Adama Science and Technology University

School of Electrical Engineering and Computing

Department of Electrical and Computer Engineering

Investigation of Power System Reliability Improvement by Using Distributed Generation (Case Study of Bishoftu Distribution Substation)

By

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A Thesis Submitted to School of Electrical Engineering and Computing in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Electrical Power Engineering

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Declarations

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

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

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Approval

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Abstract

Power system is divided into the subsystems of generation, transmission, and distribution facilities according to their functions. The distribution systems account for up to 90% of all customer reliability problems. Improving distribution system reliability is the key to improving customer reliability and it is the most important part of a power system, which consists of many step-down transformers, distribution feeders, and customers. Therefore, evaluation of the reliability of power distribution is highly important at the distribution system.

In the context of Ethiopia, electric power interruption is becoming a day to day phenomenon. Even there are times that electric power interruption occurs several times a day, not only at the low voltage but also at the medium voltage distribution systems. Distributed Generators (DGs) are now commonly used in distribution system to reduce the power disruption in the power system network which results in a considerable reduction in the total power loss in the system, improved voltage profiles of the bus and reliability indices. Therefore, integrating distributed generation to an existing distribution system provides profit for both utility and end users. This research work shows that the reliability of Bishoftu substation II does not meet the requirements set by the regulatory body that is, Ethiopian Electric Agency (EEA). The system average interruption frequency index (SAIFI) of the substation is 179.619 interruptions per customer per year with system average interruption duration (SAIDI) of 276.585 hours per customer per year at the basecase. Based on the simulation result, the installation of DG at 0.4 kV buses of the feeders (K-7, K-8, K-9 and L-3) which experience more interruptions, resulted in the improvement of SAIFI by 92.335%, SAIDI by 88.956%, and Energy not supplied (ENS) by 97.735%. The energy not supplied is reduced from 5666.367 MWh/yr to 128.327 MWh/yr and EIC is reduced from 2.92 million $/yr to 0.741 million $/yr with average revenue saving of about 2.179 million $/yr. Thus, Ethiopian Electric Utility (EEU) can increase its revenue by 74.623% for that area by reducing the energy not supplied (ENS) due to interruptions.

Keywords: *Distributed Generations, Power System Reliability, Optimum location, Voltage profile, Energy Not Supplied (ENS) and Powerfactory.*

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List of Acronyms

AAC	All Aluminum Conductors
AENS	Average Energy Not Supplied
ASAI	Average Service Availability Index
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
DER	Distributed Energy Resource
DG	Distributed Generation
DIgSILENT	Digital Simulation and Electrical Network
DPEF	Distribution Permanent Earth Fault
DPSC	Distribution Permanent Short Circuit
EEA	Ethiopian Electric Agency
EENS	Expected Energy Not Supplied
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
ENS	Energy Not Supplied
IEEE	Institute of Electrical and Electronic Engineers
Int	Interruption
KVA	Kilovolt Ampere
Kwh	Kilowatt hour
MTTF	Mean Time to Failure

MTTR	Mean Time to Repair
MV	Medium Voltage
MVA	Mega Volt Ampere
MVAR	Mega Volt Ampere Reactive
MWh/yr.	Mega Watt hour per year
M$/yr.	Million dollar per year
NASA	National Aeronautics and Space Administration
OPR	Operational
P	Active power
PBC	Partial Bishoftu City
Pf	Power factor
PV	Photo Voltaic
Q	Reactive power
RBTS	Reliability Busbar Test System
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
Syst.	System
TEF	Temporary Earth Fault
TSC	Temporary Short Circuit
Trafo	Transformer
USD	United State Dollar

CHAPTER ONE

INTRODUCTION

1.1 Background

Energy has a major impact on every aspect of the socio-economic life and it plays a vital role in the economic, social and political development of any nation. Despite the abundance of energy resources in Ethiopia, the country still in short supply of electrical power. Even the electricity supply to the consumers that are connected to the grid is not reliable. These unreliable power supply have a significant impact on both the power supplying company and the customer of electric service. The cost of the energy not supplied during the major power outage confined to one distribution system can be on the order of millions of dollars [1].

With recent advances in technology, the use of distributed generation (DG) in the radial distribution system is increasing. Incorporating DG in to the radial distribution system possess numerous challenges in terms of interconnection, protection coordination, system losses and voltage regulation. Some of the main advantages while installing DG units in distribution level are peak load sharing, enhanced system security and reliability, improved voltage stability, grid strengthening, reduction in the on-peak operating cost, reduction in network loss etc. The improvements in the reliability of the distribution network and reduced cost of interruption have come out as one of the most important benefits of adding DG to an existing distribution network [2]. The proposed method uses a DigSilent power factory simulation of the power systems stochastic model in combination with either qualitative or quantitative techniques.

1.2 Statement of the problem

The main problem facing the electric power utilities in the developing countries today is that the power demand is increasing rapidly where supply growth is constrained by economic, environmental and other societal concerns. The Ethiopian economy is growing rapidly and this has led to higher growth in the consumption of electricity by various consumers such as heavy industries and big commercial institutions. However, satisfying this increased demand needs to study the issue of reliability which is of great concern in our daily life. Since Bishoftu city is one of the rapidly growing city and a preferred location for most of the industries, considerable share of the electric power supply is directed towards the city. But, electric power interruption is becoming a day to day phenomenon in the area. Even there are times that electric power interruption occurs several times a day, not only at the low voltage but also at the medium voltage distribution systems. In general, Bishoftu distribution substation is faced the problem of distribution inefficiency, infrequent and repetitive power interruptions and power quality problems. This resulted in a need for more extensive justification for the new system facilities and improvements in production and use of electric energy. Especially for factories and industries, it is really challenging to tolerate power interruption since it causes much revenue loss within hours of interruption. So the root cause of this problem should first be identified and the possible solution has to be performed.

1.3 Objective of the thesis

1.3.1 General Objective

The main objective of this thesis is to investigate the power distribution system reliability and its improvement by using distributed generation.

1.3.2 Specific Objectives

The specific objectives of this thesis are listed below;

- ✓ To collect and analyze the power system reliability data of the currently existing system.
- ✓ To investigate the power distribution problems that arise from both the customer side and the Electric utility side of Bishoftu distribution substation.
- ✓ To identify possible solutions for those reliability problems.
- ✓ To develop a suitable dynamic model for the DG unit for different simulation and investigation purposes as well as its impact on reliability of the system.
- ✓ Draw relevant conclusions and recommendations from the result of the investigation on how the reliability and transient stability of the grid is improved.

1.4 Scope of the thesis

The main scope of this thesis is to investigate the current power system reliability problems of the substation, their causes, percentage of improvements gained by penetrating distributed generators to the present Bishoftu city distribution substation.

1.5 Significance of the study

The outcome of this study is important for both the power supplying company and consumers. The study has a great significance as integrating DG depends on the impact it will have on the power system and it will try to identify whether it improves the power system quality and reliability of the system.

1.6 Motivation for Distributed Generation

The ever increasing demand for electrical power has created many challenges for the energy industry which can affect the reliability of the generated power in short and long terms [3]. Therefore, DG is gaining a lot of attention as it provide a solution for both short and long term problems [4].Small DG units are expected to spread rapidly within power systems and have the potential to account for 20-30% of the distribution system demand by 2020 [5]. Another important thing that motivated me to use DG in this research is, the DG applications which is so intensive and all customers benefited from it and some of these applications are listed in the next section under chapter two of this thesis. The maintenance cost for transmission and distribution is so expensive, therefore DG installation can also overcome this cost expenditure [6]. The owner of this DG can be the government company (EEU/EEP) or any other private company according to the regulation set by Ethiopian energy policy.

1.7 Methodology

The first task of this thesis is to investigate the problems of reliability and the impact of integrating DG to the distribution grid of the system and studying or evaluating the reliability of the existing distribution system. Next, by collecting and analyzing data from Bishoftu substation II for the calculation of the most powerful reliability indices. Then this calculated reliability indices is compared with the EEP's standard and the standard of other countries. To address the challenges of the existing distribution system, integration of DG to substation has been proposed as a solution to tackle the problem. Reliability analysis needs interruption duration, interruption frequency, total number of customers served, customers interrupted, loads connected and so on. These data are then analyzed to clearly identify the current reliability level of the substation.

1.7.1 Data collection and analysis

The major data source for this thesis work is EEP/EEU most specifically Bishoftu distribution substation and review of range of books, manuals, standards and researches. Then interpretation of the collected data can be analyzed through power simulation softwares like Digsilent and Matlab or any other appropriate software as per required. Generally, the following methodology is followed in conducting the thesis work.

- ✓ Site visiting
- ✓ Technical data collection from the selected distribution substation
- ✓ The feeder length, number and ratings of transformers has been collected from the existing system and the districts.
- ✓ Three years (2014-2016 GC) power interruption data has been collected from Bishoftu substation II.
- ✓ The collected data has been used to clearly analyze the problems of the feeder under study and identification of reliability problems and its causes in the site.

1.7.2 System modelling and analysis

- ✓ Reliability indices have been calculated for the existing systems.
- ✓ Modelling of DG with appropriate size and location.
- ✓ Simulation and analysis of the reliability improvements.
- ✓ The system has been designed and simulated using a latest electrical software, Digsilent Power Factory 15.1.7

The power system reliability indices such as System average interruption duration indices (SAIDI), System average interruption frequency indices (SAIDI), customer average interruption duration indices etc (CAIDI) are determined based on the different scenarios.

- ✓ Analyzing optimal allocation of distributed generation in radial feeder.
- ✓ Size of DG vs. reliability
- ✓ Distance of DG from the grid vs. reliability

- ✓ Power system transient stability limit analysis
- ✓ Analyzing if the integrate DGs violates the system voltage profile or not.
- ✓ Analyzing the economic feasibility of the designed system.

In general, the following step wise cases can be used under this methodology.

Case: 1 Obtain important data needed for the case study analysis from the study area. This data includes the following type.

- ✓ Rated system voltage:
- ✓ Rated power of substation transformers
- ✓ Number of medium-voltage nodes
- ✓ Number of load nodes
- ✓ Initial total load rated power
- ✓ Overall line length etc.

Case: 2 DG load point modelling

Case: 3 Base case reliability analysis of the system without DG

Case: 4 Connecting DG to the selected feeders' busbar at different locations from the supply.

Case: 5 Draw conclusions from the simulation and reliability analysis.

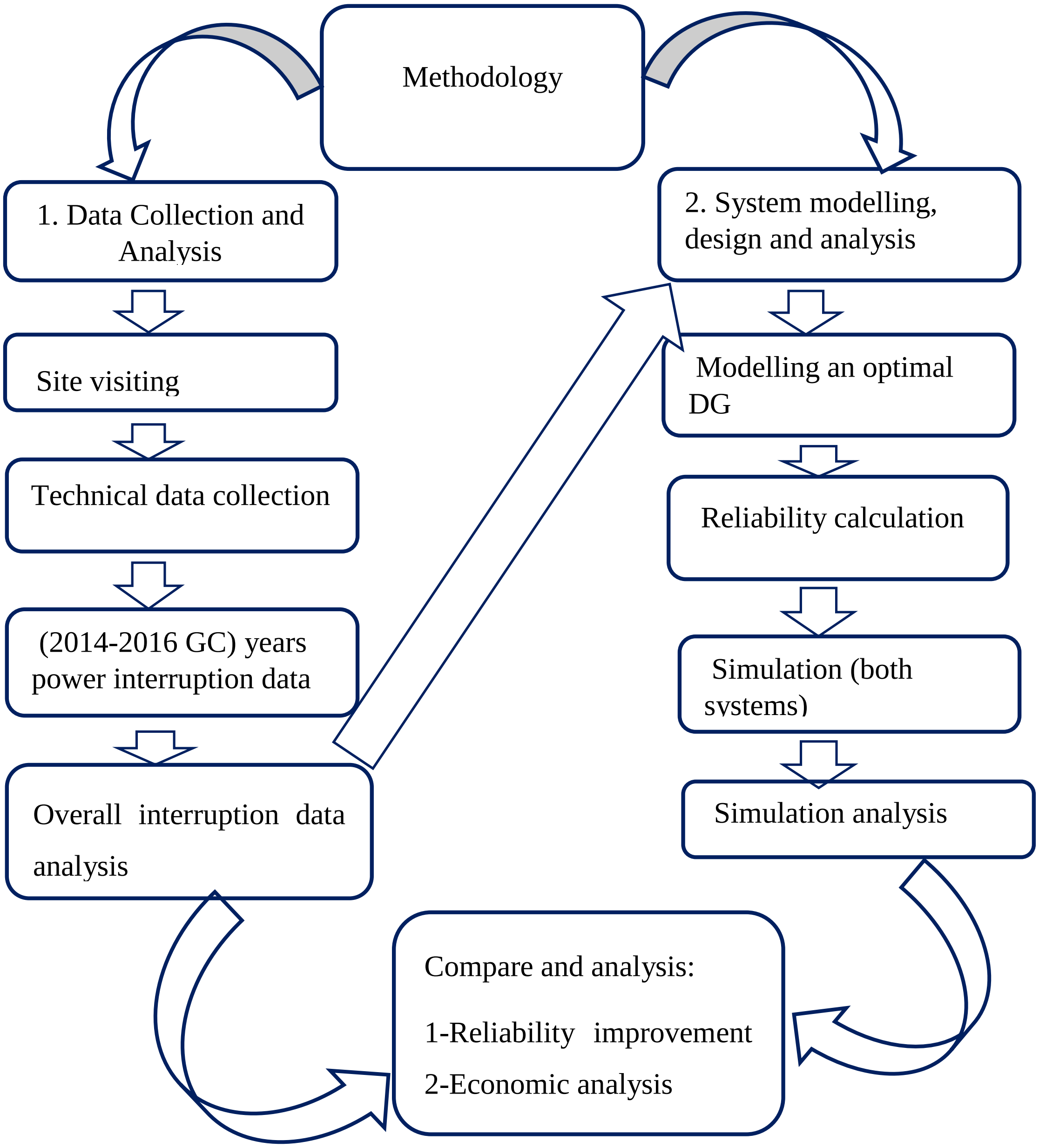

Figure 1.1: Overall methodology used in the thesis

1.8 Description of the study area

Bishoftu city is located in West Shewa, Oromiya region; its geographical coordinates are 9° 6' 0" North, 37° 15' 0" East. Since the location of Bishoftu city is near to the capital city (Addis Ababa), the Ethiopian government selects the city to be one of the industry zones in the country. The city has also different natural resources which attract tourists come to the city, so it is also a place where different hotels and resorts are under construction. Bishoftu substation II is located at Bishoftu town which is the main substation to supply Bishoftu town and small towns around Bishoftu including dire town, Amerti, Minjar and partial load of Dukem town. And there are many industries supplied from the substation. The incoming line from Kality substation which is called Koka tap carrying 132 KV is the input of the substation. The installed capacity of the substation is 88MVA and inside of this substation there are three power transformers which steps-down 132 kV to 15 kV distribution voltage levels.

Figure 1.2: Bishoftu substation II taken during site visit

Figure 1.3: Control room of Bishoftu substation II

1.9 Outline of the thesis

The thesis has an overall of six chapters and can be summarized as follows.

Chapter 1 provides the background, problem statement, objectives, scope of the thesis, significance of the study, motivation for DG and Descriptions of the study area.

Chapter 2 focuses on the theoretical backgrounds and literature review of the distributed generations (DG) and power system reliability.

Chapter 3 describes the collected data of the substation and the calculated results of reliability indices.

Chapter 4 presents the modelling and some network issues of DG including the methods used for optimal location and sizing of DG.

Chapter 5 describes the simulation and discussion of the results.

Chapter 6 summarizes the overall conclusion, recommendation and future work of the thesis.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

Distributed generation (DG) is a new approach in electrical industry and has been gradually increasing in the last few years and will rise even more in near future .It is generally refers to small-scale (typically 1 kW – 50 MW) electric power generators that produce electricity at a site close to customers or that are tied to an electric distribution system [7]. Distributed generators are connected to the medium or low voltage grid and it has so many resources both renewable and non-renewable. In this chapter the most important theoretical concepts of DG are discussed. The first part of this chapter discusses the effects of distributed generation on the voltage profile in the distribution grid. In many cases voltage limit violations are more critical than over loading of cables or transformers [8].

2.1 Distribution Systems

The electric power systems can be divided into generation plant, generation sub-station, transmission system, sub-transmission and distribution sub-stations. Distribution systems serve as the link from the distribution substation to the customer. This system provides the safe and reliable transfer of electric energy to various customers throughout the service territory. Typical distribution systems begin as the medium-voltage three-phase circuit, typically about 11 to 66 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 [9].

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. Figure below illustrates a typical electric power system general configuration [9].

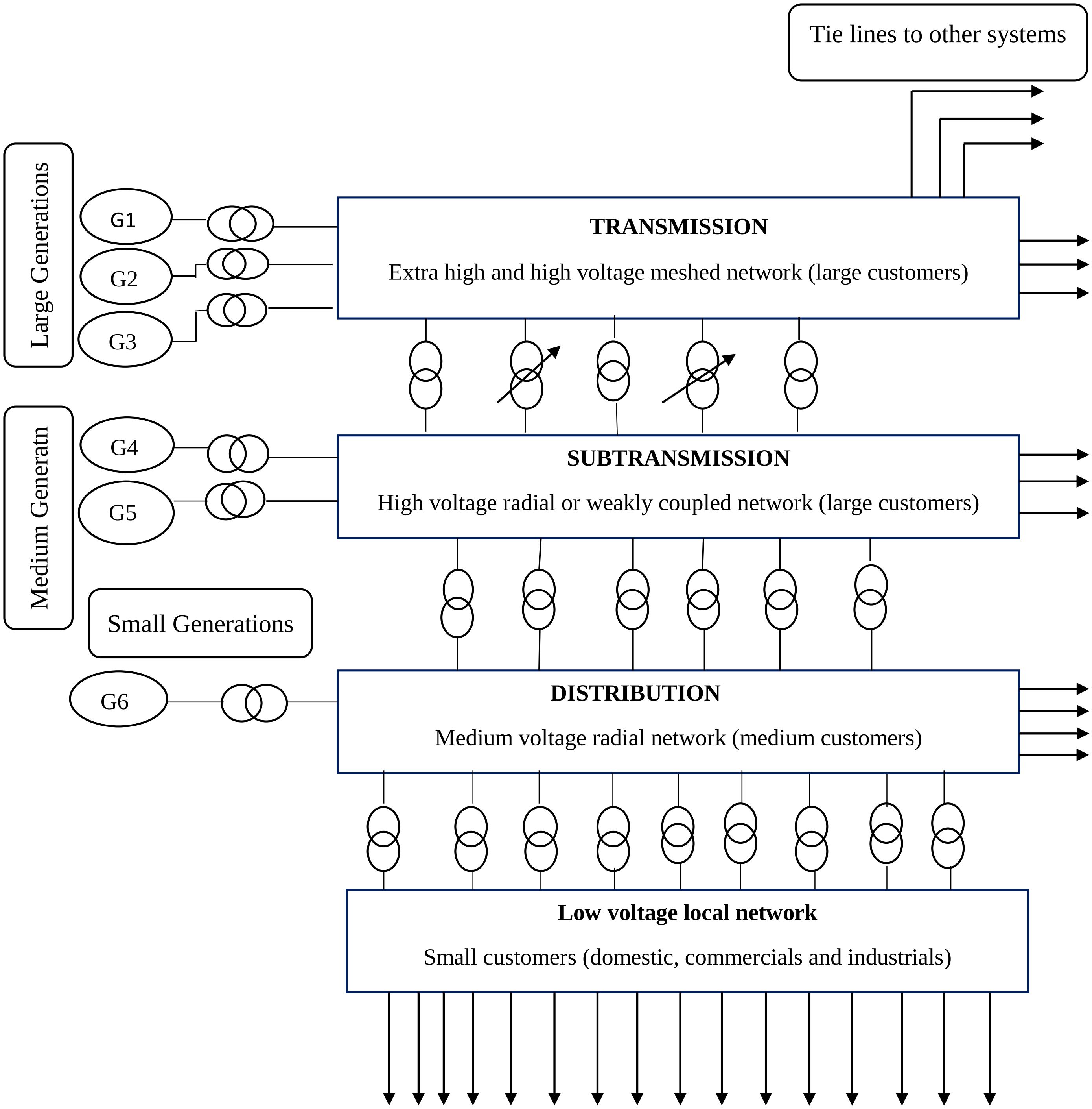

Figure 2.1: Basic configuration of power system network

The distribution system can be divided into primary or secondary systems. The primary distribution system comprises of distribution substations and feeders. The distribution substations step down power from the sub-transmission system to a voltage between 11 kV and 45 kV.

2.2 Distributed Generation

The concept of DG contrasts with the traditional centralized power generation concept, where the electricity is generated in large power stations and is transmitted to the end users through transmission and distributions lines. While central power systems remain critical to the global energy supply, their flexibility to adjust to changing energy needs is limited. Central power is composed of large capital-intensive plants and a transmission and distribution (T&D) grid to disperse electricity [7].

The IEEE defines distributed generation as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system. Therefore, Distributed Generation (DG) is one of the new trends in power system used to support the increased energy demand, peak sharing and to use as a backup generator. From an environmental prospective, use of renewable energy reduces emissions as well as help in avoidance of construction of new transmission lines and large power plants. DG units can also have a beneficial impact on power quality and reliability such as improved voltage profile, reduced power losses and network congestion. Figure 2.2 and Figure 2.3 below shows the direction of power flows in traditionally centralized power generation(currently existing system) and DG connected to the system(proposed power flow with DG interfaced) respectively.

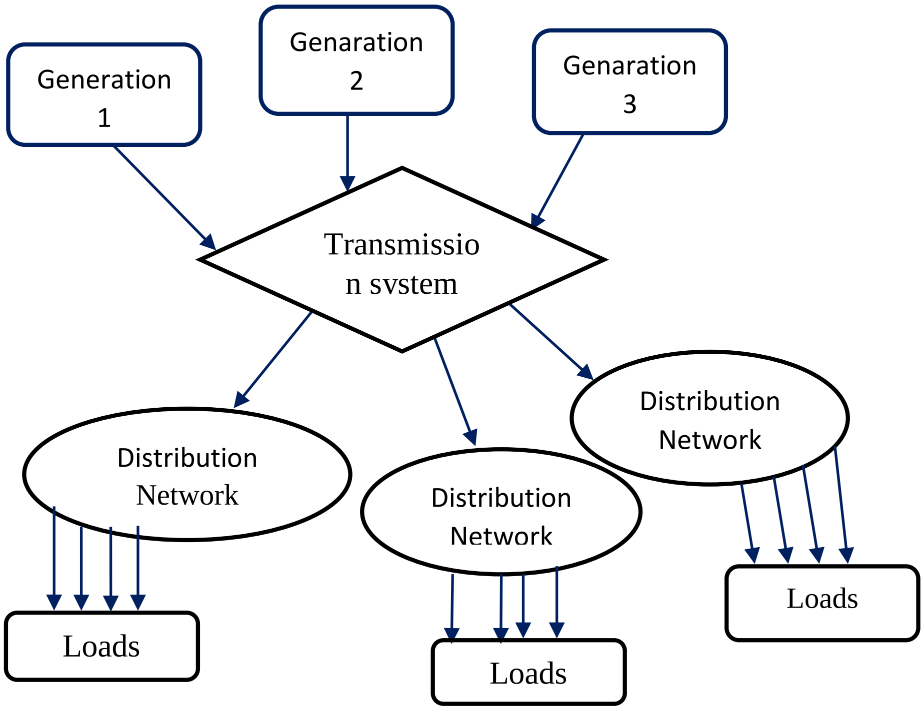

Figure 2.2: Current existing power flow without DG connection

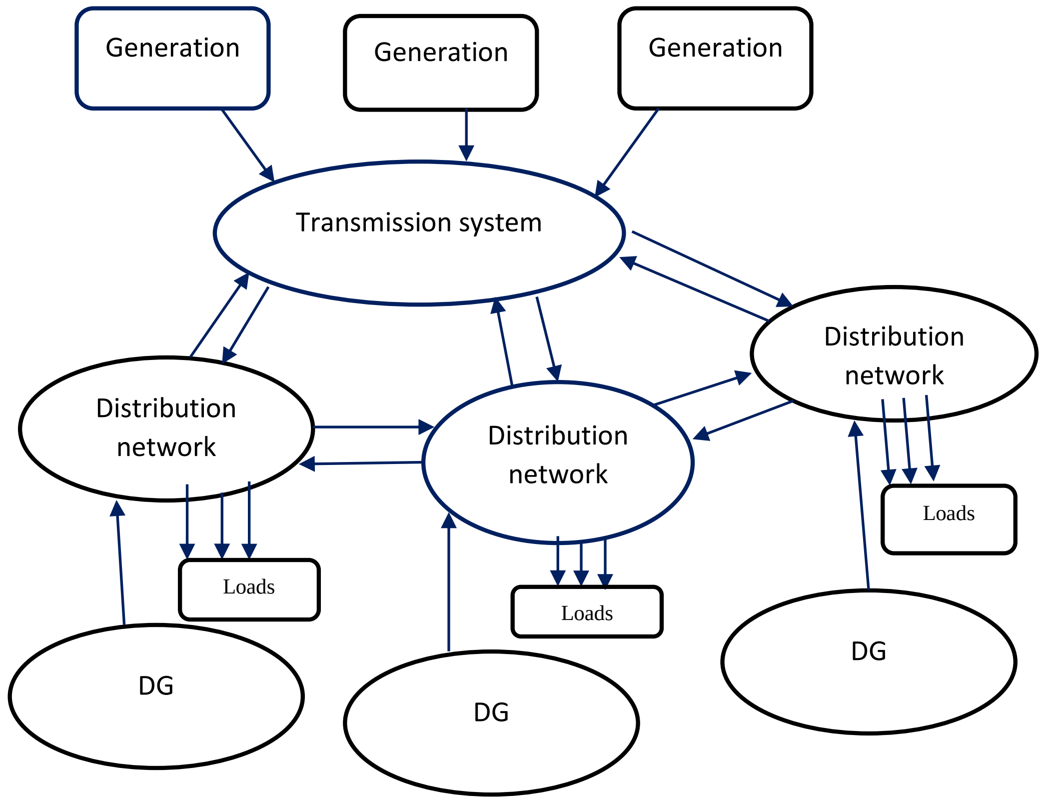

Figure 2.3: Power flow direction when DG unit is interfaced.

The technologies for Distributed Generators are based on reciprocating engines, photovoltaic, fuel cells, combustion gas turbines, micro turbines and wind turbines. This technology is also known as alternative energy system [10]. By connecting distributed generators in the distribution system, the power demand of the system can be satisfied and also improves the reliability of the Electrical network .To clarify about the DG concept, some categories that define the size of the generation units are presented below and the size of DG is defined according to the reference [11]: The two main classifications of DGs are based on unit capacity and unit technology. The first classification is based on unit capacity which is shown below:

- Micro distributed generation between 1W -5kW
- Small distributed generation between 5kW - 5 MW
- Medium distributed generation between 5 MW -50MW
- Large distributed generation between 50MW -300MW

The second classification is based upon unit technologies which are renewable, modular or combined heat and power (CHP). DG units based on renewable energy resources can be readily replenished and are viewed as ‘environmentally friendly’. Modular DG units refers to that can be built and placed within a short time span and can be operated together (as distinct units) to meet larger output requirements [11].

The concepts created in this thesis refer to most of the types of DG, however the DG technologies that have the biggest market shares are wind and solar power generation and as a results all case studies will relate to them. In 2015, 28.9 GW of new power generating capacity was installed in the EU, 2.4 GW more than in 2014. Wind power was the energy technology with the highest installation rate in 2015: 12.8 GW, accounting for 44.2% of all new installations. Solar PV came second with 8.5 GW (29.4% of 2015 installations) and coal third with 4.7 GW (16.3%). Gas installed 1.9 GW (6.4 % of total installations), CSP 370 MW (1.3%), hydro 238.5 MW (0.8%), biomass 232.4 MW (0.8%), waste 118.5 MW, nuclear 100 MW, geothermal 4.3 MW and ocean 4.1 MW. These statistics can be also represented by Figure 2.4 below.

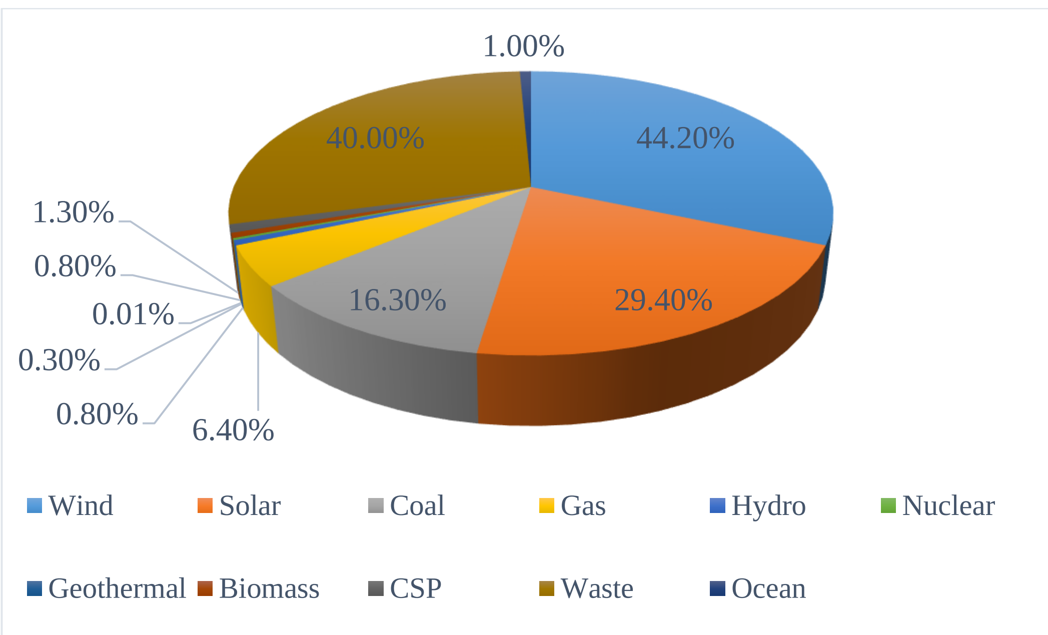

Figure 2.4: Share of new power capacity installation during 2015 in EU

2.2.1 Types of distributed generation technologies

Distributed Generation technologies and resources are categorized to many different groups. It can be classified as conventional and renewable DG technologies. Some of them are: Photovoltaic system (PV), Wind turbines, Fuel cells, Micro-turbine, Gas turbine and other renewable resources.

2.2.1.1 Photovoltaic system

A photovoltaic system (PV), converts the light energy received from the sun radiation to electric energy commonly known as solar panels [12].It is a well-established technology for supplying power to sites at a way the distribution substation and the power generated by PV based DG units are inherently intermittent, less variable and much easier to predict. It is currently being considered for integration into distribution system for large scale, medium scale and small scale DG. Photovoltaic (PV) panels are widely available for both commercial and domestic use [13]. Materials that are used for photovoltaic are mono crystalline silicon, polycrystalline silicon, microcrystalline sili-con, cadmium telluride and copper indium selenide [14]. The basic unit of a photovoltaic power system is the PV cell, where cells may be grouped to form panels or modules. The panels then can be grouped to form large photovoltaic array that connected in series or parallel. [15]. Panels range from less than 5 kW and units connected in parallel increase the current and connected in series provide a greater output voltage to form a system of any size. The PV energy is produced when the solar cells are exposed to direct sunlight, each cell generates less than one watt of DC power, with the lowest voltage around 0.5 V. A solar cell is basically a semiconductor diode in which the photons of sunlight fall on the cell and generate electron-hole pairs separated on the diode junction, thus forming the junction potential or voltage. The generated voltage potential is limited by the forward potential drop across the semiconductor p-n junction. The current produced is proportional to the surface area and to the density of the solar power radiation [16]. The output characteristics of PV module depends on the solar irradiance, the cell temperature and output voltage of PV module. They produce no emissions, and require minimal maintenance. However, they can be quite costly. Less expensive components and advancements in the manufacturing process are required to eliminate the economic barriers now impeding wide-spread use of PV systems. Figure 2.5 below shows PV system and the strength, weakness of photovoltaic have been listed in table 2.1 below [17].

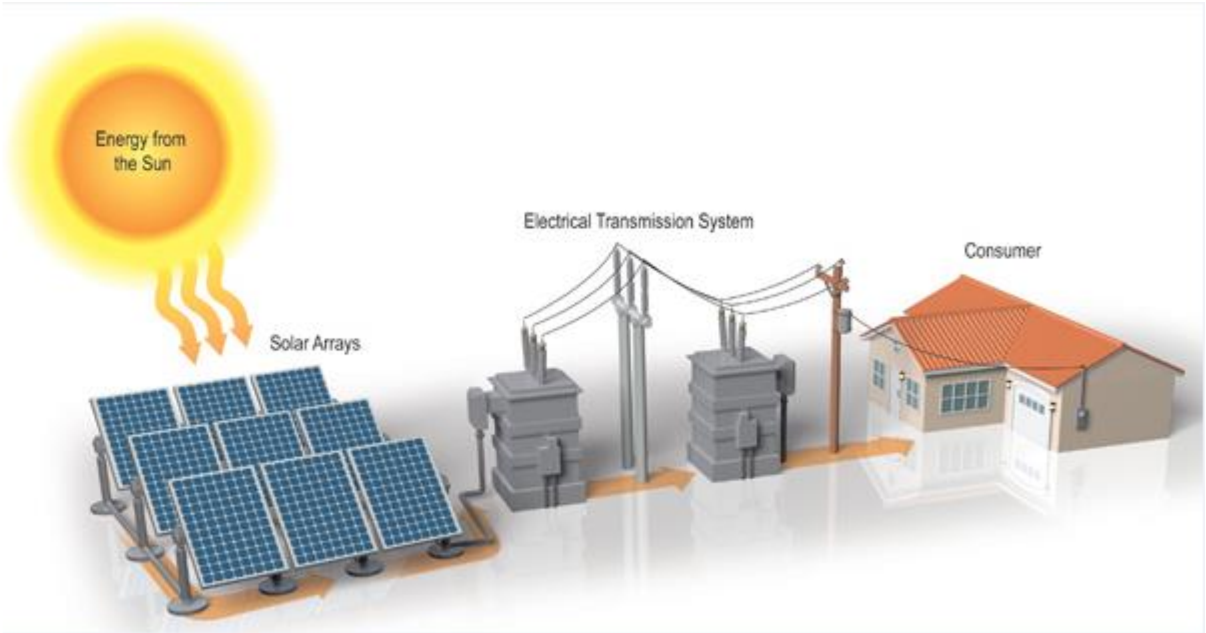

Figure 2.5: Photovoltaic system

Table 2.1: Advantage and Disadvantage of Photovoltaic

Advantage	Disadvantage
Work well for remote location	-Local weather patterns and sun conditions directly affect the potential of PV system. Some location will not be able to use solar power. -Use of toxic material such as the cadmium in cadmium telluride solar cells.
Require no fuel supply	
Require very little maintenance	
Completely silent	
Long shelf life	
No emission(env'lly friendly)	
Low maintenance	High cost

The system generates DC voltage then transferred to AC with the aid of inverters. The design of such systems can be with and without battery storages. These system has environmental friendly without any pollution and emission. Easy to use, simple design and it does not require any other fuel than solar light and these is why I prefer PV system with wind energy in my thesis analysis. The cumulative increase of global solar installed capacity can be represented as follows:

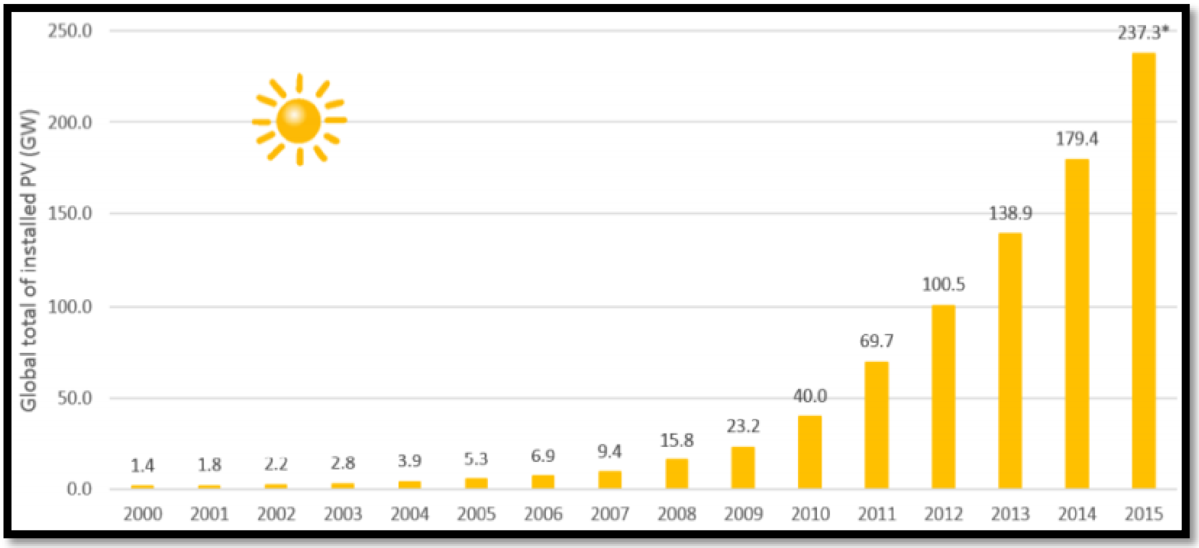

Figure 2.6: Global cumulative solar power installation [18].

2.2.1.2 Wind power generation based DG system

At this point of time, around 433 GW are installed globally out of which about 63 GW were installed in the last year [18]. Wind turbines are capable of converting wind energy into electricity. Wind turbines are currently available from many manufacturers and range in size from less than 5 to over 1,000 kW. They provide a relatively inexpensive (compared to other renewable) way to produce electricity, but as they rely upon the variable and somewhat unpredictable wind, are unsuitable for continuous power needs. There are two conversion steps in wind turbines. First, the rotor takes the kinetic energy of the wind; convert it into mechanical torque in the shaft; and then the generator system converts this mechanical torque into electricity. Mostly, the generator system gives an AC output voltage which is dependent on the wind speed. As wind speed is not constant, the voltage generated must be transferred to DC and back again to AC with the aid of inverters. However, turbines with fixed wind speed can directly be connected to grid [19]. The power generated by a wind turbine is proportional to the swept area of the rotor disc and to the cube of wind speed that pass through the mentioned disc. Also the air density and a power coefficient that express the average of extracted energy from the wind by the turbine rotor are implicated [20]. Among these factors, the most important factor is the wind speed, since its impact is cubic. A general scheme of a wind turbine is shown in Figure 2.7 with its main components.

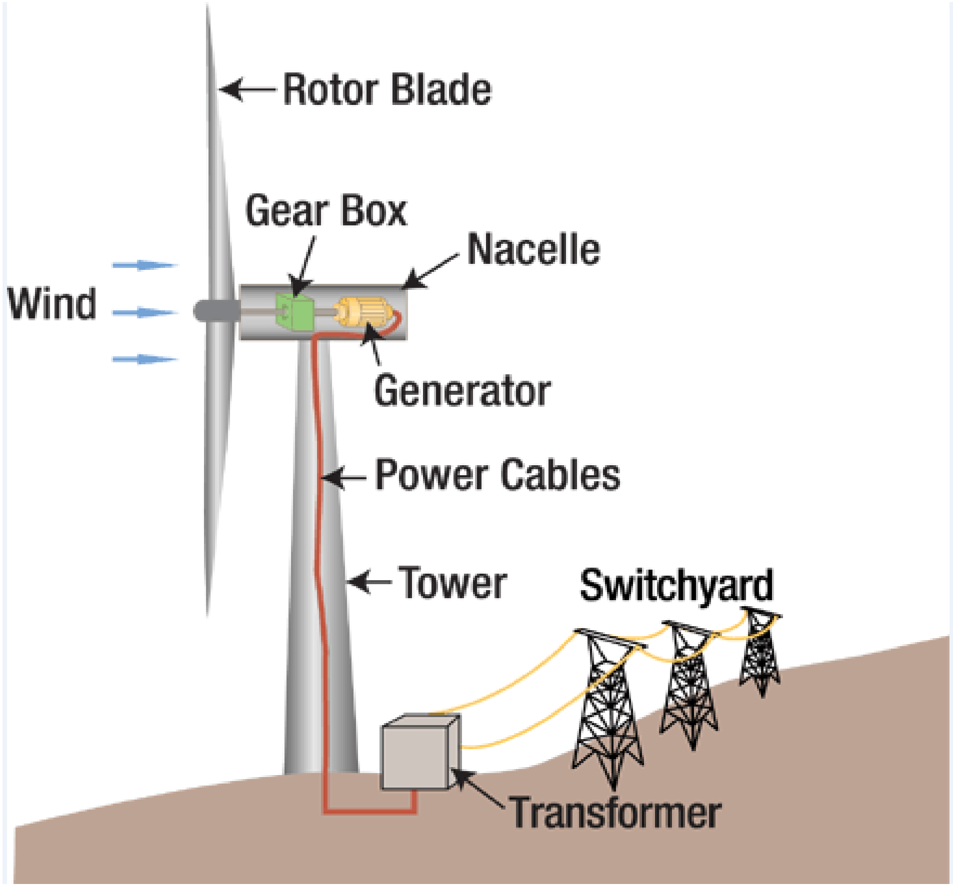

Figure 2.7: Main components of wind power generation based DG system [19].

Table 2.2: Advantage and Disadvantage of Wind Turbine

Advantage	Disadvantage
Power generated from wind farm can be inexpensive	Variable power output due to the fluctuation in wind speed
Low cost of energy	Location
Minimal land use-the land below each turbine can be used for animal grazing or farming.	Visual impact-aesthetic problem of placing them in higher population density areas
No harmful emissions	Bird mortality
No fuel required	Noise pollution-these noise pollution from commercial wind turbines are sometimes similar to a small jet engine

2.2.1.3 Fuel Cells System

Fuel cells supplies electricity by combining hydrogen and oxygen electrochemically without combustion. However, while the battery is a storage device for energy that is eventually used up and must be recharged, the fuel cell is permanently fed with fuel and an oxidant, so that the electrical power generation continues [21]. The advantage and disadvantage of Fuel cell have been listed in Table 2.3 below.

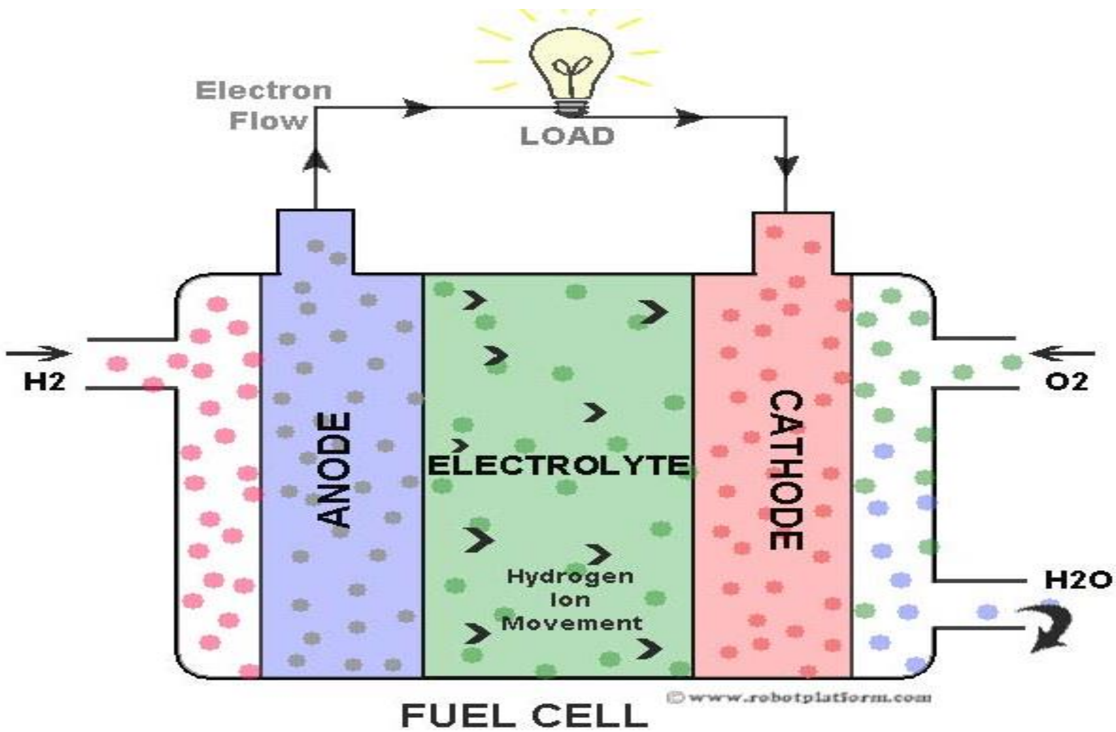

Figure 2.8: Fuel cell system

Types of Fuel Cells

Fuel cells are classified according to the type of electrolyte used. There are various fuel cell types at different stages of development. The various types of fuel cells in the increasing order of their operating temperature are [22].

- Proton exchange membrane fuel cell (PEMFC-175 F^0)
- Phosphoric acid fuel cell (PAFC-400 ^0F)
- Molten carbonate fuel cell (MCFC-1250 ^0F)
- Solid oxide fuel cell (SOFC-1800 ^0F)

Table 2.3: Advantage and Disadvantage of Fuel Cells [17].

	PAFC	MCFC	SOFC	PEMFC
Advantage	Quiet	Quiet	Quiet	Quiet
	Low emissions	Low emissions	Low emissions	Low emissions
	High efficiency	High efficiency	High efficiency	High efficiency
	Proven reliability	Self-reforming	High energy density	Synergy,with automotive R&D
			Self-reforming	
Disadvantage	High cost	Need.to.demonstrate long-term dependability	Planar SOFCs are still in the R&D stage but recent developments-in-low temperature-operation show promise	Low-temperature waste-heat.many limit, cogeneration potential.
	Low,energy.density	High cost	High cost	Limited field test experience
				High cost

2.2.1.4 Micro Turbine

A new and emerging technology, microturbines are currently only available from a few manufacturers. As the name implies, microturbines are small combustion turbines that burn gaseous or liquid fuels to drive an electrical generator, and have been commercially available for more than a decade. A micro-turbine is a mechanism that uses the flow of a gas, to convert thermal energy into mechanical energy. There are two types of micro turbine: Recuperated MT and UN recuperated MT. Recuperated micro turbines, which recover the heat from the exhaust gas to boost the temperature of combustion and increase the efficiency. UN recuperated micro turbines, which have lower efficiencies, but also lower capital costs.

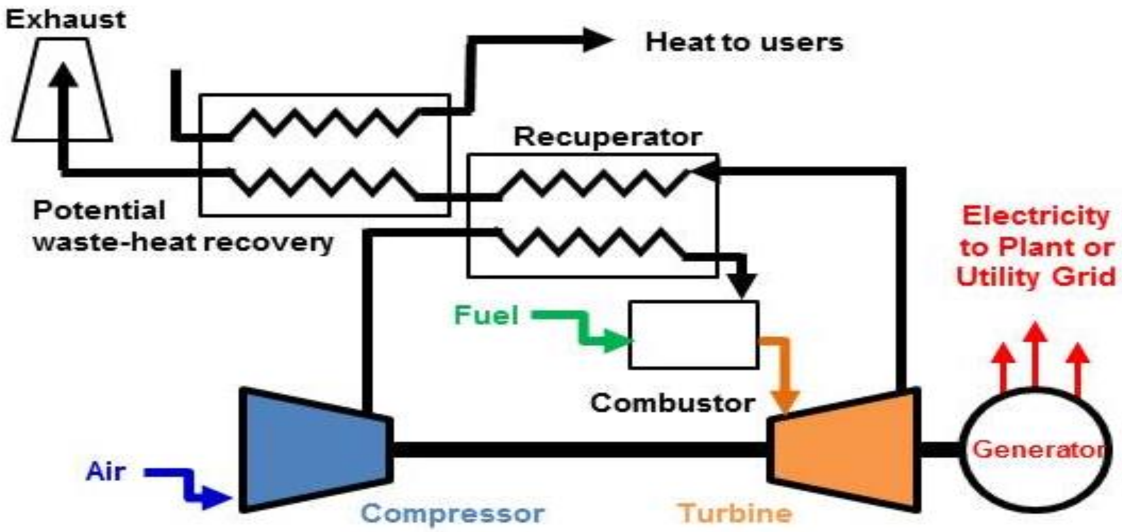

Figure 2.9: Micro turbine system

Table 2.4: Advantage and Disadvantage of Microturbines

Advantage	Disadvantage
Small number of moving parts	Low fuel to electricity efficiencies
Compact in size & Good efficiencies in cogeneration	Loss of power output and efficiency with higher ambient temperatures and elevation
Light weight & Can utilize waste fuels	Small system cost and efficiency not as good as larger system.
Long maintenance intervals	High maintenance cost

2.2.2 Benefits of utilizing DG units

In many applications, DG technology can provide valuable benefits for both the consumers and the electric-distribution systems. The small size and the modularity of DG units encourage their utilization in a broad range of applications. Connection of Distributed Generation can provide several advantages [23]. A great number of benefits is arising from the usage of DG in case it is integrated optimally in terms of location and size in the distribution grid. Specifically, DG can:

- Improve the voltage profile of an electric power system
- Reduce the losses of the system
- Relieve the overloads of the feeders
- Reduce costs by deferring the upgrade of the distribution system

- Improve system reliability and power quality
- Enhance the rural electrification in which costs for arising from transmission and distribution are high
- Reduce healthcare costs since they reduce CO_2 emissions in the environment
- Renewable energy based DG like PV and wind turbines play great role in the reduction of greenhouse gases.

2.2.3 Applications of DG units

DG can be used for different applications in power systems due to their small size, modularity and location. The main applications of DG units include the following fields:

- Generating the base-load power, as in the case of variable-energy DG sources
- Providing additional reserve power at peak-load intervals
- Providing emergency or back-up power to increase the stability and reliability of important loads
- Supplying remote loads separated from the main-grid system
- Supporting the voltage and reliability by providing power services to the grid
- Cooling and heating purposes

It is also possible to use DG to cover the load demand most of the time. In this case, DG has to be connected to a local grid for back-up power.

2.2.4 Impacts of DG penetration on the power system grid

Distribution systems initially designed to operate without any generation on the distribution system or at customer loads. The introduction of generating sources in to the distribution network called distributed generation (DG) can produce significant impact on power flow through the network, voltage condition at various utility consumer equipment and switchgear fault ratings. The severity of impact depends on the location (site) and size (penetration level) of the generating sources. The network has to be designed or existing network should enable DG connections without violating the statutory technical limits or standards such as voltage variation, phase imbalance and fault current limit etc.

When DG is connected in small amounts, the impact on the power system transient stability will be negligible, however, when the penetration of DG increases, its impact is no longer restricted to the distribution network but starts to influence the whole system, including the transmission system transient stability. DG can improve regulation or cause problems with regulation. Some of the main ways that DG can cause regulation problems are as discussed below:

2.2.4.1 Impact on voltage regulation

The DG integration can impact the overall voltage profile of the system. DG can improve feeder voltage of distribution networks in areas where voltage dip or blackouts are of concern for utilities. Some techniques to regulate voltage using the optimal DG allocation for minimum losses and proper voltage and reliability support.

1. Low voltage due to DG just downstream of a regulator with line-drop compensation:

When the DG causes downstream the system, it can confuse the voltage regulation by setting a voltage lower than the standard value and can cause the voltage to change above or below the permissible range. The impacts of distributed generation on voltage regulation can be balanced by using Online Load Tap Changing (OLTC) transformer controls to avoid under-voltage and over-voltage. Line drop compensation is the technique commonly applied by LTC transformer controllers and line voltage regulators to control the voltage on the distribution system based on the line current. Under heavy load, a generator just downstream of the generator will reduce the observed load on the feeder (so the regulator will not boost the voltage as much). This leads to lower voltage downstream of the regulator.

2. High voltage due to DG:

Because of the unidirectional design of the traditional distribution network the voltage reduces with distance from the generator or transformer. These voltage drop are predictable and they are taken in to account in the design of the network so that the voltage is within the tolerance under normal conditions. When a DG unit is connected, the current flows are changed or even reversed, and the voltage will generally increase in a way that is not easy to predict. The requirement to meet statutory voltage limits restricts the capacity of DG that can be connected to the system, particularly at the low voltage level. High voltages may be caused by reverse power flow. Under light load for a location where the primary voltage is already high, the voltage rise can be enough to push the voltage above ANSI limits.

3. Interaction with regulating equipment:

Another area of concern is interaction of regulation equipment with DG. If the DG has varying output, it may change the system voltage or current flows enough to cause a regulator tap change or an operation of a switched capacitor. Likewise, a distributed generator that has feedback to control voltage may interact negatively to the utility regulation equipment. There may be undesirable cycling of regulation devices and noticeable power quality impacts under such conditions.

DG operating ranges per standard:

Table 2.6 shows the normal operating range of photovoltaic per the IEEE 929-2000 interface standard [24]. Note that the high-end limit of 132 V is well above the ANSI range B upper limit of 127 V for the service and utilization voltage. Since DG can cause a voltage rise because it injects real power, this is inconsistent with the ANSI range B upper limits and could lead to long-duration over voltages caused by DG. The IEEE P1547 interconnection standard is currently in draft form that applies to all distributed generation was initially based on IEEE 929 but has evolved slightly to have different trip levels and tripping times as shown in Table 2.5. Qualitatively, the proposed settings of IEEE P1547 are still quite similar to IEEE 929 and both standards allow sustained DG operation outside of the ANSI C84.1 limits. Within the industry, this topic has been an area of active discussion as to the pros and cons of this approach. In subsequent sections of this thesis, the voltage regulation issues related to DG are discussed.[24].

Table 2.5: Standard trip thresholds (120-V nominal) for DG operations per the IEEE 929 photovoltaic interface guideline.

RMS Voltage	Trip time
V<60	6 cycles
60≤V<106	120 cycles
106≤V≤132	Nominal operation
132<V<165	120 cycles
165≤V	2 cycles

Table 2.6: Proposed voltage trip settings per IEEE P1547-D7

Voltage range(%of base voltage)[Note1]	Clearing time(second)[Note2]
V<50	0.16
50≤V<88	2
88≤V<110	Operation allowed (no trip)
110≤V<120	1
V≥ 120	0.16
Note 1: Base voltages are the nominal voltages stated in ANSI C84.1 Note 2: DR≤30 kW Maximum Clearing Time. DR>30 kW, Default Clearing Time or area EPS operator may specify different voltage settings or trip times to accommodate area EPS system requirements	

Note the IEEE P1547 document is a proposed standard under development and these settings could change pending committee review.

2.2.4.2 Impact on power loss

High levels of penetration of distributed generation (DG) are a new challenge for traditional electric power systems. The impacts of the DGs on the power losses form a bath-tub shape with penetration level. This indicates that at lower penetration of DG, the losses are reduced, however, as the penetration increases, a time will come that the power losses begin to increase. Power injections from DGs change network power flows modifying energy losses [24]. Although it is considered that DG reduce losses, this paper shows that this is not always true. The appropriate location of DG units in the existing system is an important criterion that has to be analyzed to be able to achieve a better reliability of the system with reduced losses. One of the advantages of the DG usage is that DG can inject both active and reactive power of any combination to improve system conditions and satisfy customer's demands instantaneously.

2.2.4.3 Impact on reliability indices

The connection of DG to a distribution system helps to improve the reliability of the system [25]. The use of the existing distribution system will be the best if DG is allocated optimally and if the development from passive to active is planned optimally with all relevant considerations taken into account. The reliability improvement will be maximum if the location of the DG is such that it provides maximum access to the customers in terms of customer numbers, overall demand and priority of customer. DG may be used as standby or backup source. When DG units are applied as stand-by units, it only affects the outage duration and do not affect the interruption frequency. Indices (except SAIFI) are too sensitive to location, number and availability of DG units [25]. In general, integration of DG in the distribution system has positive and negative impact on reliability indices and power reliability. The positive impacts included faster restoration service to the customer and reduced voltage sags while the negative impacts could be sympathetic tripping, increased fuse blowing etc.

2.2.4.4 Congestion alleviation

Congestion in power system is a consequence of network constraints characterizing a finite network capacity that limits the simultaneous transfer of power from all required transactions. As load increases, the utility company has to look for different mechanisms to satisfy the customer demand requirement and avoid the distribution substation congestion. Traditionally, the transformer capacity expansion or a new distribution substation is the solution, but it needs high investments and large areas for expansion of construction. Therefore, integrating DG to the distribution substation is a good option to mitigate the congestion. Transmission congestion also exists in power systems as a natural consequence of supply and demand [24].

2.2.4.5 Impact on fault level and protection devices

Connection of DG not only alters the load flow in the distribution grid but can also alter the fault current during a grid disturbance. Most distribution grid protective systems detect an abnormal grid situation by discerning a fault current from the normal load current. Because DG changes the grid contribution to the fault current, the operation of the protective system can be affected. The connection of DG to distribution feeders changes the fault currents in faulted feeders. The rate of change of the fault currents strongly depends on the ability of the DG to contribute to the fault current. DG based on an asynchronous generator does not provide a sustainable fault current during a grid-disturbance. The same holds mostly for inverter-connected DG such as micro-turbines, fuel-cells and PV-systems, from which the fault current contribution can be neglected.

A significant contribution to the fault current of the DG-unit affects the protective devices in the distribution system. Because the fault currents are affected by the DG-units, the measured currents used for protection purposes, are affected as well. This can lead to incorrect operation of the protective system and causes fault detection problems and selectivity problems.

2.2.5 Drawbacks of DG

However, if the allocation of DG is not compatible with the properties and the technical constraints of the grid topology several issues might arise such as:

- Increase in short-circuit currents due to bidirectional power flows
- Overvoltages
- Increase in power losses
- Voltage Flickers
- Malfunctions in the protective relays due to bidirectional power flows

2.3 Power system reliability and some related terminologies

Power system reliability can be defined as the measure of the ability of the power system to deliver electricity to all points of utilization within accepted standards and in the amount desired, for the period of time intended, under the operating conditions intended. The reliability of the interconnected bulk power system is defined in two ways [26].

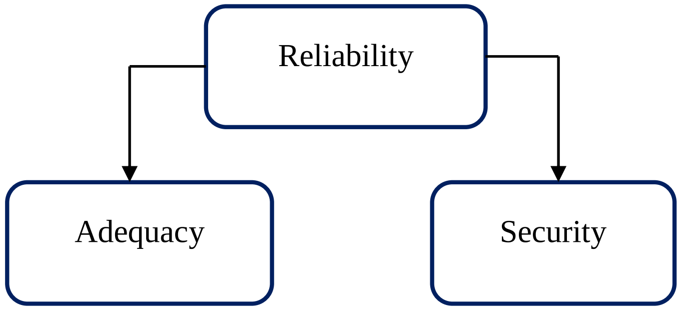

Figure 2.10: Reliability evaluation elements.

1.Adequacy: A measure of the ability of the power system to supply the aggregate electric power and energy requirements of the customers within components ratings and voltage limits, taking into account planned and unplanned outages of system components. Adequacy measures the capability of the power system to supply the load in all the steady states in which the power system may exist considering standards conditions.

2. Security*:* A measure of power system ability to withstand sudden disturbances such as electric short circuits or unanticipated losses of system components or load conditions together with operating constraints [27]. Another aspect of security is system integrity, which is the ability to maintain interconnected operation. Integrity relates to the preservation of interconnected system operation, or avoidance of uncontrolled separation, in the presence of specified severe disturbances. Most of the probabilistic techniques for reliability assessment are with respect to adequacy assessment [28].

In brief, reliability has to do with total electric interruptions and complete loss of voltage, not just deformations of the electric sine wave. This means reliability does not cover sags, swells, impulses or harmonics. Reliability assessment involves determining, generally using statistical methods, the total electric interruptions for loads within a power system during an operating period. The interruptions are described by several indices. Reliability indices typically consider such aspects as [29]:

- The number of customers [N].
- The connected load, normally expressed in [kW].
- The duration of the interruptions, normally expressed in [h] = 'hours'.
- The amount of power interrupted, expressed in [kW].

- The frequency of interruptions, normally expressed in [1/a] = 'per annum'.
- Repair times are normally expressed in [h] = 'hours'.
- Probabilities or expectancies are expressed as a fraction or as time per year ([h/a], [min/a]).

Network reliability assessment is used to calculate expected interruption frequencies and annual interruptions costs, and to compare alternative network designs. Reliability analysis is an automation and probabilistic extension of contingency evaluation. For such analysis, it is not required to pre-define outage events, instead the tool can automatically choose the outages to consider [27].The relevance of each outage is considered using statistical data about the expected frequency and duration of outages according to component type. The effect of each outage is analyzed automatically such that the software simulates the protection system and the network operator's actions to re-supply interrupted customers. Because statistical data regarding the frequency of such events is available, the results can be formulated in probabilistic terms. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply [26].

Note: Reliability assessment tools are commonly used to quantify the impact of power system equipment outages in economic terms. The results of a reliability assessment study may also be used to justify investment in network upgrades such as new remote control switches, new lines/ transformers, or to assess the performance of under voltage load shedding schemes.

There are many terms and definitions used in reliability engineering. Some of the frequently used terms and definitions are presented below [27].

Reliability (R (t)): This is the probability that an item will carry out its assigned mission satisfactorily for the stated time period when used under the specified conditions. Or Reliability refers to the probability that a component experiences no failure during a time period.

Availability(A): The probability that an item is available for application or use when needed or Availability is the probability that the component is normal at an arbitrary time t, given that it was good at time zero [30].

Availability,

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

Unavailability (U): Unavailability is the probability that the component is down at an arbitrary time t and unable to operate [30].

Unavailability,

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

From the above formula, 8760 in the right part is the total hours of one year, because MTTR is measured in hours according to the definition of availability and unavailability [26].

According to probability technique, these can be expressed as the following equation;

$$U = 1 - A \qquad 2.3$$

The concept pairs of reliability/failure probability and availability/unavailability are more or less the same. The difference between them is whether the maintenance of the component is considered. If a healthy component is under maintenance to be checked for its quality, then it is reliable, but unavailable [27].

- Mean Time to Failure (MTTF)**:** The average time it takes to the occurrence of a component or system failure measured from t=0.
- Mean Time to Repair (MTTR): The average time it takes to identify the location of a failure and to repair that failure.

Failure: The inability of an item to function within the initially defined guidelines.

Failure Frequency (f): The Failure frequency refers to the number of failures that may happen during a time period. In this study, the dimension of the failure frequency is failures per year.

$$f = \frac{Number\ of\ failure}{Studied\ period} \qquad 2.4$$

Therefore, the relationship between the failure frequency and the Mean Time to Failure is:

$$f = \frac{1}{MTTF + MTTR} \qquad 2.5$$

The unit for Mean Time to Failure is years.

The availability is the fraction of time when the component is in service; the unavailability is the fraction of time when it is in repair.

Failure Probability (F (t)): The failure probability is the probability that, under stated conditions, the system or component fails within a stated period. It is identical to unreliability, which is denoted as (F (t)).

$$F(t) = 1 - R(t) \qquad 2.6$$

Maintainability: The probability that a failed item will be repaired to its satisfactory working state.

2.4 Electricity service interruption

Interruption of electricity service to a customer involves a reduction in voltage magnitude to zero at the customer delivery point [31].

2.4.1 Some terminologies related to electric power interruption:

Transient Fault

A transient fault is a fault that is no longer present if power is disconnected for a short time and then restored; or an insulation fault which only temporarily affects a device's dielectric properties which are restored after a short time. Many faults in overhead power lines are transient in nature. When a fault occurs, equipment used for power system protection operate to isolate the area of the fault. A transient fault will then clear and the power-line can be returned to service. Typical examples of transient faults include: momentary tree contact, bird or other animal contact, lightning strike, conductor clushing. Transmission and distribution systems use an automatic re-close function which is commonly used on overhead lines to attempt to restore power in the event of a transient fault [26].

Permanent forced outage duration

An outage whose cause is not immediately self-clearing but must be corrected by eliminating the hazard or by repairing or replacing the component before it can be returned to service. An example of a permanent forced outage is a lightning flashover which shatters an insulator, thereby disabling the component until repair or replacement can be made.

In electrical engineering, forced outage is the shutdown condition of a power station, transmission line or distribution line when the generating unit is unavailable to produce power due to unexpected breakdown. Generally, it is the shutdown of a generating unit, transmission line, or other facility for emergency reasons or a condition in which the generating equipment is unavailable for load due to unanticipated breakdown [31].

Transient forced outage duration

An outage whose cause is immediately self-clearing so that the affected component can be restored to service either automatically or as soon as a switch or circuit breaker can be reclosed or a fuse replaced [32]. An example of a transient forced outage is a lightning flashover which shatters an insulator, thereby disabling the component until repair or replacement can be made.

Causes of interruptions

A power outage (also called a power cut, a power blackout or power failure) is a short-term or a long-term loss of the electric power to a particular area. These power interruptions are caused by either planned or unplanned opening operations of switching devices, disconnecting primary equipment from the network. Faults are caused by external factors, such as road traffic accidents, digging into buried cable, vegetation, animals and severe weather, and by equipment failure [32].

2.4.2 Power system interruption characteristics

Interruptions are classified by IEEE 1159 into either a short-duration or long-duration variation. However, the term "interruption" is often used to refer to short-duration interruption, while the latter is preceded by the word "sustained" to indicate a long-duration. They are measured and described by their duration since the voltage magnitude is always less than 10% of nominal. It is one of the general categories of power quality problems mentioned in the second post of the power quality basics series of this site [27].

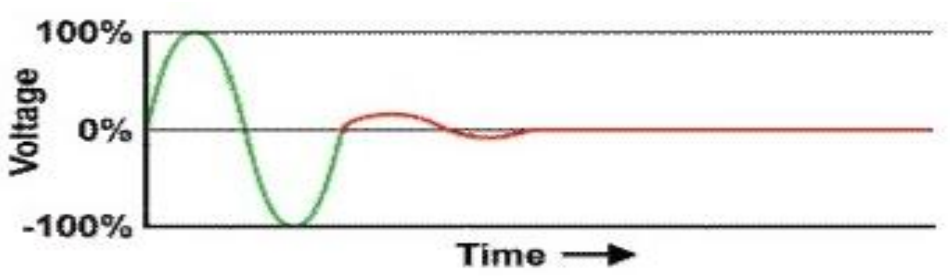

Figure 2.11: Definition of interruption

Interruption is the power quality problem with the most perceivable effect on facilities. Generally, it affects the industrial sector, particularly the continuous process industry. In addition, the communication and information processing business is also significantly disturbed. Power system interruption can be classified in to two main categories. These are: Short duration and Long duration interruptions.

2.4.2.1 Short duration interruptions

Interruption is defined as the decrease in the voltage supply level to less than 10% of nominal for up to one (1) minute duration. They are further subdivided into: Instantaneous (1/2 to 30 cycles), Momentary (30 cycles to 3 seconds) and Temporary (3 seconds to 1 minute).

Interruptions with a shorter duration are termed momentary interruptions. The brief loss of power delivery to one or more customers caused by the opening and closing operation of an interrupting device. Interruptions mostly result from reclosing circuit breakers or reclosers attempting to clear nonpermanent faults, first opening and then reclosing after a short time delay. The devices are usually on the distribution system, but at some locations, momentary interruptions also occur for faults on the sub-transmission system. The extent of interruption will depend on the reclosing capability of the protective device. For example, instantaneous reclosing will limit the interruption caused by a temporary fault to less than 30 cycles. On the other hand, time delayed reclosing of the protective device may cause a momentary or temporary interruption. Aside from system faults, interruptions can also be due to control malfunctions and equipment failures.

Consequences of short interruptions are similar to the effects of voltage sags. Interruptions may cause the following (but not limited to):

- Stoppage of sensitive equipment (i.e. computers, PLC, ASD)
- Unnecessary tripping of protective devices

- Loss of data
- Malfunction of data processing equipment

2.4.2.2 Long duration interruption

Sustained interruptions/non-momentary

Sustained Interruption is defined by IEEE 1159 as the decrease in the voltage supply level to zero for more than one (1) minute. It is classified as a long duration voltage variation phenomena. Sustained interruptions are often permanent in nature and require manual intervention for restoration. In addition, they are specific power system phenomena and have no relation to the usage of the term outage. Outage does not refer to a specific phenomenon, but rather to the state of a system component that has failed to function. Furthermore, in the context of power quality monitoring, interruption has no relation to reliability or other continuity of service statistics.

Sustained interruptions are usually caused by permanent faults due to storms, trees striking lines or poles, utility or customer equipment failure in the power system or miscoordination of protection devices. Consequently, such disturbances would result to a complete shutdown of the customer facility.

Planned and Unplanned Interruptions

Planned Interruption is disconnecting or disabling a utility system as part of a construction, demolition, maintenance, testing, or repair process at a known point in time for a specifically estimated duration and the customers and the customers have been notified beforehand of the interruption. On the other hand, if the occurrence time of the interruption has not been selected, then the interruption is unplanned. Unplanned interruption occurs, for example, due to fault clearing, unwanted operation of the protection system or due to inadvertent initiation of opening operation of a switching device by a human. Planned interruptions occur mainly for the purpose of construction, preventative maintenance or repair [33].

2.5 Reliability Analysis Methods

Reliability analysis of electrical distribution system is considered as a tool for the planning engineer to ensure a reasonable quality of service and to choose between different system expansions plans that cost wise were comparable considering system investment and cost of losses.

There are two main approaches applied for reliability evaluation of distribution system, namely Simulation (Monte Carlo) method and analytical methods. The simulation (Monte Carlo) method is based on drawings from statistical distributions and that of Analytical methods is based on solutions of mathematical models. Reliability indices are usually evaluated by analytical approach based on failure mode assessment and the use of equations for series and parallel networks.
There are three common reliability indices used in this method of reliability evaluation. These are: expected failure rate (λ), the average outage time(r), and the expected annual outage time (U), which are enough for the simple radial system [34].

2.5.1 Reliability Evaluation of Power System using Analytical (Markov Models)

Markov models are commonly used to perform reliability analysis of engineering systems and fault tolerant systems. They are also used to handle reliability and availability analysis of repairable systems and is the most commonly used method in the quantitative reliability analysis. This approach is based on contingency enumeration and involves the analysis of the adequacy evaluation of the composite system, taking in consideration all possible contingency states. Analytical method generally evaluates expected value of reliability indices utilizing numerical solution from mathematical model that represents the status of the system components. It relies on capacity outage that tells the exact probability of each level of outage capacity of the systems. However, building capacity outage probability for the real power systems is much more complicated due to the huge amount of outage combinations among generators in the system.

2.5.2 Monte Carlo Simulation Method

Monte Carlo simulation is a powerful tool for modeling and analysis of the reliability of a power system. It relies on repeated random sampling to compute the statistics and uses statistics to mathematically model a real life process and then estimate the likelihood of the possible outcomes. Before performing the Monte Carlo simulation, the statistical distribution of failure and repair process must be determined. Once the failure and repair distributions are known a Monte Carlo simulation can be performed to model the process over time. It is used for obtaining numerical solutions to problems which are too complicated to solve analytically. Monte Carlo simulation methods estimate power system reliability indices by simulating the actual operations and random events in the system. The method treats the problem as a series of real experiments. The techniques can take into account virtually all aspects and contingencies inherent in the operation of a power system. The goal of Monte Carlo simulation is to achieve the statistics of the realistic system by making a large amount of trials for the happening in the system. This recorded information permits the expected values of reliability indices together with their frequency distributions to be evaluated.

2.6 Power System Reliability Indices

To measure system performance, the electric utility industry has developed several performance measures of reliability. These reliability indices include measures of outage duration, frequency of outages, system availability, and response time. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply. There are many indices for measuring reliability. The three most common reliability indices are SAIFI, SAIDI, and CAIDI, as defined in IEEE Standard 1366.The other reliability indices are referred from these most common indices.

I. System Indices

2.6.1 System Average Interruption Frequency Index (SAIFI):

System Average Interruption Frequency Index (SAIFI), in units of [1/C/a], indicates how often the average Customer experiences a sustained interruption during the period specified in the calculation. It is the total number of customer interruptions divided by the total number of customers served [35].

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_T} \qquad 2.7$$

Where: λ_i *is the failure rate at load point i*

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

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

SAIFI can also be found by dividing the SAIDI value by the CAIDI value:

$$SAIFI = \frac{SAIDI}{CAIDI} \qquad 2.8$$

2.6.2 Customer Average Interruption Frequency Index (CAIFI):

Customer Average Interruption Frequency Index, in units of [1/A/a], is the mean frequency of sustained interruptions for those customers experiencing sustained interruptions. Each customer is counted once regardless of the number of times interrupted for this calculation. The CAIFI measures the average number of interruptions per customer interrupted per year [35]. The CAIFI is expressed as;

$$CAIFI = \frac{\sum N_o}{\sum N_i} \qquad 2.9$$

Where N_o = Total number of interruptions

N_i =Total number of customers interrupted

2.6.3 System Average Interruption Duration Index (SAIDI):

System Average Interruption Duration Index, in units of [h/C/a], indicates the total duration of interruption for the average customer during the period in the calculation. It is commonly measured in customer minutes or customer hours of interruption. SAIDI is normally calculated on either monthly or yearly basis; however, it can also be calculated daily, or for any other time period. It is the sum of the restoration time for each interruption event times the number of interrupted customers for each interruption event divided by the total number of customers.

$$SAIDI = \frac{\sum r_i * N_i}{\sum N_T} \qquad 2.10$$

Where: r_i= restoration time, minutes

N_i=Total numbers of customers interrupted

N_T=Total numbers of customers

2.6.4 Customer Average Interruption Duration Index (CAIDI):

Customer Average Interruption Duration Index, in units of [h], is the mean time to restore service. It is the average time needed to restore service to the average customer per sustained interruption. It is the sum of customer interruption durations divided by the total number of customer interruptions. CAIDI is calculated similar to SAIDI except that the denominator is the number of customers interrupted versus the total number of utility customers. CAIDI is

$$CAIDI = \frac{\sum U_i * N_i}{\sum \lambda_i * N_i} = \frac{SAIDI}{SAIFI} \qquad 2.11$$

Where: λ_i= Failure rate at load point i

U_i=Annual outage time at load point i

N_i=Total numbers of customers interrupted

2.6.5 Average Service Availability Index (ASAI):

Average Service Availability Index, this represents the fraction of time that a customer is connected during the defined calculation period or the index that represents the fraction of time (often in percentage) that a customer has power provided during one year or the defined reporting period. It is the ratio of the total number of customer hours that service was available during a given time period to the total customer hours demanded. This is sometimes called the service reliability index. The ASAI is usually calculated on either a monthly basis (730 hours) or a yearly basis (8,760 hours), but can be calculated for any time period. The ASAI is calculated as:

$$ASAI = \left[1 - \frac{r_i * N_i}{\sum N_T * T}\right] * 100 \qquad 2.12$$

Where: T=Time period under study, in hour

r_i =restoration time, in hour

N_i=Total number of customer interrupted at load point *i*.

N_T=Total number of customer served.

Another formula to calculate the ASAI is

$$ASAI = \left[\frac{8760 - SAIDI}{8760}\right] * 100 \qquad 2.13$$

2.6.6 Average Service Unavailability Index (ASUI):

Average Service Unavailability Index, is the probability of having loads unsupplied and it is the complementary value to the average service availability index (ASAI).

$$ASUI = 1 - ASAI = \frac{customer\ hours\ of\ unavailable\ service}{customers\ hours\ demanded}$$

$$= \frac{\sum U_i N_i}{\sum N_i * 8760} \qquad 2.14$$

II .Load Point or Energy-Oriented Indices

2.6.7 Energy Not Supplied Index (ENS):

Energy Not Supplied, in units of [MWh/a], is the total amount of energy on average not delivered to the system loads. This index represents the total energy not supplied by the system [35].

$$ENS = \sum La(i) U_i \qquad 2.15$$

Where: La (i) is the average load given by:-

$$La(i) = L_p(i) L_F(i) = \frac{E_d(i)}{t} \qquad 2.16$$

Where: -L_p is the peak load demand, L_F is the load factor and E_d is the total energy demanded in the period of interest t.

2.6.8 Average Energy Not Supplied Index (AENS):

Average Energy Not Supplied, in units of [MWh/Ca], is the average amount of energy not supplied, for all customers or the index that represents the average energy not supplied by the system-[26].

$$AENS = \frac{Total\ energy\ not\ suplied}{Total\ number\ of\ customers\ affected} = \frac{\sum La(i) * U_i}{\sum N_o} \qquad 2.17$$

2.6.9 Momentary Average Interruption Frequency Index (MAIFI)

Momentary Average Interruption Frequency Index, in units of [1/Ca], evaluates the average frequency of momentary interruptions. The calculation is described in the IEEE Standard 1366 'IEEE Guide for Electric Power Distribution Reliability Indices'. It is the total number of customer momentary interruptions divided by the total number of customers served. The momentary interruptions are the interruptions that occur in a specified time not to exceed five minutes.

$$MAIFI = \frac{Total\ number\ of\ customer\ momentary\ interruption}{Total\ number\ of\ customer\ served}$$

$$= \frac{\sum ID_i * N_i}{\sum N_T} \quad 2.18$$

Where: ID_i is the number of interrupting device operations, N_i is the number of customers experiencing momentary interruptions, and N_T is the total number of customers served [35].

2.7 Relationship of economics and reliability

In order to make a consistent appraisal of economics and reliability, it is necessary to assess the economic value for achieving a specified reliability level of system. Traditional cost evaluation techniques include cost-benefit analysis and lifecycle energy cost models. In economic evaluation of power system, cost-benefit analysis is often used to calculate and compare the benefits and costs of a given service area, while lifecycle energy cost models can be used to evaluate the cost sensitivity of power system with respect to the variation of component reliability. Typically, as investment in system reliability increases, the reliability improves, but it is not a linear relationship [36]. Evaluation of the costs and reliability associated with different system configurations is generally designated as reliability cost-benefit assessment. Reliability cost-benefit studies can be performed through incorporating economics factors into decision making process of reliability evaluation. Customer damage costs resulting from power supply interruptions are uncertain, which may be estimated by the traditional models such as customer damage function (CDF) or composite customer damage function (CCDF). The customer damage function (CDF) is a cost function of each customer sector (industrial, commercial and residential customers).A CDF provides the interruption cost versus interruption duration for a specific group of customers. The composite customer damage function (CCDF), is an aggregation of the CDF at specified load points and is weighted proportionally to the load at the load points [26]. The CCDF represents the total interruption cost as a function of the interruption duration in a particular service area or at a specific bus.

$$CCDF = \sum C_i * CDF_i * \frac{cost}{KW} \quad 2.19$$

Where C_i=energy demand of customer type i.

In CCDF, it is necessary to predict future interruption costs with data collected through estimating the system reliability indicators such as expected energy not supplied (EENS) and expected customer damage cost (ECOST). Outage costs are generally divided between utility outage costs and customer outage costs [26].Utility outage costs include the loss of revenue for energy not supplied and the increased maintenance and repair costs to restore power to the customers affected. The maintenance and repair costs can be expressed as [36].

$$C_{m,r} = \sum C_l + C_{co} \quad 2.20$$

Where: C_l= is labor cost, C_{co}= is component replacement/repair cost.

The total utility cost for an outage is given by:

$$C_{tot} = (ENS)X\left(\frac{cost}{KWH}\right) + C_{cu,r} \quad 2.21$$

Where: ENS=Energy Not Supplied and $C_{cu,\,r}$ = Cost for customer sector type.

For a reliability planning, in addition to the load point indices of λ, r, and U, one has to determine the following reliability cost/worth indices [36]:

1. Expected Energy Not Supplied (EENS) index:

$$EENS = \sum L_i * r_{ij} * \lambda_{ij} \quad 2.22$$

Where L_i=average load at load point *i*

r_{ij} = failure duration at point i due to component j.

λ_{ij} = failure rate at point *i* due to component j

2. Expected customer outage cost (ECOST) index. It is defined as:

$$ECOST_i = \sum CDF_{ij} * r_{ij} * \lambda_{ij} \quad 2.23$$

Where: CDF_{ij} is sector customer damage function at load point *i* due to component *j*.

3. Interrupted energy assessment rate (IEAR) index. It is defined as

$$IEAR_i = \frac{ECOST_i}{EENS_i} \quad 2.24$$

Where $ECOST_i$ is Expected Customer Outage Cost at load point *i*, and $EENS_i$ is Expected Energy Not Supplied at load point *i*, This index provides a quantitative worth of the reliability for a particular load point in terms of cost for unit of energy not supplied.

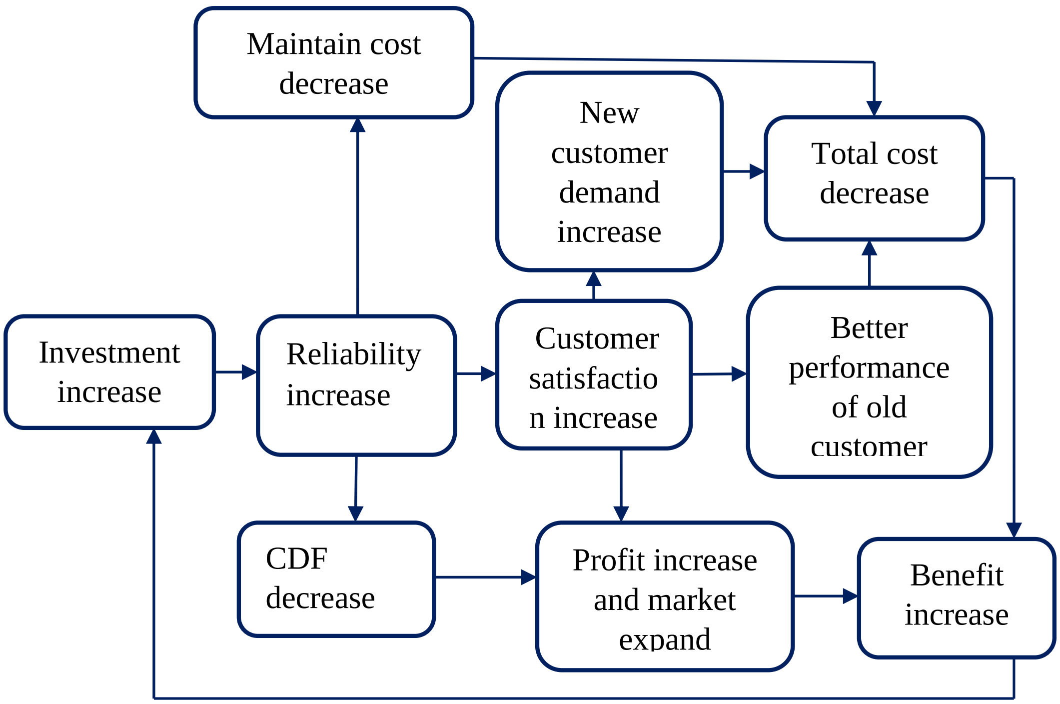

Figure 2.12: Relationship between reliability and economics.

2.8 Review of some related current research works

A number of publications have been reviewed at the DG interfacing, optimizing the placement and sizing based on various criteria to analyze the reliability of the power system network. Selections of the more relevant publications are given as below.

In author [37] outlines a technique for assessing the reliability of alternative conceptual design architectures. The method is based on identification of criticality and sensitivity of system components, and a simulation model that incorporates probability and failure rates of individual components such that system level reliability measures can be computed. This analysis at the system level supports decision making early in the design process and assists the designers evaluate and identify critical elements of different conceptual architectures, and to select among or integrate different architectural solutions to ensure improved reliability.

In the author [38] the optimal power flow (OPF) technique is used to maximize DG capacity with respect to voltage and thermal constraints. But short circuit levels, short circuit ratio, equipment ratings, Slack bus limit, Power balance limits and losses are not considered.

Author [39] according to this author power system analysis was made with and without DGs in terms of total power loss and voltage profile of all the buses. The total power loss in with DG was reduced to 37% of total power losses in the system and the voltage profile of all the buses remained stable within the tolerable limits. The reliability indices EENS and ECOST are also reduced by about 29 %.

Author [33] implementations of reliability improvement solutions on a test system have been evaluated from a socio-economical point of view. For each of the alternative solutions implemented on the test system, the average annual supply interruption cost to the customers supplied from the test system has been estimated. Furthermore, the maximum annual capital cost associated with the implementation of each solution has been estimated. Then, a reliability improvement solution is considered justified socio-economically if the capital cost associated with its implementation is less than the resulting reduction in the interruption cost to the customers.

In author [40] a method is presented by utilizing OPF for the allocation of generation capacity, which includes a detailed fault level constraint. Short circuit constraints are not considered and the focus of the objective function is on optimal investment rather than maximizing renewable energy.

Solomon Derbie [26] mainly focused on the reliability problem of the existing power grid of Adama city and the smart grid has been proposed as a solution. Therefore, the appropriate components of smart grid are selected to design the overall system. Smart Reclosers are the key components of Smart Grid which are used for fault detection, isolation and restoration programs in the distribution systems and the result of this fact has been an unprecedented increase of global demand for this product. A smart recloser offers a complete design solution with integrated smart grid capabilities offering not only remote control but automation and the analogue data measurement and logging capabilities to achieve the utilities business drivers. The designed system is simulated using the softwares DigSilent and Windmill that are used to analyze the reliability of the overall system. The simulation of the designed model shows that the application of smart reclosers can improve the reliability of the overall system from 50% to 75%.

Author [41] examined the amount of losses experienced with increasing penetrations of DG sources. The authors propose a method which places DG at the optimal place along feeders and within networked systems with respect to losses. The allocation of losses to distributed generators in the network has been addressed in Previous work has attempted to quantify the net benefits of DG [42] where a number of benefits such as reduced losses and voltage profile were assessed.

Author [43] develops a new reliability and security index that reflects both on direct and indirect characteristics. Direct characteristics deal with the risk to not fully supply load in various contingencies. Indirect characteristics address such undesirable conditions as circuit overloads, voltage problems, low stability margins, area interchange violations, in-sufficient generation reserves, unfeasible power flows, etc. Although indirect characteristics do not necessarily cause load losses, they nevertheless signal about a reduced security/reliability margin. This reduced margin may lead to sometimes hardly predictable and quantifiable load losses (via remedial actions, islanding, and instability), unforeseen events (cascading outages), and severe system failures (voltage collapse), etc. The new index gives a more comprehensive answer regarding the general degree of both reliability and security in the system by combining diverse contributing factors using a fuzzy logic like approach. It is designed to flexibly accommodate various priorities and admittance of power utilities regarding particular characteristics integrated in the index. The existing indices such as expected unserved energy, system minutes, stability margins, and others can be linked to or derived from the general index.

In author [44] reliability worth assessment was undertaken with the installations of DG at supply point which barley improve system reliability. As DG location is far from the substation, the system reliability indices increase. The best location for the placement of the DG is at the end of the line where much improvement is achieved.

CHAPTER THREE

DATA COLLECTION AND ANALYSIS

The current Bishoftu distribution substation II is arranged in radial distribution fashion. From my observation to the site both the substation design structure and the control room is old system of operation and the control room has old type of oil circuit breakers which is also not well equipped. All the interruption data are collected manually. Therefore, under this chapter the collected failure data and basic electrical power system equipment data which are necessary for reliability analysis are presented. These data are evaluated and analyzed to identify the current reliability status of the substation and to differentiate the main cause of power interruption to give the possible solutions to the problems.

3.1 Basic data of Bishoftu Substation II

The Ethiopian Electric power is (EEP) is a service provider of electric power in the country. Bishoftu substation II has been supplied from the national grid which tapped from Koka/Galan substation. A 132 kV transmission line is tapped into the substation, there by the distribution system in the city has a primary voltage of 15 kV. This voltage value is stepped down to 400V/220V in three phase or single phase respectively. The network topology for Bishoftu Substation II is radial and the bus bar scheme or layout is parallel single bus bar system. The substation has 13 outgoing feeders as shown in the one line diagram below and the major rating data for the substation main transformers is shown in table 3.1 below.

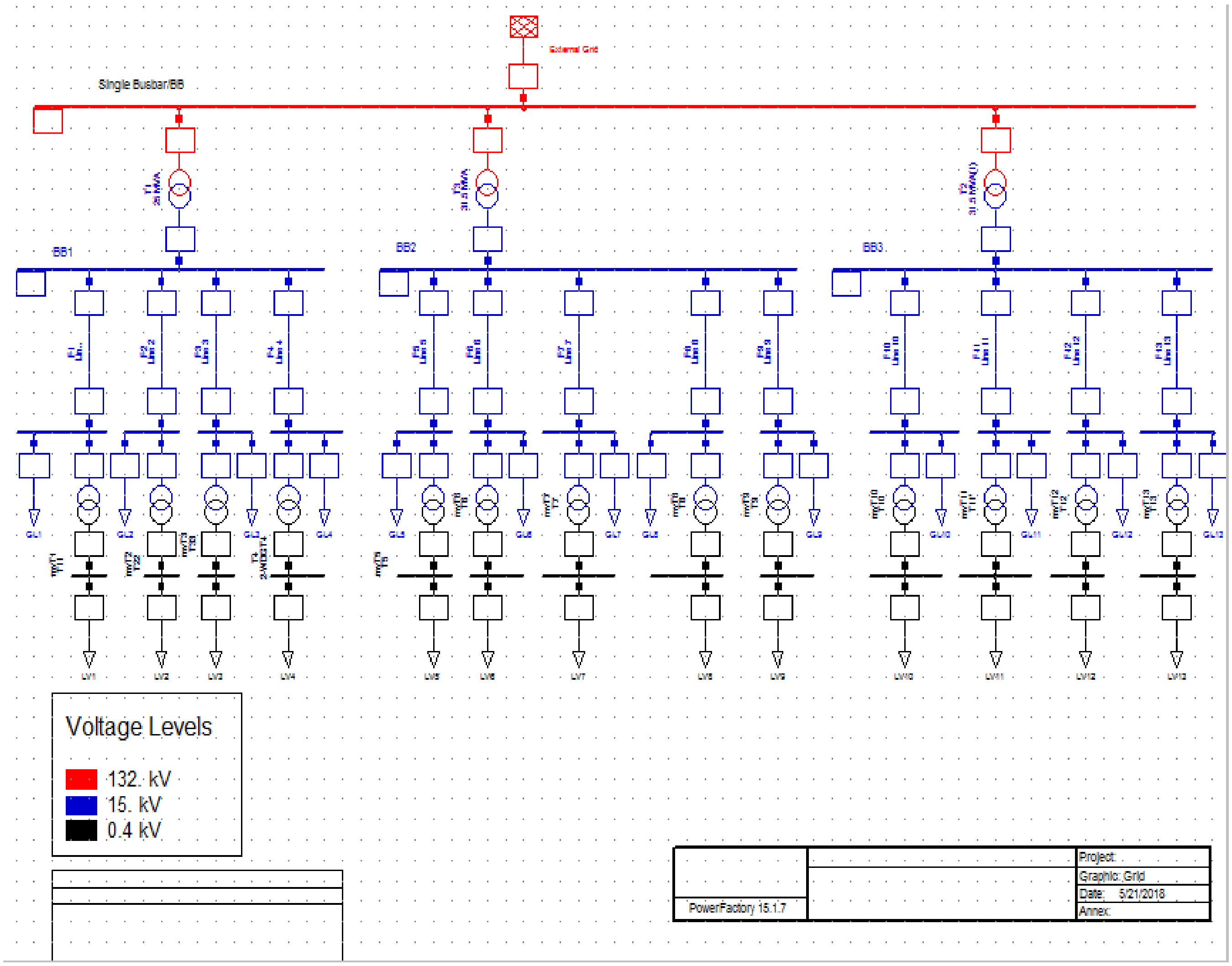

Figure 3.1: Current one line diagram of Bishoftu distribution substation II.

Table 3.1 and 3.2 below shows the number, capacity of transformers and the data of 13 feeders of the distribution substation network and Table 3.3 gives the annual average energy and power consumption of each feeder. The annual average energy is calculated using the recorded data obtained from the substation in the years 2014/15 GC (2006 E.C) to 2015/17 GC (2008 E.C).

Table 3.1: The number & capacity of transformers:

Transformer No.	Type of winding	Rating in MVA	Voltage level in kV
Transformer 1	2 winding	25	132/15
Transformer 2	2 winding	31.5	132/15
Transformer 3	2 winding	31.5	132/15

Table 3.2: Bishoftu substation feeders' basic data.

Feeders (15 kV)	Total No of distribution transformer:	Total Cap of,Trafo: (KVA)	Customers	Length of Feeders (km)	Conductor type and size (mm^2)
L1	2	2500	China&Ethio.Metal industry	7.5	AAC95
L2	3	3300	Sheba.Metal industry	6.5	AAC95
L3	9	9300	105Bishoftu city and Dukem	45	AAC95
K1	2	2500	Steely	2.3	AAC95
K2	2	2500	Steely	2.3	AAC95
K6	16	5650	Steely & PBC	34	AAC95
K7	7	10435	Bishoftu Automtive.	19	AAC50
K8	6	6390	D/Zeyet Town	14.5	AAC95
K9	65	2192	Airforce& PBC	14.9	AAC95
K12	2	3750	Abyssinia	3.5	AAC95
K13	2	3750	Abyssinia	3.5	AAC50
K14	5	4350	Abyssinia & dire town.	54	AAC95
K15	12	4020	Abesha,Steely.&PBC	24	AAC50

Table 3.3: Annual average energy and power consumption of each feeders bus bars:

Feeders (15 kV)	Average energy consumption		Average power consumption	
	Active(KWh)	Reactive(KVArh)	Active(MW)	Reactive(MVAr)
BB1(K5)	21766150.61	6829710	10.65	5.55
BB2(K10)	7936518.73	867472	14.47	5.59
BB3(K15)	76362800.35	418533	12.63	7.41
Total	106,065,469.71	11883115	37.75	15.55

From Table 3.3 the power factor of the substation can be calculated by using the relation:

$$Pf=Cos\ (tan^{-1}(Q/P)) =0.89$$

Table 3.4: The type and number of connected customers to each feeders:

Feeders	Residential	Commercial	Industrial	Total
L1	-	-	1	1
L2	-	-	8	8
L3	799	74	6	879
K1	-	-	1	1
K2	-	-	1	1
K6	3300	152	1	3362
K7	-	-	7	7
K8	69	9	7	85
K9	5128	1	12	5141
K12	-	-	1	1
K13	-	-	1	1
K14	1452	27	6	1485
K15	3250	643	74	3967
System	13998	906	125	15025

Table 3.5: Minimum, Maximum and Average load of each feeders in a substation: (Typical monthly load: June/2015).

Feeders	Minimum Load(MW)	Peak Load (MW)	Average Load demand (MW)
L1	0.022	5.234	2.62
L2	0.176	3.00	1.588
L3	1.193	4.837	3.015
K1	0.044	5.63	2.837
K2	0.044	5.43	2.737
K6	0.066	4.218	2.142
K7	0.044	1.303	0.673
K8	1.193	4.439	2.816
K9	1.037	4.615	2.826
K12	1.126	3.95	2.538
K13	0.574	8.48	4.527
K14	0.706	5.146	2.927
K15	0.044	5.852	2.948

Table 3.6: Hourly load (MW) of each feeders of the substation (typical: 29-June-2014):

Hrs.	L1	l2	l3	k1	k2	k6	k7	k8	k9	k12	k13	k14	k15	Total
1	1.54	0	2.12	1.01	0.97	0	2.60	2.23	1.43	4.28	4.99	0	4.11	25.28
2	1.54	0	2.12	1.01	0.97	0	3.10	2.23	1.43	4.28	4.99	0	4.11	25.78
3	4.44	0	1.87	1.13	1.12	0	1.70	2.23	1.41	0.5	5.28	0	4.75	24.43
4	4.44	0	1.87	1.34	1.41	0	2.50	2.38	1.43	3.42	3.6	0	1.65	24.04
5	4.44	0	1.87	1.34	1.41	0	3.90	2.38	1.43	3.42	3.6	0	1.65	25.44
6	4.79	0	2.09	1.19	1.15	0	2.40	2.74	2.09	3.18	5.67	0	3.2	28.5
7	5.07	0	2.09	1.24	1.15	0	4.10	3.25	2.91	0.5	3.95	0	5.61	29.87
8	4.79	0.35	3.33	1.19	1.15	0	2.30	4.1	4.06	3.07	3.82	0	4.26	32.42
9	2.18	0.44	3.77	1.61	1.72	0	2.80	4.44	4.33	2.46	3.38	0	4.55	31.68
10	4.88	0.97	3.99	1.24	1.15	0	0.62	4.46	0	2.52	3.11	0	0.95	23.89
11	4.88	0.97	3.99	1.24	1.15	0	0.62	4.46	4.44	2.52	3.11	0	0.95	28.33
12	2.29	1.46	3.64	1.19	1.15	0	0.46	4.55	0	4.5	2.69	0	4.77	26.7
13	2.29	1.46	3.64	1.19	1.15	0	0.46	4.55	4.46	4.46	2.69	1.35	4.77	32.47
14	5.76	0	0	1.69	1.72	0	0.46	3.77	3.93	0.53	2.43	3.35	5.92	29.56
15	6.78	0	4.04	1.46	1.5	0	2.70	3.86	3.71	4.5	4.33	0	4.59	37.47
16	3.62	0	4.22	1.19	1.19	0	3.10	3.77	3.49	4.12	3.86	0	4.55	33.11
17	3.95	1.32	0	1.72	1.7	0	2.70	3.66	1.87	4.55	2.65	0	2.61	26.73
18	3.72	0.88	3.25	0	0.46	0	2.50	3.86	3.93	3.88	3.82	0	2.36	28.66
19	3.72	0.88	3.25	0	0.46	0	1.88	4.33	4.35	0.53	4.37	0	2.01	25.78
20	2.43	1.32	3.68	0	0.57	0	2.00	4.26	4.28	4.55	3.16	0	4.46	30.71
21	2.43	1.32	3.68	0	0.57	0	1.60	3.82	3.6	3.93	3.69	0	2.67	27.31
22	3.2	0.97	3.42	0	0	0	1.88	3.2	2.78	4.26	3.2	0	3.09	26
23	3.2	0.97	2.25	0	0	0	2.80	2.56	2.18	4.26	4.24	0	2.43	24.89
24	3.2	0.97	2.2	1.01	1.01	0	2.83	2.16	1.59	4.15	3.47	0	3.29	25.88

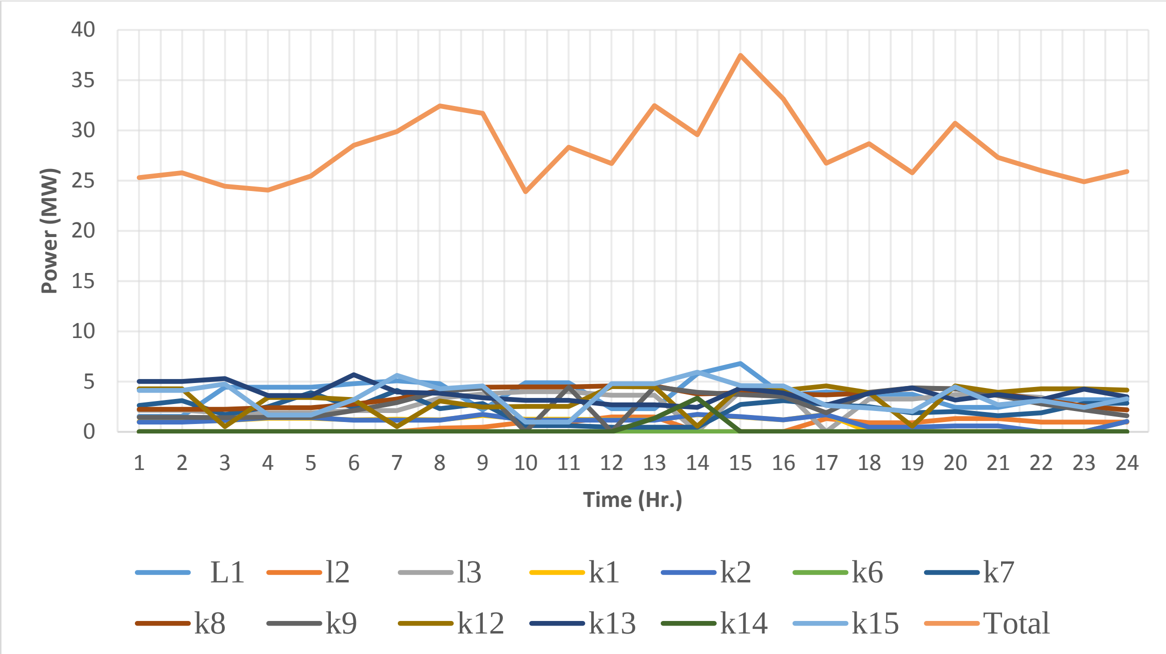

Figure 3.2: Hourly load profile (MW) of each feeders of Bishoftu Substation II

From Figure 3.2 above the following observation can be made:

- ✓ The maximum load of the system occurs from 14:00 to 16:00
- ✓ The minimum load of the system is 23.89MW while the maximum load is 37.47MW.
- ✓ From all the individual feeders the minimum load is occurred at K6 which is zero and the maximum load is occurred at L1 which is 6.78MW.

Table 3.7: Hourly load (MW) of Bishoftu substation feeders:
L-3, K-7, K-8 and K9: (Typical: 29-June-2014):

Hrs.	l3	k8	k9	K7	Total
1	2.12	2.23	1.43	2.60	8.38
2	2.12	2.23	1.43	3.10	8.88
3	1.87	2.23	1.41	1.70	7.21
4	1.87	2.38	1.43	2.50	8.18
5	1.87	2.38	1.43	3.90	9.58
6	2.09	2.74	2.09	2.40	9.32
7	2.09	3.25	2.91	4.10	12.35
8	3.33	4.1	4.06	2.30	13.79
9	3.77	4.44	4.33	2.80	15.34
10	3.99	4.46	0	0.62	9.07
11	3.99	4.46	4.44	0.62	13.51
12	3.64	4.55	0	0.46	8.65
13	3.64	4.55	4.46	0.46	13.11
14	0	3.77	3.93	0.46	8.16
15	4.04	3.86	3.71	2.70	14.31
16	4.22	3.77	3.49	3.10	14.58
17	0	3.66	1.87	2.70	8.23
18	3.25	3.86	3.93	2.50	13.54
19	3.25	4.33	4.35	1.88	13.81
20	3.68	4.26	4.28	2.00	14.22
21	3.68	3.82	3.6	1.60	12.7
22	3.42	3.2	2.78	1.88	11.28
23	2.25	2.56	2.18	2.80	9.79
24	2.2	2.16	1.59	2.83	8.78

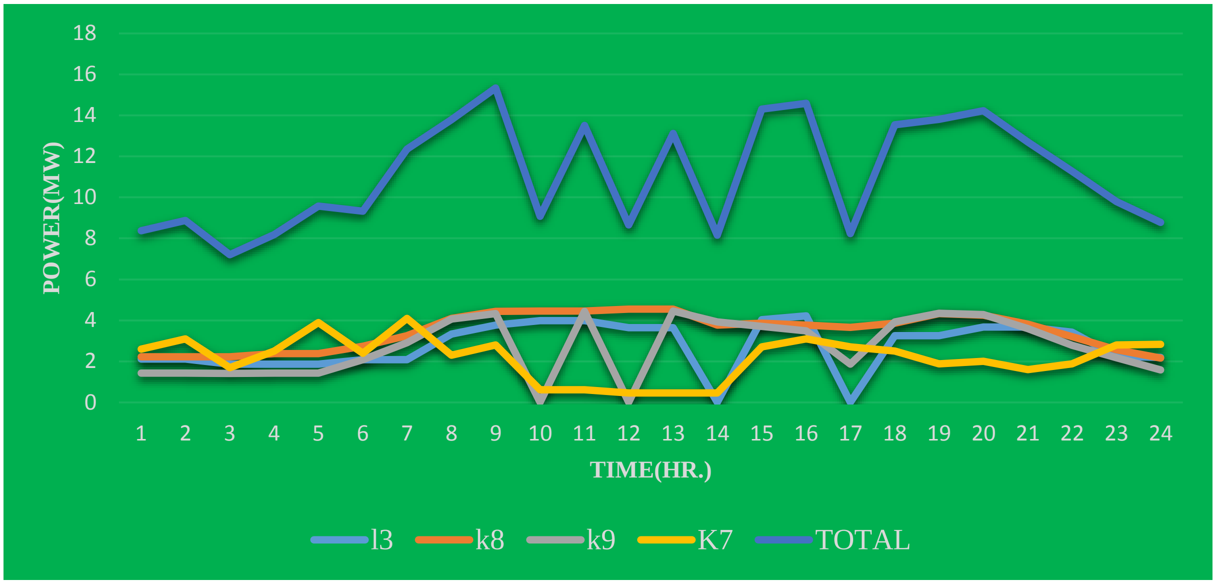

Figure 3.3: Hourly load profile (MW) of Bishoftu substation feeders: - L-3, K-7, K-8 and K-9:

From Figure 3.3 the following observation can also be made:

- ✓ The maximum load of the feeders occurs from 8:00 to 9:00,14:00 to 16:00&18:00 to 21:00
- ✓ The minimum load of the feeders is 8.16MW while the maximum load is 15.34MW.

3.2 Major causes of power interruption at Bishoftu substation II:

The major fault occurring frequently in Bishoftu substation are: short circuit, earth fault & over loading. In addition to this unplanned outage, there is also planned outage for operational and maintenance purpose. The major faults occurring can be of temporary and permanent type. Interruptions which lasts longer than five minutes is categorized under permanent or sustained interruption where as interruptions which lasts with duration of less than five minutes are termed as momentary interruption [44].As usual, only data on sustained interruptions is reported to the regulatory authority. Many of the distribution problems are temporary and mainly caused by tree, animal contact and weather condition. They can easily be solved with little or no intervention from the system. Then by simply reclosing the system will be re-energized. But permanent fault can't be restored simple re-energizing. Permanent fault can be caused by equipment malfunction, cable failure, down line or persistent tree contact [45].

Permanent or sustained interruptions can be classified as planned and unplanned interruption. Planned interruption (operational outage) occurs mainly for the purpose of construction, preventive maintenance or repair [44]. A planned interruption occurs at a selected time less inconvenient for the customers and the customers have been notified beforehand of the interruption. On the other hand, if the occurrence time of the interruption has not been selected, then the interruption is unplanned. Unplanned interruption occurs for example, due to fault clearing, unwanted operation of the protection system or due to inadvertent initiation of opening operation of switching device by human.

3.3 Power interruption data of Bishoftu substation

3.3.1 Interruption data from 2013/14 GC (2006 E.C) to 2015/16 GC (2008 E.C)

There are many different types of power system faults that are frequently occurring at Bishoftu substation. These typically includes; distribution permanent and transient earth fault, distribution permanent and transient short circuit fault, interruption due to operation/maintenance, system over load and power transformer over load. Table 3.8 below shows the duration and frequency of these different types of power system faults such as Distribution Permanent Earth Fault(DPEF), Distribution Permanent Short Circuit Fault(DPSC), Distribution Transient Earth Fault(DTEF), Distribution Transient Short Circuit Fault(DTSC),System Over Load(SOL), Power Transformer Over Load(PTOL) and Operational.

Table 3.8: Interruption duration and frequency of different faults of 2013/14 GC (2006 E.C)

Feeder	Operational		DPEF		DPSC		DTEF		DTSC		SOL/PTOL	
	Freq (Int/yr.)	Dur(Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)
L1	2	1.81	6	9.58	10	21.8	10	0.89	16	0.606	1	0.06
L2	64	24.79	1	0.03	1	0.01	1	0.03	1	0.07	1	0.11
L3	169	82.59	42	79.01	74	129.3	286	15.28	221	8.45	13	6.64
K1	7	23.22	1	0.09	5	56.28	1	0.41	1	0.01	1	0.03
K2	6	23.16	1	0.03	5	56.28	1	0.41	2	0.01	1	0.03
K6	4	60.27	1	0.5	3	12	1	1.1	1	0.08	1	0.23
K7	124	100.8	11	9.64	35	71.11	50	6.93	61	5.65	7	7.16
K8	101	120.7	37	99.4	45	161.3	40	8.76	37	3.76	53	154.9
K9	103	119.2	45	128.7	62	160.7	57	4.77	102	7.46	53	116.8
K12	8	3.77	1	0.26	1	0.01	1	0.01	1	0.03	1	0.06
K13	8	16.5	4	1.1	1	2.21	47	8.66	12	0.56	12	2.99
K14	93	129.7	5	10.25	20	51.62	4	2.13	15	6.99	75	185.4
K15	41	35.25	5	14.47	15	64.72	5	0.55	17	1.15	10	18.34
Total	**728**	**741.8**	**160**	**353.1**	**277**	**787.4**	**504**	**49.93**	**487**	**34.83**	**229**	**492.8**

Table 3.9: Interruption duration and frequency of different faults of 2014/15 GC (2007 E.*C)*

Feeder	Operational		DPEF		DPSC		DTEF		DTSC		SOL/PTOL	
	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)	Freq (Int/yr.)	Dur (Hrs.)
L1	7	20.79	2	0.96	4	20.31	1	0.51	1	0.07	16	48.53
L2	4	8.91	3	491.1	1	0.5	1	0.53	1	0.81	1	1
L3	95	89.69	17	29.48	39	70.04	29	1.52	40	1.39	64	207.01
K1	15	44.65	13	31.46	8	22.58	2	0.13	1	0.63	12	36.57
K2	13	39.63	4	8.99	9	23.15	1	0.06	1	0.07	6	13.7
K6	10	24.3	2	3.55	1	0.31	1	0.78	1	0.11	5	17.29
K7	32	18.25	11	15.47	20	44.03	4	0.16	22	0.85	10	28.14
K8	187	174.1	36	58.72	69	190.2	24	0.95	56	4.12	57	213.77
K9	207	199	50	90.46	72	116.4	51	1.87	82	3.8	54	119.68
K12	1	1.23	1	0.05	1	0.43	1	0.34	1	0.6	1	0.81
K13	9	8.95	8	4.05	4	8.46	7	1.23	5	0.22	6	16.58
K14	72	57.33	8	16.53	55	179.5	5	0.24	28	1.06	28	56.1
K15	110	84.79	3	0.61	22	98.15	3	0.1	21	0.7	23	56.3
Total	**762**	**771.6**	**158**	**747.4**	**305**	**774.1**	**130**	**8.42**	**260**	**14.43**	**267**	**815.48**

Table 3.10: Interruption duration and frequency of different faults of 2015/16 GC (2008 E.C)

Feeder	Operational		DPEF		DPSC		DTEF		DTSC		SOL	
	Freq: (Int/yr.)	Dur: (Hrs.)	Freq: (Int/yr.)	Dur: (Hrs.)	Freq: (Int/yr.)	Dur: (Hrs.)	Freq: (Int/yr.)	Dur: (Hrs.)	Freq: (Int/yr.)	Dur: (Hrs.)	Freq: (Int/yr.)	Dur: (Hrs.)
L1	24	21.04	2	7.64	8	64.23	1	0.08	9	1.22	2	4.7
L2	4	5.32	1	15.66	7	82.42	3	0.23	5	0.94	1	0.05
L3	158	133.5	16	32.76	34	71.71	24	1.37	53	3.57	12	31.81
K1	6	6.72	5	59.29	3	26.01	1	0.08	1	0.41	2	12.31
K2	5	4.52	5	312.1	3	11.37	9	0.7	5	0.55	1	0.03
K6	4	1.92	1	0.05	1	0.61	1	0.31	2	0.19	1	0.01
K7	11	9.55	1	0.9	3	5.67	1	0.01	1	0.05	1	0.14
K8	350	163.5	25	95.37	64	223.5	60	6.34	85	5.58	8	26.41
K9	312	186.1	47	78.34	54	138.2	136	10.77	59	4.94	10	34.83
K12	10	6.76	1	0.05	4	24.19	2	0.08	1	0.51	1	0.08
K13	13	6.48	1	0.08	1	12.33	1	0.31	1	0.27	1	0.09
K14	88	71.48	6	36.33	48	257.9	9	1.21	53	3.87	10	62.2
K15	94	66.4	2	1.93	24	112.5	2	0.06	36	3.26	1	0.5
Total	**1079**	**683.4**	**113**	**640.5**	**254**	**1030.**	**250**	**21.55**	**311**	**25.36**	**51**	**173.2**

Table 3.11: Planned and Unplanned interruption duration (Hr.) of 2006EC, 2007EC and 2008EC

Feeders	2006 E.C			2007 E.C			2008 E.C		
	Planned	Unplanned	Total	Planned	Unplanned	Total	Planned	Unplanned	Total
L1	1.81	32.94	34.75	20.79	70.38	91.17	21.04	77.87	98.91
L2	24.79	0.25	25.04	8.91	493.94	502.8	5.32	98.91	104.2
L3	82.59	238.6	321.3	89.69	309.44	399.1	133.5	141.22	274.7
K1	23.22	56.82	80.04	44.65	91.37	136.0	6.72	98.1	104.8
K2	23.16	56.76	79.92	39.63	45.97	85.6	4.52	324.75	329.3
K6	60.27	13.91	74.18	24.3	22.04	46.34	1.92	1.17	3.09
K7	150.8	157.9	308.7	108.25	188.65	296.9	209.55	106.77	316.3
K8	120.7	428.1	548.8	174.1	467.76	641.9	163.5	357.2	520.7
K9	119.2	418.4	537.6	199	332.21	531.2	186.1	267.08	453.2
K12	3.77	0.37	4.14	1.23	2.23	3.46	6.76	24.91	31.67
K13	16.5	15.52	32.02	8.95	30.54	39.49	6.48	3.08	19.56
K14	129.7	256.3	386.1	57.33	253.43	410.8	71.48	361.51	432.9
K15	35.25	99.23	134.5	84.79	155.86	240.6	66.47	118.25	184.7
Syst.	**741.76**	**1718.3**	**2460.4**	**771.62**	**2363.8**	**3235.**	**683.36**	**1880.8**	**2574**

Table 3.12: Planned and Unplanned interruption frequency (Int/yr.) of 2006EC, 2007EC &2008EC

Feeders	2006 E.C			2007 E.C			2008 E.C		
	Planned	Unplanned	Total	Planned	Unplanned	Total	Planned	Unplanned	Total
L1	2	43	45	7	24	31	24	22	46
L2	64	5	69	4	7	11	4	18	22
L3	169	636	805	95	189	284	158	139	297
K1	7	9	16	15	36	51	6	13	19
K2	6	10	16	13	21	34	5	23	28
K6	4	7	11	10	10	20	4	6	10
K7	124	264	388	132	167	299	101	187	288
K8	101	213	313	187	242	429	350	242	592
K9	103	319	422	207	309	516	312	306	618
K12	8	5	13	1	5	6	10	9	19
K13	8	76	84	9	30	39	13	5	18
K14	93	119	212	72	124	196	88	126	214
K15	41	52	93	110	70	180	94	77	171
System	730	1658	2387	762	1134	1896	1079	993	2072

NB: Planned outage means power outage for operational purpose and unplanned outage include; Distribution Permanent Earth Fault (DPEF), Distribution Permanent Short circuit Fault (DPSC), Distribution Transient Earth Fault (DTEF), Distribution Transient Short circuit Fault (DTSC), System over Load (SOL) or Power Transformer over Load (PTOL). The following Table 3.13 consists of the overall average interruption frequency and duration at the substation and these average data is derived from the above Table 3.11 and Table 3.12. Then the overall evaluation and analysis can be made on the basis of these data.

Table 3.13: Average interruption frequency and duration per year:

Feeders	Frequency of Interruption (int/yr.)			Duration of Interruption (Hrs. /yr.)		
	Planned	Unplanned	Total	Planned	Unplanned	Total
L1	11	29.66	40.66	14.41	60.4	74.81
L2	32	30	62	13.01	197.7	210.7
L3	140.67	321.3	461.9	101.93	229.78	331.7
K1	9.33	19.33	28.66	24.86	82.09	106.9
K2	8	18	26	22.44	142.49	164.9
K6	6	7.66	13.66	28.83	12.37	42.2
K7	119	206	325	156.2	151.16	307.3
K8	212.66	232	444.7	152.76	417.69	570.5
K9	207.33	311.33	518.2	168.1	339.24	507.3
K12	6.33	6.33	12.66	3.92	9.17	13.09
K13	10	37	47	10.64	16.38	27.02
K14	84.33	123	207.3	86.17	290.44	376.6
K15	81.66	66.33	148	62.17	124.45	186.6
Syst.	71.41	108.3	179.7	65.03	159.48	224.5

From the above Table 3.13 average interruption frequency and duration per year, we can conclude that, the feeders K-7, K-8, L-3 and K-9 are the main feeders experiencing longer interruption duration and frequency. Therefore, it is better to locate DG unit at these feeders. The data given above are in hours and the percentage of each of the faults is shown in Table 3.14 and Table 3.15 below.

Table 3. 14: Percentages of causes of the average planned and unplanned interruption duration:

Years	Operational [%Dur(Hr)]	DPEF [%Dur(Hr)]	DPSC [%Dur(Hr)]	DTEF [%Dur(Hr)]	DTSC [%Dur(Hr)]	SOL/PTOL [%Dur(Hr)]
2015GC/2006EC	30	14	32	2	2	20
2016GC/2007EC	24.7	23.93	24.78	0.26	0.46	26
2017GC/2008EC	26.5	24.87	40	0.8	0.98	6.7
Average	27	21	32	1	1	18

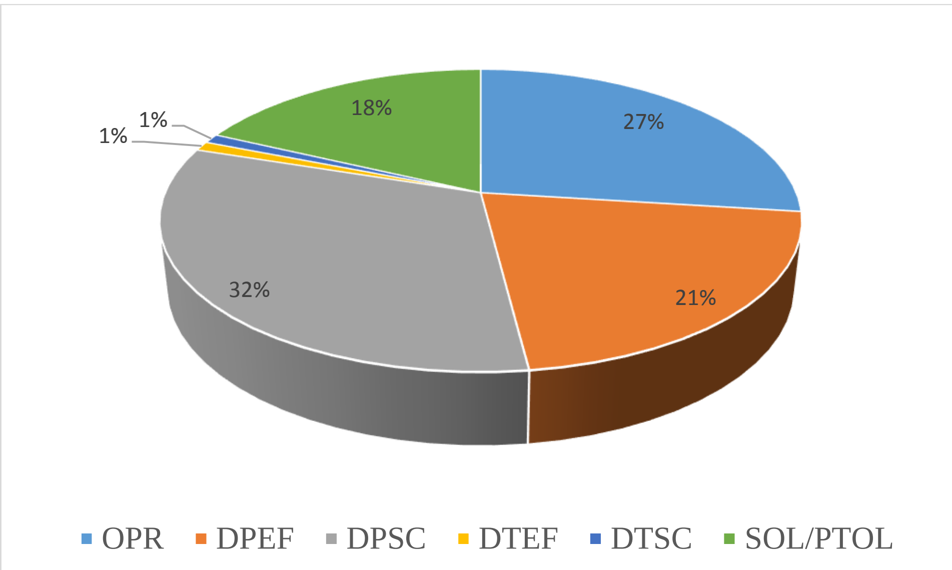

Figure 3.4: Percentage of causes of the average planned and unplanned interruption duration

As can be seen from the pie chart, 32% (Hr.) of the interruption duration is caused due to DPSC (Distribution Permanent Short Circuit), 27% is due to Operational and maintenance, 21% due to DPEF (Distribution Permanent Earth Fault), 18% SOL/PTOL (System/Power Transformer over Loading) and DTEF, DTSC 1% each.

Table 3.15: Percentages of causes of the average planned and unplanned interruption frequency:

Years	Operational	DPEF	DPSC	DTEF	DTSC	SOL/PTOL
	%Freq. (int/yr.)	%Freq. (int/yr.)	%Freq. (int/yr.)	%Freq. (int/yr.)	%Freq (int/yr.)	%Freq. (int/yr.)
2015GC/2006EC	30	7	12	21	20	10
2016GC/2007EC	41	8	16	7	14	14
2017GC/2008EC	52	6	12	12	15	3
Average	41	7	14	13	16	9

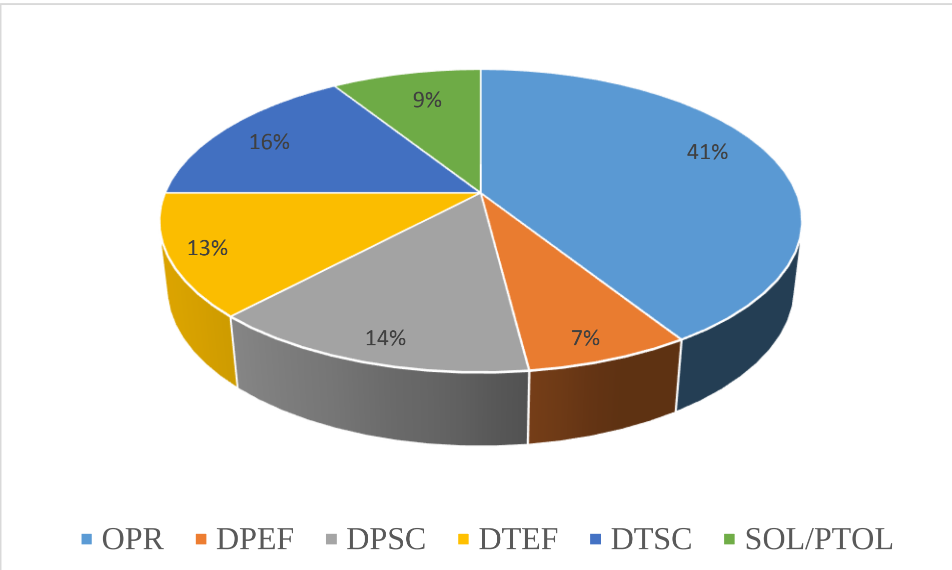

Figure 3.5: Percentage of causes of the average planned and unplanned interruption frequency

Figure 3.5 shows that 41 % of the interruption frequency is due the operational and maintenance, and 16% is due to DTSC, 14% DPSC (permanent short circuit), 13% due to DTEF, 9 % is because of SOL/PTOL and 7% due to DPEF.

3.4 Reliability Indices Calculation

The reliability indices of the existing substation can be calculated using equations (2.7) to (2.18), which are given in chapter two. Based on the data given in Table 3.10 and 3.11, we can calculate some of the reliability indices of 2013/14(2006), 2014/15(2007) and 2015/16(2008) and the average of the three years for the feeders. Therefore, Table 3.16 and 3.17 show the calculated reliability indices for the years 2013/14 (2006 E.C), 2014/15 (2007 E.C), 2015/16(2008).

Table 3.16: Calculated main feeder's failure rate and annual average outage:

Substation feeders	Outage durations (Hrs.)	Interruption frequency (int. /yr.)	Failure rate λi (failures/yr)	Annual average outage U (hrs./yr)
L1	74.8	40.66	0.004641553	0.347188128
L2	210.71	62	0.007077626	1.491326484
L3	331.71	461.97	0.052736301	17.49315853
K1	106.96	28.66	0.003271689	0.349939909
K2	164.93	26	0.002968037	0.489518265
K6	42.2	13.66	0.001559361	0.065805023
K7	307.31	325	0.037100457	11.40134132
K8	570.45	444.66	0.050760274	28.95619829
K9	507.34	518.66	0.059207763	30.03846626
K12	13.09	12.66	0.001445205	0.01891774
K13	27.02	47	0.005365297	0.14497032
K14	376.61	207.33	0.023667808	8.913533253
K15	186.62	148	0.016894977	3.152940639
System	224.596	179.712	0.020515068	4.607602323

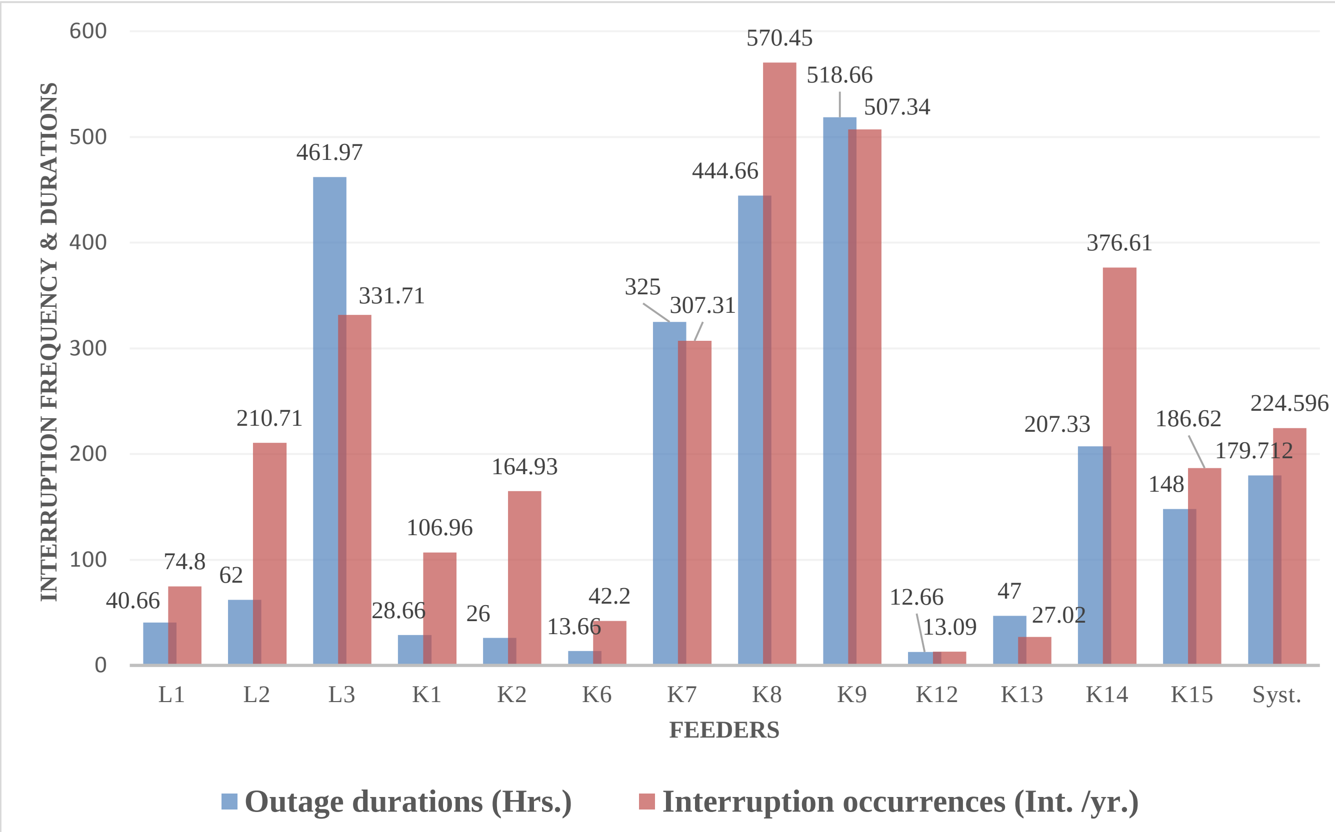

Figure 3.6: Main feeders outage duration and failure occurrence

From the above Figure 3.6 it can be easily understood that the failure occurrence and outage duration is significantly very high at the feeders L3, K7, K8 and K9. Therefore, these calculated values of failure occurrence and outage duration also approved that the same analysis could be made as in the previous case of data analyzed under Table 3.13 above. Hence, DG unit needs to be installed at these feeders which are highly prone to the interruption.

Table 3.17: Calculated load points and system reliability indices

Feeders	SAIFI	SAIDI	CAIDI	ASAI	ASUI	Peak load MW	ENS(MWh)	AENS(kW h/ca.yr)	EIC($/yr)
L1	40.66	74.8	1.8396	99.1461	0.853881	5.04	376.99	376992	201.3137
L2	62	210.71	3.3985	97.5946	2.405365	3.53	743.80	92975.78	397.1925
L3	461.97	331.71	0.7180	96.2133	3.786643	5.31	1761.3	2003.845	940.5769
K1	28.66	106.96	3.7320	98.7789	1.221004	5.41	578.65	578653.6	309.0010
K2	26	164.93	6.3434	98.1172	1.882762	4.09	674.56	674563.7	360.2170
K6	13.66	42.2	3.0893	99.5182	0.481735	4.11	173.44	51.58893	92.61802
K7	325	307.31	0.9455	96.4918	3.508105	5.14	1579.5	225653.3	843.4921
K8	444.66	570.45	1.2828	93.4880	6.511986	4.97	2835.1	33354.54	1513.962
K9	518.66	507.34	0.9781	94.2084	5.791552	5.11	2592.5	504.2807	1384.398
K12	12.66	13.09	1.0339	99.8505	0.149429	3.92	51.312	51312.8	27.40103
K13	47	27.02	0.5748	99.6915	0.308447	5.1	137.80	137802	73.58626
K14	207.33	376.61	1.8164	95.7007	4.299200	4.83	1819.0	1224.933	971.3600
K15	148	186.62	1.2609	97.8696	2.130365	5.81	1084.2	273.3204	578.9960
Syst.	179.712	224.596	1.2497	97.4361	2.56388	62.3	5632.8	175365	2986428

In the above Table 3.17 the cost of energy not supplied due to the interruption of power at Bishoftu city substation is calculated using the following formula:

Cost of Energy Not Supplied=Power * Time * tariff for electricity

From (Appendix A: Table 3A) considering an average electric price of 0.5345 Birr/KWh, the energy not supplied and the cost of the energy not supplied for the substation's outgoing feeders is calculated and listed in Table 3.17 above. On the basis of the calculated reliability indices of Table 3.17 above, it can be also possible to represent the reliability indices for the selected feeders in bar chart scheme for easy understanding and comparison.

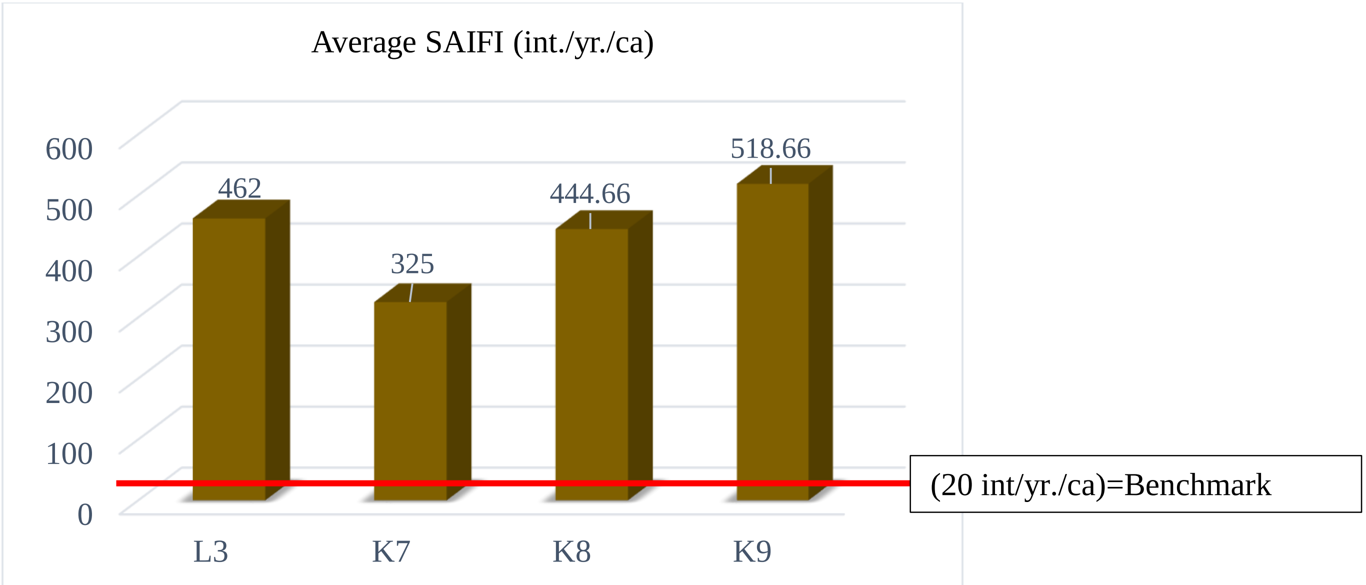

Figure 3.7: Average calculated SAIFI values of the selected feeders

As shown from the bar chart figure 3.7 above, SAIFI values of the feeders L-3, K-7, K-8 and K-9 is 462 int/yr./Ca,325int./yr,444.66 int/yr./Ca and 518.66 int/yr./Ca respectively. But as per the Ethiopian Electric Agency's (EEA) standard, SAIFI should not be exceeds 20 interruption per year per customer. Since the current calculated value of SAIFI is above the acceptable benchmark by large margin, there is a serious reliability problems in the current Bishoftu distribution substation.

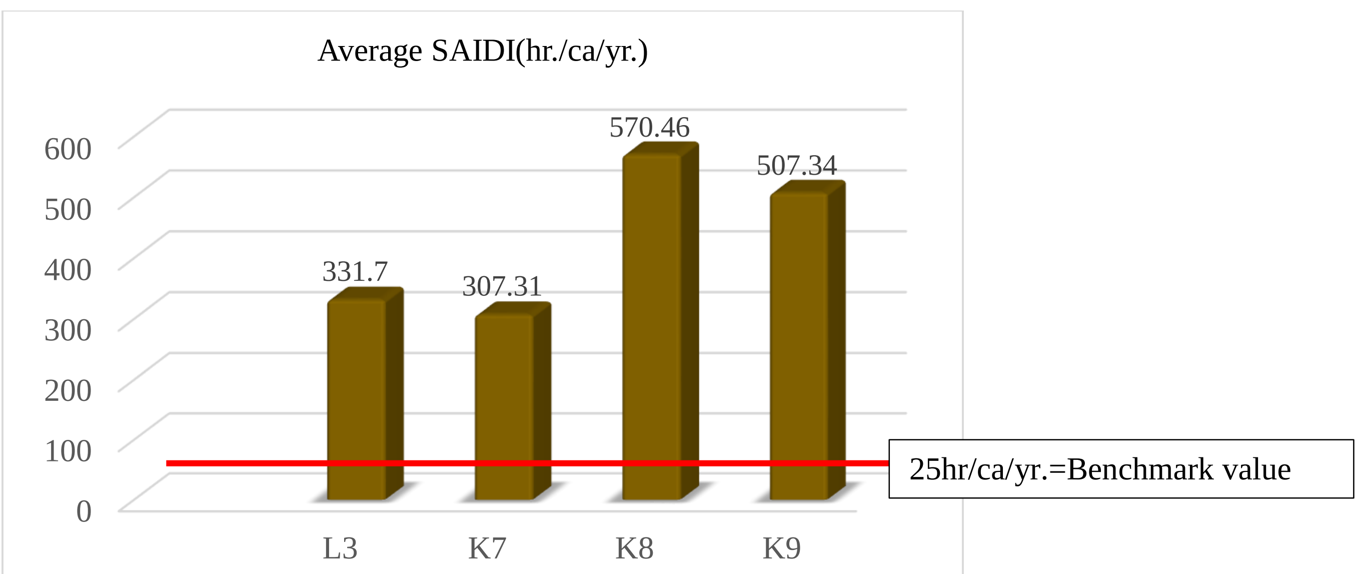

Figure 3.8: Average calculated SAIDI values of the selected feeders

From Figure 3.8, we can also see that, the SAIDI values of the feeders L-3, K-7, K-8 and K-9 are 333.1hrs./yr./Ca,307.31hrs./yr./Ca,570 hrs./yr./Ca and 507 hrs./yr./Ca respectively. This clearly shows that every customer at the indicated feeders (i.e. L-3, K-7, K-8 and k-9) experiences 331.7,307, 570.46 & 507.34 hours per year respectively. But as per the Ethiopian Electric Agency's (EEA) standard, SAIDI should not exceeds 25 hours per year per customer [46]. Since the current calculated value of SAIDI is above the acceptable benchmark by large margin, there is a serious reliability problems in the current Bishoftu distribution substation.

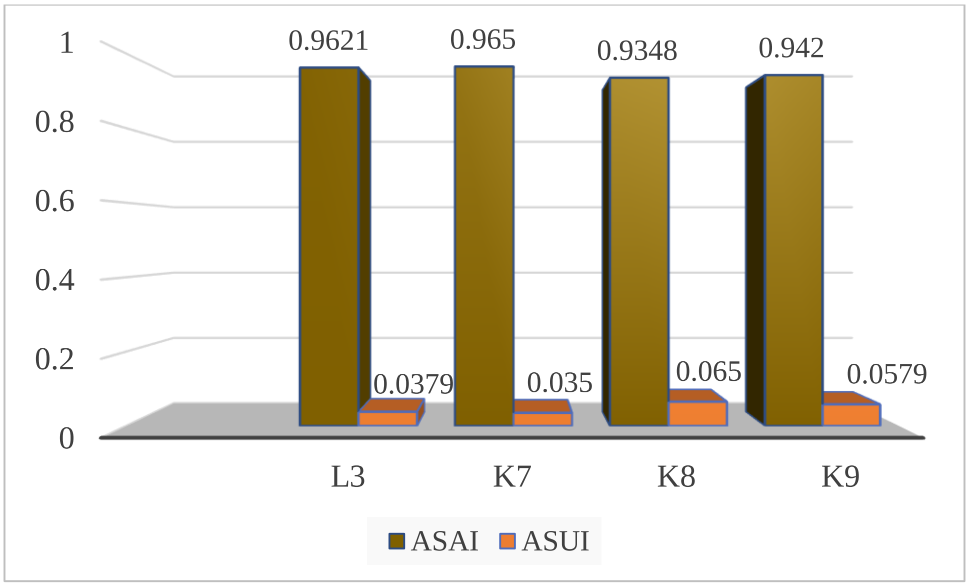

Figure 3.9: Average calculated ASAI and ASUI values of the selected feeders

As shown in Figure 3.9 above, the power supply availability of the feeders (L-3, K-7, K-8 and K-9) is 96.21%, 96.5%, 93.48% & 94.2% respectively. However, as per EEA's standard the ASAI value should be greater than 99.98% [46] .Therefore, the ASAI values of the feeders is not still good enough which indicates that the substation has poorly reliable.

From Table 3.17 above, we can put the overall values of the average calculated reliability indices in the form of bar chart in order to have a clear conclusion on the calculated values.

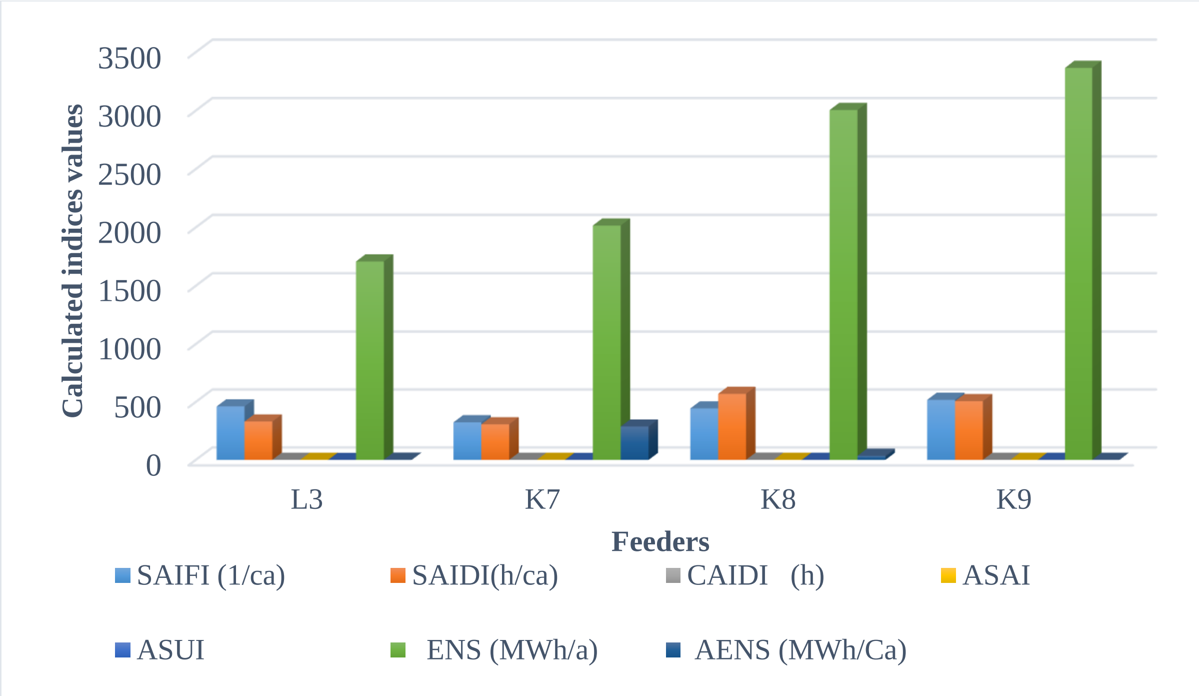

Figure 3.10: Overall Average Calculated Values of Reliability Indices of the Selected Feeders

Table 3.18: The Overall Calculated System Indices

Indices	Units	Value
SAIFI	Int./ca/yr.	179.71
SAIDI	Hrs./ca/yr.	224.59
CAIDI	Hrs./customers interruptions	1.249
ASAI	%	97.436
ASUI	%	2.564
EENS	MWh/yr	5632.8
EIC	m$/yr	2.986
AENS	MWh/ca.yr	2.175

From Table 3.18 above, it can be concluded that the calculated base case system reliability indices are SAIFI 179.71int./ca/yr which means that system average interruption frequency index for each customer is 179.71 int./ca/yr during the period of study, SAIDI is 224.59Hrs. /ca/yr. system average interruption duration under the study period and CAIDI is 1.249hrs./customers interruptions, suggesting that systems average interruptions duration for the customers that experience interruption is 1.249 hrs during the indicated time periods. The systems availability and unavailability index are 97.436% and 2.564% respectively.

3.4.1 Comparison of the calculated reliability indices with the benchmarks set by Ethiopian Electric Agency and standards of different country:

The calculated reliability indices should be compared with the benchmark values of that network (in this case the calculated results of reliability indices) is compared with the benchmark value set by the Ethiopian Electric Agency to identify if the part of the network (Bishoftu distribution substation II) is reliable or not. These calculated reliability indices should also be compared with standards of different countries. The following Table 3.19 shows the comparison of the most commonly used reliability indices (i.e. SAIFI, SAIDI and CAIDI) with different standards and benchmarks of the networks.

Table 3.19: Comparison of the calculated reliability indices with different standards

Country		SAIFI(int/yr./Ca)	SAIDI (hr./yr./Ca)	CAIDI (hr./yr./Ca)
United Kingdom		0.8	1.1	2.3
Canada		3.4	6.9	0
USA		1.5	2.3	1.4
Germany		0.5	0.383	0
Netherland		0.3	0.55	0
Ethiopia		20	25	5
Bishoftu Distribution Substation	K1	28.66	106.96	3.73
	K2	26	164.93	6.34
	K6	13.66	42.2	3.08
	K7	325	307.31	0.962
	K8	444.66	570.46	1.22
	K9	518.66	507.34	1.012
	K12	12.66	13.09	1.03
	K13	47	27.02	0.57
	K14	207.33	376.61	1.82
	K15	148	186.62	1.26
	L1	40.66	74.8	1.84
	L2	62	210.71	3.39
	L3	462	331.7	0.91
	System	179.71	224.52	1.23

3.4.2 Summary of the analysis of the reliability of Bishoftu city substation

1. As shown in Table 3.17 above, SAIFI values of the feeders L-3, K-7, K-8 and K-9 is 462 int/yr./Ca, 325 int./yr, 444.66 int/yr./Ca and 518.66 int/yr./Ca respectively. But as per the Ethiopian Electric Agency's (EEA) standard, SAIFI should not exceeds 20 interruption per year per customer. Since the current calculated value of SAIFI is above the acceptable national and international benchmark by large margin, there is a serious reliability problems in the current Bishoftu distribution substation.

2. From Table 3.17 above, we can also see that, the SAIDI values of the feeders L-3, K-7, K-8 and K-9 is 333.1hrs./yr./Ca, 307.31hrs./yr./Ca, 570 hrs./yr./Ca and 507 hrs./yr./Ca respectively. This clearly shows that every customer at the indicated feeders (i.e. L-3, K-7, K-8 and k-9) experiences 331.7, 307, 570.46 & 507.34 hours per year respectively. But as per the Ethiopian Electric Agency's (EEA) standard, SAIDI should not exceeds 25 hours per year per customer [46]. Since the current calculated value of SAIDI is above the acceptable national and international benchmark by large margin, there is a serious reliability problems in the current Bishoftu distribution substation.

3. Average Service Availability Index, this represents the fraction of time that a customer is connected during the defined calculation period or the index that represents the fraction of time (often in percentage) that a customer has power provided during one year or the defined reporting period. As shown in Table 3.17 above, the power supply availability of the feeders (L-3, K-7, K-8 and K-9) is 96.21%, 96.5%, 93.48% and 94.2% respectively. However, as per EEA's standard the ASAI value should be greater than 99.98% [46].Therefore, the ASAI values of the feeders is not still good enough which indicates that the substation has poorly reliable.

4. ENS: These is the energy not supplied in (MWh/a), unserved or the unsold energy at the feeders. From Table 3.17 above, it is shown that the unsold energy at the feeders (L-3, K-7, K-8 and K-9) is 1761.3, 1579.5, 2835.1 and 2592.5 MWh/a respectively.

5. Average Energy Not Supplied, in units of [MWh/Ca], is the average amount of energy not supplied, for all customers or the index that represents the average energy not supplied by the

system. From Table 3.17 above, it is also shown that the average energy not supplied at the feeders (L-3, K-7, K-8 and K-9) is 2.0038, 225.65, 33.351 and 0.504 MWh/Ca respectively.

Based on the above observations and data analysis the following general conclusion can be drawn:

- ✓ The reliability of Bishoftu city substation does not meet the requirements set by the regulatory body, which means the Ethiopia Electric Agency (EEA).
- ✓ The reliability of Bishoftu city substation is very poor as compared to the international reliability indices of other countries.
- ✓ There is also high service unavailability in the network.
- ✓ Due to both planned and unplanned power outage at the substation, there is also much amount of energy not supplied from the system feeders to the customer.

CHAPTER FOUR

MODELLING OF DISTRIBUTED GENERATION

As it was discussed in chapter three of this thesis Bishoftu substation has the problems of overloading (about 18%) because of the rapidly increasing urban populations and the industrial customers power demand which leads to poor reliability. In order to solve this problems of the distribution system and meet consumers demand with great capacity and reliability, it is necessary to upgrade the substation by designing the existing distribution substation with proper size, location and rating of Distributed Generation (DG). Therefore, this section gives the important mathematical modelling and decisions for selecting the appropriate renewable resources (DG) for upgrading the substation to improve the performance of the distribution system in terms of reliability.

4.1 Estimation of Future Load

Currently there are two official load forecasts used by EEP, namely the moderate, which presumes an annual average growth of 14% and the ambitious target of 17% [47]. In order to be more realistic, the World Bank's annual average growth rate of 6% of a power demand forecast have been used to estimate the capacity of the distribution substation. This estimated power demand forecast is tabulated as follows.

Table4.1: The power demand forecasted at Bishoftu city after 8 years.

Year	Forecasted Demand in (MW)	Forecasted Demand in (MVA)
2019	91.28	93.28
2020	96.75	98.87
2021	102.55	104.80
2022	108.70	111.08
2023	115.22	117.74
2024	122.11	124.80
2025	129.43	132.28
2026	137.19	140.21

From Table 4.1, it is estimated that the power demand at the substation will be approximately 137.19 MW of active power and 140.21 MVA by considering a power factor of 0.85. Therefore the power demand after 8 years will be approximately 138 MW.

4.2 Modelling DG Power Generation

DG models can be used so that the power of each DG can be computed. So for this analysis, data will be used and deterministic values of the DG outputs will be computed. Since special emphasis is given to PV and wind, the DG modeled as general one.

4.2.1 Modelling Photovoltaic Power Generation

The intermittent elements in case of solar power are two instead of one, ambient temperature and solar irradiance. To calculate the power output of the PV module, P_{pv} eq. (4.1) is used [48].

$$P_{pv=P_{STC}}\frac{I_S}{1000}\left(1+\gamma(T_c-25)\right) \qquad 4.1$$

Where: $P_{STC:}$ Photovoltaic module maximum power at Standard Test Condition (STC) (W)

I_S: Solar Irradiance on the photovoltaic module surface (W/m^2)

γ: Photovoltaic module temperature coefficient for power (℃$^{-1}$)

T_C: Photovoltaic cell (module) temperature (℃)

The photovoltaic module temperature (T_C) can be calculated as a function of solar irradiance and ambient temperature based on the module's nominal operating cell temperature (NOCT) which is given as the following equation.

$$T_c = T_\alpha + \frac{I_S}{800}(T_{NOCT} - 20) \qquad 4.2$$

Where: T_α: Ambient temperature in (℃)

T_{NOCT}:Nominal operating cell temperature in (℃) of the module.

4.2.2 Modelling Wind Turbine Power Generation

The intermittent element of wind energy is wind speed. In case wind speed is known in a specific location, wind power for a specific turbine with a concrete power model can be evaluated [49]. The power curve of a wind turbine can be modelled by means of a function split into four different parts as following equation:

$$P_{wt} = \begin{cases} 0, & v \le v_{ci} \\ \dfrac{v^2 - v_{ci}^2}{v_{nom}^2 - v_{ci}^2} P_{nom} & v_{ci \le v \le v_{nom}} \\ P_{nom,} & v_{nom \le v \le v_{co}} \\ 0, & v_{nom \le v} \end{cases} \qquad 4.3$$

Where: P_{nom}, v_{nom}, v_{ci}, v_{co} are nominal power, nominal wind speed, cut-in wind speed and cut-out wind speed of the wind turbine, respectively. P_{wt} and v are denoted power output of the wind turbine and wind speed. All the above mentioned parameters are turbine specific and can be found in the datasheets of each turbine.

4.3 Hosting Capacity of Distributed Generation (Size of DG)

Hosting Capacity (HC) is defined as the maximum level of DG penetration that a certain grid topology can withstand without exceeding one or more operational limits which can also be called as performance indices. This definition is clearly shown by Figure 4.1 below:

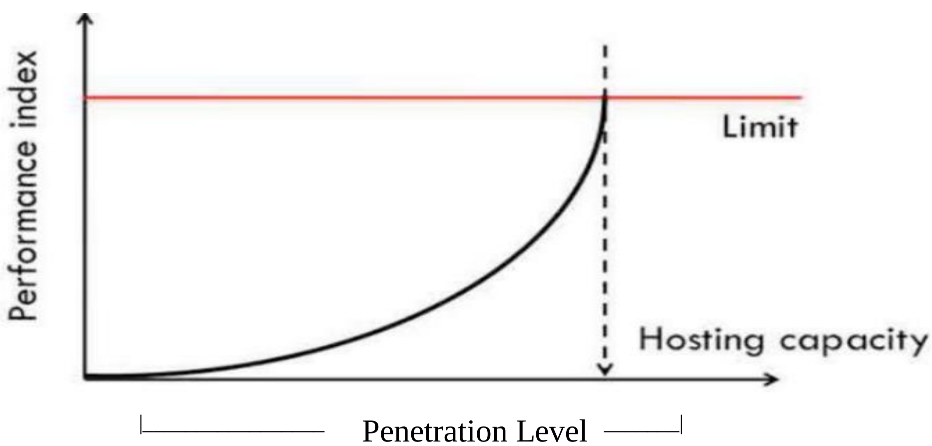

Figure 4.1: Definition of Hosting Capacity [50].

There are many performance indexes that must be considered when connecting a distributed energy resource to the distribution system in order to define the hosting capacity such as [51].

1. Steady-state voltage rise
2. Thermal line ratings
3. Transformer power ratings
4. Reverse power flow of the tap-changers
5. Power quality (flicker, harmonics)

6. Protection issues (short circuits)

In this thesis, only the first 3 out of the above mentioned indexes will be taken into account since those are the dominant factors that generally restrict the total hosting capacity. Performance indexes 4, 6 can easily be incorporated in the framework that will be created while performance index 5 is referring to the transient state and consists a new field that currently starting to be understood at the greatest extent. At the same time, special emphasis will be given in performance index 1, the steady-state voltage rise since this is currently the major issue when connecting distributed generation to a low or medium voltage distribution grid.

4.4 Technical constraints

As already referred, the steady state voltage rise performance index is the main index that restricts the hosting capacity limit per DG. As a result, in this part it will be explained more clearly the causes of this voltage rise after a DG installation over a certain infeed.

In order to understand the roots of the steady state voltage rise, a simplified diagram will be used in figure 4.2 that entails two nodes and DG. We will define U_n as the nominal voltage at the slack bus, Z as the line impedance, consisting of the series resistance R and the series reactance X.

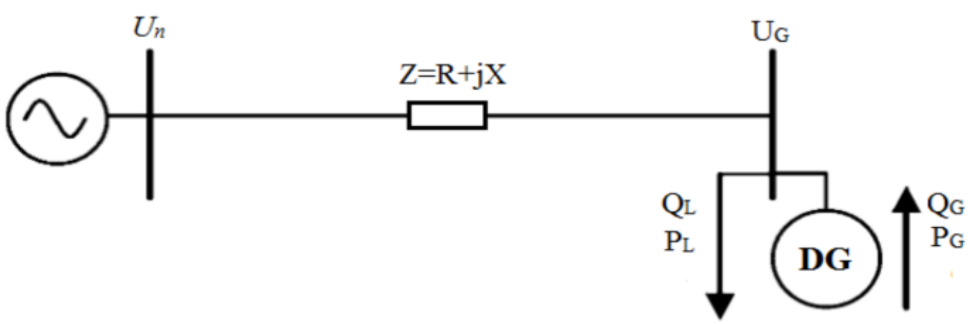

Figure 4.2: Simplified 2-Node system with Distributed Generation

From this simplified system, DG is installed in bus infeed G so we are interested in voltage rise that happens after DG penetration. We can define this voltage rise ΔU formally as in Equation (4.4):

$$\Delta U = U_G - U_n \qquad 4.4$$

In addition, we define P_G as the active power injection from the DG source, while Q_G is correspondingly the reactive power injection from the DG source which can be both positive and negative depending on if the DG source produces or consumer's reactive power. Finally, P_L is defined as the load active power demand and Q_L as the reactive load demand, which are both assumed as positive quantities. Now we can define the total amount of power injected in the system through the load bus, S as:

$$S = (P_G - P_L) + i * (Q_G - Q_L) \qquad 4.5$$

Based on Kirchhoff's Law between the two buses Equation (4.6) can be derived as:

$$\Delta U = I * Z \qquad 4.6$$

Where I is the current that flows in the branch between the two buses and is also equal to:

$$I = \left(\frac{S}{|\,Un|}\right) * = \frac{P - jQ}{|\,Un|} \qquad 4.7$$

By combining (4.6) and (4.7) we take that:

$$\Delta U = \frac{PR + QX}{|\,Un|} + \frac{j(PX - QR)}{|\,Un|} \qquad 4.8$$

In (4.5), the first part on the right side describes the direct axis component of the voltage rise, ΔU_d, while the second part refers to the quadratic axis component of the voltage rise, ΔU_q. In most of the distribution grids, the quadratic part is neglected [52] so finally the voltage change due to DG penetration is equal to:

$$\Delta U \approxeq \frac{PR + QX}{|\,Un|} \qquad 4.9$$

Now finally the proportional relation of active power DG injection P with delta voltage rise, ΔU can be clearly seen. On the other side, an inverse proportional relationship exists between delta voltage rise and active power load demand. Another also important conclusion from (4.9) is that in case DG source consumes reactive power (inductive or under-excited mode) it is able to compensate the increase of the delta voltage rise. The XQ term may be positive or negative, depending on whether the generator is exporting or importing reactive power. However, as the magnitude of the reactive power will be small compared to that of the power (unless some form of compensation is used), the R*P + X*Q term will tend to be positive. Thus, the voltage at the point of connection of the DG to will rise above that of the slack bus. Finally, parameters such R and X can be changed in order to alleviate the voltage rise problem however this will probably lead to grid reinforcements which practically means increase in costs for the DSO(Distribution System Operator).

4.4.1 Steady state voltage variation

If DG is connected to a network unit, it will change the active and reactive power flows and therefore change the voltage dropped across the lines. It has been shown that DG leads to a significant voltage rise at the end of the long, high impedance lines [53]. A rise in voltage occurs if there is low demand and high generation, which leads to a large amount of power flow along lightly loaded lines with high impedance. It is specified that voltages should remain in ±10% of the rated voltage during 95% of the time per year in order to avoid stability issues and malfunctions of the grid. In order to achieve this, DSO's during the planning stage use the static voltage rise criteria based on which:

$$\Delta V \leq \epsilon_{max} \qquad 4.10$$

Where ϵ_{max} is 2% for a MV grid or 3% for a LV grid and ΔV is the voltage difference per bus of the voltage after the DG source penetration minus the voltage of the same bus during the initial case scenario with the low demand case scenario. From the circuit shown below the voltage at the generator is given by Equation (4.11).

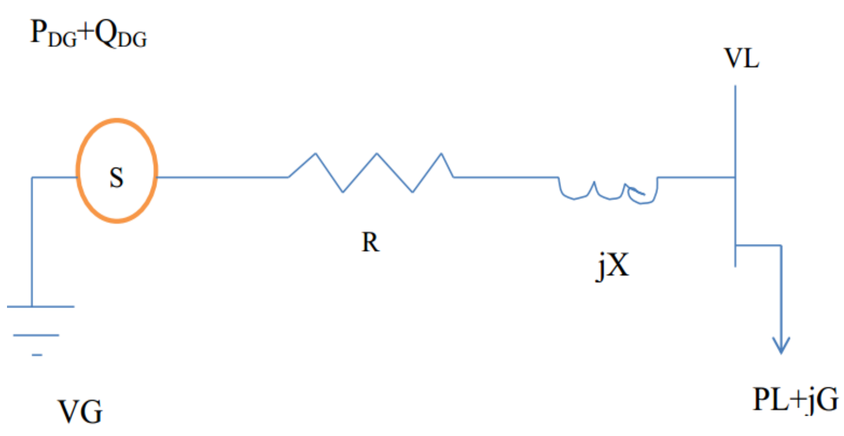

Figure 4.3: Voltage rise effect

$$V_G = V_L + \frac{RP_L + XQ_L}{V_L} + \frac{j(XP_L - RQ_L)}{V_L} \qquad 4.11$$

Where Z=R+jX is the impedance of the line, P_L and Q_L are active and reactive power at the bus and V_G and V_L are the voltages at the generator and bus respectively. Thus it can be seen that the generator voltage will be the load/bus voltage plus some value related to the impedance of the line and the power flows along that line. It is evident that the larger the impedance and power flow the larger the voltage rise. The increased active power flows on the distribution network have a large impact on the voltage level because the resistive elements of the lines on distribution networks are higher than other lines. The voltage must be kept within standard limits at each bus as given by Equation (4.12).

$$V_{min}i < V_i < V_{max}i, \qquad \forall i \epsilon N \qquad 4.12$$

Where $V_{min}i$ and $V_{max}i$ refer to the minimum and maximum voltage limits at the i^{th} bus. The relationship between voltage and power injections at each bus is determined. As megawatts are added at each bus the voltage rises. Increasing levels of generation are added incrementally at each bus in turn and load flow analysis is carried out to determine a voltage vs active power characteristic for each bus. Next the interdependence of the bus voltage levels is examined. Once again increasing levels of generation are added incrementally at each bus, but now the voltage level at every other bus is examined. Thus characteristics are determined for voltage levels at each bus due to generation at all other buses. By combination of these characteristics the voltage constraint may be formalized into algebraic equations for each bus as shown in Equation (4.13).

$$\sum_{j=1}^{N} \mu_{ij} P_{DG,j} + \beta_i \leq V_{max}\ j, i \forall \epsilon N \qquad 4.13$$

Where: $\boldsymbol{\mu}_{ij}$ *is* the dependency of the voltage level at bus *j* on power injections at bus *i*, i.e. the slope of the voltage vs. power injection characteristic of the i^{th} bus.

β_i= the initial voltage level at the i^{th} bus with no generation,

$\boldsymbol{\mu}_{ji}$= the dependency of the voltage level at bus *i* on power injections at bus j.

4.4.2 Thermal line limit

Regarding the lines in a distribution grid, correspondingly with the transformers, several maximum values per current exist that should not be exceeded in order to avoid damage of several components in the grid or short circuits faults. For this constraint there are several representations referring to either the currents across the lines or the apparent power limits. In this formulation the apparent power representation is adopted and as a results the constraint can be expressed formally as in the Equation (4.14, 4.15, 4.16, and 4.17).

$$S_{max} = \sqrt{3} * I_{max} * V_n \qquad 4.14$$

Appropriate inequality constraints are constructed from each line ij, where i is the starting bus and j the ending bus. As a result, we take the following inequality constraint for the apparent power per line:

$$S_{ij} \leq S_{ij,max} \qquad 4.15$$

Where S_{ij} equals to:

$$S_{ij} = \sqrt{\left(\left(P_{ij}^2\right) + \left(Q_{ij}^2\right)\right)} \leq S_{ij,max} \qquad 4.16$$

Where: S_{ij}= the line apparent power from starting bus i to ending bus j

P_{ij}= the line real power from starting bus i to ending bus j

Q_{ij}= the line reactive power from starting bus i to ending bus j

S_{ij}, *max*= the maximum line apparent power rating from starting bus i to ending bus j

The active and reactive powers per line ij can be computed as in Equation (4.17) and (4.18).

$$P_{ij} = |\ V_i^2|\ G_{ij} - V_i V_j G_{ij}\ Cos\left(\beta_i - \beta_j\right) - V_i V_j B_{ij}\ Sin\left(\beta_i - \beta_j\right) \qquad 4.17$$

$$Q_{ij} = -|\ V_i^2|\ B_{ij} - V_i V_j G_{ij}\ Sin\left(\beta_i - \beta_j\right) + V_i V_j B_{ij}\ Cos\left(\beta_i - \beta_j\right) \qquad 4.18$$

Where: G_{ij}, B_{ij} are the conductance and the susceptance per line ij derived from the admittance matrix Y_{ij} which is topology specific. In addition V_i and β_i refers to the state variable of the optimization problem which are the voltages and angles of bus i.

Simply, the rated current of the lines could not be exceeded. It is given by Equation (4.19)

$$I_i \leq I_{i,rated} \quad for\ \forall i \epsilon N \qquad 4.19$$

Where I_i is the current flowing from generator *i* to bus *i* and $I_{i,rated}$ is the maximum rated current for the line between each generator and its corresponding bus.

4.4.3 Transformer power ratings

Correspondingly to line thermal limits, each transformer has its own power ratings which should not be exceeded since the remaining life of transformer is dependent on the power capability. In order not to deteriorate the remaining life of the transformers, the apparent of the transmission transformer must be less or equal to the maximum apparent power limit based on the nominal values and this constraint can be expressed formally as in Equation (4.20).

$$S_{tran=}\sqrt{P_{tran}^2 + Q_{tran}^2} \leq S_{tran,max} \qquad 4.20$$

Where P_{tran}, Q_{tran} are the active and reactive power of the transformer.
The extent of generation connected minus the lowest load must not exceed the transformer rating at the higher voltage. If there is some existing generation then this must be subtracted from the total.

4.4.4 Power balance limits

For each bus, active and reactive power balance equations must hold which are actually the same equations derived from a typical power flow analysis, including the DG penetrations. These equality constraints for each bus *i* can be expressed formally in the Equation:

$$P_{sl} + P_{DG,i} - P_{load,i} = V_i \sum_{j=0}^{N} V_j\left[G_{ij}\ Cos\left(\beta_i - \beta_j\right) + B_{ij}\ Sin\left(\beta_i - \beta_j\right)\right] \qquad 4.21$$

$$Q_{sl} + Q_{DG,i} - Q_{load,i} = V_i \sum_{j=0}^{N} V_j[G_{ij}\ Sin\left(\beta_i - \beta_j\right) - B_{ij}\ \mathrm{Cos}\left(\beta_i - \beta_j\right)] \qquad 4.22$$

Where: $Q_{DG,\,i}$= tan ($\cos^{-1}$(Pf))

Variables P_{sl} & Q_{sl} exists only in the two equations that refer to the slack bus and are real numbers either positive or negative. For our case, since the objective function is the maximization of DG penetration it is anticipated that P will be negative which actually means export of the extra DG active power to the upper part of the grid topology.

4.4.5 Slack bus limits

For reference reasons which exist in optimal power flow analysis, the voltage magnitude must be set equal to a value, depending on the DSO this ranges from 1pu to 1:3 Pu. Here, the typical case of 1 will be considered so this can be expressed as:

$$V_{slack} = 1 \qquad 4.23$$

4.4.6 Short circuit level constraint

One characteristics of distribution networks is its design short-circuit capacity, i.e. a maximum fault current never to be exceeded, related to the rating of switchgear and the thermal and mechanical endurance of all equipment and standardized constructions [54]. Therefore, the basic requirement for permitting the interconnection of DG is to insure that the resulting SCL remains below the network design value (SCL_{rated}). The SCL is highest at the medium voltage busbars of the infeeding substation, (SCL_{max}). The following relation gives the constraint.

The size of the transient voltage drop experienced at the buses in a network is a sign of strength of the system. In this way the SCL is a measure of the strength or robustness of a system [53]. The SCL of a system denotes to the current that results when there is a fault on the system. A maximum short circuit rating for all equipment is laid down in IEEE distribution codes. A short circuit constraint should not be exceeded as the level of installed capacity increases. These constraint is given by:

$$SCL_{tx} < SCL_{rated} \qquad 4.24$$

Or

$$SCL_{max} < SCL_{rated} \qquad 4.26'$$

Where: SCL_{tx}= the short circuit level at the transmission substation busbar

SCL_{rated}= the highest current that switchgear can safely break under fault conditions.

Therefore, The SCL contributions of generation at each bus are combined and formalized into an algebraic equation as shown below:

$$\sum_{j=1}^{n}(\beta_j T_x P_{DGi} + \alpha Tx \leq SCL_{rated}) \qquad 4.27$$

Where βjTx is the dependency of the SCL at the transmission station to power injections at bus j, i.e. the slope of the SCL vs. power injection characteristic of the j^{th} bus.

P_{DGj}= the power injection at the jth bus

αTx= the initial SCL at the transmission bus with no generation present.

4.5 Hosting capacity evaluation

In order to find the hosting capacity, an algorithm should be created that gives as output the maximum value for DG so that the desired technical constraints are not exceeded. As already mentioned, the performance indexes that will be used are steady state voltage rise, thermal line limits and transformer power capability. The two basic components that are going to be used for evaluating the hosting capacity limit per in-feed are:

- ✓ Power Flow Analysis
- ✓ Iterative loop

At first, the idea has been to calculate the hosting capacity per infeed by gradually increasing the amount of penetration in small incremental steps until one of the performance indexes are violated. A power flow analysis will be performed after each increment in DG penetration. The voltages, currents and power will be compared to the maximum allowed value after each power-flow calculation, in order to check whether the grid still has capacity for more penetration. It should be stressed that for each step, the comparisons of the new state voltages should be made with the initial state (and not the previous lower DG state) of the grid topology without any DG penetration. If none of the maximum values was reached, penetration will increase and all the calculations will be repeated. This will continue until one of the maximum values has been exceeded. Then, the total amount of penetration at that particular step will be considered the hosting capacity of the in-feed. After the Hosting Capacity in one certain in-feed is calculated, the next bus is investigated and the study ends when all of the distribution grid's buses are checked.

There are two ways of simulating the DG source in the distribution grid [55],

- ✓ PQ flow representation (reverse load-ability)
- ✓ PV flow representation

In case there a control circuit exists in order to connect DG to the grid, then a general rule is that when the control circuit is designed to control active & reactive power flow independently, the DG unit model shall be modelled as a PQ node while then the control circuit controls active power & voltage independently then the DG model shall be modelled as a PV node [57]. The most common is the first which will also be used in this thesis since we investigate the voltage increase that is arising through the connection of the DG source, which is not possible if we take into account the second evaluation that assumes constant voltage in the connection point [56]. DG power factor is assumed equal to 1, which prevents generators from importing or exporting any reactive power. A simplified flow chart of this algorithm can be represented in Figure 4.3.

After the DG incremental DG Penetration and the power flow analysis, the technical constraints are-evaluated.

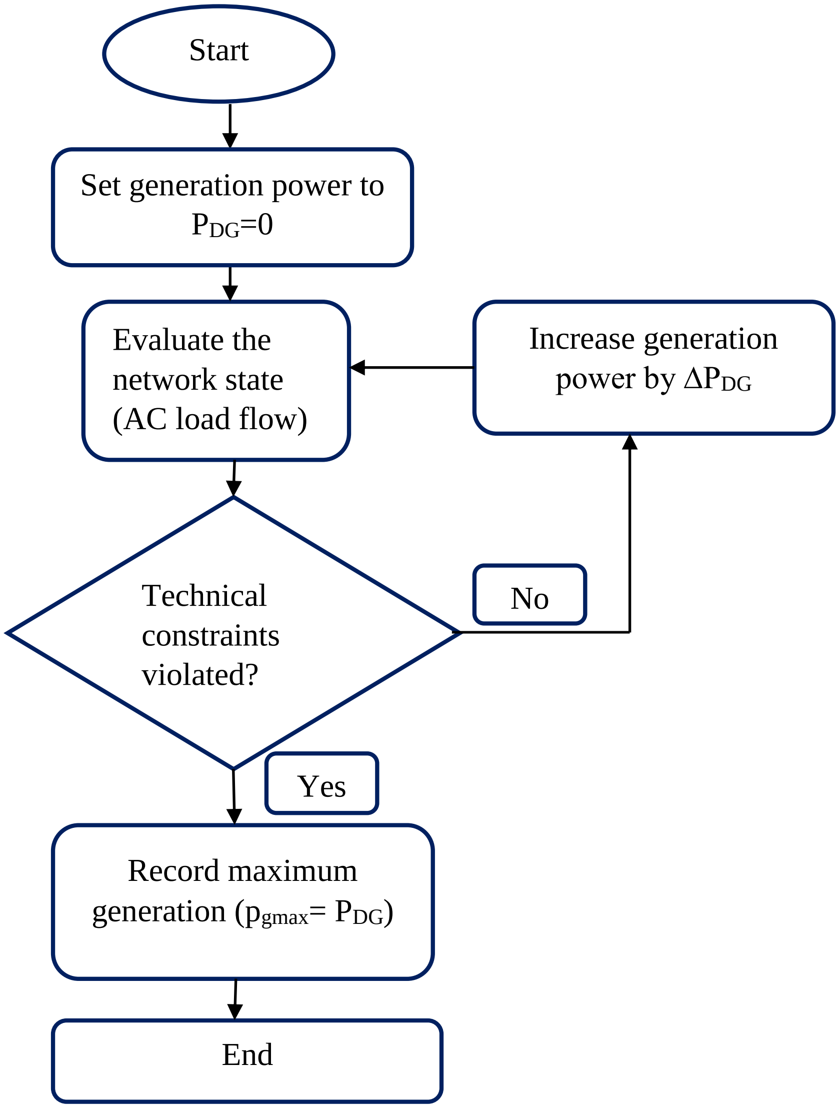

Figure 4.4: Algorithm for evaluation of HC in each infeed in a distribution network.

4.6 Optimal allocation of distributed generation

4.6.1 Theoretical analysis

The prime objective of optimal placement of DG can be classified into single objective function (or multi objective function if combined) which most commonly are as follows [58]:

- Minimize the total power/energy losses and so does its cost
- Improve the voltage profile in a distribution system

- Maximize the total DG capacity per grid
- Minimize investment, operational and maintenance costs of DG

Regarding to the design variables of Distributed generation in the optimization problem they can be summed as follows:

- Size of DG
- Location of DG
- Type of DG
- Number of DG units

From optimization perspective, DG allocation problem is both non-linear and highly constrained and depending on its formulation can also be multiobjective and mixed -integer, wherein finding near global solutions is very difficult [59]. The approaches that have been applied to DG allocation problem can be categorized as below:

Sensitivity analysis method-These approaches are used to find the appropriate location of DG units. Based on a sensitivity index, they try to find the location (s) that is (are) the most sensitive [60].Although, these approaches offer low computational time, the degree of optimality of achieved solutions is unknown and they can only compute optimal location of DG units.

Classical Mathematical Methods-The most used methods for network planning problem include linear programming (LP) [61], dynamic programming (DP), non-linear programming (NLP), mixed integer programming (MIP) and mixed integer non-linear programming (MNLP) [62].In general, the mathematical programming methods have a drawback that the final solution is affected by the initial one due to the use of approximation.

Heuristic Methods- Are used to describe all those techniques that go step by step generating, evaluating and selecting alternatives with or without the users help [63]. Basic heuristic methods include genetic algorithms (GA), expert systems and particle swarm optimization (PSO) [64] . The main drawback of heuristic approaches is that there is no guarantee that an optimum solution can be found.

4.7 Mathematical formulation

4.7.1 Objective function

The objective is to maximize generation capacity subject to the constraints outlined in section 4.2 above. This methodology ensures optimal use of the existing network assets, thus helping to meet the renewable energy targets in a cost effective manner. Generation capacity should be allocated across the buses such that none of the technical constraints are breached and the capacity maximized. Therefore the proposed objective function is as shown in eqn (4.28) and eqn 4.29 below.

$$\text{Maximize}\, J = \sum_{i=1}^{N} P_{DG,i} \qquad 4.28$$

Where P_{DGi} is the DG capacity at the i^{th} bus and N is the number of buses. Without loss of generation, it is assumed that there is one generator connected at each bus.

$$Minimize\ EIC = \sum_{i=1}^{n_i} L_a(i)\, C_i \lambda_i r_i \qquad 4.29$$

Where- $L_{a(i)}$= average load connected to the load point *i*

C_i=outage cost ($/KWh) of customer at load point *i*

λ_i=failure rate at load point *i*

r_i= failure duration in hour

n_i=total number of load point *i*

The objective function J (MW), given in Equation (4.28) is maximized and EIC ($/KWh) given in equation 4.29 is minimized subject to the constraints, which are formalized under section 4.4.

4.7.2 Optimal Power Flow (OPF)

The Optimal Power Flow (OPF) model represents the problem of determining the best operating levels for electric power plants in order to meet demands given throughout a transmission network, usually with the objective of minimizing operating cost. In this thesis, Optimal Power Flow Analysis (OPF) has been used to address the DG allocation optimization problem. OPF has been used for many years to address problems ranging from economic dispatch to loss minimization [65] and is a common feature in many power flow packages such as Matpower. The typical formulation of OPF for an economic dispatch analysis where the goal is to minimize the overall fuel costs, taking into account line flow and voltage limits is the following:

$$\text{Min } C = \sum C_g P_g \tag{4.30}$$

Subject to:

$$V_{min} \leq V \leq V_{max}$$
$$S_{min} \leq S \leq S_{max}$$
$$P_{g,min} \leq Pg \leq P_{g,max}$$

Where C= fuel overall cost, C_g= cost per generator unit g, P_g= active power per unit g and $P_{g,\ min}$, $P_{g,\ max}$ refer to active power capability of each generator g by giving the minimum and maximum values.

The aforementioned OPF formulation enables a search for an optimal amount of active power output from the participating generators to meet demand and losses and to satisfy network limits at minimum fuel costs. In terms of its application to DG, OPF can be adopted to evaluate the available hosting capacity across multiple sites with a number of different technical constraints such as voltage limits, line thermal limits, transformer limits, security constraints, DG active & reactive power capability, power factor constraints and other that refer to active distribution network methods.

CHAPTER FIVE

SOFTWARE IMPLIMENTATION

Currently there are a wide variety of software applications that can model DG systems, including PSCAD, SKM PowerTools, ETAP and DigSILENT. DigSILENT is chosen as the software application to be used for this analysis.

DigSILENT Powerfactory

DigSILENT Powerfactory is a leading power system analysis software for applications in generation, transmission, distribution and industrial systems. It is integrating all required functions, easy to use, fully Windows compatible and combines reliable and flexible system modeling capabilities with state-of-the-art algorithms and a unique database concept. The Powerfactory Monitor fully integrates with DigSILENT Powerfactory software offering easy access to recorded data, analysis of trends, verification of system upset responses and test results. It provides a reliable central protection settings database and management system for the complete power system substation data, both to manage the various control parameters and to centrally store substation related information and data, based on latest NET technology. DigSILENT GridCode is dedicated to the analysis of country-specific connection requirements for wind and solar power: low voltage ride through, model validation, harmonic and flicker emission level, maximum allowed voltage drop, etc.

The DigSILENT Powerfactory version 15.1.7 was chosen for this thesis because of the following reasons:

- ✓ Economical all-in-one solution with broad coverage of state-of-the-art power system application.
- ✓ Extensive and flexible modelling capabilities with rich suite of power equipment models and libraries.
- ✓ Supports all network representations and phase technologies, i.e. any kind of radial or meshed 1-, 2-, 3- and 4-wire (combined) AC and DC networks
- ✓ Powerful network diagrams and graphic/visualization feature

- ✓ Single and multi-user environment with full support of team working, user accounting, profiles and flexible customization
- ✓ Unlimited opportunities in process optimization based on integrated scripting functionality
- ✓ Rich interfacing and system integration options (e.g. GIS, SCADA, and EMS)

5.1 Procedure for reliability evaluation by using DigSilent

DigSILENT is based on Monte Carlo simulation and enumeration techniques. Figure 5.1 shows the reliability evaluation procedure taken in DigSilent to achieve the reliability indices for both load point and the overall system.

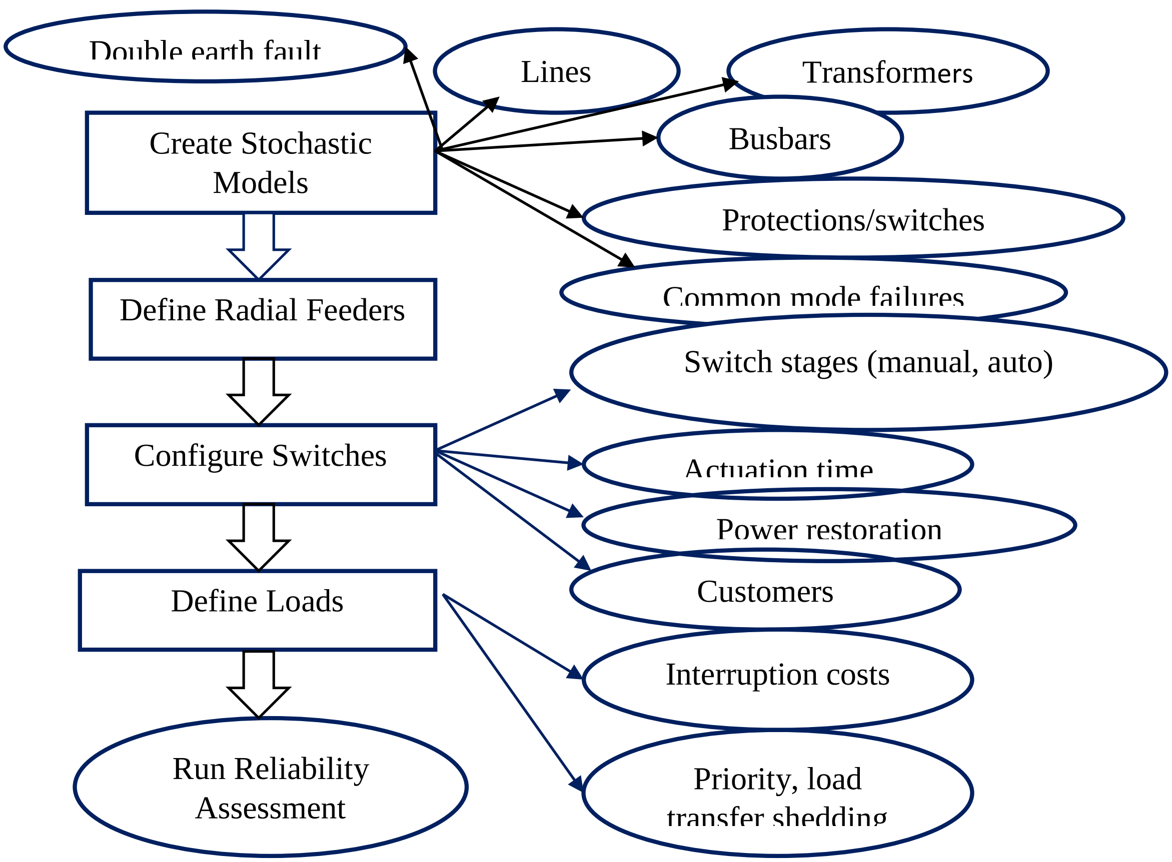

Figure 5.1: Reliability assessment procedures by using DigSilent power factory

The stochastic failure models used for this simulation are:

- ✓ Transformer stochastic model
- ✓ Busbar/terminal stochastic model
- ✓ Line/cable stochastic model

Table 5.1 and Table 5.2 below shows the stochastic failure models for each components used as an input for the simulation of the system.

Table 5.1: Stochastic failure models for transformers and busbars

Transformer stochastic model			
Components	Failure frequency (1/a)		Repair time (hr.)
Transformer:132/15 kV	0.004		2
Transformer: 15/0.4 kV	0.005		6
Busbar stochastic model			
Bus name	Failure frequency (1/a)	Additional failure per connection (1/a)	Repair time (hr.)
Busbar: 132 kV	19	4	0.2
Busbar: 15 kV	28	9	2
Busbar: 0.04 kV	23	4	7

Table 5.2: Line/outgoing feeders stochastic model

Line No	Failure frequency(1/a*km)	Repair duration(h)	Transient fault frequency(1/a*km)
1-K1	8	4	1
2-K2	6	3	1
3-K6	6	2	4
4-K7	3	2	6
5-L1	7	4	1
6-L2	12	9	12
7-L3	10	22	14
8-K8	22	7	6
9-K9	12	9	1
10-K12	22	7	6
11-K13	20	20	1
12-K14	13	6	4
13-K15	11	8	2

Source for Table 5.1 and 5.2: These failure data are obtained from different researches on substation automation at Bishoftu distribution substation since EEU has no such data.

It is possible to define stochastic model for every components within the network. The stochastic model listed above can be defined either through object type or through the object element. Thus, reliability analysis is obtained by performing the following procedures in the DigSilent power factory software. Here, the procedure is for busbar type stochastic modeling but the same procedure is done for transformer, line and other components.

- ✓ Draw the one line diagram on the working plane of the software
- ✓ Open the dialogue box for the busbar type and select the basic data tab.
- ✓ Specify the voltage and power levels for each component
- ✓ Open the dialogue box for the busbar type and select the reliability tab.
- ✓ Enter the created stochastic models in each component (failure data for busbar, line transformer and define feeder)

- ✓ Enter the mean repair duration
- ✓ Press OK and execute the reliability assessment.

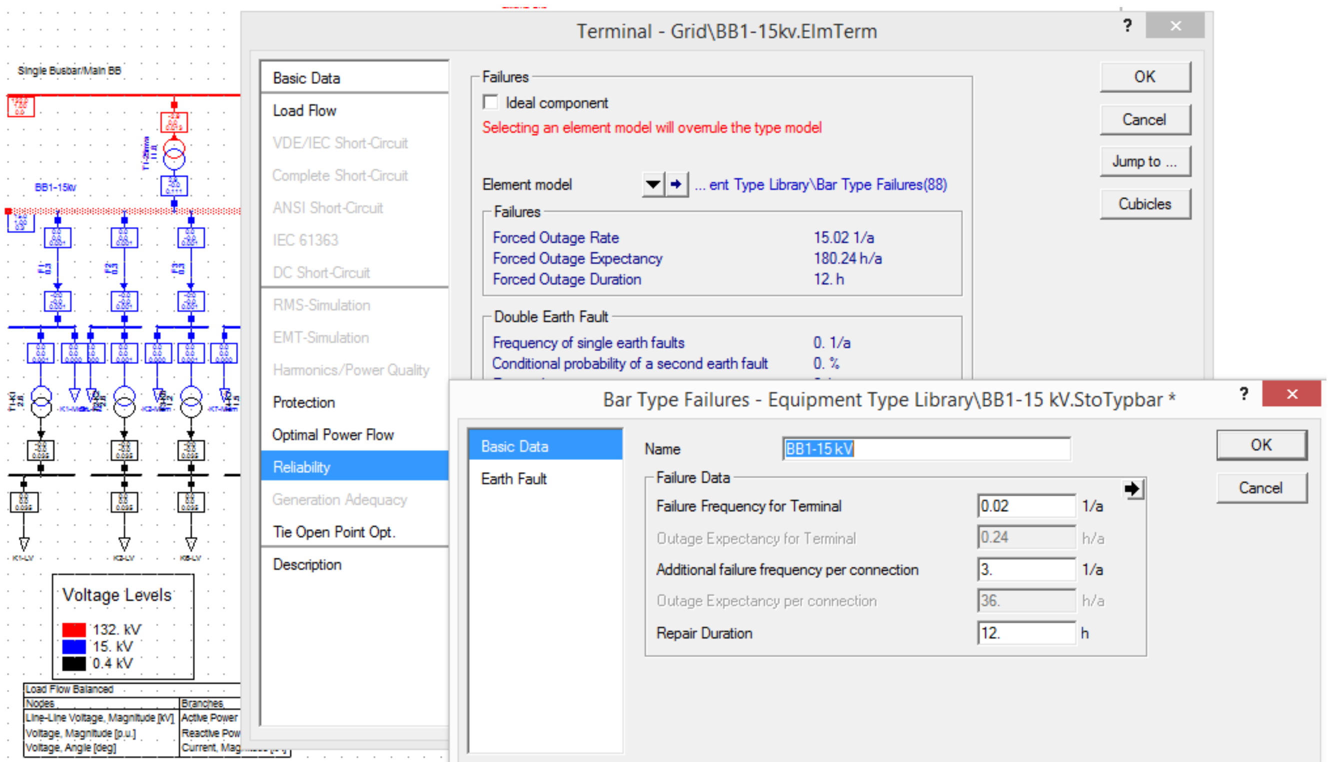

Figure 5.2: Procedures in the DigSilent powerfactory simulation.

5.2 Simulation and simulation results (Base case study)

The existing system shown in Figure 5.3 below is modeled using DigSilent Powerfactory software. The software needs the one line diagram, the voltage and power levels for each component and the stochastic failure models (as indicated in Table 5.1 and 5.2 above) for each components as an input and gives the system reliability indices, the load point reliability indices as an output. All of these stochastic failure data, voltage and power level data are as indicated in Table 5.1 and Table 5.2 above. By using these input data and following the reliability assessment procedures listed under section 5.1 above the existing system of Bishoftu distribution substation can be modeled and simulated as below.

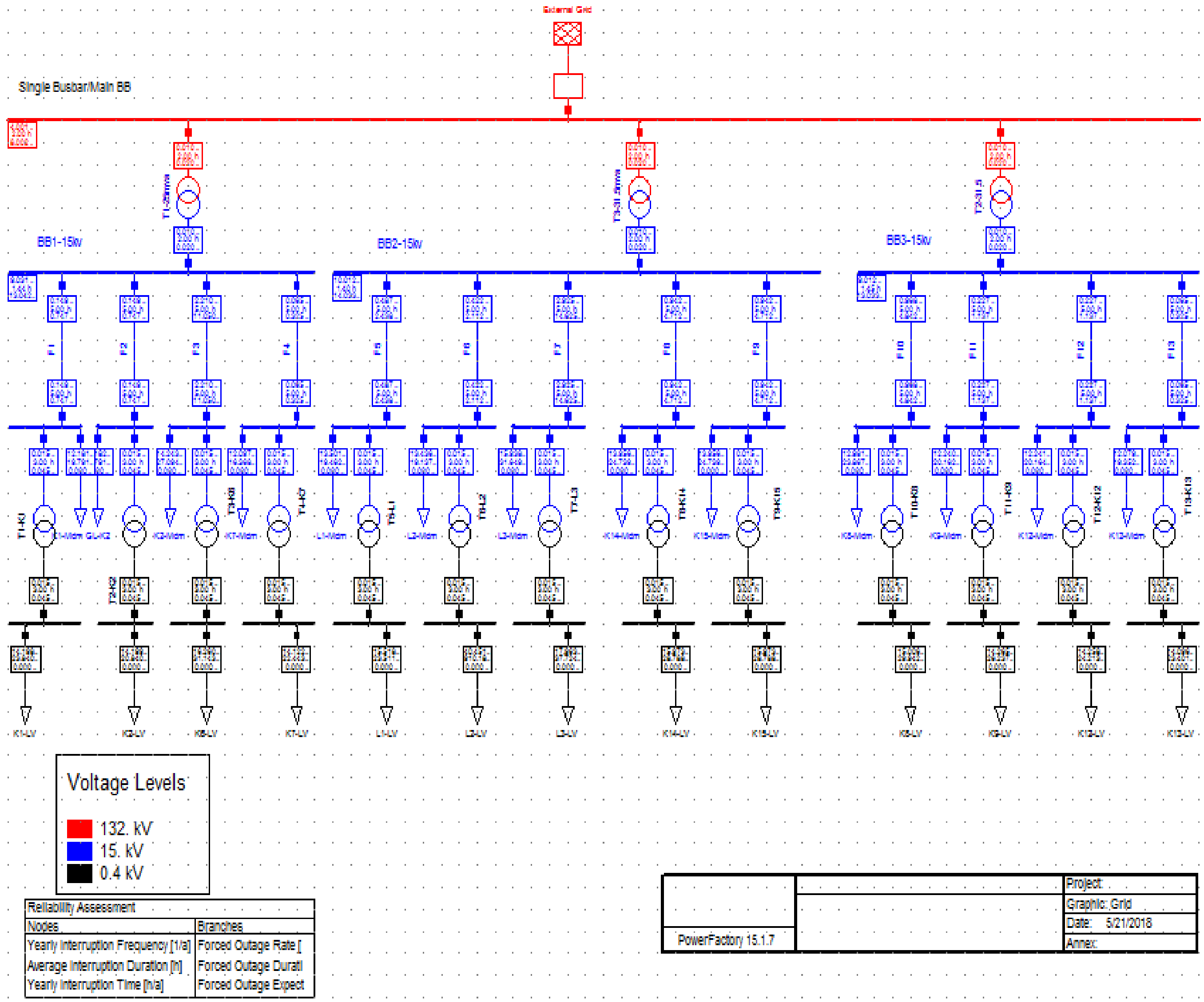

Figure 5.3: Simulated base case distribution substation

The output of the simulation is as indicated in Table 5.3 below and based on this base case simulation it can be observed that system reliability indices and load point reliability indices are significantly very large value. Hence, this shows that the existing substation has reliability problems since the indices are higher for the failure models used as input. The following Table 5.3 shows the simulated output reliability indices of the system.

Table 5.3: Simulation output of system reliability indices for the existing system

```
---------------------------------------------------------------------------------------------------------------------------
|                |                                                         |  DIgSILENT   | Project:                     |
|                |                                                         | PowerFactory |------------------------------
|                |                                                         |    15.1.7    | Date:   5/21/2018            |
---------------------------------------------------------------------------------------------------------------------------
| Reliability Assessment                                                                                                  |
|   Method                                   Load flow analysis                                                           |
|   Network                                  Distribution (Optimal Power Restoration)                                     |
|   Calculation time period                  2106                                                                         |
|   Consider Maintenance                     No                                                                           |
|   Fault Clearance Breakers                 Use all circuit breakers                                                     |
|   Switching procedures                     Concurrently                                                                 |
|   Consider Sectionalizing (Stages 1-3)     Yes                                                                          |
|   Time to open remote controlled switches  1.00 min.                                                                    |
|                                                                                                                         |
| Automatic Contingency Definition                                                                                        |
|   Selection                                Whole System                                                                 |
|   Busbars / terminals                      Yes               Common mode                              No                |
|   Lines / cables                           Yes               Independent second failures              No                |
|   Transformers                             Yes               Double earth faults                      Yes               |
|                                                              Protection/switching failures            No                |
---------------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------------
| Study Case: Study Case                                                                   | Annex:                 / 1   |
---------------------------------------------------------------------------------------------------------------------------
| System Summary                                                                                                          |
---------------------------------------------------------------------------------------------------------------------------
| System Average Interruption Frequency Index        :  SAIFI  =  179.612866 1/Ca                                         |
| Customer Average Interruption Frequency Index      :  CAIFI  =  179.612866 1/Ca                                         |
| System Average Interruption Duration Index         :  SAIDI  =  276.585    h/Ca                                         |
| Customer Average Interruption Duration Index       :  CAIDI  =    1.540    h                                            |
| Average Service Availability Index                 :  ASAI   =    0.9684264230                                           |
| Average Service Unavailability Index               :  ASUI   =    0.0315735770                                           |
| Energy Not Supplied                                :  ENS    = 5666.366    MWh/a                                        |
| Average Energy Not Supplied                        :  AENS   =    0.286    MWh/Ca                                       |
| Average Customer Curtailment Index                 :  ACCI   =    0.286    MWh/Ca                                       |
| Expected Interruption Cost                         :  EIC    =    2.920    M$/a                                         |
| Interrupted Energy Assessment Rate                 :  IEAR   =    0.515    $/kWh                                        |
| System energy shed                                 :  SES    =    0.000    MWh/a                                        |
| Average System Interruption Frequency Index        :  ASIFI  =  192.604216 1/a                                          |
| Average System Interruption Duration Index         :  ASIDI  =  320.615116 h/a                                          |
| Momentary Average Interruption Frequency Index     :  MAIFI  =    0.000000 1/Ca                                         |
---------------------------------------------------------------------------------------------------------------------------
```

From Table 5.3 above, it can be seen that the simulated base case system reliability indices resulted in a value for SAIFI 179.6128 1/ca, SAIDI is 276.585 hrs. /ca and energy not supplied is 5666.366 MWh/ca. There is also high service unavailability at the substation as the average service availability (ASAI is 96.842%) which is below the bench mark value set by EEA (i.e ASAI should be greater than 99.98%). The revenue losses (in terms of Expected Interruption Cost) at the substation is also high as it can be seen from the above simulation result.

Table 5.4: Simulated results of Bus bar/ terminal indices for the existing system

		DIgSILENT PowerFactory 15.1.7	Project: Date: 5/21/2018

Reliability Assessment

Method	Load flow analysis
Network	Distribution (Optimal Power Restoration)
Calculation time period	2106
Consider Maintenance	No
Fault Clearance Breakers	Use all circuit breakers
Switching procedures	Concurrently
Consider Sectionalizing (Stages 1-3)	Yes
Time to open remote controlled switches	1.00 min.

Automatic Contingency Definition

Selection	Whole System		
Busbars / terminals	Yes	Common mode	No
Lines / cables	Yes	Independent second failures	No
Transformers	Yes	Double earth faults	Yes
		Protection/Switching failures	No

Study Case: Study Case | Annex: / 1

Buses Name	AIT h/a	AIF 1/a	AID h
LVBB11	555.16	212.81	2.61
MBB11	492.36	154.01	3.20
LVBB7	431.73	256.61	1.68
LVBB10	304.76	218.61	1.39
MBB7	288.53	185.00	1.56
LVBB4	248.13	192.06	1.29
LVBB8	241.53	221.81	1.09
MBB10	237.36	153.01	1.55
LVBB6	219.33	208.21	1.05
MBB8	196.53	180.00	1.09
LVBB3	188.33	178.08	1.06
LVBB2	180.37	155.09	1.16
LVBB13	180.16	164.21	1.10
LVBB9	178.77	202.06	0.88
MBB4	168.01	152.00	1.11
LVBB1	167.28	171.09	0.98
LVBB12	164.16	156.91	1.05
MBB3	156.01	146.00	1.07
MBB6	148.53	173.00	0.86
MBB9	144.53	168.00	0.86
LVBB5	142.73	198.31	0.72

Study Case: Study Case | Annex: / 2

Buses Name	AIT h/a	AIF 1/a	AID h
MBB1	141.01	145.00	0.97
MBB2	138.01	134.00	1.03
MBB13	115.36	132.01	0.87
MBB12	110.36	130.01	0.85
MBB5	85.53	170.00	0.50
BB1	80.01	108.00	0.74
BB2	18.53	150.00	0.12
BB3	14.36	108.01	0.13
Single Busbar /BB	7.00	35.00	0.20

From the simulations output of the existing system above, the busbars/terminals indices as given in Table 5.4 above, it can be clearly observed that the busbars indices such as average interruption time (AIT), average interruption frequency (AIF) and average interruption duration (AID) are high which indicate, the substation is poorly reliable. Similarly, from the load point indices as indicated below in Table 5.5 of the simulation output it can be seen that the load point energy not supplied (LPENS), load point interruption cost (LPIC), average customer interruption frequency (ACIF), total customer interruption time (TCIT) and average interruption duration (AID) have significantly high value. Thus, generally the existing Bishoftu distribution substation is highly unreliable.

Table 5.5: The load point indices of the existing substation

DIgSILENT PowerFactory 15.1.7 | Project: | Date: 5/21/2018

Reliability Assessment
- State Enumeration - Automatic Power Restoration
- Load flow analysis - 0

Selection = Whole System
No = Common mode | No = Independent second failures
Yes = Busbars / terminals | Yes = Double earth faults
Yes = Lines / cables | No = Consider Maintenance
Yes = Transformers

Study Case: Study Case | Annex: / 1

Load Interruptions Name	TCIT Ch/a	TCIF C/a	AID h	LPENS MWh/a	LPIC $/a	ACIF 1/a	ACIT h/a
LV11	2854057.00	1094040.79	2.61	3253.62	23696.92	212.81	555.16
GL11	4431.20	1386.06	3.20	0.00	0.00	154.01	492.36
LV7	129519.00	76981.50	1.68	147.65	1667.42	256.61	431.73
LV10	213329.20	153024.90	1.39	243.20	3314.52	218.61	304.76
GL7	28853.00	18500.50	1.56	0.00	0.00	185.00	288.53
LV4	173689.60	134444.80	1.29	198.01	2912.07	192.06	248.13
LV8	144918.00	133083.00	1.09	165.21	2882.58	221.81	241.53
GL10	1898.85	1224.06	1.55	0.00	0.00	153.01	237.36
LV6	52639.20	49969.20	1.05	60.01	1082.33	208.21	219.33
GL8	2751.42	2520.07	1.09	0.00	0.00	180.00	196.53
LV3	633158.74	598718.41	1.06	721.80	12968.24	178.08	188.33
LV2	324662.40	279169.20	1.16	370.12	6046.80	155.09	180.37
LV13	97284.24	88671.78	1.10	110.90	1920.63	164.21	180.16
LV9	57206.40	64660.80	0.88	65.22	1400.55	202.06	178.77
GL4	5040.24	4560.12	1.11	0.00	0.00	152.00	168.01
LV	167278.00	171094.00	0.98	190.70	3705.90	171.09	167.28
LV12	65662.40	62762.80	1.05	74.86	1359.44	156.91	164.16
GL3	1092.06	1022.03	1.07	0.00	0.00	146.00	156.01
GL6	10397.10	12110.35	0.86	0.00	0.00	173.00	148.53
GL9	867.18	1008.03	0.86	0.00	0.00	168.00	144.53
LV5	57092.00	79322.00	0.72	65.08	1718.11	198.31	142.73
GL1	1410.08	1450.04	0.97	0.00	0.00	145.00	141.01
GL2	2760.16	2680.08	1.03	0.00	0.00	134.00	138.01
GL13	461.42	528.03	0.87	0.00	0.00	132.01	115.36
GL12	441424.00	520028.00	0.85	0.00	0.00	130.01	110.36
GL5	342.12	680.02	0.50	0.00	0.00	170.00	85.53

5.3 Simulation and result discussion of the modified system

The objective of this case study is to design an upgraded system that would make Bishoftu town distribution system a near net-zero consumer interruption. That is to make a facility that has nearly 100% of its energy demand available all the time and generated locally to support the existing grid system. The following are among the reasons or justifications for implementing such a design (renewable energy like PV and wind) at Bishoftu substation.

- ✓ Firstly, a large town such as Bishoftu has energy demand increasing from time to time which leads to a large electricity interruption in the town. Thus, the investments for distributed generation can be justified easily.
- ✓ The town of Bishoftu has high solar insolation levels with averagely 5.06 kWh/m^2/d [NASA] and consistent wind stream averagely in between 6-10 m/s). This data is obtained from NASA website based on the latitude and longitude location of the site and it is tabulated under appendix D of this thesis. Hence, the area is good for the selected renewable energy resources.
- ✓ A capacity of 1 MW for solar based DG and 2MW wind DG used in this case study and this size of DG is selected based on minimum power loss criteria while increasing the hosting capacity by keeping the constraints within the network limit as indicated in chapter four. Throughout this modified system, a single DG refers to a capacity of 3 MW at the selected bus.
- ✓ The contribution of wind energy based DG is accounted to be 66.66% that is 2 MW and that of solar PV is 33.33% or 1 MW. The reason for this size classification is due to high cost of solar PV system as compared with wind which is previously discussed in detail under chapter two of this thesis.

5.3.1 Simulation results of the modified system (DG at 15 kV of the selected buses; K-7, K-8, K-9 and L-3)

The change is that, the existing system is connected with DG units at the 15 kV bus of the most interruption affected feeders (K-7, K-8, K-9 and L-3) as shown in the simulated single line diagram below. The reliability improvement after DG connection is as shown on the output window of the software which is indicated in Table 5.6.

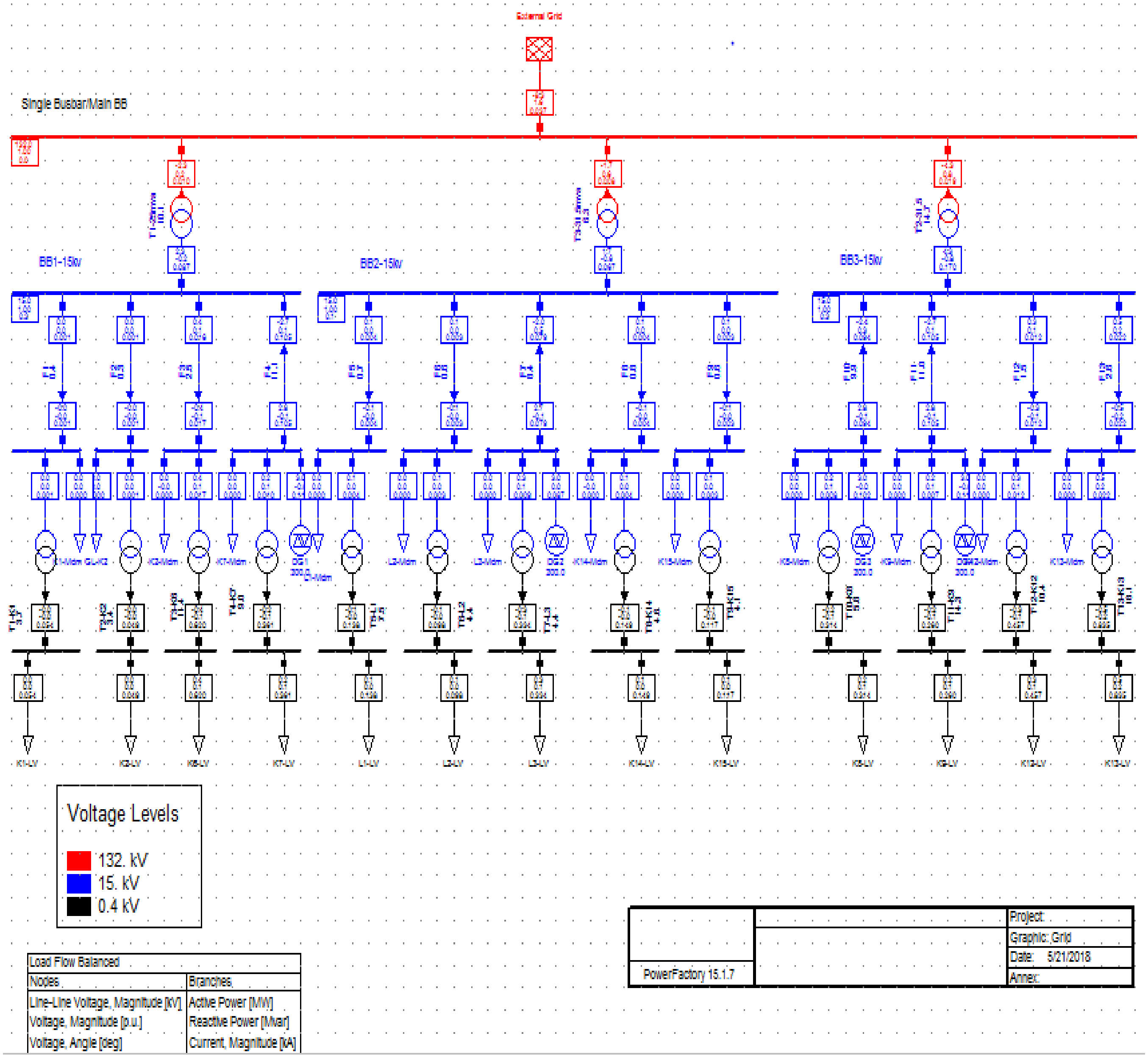

Figure 5.4: The simulated modified distribution substation with DG at 15kV

Table 5.6: Simulation output of system reliability indices with DG unit at 15 kV busbar of the selected feeders (K-7, K-8, K-9 and L-3)

```
-------------------------------------------------------------------------------------------------------
|              |                                                   |   DIgSILENT   | Project:             |
|              |                                                   | PowerFactory  |----------------------
|              |                                                   |    15.1.7     | Date:  5/21/2018     |
-------------------------------------------------------------------------------------------------------
| Reliability Assessment                                                                               |
|   Method                                  Load flow analysis                                         |
|   Network                                 Distribution (Optimal Power Restoration)                   |
|   Calculation time period                 2106                                                       |
|   Consider Maintenance                    No                                                         |
|   Fault Clearance Breakers                Use all circuit breakers                                   |
|   Switching procedures                    Concurrently                                               |
|   Consider Sectionalizing (Stages 1-3)    Yes                                                        |
|   Time to open remote controlled switches 1.00 min.                                                  |
|                                                                                                      |
| Automatic Contingency Definition                                                                     |
|   Selection                               Whole System                                               |
|   Busbars / terminals                     Yes           Common mode                      No          |
|   Lines / cables                          Yes           Independent second failures      No          |
|   Transformers                            Yes           Double earth faults              Yes         |
|                                                        Protection/switching failures    No          |
-------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------
| Study Case: Study Case                                                          | Annex:        / 1  |
-------------------------------------------------------------------------------------------------------
| System Summary                                                                                       |
-------------------------------------------------------------------------------------------------------
| System Average Interruption Frequency Index       :  SAIFI  =   96.304275 1/Ca                       |
| Customer Average Interruption Frequency Index     :  CAIFI  =   96.304275 1/Ca                       |
| System Average Interruption Duration Index        :  SAIDI  =  251.412    h/Ca                       |
| Customer Average Interruption Duration Index      :  CAIDI  =    2.611    h                          |
| Average Service Availability Index                :  ASAI   =    0.9713000307                        |
| Average Service Unavailability Index              :  ASUI   =    0.0286999693                        |
| Energy Not Supplied                               :  ENS    = 4604.654   MWh/a                       |
| Average Energy Not Supplied                       :  AENS   =    0.257    MWh/Ca                      |
| Average Customer Curtailment Index                :  ACCI   =    0.257    MWh/Ca                      |
| Expected Interruption Cost                        :  EIC    =    1.413    M$/a                        |
| Interrupted Energy Assessment Rate                :  IEAR   =    0.307    $/kWh                       |
| System energy shed                                :  SES    =    0.000    MWh/a                       |
| Average System Interruption Frequency Index       :  ASIFI  =  107.870438 1/a                        |
| Average System Interruption Duration Index        :  ASIDI  =  296.932320 h/a                        |
| Momentary Average Interruption Frequency Index    :  MAIFI  =    0.000000 1/Ca                       |
-------------------------------------------------------------------------------------------------------
```

From Table 5.6, it can be seen that 3 MW DG is connected to the MV feeders (K-7, K-8, K-9 and L-3) and the simulation is conducted. The result of the simulation shows that the overall improvement in the indices SAIFI, SAIDI and ENS is 46.529%, 9.101% and 18.737% respectively. This shows the same magnitude of DG connected at different feeders' busbar which gives an improvement in reliability. This is because feeders K-7, K-8, K-9 and L-3 were experiencing more interruption duration and frequency. Here, DGs are used as backup and needs to cover power shortage at the station loads.

5.3.2 Simulation results of the modified system (DG at 0.4 kV of the selected buses; K-7, K-8, K-9 and L-3).

Now, 3 MW DG unit is connected at low voltage sides (15/0.4 kV) i.e. 0.4 kV busbars of the feeders (K-7, K-8, K-9 and L-3) and simulation is conducted as shown in the single line diagram below. The overall reliability indices improvement after DG connected is indicated in Table 5.7 from the output window of the simulation.

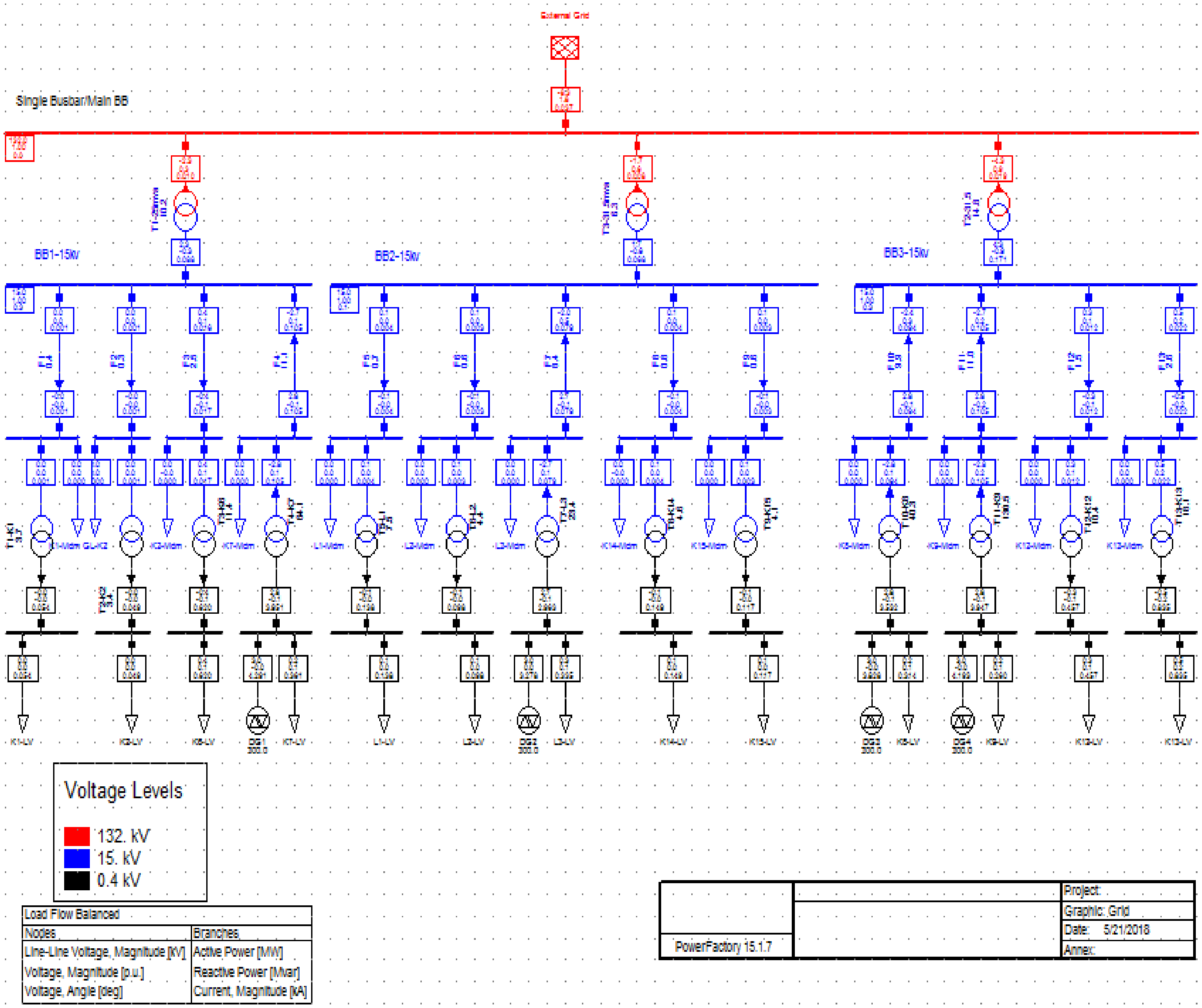

Figure 5.5: The simulated modified distribution substation with DG at 0.4 kV

Table 5.7: Simulation output of system reliability indices with DG at all 0.4 kV selected feeders (K-7, K-8, K-9 and L-3)

```
-------------------------------------------------------------------------------------------------------------------------
|                |                                                        |   DIgSILENT   | Project:                    |
|                |                                                        |  PowerFactory |-----------------------------
|                |                                                        |    15.1.7     | Date:  5/21/2018            |
-------------------------------------------------------------------------------------------------------------------------
| Reliability Assessment                                                                                                |
|   Method                                    Load flow analysis                                                        |
|   Network                                   Distribution (Optimal Power Restoration)                                  |
|   Calculation time period                   2106                                                                      |
|   Consider Maintenance                      Yes                                                                       |
|   Fault Clearance Breakers                  Use all circuit breakers                                                  |
|   Switching procedures                      Concurrently                                                              |
|   Consider Sectionalizing (Stages 1-3)      Yes                                                                       |
|   Time to open remote controlled switches   1.00 min.                                                                 |
|                                                                                                                       |
| Automatic Contingency Definition                                                                                      |
|   Selection                                 Whole System                                                              |
|   Busbars / terminals                       Yes               Common mode                                 No          |
|   Lines / cables                            Yes               Independent second failures                 No          |
|   Transformers                              Yes               Double earth faults                         No          |
|                                                               Protection/switching failures               No          |
-------------------------------------------------------------------------------------------------------------------------
-------------------------------------------------------------------------------------------------------------------------
| Study Case: Study Case                                                                   | Annex:                / 1  |
-------------------------------------------------------------------------------------------------------------------------
| System Summary                                                                                                        |
-------------------------------------------------------------------------------------------------------------------------
| System Average Interruption Frequency Index        :  SAIFI  =   13.767436 1/Ca                                       |
| Customer Average Interruption Frequency Index      :  CAIFI  =   13.767436 1/Ca                                       |
| System Average Interruption Duration Index         :  SAIDI  =   30.546    h/Ca                                       |
| Customer Average Interruption Duration Index       :  CAIDI  =    2.219    h                                          |
| Average Service Availability Index                 :  ASAI   =    0.9965130662                                         |
| Average Service Unavailability Index               :  ASUI   =    0.0034869338                                         |
| Energy Not Supplied                                :  ENS    =  128.327    MWh/a                                      |
| Average Energy Not Supplied                        :  AENS   =    0.018    MWh/Ca                                     |
| Average Customer Curtailment Index                 :  ACCI   =    0.019    MWh/Ca                                     |
| Expected Interruption Cost                         :  EIC    =    0.069    M$/a                                       |
| Interrupted Energy Assessment Rate                 :  IEAR   =    0.534    $/kWh                                      |
| System energy shed                                 :  SES    =    0.000    MWh/a                                      |
| Average System Interruption Frequency Index        :  ASIFI  =   16.204548 1/a                                        |
| Average System Interruption Duration Index         :  ASIDI  =   50.854262 h/a                                        |
| Momentary Average Interruption Frequency Index     :  MAIFI  =    0.000000 1/Ca                                       |
-------------------------------------------------------------------------------------------------------------------------
```

Now from Table 5.7 above, when 3 MW DG unit is connected to the LV side busbar of the feeders (K-7, K-8, K-9 and L-3) and the simulation is conducted the overall improvement in the indices SAIFI, SAIDI and ENS are 92.335%, 88.956% and 97.735% respectively. This shows that same magnitude of DG unit connected at different busbars which gives more reliability improvement. Hence, reliability indices (SAIDI, CAIDI and ENS) is improved as the DG is installed away from the substation and closer to the loads. Therefore, from the simulation it can be concluded that when DG unit is placed at the end of the line, best improvement in reliability indices is resulted.

5.4 Comparison of simulated results of the base case and modified case system

Table 5.8: Simulated results of basecase and modified case

System Indices	Basecase (No DG)	Modified case (3MW) DG@15kV bus.	Modified case (3MW) DG@0.4kV bus).
SAIFI (1/ca)	179.612	96.304	13.767
CAIFI (1/ca)	179.612	96.304	13.767
SAIDI (h/ca)	276.585	251.412	30.546
ENS (MWh/a)	5666.366	4604.654	128.327
AENS (MWh/ca)	0.286	0.257	0.025
EIC (m$/yr.)	2.920	1.413	0.069
ASAI	0.9684	0.9713	0.9965
ASUI	0.03158	0.0286	0.0034

It can be seen from Table 5.8 that, at the base case the system reliability is highly poor as the indices value is very large. When 3 MW DG unit is installed at the beginning of the feeder barely improve the reliability indices i.e. DG installed at 15 kV, the reliability indices are slightly improved (for instance, the SAIFI, SAIDI and ENS are improved by 46.529%, 9.101% and 18.73%) respectively. The other system reliabilities are also improved as we can clearly see from the table. Similarly, DG installed at 0.4 kV the reliability of the system is further improved with a greater percentage. This is because placing the DG at the end of the line i.e. near the load point provides capability to pick up the load if the failure occurs in the original system. Therefore, the percentage improvement in the energy not supplied, system average interruption frequency and system average interruption duration is 97.735%, 92.335% and 88.956% respectively. The average service availability of the system is also improved very significantly as it can be observed from the table. From Table 5.8 above, we can also put the values in the following bar charts (Figure 5.6) for easy understanding of the comparisons.

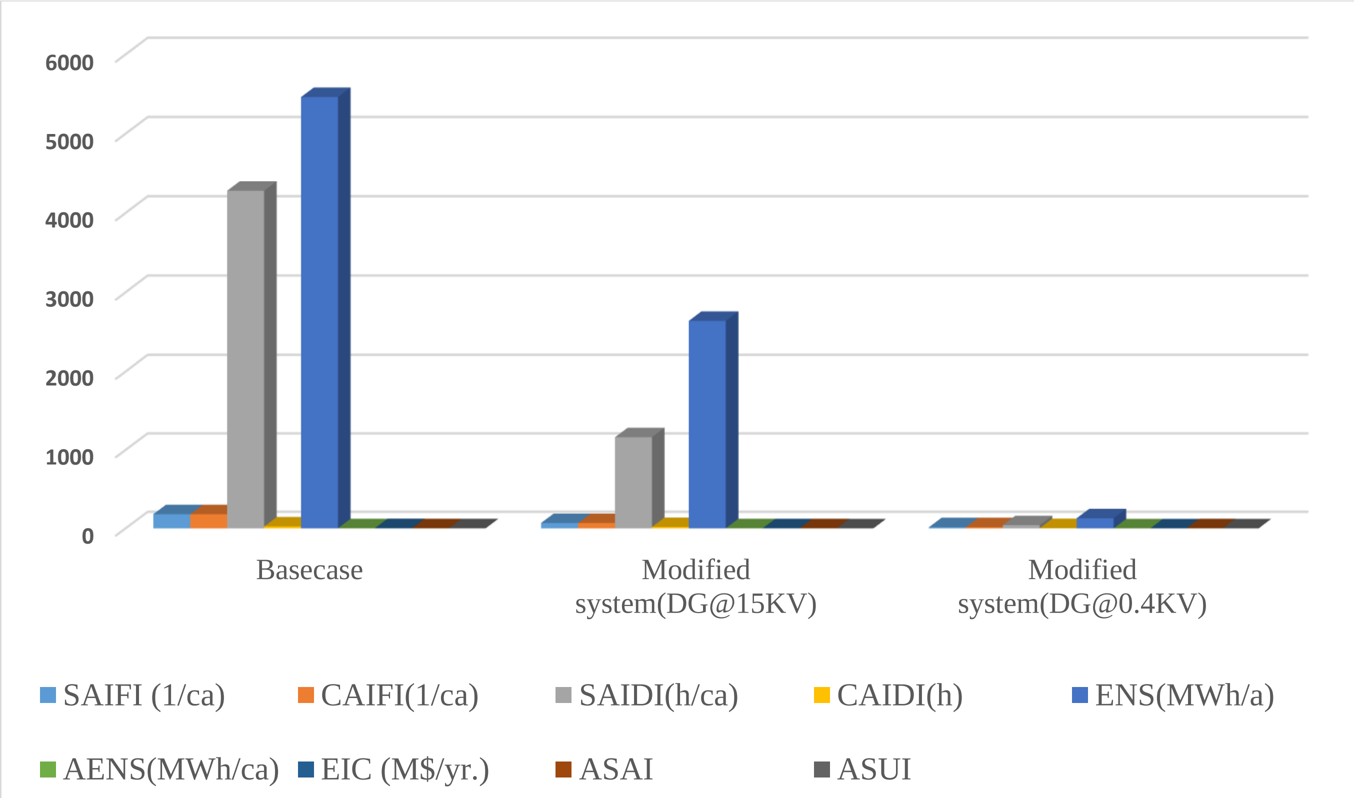

Figure 5.6: Comparison of basecase and modified system

5.5 Economic aspects of the designed system

Power interruption costs affects both the utility company and the customers which can be analyzed by using the energy not supplied. This technique is used to know how much revenue could be lost at the Basecase system and the new designed system. In Bishoftu city there are roughly three customers; residential, commercial and industrial customers. The revenue loss of commercial and industrial customers as a result of power interruption is so large. Specially, for industrial customers (feeder k-7), power interruption costs are highly related to production losses. This is in the sense that, Bishoftu Automotive industry (feeder k-7) works with 218 small and medium enterprises which are providing its input. Its annual turnover has reached 2.2 billion birr, with a production capacity of manufacturing 16 pickups, 10 trucks and 4 buses on the daily basis. Power interruption to this company has a great impact on its economy with an average revenue loss estimated to be 254.4 million ETB or 9.24 million dollars on the average annual basis of the studied period.

From Table 5.6 above, the energy interruption cost for the Basecase and DG at 15kV, DG at 0.4kV of the feeders (K-7, K-8, K-9 and L-3) are 2.920 M$/yr, 1.413 M$/yr & 0.069 M$/yr respectively. Using the average energy interruption cost with DG at 15 kV and DG at 0.4 kV which is 0.741 M$/yr it is possible to calculate the revenue saved after the improvement by the modified system as follows:

i.e. 2.92 M$/yr-0.741M$/yr=2.179 M$/yr saved.

Table 5.9: Estimated cost of 2 MW wind turbine system

Cost of equipment and works	Investment($)	Subtotal cost in %
Turbine(ex-works)	30930.24	75.6
Grid connection	3632.97	8.9
Foundation	2666.4	6.5
Land rent	1599.84	3.9
Electric installation	599.94	1.5
Consultancy	499.95	1.2
Financial costs	499.95	1.2
Road construction	366.63	0.9
Control system	333.32	0.3
Total	82058.48	100

Table 5.10: Estimated cost of 1 MW PV system

Sr.No	Equipment and works	Unit	Unit price($)	Sub-total($)	Share of total cost %
1	PV module	$/W	2.5	2,500,000	42.01
2	Power conditioner	$/kw	261.421	261421.32	8.58
3	Mounting structure	$/kw	538.578	538578.68	18.74
4	Other equipment cost	$/kw	219.796	219796.95	7.05
5	Civil work			148730.96	4.45
6	Other work and cost for procedure		*1	239593.91	7.78
7	Contingency cost		*2	38832.48	1.42
8	Technical service cost		*3	53553.29	1.96
9	Land rent			1000	2%
10	Charge controller			1200	2%
11	Battery			100	2%
12	Inverter			200	2%
Total				4003007.59	100%

NB: *1: 10% of total of items 1 to 5 above

*2: 10% of total of items 5 and 7 above

*3: 2% of total of items 1 to 7 above

Source: Questionnaires from experts, study Team based on collected Price Quotation/Information and analysis.

Table 5.9 and Table 5.10 has shown that the total cost of 3 MW DG is 4085066.07 USD or based on the exchange rate of Commercial Bank of Ethiopia on 18 April, 2018 with one USD equals to 27.54 ETB, the cost of 3 MW DG is 112502719.56 ETB. As shown in the simulation base case study under section 5.2 above, the total revenue loss from the substation at the utility side due to ENS is 2.92 million dollar per annual. When we divide the cost of 3 MW DG to this cost of annual energy loss, we get 1.4 years. Thus, the cost of 3 MW DG can be repaid from the 1.4 years of revenue loss from the substation.

CHAPTER SIX

CONCLUSION, RECOMMENDATION AND FUTURE WORK

Based on the results obtained from this research work on reliability problems of Bishoftu distribution substation II and the simulation conducted with distributed generation for mitigating the reliability and overloading problems, the following conclusions and recommendation have been made and the possible future works are proposed.

6.1 Conclusion

This research work shows that the reliability of the Bishoftu substation II does not meet the requirements set by the regulatory body that is, Ethiopian Electric Agency (EEA). The average frequency of interruptions (SAIFI) at the substation is 179.612 interruptions per customer per year and the average duration of interruptions (SAIDI) is 276.585 hours per customer per year at the existing system. Also, there is high unavailability of electric power in the distribution network due to poor system reliability. In the base case study there is a huge loss of unsupplied energy due to planned and unplanned outages. Therefore, there is a higher vulnerability in term of reliability worth; ENS (5666.3667 MWh/a) and this results in revenue losses of around 2.92 M$/yr from the substation.

DGs were connected to the four feeders (K-7, K-8, K-9 and L-3) which experience more interruptions. As a result of these DGs, the overall system's reliability is improved. So DGs should be located on a load point where there is most interruption and most customers are found and where much of the load is supplied. Based on the simulation result, the installation of DG at 0.4 kV buses of the selected feeders were achieved 92.335% improvement in SAIFI value, 88.956% improvement in SAIDI value, 97.735% improvement in ENS value. The ENS is reduced from 5666.366 MWh/yr to 128.327 MWh/yr and EIC is reduced from 2.92 M$/yr to 0.741 M$/yr with average revenue saving of about 2.179 million $/yr. Thus, Ethiopian Electric Utility (EEU) can increase its revenue by 74.623% for that area by reducing the energy not supplied (ENS) due to interruptions.

6.2 Recommendations

The following important recommendations can be obtained based on the findings of the research:

- ✓ The EEU should work to improve the reliability of the power grid at Bishoftu city and in the country as a whole to meet the customer need and the country's development need.
- ✓ Renewable energy based DG options should be promoted by the power supplier not only for rural electrification but also for urban areas as a backup.
- ✓ EEP should implement substation automation technologies to improve the reliability of the power supply.
- ✓ As the system is not computerized there was difficult to identify each load point and the corresponding data of that load point. This made the analysis in this thesis to be difficult. So, I recommend to EEU to distinguish each load point and their corresponding failure data.

6.3 Future Work

The future works to be done on the area of reliability improvement by using DG are presented.

- ✓ DG can be used for a backup purpose or for peak load sharing. So for each of these purposes, there should be a control system modeled between the DG and the existing grid.
- ✓ This research work only conducted the 15 kV line feeders, future work use the same analysis to improve reliability of the 33 kV and 45 kV line feeders of the substations.
- ✓ The modeling of the distribution system is done by treating the system as a radial network. Other forms of distribution systems such as meshed networks may be considered for reliability evaluation in the future.
- ✓ Different distributed generation options other than PV and Wind energy can be studied for this substation's reliability improvement.

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Appendix A: System inputs

Table1A: Line data

R'	Ro'	X'	Xo'	B'	Bo'
0.6961	1.0875	0.5179	1.4741	3.8259	1.8702

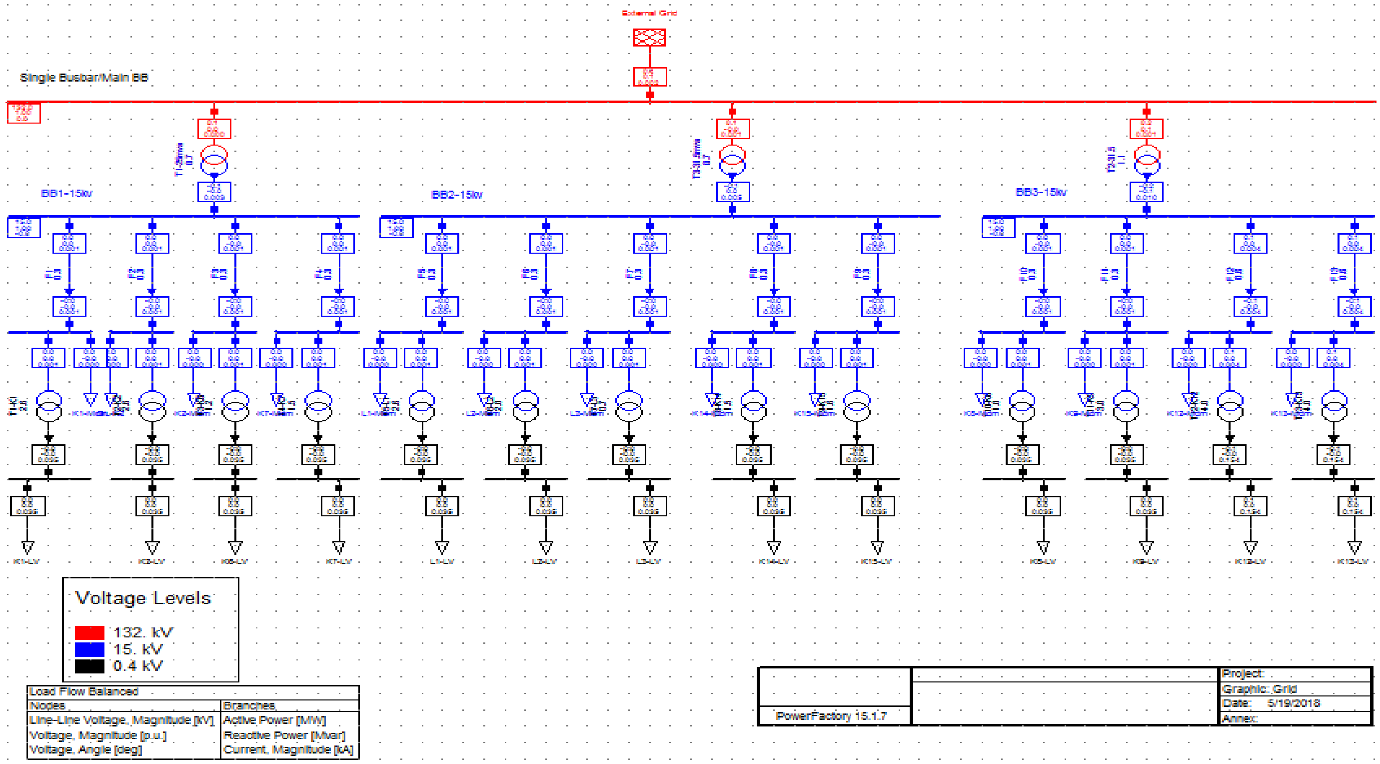
Table 2A: Basic feeders data

Feeders	Length(km)	Conductor Type and Size(mm^2)	Voltage level(KV)	No. of Trafo's	Total KVA
L1	7.5	AAC95	15	2	2500
L2	6.5	AAC95	15	3	3300
L3	45	AAC95	15	9	9300
K1	2.3	AAC95	15	2	2500
K2	2.3	AAC95	15	2	2500
K6	34	AAC95	15	16	5650
K7	19	AAC50	15	7	10435
K8	14.5	AAC95	15	6	6390
K9	14.9	AAC95	15	65	2192
K12	3.5	AAC95	15	2	3750
K13	3.5	AAC50	15	2	3750
K14	54	AAC95	15	5	4350
K15	24	AAC50	15	12	4020

Table 3A: EEP/EEU electricity tariff (Birr/kwh) [46]

Residential	Active Energy Range (KWh)	Price Rate (Birr/KWh)
	0-50	0.2730
	51-100	0.3564
	101-200	0.4993
	201-300	0.5500
	301-400	0.5666
	401-500	0.5880
	Above 500	0.6943
Commercial	0-50	0.6088
	Above 50	0.6943
Industrial@15kv	Peak	0.7426
	Off-Peak	0.5354

Appendix B: Animated load flow at the base case (without DG integration)

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|                |                                                      | DIgSILENT     | Project:                       |
|                |                                                      | PowerFactory  |--------------------------------
|                |                                                      |    15.1.7     | Date:  5/19/2018               |

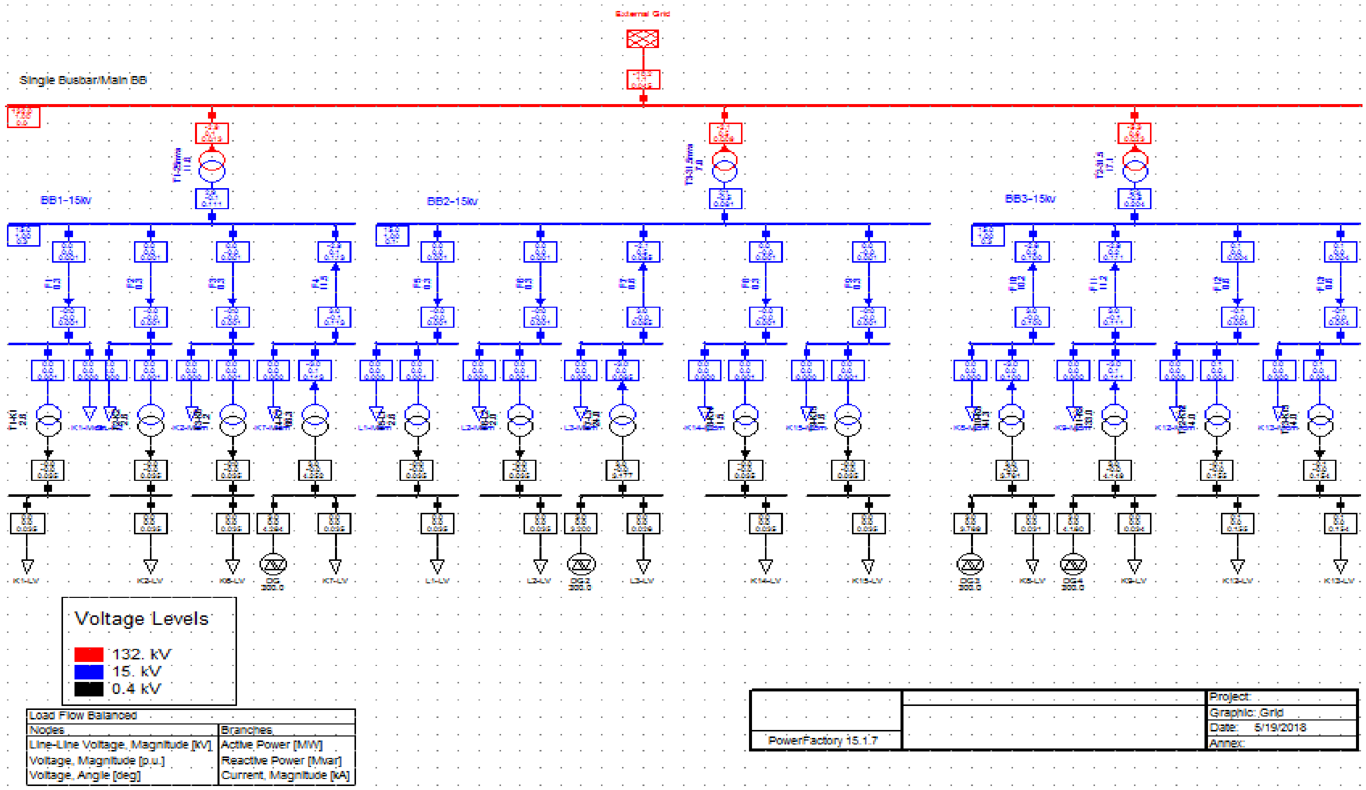
| Load Flow Calculation                                                                                    Grid Summary |

|     AC Load Flow, balanced, positive sequence          |     Automatic Model Adaptation for Convergence        No     |
|     Automatic Tap Adjust of Transformers          Yes   |     Max. Acceptable Load Flow Error for                      |
|     Consider Reactive Power Limits                 Yes   |         Nodes                                          1.00 kVA |
|                                                         |         Model Equations                                0.10 %   |

| Grid: Grid                  System Stage: Grid          | Study Case: Study Case               | Annex:              / 1  |

| Grid: Grid                  Summary                                                                                  |
|                                                                                                                      |
| No. of Substations       1          No. of Busbars       30        No. of Terminals      12        No. of Lines         13  |
| No. of 2-w Trfs.         16         No. of 3-w Trfs.     0         No. of syn. Machines  0         No. of asyn.Machines  0  |
| No. of Loads             26         No. of Shunts        0         No. of SVS            0                                    |
|                                                                                                                      |
| Generation            =      0.00  MW           0.00  Mvar      0.00  MVA                                           |
| External Infeed       =     27.30  MW          12.58  Mvar     30.06  MVA                                           |
| Inter Grid Flow       =      0.00  MW           0.00  Mvar                                                          |
| Load P(U)             =     24.79  MW           9.71  Mvar     26.62  MVA                                           |
| Load P(Un)            =     24.79  MW           9.71  Mvar     26.63  MVA                                           |
| Load P(Un-U)          =      0.00  MW           0.00  Mvar                                                          |
| Motor Load            =      0.00  MW           0.00  Mvar      0.00  MVA                                           |
| Grid Losses           =      2.51  MW           2.87  Mvar                                                          |
| Line Charging         =                        -0.10  Mvar                                                          |
| Compensation ind.     =                         0.00  Mvar                                                          |
| Compensation cap.     =                         0.00  Mvar                                                          |
|                                                                                                                      |
| Installed Capacity    =      0.00  MW                                                                                |
| Spinning Reserve      =      0.00  MW                                                                                |
|                                                                                                                      |
| Total Power Factor:                                                                                                  |
|   Generation          =        0.00  [-]                                                                             |
|   Load/Motor          =  0.93 / 0.00  [-]                                                                            |
```

Appendix C: Animated load flow after DG integration




```
-----------------------------------------------------------------------------------------------------------
|                  |                                                 |   DIgSILENT   | Project:           |
|                  |                                                 | PowerFactory  |--------------------|
|                  |                                                 |    15.1.7     | Date:  5/19/2018   |
-----------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                    Grid Summary |
-----------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence             | Automatic Model Adaptation for Convergence      No  |
|     Automatic Tap Adjust of Transformers          Yes     | Max. Acceptable Load Flow Error for                 |
|     Consider Reactive Power Limits                Yes     |      Nodes                                 1.00 kVA |
|                                                           |      Model Equations                       0.10 %   |
-----------------------------------------------------------------------------------------------------------
| Grid: Grid                  System Stage: Grid        | Study Case: Study Case          | Annex:      / 1 |
-----------------------------------------------------------------------------------------------------------
| Grid: Grid                  Summary                                                                     |
|                                                                                                         |
| No. of Substations     1         No. of Busbars       30        No. of Terminals     12        No. of Lines          13 |
| No. of 2-w Trfs.       16        No. of 3-w Trfs.      0        No. of syn. Machines  0        No. of asyn.Machines   0 |
| No. of Loads           26        No. of Shunts         0        No. of SVS            0                               |
|                                                                                                         |
| Generation          =     12.00  MW        0.00  Mvar     12.00  MVA                                   |
| External Infeed     =    -10.19  MW        1.12  Mvar     10.26  MVA                                   |
| Inter Grid Flow     =      0.00  MW        0.00  Mvar                                                  |
| Load P(U)           =      0.44  MW        0.19  Mvar      0.48  MVA                                   |
| Load P(Un)          =      0.44  MW        0.19  Mvar      0.48  MVA                                   |
| Load P(Un-U)        =      0.00  MW       -0.00  Mvar                                                  |
| Motor Load          =      0.00  MW        0.00  Mvar      0.00  MVA                                   |
| Grid Losses         =      1.36  MW        0.94  Mvar                                                  |
| Line Charging       =                     -0.15  Mvar                                                  |
| Compensation ind.   =                      0.00  Mvar                                                  |
| Compensation cap.   =                      0.00  Mvar                                                  |
|                                                                                                         |
| Installed Capacity  =      3.20  MW                                                                     |
| Spinning Reserve    =      0.00  MW                                                                     |
|                                                                                                         |
| Total Power Factor:                                                                                     |
|   Generation        =        1.00  [-]                                                                  |
|   Load/Motor        =  0.92 / 0.00  [-]                                                                 |
-----------------------------------------------------------------------------------------------------------
```

Appendix D: Solar and wind resource availability at Bishoftu (Source: NASA)

A) Solar energy resource

Monthly Averaged Insolation Incident On Horizontal Surface (kWh/m2/day)

Lat 9.1 Lon 37.25	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-yrs Average	6.16	6.58	6.47	6.5	6.3	5.6	4.9	5	5.7	6.1	6.1	6

Monthly Averaged Clear Sky Insolation Incident On A Horizontal Surface (kWh/m2/day)

Lat 9.1 Lon 37.25	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
22-yrs Average	6.61	7.11	7.28	7.53	7.28	6.68	6.7	6.99	6.79	6.79	6.6	6.46

B) Wind energy resource

Monthly Averaged Wind Speed at 50m above the Surface of the Earth (m/**s)**

lat 9.1 Lon 37.25	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
10-year Average	8.4	8.2	7.86	7.9	7.87	8.3	8.01	7.26	7.04	7.29	7.94	8.37	7.88

Monthly Averaged Wind Speed at 10m above the Surface of the Earth (m/s)

Lat: 9.1 Lon 37.25	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual average
10-year Average	7.5	7.33	7.05	7.1	7.06	7.47	5.18	6.58	6.4	6.6	7.11	7.45	7.06