5.72	5.14	37.91	100,351.56
Sept. 2015	92	5.26	4.73	35.56	86,622.38
Aug. 2015	82	4.69	4.22	85.55	185,925.82
Jul. 2015	76	4.34	3.91	44.91	90,433.02
June. 2015	68	3.89	3.50	28.76	51,839.90
May. 2015	64	3.66	3.29	59.6	100,983.26
Aprli. 2015	68	3.89	3.50	78.23	141,009.58
March. 2015	68	3.89	3.50	28.96	52,200.40
Feb. 2015	60	3.43	3.09	12.25	19,494.04
			Total	571.41	1,312,710.80

Table 4.12: Tariff rate of EEU [EEU]

No.	Tariff Category & Block	Monthly Energy Consumption (kWh)	Price Rate (Birr/kWh)
1	Domestic		
	Equivalent flat rate		0.4735
	1st block	0 – 50	0.2730
	2nd block	51 – 100	0.3564
	3rd block	101 – 200	0.4993
	4th block	201 – 300	0.5500
	5th block	301 – 400	0.5666
	6th block	401 – 500	0.5888
	7th block	Above 500	0.6943
2	General		
	Equivalent flat rate		0.6723
	1st block	0 -50	0.6088
	2nd block	Above 50	0.6943
3	Low Voltage Industry		
	Equivalent flat rate		0.5778
	Peak		0.7426
	Off Peak		0.5453
4	High Voltage Industry @15KV		
	Equivalent flat rate		0.4086
	Peak		0.5085
	Off Peak		0.3933

Assuming an average tariff or flat rate of 0.53305, the total loss of yearly direct revenue due to the ENS (energy not served) is:

ENS (yearly) KWh * 0.53305 Birr/KWh

= 1,312,710.80KWh * 0.53305 Birr/KWh = **699,740.50 Birr/year**

This amount of financial loss per year is significant such that the cost of purchasing five smart reclosers can be returned in a couple of years. The cost of unserved energy is usually valued few times higher than loss of sales due to economic and social considerations. If we consider the social and economic impact of the interruptions, the loss would be even much higher.

4.6.2 Cost Benefit Analysis of Substation and Network Upgrading

The financial analysis serves to assess the financial viability of upgrading Legetafo substation and medium voltage network. The financial evaluation is carried out in terms of net present value (NPV), cost benefit analysis (B/C ratio) and internal rate of return (IRR).

Net Present Value is the present value of a security or an investment project, found by discounting all present and future benefits and costs at an appropriate rate of discount [33]. For example, present value of a benefit Bt at year t is given by the following equation (same for present value of costs) [36]:

$$PV = \frac{Bt}{(1+r)^t} \tag{4.3}$$

where PV present value and r is discount rate

Bt is a benefit at year t from now and t is years from now

The benefit-cost ratio is the present value of project benefits divided by the present value of project costs [36]:

$$B/C = \frac{PV\ (I)}{PV\ (O)} \tag{4.4}$$

Where I are the inflows and O the outflows. If B/C >1 the project is suitable because the benefits measured by the Present Value of the total inflows, are greater than the costs, measured by the Present Value of the total outflows.

The IRR is the interest rate earned on the unrecovered project balance of an investment project such that when the project terminates the unrecovered project balance is zero. If the computed IRR exceeds the minimum acceptable rate of return (MARR) or the discount rate, the investment is deemed economically worthwhile [36].

The costs are composed of Legetafo substation upgrading cost, including medium voltage line extensions and intelligent reclosers and upstream costs necessary to produce and transport the additional energy being delivered (grid energy cost).

The benefit is calculated by subtracting the supply losses due to power interruptions from the total energy benefit that could be gained.

For financial and economic analysis, the following base points are assumed [reference used is base point assumptions for financial and economic analysis of similar projects in Ethiopian Electric Power]:

- Ethiopian Ministry of Finance and Economic Development recommends a discount rate of 10% for public sector projects.
- Life time of 35 years up to 2051 is assumed for the facility.
- Grid energy cost of 0.03$/kWh is assumed. This is the operation cost ($/kWh) of generation, transmission and distribution of 1 kWh at distribution point. This includes cost of fuel, maintenance, spares, personnel etc.
- Weighted average tariff of 0.03 $/kWh the first five years then 0.06 $/kWh up to 2051.
- Insurance and interim replacement of 0.5% and operation and maintenance cost of 1%.

Table 4.13: Summary of cost estimates [EEP]

Item	Unit	Quantity	Unit price ($)	Total price ($)
Substation upgrading (including 5% for engineering and administration, 10% physical and price contingency)	Lot	1	7,553,200.00	7,553,200.00
MV network OH line extensions	Lot	1	2,548,000.00	2,548,000.00
Intelligent reclosers	Pieces	5	15,000.00	75,000.00
			Grand total (in USD)	10,176,200.00
			Grand total (in Birr) @ 1$ = 21.6Birr	219,805,920.00

Table 4.14: Financial analysis of upgrading Legetafo substation and medium voltage network

Year	Capital Cost (M.$)	Annual Costs				Demand (MWh)	Benefit (M. $)	Net Benefit (M. $)
		Oper. & Maint.	Grid energy cost (M.$)	Insurance cost (M.$)	Total Cost (M.$)			
2016	10.18		0.00	0.051	10.23	0	0.00	-10.23
2017			4.01	0.051	4.07	133,818.45	4.01	-0.05
2018		0.10	4.30	0.051	4.45	143,185.74	4.30	-0.15
2019		0.10	4.60	0.051	4.75	153,208.75	4.60	-0.15
2020		0.10	4.92	0.051	5.07	163,933.36	4.92	-0.15
2021		0.10	5.26	0.051	5.41	175,408.69	5.26	-0.15
2022		0.10	5.63	0.051	5.78	187,687.30	11.26	5.48
2023		0.10	6.02	0.051	6.18	200,825.41	12.05	5.87
2024		0.10	6.45	0.051	6.60	214,883.19	12.89	6.29
2025		0.10	6.90	0.051	7.05	229,925.01	13.80	6.75
2026		0.10	7.38	0.051	7.53	246,019.76	14.76	7.23
2027		0.10	7.90	0.051	8.05	263,241.15	15.79	7.74
2028		0.10	7.98	0.051	8.13	265,873.56	15.95	7.82
2029		0.10	8.06	0.051	8.21	268,532.30	16.11	7.90
2030		0.10	8.14	0.051	8.29	271,217.62	16.27	7.98
2031 - 2051		0.10	8.22	0.051	8.37	273,929.79	16.44	8.07

Table 4.15: Financial Analysis result with average tariff rate of 0.06$/kWh after 5 years

Discount rate	FNPV million $	Benefit Cost ratio (B/C)	FIRR (Financial Internal Rate of Return)	NPV of cost	NPV of Benefit
8%	42.42	1.52	23%	88	134
10%	29.04	1.40		75	104
12%	19.83	1.28		65	84

Table 4.16: Financial Analysis result with average tariff rate of 0.06$/kWh after 10 years

Discount rate	**FNPV million $**	**Benefit Cost ratio (B/C)**	**FIRR (Financial Internal Rate of Return)**	**NPV of cost**	**NPV of Benefit**
8%	26.30	1.32	16%	88	116
10%	15.36	1.20		75	89
12%	8.18	1.08		65	71

The financial analysis result shows that the upgrading Legetafo substation and the 33 kV network to serve Sendafa industry zone is financially attractive.

In addition to the financial benefits, there are also different quantitative and qualitative economic advantages attributed to reliable electric power supply with minimized interruptions and in line with the expected load growth. Stimulating economic growth and encouraging economic cooperation with investors could also be discussed as qualitative advantage leading to economic benefits. In general given the importance and relevance of industrialization, the project would have tremendous indirect economic benefits in addition to direct financial benefits.

Chapter Five

Conclusion, Recommendation and Future works

5.1 Conclusion

As dealt with in the thesis, the electric power supply of Sendafa industrial zone is far behind the national and international reliability and quality requirements. The major factors observed in the network are highly extended radial network configuration, lack of contingency considerations to ensure reliability, a network which is not well equipped in terms of protection devices, a substation very far from the load center in a situation where there is continuous load growth and a substation not rated to handle this continuous rise in demand. All these factors were discussed to be causing intolerable frequent interruptions and long restoration times.

One of the works carried out in this thesis is evaluate the technical and financial feasibility of the substation upgrading options and propose the best option considering the anticipated load growth and voltage regulation requirements. The medium voltage network of the industrial area is also redesigned proposing an open loop configuration equipped with intelligent reclosers to the backbone feeders featuring programmed local automation for fault detection, isolation and restoration. Fuses are used for some branch networks and manual operated disconnectors are also employed to minimize line segments affected by permanent faults. Protection devices coordination is considered so that faults are localized to the nearest devices instead of affecting the whole network and this is also covered in the thesis. Reliability calculations and steady state voltage regulations of the redesigned industrial network are also performed. The financial analysis also shows that the overall investment of upgrading the high voltage and medium voltage network of the industrial zone is financially and economically attractive.

With all these design issues dealt with, it is shown that standard network performance can be achieved in terms of network reliability while keeping the power quality requirement mainly voltage stability. A SADI of 3.61 hrs/yr and SAIFI 1.91 int/yr can be achieved comparable with international standards while keeping the medium voltage supply within limit.
In general, it has been shown that standard performances can be achieved with due consideration of the necessary design and operational requirements for an industrial electric network.

5.2 Recommendation

In this research, it is shown that the poor performance of the existing network supplying Sendafa industry zone is mainly attributed to not following strict design and operational standards and procedures. Therefore, it is recommended that Ethiopian Electric Utility (EEU) and its counterpart Ethiopian Electric Power (EEP) or other stake holders like Ethiopian Electric Authority (EEA) set and follow minimum standards and requirements while planning distribution networks to cater the demand for reliable power by industrial zones.

5.3 Future Works

As further work on the subject matter, the following specific issues but not limited can also be addressed:

In this research, a single source of supply is considered to supply the substation which is part of the national grid. The presence of distributed generation and cogeneration in the industrial areas and corresponding issues with respect to network protection coordination and power quality can be further studied to improve the power reliability problem

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Appendix A: Fault statistics of the existing 33 kV outgoing feeder

Month: Tahsas 21 - Tir 20, 2008 (Dec. 31, 2015 - Jan. 29, 2016)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (hr:min)	Fault type
	Date	Time	Date	Time		
1	30/12/2015	7:44	30/12/2015	7:46	0:02	TEF
2	30/12/2015	11:43	30/12/2015	11:48	0:05	TEF
3	30/12/2015	13:21	30/12/2015	13:42	0:21	PEF
4	31/12/2015	9:57	31/12/2015	10:06	0:09	Operational
5	31/12/2015	13:42	31/12/2015	15:20	1:38	PEF
6	1/1/2016	7:21	1/1/2016	14:43	7:22	Operational
7	2/1/2016	7:53	2/1/2016	12:23	4:30	Operational
8	2/1/2016	14:38	2/1/2016	16:11	1:33	Operational
9	3/1/2016	8:16	3/1/2016	8:20	0:04	TEF
10	4/1/2016	8:28	4/1/2016	8:36	0:08	TEF
11	4/1/2016	10:45	4/1/2016	11:26	0:41	PEF
12	4/1/2016	17:02	4/1/2016	17:07	0:05	TEF
13	6/1/2016	6:36	6/1/2016	7:20	0:44	PEF
14	6/1/2016	10:35	6/1/2016	11:11	0:36	Operational
15	6/1/2016	3:08	6/1/2016	12:36	9:28	Operational
16	6/1/2016	16:24	6/1/2016	18:00	1:36	Total
17	7/1/2016	15:15	7/1/2016	16:00	0:45	PEF
18	8/1/2016	13:56	8/1/2016	14:00	0:04	TEF
19	8/1/2016	14:15	8/1/2016	14:43	0:28	PEF
20	8/1/2016	14:58	8/1/2016	15:54	0:56	PEF
21	8/1/2016	16:58	8/1/2016	17:17	0:19	Operational
22	9/1/2016	11:55	9/1/2016	11:59	0:04	TEF
23	9/1/2016	12:26	9/1/2016	13:36	1:10	PDF
24	9/1/2016	16:28	9/1/2016	16:36	0:08	Operational
25	9/1/2016	17:21	9/1/2016	18:37	1:16	PEF

26	10/1/2016	10:56	10/1/2016	11:06	0:10	Operational
27	11/1/2016	7:30	11/1/2016	7:35	0:05	TEF
28	11/1/2016	21:28	11/1/2016	23:00	1:32	PEF
29	12/1/2016	4:21	12/1/2016	5:58	1:37	PEF
30	12/1/2016	8:02	12/1/2016	8:13	0:11	TEF
31	13/1/2016	12:18	13/1/2016	12:23	0:05	TEF
32	14/1/2016	9:56	14/1/2016	10:15	0:19	Operational
33	14/1/2016	11:20	14/1/2016	11:25	0:05	Operational
34	14/1/2016	3:02	14/1/2016	7:05	4:03	PEF
35	15/1/2016	16:08	15/1/2016	16:20	0:12	PEF
36	15/1/2016	16:47	15/1/2016	20:14	3:27	PEF
37	16/1/2016	4:36	16/1/2016	9:50	5:14	Operational
38	16/1/2016	10:35	16/1/2016	10:37	0:02	TEF
39	16/1/2016	23:07	16/1/2016	23:11	0:04	TEF
40	17/1/2016	7:57	17/1/2016	10:51	2:54	Total
41	17/1/2016	10:22	17/1/2016	15:36	5:14	Operational
42	18/1/2016	7:32	18/1/2016	7:45	0:13	Operational
43	19/1/2016	14:44	19/1/2016	14:48	0:04	TEF
44	19/1/2016	17:31	19/1/2016	18:02	0:31	PSC
45	23/1/2016	14:16	23/1/2016	14:20	0:04	TEF
46	23/1/2016	14:23	23/1/2016	14:28	0:05	TEF
47	23/1/2016	14:30	23/1/2016	14:54	0:24	PEF
48	24/1/2016	11:56	24/1/2016	13:34	1:38	PEF
49	24/1/2016	16:34	24/1/2016	16:57	0:23	Operational
50	25/1/2016	10:10	25/1/2016	10:12	0:02	TEF
51	27/1/2016	12:11	27/1/2016	12:17	0:06	TEF
52	27/1/2016	12:29	27/1/2016	13:57	1:28	PEF
53	27/1/2016	17:03	27/1/2016	17:15	0:12	Operational
54	28/1/2016	12:47	28/1/2016	13:45	0:58	PEF
55	28/1/2016	14:02	28/1/2016	14:04	0:02	TEF

Month: Hidar 21 - Tahsas 20, 2008 (Dec. 1, 2015 - Dec. 30, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	25/12/2015	4:32	25/12/2015	7:39	3:07	Blackout
2	26/12/2015	11:23	4/16/2015	11:30	0:07	TSC
3	26/12/2015	11:32	26/12/2015	12:10	0:38	PEF
4	30/12/2015	7:16	30/12/2015	7:36	0:20	PEF
5	30/12/2015	12:58	30/12/2015	13:04	0:06	TEF
6	30/12/2015	13:58	30/12/2015	14:04	0:06	TEF
7	30/12/2015	14:10	30/12/2015	15:14	1:04	PEF
8	1/12/2015	6:23	1/12/2015	6:27	0:04	TEF
9	1/12/2015	7:05	1/12/2015	7:13	0:08	TEF
10	1/12/2015	12:30	1/12/2015	12:33	0:03	TEF
11	1/12/2015	13:30	1/12/2015	13:38	0:08	TEF
12	2/12/2015	7:01	2/12/2015	7:15	0:14	PEF
13	2/12/2015	12:18	2/12/2015	12:30	0:12	Operational
14	3/12/2015	7:10	3/12/2015	7:12	0:02	TEF
15	4/12/2015	8:50	4/12/2015	8:53	0:03	TEF
16	4/12/2015	16:18	4/12/2015	16:38	0:20	PEF
17	5/12/2015	11:09	5/12/2015	11:12	0:03	TSC
18	5/12/2015	18:53	5/12/2015	18:59	0:06	TSC
19	6/12/2015	9:35	6/12/2015	11:49	2:14	PDF
20	6/12/2015	11:50	6/12/2015	12:13	0:23	Operational
21	6/12/2015	14:07	6/12/2015	16:32	2:25	Operational
22	7/12/2015	9:32	7/12/2015	9:45	0:13	Operational
23	7/12/2015	10:22	7/12/2015	10:57	0:35	Operational
24	7/12/2015	12:50	7/12/2015	13:30	0:40	Operational
25	7/12/2015	13:35	7/12/2015	14:08	0:33	Operational
26	7/12/2015	14:10	7/12/2015	14:54	0:44	Operational
27	7/12/2015	16:02	7/12/2015	16:04	0:02	TEF
28	7/12/2015	19:04	7/12/2015	19:06	0:02	TEF
29	8/12/2015	9:11	8/12/2015	9:18	0:07	TSC

30	8/12/2015	10:20	8/12/2015	10:45	0:25	Operational
31	8/12/2015	10:59	8/12/2015	11:02	0:03	TSC
32	8/12/2015	11:47	8/12/2015	12:12	0:25	TSC
33	9/12/2015	10:28	9/12/2015	10:39	0:11	Operational
34	9/12/2015	11:35	9/12/2015	12:02	0:27	Operational
35	9/12/2015	19:09	9/12/2015	19:13	0:04	TSC
36	10/12/2015	6:42	10/12/2015	6:47	0:05	TEF
37	10/12/2015	18:19	10/12/2015	18:22	0:03	TSC
38	10/12/2015	19:21	10/12/2015	19:23	0:02	TSC
39	11/12/2015	5:57	11/12/2015	10:04	4:07	Blackout
40	11/12/2015	10:00	11/12/2015	10:05	0:05	TSC
41	11/12/2015	10:50	11/12/2015	10:54	0:04	TSC
42	11/12/2015	11:25	11/12/2015	11:27	0:02	TSC
43	11/12/2015	11:30	11/12/2015	12:27	0:57	PSC
44	11/12/2015	14:06	11/12/2015	14:45	0:39	PEF
45	11/12/2015	16:05	11/12/2015	16:17	0:12	Operational
46	11/12/2015	18:14	11/12/2015	18:24	0:10	Operational
47	11/12/2015	18:54	11/12/2015	19:03	0:09	TSC
48	12/12/2015	9:34	12/12/2015	9:36	0:02	Operational
49	12/12/2015	11:05	12/12/2015	11:10	0:05	TEF
50	12/12/2015	13:36	12/12/2015	13:44	0:08	TSC
51	12/12/2015	17:03	12/12/2015	17:06	0:03	TEF
52	12/12/2015	18:54	12/12/2015	18:58	0:04	TSC
53	12/12/2015	19:07	12/12/2015	19:21	0:14	TSC
54	12/12/2015	20:21	12/12/2015	20:27	0:06	TEF
55	12/12/2015	23:05	13/12/2015	8:31	9:26	PEF
56	13/12/2015	8:35	13/12/2015	8:37	0:02	Operational
57	13/12/2015	8:38	13/12/2015	13:05	4:27	Operational
58	14/12/2015	2:10	14/12/2015	11:30	9:20	PEF

59	14/12/2015	17:31	14/12/2015	17:57	0:26	PSC
60	14/12/2015	18:13	14/12/2015	18:19	0:06	TSC
61	14/12/2015	18:30	14/12/2015	19:37	1:07	TSC
62	15/12/2015	5:38	15/12/2015	5:48	0:10	TEF
63	15/12/2015	12:23	15/12/2015	12:36	0:13	Operational
64	15/12/2015	8:50	15/12/2015	9:04	0:14	PSC
65	16/12/2015	15:16	16/12/2015	15:23	0:07	TEF
66	16/12/2015	15:30	16/12/2015	16:34	1:04	Operational
67	16/12/2015	18:58	16/12/2015	19:10	0:12	TSC
68	17/12/2015	5:28	17/12/2015	5:31	0:03	Operational
69	17/12/2015	6:51	17/12/2015	6:55	0:04	TEF
70	17/12/2015	10:35	17/12/2015	11:58	1:23	Operational
71	17/12/2015	12:56	17/12/2015	13:00	0:04	Operational
72	18/12/2015	8:32	18/12/2015	8:36	0:04	TEF
73	18/12/2015	11:04	18/12/2015	11:12	0:08	TSC
74	18/12/2015	11:47	18/12/2015	13:31	1:44	PSC
75	18/12/2015	14:09	18/12/2015	16:20	2:11	PSC
76	18/12/2015	16:30	18/12/2015	16:38	0:08	Operational
77	18/12/2015	19:10	18/12/2015	19:12	0:02	TSC
78	18/12/2015	19:44	18/12/2015	20:16	0:32	PSC
79	18/12/2015	21:52	18/12/2015	22:07	0:15	PSC
80	19/12/2015	9:00	19/12/2015	9:02	0:02	TSC
81	19/12/2015	9:42	19/12/2015	9:50	0:08	TSC
82	19/12/2015	10:58	19/12/2015	11:44	0:46	PSC
83	19/12/2015	16:34	19/12/2015	16:41	0:07	Operational
84	19/12/2015	18:56	19/12/2015	19:05	0:09	TSC
85	20/12/2015	5:25	20/12/2015	5:28	0:03	Operational
86	21/12/2015	6:25	21/12/2015	6:30	0:05	TEF
87	21/12/2015	9:28	21/12/2015	9:36	0:08	TSC
88	22/12/2015	15:37	22/12/2015	17:16	1:39	Blackout

Month: Tikimt 21 - Hidar 20, 2008 (Nov. 1 - Nov. 30, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	18/11/2015	7:53	18/11/2015	7:59	0:06	TEF
2	20/12/2015	9:35	20/12/2015	9:48	0:13	TEF
3	20/12/2015	16:43	20/12/2015	17:24	0:41	Operational
4	20/12/2015	18:37	20/12/2015	18:40	0:03	Overload
5	20/12/2015	18:53	20/12/2015	20:58	2:05	Overload
6	21/12/2015	18:41	21/12/2015	18:49	0:08	Overload
7	24/12/2015	18:48	24/12/2015	18:52	0:04	Overload
8	25/12/2015	18:56	25/12/2015	19:17	0:21	Overload
9	25/12/2015	19:26	25/12/2015	19:43	0:17	Overload
10	25/12/2015	19:49	25/12/2015	20:07	0:18	Overload
11	28/12/2015	12:23	28/12/2015	17:03	4:40	PSC
12	28/12/2015	17:37	28/12/2015	17:44	0:07	Overload
13	28/12/2015	18:00	28/12/2015	18:33	0:33	Overload
14	28/12/2015	18:37	28/12/2015	20:11	1:34	Overload
15	28/12/2015	20:20	28/12/2015	20:25	0:05	Overload
16	28/12/2015	20:34	28/12/2015	21:32	0:58	Overload
17	1/11/2015	13:49	1/11/2015	13:53	0:04	TSC
18	1/11/2015	16:09	1/11/2015	20:26	4:17	PSC
19	1/12/2015	10:46	1/12/2015	11:15	0:29	Operational
20	1/12/2015	18:46	1/12/2015	18:50	0:04	Overload
21	1/12/2015	18:58	1/12/2015	19:00	0:02	Overload
22	6/12/2015	18:47	6/12/2015	18:51	0:04	Overload
23	6/12/2015	19:08	6/12/2015	19:14	0:06	Overload
24	9/12/2015	19:12	9/12/2015	19:15	0:03	Overload
25	10/11/2015	18:59	10/11/2015	19:29	0:30	Overload
26	10/11/2015	19:41	2/30/08	19:43	0:02	Overload

27	11/11/2015	18:57	11/11/2015	19:09	0:12	Overload
28	12/11/2015	18:42	12/11/2015	20:02	1:20	Overload
29	12/11/2015	20:21	12/11/2015	21:08	0:47	Overload
30	14/11/2015	18:44	14/11/2015	18:53	0:09	Overload
31	14/11/2015	19:04	14/11/2015	19:08	0:04	Overload
32	17/11/2015	11:31	17/11/2015	11:43	0:12	Operational
33	18/11/2015	16:31	18/11/2015	16:43	0:12	Operational
34	18/11/2015	18:49	18/11/2015	18:53	0:04	Overload
35	18/11/2015	19:01	18/11/2015	19:04	0:03	Overload
36	18/11/2015	19:14	18/11/2015	19:51	0:37	Overload
37	18/11/2015	20:03	18/11/2015	20:06	0:03	Overload
38	19/11/2015	9:35	19/11/2015	9:48	0:13	TEF
39	19/11/2015	16:43	19/11/2015	17:24	0:41	Operational
40	19/11/2015	18:37	19/11/2015	18:40	0:03	Overload
41	19/11/2015	18:53	19/11/2015	20:58	2:05	Overload
42	20/11/2015	18:41	20/11/2015	18:49	0:08	Overload
43	24/11/2015	18:48	24/11/2015	18:52	0:04	Overload
44	25/11/2015	18:56	25/11/2015	19:17	0:21	Overload
45	25/11/2015	19:26	25/11/2015	19:43	0:17	Overload
46	25/11/2015	19:49	25/11/2015	20:07	0:18	Overload
47	28/11/2015	12:23	28/11/2015	17:03	4:40	PSC
48	28/11/2015	17:37	28/11/2015	17:44	0:07	Overload
49	28/11/2015	18:00	28/11/2015	18:33	0:33	Overload
50	28/11/2015	18:37	28/11/2015	20:11	1:34	Overload
51	28/11/2015	20:20	28/11/2015	20:25	0:05	Overload
52	28/11/2015	20:34	28/11/2015	21:32	0:58	Overload

Month: Meskerem 21 - Tikimt 20, 2008 (Oct. 2, 2015 -Oct. 31, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	3/10/2015	8:39	3/10/2015	8:43	0:04	TEF
2	6/10/2015	7:10	6/10/2015	7:15	0:05	TEF
3	7/10/2015	23:38	7/10/2015	23:44	0:06	TEF
4	8/10/2015	12:06	8/10/2015	12:19	0:13	Operational
5	8/10/2015	15:36	8/10/2015	15:54	0:18	PSC
6	8/10/2015	18:58	8/10/2015	19:35	0:37	PSC
7	9/10/2015	1:42	9/10/2015	2:22	0:40	Operational
8	9/10/2015	2:48	9/10/2015	11:13	8:25	PEF
9	9/10/2015	11:21	9/10/2015	13:35	2:14	PEF
10	9/10/2015	14:22	9/10/2015	14:42	0:20	PEF
11	9/10/2015	15:43	9/10/2015	15:48	0:05	Operational
12	9/10/2015	23:00	9/10/2015	23:18	0:18	Operational
13	10/10/2015	9:53	10/10/2015	10:06	0:13	Operational
14	10/10/2015	11:26	10/10/2015	11:29	0:03	TEF
15	10/10/2015	14:26	10/10/2015	18:05	3:39	Operational
16	11/10/2015	11:43	11/10/2015	12:11	0:28	TSC
17	11/10/2015	13:12	11/10/2015	13:58	0:46	PSC
18	13/10/2015	5:20	13/10/2015	5:48	0:28	Operational
19	13/10/2015	10:09	13/10/2015	10:31	0:22	Operational
20	14/10/2015	11:43	14/10/2015	12:11	0:28	Operational
21	14/10/2015	13:12	14/10/2015	13:48	0:36	PSC
22	15/10/2015	12:18	15/10/2015	13:21	1:03	PSC
23	16/10/2015	7:55	16/10/2015	8:00	0:05	PEF
24	17/10/2015	16:34	17/10/2015	16:40	0:06	TSC
25	18/10/2015	9:04	18/10/2015	9:08	0:04	TEF

26	18/10/2015	3:49	18/10/2015	8:40	4:51	PEF
27	18/10/2015	10:53	18/10/2015	10:56	0:03	TEF
28	18/10/2015	17:12	18/10/2015	17:14	0:02	TEF
29	19/10/2015	7:30	19/10/2015	7:35	0:05	TEF
30	19/10/2015	16:49	19/10/2015	17:05	0:16	TSC
31	19/10/2015	17:25	19/10/2015	17:30	0:05	TSC
32	19/10/2015	23:04	19/10/2015	23:34	0:30	Operational
33	20/10/2015	16:33	20/10/2015	16:38	0:05	TEF
34	20/10/2015	17:29	20/10/2015	17:32	0:03	TEF
35	23/10/2015	6:11	23/10/2015	6:14	0:03	TEF
36	24/12/2015	6:23	24/12/2015	6:33	0:10	TEF
37	25/12/2015	8:59	25/12/2015	9:05	0:06	TEF
38	25/12/2015	17:05	25/12/2015	17:30	0:25	PSC
39	26/12/2015	8:20	26/12/2015	8:22	0:02	TEF
40	27/12/2015	3:42	27/12/2015	9:00	5:18	PEF
41	27/12/2015	9:46	27/12/2015	9:52	0:06	TEF
42	28/12/2015	9:57	28/12/2015	10:33	0:36	PEF
43	29/12/2015	6:21	29/12/2015	6:36	0:15	TEF
44	29/12/2015	11:07	29/12/2015	11:14	0:07	TSC
45	29/12/2015	18:17	29/12/2015	18:58	0:41	PSC
46	30/12/2015	5:48	30/12/2015	5:53	0:05	TSC
47	30/12/2015	7:51	30/12/2015	7:56	0:05	TSC
48	30/12/2015	10:51	30/12/2015	10:54	0:03	TSC
49	30/12/2015	11:29	30/12/2015	13:24	1:55	PSC
50	31/12/2015	8:45	31/12/2015	8:50	0:05	TSC
51	31/12/2015	12:38	31/12/2015	12:45	0:07	TEF

Month: Nehase 21, 2007 - Meskerem 20, 2008 (Aug. 27, 2015 - Oct. 1, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	26/8/2015	10:50	26/8/2015	10:53	0:03	TEF
2	26/8/2015	12:13	26/8/2015	13:25	1:12	PEF
3	26/8/2015	14:58	26/8/2015	15:02	0:04	TEF
4	29/8/2015	10:04	29/8/2015	10:09	0:05	TEF
5	29/8/2015	11:00	29/8/2015	11:33	0:33	PEF
6	29/8/2015	11:29	29/8/2015	12:45	1:16	PEF
7	29/8/2015	13:10	29/8/2015	13:42	0:32	Operational
8	29/8/2015	14:36	29/8/2015	14:39	0:03	TEF
9	30/8/2015	11:38	30/8/2015	11:41	0:03	TEF
10	31/8/2015	8:21	31/8/2015	13:07	4:46	Operational
11	31/8/2015	16:10	31/8/2015	16:39	0:29	PEF
12	3/9/2015	6:00	3/9/2015	6:06	0:06	TEF
13	3/9/2015	16:12	3/9/2015	16:20	0:08	Operational
14	3/9/2015	16:29	3/9/2015	16:35	0:06	Operational
15	4/9/2015	6:05	4/9/2015	6:17	0:12	Operational
16	4/9/2015	12:54	4/9/2015	15:31	2:37	Operational
17	4/9/2015	19:06	4/9/2015	19:08	0:02	TEF
18	5/9/2015	5:31	5/9/2015	7:55	2:24	PSC
19	5/9/2015	9:38	5/9/2015	12:26	2:48	Operational
20	5/9/2015	13:14	5/9/2015	13:35	0:21	PSC
21	5/9/2015	19:27	5/9/2015	19:35	0:08	TSC
22	5/9/2015	19:47	5/9/2015	20:16	0:29	PSC
23	6/9/2015	9:32	6/9/2015	9:34	0:02	TEF
24	6/9/2015	9:50	6/9/2015	10:12	0:22	TEF
25	6/9/2015	17:32	6/9/2015	18:22	0:50	PEF
26	7/9/2015	11:26	7/9/2015	11:29	0:03	TEF

27	7/9/2015	16:50	7/9/2015	16:58	0:08	TEF
28	7/9/2015	17:35	7/9/2015	17:38	0:03	TEF
29	7/9/2015	17:39	7/9/2015	18:04	0:25	TEF
30	7/9/2015	18:28	7/9/2015	18:30	0:02	Operational
31	8/9/2015	9:46	8/9/2015	9:48	0:02	Operational
32	8/9/2015	11:48	8/9/2015	13:17	1:29	Operational
33	10/9/2015	8:16	10/9/2015	8:19	0:03	TSC
34	10/9/2015	10:56	10/9/2015	10:59	0:03	TSC
35	10/9/2015	13:40	10/9/2015	13:53	0:13	TSC
36	11/9/2015	6:15	11/9/2015	6:21	0:06	TEF
37	11/9/2015	12:56	11/9/2015	13:04	0:08	TEF
38	12/9/2015	6:32	12/9/2015	6:34	0:02	TEF
39	13/9/2015	3:13	13/9/2015	3:21	0:08	TSC
40	13/9/2015	7:07	13/9/2015	7:15	0:08	TSC
41	13/9/2015	7:32	13/9/2015	7:45	0:13	Operational
42	13/9/2015	7:50	13/9/2015	8:13	0:23	Operational
43	13/9/2015	8:14	13/9/2015	9:04	0:50	Operational
44	13/9/2015	9:05	13/9/2015	9:19	0:14	Operational
45	13/9/2015	13:30	13/9/2015	13:35	0:05	TEF
46	13/9/2015	18:31	13/9/2015	18:34	0:03	TEF
47	14/9/2015	6:12	14/9/2015	6:36	0:24	Operational
48	14/9/2015	6:51	14/9/2015	6:53	0:02	TEF
49	14/9/2015	14:57	14/9/2015	15:03	0:06	TEF
50	14/9/2015	15:45	14/9/2015	17:01	1:16	Operational
51	16/9/2015	11:26	16/9/2015	12:23	0:57	Operational
52	17/9/2015	18:56	17/9/2015	20:30	1:34	Operational
53	17/9/2015	13:53	17/9/2015	18:58	5:05	Operational
54	19/9/2015	7:57	19/9/2015	8:23	0:26	Operational
55	20/9/2015	10:14	20/9/2015	10:17	0:03	TEF

56	21/9/2015	6:50	21/9/2015	7:00	0:10	TSC
57	21/9/2015	12:05	21/9/2015	12:12	0:07	TEF
58	21/9/2015	13:27	21/9/2015	13:32	0:05	TEF
59	23/9/2015	16:00	23/9/2015	16:15	0:15	PSC
60	24/9/2015	15:36	24/9/2015	15:39	0:03	TEF
61	26/12/2015	8:38	26/12/2015	8:48	0:10	TSC
62	26/12/2015	16:51	26/12/2015	16:57	0:06	TEF
63	27/12/2015	6:55	27/12/2015	7:00	0:05	TEF
64	28/12/2015	7:38	28/12/2015	7:38	0:00	TEF
65	29/9/2015	6:14	29/9/2015	6:16	0:02	Operational
66	29/9/2015	14:22	29/9/2015	14:26	0:04	TEF
67	30/9/2015	17:28	30/9/2015	17:31	0:03	TEF

Month: Hamle 21 - Nehase 20, 2007 (July 28, 2015 - Aug. 26, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	28/7/2015	8:00	28/7/2015	17:09	9:09	PEF
2	29/7/2015	7:12	29/7/2015	7:14	0:02	TEF
3	29/7/2015	7:15	29/7/2015	7:18	0:03	TEF
4	30/7/2015	7:51	30/7/2015	7:53	0:02	TEF
5	30/7/2015	9:07	30/7/2015	9:13	0:06	TEF
6	30/7/2015	9:22	30/7/2015	10:23	1:01	PEF
7	30/7/2015	10:26	30/7/2015	11:55	1:29	PEF
8	30/7/2015	17:10	30/7/2015	17:14	0:04	Operational
9	31/7/2015	5:00	31/7/2015	5:05	0:05	Operational
10	31/7/2015	7:19	31/7/2015	7:24	0:05	Operational
11	1/8/2015	19:14	1/8/2015	20:11	0:57	Operational
12	2/8/2015	12:52	2/8/2015	12:54	0:02	TEF
13	3/8/2015	11:46	3/8/2015	11:58	0:12	TEF
14	3/8/2015	14:24	3/8/2015	14:37	0:13	TEF
15	4/8/2015	5:06	4/8/2015	5:11	0:05	Operational

16	4/8/2015	7:30	4/8/2015	8:43	1:13	PEF
17	4/8/2015	16:48	4/8/2015	16:52	0:04	TEF
18	4/8/2015	18:07	4/8/2015	23:16	5:09	Operational
19	5/8/2015	15:00	5/8/2015	15:20	0:20	Operational
20	5/8/2015	16:20	5/8/2015	16:22	0:02	TEF
21	7/8/2015	16:42	7/8/2015	16:44	0:02	TEF
22	8/8/2015	1:38	8/8/2015	9:40	8:02	Operational
23	8/8/2015	10:17	8/8/2015	11:18	1:01	Operational
24	8/8/2015	13:02	8/8/2015	13:12	0:10	Operational
25	8/8/2015	17:14	8/8/2015	17:20	0:06	Operational
26	9/8/2015	11:18	9/8/2015	12:42	1:24	Operational
27	9/8/2015	21:36	9/8/2015	21:54	0:18	PEF
28	10/8/2015	3:05	10/8/2015	3:44	0:39	PSC
29	10/8/2015	9:03	10/8/2015	10:08	1:05	PEF
30	10/8/2015	14:06	10/8/2015	14:12	0:06	Operational
31	11/8/2015	11:19	11/8/2015	11:22	0:03	TEF
32	11/8/2015	12:34	11/8/2015	13:02	0:28	PEF
33	13/8/2015	2:31	13/8/2015	7:49	5:18	PEF
34	13/8/2015	23:42	14/8/2015	4:58	5:16	PEF
35	15/8/2015	6:27	15/8/2015	6:34	0:07	TEF
36	15/8/2015	7:02	15/8/2015	7:05	0:03	TEF
37	15/8/2015	9:59	15/8/2015	12:27	2:28	Total
38	15/8/2015	19:02	15/8/2015	20:15	1:13	Operational
39	16/8/2015	6:56	16/8/2015	7:00	0:04	TEF
40	16/8/2015	8:04	16/8/2015	10:39	2:35	PEF
41	16/8/2015	23:30	16/8/2015	23:44	0:14	TEF
42	17/8/2015	5:50	17/8/2015	5:53	0:03	TEF
43	17/8/2015	5:54	17/8/2015	18:20	12:26	PEF
44	17/8/2015	23:15	18/8/2015	0:26	1:11	Total
45	18/8/2015	7:47	18/8/2015	7:49	0:02	TEF
46	18/8/2015	7:56	18/8/2015	9:21	1:25	PEF

47	18/8/2015	9:59	18/8/2015	10:21	0:22	Operational
48	18/8/2015	10:43	18/8/2015	10:45	0:02	TEF
49	18/8/2015	13:38	18/8/2015	13:53	0:15	PEF
50	18/8/2015	14:59	18/8/2015	15:18	0:19	PEF
51	18/8/2015	17:40	18/8/2015	17:44	0:04	TEF
52	18/8/2015	18:09	18/8/2015	18:36	0:27	PEF
53	19/8/2015	6:57	19/8/2015	6:59	0:02	TEF
54	19/8/2015	7:28	19/8/2015	11:15	3:47	Operational
55	19/8/2015	11:22	19/8/2015	11:40	0:18	PEF
56	20/8/2015	12:24	20/8/2015	18:14	5:50	PEF
57	21/8/2015	8:07	21/8/2015	8:11	0:04	TEF
58	21/8/2015	16:21	21/8/2015	16:25	0:04	TSC
59	21/8/2015	16:40	21/8/2015	16:55	0:15	PEF
60	21/8/2015	22:46	21/8/2015	22:49	0:03	TEF
61	22/8/2015	7:52	22/8/2015	8:05	0:13	Operational
62	22/8/2015	10:26	22/8/2015	10:30	0:04	TEF
63	22/8/2015	11:52	22/8/2015	12:12	0:20	PEF
64	22/8/2015	13:15	22/8/2015	13:29	0:14	PEF
65	22/8/2015	14:54	22/8/2015	16:46	1:52	Operational
66	23/8/2015	6:35	23/8/2015	7:22	0:47	PEF
67	23/8/2015	10:51	23/8/2015	10:53	0:02	TEF
68	24/8/2015	15:44	24/8/2015	15:52	0:08	TEF
69	25/8/2015	23:29	25/8/2015	23:31	0:02	TEF
70	26/8/2015	12:23	26/8/2015	12:58	0:35	Operational
71	26/8/2015	13:24	26/8/2015	13:53	0:29	PEF
72	26/8/2015	21:16	26/8/2015	0:00	2:44	Operational

Month: Sene 21 - Hamle 20, 2007 (June 28, 2015 - July 27, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	28/6/2015	9:42	28/6/2015	9:45	0:03	TEF
2	28/6/2015	9:56	28/6/2015	10:28	0:32	Operational

3	28/6/2015	12:45	28/6/2015	14:48	2:03	PEF
4	29/6/2015	6:04	29/6/2015	6:08	0:04	TEF
5	30/6/2015	8:04	30/6/2015	11:47	3:43	Operational
6	30/6/2015	17:04	30/6/2015	17:07	0:03	TEF
7	1/7/2015	8:43	1/7/2015	8:47	0:04	TEF
8	1/7/2015	9:53	1/7/2015	9:57	0:04	TEF
9	1/7/2015	9:58	1/7/2015	11:10	1:12	PEF
10	1/7/2015	13:16	1/7/2015	13:18	0:02	TEF
11	2/7/2015	8:13	2/7/2015	8:17	0:04	TEF
12	2/7/2015	10:14	2/7/2015	13:34	3:20	Operational
13	2/7/2015	17:29	2/7/2015	18:15	0:46	PEF
14	3/7/2015	10:11	3/7/2015	10:24	0:13	PEF
15	3/7/2015	11:51	3/7/2015	12:53	1:02	Operational
16	4/7/2015	6:37	4/7/2015	9:42	3:05	Operational
17	4/7/2015	9:49	4/7/2015	9:50	0:01	TEF
18	4/7/2015	9:52	4/7/2015	11:43	1:51	PEF
19	5/7/2015	10:56	5/7/2015	11:12	0:16	PEF
20	5/7/2015	19:58	5/7/2015	20:53	0:55	Operational
21	7/7/2015	10:34	7/7/2015	10:38	0:04	TEF
22	8/7/2015	9:03	8/7/2015	9:08	0:05	TEF
23	8/7/2015	13:52	8/7/2015	13:56	0:04	Operational
24	10/7/2015	8:00	10/7/2015	11:18	3:18	PEF
25	10/7/2015	11:38	10/7/2015	11:57	0:19	Operational
26	11/7/2015	7:56	11/7/2015	7:58	0:02	TEF
27	11/7/2015	8:27	11/7/2015	8:52	0:25	PEF
28	12/7/2015	17:21	12/7/2015	17:23	0:02	TEF
29	12/7/2015	17:44	12/7/2015	18:23	0:39	PEF
30	13/7/2015	8:56	13/7/2015	8:58	0:02	TEF
31	13/7/2015	14:40	13/7/2015	14:42	0:02	TEF
32	13/7/2015	15:44	13/7/2015	15:46	0:02	TEF
33	13/7/2015	17:56	13/7/2015	17:58	0:02	TEF

34	14/7/2015	18:35	14/7/2015	18:38	0:03	TEF
35	15/7/2015	6:54	15/7/2015	6:56	0:02	TEF
36	15/7/2015	9:11	15/7/2015	9:20	0:09	PEF
37	15/7/2015	11:04	15/7/2015	11:10	0:06	TEF
38	16/7/2015	9:58	16/7/2015	10:03	0:05	TEF
39	17/7/2015	8:54	17/7/2015	8:58	0:04	TEF
40	17/7/2015	8:59	17/7/2015	9:01	0:02	TEF
41	17/7/2015	10:10	17/7/2015	14:50	4:40	PEF
42	18/7/2015	6:50	18/7/2015	7:28	0:38	PEF
43	18/7/2015	16:46	18/7/2015	17:05	0:19	PEF
44	20/7/2015	6:43	20/7/2015	6:47	0:04	TEF
45	20/7/2015	6:47	20/7/2015	13:06	6:19	PEF
46	20/7/2015	13:28	20/7/2015	13:36	0:08	PEF
47	21/7/2015	17:40	21/7/2015	17:45	0:05	TEF
48	21/7/2015	5:37	21/7/2015	6:13	0:36	Operational
49	22/7/2015	18:25	22/7/2015	18:27	0:02	TEF
50	23/7/2015	7:14	23/7/2015	7:23	0:09	TEF
51	23/7/2015	7:30	23/7/2015	7:52	0:22	TEF
52	23/7/2015	11:38	23/7/2015	11:41	0:03	TEF
53	23/7/2015	11:50	23/7/2015	12:32	0:42	PEF
54	23/7/2015	12:50	23/7/2015	13:09	0:19	Operational
55	23/7/2015	13:10	23/7/2015	13:20	0:10	Operational
56	23/7/2015	19:26	23/7/2015	20:32	1:06	Operational
57	24/7/2015	1:22	24/7/2015	2:40	1:18	PEF
58	24/7/2015	11:12	24/7/2015	11:14	0:02	TEF
59	11/18/2007	12:11	11/18/2007	12:30	0:19	PSC
60	11/18/2007	21:26	11/19/2007	0:00	2:34	PSC

Month: Ginbot 21 - Sene 20, 2007 E.C. (May 29, 2015 - June 27, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	29/5/2015	6:41	29/5/2015	6:43	0:02	TEF
2	29/5/2015	18:15	29/5/2015	18:34	0:19	PEF

3	30/5/2015	10:42	30/5/2015	12:50	2:08	PEF
4	1/6/2015	7:15	1/6/2015	7:50	0:35	PEF
5	1/6/2015	14:05	1/6/2015	14:10	0:05	TEF
6	1/6/2015	17:05	1/6/2015	17:45	0:40	PEF
7	3/6/2015	9:55	3/6/2015	9:57	0:02	TEF
8	3/6/2015	15:44	3/6/2015	15:58	0:14	PSC
9	4/6/2015	9:14	4/6/2015	9:30	0:16	TEF
10	4/6/2015	9:38	4/6/2015	9:42	0:04	TEF
11	4/6/2015	13:50	4/6/2015	19:52	6:02	TEF
12	5/6/2015	6:50	5/6/2015	7:00	0:10	TEF
13	5/6/2015	10:10	5/6/2015	12:05	1:55	Operational
14	5/6/2015	16:26	5/6/2015	16:28	0:02	TEF
15	7/6/2015	5:26	7/6/2015	5:38	0:12	Operational
16	7/6/2015	16:49	7/6/2015	17:49	1:00	Operational
17	8/6/2015	7:26	8/6/2015	7:30	0:04	TEF
18	8/6/2015	11:20	8/6/2015	11:24	0:04	TEF
19	14/6/2015	9:54	14/6/2015	9:58	0:04	TEF
20	17/6/2015	5:00	17/6/2015	8:25	3:25	Operational
21	17/6/2015	11:46	17/6/2015	12:16	0:30	Operational
22	17/6/2015	14:46	17/6/2015	14:58	0:12	Operational
23	22/6/2015	15:06	22/6/2015	15:08	0:02	TEF
24	22/6/2015	15:13	22/6/2015	15:42	0:29	PEF
25	23/6/2015	4:55	23/6/2015	7:01	2:06	Operational
26	23/6/2015	13:05	23/6/2015	13:07	0:02	TEF
27	23/6/2015	16:34	23/6/2015	16:47	0:13	Blackout (partial)
28	24/6/2015	16:39	24/6/2015	16:44	0:05	TEF
29	26/6/2015	9:23	26/6/2015	9:25	0:02	TEF
30	26/6/2015	19:42	26/6/2015	20:39	0:57	Operational
31	27/6/2015	14:11	27/6/2015	20:56	6:45	Operational

Month: Miazia 21 - Ginbot 20, 2007 E.C. (April 29, 2015 - May 28, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	1/5/2015	19:12	1/5/2015	20:56	1:44	Operational
2	2/5/2015	14:12	2/5/2015	21:03	6:51	Operational

3	3/5/2015	9:44	3/5/2015	11:36	1:52	Operational
4	5/5/2015	12:01	5/5/2015	13:37	1:36	Operational
5	5/5/2015	13:54	5/5/2015	14:27	0:33	PEF
6	6/5/2015	8:32	6/5/2015	8:34	0:02	Operational
7	6/5/2015	15:19	6/5/2015	15:29	0:10	TEF
8	7/5/2015	9:44	7/5/2015	9:59	0:15	PEF
9	7/5/2015	18:35	7/5/2015	22:05	3:30	Operational
10	8/5/2015	2:02	8/5/2015	5:41	3:39	Blackout
11	8/5/2015	10:22	8/5/2015	13:35	3:13	Operational
12	8/5/2015	18:59	8/5/2015	19:04	0:05	TSC
13	9/5/2015	7:39	9/5/2015	7:45	0:06	TEF
14	9/5/2015	11:53	9/5/2015	11:58	0:05	TEF
15	9/5/2015	12:06	9/5/2015	15:54	3:48	PEF
16	9/5/2015	15:12	9/5/2015	15:24	0:12	Operational
17	11/5/2015	7:45	11/5/2015	7:49	0:04	TEF
18	11/5/2015	7:52	11/5/2015	7:55	0:03	TEF
19	11/5/2015	8:30	11/5/2015	9:53	1:23	PEF
20	12/5/2015	19:42	12/5/2015	20:36	0:54	Operational
21	13/5/2015	7:57	13/5/2015	8:00	0:03	TEF
22	13/5/2015	11:37	13/5/2015	12:17	0:40	Operational
23	14/5/2015	7:19	14/5/2015	7:27	0:08	PEF
24	14/5/2015	12:07	14/5/2015	13:10	1:03	Operational
25	17/5/2015	9:57	17/5/2015	16:23	6:26	PEF
26	18/5/2015	10:19	18/5/2015	10:24	0:05	Operational
27	19/5/2015	6:08	19/5/2015	6:13	0:05	TEF
28	19/5/2015	8:16	19/5/2015	8:20	0:04	TEF
29	22/5/2015	16:08	22/5/2015	16:14	0:06	TEF
30	23/5/2015	10:02	23/5/2015	10:23	0:21	PEF
31	25/5/2015	17:02	25/5/2015	17:07	0:05	TEF
32	26/5/2015	6:42	26/5/2015	7:16	0:34	Blackout
33	26/5/2015	16:05	26/5/2015	20:58	4:53	Operational

34	26/5/2015	21:56	26/5/2015	21:58	0:02	TEF
35	27/5/2015	6:45	27/5/2015	12:56	6:11	Operational
36	27/5/2015	16:21	27/5/2015	16:22	0:01	TEF

Month: Megabit 21 - Miazia 20, 2007 E.C. (March 30, 2015 - May 27, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	7/21/2007	8:54	7/21/2007	8:59	0:05	Operational
2	7/21/2007	11:42	7/21/2007	12:46	1:04	Operational
3	7/22/2007	19:10	7/22/2007	20:55	1:45	Operational
4	7/23/2007	9:13	7/23/2007	9:25	0:12	Operational
5	7/24/2007	8:17	7/24/2007	8:31	0:14	PEF
6	7/24/2007	20:00	7/24/2007	21:07	1:07	Operational
7	7/27/2007	8:08	7/27/2007	8:11	0:03	TEF
8	7/29/2007	13:26	7/29/2007	13:28	0:02	TEF
9	7/29/2007	19:08	7/29/2007	22:11	3:03	Operational
10	7/30/2007	7:54	7/30/2007	7:58	0:04	TEF
11	7/30/2007	9:08	7/30/2007	14:05	4:57	Operational
12	8/1/2007	8:29	8/1/2007	17:41	9:12	Operational
13	8/1/2007	18:21	8/1/2007	18:23	0:02	TEF
14	8/4/2007	17:57	8/4/2007	17:59	0:02	TEF
15	8/7/2007	6:24	8/7/2007	11:51	5:27	Operational
16	8/8/2007	7:50	8/8/2007	13:07	5:17	Operational
17	8/9/2007	5:50	8/9/2007	6:09	0:19	PEF
18	8/9/2007	18:58	8/9/2007	20:54	1:56	Operational
19	8/10/2007	11:42	8/10/2007	11:44	0:02	Operational
20	8/10/2007	12:24	8/10/2007	21:14	8:50	Operational
21	8/11/2007	8:17	8/11/2007	8:19	0:02	TEF
22	8/11/2007	8:31	8/11/2007	14:47	6:16	Operational
23	8/12/2007	14:01	8/12/2007	14:05	0:04	Operational
24	8/12/2007	19:18	8/12/2007	19:21	0:03	Operational

25	8/13/2007	11:28	8/13/2007	20:01	8:33	Operational
26	8/14/2007	15:29	8/14/2007	15:35	0:06	TEF
27	8/14/2007	20:21	8/14/2007	23:26	3:05	Operational
28	8/15/2007	9:20	8/15/2007	9:21	0:01	TEF
29	8/15/2007	12:31	8/15/2007	18:11	5:40	Operational
30	8/16/2007	7:25	8/16/2007	7:30	0:05	TEF
31	8/16/2007	11:50	8/16/2007	11:52	0:02	TEF
32	8/16/2007	11:52	8/16/2007	14:21	2:29	Operational
33	8/16/2007	15:05	8/16/2007	15:10	0:05	Operational
34	8/16/2007	15:12	8/16/2007	15:20	0:08	Operational
35	8/17/2007	7:11	8/17/2007	12:35	5:24	Operational
36	8/18/2007	12:22	8/18/2007	12:25	0:03	Operational
37	8/18/2007	13:40	8/18/2007	13:47	0:07	TEF
38	8/19/2007	14:28	8/19/2007	14:33	0:05	TEF
39	8/19/2007	16:14	8/19/2007	16:26	0:12	Operational
40	8/20/2007	9:26	8/20/2007	9:30	0:04	TEF
41	8/20/2007	10:10	8/20/2007	12:11	2:01	Operational

Month: Yekatit 21 - Megabit 20, 2007 E.C. (Feb. 28, 2015 - March 29, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	27/2/2015	16:40	27/2/2015	16:49	0:09	TEF
2	3/3/2015	10:58	3/3/2015	11:06	0:08	Operational
3	5/3/2015	6:15	5/3/2015	6:29	0:14	PEF
4	5/3/2015	15:48	5/3/2015	16:29	0:41	Operational
5	8/3/2015	15:48	8/3/2015	15:57	0:09	Operational
6	11/3/2015	14:16	11/3/2015	14:26	0:10	Operational
7	12/3/2015	8:30	12/3/2015	8:37	0:07	TEF
8	12/3/2015	12:32	12/3/2015	12:54	0:22	PEF
9	13/3/2015	11:30	13/3/2015	11:35	0:05	TEF
10	14/3/2015	9:31	14/3/2015	9:38	0:07	TEF

11	14/3/2015	15:29	14/3/2015	15:59	0:30	Operational
12	15/3/2015	14:20	15/3/2015	17:01	2:41	Total
13	17/3/2015	6:10	17/3/2015	6:20	0:10	Operational
14	17/3/2015	13:38	17/3/2015	14:14	0:36	PEF
15	18/3/2015	19:26	18/3/2015	20:00	0:34	Operational
16	19/3/2015	7:21	19/3/2015	7:59	0:38	PEF
17	20/3/2015	8:34	20/3/2015	8:35	0:01	TEF
18	21/3/2015	8:49	21/3/2015	13:54	5:05	Operational
19	21/3/2015	19:20	21/3/2015	21:37	2:17	PEF
20	22/3/2015	8:37	22/3/2015	8:39	0:02	TEF
21	22/3/2015	12:05	22/3/2015	12:07	0:02	TEF
22	22/3/2015	19:55	22/3/2015	20:35	0:40	Operational
23	23/3/2015	8:18	23/3/2015	8:26	0:08	TEF
24	23/3/2015	8:40	23/3/2015	10:06	1:26	TEF
25	23/3/2015	10:07	23/3/2015	10:50	0:43	PEF
26	23/3/2015	16:16	23/3/2015	17:46	1:30	PEF
27	25/3/2015	14:33	25/3/2015	14:40	0:07	TEF
28	26/3/2015	6:10	26/3/2015	11:54	5:44	PEF
29	26/3/2015	12:06	26/3/2015	12:24	0:18	Operational
30	26/3/2015	13:46	26/3/2015	14:15	0:29	Operational
31	27/3/2015	13:13	27/3/2015	13:24	0:11	Operational
32	28/3/2015	15:06	28/3/2015	15:26	0:20	PEF
33	29/3/2015	9:09	29/3/2015	11:43	2:34	Operational

Month: Tir 21 - Yekatit 20, 2007 E.C. (Jan. 29, 2015) - March 27, 2015)

No.	Date and Time of Interruption		Date and Time of Restoration		Duration (Hr)	Fault type
	Date	Time	Date	Time		
1	5/21/2007	17:45	5/21/2007	17:51	0:06	TEF
2	5/22/2007	7:15	5/22/2007	7:32	0:17	TEF
3	5/22/2007	9:00	5/22/2007	9:11	0:11	TEF
4	5/22/2007	11:10	5/22/2007	11:21	0:11	TEF

5	5/22/2007	13:15	5/22/2007	15:00	1:45	PEF
6	5/22/2007	16:01	5/22/2007	16:04	0:03	TEF
7	5/22/2007	16:33	5/22/2007	16:51	0:18	Operational
8	5/22/2007	18:21	5/22/2007	18:34	0:13	Operational
9	5/23/2007	3:24	5/23/2007	3:26	0:02	TEF
10	5/23/2007	7:44	5/23/2007	10:00	2:16	Operational
11	5/23/2007	17:59	5/23/2007	18:10	0:11	TEF
12	5/25/2007	10:11	5/25/2007	10:22	0:11	TEF
13	5/25/2007	13:50	5/25/2007	15:30	1:40	Operational
14	5/29/2007	17:10	5/29/2007	17:19	0:09	TEF
15	6/2/2007	14:55	6/2/2007	14:59	0:04	Operational
16	6/4/2007	6:28	6/4/2007	6:32	0:04	TEF
17	6/4/2007	7:04	6/4/2007	7:08	0:04	TEF
18	6/5/2007	8:09	6/5/2007	8:14	0:05	TEF
19	6/5/2007	9:34	6/5/2007	10:30	0:56	PSC
20	6/5/2007	13:53	6/5/2007	14:07	0:14	TEF
21	6/6/2007	8:12	6/6/2007	8:18	0:06	TEF
22	6/6/2007	11:59	6/6/2007	12:21	0:22	Operational
23	6/7/2007	9:32	6/7/2007	9:36	0:04	TEF
24	6/7/2007	11:40	6/7/2007	11:50	0:10	TEF
25	6/8/2007	9:52	6/8/2007	10:02	0:10	TEF
26	6/9/2007	16:33	6/9/2007	16:40	0:07	TEF
27	6/9/2007	17:27	6/9/2007	17:39	0:12	TEF
28	6/10/2007	11:08	6/10/2007	12:10	1:02	Operational
29	6/11/2007	9:12	6/11/2007	9:20	0:08	TEF
30	6/12/2007	13:03	6/12/2007	13:07	0:04	TEF
31	6/12/2007	15:04	6/12/2007	15:07	0:03	Operational
32	6/13/2007	18:04	6/13/2007	18:20	0:16	PEF
33	6/17/2007	13:01	6/17/2007	13:09	0:08	TEF
34	6/17/2007	14:51	6/17/2007	15:01	0:10	TEF
35	6/18/2007	16:01	6/18/2007	16:08	0:07	TEF
36	6/19/2007	7:49	6/19/2007	7:55	0:06	TEF

Appendix B: MATLAB file to plot protection coordination curves

Loop section Via F2

```
>> t is operating time in seconds
>> I is current in Amps
t1 = [46.59,47.75,48.5,53,75,100,200,400,700,1000,2000,3000,4000,5000];
I1 =
[1007.7,212.5,140.7,46.48,10.9,5.8,2.03,0.88,0.48,0.33,0.16,0.11,0.08,0.06];
t2 =
[79.3,79.8,80.58,85.08,107.08,132.08,232.08,432.08,732.08,1032.08,2032.08,303
2.08,4032.08,5032.08];
I2 =
[1007.67,623.06,396.2,124.4,28.6,15.2,5.3,2.31,1.25,0.86,0.42,0.28,0.2,0.16];
t3 =
[125.32,125.82,126.57,131.07,153.07,178.07,278.07,478.07,778.07,1078.07,2078.
07,3078.07,4078.07,5078.07];
I3 =
[1001.9,726.63,514.6,187.05,45.5,24.5,8.6,3.7,2.02,1.38,0.68,0.45,0.33,0.27];
t4 = [14.95,14.95,14.95,14.95,14.95,14.95,14.95,15,20,30,50,80,200,700];
I4 = [600,400,200,90,70,50,30,15,3,0.85,0.3,0.15,0.05,0.03];
I = logspace(1.5,3.6)
loglog(I1,t1,I2,t2,I3,t3,I4,t4)
xlabel('current in Amps');
ylabel('time in sec');
title('Protection coordination - loop Via Feeder 2');
grid on
```

Loop section Via F3

```
I1 =
[15.81,16.31,17.06,21.56,43.56,68.56,168.56,368.56,668.56,968.56,1968.56,2968
.56,3968.56,4968.56];
t1 =
[1002.86,296.62,144.24,35.33,7.532,3.98,1.376,0.6,0.322,0.221,0.108,0.071,0.0
5,0.04];
I2 =
[57.09,57.6,58.35,62.85,84.85,109.85,209.85,409.85,709.85,1009.85,2009.85,300
9.85,4009.85,5009.85];
t2 =
[903.06,526.72,324.11,97.98,22.21,11.82,4.11,1.79,0.97,0.66,0.32,0.21,0.16,0.
13];
I3 =
[59.36,59.86,60.61,65.11,87.11,112.11,212.11,412.11,712.11,1012.11,2012.11,30
12.11,4012.11,5012.11];
t3 =
[1014.91,491.76,277.33,76.69,16.9,8.96,3.11,1.35,0.73,0.5,0.244,0.16,0.12,0.0
9];
I = logspace(1,3.6)
loglog(I1,t1,I2,t2,I3,t3)
xlabel('current in Amps');
ylabel('time in sec');
title('Protection coordination - loop Via Feeder 3');
grid on
```

Via F2 Tie recloser R3 closed and R5 open

```
t1 =
[41.88,42.38,43.13,47.63,69.63,94.63,194.63,394.63,694.63,994.63,1994.63,2994
.63,3994.63,4994.63];
I1 =
[1002.86,360,183.5,46.57,10.01,5.3,1.83,0.8,0.43,0.29,0.14,0.09,0.07,0.06];
t2 =
[58.32,58.82,59.57,64.07,86.07,111.07,211.07,411.07,711.07,1011.07,2011.07,30
11.07,4011.07,5011.07];
I2 =
[1008.43,601.8,374.99,114.98,26.2,13.95,4.86,2.1,1.14,0.78,0.38,0.25,0.19,0.1
5];
t3 =
[101.2,101.7,102.45,106.95,128.95,153.95,253.95,453.95,753.95,1053.95,2053.95
,3053.95,4053.95,5053.95];
I3 =
[1001.25,706.76,490.4,172.9,41.5,22.27,7.8,3.4,1.84,1.26,0.61,0.4,0.3,0.24];
t4 =
[139.97,140.5,141.22,145.72,167.72,192.72,292.72,492.72,792.72,1092.72,2092.7
2,3092.72,4092.72,5092.72];
I4 =
[1006.2,774.35,575.4,226.4,57.1,30.9,10.9,4.7,2.6,1.8,0.9,0.56,0.4,0.33];
t5 =
[218,218.5,219.25,223.75,245.75,270.75,370.75,570.75,870.75,1070.75,2070.75,3
070.75,4070.75,5070.75];
I5 =
[1020.6,816.48,628.06,263.4,68.6,37.3,13.2,5.75,3.1,2.1,1.04,0.69,0.5,0.4];
I = logspace(1,4);
loglog(I1,t1,I2,t2,I3,t3,I4,t4,I5,t5)
xlabel('current in Amps');
ylabel('time in sec');
title('Protection coordination Tie rec R3 closed');
```

Appendix C: PSS/E load flow result with existing and additional loading at Cotebe substation

Cotebe substation HV network load flow before additional 34MVA load

```
PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS(R)E     MON, APR 11 2016  11:43
 ETHIOPIAN POWER SYSTEM TRANSMISSION  STUDY
 YEAR 2014  - PEAK LOAD FLOW
            OUTPUT FOR AREA 2 [EASTERN A.A.]  ZONE 14 [ADDIS ABABA ]
 SUBSYSTEM LOADING CHECK (INCLUDED: LINES; TRANSFORMERS) (EXCLUDED: BREAKERS AND SWITCHES)
 LOADINGS ABOVE 100.0 % OF RATING SET A (MVA FOR TRANSFORMERS, CURRENT FOR NON-TRANSFORMER
BRANCHES):
X--------- FROM BUS ----------X X---------- TO BUS -----------X
 BUS# X-- NAME --X BASKV  AREA   BUS# X-- NAME --X BASKV  AREA CKT LOADING  RATING PERCENT
 102003 COTOBI-I    132.00*    2 102007 Legetafo   132.00     2  1    105.8    82.0   129.0
 102003 COTOBI-I    132.00*    2 3WNDTR KOTEBIE 3WT  WND 1     2  1     16.4    12.0   136.5
 702001 ADDIS-E1    45.000*    2 802001 ADDIS-E1    15.000     2  1      7.1     6.0   118.4
 702001 ADDIS-E1    45.000*    2 802001 ADDIS-E1    15.000     2  2      7.0     6.0   116.7
 702002 COTOBIE     45.000*    2 3WNDTR KOTEBIE 3WT  WND 2     2  1     14.7    12.0   122.2
```

Cotebe substation HV network load flow after additional 34MVA load

```
PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS(R)E     MON, APR 11 2016  11:42
 ETHIOPIAN POWER SYSTEM TRANSMISSION  STUDY
 YEAR 2014  - PEAK LOAD FLOW
            OUTPUT FOR AREA 2 [EASTERN A.A.]  ZONE 14 [ADDIS ABABA ]
 SUBSYSTEM LOADING CHECK (INCLUDED: LINES; TRANSFORMERS) (EXCLUDED: BREAKERS AND SWITCHES)
 LOADINGS ABOVE 100.0 % OF RATING SET A (MVA FOR TRANSFORMERS, CURRENT FOR NON-TRANSFORMER
BRANCHES):

 X--------- FROM BUS ----------X X---------- TO BUS -----------X
 BUS# X-- NAME --X BASKV  AREA   BUS# X-- NAME --X BASKV  AREA CKT LOADING  RATING PERCENT
 102003 COTOBI-I    132.00*    2 102007  Legetafo   132.00     2  1    112.6    82.0   137.3
 102003 COTOBI-I    132.00*    2 3WNDTR KOTEBIE 3WT  WND 1     2  1     16.5    12.0   137.7
 702001 ADDIS-E1    45.000*    2 802001 ADDIS-E1    15.000     2  1      7.1     6.0   118.6
 702001 ADDIS-E1    45.000*    2 802001 ADDIS-E1    15.000     2  2      7.0     6.0   117.0
 702002 COTOBIE     45.000*    2 3WNDTR KOTEBIE 3WT  WND 2     2  1     14.7    12.0   122.7
```

Appendix D: Operating Logic of Protection Devices

Operating logic of the substation breakers and the smart reclosers is summarized as follows:

Circuit breakers (CB-F2 and CB-F3) have same logic:

- Auto-reclose 2 sec after temporary faults
- Lockout just after first reclose trial

Feeder reclosers (R1 and R5) have same operating logic:

- Auto-reclose 2 sec after temporary faults
- Lockout after first reclose trial
- Open and lockout for second consecutive loss of source side voltage

Mid-point reclosers (R2 and R4) have same operating logic:

- Auto-reclose 2 sec after temporary faults
- Lockout just after first reclose trial
- Activate their alternate or reverse protection group with reverse side voltage

Tie recloser (R3) operating logic:

- R3 closes after 4 sec when supply is lost from either side
- Recloses 2 sec after the first attempt
- Locks out if the second attempt is not successful