Distribution Network Forecasting and Expansion Planning with Optimal Location and Sizing of Solar Photovoltaic Based Distributed Generation
(Case Study Area: Yirgalem I Distribution Substation)

Endalk Dessalegn Melaku

A Thesis Submitted to Department of Electrical Power and Control Engineering
School of Electrical Engineering and Computing
Presented in Partial Fulfillment of the Requirements for the Degree of Master's
in Electrical Power and Control Engineering (Power System Engineering)

Office of Graduate Studies
Adama Science and Technology University

June, 2022
Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled **Distribution Network Forecasting and Expansion Planning with Optimal Location and Sizing of Solar Photovoltaic Based Distributed Generation (Case Study Area: Yirgalem I Distribution Substation)** is my work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Endalk Dessalegn Melaku		
Name of student	Signature	Date

RECOMMENDATION

I, the advisor of this Thesis, hereby certify that I have read the revised version of the thesis entitled "**Distribution Network Forecasting and Expansion Planning with Optimal Location and Sizing of Solar Photovoltaic Based Distributed Generation" (Case Study Area: Yirgalem I Distribution Substation)** prepared under my guidance by **Endalk Dessalegn Id no Pgr/21844/13** submitted in partial fulfillment of the requirements for the degree of Master's of Science in Power System Engineering Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr.Molla Biweta	________________________	________________
Advisor	Signature	Date

APPROVAL PAGE

I, the advisor of the thesis entitled "**Distribution Network Forecasting and Expansion Planning with Optimal Location and Sizing of Solar Photovoltaic Based Distributed Generation" (Case Study Area: Yirgalem I Distribution Substation)**" and developed by **Endalk Dessalegn Melaku**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr.Molla Biweta	______________________	_______________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Endalk Dessalegn Melaku** have read and evaluated the thesis entitled **Distribution Network Forecasting and Expansion Planning with Optimal Location and Sizing of Solar Photovoltaic Based Distributed Generation" (Case Study Area: Yirgalem I Distribution Substation)**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in power System Engineering.

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LIST OF ABBREVIATIONS

AAC	All Aluminium Conductor
AC	Alternating Current
BOS	Balance of the System
DC	Direct Current
DG	Distributed Generation
DPEF	Distribution Permanent Earth Fault
DPSC	Distribution Permanent Short Circuit
DTEF	Distribution Temporary Earth Fault
DTSC	Distribution Temporary Short Circuit
EEU	Ethiopian Electric Utility
ETAP	Electrical Transient Analyzer Program
ETB	Ethiopian Birr
FACDs	Flexible AC Distribution system
GC	Gregorian Calender
GDP	Gross Domestic Product
GHG	Green House Gas
GPS	Global Positioning System
IEA	International Electric Agency
IEEE	International Electrical and Electronic Engineering
IMP	Current at Maximum Power
IRENA	International Renewable Energy Agency
ISC	Short Circuit Current
KM	Kilo Meter
KV	Kilo Volt
KVA	Kilo Volt-Amper
KVARH	Kilo Volt Amper Reactive Hour
KW	Kilo Watt
KWH	Kilo Watt-Hour
LTCs	Long-Term Compensation Scheme
MATLAB	Matrix Laboratory

MLDG	Multiple Location Distributed Generation
MPPT	Maximum Power Point Tracking
MVA	Mega Volt
MVAR	Mega Volt Amper Reactive
MW	Mega Watt
MWH	Mega Watt Hour
NASA	National Aeronautic and Space Administration
OL	Over Load
PD	Peak Demand
PF	Power Factor
PL	Power Loss
PLR	Power Loss Reduction
Pmax	Maximum Power
Pmin	Minimum Power
PU	Per Unit
PV	Photovoltaic
RDN	Radial Distribution Network
SPV	Solar Photovoltaic
THD	Total Harmonic Distortion
USD	United States Dollar
VAR	Volt-Ampere Reactive
VMP	Voltage at Maximum Power
VOC	Open Circuit Voltage

ABSTRACT
Load forecasting is the prediction of demand for a future period, and it is a critical necessity for distribution system design and growth while also meeting all operational and technical constraints. Solar Photovoltaic (SPV) based Distributed Generation (DG) technology is the most direct way to convert solar energy into electrical energy without emitting carbon dioxide or causing greenhouse gas emissions. It also provides consumers with a reliable, clean, efficient, and continuous source of electrical energy. The integration of SPV DG changes the operating characteristics of modern power systems, resulting in significant economic and technical outcomes such as minimizing losses, and improving voltage profile. In this thesis, the peak load demand forecast for Yirgalem I distribution network for the years 2020/21- 2030/31 is done using least square extrapolation technique and the load growth rate of each feeder has been computed. In addition, from two-year average recorded data, the case study distribution feeder was identified as having higher interruption as compared to other feeders. As a result, Yirgalem town feeder has been chosen as a case study feeder. The modeling and simulation of this feeder has been carried out using ETAP software with and without integration SPV DG and sizing is done by Analytical method with the help of MATLAB program. *The load flow result before integration showed that the total real and reactive power loss was 1.1133 MW and 0.5451 MVAR respectively with majority of bus voltages being outside the allowable range of 1 ± 5%. Based on the Analytical approach and load flow analysis, SPV DG has been installed in the system at the appropriate capacity and location to reduce overall power losses, as well as to bring all node voltages within acceptable ranges. The proper site and size of the SPV DG were determined to be at bus 9 with a proper active power size of 7.86 MW and reactive power size of 4.03 MVAR. As a result, the percentage reduction of real and reactive loss was found to be 90.95% and 92.9% respectively with all bus voltages being within the limit and the minimum voltage at bus 24 improved from 0.8428 p.u to 0.9583 p.u. For further reduction of power loss, enhancement of voltage profile, and, economic benefits, the optimal size of SPV DG at two locations is considered with selected scenarios. Results show that the injection of 6.29 MW plus 3.23 MVAR at bus 9 and 1.57 MW plus 0.8 MVAR at bus 24, reduces the active and reactive power loss by 94.03% and 96.07%, respectively and the voltage profile improved drastically as compared to a single SPV DG location. Furthermore, SPV DG of the same size at two locations saves 359,961 Birr per year more than at a single location.*

Keywords: Analytical technique, Distributed generation (DG), Distribution expansion planning, ETAP software, least square, MATLAB, Power loss, Solar Photovoltaic, Voltage profile

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Distribution system planning involves the principle to grow a strategy to meet the utility's long-term power delivery needs, usually minimizing cost by bringing about an optimal balance between capital additions and operational costs. It particularly requires that the distribution planner review every alternative, including load forecasts, revenue constraints, reliability, and a lot of other factors. In this thesis, the planned method addressed a solution for distribution network expansion planning while meeting the proposed constraints of the network.

Distributed Generation (DG) is a modest source of electric power generation that ranges from a few kilowatts to several tens of megawatts and is connected to the distribution network or directly to the loads rather than being located in a central power plant. Energy sources for DG might be renewable or non-renewable. Combustion turbines, steam turbines, micro-turbines, and fuel cells that use natural gas or petrol are non-renewable energy sources, whereas solar, wind turbines, small-hydro, biomass, and geothermal are renewable DG energy sources. The implementation of DGs in the power system has grown in recent decades due to several benefits, including power losses reduction, power quality enhancement, voltage deviation improvement, power generation cost reduction, reducing Total Harmonic Distortion (THD), and increasing the efficiency, with less pollution. The DGs are modular systems; their planning and time required for installation are shorter than other centralized power plants. Furthermore, it is easy to implement them in remote areas to supply electricity without requiring long transmission and distribution lines (Kamaruzzaman et al., 2015).

The load current drawn from the source would rise dramatically in a heavily loaded distribution network. As a result, voltage drop and system losses may increase. Because of the decrease in voltage magnitude and increase in distribution network losses, the distribution system's performance deteriorates. As a result, the changing environment of power system design and operation has necessitated the incorporation of distributed generators into an active distribution network (DG).

Short circuit current, voltage output, line losses, system stability, and reliability are all affected by DG integration. As a result, these parameters must be studied prior to introducing DG into the system. The studies conducted so far have proved that the non-optimal placement of DG can overshoot the line losses which can exceed the line losses without DG. If DG sizing is enhanced; it can reduce the line losses but a further rise in size can increase losses. Moreover; if the DG is placed at a particular bus at which voltage is lowest; it can improve the voltage but if it is placed at a node where the voltage is already high; it can cause a violation of permissible voltage limits. The appropriate and optimal placement of DG can be carried out using Analytical methods; intelligent methods and numerical methods (Kaur et al., 2016).

In this thesis, Load flow analysis with an injection of SPV DG at each bus with corresponding capacity found at each bus by considering total power loss reduction and voltage profile improvement was determined with proper capacity and placement of SPV DG. The load flow study of the sample network was simulated using the ETAP software tool and sizing of SPV DG is done with Analytical method with the help of MATLAB program. By integrated SPV DG, this thesis addresses the problems of voltage profile, power loss of the distribution network and to meet the future load demand. It also investigates the role of SPV DG integration in the expansion planning of distribution systems for a sustainable and clean energy supply.

1.2. Statement of the Problem

Nowadays, in Ethiopia demand for electrical energy is rising due to fast population growth, social and economic developments as well as transformation plans. But the existing distribution system cannot be capable of supplying the load (residential, commercial, and industrial) reliably in the next years due to technical and operational problems.

Yirgalem I distribution substation has five outgoing feeders supplying different areas of the city which include residential, commercial, and industrial loads. The current problems in the Yirgalem I distribution network are a high frequency of Interruptions, power losses, and voltage drops and as a result, economic losses have been seen at the end-user. The main reasons for these problems may be that the power grid is too old, and networks were constructed without proper planning. One of the best solutions used to enhance the overall performance of the distribution system is integrating with distributed generation especially solar photovoltaic-based DG. Proper installation of SPV DG minimize the total power loss as well as improve the voltage profile of the system. In addition to these, advancements in SPV DG technologies have made them a reasonable and desirable option for system expansion planning to support the grid and to meet the future load demand.

1.3. General and Specific Objectives

The general and specific objectives of the study are summarized in this section.

1.3.1. General Objective

The main goal of this thesis is to integrate SPV-based Distributed Generation (DG) with distribution network expansion planning to satisfy expected load requirements, reduce power loss, and enhance voltage profile.

1.3.2. Specific Objectives

The specific objectives are to:

- Identify the base case distribution feeder from the rest of the feeders based on their longer duration and higher frequency of interruption.
- Forecast the peak load demand of Yirgalem I distribution substation for the next 10 years.
- Determine the proper size and identify the proper location of SPV DG.
- Improve the distribution network specifically in terms of voltage profile and power loss.

1.4. Significance of the Study

This thesis provides an analytical method branch current loss-based technique apply in distribution network expansion planning considering SPV DG for power loss and voltage deviation minimization by optimally placing and sizing of the SPV DG in the distribution network has a significant role for the local distribution company as well as the end-users such as:

- To know the future electrical load demands.
- To minimize power loss and optimize the voltage profile
- To reduce the cost of transmission and distribution, and increase profitability.
- Emission-free, resulting in environmental benefit.

1.5. Scope of the Study

This thesis covers, forecasting future demand, studying, and analyzing Distribution network expansion planning in the case of Yirgalem I distribution system using ETAP software, and studying the current power system problems such as power loss and voltage profile of the of the distribution system. And the research is limited to:

- Only the SPV DG's integration is considered.
- The number of SPV DG is limited to two.
- To avoid reverse power flow in the network SPV DG capacity is limited to 20 to 85 percent of total feeder demands in distribution networks and, voltage constraints are kept to within $\pm$ 5% of the nominal value.

1.6. Organization of the Thesis

This thesis is organized with six chapters which are summarized below:

The first chapter of the thesis work focuses on the study's background, objective, problem statement, significance, scope of the study.

The second chapter discuss the theoretical background related to this work and review of different literature such as journal articles, conference papers, and thesis works related to this study.

Chapter three focuses on site description, data collection, and data analysis of Yirgalem I distribution system.

Chapter four deals with the distribution system demand forecasting and the methodology of SPV DG sizing and placement is discussed in this chapter.

Chapter five covers distribution feeder modeling and simulation with ETAP 19.01 software before and after integration of SPV DG. In addition, cost analysis of the designed system.

Conclusion, recommendations, and suggestions for future work are included in chapter six.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Theoretical Background

Power system planning is a subset of a larger issue, energy, and economic development planning. Its goal is to come up with a low-cost strategy for the long-term growth of a generation, transmission, and distribution system that will meet the load prediction while staying within a set of technical and economic restrictions (Praveen et al., 2018).

This chapter focused on theoretical background and review of different kinds of literature related to distribution network expansion planning and demand forecasting with its techniques. moreover, this chapter includes a critical examination of distributed generation concepts and technology, as well as their technical impacts and the role of DG technology in modernizing the existing distribution network.

2.1.1. Distribution Expansion Planning

Distribution network expansion planning is needed to verify that the growing energy demand can be fulfilled by distribution system additions that are both technically adequate and reasonably inexpensive. Although substantial work has been undertaken in the past on the use of some type of systematic methodology for generation and transmission system planning, its application to distribution system planning has unfortunately been relatively overlooked. Electric utilities will need a fast and cost-effective planning tool in the future, more than ever before, to evaluate the consequences of various proposed alternatives and their impact on the rest of the system to provide consumers with the necessary affordable, reliable, and safe electric energy.

The goal of distribution network expansion planning is to ensure that rising electricity demand, as measured by increasing growth rates and high load densities, can be met in the most effective way possible by additional distribution systems, ranging from secondary conductors to bulk power substations, that are both technically adequate and reasonably cost-effective. All these issues, as well as others such as the shortage of usable land in urban areas and environmental concerns, can make the challenge of optimal distribution system expansion planning beyond the human mind's ability to solve. Within the planning period, distribution planners must guarantee that there is enough distribution substation and electrical feeder capacity to meet the expected load. The distribution substations must then be situated and sized to serve the load as cost-effectively as possible by minimizing feeder losses and construction costs while keeping service reliability in consideration.

Most power systems are assumed to be radial, meaning that electricity travels from the source to the load or from the generator to the consumers. With the development of distributed generation technology, this paradigm has developed, and electricity now flows not only from centralized sources but also from other sources, such as distributed generation, allowing power to flow from centralized to distributed generation and vice versa (Gonen, 2015).

2.1.2. Distribution System Demand Forecasting

Predicting future load demand for industries, utility corporations, and customers over a specified period is known as electrical load demand forecasting (Gupta & Pal, 2017). There are three types of load forecasting based on time duration these are:

- Long-term load forecasting (10 years period).
- Medium-term load forecasting (5-6 years period).
- Short-term load forecasting (1-2 years).

2.1.3. Demand Forecasting Techniques

A fundamental necessity for expansion planning studies is load forecasting.Transmission planning, generation planning, distribution planning, and operational planning all require load forecast results. Large consumers are frequently more optimistic about future growth than the current economic context warrants. This could lead to an overestimation of load and, as a result, an overinvestment. Decisions based on rough growth in the past may not be a good guide to growth in the future in power markets where demand is going to saturate.

The technique adopted will depend on the time frame under consideration, the size of the system, and the plant available. In other words, the type of demand forecasting technique used should be appropriate for the study's requirements (Hailemariam, 2018). There are four main demand forecasting techniques.

- Intuitive based demand forecasting
- Extrapolation based demand forecast
- End-user demand forecast
- Econometric demand forecasting

Intuitive Based Demand Forecasting

Intuitive forecasting refers to methods that rely heavily on experience and quick calculations based on simple assumptions (i.e., the application of recent performance and the assumption that change rates would remain unchanged in the future).

The intuitive load forecast should not be completely discounted; after all, it is at the back of reviewers' thoughts when they evaluate other people's demand forecasts. Due to a lack of relevant data in some cases, intuitive forecasting may be the only choice. Minor developments, isolated systems, and small island utilities may benefit from the forecast.

A different technique, but one that is still within the intuitive forecasting framework, is to use a growth factor calculated for a country with similar economic characteristics. Indeed, comparing load estimates to the performance of a similar system in another part of the world at a similar stage of development could be beneficial. This will be especially true in situations where i) there is limited statistical information on previous loads, such as in new areas of supply, ii) data inaccuracies are difficult to correct, or iii) forecasting is based on direct inquiry, demographic, and economic statistics. Although such forecasting is merely guesswork, the data can be used to double-check forecasts made using more scientific approaches. When developing a new forecasting system, a comparison of previous intuitive forecasts and subsequent performance is typically beneficial.

Extrapolation Based Demand Forecasting

Historical trends in energy and power demand are extrapolated into the future using extrapolation methods. Any time series can be divided into three main components.

- Trend
- Seasonal variation
- Auto-regression

The trend forecasting technique takes past growth rates of electrical load demand and extrapolates them into the future using a variety of techniques ranging from the most basic to the most complicated. This technique uses previous electrical load demand changes to forecast future electrical load demand changes, and it is continuously updated based on knowledge of future developmental aspects that cause future electrical demand to behave differently than past electrical demand. When there isn't enough data to apply more complicated approaches, trend analysis is a basic, quick, and inexpensive option.

End-user Based Demand Forecasting

Many utility forecasting approaches are used in end-user demand forecast modeling. The detailed description of how energy is used is the defining feature of end-user modeling. Typically, such models start by identifying the end applications for which energy is required, such as heating water, cooling buildings, and cooking food. The model then defines the sorts of energy-consuming equipment that enterprises and homes have, as well as how much energy each type of equipment uses to meet the predetermined amounts of end-use energy requested, using mathematical equations and accounting identities. A model like this requires a lot of survey data and statistics. Optimization Accounting end-user models are a step up from end-user models. The accounting end-user model can be transformed into a device that predicts how customers will act (assuming that their objective function is properly specified) given the assumptions about costs and constraints by specifying an objective function (such as minimizing cost) and identifying both the unit costs of using energy in the given processes and the constraints to the system.

End-user models are typically bad at predicting consumer fuel usage. They can simply characterize where energy is utilized and for what purposes using the available data, but they are restricted in their capacity to predict the future without a theory to explain choices. The ideal end-user model (rarely realized) would, for example, inform us not just the average watts of lighting energy consumed in households and how this has changed over time, but also what prompted households and/or housing operators to make these changes.

End-user forecasting, particularly for green-field initiatives and residential demand estimates, can be extremely accurate. Load density-based forecasting is an extension of end-user demand forecasting, in which the maximum load in each region is determined by the surface area occupied by each consumer type and the power density (watts per square meter) associated with that consumer type. This is especially beneficial when it comes to distribution planning. End-user projections also include advances in industries and agriculture, where consumption patterns, such as cement manufacturing or water pumping, can be developed.

Econometric Based Demand Forecasting

This type of model, like the time series model (extrapolation), forecasts the future using historical data. Econometric analysis, on the other hand, seeks to go beyond time series models by explaining the causes of observed trends. Economic (e.g. GDP), technological (e.g. number and type of appliances; industrial processes), demographic (e.g. population), or other variables are all included in econometric models (e.g. weather).

If these assumptions are correct, it should be possible to determine historical connections between electricity demand and variables such as GDP by sector, personal income, electricity prices, and so on. These economic variables' future values are then predicted and utilized as inputs to calculate future consumption levels. The ease with which high and low scenario load projections may be obtained, as well as the logical basis on which they can be built, is one advantage of econometric forecasting. Changes in the forecast rate of the input variables, such as economic growth and electricity price, are all that is required. Faster economic growth will result in higher load forecasts, whereas price rises will result in lower energy demand forecasts. In favor of econometric modeling, time series analysis should be avoided. Even if both strategies were equally accurate at forecasting demand changes, the econometric model would be more useful because it might aid in understanding why demand changes were occurring.

2.1.4 Distributed Generation

Distributed Generation is a small-scale electricity generating technology that is connected to loads of consumers via a power utility's distribution system to provide electricity closer to customers than a central station. DG is a new approach based on renewable energy resources that have the potential to become a critical component of the electric power grid. DG can alternatively be thought of as a power generation unit that is injected into the distribution network without regard for transmission lines. The power generated by these DGs is not connected to the national grid because the output varies from a few kilowatts to several megawatts depending on the voltage rate (Sarabia, 2011).

Table 2. 1 Classification and DG Sizing

Classification of DG	Size of DG	
	P_{min}	P_{max}
Micro distributed generation	1 W	5 KW
Small distributed generation	5 KW	5 MW
Medium distributed generation	5 MW	50 MW
Large distributed generation	50 MW	300 MW

2.1.5. Distributed Generation Technologies

Distributed Generation technologies are modular generating units that are used as an alternative to conventional power systems to reduce power outages. They each have their own set of limitations, features, and benefits. The distribution system's reliability was examined using renewable resources such as wind turbines and solar energy. There are two types of distributed generation technologies: The diagram below shows renewable versus non-renewable distribution technology.

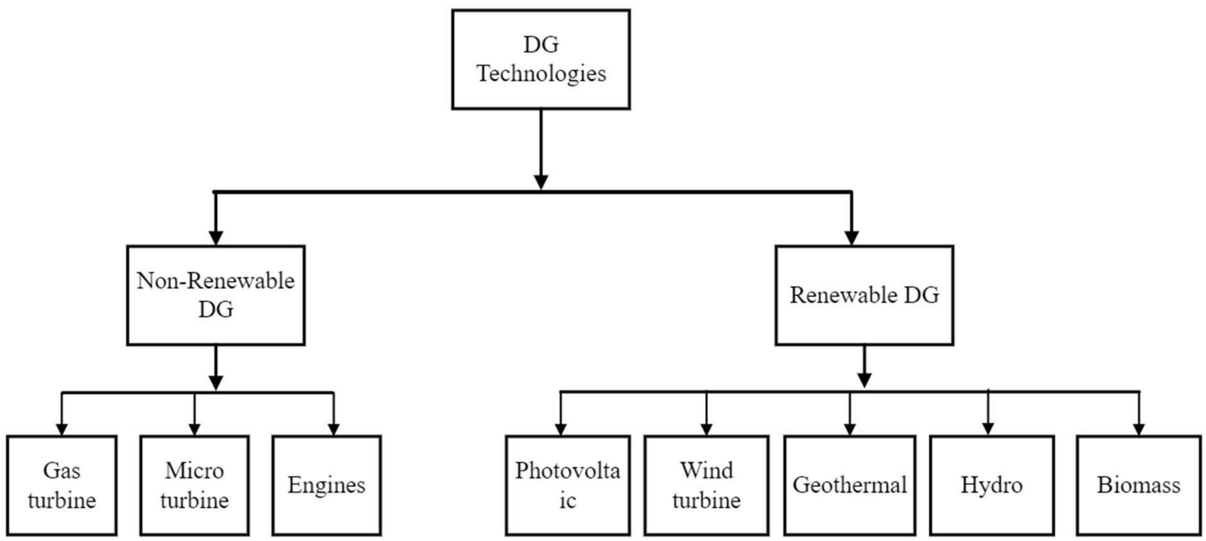

Figure 2. 1 Types of DG technologies (Getie, 2020)

Non-renewable technologies rely on fossil-based fuels like natural gas, coal, and petroleum to produce energy for different operations. However, the burning of fossil fuels is responsible for most of the global warming, greenhouse gas (GHG) emissions, acid rain, and petrochemical pollution currently being experienced around the planet. Non-renewable resources are unsustainable and cannot be transformed by natural processes. They will eventually run out of use as a result of these factors, as the high rate of energy demand from non-renewable energy resources outpaces the process of repairing them within the Earth.

Through a cogeneration arrangement, nonrenewable DG technologies can be employed for power generation as well as the production of heat energy for household and industrial uses. Reciprocating engines, gas turbines, micro-turbines, and steam turbines are examples of non-renewable technologies (Getie, 2020).

Renewable distributed generation (DG) technologies are medium or low voltage electric power generation resources that are directly connected to a load of customers on distribution systems.

Geothermal power, biomass, photovoltaic (PV), small/mini/micro-hydropower, and wind turbines are examples of DG technologies that fall into this category. Renewable DG technologies' output electricity can be routed to the grid at the request of utility grid operators or used as a stand-alone system to service a specific load or area.

2.1.5.1 Wind turbine

Wind energy has been around for a long time and can be considered a distributed generating source if it is close to a demand source. Wind turbine farms can generally be found in places with high and consistent wind speeds throughout the year. The yearly capacity factor of a typical wind turbine area is 20-40%. With six-month interval maintenance, a typical wind turbine can operate for more than 20 years. The rotation of the wind turbine transfers mechanical energy from the wind to a gearbox attached to an electrical generator. The typical size of a wind turbine ranges from a few hundred watts for household use to massive turbines with a power of over 5 MW (Wilson & Spera, 2009).

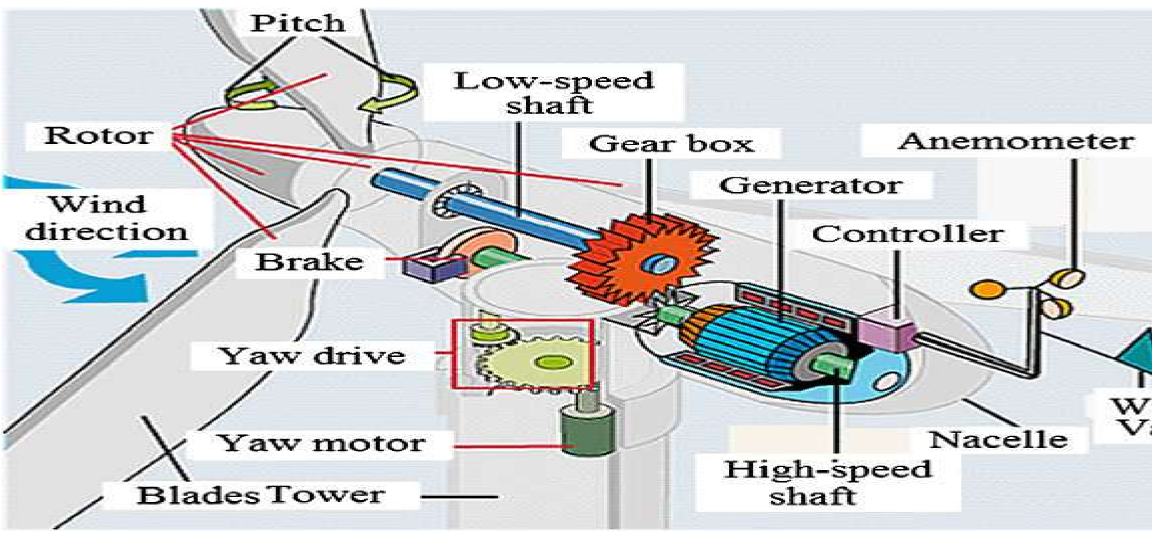

Figure 2. 2 Parts of wind turbine (Mahmoud & Xia, 2012)

2.1.5.2 Solar Photovoltaic system

The PV system consists of an array of PV cells, a controller, an electronics interface, and other associated auxiliaries that convert solar radiation into electrical energy directly. Solar insolation, PV module position, and cell temperature all influence the PV cell's output power. Because of the environmentally friendly nature of solar resources, it is a viable alternative to the conventional power system. PV systems can be configured to produce either alternating current or direct current, depending on the load requirements, with the right configuration and conversion devices. PV systems can run in parallel with the utility grid to reduce peak demand, or they can run independently to fulfill a specific load. PV systems can be configured and connected to the grid using feed-in and net metering methods.

PV systems are modular, simple to install, energy independent, and environmentally friendly, with no fuel expenditures, no pollution, long service lifespan, and low operating and maintenance costs. Solar energy is widely recognized as one of the renewable energy sources that can help to minimize reliance on fossil-fuel-based conventional power generation.

Solar systems come in a variety of shapes and sizes, ranging from small residential systems with a capacity of less than 10 kW to medium-sized systems with a capacity of 10–100 kW and large systems with a capacity of more than 100 kW. These systems can be employed as stand-alone systems, hybrid systems with other energy sources, or directly connected to the power grid for interactive energy exchange.

Commercial solar modules generate electricity from the sun with a 10-20% energy efficiency. This indicates that 10-20% of the solar energy that strikes the module is captured and converted into electricity. Scientists and research facilities are putting in a lot of work to improve these efficiency ratios and lower the costs of solar applications.

A solar array is a collection of numerous modules that are electrically connected in series and parallel to generate the desired current and voltage. The essential elements of a PV system are the modules, which are commonly connected in series and parallel are referred to as a PV string. But several components are needed to construct a grid-connected PV system to perform the power generation and conversion functions.

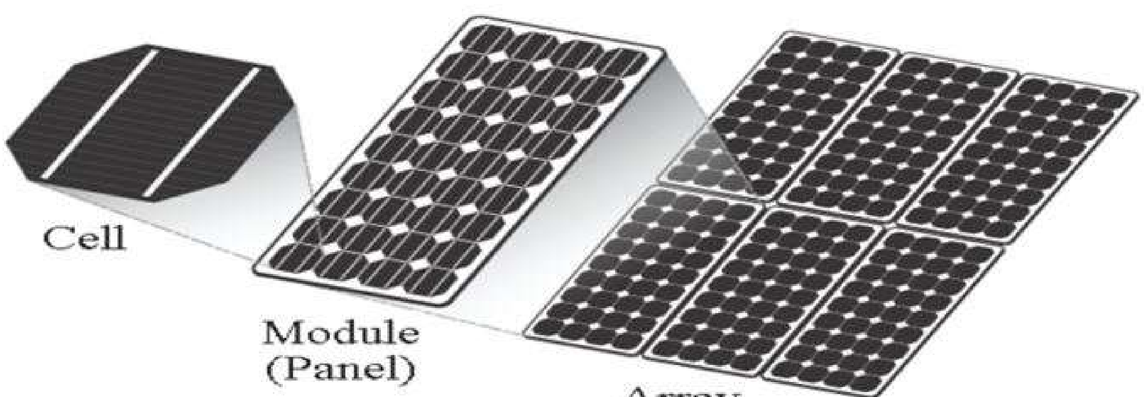

Figure 2. 3 Distinction between cells, modules, and arrays (Afrouzi et al., 2013)

The power conversion of the array output power into AC power suitable for grid injection is done by a three-phase inverter. Pulse width modulation control is one method for shaping the magnitude and phase of the inverter output voltage.

Solar photovoltaic DG applicable from micro-scale to utility-scale:

- Micro-scale SPV DG - highly distributed as single-phase units (e.g 200-400 w) size.
- Small-scale SPV DG -such scale is installed on the roof of residential buildings as single-phase units (e.g 5 to 10 kW) size.
- Medium-scale SPV DG-consist of larger size in Kw which installed on the top roof of commercial building as three-phase units (e.g 10 to 500 kw) size.
- Utility-scale SPV DG- consists of mega-watt size three-phase units and nominal capacity is decided by the utility company.

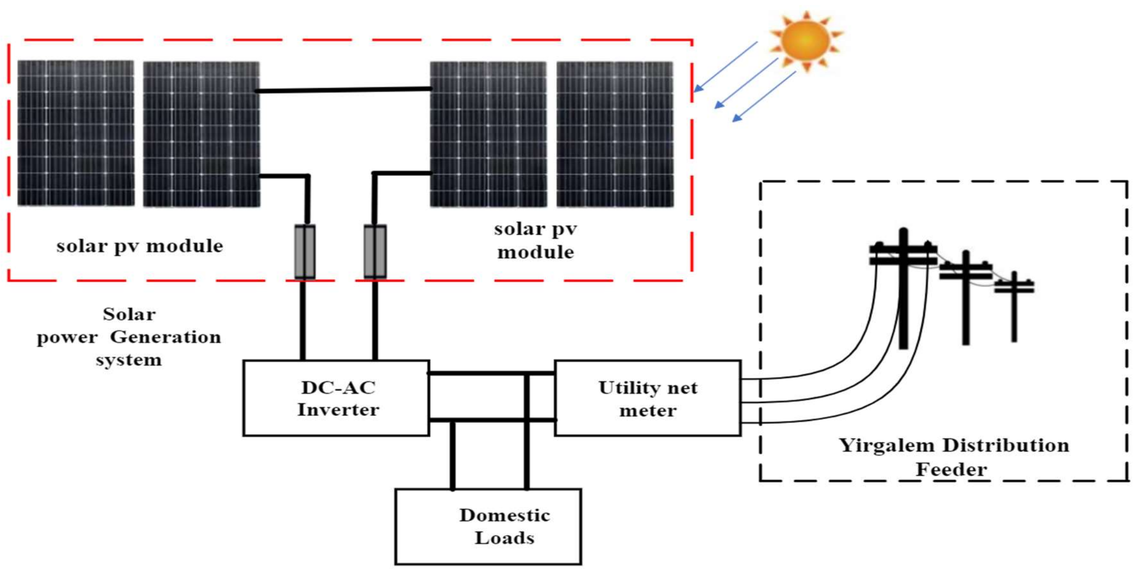

Figure 2. 4 Schematic diagram of grid-connected solar PV system

Impacts of SPV Distributed Generation Integration on Distribution System

Potential grid-connected solar photovoltaic system implications on distribution systems Renewable energy sources, particularly PV systems, have become highly important sources. Connecting large PV systems to utility grids, on the other hand, might cause dozens of new distribution network problems. The severity of these problems is largely determined by the location of the installation and the percentage of PV penetration. As a result, understanding the potential consequences of large grid-connected PV systems on distribution networks helps in making intelligent and practical decisions before the installation and operation of integrated systems (Caamaño-Martín et al., 2008).

1) **Impact of the photovoltaic plant on voltage profile**

Power is fed at the highest voltage level and consumed at the lowest voltage level in typical electrical distribution networks. As a result, the line voltage drops in direct proportion to the distance between the voltage source and the loads present now of measurement. The voltage must, however, be kept within the range prescribed by recommendations and standards for the safety of machinery and appliances. Power utilities use a variety of technical countermeasures to keep the voltage within a certain range.

When the amount of electricity generated by a PV system exceeds the amount of electricity consumed at the point of use, the excess power is likely to be returned to the grid. The voltage rises as a result, and the electric current flow inverts, moving towards the end. This issue is unimportant in urban grids with strong networks but limited PV capacity but high grid impedance. The voltage can rise above the maximum limit if PV penetration increases or if several PV systems are connected to a low-impedance rural grid. The voltage profile could be improved if efforts are made to optimize the site while connecting PV to a distribution network. This is especially important for long-distance feeders, which must avoid voltage drops (Alzyoud et al., 2021).

2) **Impact of a photovoltaic plant on power loss**

Huge amounts of power is lost in a variety of ways when power is transferred and delivered to loads, especially when big power plants are located hundreds of kilometers from the site of demand. Power travels with a proportionality loss and a distance that varies depending on geography. PV systems, which offer minimal power loss, produce power at the sites of use and are dependent on the availability of solar radiation. Because the PV unit can be integrated with, or mounted on, the building demanding electricity, no land is required. As a result, the PV system's value to the grid is increased. The value of on-site PV output generation at the point of demand is used by most IEA members.

The placement of DG units for loss reduction is like the placement of capacitor banks for loss reduction. The main difference between the two cases is that DG may supply both active and reactive power (P and Q). Capacitor banks, on the other hand, are only used to support in the flow of reactive power (Q). The photovoltaic system has a unity power factor but due to interfacing the inverter mostly operates with a power factor of 0.9 lagging to unity (Begovic et al., 2012). Inverters, on the other hand, help with reactive power compensation.

The best DG placement can be found utilizing load flow analysis software, which can explore the best DG location within the system to minimize losses. If feeder losses are substantial, for example, adding several small capacities DGs will have a significant positive effect on the losses and will be beneficial to the system. If additional units are added, however, they must be put within the feeder capacity restrictions (Rasmin, 2014). For example, because overhead lines and cables have thermal characteristics that cannot be exceeded, feeder capacity may be limited.

3) Impact of a photovoltaic plant on short circuit level

The DG's nature also affects the short circuit levels. The synchronous generator is the DG that focuses on mistakes the most. During the first few cycles, it contributes equally to the induction generator and the self-excited synchronous generator, but after those cycles, the synchronous generator is the DG type that contributes the most fault current. The fault current contribution of the inverter interfaced DG type is the smallest, with some inverter types sustaining the fault contribution for less than one cycle. Even while a few cycles is a short duration, in some circumstances it may be long enough to affect fuse breaker coordination and breaker responsibilities (Jennett et al., 2012).

Because the DG inverter is interfaced and has minimal fault current impacts, PV grid-connected systems do not significantly contribute to distribution network short-circuit faults, and the short-circuit current of a PV array is self-limited, ideally 10 percent -20 percent higher than the maximum rated power current (Caamaño-Martín et al., 2008). The impact of fault should be considered when inverter controls are altered to fulfill other tasks, such as voltage support, or when controls are operating in weak networks. In any case, for short-circuit protection at various fault levels, proper coordination of multiple protection techniques (customer sites, PV-DG, and network) is necessary.

Mitigation measures

The nature of the impacts identified during the studies (steady-state, dynamic, or both) as well as applicable legislation, policies, and standards determine mitigation solutions. Traditional and smart grid approaches to minimizing PV-DG consequences can be divided into two categories. One of the usual methods is to use current technologies. (Begovic et al., 2012), examples of this are:

- Set line voltage regulators and LTCs to cogeneration or bidirectional operating modes, and adjust or tune their control parameters (e.g. reference voltage) to account for the voltage rise and load offset introduced by PV-DG plants (e.g. for Line Drop Compensation applications).

- Capacitor bank control settings should be changed, existing capacitor banks should be relocated, and fixed capacitor banks should have controls installed.
- Rebalance feeder loads to reduce voltage fluctuations and prevent steady-state high voltage, voltage, and current unbalance.
- Use express or dedicated feeders for independent connections of utility-scale PV-DG installations. When selecting the length of express feeders and the maximum capacity of PV-DG plants to be coupled by them, factors such as express feeder voltage and annual energy losses are necessary to consider.

The other one is smart grid approaches make use of new technologies (Begovic et al., 2012). Examples of this are

- Under the power factor schedule, adjusting SPV DG to run at non-unity power factor (absorbing var within inverter limit). However, in some circumstances, using a fixed non-unity leading power factor does not minimize voltage variations or voltage violations produced by intermittency during rapid PV-DG output fluctuations (incident solar radiation fluctuation due to clouding). Such a situation may require implementing a dynamic volt-VAr compensation scheme using PV-DG inverters, this scheme dynamically modifies the inverter's reactive power output, i.e., the plant power factor, to keep voltages within predefined limits.
- Implement volt-var compensation scheme either by using PV-DG inverter or using flexible AC distribution system (FACDS) such as distribution static synchronous compensator known as D-var.
- To avoid overcurrent protection failure, use directional protection.
- Use a GPS-based synchro phasor measuring approach to detect islanding.

Advantages and drawbacks of a solar photovoltaic system

Solar energy has both benefits and drawbacks; the benefits of solar energy systems can be seen by

- Solar energy is widely available, and solar systems are flexible; They can be utilized in a range of applications and are easy to install.
- Peak demand occurs during the midday hours, when solar energy delivers more energy.
- Solar structures can work for long periods 25-30 years with minimum maintenance and operating costs.
- Solar energy is pollution-free, clean, and safe for the environment.
- The major and most fundamental benefit of solar systems is that their energy source is endless, free of charge, and available at all times.

Although solar energy is a clean and inexpensive source of electricity, it does have some drawbacks. The primary drawbacks of solar energy are as follows:

- Solar energy must be stored in batteries, especially in remote places, which increases prices and requires additional maintenance.
- The most important drawback of solar energy resides in its initial costs if compared to other large-scale electrical power sources. However, in the last 10 years, the costs of solar energy have decreased to about in great extent due to the use of new technologies in their production and development.
- Another disadvantage of solar systems is that its output power varies depending on solar irradiation and temperature. Areas that have short day times or are covered by clouds for long periods will produce very low amounts of energy. Over more, the efficiency of solar arrays is less than 20 %; this means more and more reduction in power generation.

2.1.6. Types of Electrical Loads

The nature of the load has a significant impact on the design and functioning of a power system. It's difficult to predict the load's exact composition. Its composition also varies depending on a variety of elements such as time, weather, and the situation of the economy. In power flow studies, the composite load characteristic as seen from power delivery locations is typically represented. Constant power load models can be used to represent loads in transmission networks because voltages are frequently regulated by various control devices at delivery points. Because most nodes in distribution systems are not voltage controlled, voltages vary greatly along with system feeders; as a result, load characteristics are more essential in distribution system analysis (Roy et al., 2011). Most distribution scheme study is considering static load models such as:

Constant impedance load (constant Z): The power varies with the square of the voltage magnitude in a static load scenario. The constant admittance load model is another name for it.

Constant current load (constant I): A static load model in which power is proportional to voltage magnitude.

Constant power load (constant P): A static load model in which the power does not change while the voltage magnitude varies. The constant MVA load model is another name for it.

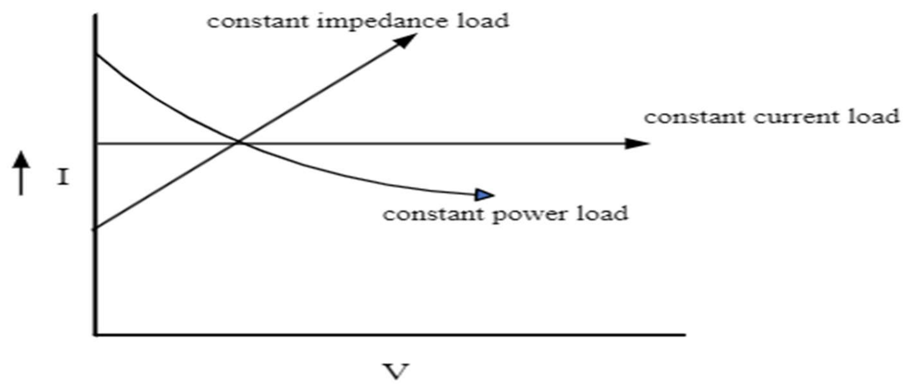

Figure 2. 5 V-I Curve of electrical loads *(Degefa et al., 2013)*

Power (P) = $P_i \left(\frac{V}{Vi}\right)^k$ k=0, for constant power load

P=power at voltage v k=1, for constant current load

P_i=nominal power at nominal voltage v_i k=2, for constant impedance load

K is constant

2.1.7. Solar Energy Potential in Ethiopia

Ethiopia is one of the East African nations with an abundance of solar energy. The country's average annual irradiance is at 5.2 kWh/m2/day. The solar resource is lower in the central, northern, and western high lands of the country and higher solar resource is available in the areas near to rift valley, western and eastern low lands with average annual irradiance of 6kwh/m^2/day (Hailu & Kumsa, 2021). This indicates the annual available solar resources are enough to generate thousands of megawatt power but only 14 MW of power is installed for the application of lighting, telecom service, and pumping purposes in remote areas of the country. (Senshaw, 2014) currently, Ethiopia plans to construct the 100 MW PV power project located in near Metehara while, the remaining sites are in Mekele and Humera, were not awarded. In addition to this, the country planned to construct 125 MW of solar PV power in Somali and Afar regions (Hailu & Kumsa, 2021).

off-grid solar solutions should be prioritized by the government as an immediate solution for un-electrified rural households that are far from the electric grid and not covered by the densification program in the short term.

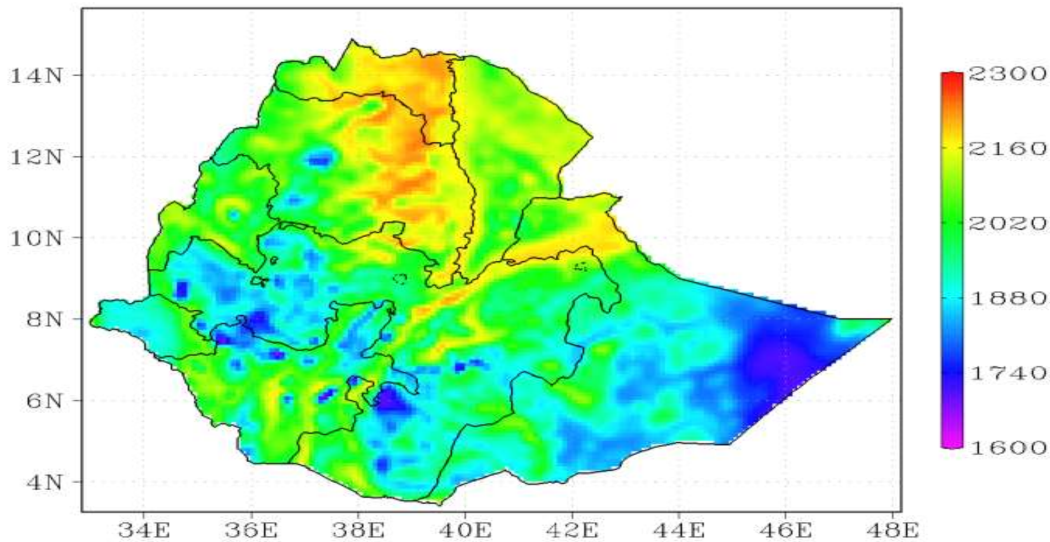

Figure 2. 6 Distribution of average annual total solar radiation in kWh/m2 (Derbew, 2013)

2.2. Review of other Related Works

According to (Acharya et al., 2006) DG can offer a fraction of real and/or reactive power in distribution networks, lowering the feeder current and improving voltage profile by minimizing losses. In contrast, this article proposes an analytical expression to calculate the optimal size and an effective methodology to identify the corresponding optimum location for DG placement in primary distribution systems for minimizing total power losses and shows that poor location and size selection would result in higher losses than losses without DGs.

The paper (Jamil & Anees, 2016) is based on an analytical technique for optimal SPV-based multiple location distributed generation (MLDG) placement and sizing to improve voltage profile and reduce distribution network power loss. According to this study, MLDG's optimal location and sizing are more significant and cost-effective than DG at a single location.

The paper in (Singh & Ghosh, 2014) focuses on comparing two analytical methodologies for the appropriate placement and sizing of the DG unit by minimizing power losses and voltage deviation by assessing several indices. After comparing the two methods, it can be determined that the loss sensitivity method reduces loss more and is better at judging the site of DG. The voltage sensitivity analysis index method is a preferable option when it comes to sizing.

(Ehsan & Yang, 2018) Several traditional, analytical techniques and metaheuristic strategies for addressing the optimal distributed generation planning problem are discussed in this paper.

According to (Madjissembaye et al., 2016) the strategic siting and sizing of the SPV DG for loss reduction in a radial distribution network (RDN) was explored with various loading cases, taking into account constraints on power generation capacity and voltage limits of the SPV DG penetration. The power loss and the amount of DG that was required to be installed to mitigate the power loss were calculated using the branch current loss formula.

According to (Wang & Nehrir, 2004) To reduce power losses, an analytical approach is used to find the ideal location of DGs in radial distribution systems. Because the analytical technique does not use iterative algorithms, there are no convergence issues, and the findings can be acquired rapidly, as mentioned in this study.

In (Hosseini et al., 2013) The location and capacity of DGs can be determined by improving one or more parameters to increase efficiency and mitigate the negative effects of their installation. However, locating and sizing DGs to improve a single metric dramatically improves that parameter while negatively impacting the network's other parameters. On the other hand, locating and sizing DGs to improve some network parameters will improve the parameters in question. When it comes to multi-objective siting and sizing, considering the effects of many elements are critical.

The paper (Saad et al., 2018) describes the impact of SPV DG placement and distribution power system size was examined and investigated in this paper. The typical distribution system and the distribution system with SPV DG penetration have been compared in terms of load flow and short circuit calculations.

The paper (Hung & Mithulananthan, 2012) Two new methodologies for determining the optimal sizes and power factors of distributed generation (DG) units at various locations to minimize power losses, as well as a methodology for finding the best placement, are proposed, each based on alternative analytical expressions. By considering time-varying demand and all possible DG unit operating conditions, these approaches can simply be customized to accommodate various types of renewable DG units (e.g., biomass, wind, and photovoltaic) to reduce energy losses.

In the paper (Mujtaba et al., 2020) active losses, reactive losses, low power factor, low voltage on the demand side, and overloaded transformers and distribution lines were investigated at a 132 kV grid station in Layyah, Pakistan. To eliminate power shortages, solar plants are integrated into an 11 kV distribution system, which significantly improves voltage profile, line loss, and overloaded transformers under normal conditions.

The application of distributed generation for loss reduction is discussed in this study (Reddy, 2014). The two essential issues of determining the best appropriate location and scale of distributed generation for loss reduction were examined using one of the analytical methods, the "exact loss formula." For large-scale distribution systems, however, this method is ineffective.

This paper (Lu et al., 2006) has examined the impact of distributed resources on the transmission network in terms of influence issues.

In the research (Kashem et al., 2006) Adjusting the size, placement, and operating point of the DG model to reduce power losses in a distribution feeder is described. In terms of DG size and DG operating point, a sensitivity assessment for power losses was conducted. Constant impedance and constant current models were used to construct the proposed approaches, which took into consideration load characteristics and represented loads independently.

According to (Baldwin et al., 2015) Distributed generators are more effective in reducing power losses when compared to other alternatives. PV system integration, on the other hand, might cause unanticipated issues such as voltage and power fluctuation, harmonic distortions, high transmission and distribution losses, feeder over/underloading, and protection system failure. As a result, there is a critical need to examine the effects of increasing SPV system integration levels to meet consumer demand.

In general, different studies have attempted by different algorithms to study the optimal placement and sizing of DG, but the important distinction is in how the issues were formulated and the assumptions made with the constraints. But the optimal size of DG with an appropriate location is not dependent on at non unity power factor. In my thesis work optimal sizing SPV DG using analytical method “branch current loss formula” with inverter interfaced at non-unity power factor has been addressed.

CHAPTER THREE

METHODOLOGY

3.1. Introduction

The following are the steps and techniques serving to accomplish the specified objectives.

Literature review: several journal articles, conference papers, thesis papers, and books are reviewed related to distribution network expansion planning, demand forecasting, optimal sizing, and placement of distributed generation, especially solar photovoltaic-based DG.

Site selection: site-selection should be the main task in case study-related research to ensure the site has problems resolved by your idea of research. In this thesis Yirgalem I distribution substation is selected as a case study area because of its severe interruption problems.

Data collection: Historical peak load, duration, and frequency interruption of all feeders, number, and rating of distribution transformers, conductor type, and size of the distribution system is collected by site visiting, observation, and capturing raw data from the site office.

Data analysis: The above collected data have been analyzed successfully.

Load Forecasting and Expansion Planning with DG: Load forecasting is done by least square extrapolation technique and methodology of optimal sizing and location of solar photovoltaic based DG for distribution system expansion planning has been carried out for the study distribution network.

Modeling and result analysis: Modelling and load flow is done by ETAP 19.0.1 software and SPV DG sizing has been computed using analytical method with the help of MATLAB 2019 b.

3.2. Overview of the Case Study Area

Yirgalem I distribution substation is found in the Sidama region of Ethiopia at Yirgalem city is selected as a case study area. Its geographical location is the latitude of 6^{o} 45' N and longitude 38^{o} 25'E and an elevation of 1776 meters. it's about 45 km from the south of Awassa and 322 km south of Addis Ababa. Based on the Central Statistical Agency of Ethiopia published in 2005, Yirgalem has an estimated total population of 43,815 and in 2019 total population of Yirgalem town is 79,506 with 9218 households (Dache et al., 2021).

The substation is powered by a 132 kV incoming line from Awassa substation, which is connected to single bus bars at Yirgalem I distribution substation, each of which is coupled to one three-winding power transformer with a capacity of 25/12.5/12.5 MVA and a voltage rating of 132/33/15 kV. This substation also provides direct 132kV voltage inputs to the Dilla and Shakiso substations. The substation has five outgoing feeders three 33 KV feeders such as Bansadaye, Kura canco, and Awudando industry feeders and two 15 KV feeders supplied to Yirgalem town and small towns around Abosto. Recently another 15 KV Aleta wendo feeder is detached from Yirgalem I distribution substation. This feeder supplies to villages the longest distance from the substation and is now added to Yirgalem II substation.

Figure 3. 1 Layout of Yirgalem I distribution substation

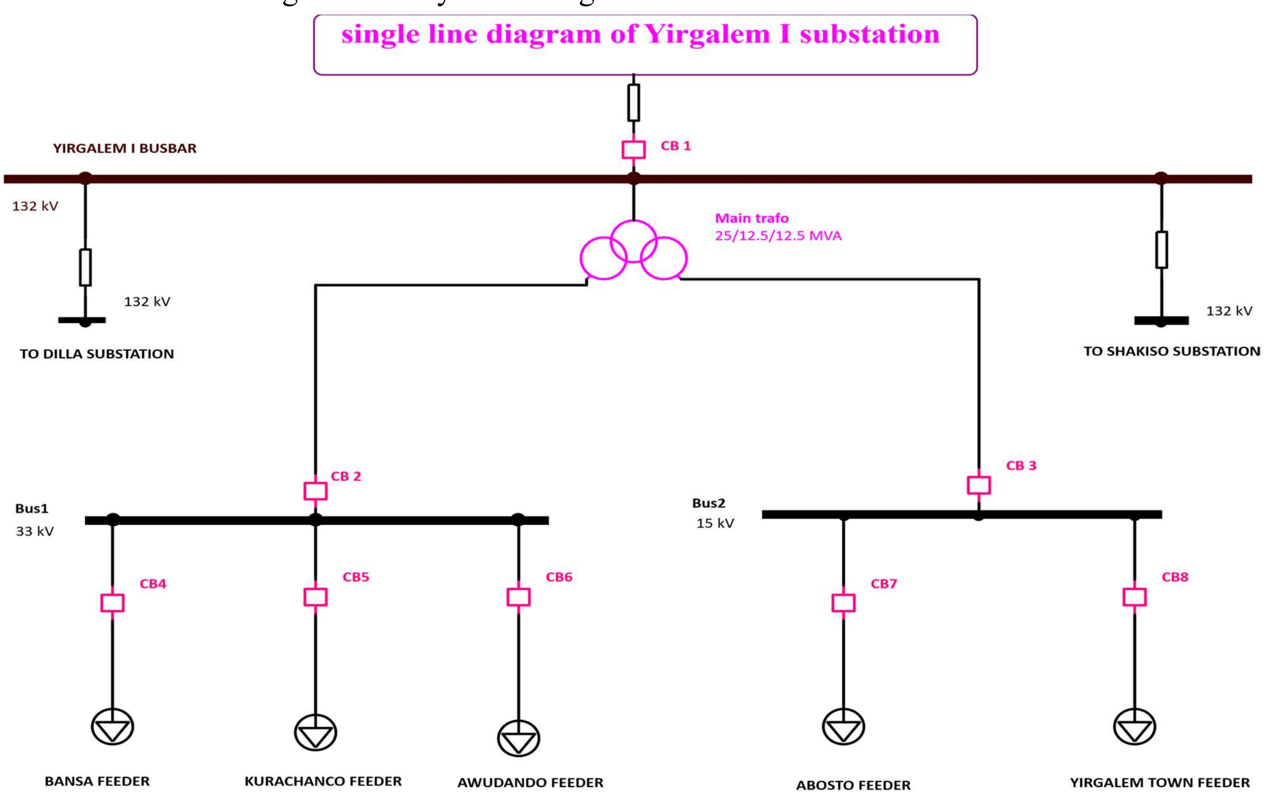

Figure 3. 2 Single line diagram of Yirgalem I distribution substation

3.3. Data collection

This section briefly deals with data collection of the existing Yirgalem I distribution system from the distribution system site office. The data have been collected from Southern region transmission, substation operation and maintenance office at Hawassa, and other technical data are captured from Yirgalem I substation and utility offices. The data has been assessed and collected by site observation, discussion, and taking raw data from the site office.

3.3.1. Existing Distribution System Data

Three winding transformers give two different voltage levels (33 &15 Kv) at the secondary side supplies to those feeders:

Yirgalem town feeder: This feeder has a 15 Kv voltage rating and supplies to Bokaso, Leku, and Dongora villages with residential, commercial, and small industrial loads.

Abosto feeder: This is another 15 Kv feeder that supplies small villages such as Aposto, Chuko, Sasamo, Della, Hantate, and Anferara.

Bansadaye feeder: This 33 Kv outgoing feeder supplies a larger part of villages such as Qosorich, Gambella, Rufu Malaya, Seqe, Aganja, Bergicho,Arefama, Bura,Bore, Abara, Bansa Daye, Bona, Bensa Kabado, and Chebe which have their utilities.

Kura chanco feeder: This 33 Kv outgoing feeder supplies to Kura Canco, Dasse, Chelbessa Sala Kabado, Gudumo, Foqa, and Badalich areas.

Awudando feeder: This 33 Kv outgoing feeder gives service to chipud factory near Yirgalem town and this feeder does not include in the demand forecasting of Yirgalem distribution network because the feeder has no load growth rate from year to year only supply to the factory. The historical peak load demands of the four outgoing feeders are recorded from 2017/18 to 2020/21 at Yirgalem substation and Hawassa transmission substation maintenance and operation office are arranged in table 3.1.

Table 3. 1 Historical peak load demand data 2017/18-2020/21 G.C

Feeder name	Year in (G.C)	Yearly peak Power demand (Mw)	Voltage level KV)	Total number of trafo	Feeder length (Km)	Total Transformer capacity (KVA)
Abosto feeder	2017/18	27.25	15	35	242.16	4575
	2018/19	28.54	15			
	2019/20	27.5	15			
	2020/21	27.8	15			
Yirgalem town feeder	2017/18	38.9	15	45	16.032	11165
	2018/19	44.4	15			
	2019/20	45.6	15			
	2020/21	44.3	15			
Bansa feeder	2017/18	30.3	33	No detail	249.82	No detail
	2018/19	30.1	33			
	2019/20	34.2	33			
	2020/21	35.25	33			
Kurachanco feeder	2017/18	28.15	33	19	97.05	2230
	2018/19	26.8	33			
	2019/20	28.7	33			
	2020/21	33.7	33			

Table 3. 2 Monthly average energy consumption of 15KV and 33KV feeders

Month	15KV feeders		33KV feeders	
	Active energy (KWH)	Reactive energy (KVARH)	Active energy (KWH)	Reactive energy (KVARH)
September	7860000	1944000	2278500	825000
October	5329500	4521750	1439250	17250
November	508500	305000	697500	22500
December	65250	42300	459750	36200
January	38250	34650	687000	22500

February	132000	112500	2182500	1750200
March	24600	22450	1285500	1215000
April	41500	36000	115500	75000
May	17250	15900	675200	36300
June	50200	46450	7374750	6648250
July	47850	44050	2317050	2207650
August	52500	10500	1268250	1069750
Total	14,167,400	7,135,550	20,780,750	13,925,600

The table 3.2 contains the monthly average energy consumption of 15KV and 33KV feeders. The power factor (Pf) of the distribution feeders is determined using the formula below using data from 2020/21G.C.

$$\text{power factor (PF)} = \text{Active Energy} / \sqrt{\text{Active Energy}^2 + \text{Reactive Energy}^2}$$

Based on table 3.2 the power factor of the distribution system can be calculated as:

$$PF(33Kv)=(20,780,750) / \sqrt{20,780,750^2 + 13,925,600^2} = 0.83$$

$$PF(15Kv)=(14,167,400) / \sqrt{14,167,400^2 + 7,135,550^2} = 0.89$$

3.3.2. Yirgalem I Distribution Network Interruption Data

An interruption to service occurs when an electrical load is disconnected from the system that supplies the load as a result of a fault in that system. A malfunction of a system component, a problem, or a system process due to conservation or repair might cause an irregularity in the system. Independent of the cause, interruptions are usually undesirable since they leave energy unserved and customers without service. Most of the time, disruptions occur as a result of the system responding to an issue. IEEE100-1992 defines a fault or short-circuit as an irregular low-impedance connection between two locations of different potentials, whether established accidentally or intentionally. (Alebachew, 2019).

The substation interruption data of each feeder is reported to Hawassa region office. From the report, two years of data are taken from the regional office from 2019/20 G.C to 2020/21G.C. The two years report includes frequency and duration of interruption and cause of interruptions such as distribution permanent earth fault (DPEF), distribution temporary earth fault (DTEF), distribution permanent short circuit (DPSC), distribution temporary short circuit (DTSC), overload, and operational. The average yearly interruption report with their causative agents is arranged below in table 3.3 & 3.4. From the average yearly report earth fault and short circuits are the main problems that happen in Yirgalem I distribution network.

Table 3. 3 power interruption data and their causes of interruption (01/12/2019-30/11/2020)

Feeders name	Voltage (kv)	Cause of power interruption												Total (F)	Total (D)
		DPEF		DPSC		DTEF		DTSC		OL		OP			
		F	D	F	D	F	D	F	D	F	D	F	D		
F1	15	434	544.4	142	217.1	182	69.9	90	122.7	7	12.4	172	147	1027	1113.5
F2	15	491	668.1	195	313.6	167	55.3	66	120.6	52	114	185	212	1156	1483.6
F3	33	305	508.8	150	288.2	101	64.1	57	107.1	5	8.7	163	157.3	781	1134.2
F4	33	376	345.8	309	651.1	198	37.2	81	111	2	5.1	109	131.7	1075	1281.9
F5	33	144	197.6	134	218.7	125	72.2	86	41.8	0	0	61	71	550	601.3

F1- Abosto feeder F3- Bansa feeder F5- Awudando feeder
F2- Yirgalem town feeder F4- Kurachanco feeder

Table 3. 4 power interruption data and their causes of interruption (01/12/2020-30/11/2021)

Feeders name	Voltage (kv)	Cause of power interruption												Total (F)	Total (D)
		DPEF		DPSC		DTEF		DTSC		OL		OP			
		F	D	F	D	F	D	F	D	F	D	F	D		
F1	15	297	465.5	127	267.9	45	62.7	23	56.1	2	2.4	198	216.6	692	1071.2
F2	15	364	762.6	240	367.6	30	42.7	29	65.6	31	134.7	168	171.8	862	1545
F3	33	543	851.6	106	224.7	28	31.6	7	11.9	1	1.2	63	120.6	748	1241.6
F4	33	340	741	113	199.5	15	0.72	1	0.05	0	0	69	229.7	538	1170.97
F5	33	159	190.1	134	70.6	24	31.7	13	15.9	0	0	39	42.4	369	350.7

F1- Abosto feeder F3- Bansa feeder F5- Awudando feeder
F2- Yirgalem town feeder F4- Kurachanco feeder

The two-year average frequency and duration of interruption is graphically shown based on the table above to demonstrate which distribution feeder has experienced more interruption problems, as seen in figures 3.3 and 3.4 below.

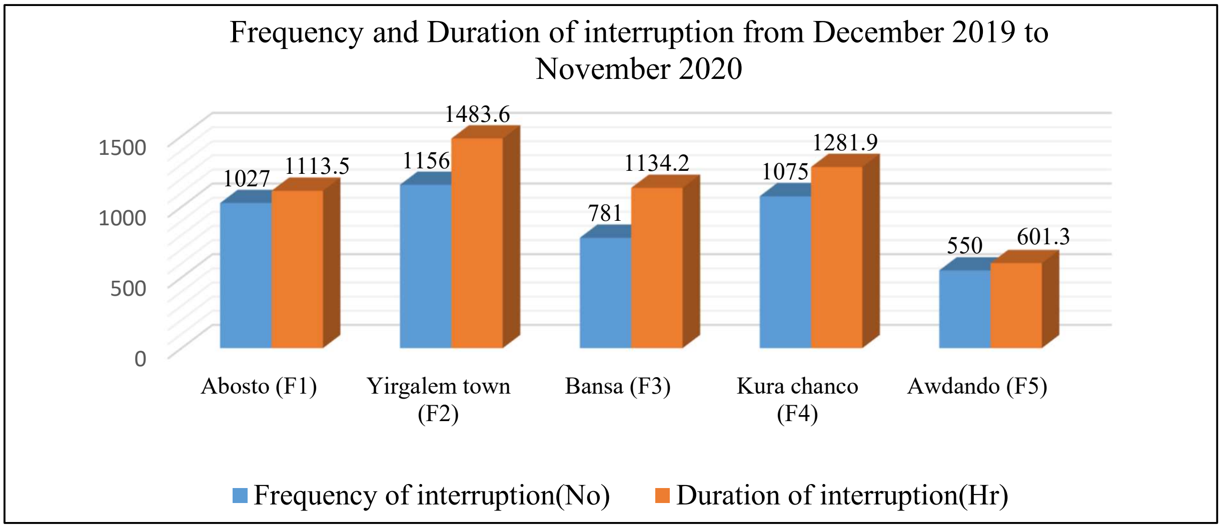

Figure 3. 3 Yearly average interruption of Yirgalem I distribution feeders (2019-2020)

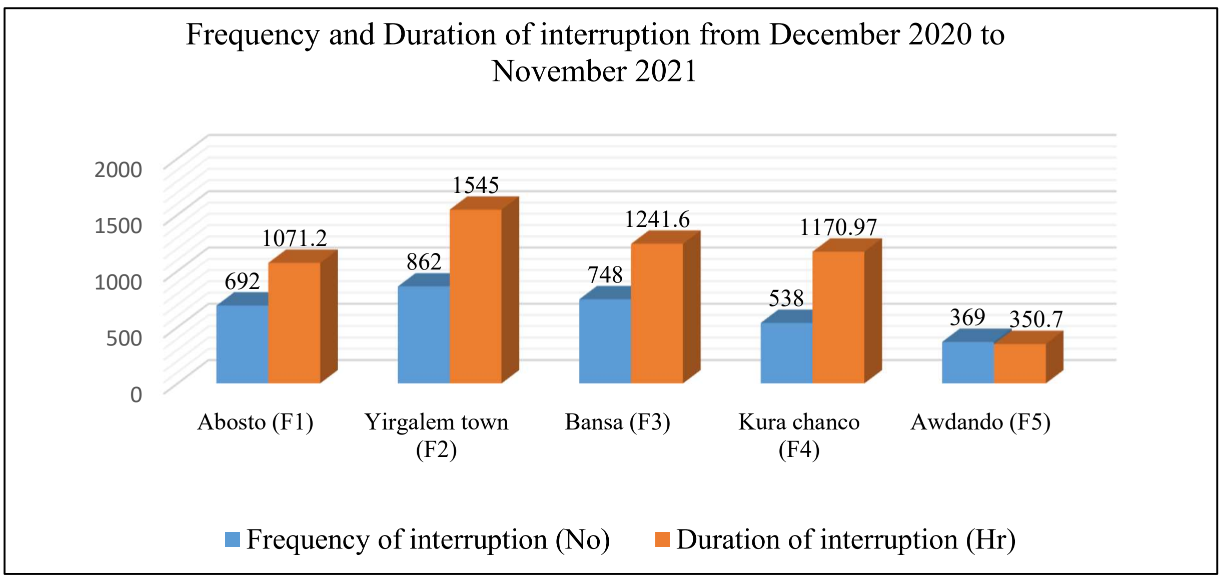

Figure 3. 4 Yearly average interruption of Yirgalem I distribution feeders (2020-2021

3.3.3. Solar Energy Resource of the Site

The assessment of the potential for solar energy of the selected area is done by taking data from National Aeronautics and Space Administration (NASA) website. Using Yirgalem town latitude and longitude as input data. The four-year average global horizontal radiation is obtained in figure 3.5 below. (See **appendix D**)

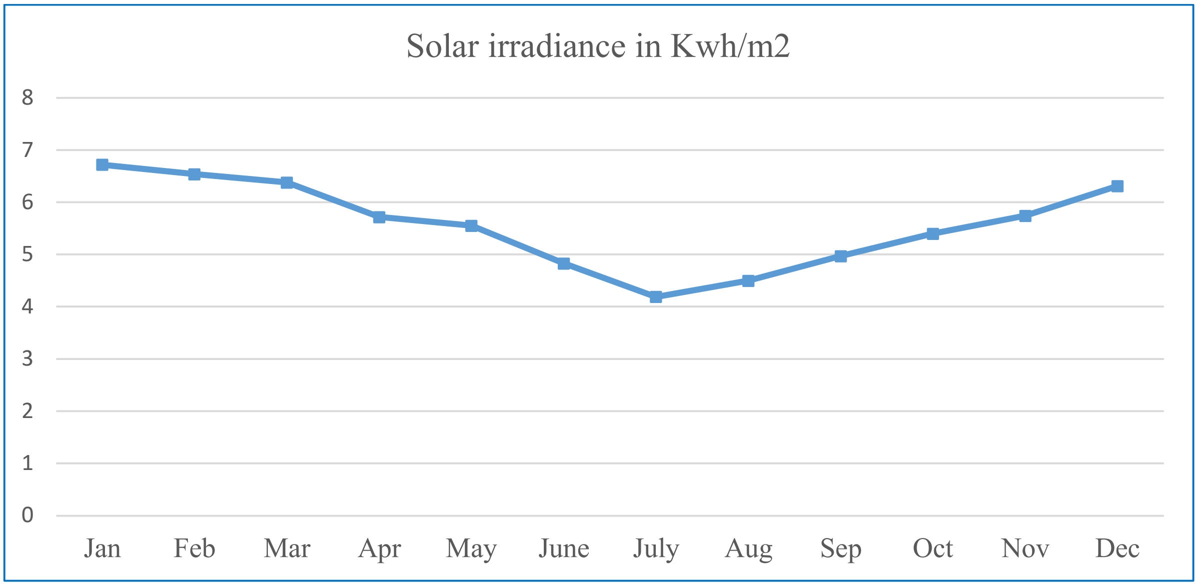

Figure 3. 5 Average solar radiation of Yirgalem Town in Kwh/m2

CHAPTER FOUR

DEMAND FORECASTING AND EXPANSION PLANNING WITH SPV DG INTEGRATION

4.1. Introduction

This section covers peak load demand forecasting of Yirgalem I distribution network using least square extrapolation technique and methodology of optimal sizing and location of solar photovoltaic based DG for distribution system expansion planning included in this chapter.

4.2. Peak Power Demand Forecasting of Yirgalem I Distribution System

Using the historical peak load demand data of Yirgalem I distribution system that was recorded from the distribution system office in the period of 2017/18 G.C to 2020/21G.C. Based on the collected data the forecasting power demand of all distribution feeders is carried out using the least square extrapolation technique for the next 10 years period is applied to this thesis. Using the function y=f(x) can be fitted with the points (X1, Y1), (X2, Y2) to minimize the sum of errors squared at each point. i.e

$$\sum_{i=1}^{n} [Y_i - f(x)]^2 = \text{minimum} \tag{4.1}$$

Finding the equation of the curve of best fit which may be most suitable for predicting the unknown values, if we believe $y = a_0 + a_1 x$,then $(Y-(a_0+a_1x))$ should be minimum or zero (Johnson, 2020).

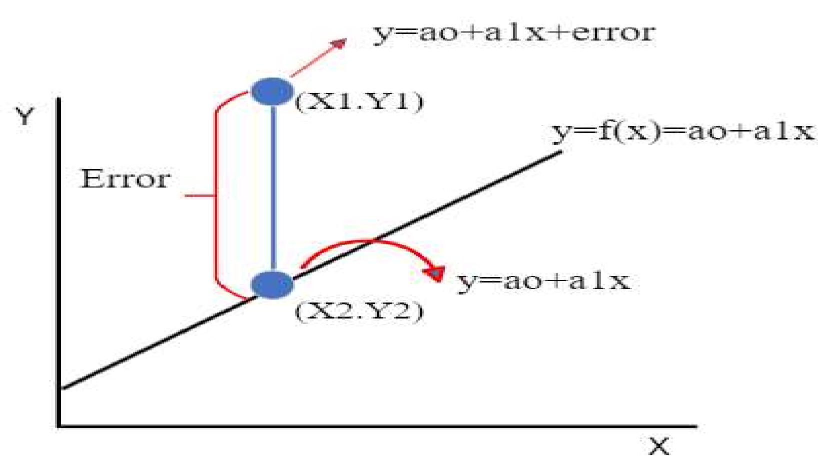

Figure 4. 1 Least square error line graph between two points

The basic least square line is used to forecast the load among the other typical regression curves used in power arrangement forecasting. As a result, the line is well-fitting to the points. (X1, Y1), (X2, Y2) … (Xn, Yn)

$$\varepsilon^2=\sum_{i=1}^{n}[Y_i-(a_0+a_1x_i)]^2=\text{minimum} \tag{4.2}$$

Making a partial derivative of equation (4.2) concerning regression coefficients a_0 and a_1 by setting the equation equal to zero to get the minimum error criterion gives:

$$\frac{\partial}{a_0}\{\sum_{i=1}^{n}[Y_i-(a_0+a_1x_i)]^2\}=0\cong Na_0+a_1\sum_{i=1}^{n}X_i=\sum_{i=1}^{n}Y_i \tag{4.3}$$

$$\frac{\partial}{a_1}\{\sum_{i=1}^{n}[Y_i-(a_0+a_1x_i)]^2\}=0\cong a_0\sum_{i=1}^{n}X_i+a1\sum_{i=1}^{n}X^2{}_i=\sum_{i=1}^{n}X_iY_i \tag{4.4}$$

Table 4. 1 Input historical data analysis of all distribution feeders

	Year	Peak demand	X_i	$P_{Di}=\frac{Peak\ demand}{10}$	$Y_i=\ln P_{Di}$	X_iY_i	X_i^2
Abosto Feeder	2017/18	27.25	-2	2.725	1.002468	-2.004936	4
	2018/19	28.54	-1	2.854	1.048722	-1.048722	1
	2019/20	27.5	0	2.75	1.011601	0	0
	2020/21	27.8	1	2.78	1.022451	1.022451	1
			$\sum X_i=-2$		$\sum Y_i=4.085242$	$\sum X_iY_i=-2.031207$	$\sum X_i^2=6$
	Year	Peak demand	X_i	$P_{Di}=\frac{Peak\ demand}{10}$	$Y_i=\ln P_{Di}$	X_iY_i	X_i^2
Yirgalem Town feeder	2017/18	38.9	-2	3.89	1.358409	-2.716818	4
	2018/19	44.4	-1	4.44	1.490654	-1.490654	1
	2019/20	45.6	0	4.56	1.517323	0	0
	2020/21	44.3	1	4.43	1.488399	1.488399	1
			$\sum X_i=-2$		$\sum Y_i=5.854785$	$\sum X_iY_i=-2.719073$	$\sum X_i^2=6$
	Year	Peak demand	X_i	$P_{Di}=\frac{Peak\ demand}{10}$	$Y_i=\ln P_{Di}$	X_iY_i	X_i^2
Bansa Feeder	2017/18	30.3	-2	3.03	1.108563	-2.217126	4
	2018/19	30.1	-1	3.01	1.101940	-1.101940	1
	2019/20	34.2	0	3.42	1.229641	0	0
	2020/21	35.25	1	3.525	1.259880	1.259880	1

			$\sum X_i = -2$		$\sum Y_i = 4.700024$	$\sum X_i Y_i = -2.059186$	$\sum X_i^2 = 6$
Kura Chanco feeder	Year	Peak demand	X_i	$P_{Di} = \frac{Peak\ demand}{10}$	$Y_i = \ln P_{Di}$	$X_i Y_i$	X_i^2
	2017/18	28.15	-2	2.815	1.034962	-2.069924	4
	2018/19	26.8	-1	2.68	0.985817	-0.985817	1
	2019/20	28.7	0	2.87	1.054312	0	0
	2020/21	33.7	1	3.37	1.214913	1.214913	1
			$\sum X_i = -2$		$\sum Y_i = 4.290004$	$\sum X_i Y_i = -1.840828$	$\sum X_i^2 = 6$

From equations (4.3) & (4.4) the coefficients a_0 and a_1 are calculated from the simultaneous equations considering four years of peak demand data (N=4) and taking 2019/20 as a reference year (i.e $x_i = 0$).

Table 4. 2 Regression coefficients for all feeders

Feeders	Abosto feeder		Yirgalem town Feeder		Bansa feeder		Kura chanco Feeder	
Coefficients	a_0	a_1	a_0	a_1	a_0	a_1	a_0	a_1
	1.0225	0.0023	1.4845	0.0417	1.2041	0.0582	1.1029	0.0608

Using the coefficient values calculated in the table 4.2 the peak load demand forecasting for the next 10 years is performed depending on equations (4.5) & (4.6) by varying the value x_i in successive years.

$$Y = a_0 + a_1 x_i \qquad (4.5)$$

$$P_n = 10e^Y \qquad (4.6)$$

The forecasted peak load for all Yirgalem I distribution feeders from 2017/18-2030/31 based on the equation (4.5) & (4.6) was found in table 4.3 below:

Table 4. 3 Forecasted power demand of Yirgalem I distribution system from (2021 -2031) G.C

	Historical Peak Demand (MW)				Forecasted Peak Demand (MW)			
year	Abosto/F	YIR/F	Bansa/F	Kura/F	Abosto/F	YIR/F	Bansa/F	Kura/F
2017/18	27.25	38.9	30.3	28.15	27.67	40.6	29.68	26.68
2018/19	28.54	44.4	30.1	26.8	27.74	42.33	31.45	28.35
2019/20	27.5	45.6	34.2	28.7	27.8	44.13	33.34	30.13
2020/21	27.8	44.3	35.25	33.7	27.86	46.01	35.33	32.02
2021/22	_	_	_	_	27.93	47.96	37.45	34.03
2022/23	_	_	_	_	27.99	50	39.69	36.16
2023/24	_	_	_	_	28.06	52.13	42.07	38.43
2024/25	_	_	_	_	28.12	54.35	44.59	40.84
2025/26	_	_	_	_	28.18	56.66	47.26	43.4
2026/27	_	_	_	_	28.25	59.07	50.09	46.12
2027/28	_	_	_	_	28.31	61.59	53.09	49.02
2028/29	_	_	_	_	28.38	64.21	56.27	52.09
2029/30	_	_	_	_	28.44	66.94	59.64	55.36
2030/31	_	_	_	_	28.51	69.78	63.21	58.83

Based on the four years of historical demand data of the distribution feeders the forecasted demand of feeders at end of 2031 for Abosto feeder with 28.51MW, Yirgalem town feeder with 69.78MW, Bansadaye feeder with 63.21MW, and kura chancho feeder with 58.83 MW, with the growth rate of 0.23%,4.25%,5.99%, and 6.27% respectively. Figure 4.2 shows the demand at end of five and ten years for all feeders.

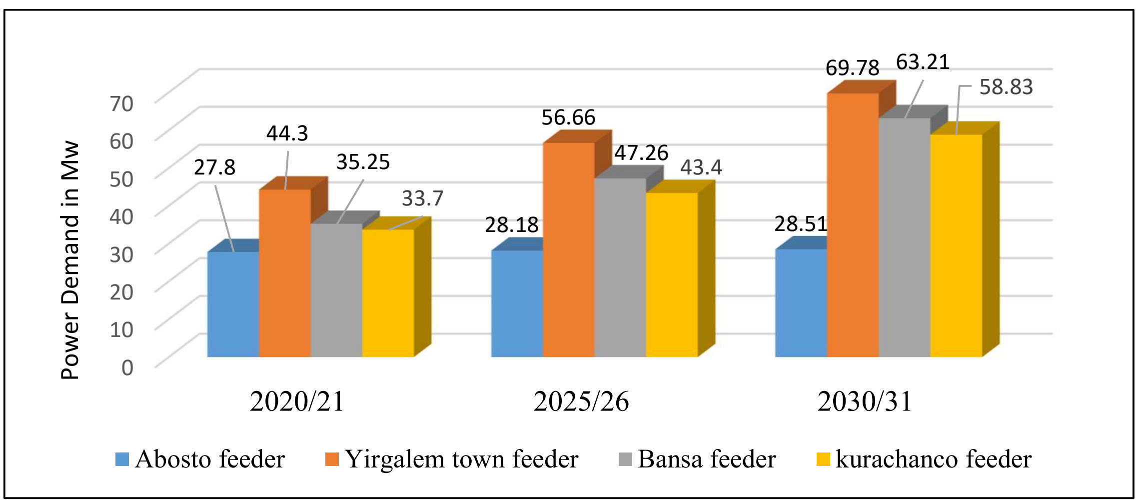

Figure 4. 2 Power demand of each feeder from 2020/21-2030/31

4.3. Methodology for Optimal Sizing and Placement of SPV DG

The addition of SPV DG to the distribution system alters the characteristics of the system. As the number of SPV DGs connected increases, a variety of technological restrictions and obstacles emerge. Changes in temperature and irradiance can affect grid performance and lead to voltage collapse due to a fast change or fluctuation if there is no sufficient reserve to peak up the load, according to the dynamic study of SPV integration (Alquthami et al., 2010). Many studies have shown that non-optimal and optimal sizing of the SPV, as well as non-optimal and optimal placement of the SPV in the distribution system, can degrade the quality of the power system, so it is critical to investigate the optimal placement of the SPV in the distribution system under the constraints of power capacity and voltage limits (Shahzad et al., 2014).

4.3.1. SPV DG Sizing

By properly locating DG units, an analytical method developed in the branch current loss formula is employed to reduce the losses associated with the absolute value of branch currents. The problem of DG unit placement helps identify the size, placement, and quantity of DG units that should be placed in a distribution system to generate optimum advantages while meeting operational restrictions at various loading levels. The total power loss in a distribution system having 'N' number of branches is given by

$$P_{Loss} = \sum_{i=1}^{N} I^2{}_i R_i \tag{4.7}$$

Ii is the magnitude of the current flowing from node i to node i+1, and PLoss is the system's total power losses. *Ri* is the resistance of the line with *N* number of branches. In Equations (4.7), the current magnitude contains two components: an active component and an imaginary component.

$$P_{Loss} = \sum_{i=1}^{N} I^2{}_{ai} R_i + \sum_{i=1}^{N} I^2{}_{ri} R_i \tag{4.8}$$

$$I_{ai} = I_i \cos\phi \tag{4.9}$$

$$I_{ri} = I_i \sin\phi \tag{4.10}$$

Where Iai and Iri are the real and imaginary current components at node i respectively.

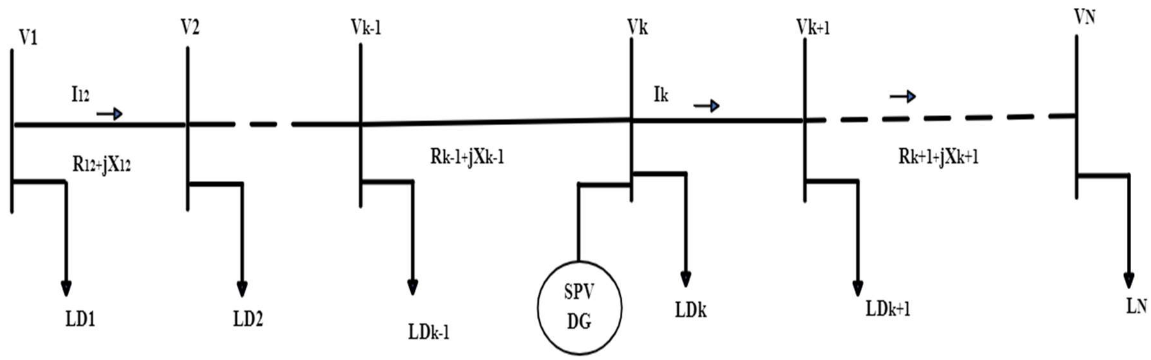

Figure 4. 3 Radial distribution network with SPV DG connected

Consider a network of N branches if SPV DG is placed at node k and β is a set of branches connected between source node and the node at which SPV DG is connected. The current flow in the branch will be affected by the SPV DG current, but the current flow in the rest of the networks will not be affected.

When inverter interfaced SPV DG has injected both active current (I_{DG}) and reactive current (I_{DGr}) at bus k equation (4.8) is converted to the following formula.

$$P_{Loss} = \sum_{i=1}^{k}\left[(I_{ai} + I_{DG})^2 R_i\right] + \sum_{i=k+1}^{N} I^2{}_{ai} R_i + \sum_{i=1}^{k}\left[(I_{ri} + I_{DGr})^2 R_i\right] + \sum_{i=k+1}^{N} I^2 r_i R_i \qquad (4.11)$$

Where P_{Loss} is power loss with SPV DG injected into the network. *Iai, and Iri* are the real and imaginary components of the current obtained from the initial load flow analysis by considering the average power factor of the distribution system and I_{DG} is the active current component injected by the SPV at node *k*. *Ri, is the* resistance of the line.

I_{DGr} = akI_{DG} is the imaginary part of the injected current, where I_{DG} is the real SPV current injected at node k. ak = (sign) tan(cos1(PF_{DG})), where sign =+1 indicates that DG is generating reactive power and sign=-1 indicates that DG is absorbing reactive power from the distribution network.

In this case the sign is positive because of injecting reactive power from inverter-interfaced SPV DG to the distribution system.

The majority of grid-connected PV inverters are only configured to inject power at unity power factor, which means they only produce active power. As a result, the power factor is reduced since the grid is supplying less active power but the same amount of reactive power. The problem of low power factor, on the other hand, can be solved by choosing the right inverter.

Inverters with reactive power control can be set up to generate both active and reactive power, or a non-unity power factor output. This means that the power factor of the load can be kept within reasonable limits. The loads are lumped load type by Assuming 80% constant impedance load type and 20% constant power loads.

In compared to a DG with a power factor of unity, the DG with a power factor equal to the average distribution system load power factor resulted in improved loss savings and voltage profile enhancement (Naik et al., 2015).

The power factor of SPV DG is assumed to be **0.89** in this thesis work.

The power loss reduction is the subtraction of the total losses with DG integrated in equation (4.11) from the initial power loss in equation (4.8);

$$\Delta P_{Loss} = -2I_{DG}\sum_{i=1}^{k} I_{ai}R_i - I^2{}_{DG}\sum_{i=1}^{k} R_i - 2a_k I_{DG}\sum_{i=1}^{k} I_{ri}R_i - a^2{}_k I^2{}_{DG}\sum_{i=1}^{k} R_i \qquad (4.12)$$

The goal is to locate an SPV DG unit of the appropriate size to maximize system loss reduction. The derivative of equation (4.12) with respect to I_{DG} must be zero for the system loss reduction to be maximal when the SPV DG unit is placed at node 'k'. Hence,

$$\frac{\partial(\Delta P_{Loss})}{\partial I_{DG}} = 0 \cong -2\sum_{i=1}^{k} I_{ai}R_i - 2a_k\sum_{i=1}^{k} I_{ri}R_i - 2I_{DG}\sum_{i=1}^{k} R_i - 2a^2{}_k I_{DG}\sum_{i=1}^{k} R_i \qquad (4.13)$$

Rearranging of equation (4.13), the DG current during the maximum loss reduction is given as,

$$I_{DG} = -\frac{\sum_{i=1}^{k} I_{ai}R_i + a_k\sum_{i=1}^{k} I_{ri}R_i}{(1+a^2{}_k)\sum_{i=1}^{k} R_i} \qquad (4.14)$$

The size of the DG injected at that node can be evaluated using constant voltage values multiplied by the value of the current injected. The optimal branch current from Equation (4.14) multiplied with its corresponding nodal voltage magnitude will be the optimal size of power injected at selected node k:

$$P_{DG}(i) = I_{DG}(i) \times V_{ref} \qquad (4.15)$$

$$Q_{DG}(i) = a_k P_{DG}(i) \qquad (4.16)$$

The optimal size of SPV DG at each bus is computed using MATLAB 2019 m-file program based on equations (4.14) to (4.16). It has been argued that oversizing can cause line losses to exceed line losses without SPV DG.

4.3.2. SPV DG Location

The proper sizes of SPV DG at various locations have been computed using equations (4.14) to (4.16), and the overall power losses and voltage profile of the system have been determined with the proper sizes of SPV DG for each case using load flow study with the help of ETAP software. The power loss and voltage profile of each bus are determined for each case load flow analysis. The bus with the least loss and the voltage within the permitted limit is the best SPV DG location, according to the load flow result. The flow chart below depicts the entire computational procedure.

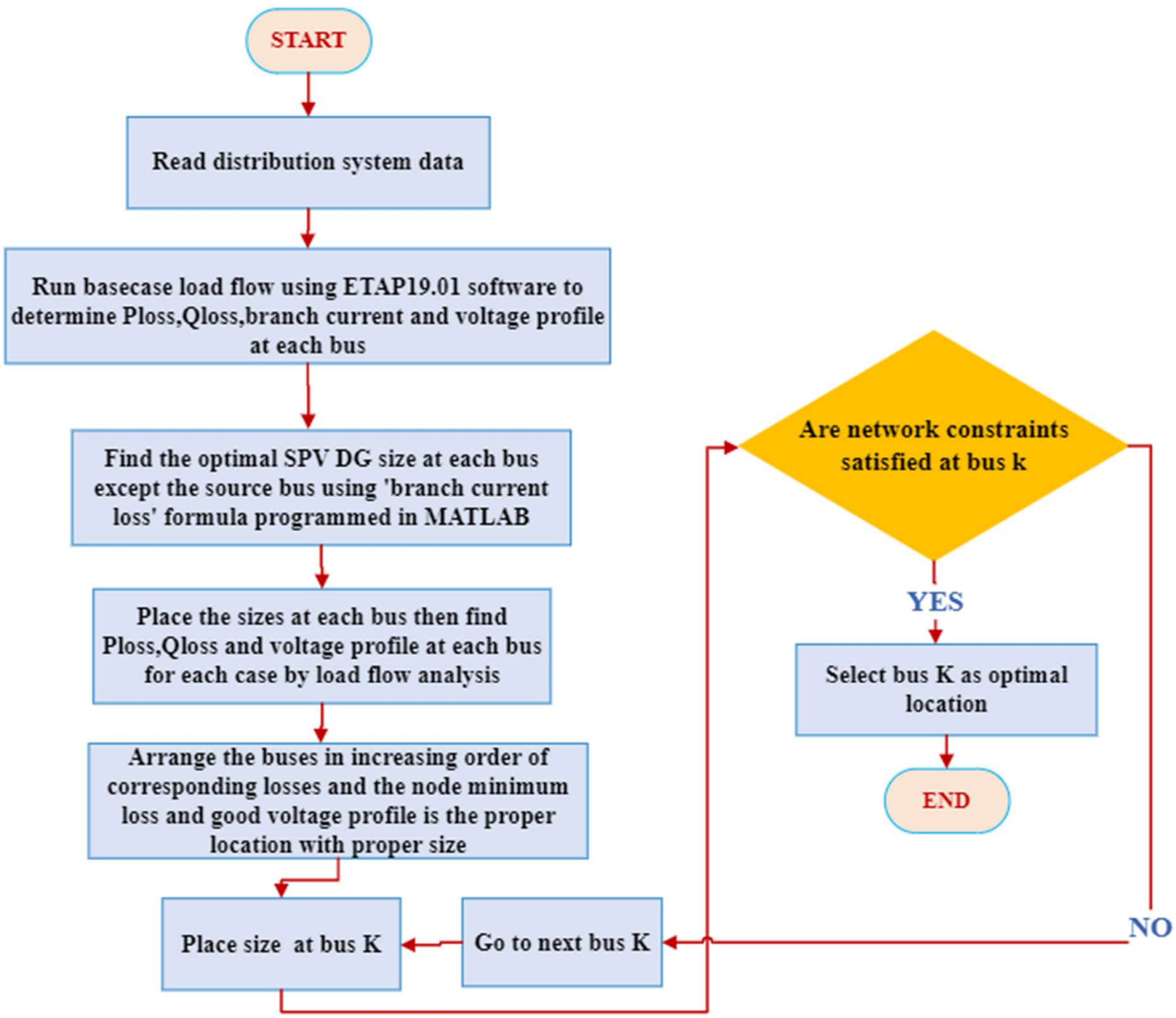

Figure 4. 4 Analytical DG allocation flow chart based on branch current loss equations

4.3.3. Constraints

The constraint is a restriction in power system optimization, and an issue develops that is influenced by the quantity of distributed generation (DG) incorporated into the distribution network. The following constraints must not be violated to integrate the SPV DG into the distribution feeder, some of which are:

i) Bus voltage constraints

As a technical standard IEEE 1547 has provided local, state, and federal regulators and policy makers a technical basis for promoting transparency, openness, and fairness in implementing distributed energy resource interconnecting to the grid. The distribution feeder voltage should be varied within the specified limit.

$$Vi_{min} \leq Vi \leq Vi_{max} \quad (4.17)$$

In this thesis, bus voltage is limited to $\pm 5\%$ of the nominal voltage of the feeder by assuming all the bus voltage is 15KV.

ii) DG power rating constraint

The capacity of the DG connected to the distribution feeder must not exceed the feeder load demand plus the feeder's total power loss.

$$P_{DG} \leq P_{load} + P_{loss} \quad (4.18)$$

To minimize reverse power, SPV DG capacity in distribution networks is limited to 20 to 85 percent of total feeder demands is decided in this paper.

iii) Active and Reactive power loss constraints

The losses after integrating DG should be less than the losses before integrating DG.

$$\begin{pmatrix} \text{PL with } D_G < \text{PL without } D_G \\ \text{QL with DG} < \text{QL without } D_G \end{pmatrix} \quad (4.19)$$

iv) Line loading constraint

To avoid overloading feeder lines by installing DG units, the current flowing in each branch should be less than or equal to the maximum capacity rating.

$$\text{Line loading} \leq 100\% \quad (4.20)$$

CHAPTER FIVE

MODELLING, SIMULATION AND RESULT ANALYSIS

5.1. Introduction

This chapter focuses on the modeling, simulation, and analysis of the proposed radial distribution system with and without SPV DG integration using ETAP 19.01 simulation software. Furthermore, the distribution system power loss and voltage profile were computed using load flow analysis for the existing system and with SPV DG by using optimal sizing and location. On the other hand, the effect of load growth on distribution feeder with the integration of SPV DG had been addressed.

As discussed in chapter three, the main advantage of studying the interruption situation of the distribution network is problem identification of the distribution feeders to minimize the scope of the study and to proclaim that the feeder having higher interruption gives attention to the concerned organization. As the evidence from the average two years interruption of Yirgalem I distribution system shown graphically in figure 3.3 & 3.4, Yirgalem town feeder is selected due to higher frequency and duration of interruption as compared to other feeders. The SPV DG integration is applied to this feeder based on the necessary data taken from Yirgalem utility office. Figure 5.1 shows a single line diagram of the feeder sketch with Microsoft Visio. Modeling and simulation have been done by using ETAP 19.01 software.

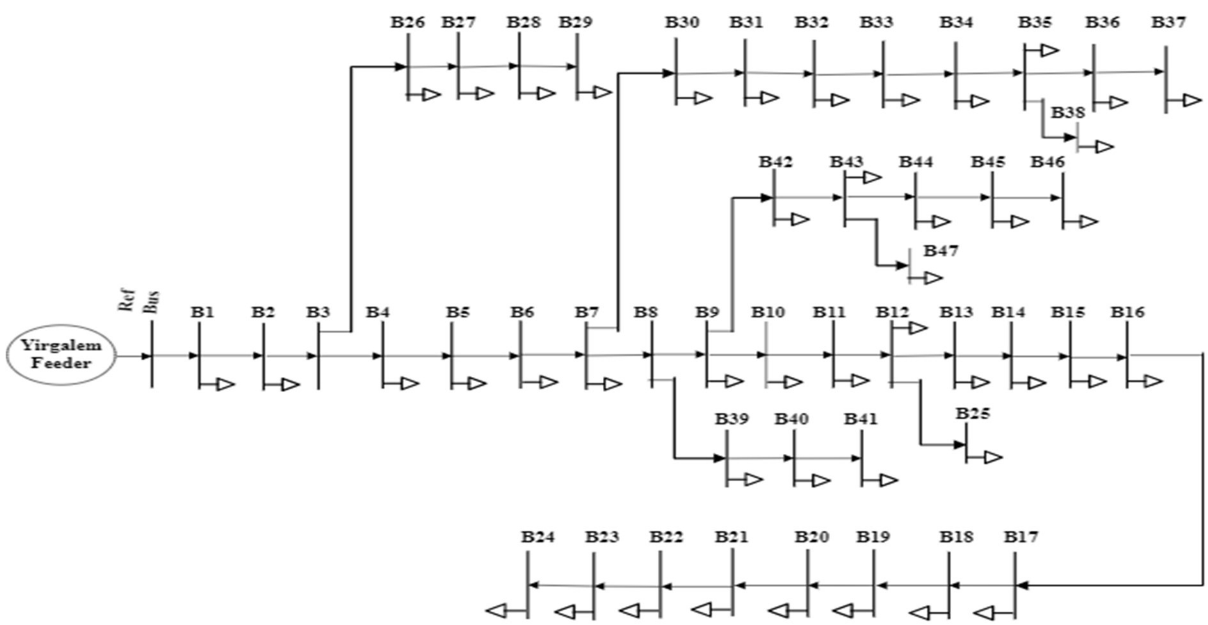

Figure 5. 1 Single line diagram of Yirgalem town feeder

5.2. Line Parameters of Yirgalem Town Distribution Feeder

Yirgalem town feeder is a 15 kV radial distribution system with conductor type of all aluminum (AAC) 50 mm^2 size seven stranded stretched from the substation to its load sites in the three-phase three-wire system through overhead wooden poles of height from 10 to 12 meters, mostly equipped/supported with pin-type insulators. For AAC-50 conductor type, the positive sequence impedance at 20°c from the ETAP library is Z_a=0.5785+j0.3517Ω/km.

According to the norms IEC 60889 and 60028 (Cortaillod, 2015) the values generally admitted for the temperature coefficient per degree Celsius at 20°c (α_{20}) for copper is 0.00393 and for aluminum is 0.00403. The resistance at a temperature of 75°c is calculated by the following formula:

$$Rt=R_{20}[1+\alpha_{20}(t-20)] \tag{5.1}$$

=0.706+ j0.3517Ω/km (resistance of the conductor at 75°c without considering skin effect)

Each conductor in a three-phase system has the same impedance (i.e., Za = Zb = Zc). Then multiply impedance per kilometer by the length of the actual value to get the impedance of the positive sequence of conductors (see **appendix C3** detail). The per-unit impedance of each line is calculated in equations (5.2) to (5.4) using a base 100 MVA and 15 KV base voltage seen values from the load flow analysis in **appendix B1.**

$$Z_{base} = \frac{KV^2{}_{base}}{MVA_{base}} = \frac{15000^2}{100\times10^6} = 2.25\Omega \tag{5.2}$$

$$R_{pu} = \frac{R_{actual}}{Z_{base}} \tag{5.3}$$

$$X_{pu} = \frac{X_{actual}}{Z_{base}} \tag{5.4}$$

5.3. Load Flow Analysis

Load flow analysis is an effective tool for establishing the characteristics of a power system under steady-state conditions. This thesis examines the load flow for the Yirgalem town feeder, which has a total 48 buses one swing bus, and 47 load buses. The ETAP 19.01 simulation software was used to model and simulate with and without integration of SPV DG and provides power loss and voltage profile of the distribution system. Because of its fast convergence and precision, the solution for load flow is performed by Newton Raphson method.

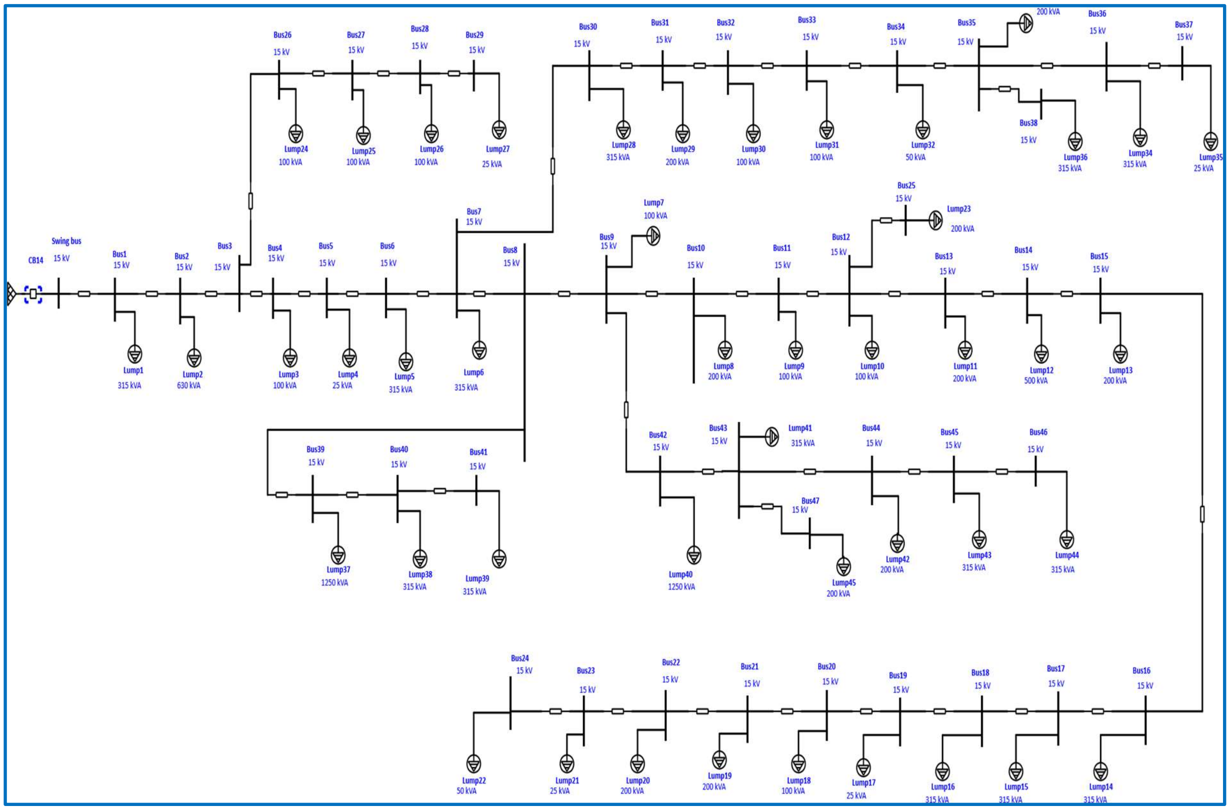

Figure 5. 2 Yirgalem town feeder modeled with ETAP

5.3.1. Power Loss without SPV DG Integration

Based on Yirgalem town distribution feeder data the base case (existing feeder) total real and reactive power losses are determined at balanced and steady load flow analysis using ETAP 19.01 software. From the load flow result the total real and reactive losses were found 1.1133 MW and 0.5451 MVAR respectively. The detailed load flow results were tabulated in **appendix B2**.

5.3.2. Voltage Profile without SPV DG Integration

a positive sequence load flow analysis is applied to the Yirgalem town feeder without integrating SPV DG. The results show that majority of the bus voltages were outside of the allowed voltage range of $1 \pm 5\%$ of the distribution feeder's nominal voltage. The bus voltage is less than the permitted range of 0.95 pu, as indicated by the red color in figure 5.3. In ETAP, this is the default range for steady-state bus voltages, and the load flow result depicts the minimum voltage is occur at bus 24 which was 0.8428 pu because the bus is furthest from the source. This verifies that the feeder's voltage profile is poor and that additional improvement is required by properly integrating SPV DG.

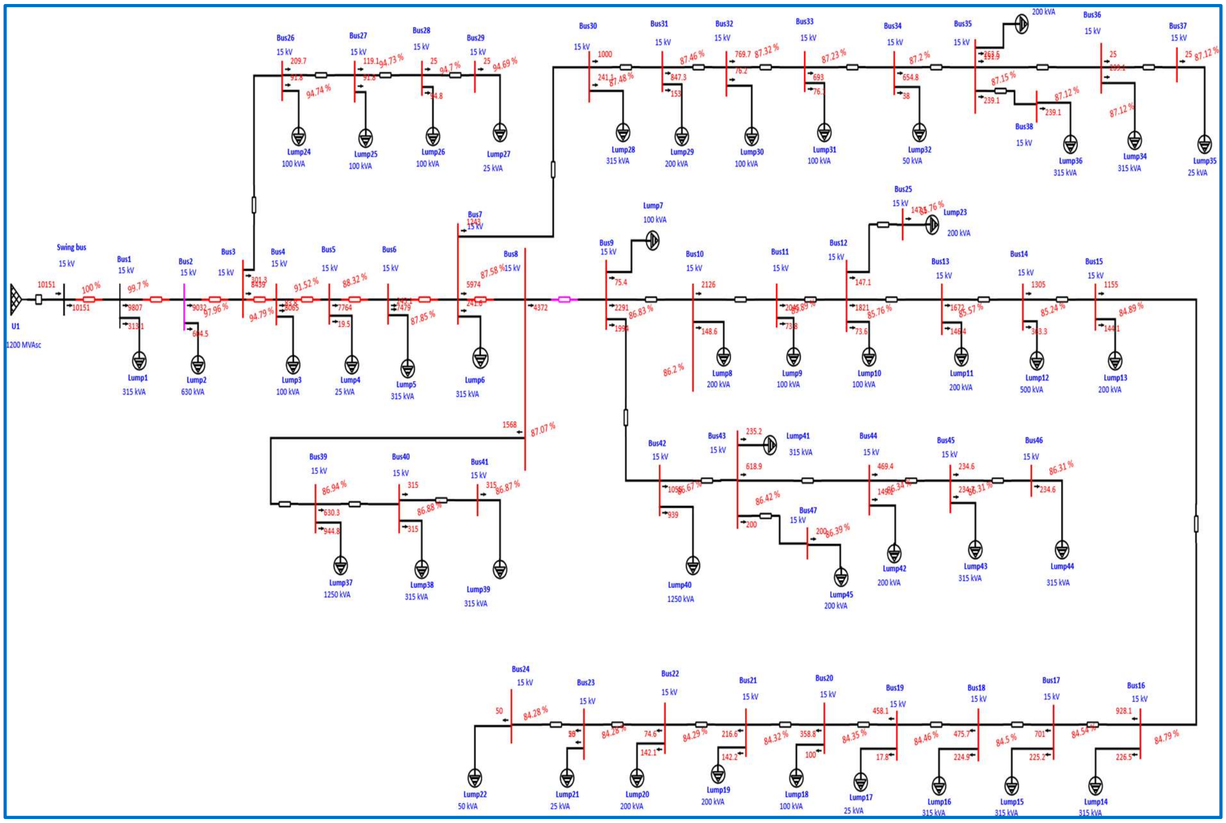

Figure 5. 3 Yirgalem town feeder before integration of SPV DG

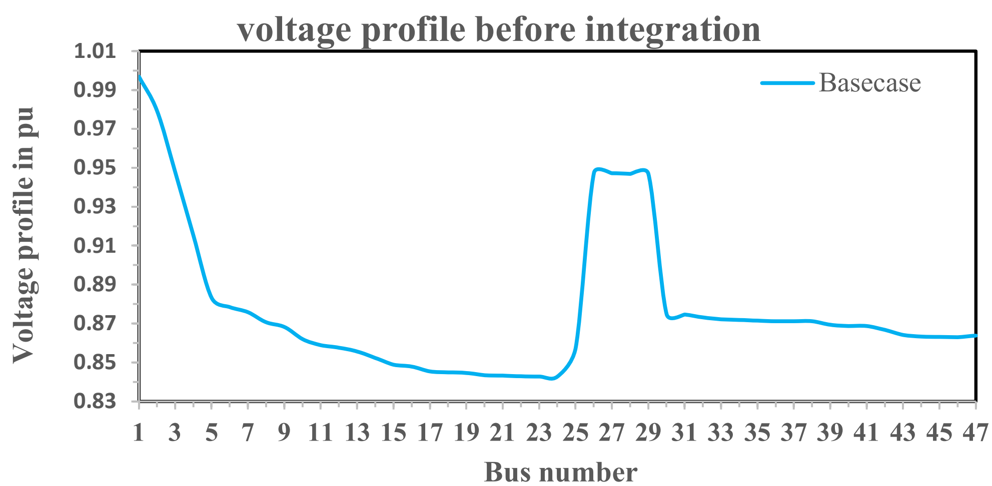

Figure 5. 4 voltage profile before SPV integration

5.4. Sizing, Location, and Power Factor of SPV DG

5.4.1 Power factor of SPV DG

The majority of grid-connected PV inverters are only configured to inject power at unity power factor, which means they only produce active power. As a result, the power factor is reduced since the grid is supplying less active power but the same amount of reactive power. The problem of low power factor, on the other hand, can be solved by choosing the right inverter. Inverters with reactive power control can be set up to generate both active and reactive power, or a non-unity power factor output. This means that the load's power factor may be kept within reasonable limits and financially beneficial to reduce the amount of active power drawn from the grid at the expense of increased charges due to a poor power factor. In this thesis feeder loads are taken as lumped load types modeled in ETAP software which are assumed as 80% constant impedance load types and 20% constant power loads (i.e., motor loads). When motor loads consume reactive power causes the voltage to fall in this situation, the inverter must be adjusted in non-unity power factor. Hence the power factor of SPV DG is assumed to be 0.89 which is the same as the distribution system average power factor.

5.4.2. SPV DG Sizing

The size of SPV DG unit was evaluated based on the analytical branch current loss formula given in equations (4.14) to (4.16) programmed in MATLAB m-file environment. This program is used to compute the optimum active (P) and reactive (Q) SPV DG sizes at various buses. Figure 5.5 depicts the capacity of SPV DG units graphically.

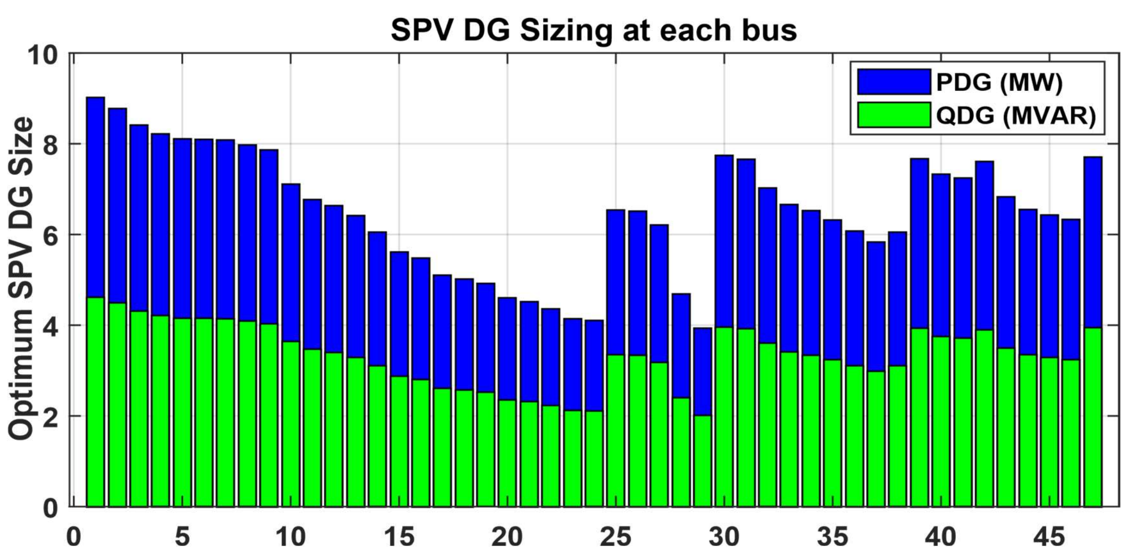

Figure 5. 5 SPV DG size at each bus

5.4.3. SPV DG Location Selection

After determining the optimum SPV DG capacity analytically, the best location of SPV DG with the best size for maximum loss reduction and an acceptable voltage profile at each bus must be determined. This is performed using positive sequence load flow analysis, which involves injecting the appropriate size of active and reactive SPV DG at the corresponding buses. The total active and reactive power loss of all buses was calculated using load flow analysis in each case shown in figure 5.6.

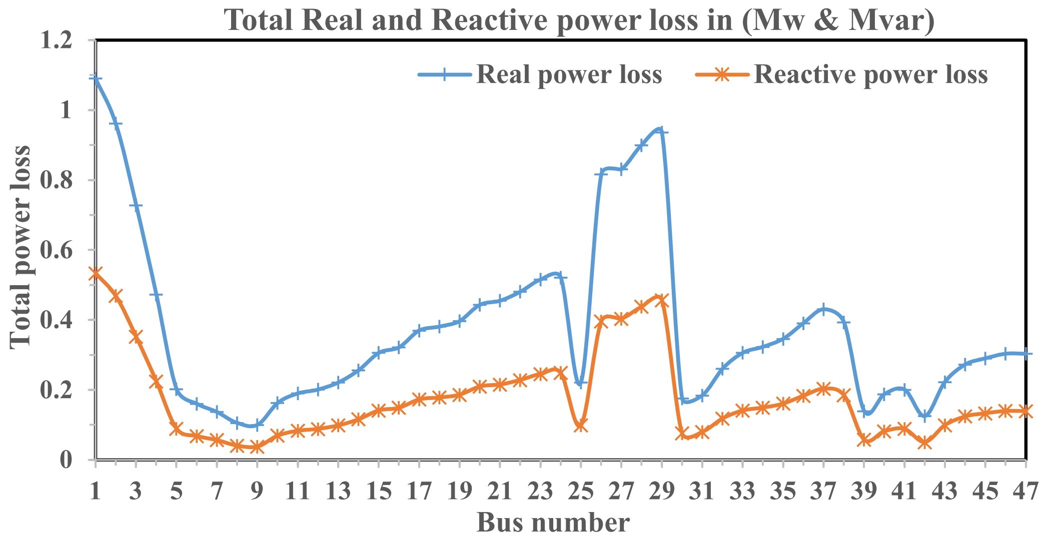

Figure 5. 6 Total power loss when optimum sizes located at each bus

5.4.4. Power Loss with SPV DG Integration

Figure 5.6 shows the minimum total real and reactive power loss was found at bus 9 which was determined to be 0.1007 MW and 0.0386 MVAR respectively with all bus voltages were within an acceptable range, when active SPV DG with size 7.86 MW and reactive SPV DG with size 4.03 MVAR injected at this bus. The total real power loss, reactive power loss, and voltage profile due to the placement of this SPV DG size at bus 9 are shown from ETAP load flow report in **appendix B3**. Due to the integration of SPV DG, the percentage reduction of real and reactive loss was found to be 90.95% and 92.9% respectively. This indicates if DG sizing is enhanced; it can reduce the line losses but a further rise in size can increase losses.

5.4.5. Voltage Profile with SPV DG Integration

After integration of SPV DG optimally, the minimum bus voltage at bus 24 which was 0.8428 p.u. had been improved to 0.9583 p.u. In this case, all bus voltages are within the allowable range which is between 0.95 pu and 1.05 pu as displayed in figure 5.7. The pink color indicates the bus voltage range is between 0.95 pu and 0.98 pu. Whereas, the black color shows the voltage range is between 0.98 pu and 1.05 pu. This voltage limit is a default in ETAP software from load flow study case. In general, the integration SPV DG to the radial distribution system improves the voltage profile, when considering the proper sizing and placement.

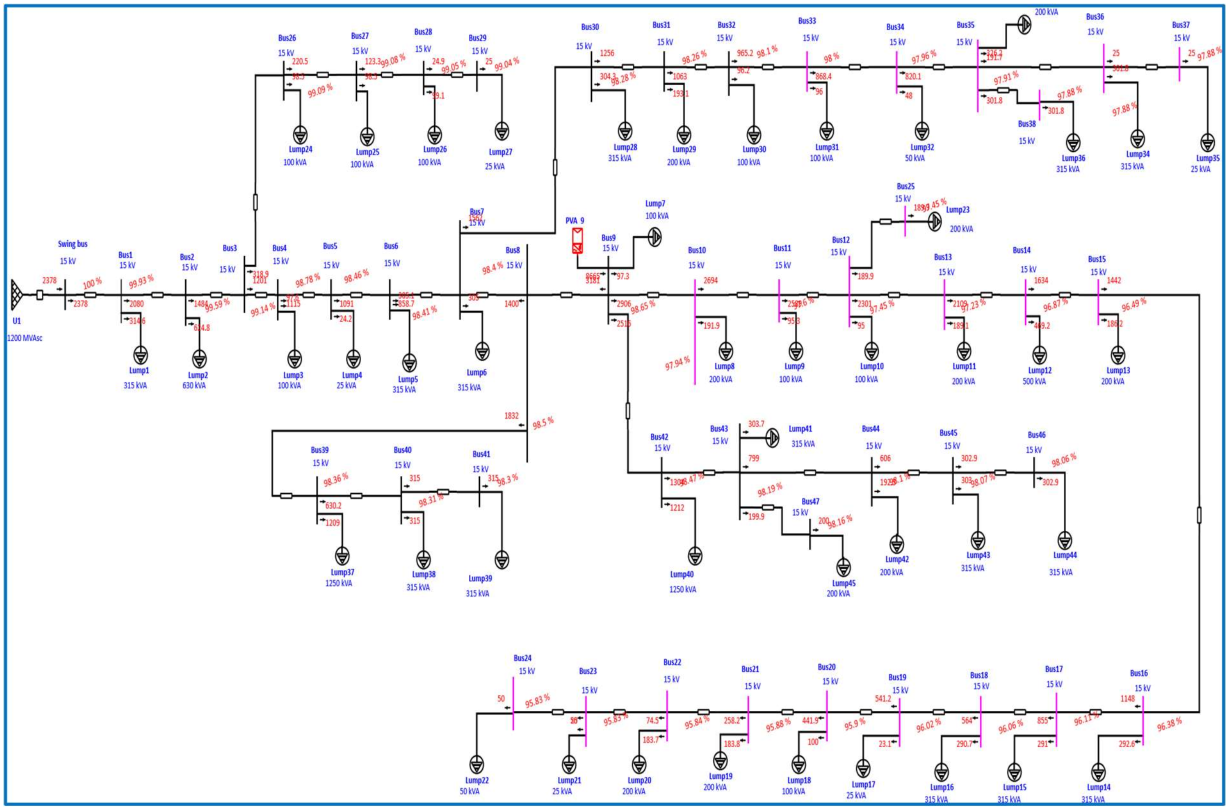

Figure 5. 7 Yirgalem town feeder after integration of one SPV DG

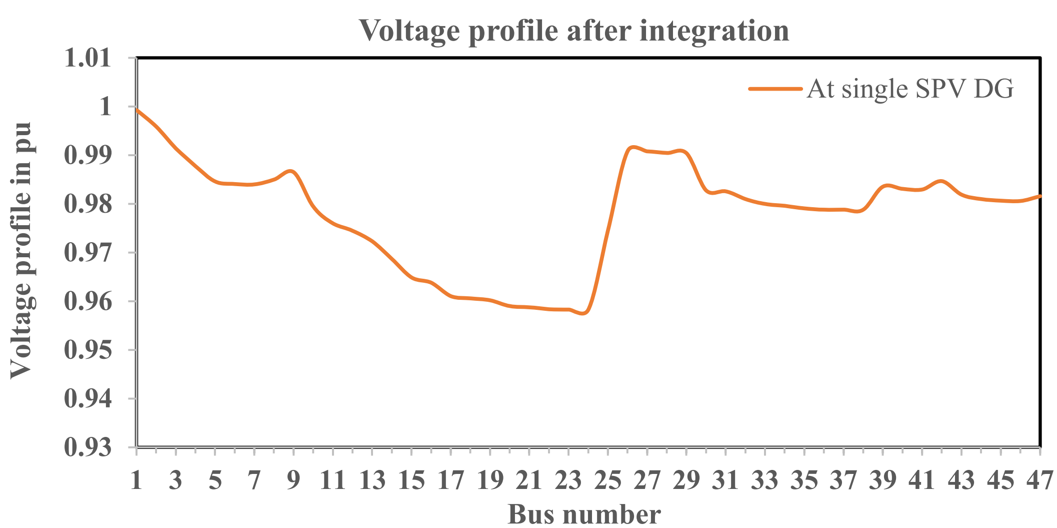

Figure 5. 8 voltage profile after SPV integration

When a single SPV DG is injected at bus 9 with 7.86 MW active power size and 4.03 MVAR reactive power size, the system's performance increases in terms of power loss reduction and voltage profile improvement. For further reduction of power loss, enhancement of voltage profile, and economic benefits, the optimal size of SPV DG at a single location serve as a constraint in locating the SPV-based multiple locations in the distribution feeder is more essential. However, in the proposed study, a constant total SPV DG power size is considered for placement at two locations.

These four scenarios are selected for deciding the SPV DG size by placing to the node at which a minimum voltage profile happened. From all buses, minimum voltage occurs at bus 24.

- ✓ Scenario 1:10% of the total DG size is placed at node 24.
- ✓ Scenario 2:20% of the total DG size is placed at node 24.
- ✓ Scenario 3:30% of the total DG size is placed at node 24.
- ✓ Scenario 4:40% of the total DG size is placed at node 24.

Table 5. 1 Real and Reactive SPV DG sizes in each scenario

Scenarios	SPV DG sizing		Power loss		Voltage profile (p.u)
	At bus 9	At bus 24	Real power loss (MW)	Reactive power loss (MVAR)	
Scenario 1	P = 7.08 Q = 3.63	P = 0.78 Q = 0.4	0.0701	0.0233	0.975
Scenario 2	P = 6.29 Q = 3.23	P = 1.57 Q = 0.8	0.0664	0.0214	0.9909
Scenario 3	P = 5.51 Q = 2.82	P = 2.36 Q = 1.21	0.087	0.0316	1.006
Scenario 4	P = 4.72 Q = 2.43	P = 3.14 Q=1.6	0.1301	0.0531	1.02

In comparison to the other scenarios, scenario 2 is the minimum power loss and a reasonable voltage profile. When 6.29 MW active and 3.23 MVAR reactive power is injected at bus 9 on the other hand 1.57 MW active and 0.8 MVAR reactive power is injected at bus 24, the real power loss is reduced from 1.1133 MW to 0.0664 MW, the reactive power loss is reduced from 0.5451 MVAR to 0.0214 MVAR, and the voltage profile is improved from 0.8428 pu to 0.9909 pu on bus 24 as shown in figure 5.9. From figure 5.10 the sharp point that is visible at bus 25 indicates the integrated SPV DG is furthest from this bus. In **Appendix B4**, all load flow results are tabulated, including active power loss, reactive power loss, and voltage profile for each bus.

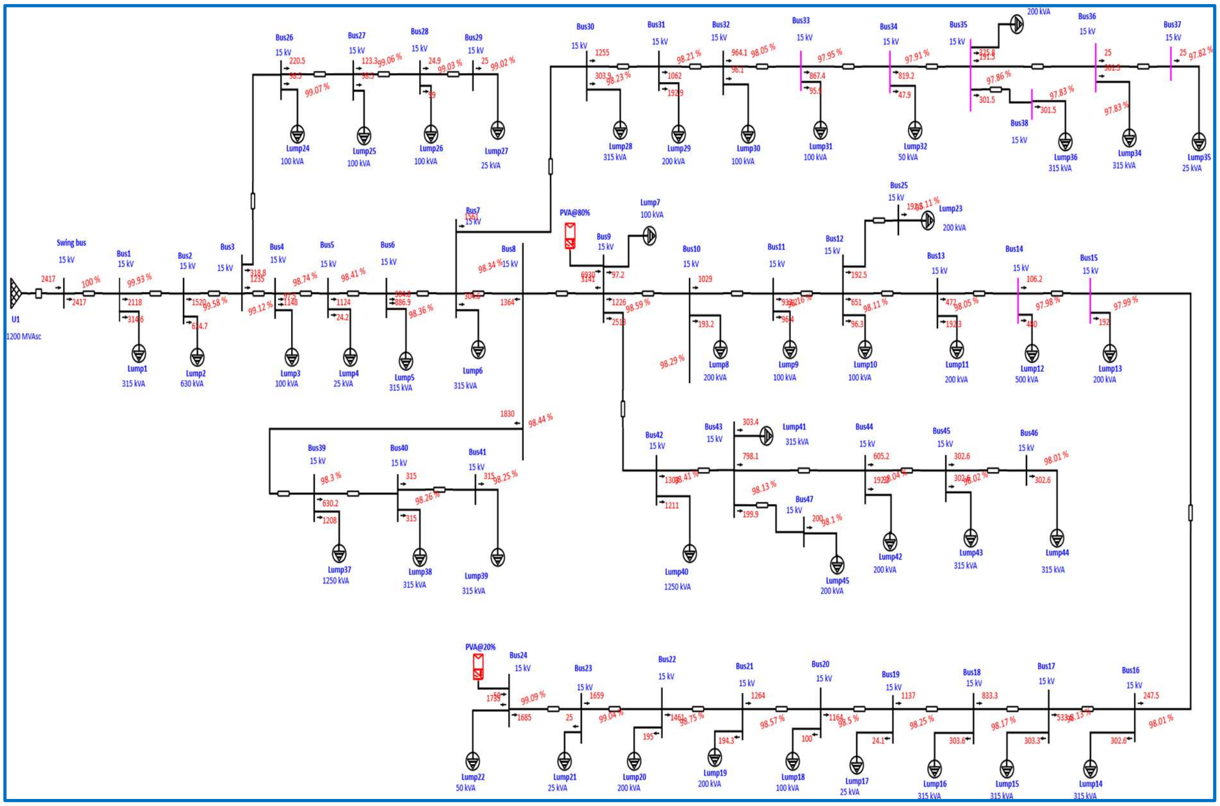

Figure 5. 9 Yirgalem town feeder after integration of SPV DG with two locations

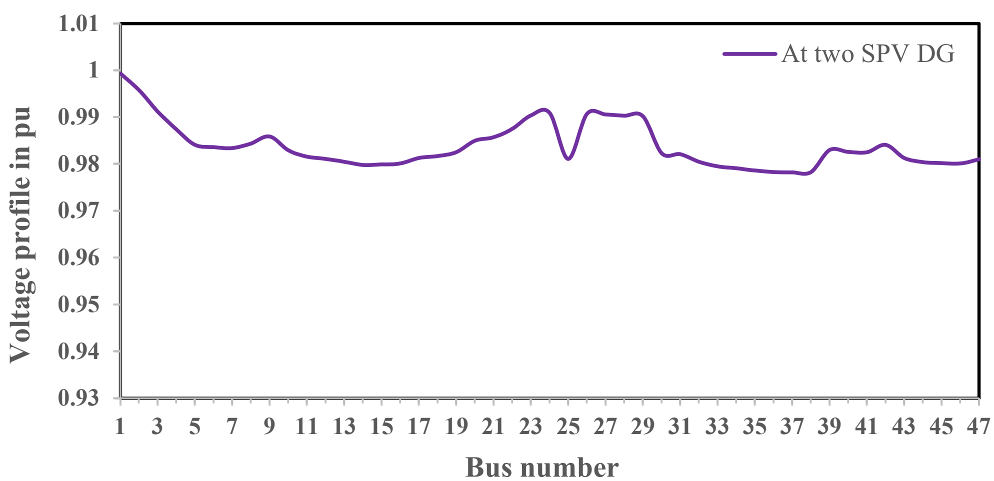

Figure 5. 10 Voltage profile after SPV integration with two SPV locations

Generally, the all-cases Figure 5.11 shows a comparison of total power loss before and after SPV DG integration generalized with three cases. In the first case during base case load flow analysis the total real and reactive power loss was determined as 1.1133 MW and 0.5451 MVAR respectively. Integration of SPV DG unit at the best location with proper size is required to reduce the system's total power losses. Taking full advantage of SPV DG integration, proper sizing, and placement of SPV DG is required; otherwise, the negative impact may lead.

In the second case, after the proper size and location were identified a positive sequence load flow analysis is applied by placing the SPV DG unit at a single location, and the total real and reactive power losses were decreased to 0.1007 MW and 0.0386 MVAR, respectively.

In the third case, based on scenario two shown in table 5.1 the same total active power of 7.86 MW and reactive of 4.03 MVAR is injected at two different buses i.e. 6.29 MW plus 3.23 MVAR at bus number 9 and 1.57 MW plus 0.8 MVAR at bus number 24. The total real and reactive power losses were reduced to 0.0664 MW and 0.0214 MVAR respectively. The percentage of reduction of total real and reactive power loss was 94.03% and 96.07% respectively. According to this study, the placement of two SPV DGs is more significant than the placement of a single DG without increasing the size.

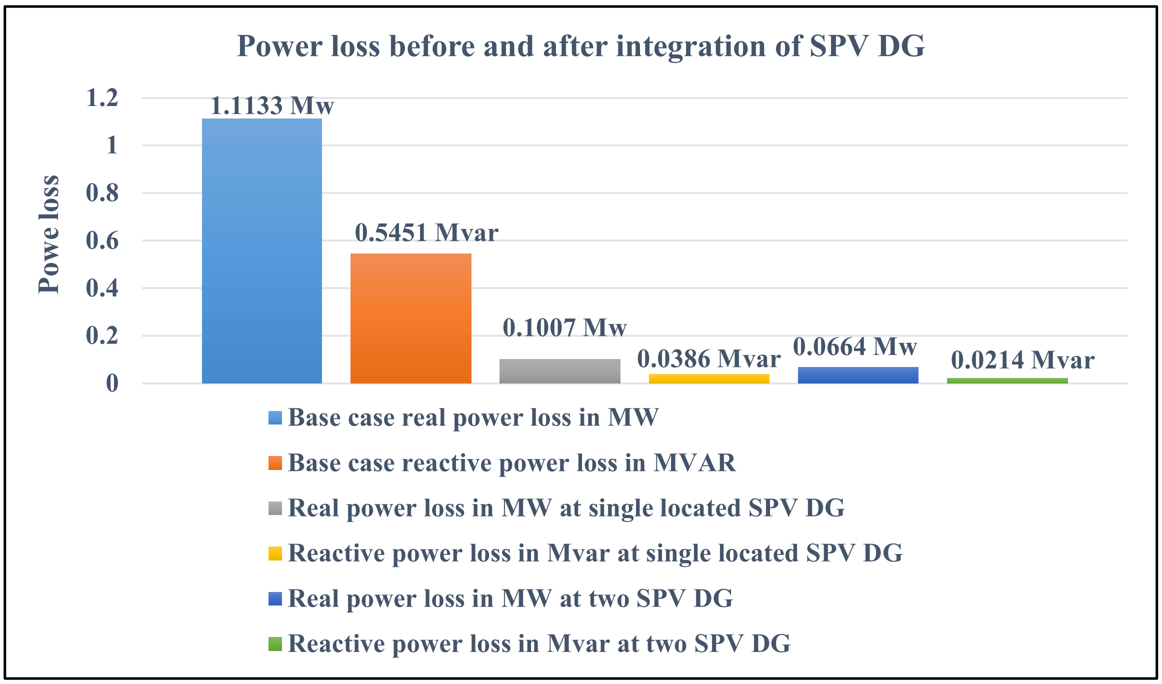

Figure 5. 11 comparisons of total power losses in all cases

As observed in figure 5.12, the minimum voltage profile uniformly occurred at bus 24 for the base case and SPV with a single location, and the average voltage magnitude varied from one case to another. The voltage at bus 24 improved from 0.8428 p.u. to 0.9583 p.u, and from 0.9583 p.u to 0.9909 p.u for SPV placed at a single location and SPV placed at two locations respectively. The SPV DG at two locations presented a better voltage profile than a single SPV

DG location. The placement of SPV at node 9 and node 24 has further improved the whole network voltage profile.

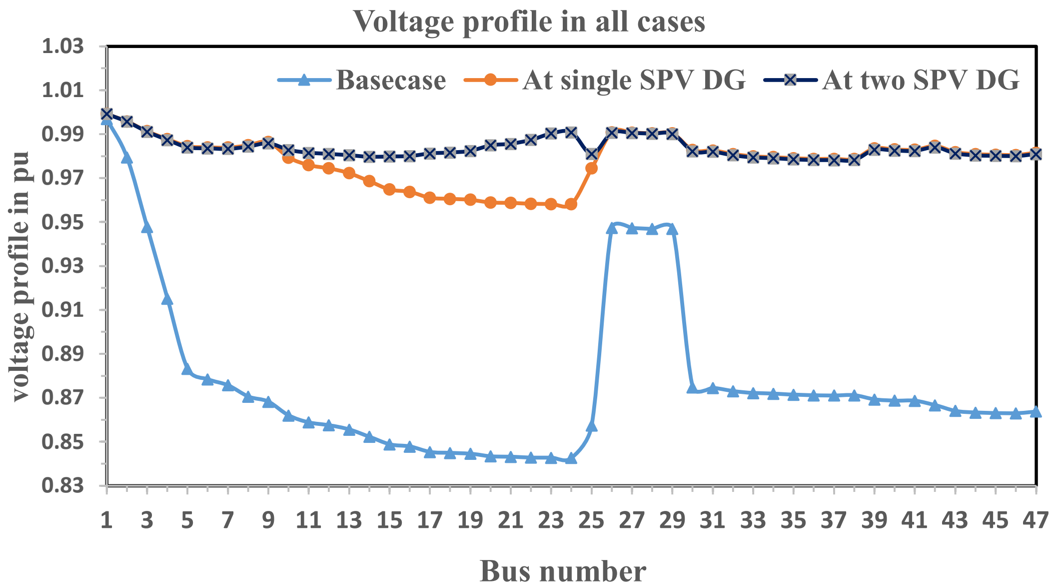

Figure 5. 12 voltage profile in all cases

5.5. Effect of Increasing Demand on Distribution System with SPV DG

In this section, the distribution system power loss and voltage profile were tested with load demand increment. The analysis starts with the current total real and reactive power demands (base year), increasing demand after one year and increasing demand after five years were considered. The comparisons were made with the SPV DG integrated system at a suitable location and size by increasing the load demand each year by 4.25%.

Using ETAP simulation software, a positive sequence load flow study was performed, and the results are summarized in Table 5.2 below. The active and reactive power losses in the system are 0.0664 MW and 0.0214 MVAR for the current year, 0.0718 MW and 0.0241 MVAR for load increments after one year, and 0.1616 MW and 0.0693 MVAR for load increments after five years, respectively, indicating that system losses increase proportionally with increased loading. Not only power loss increases also the voltage is degraded as load demand increase in each year. The bus voltages were outside of the permissible voltage range after seven years of demand increase, which is less than 0.95 p.u of the distribution feeder's nominal voltage. When load demand increases gradually, 4.25% penetration of SPV DG at proper location and size is necessary. The load flow result was tabulated in **appendix B5-B7.**

Table 5. 2 load flow result of the test system

Loading	Base year	After one year	After five years
Total active loss (MW)	0.0664	0.0718	0.1616
Total reactive loss (MVAR)	0.0214	0.0241	0.0693
Min voltage (p.u)	0.9782	0.977	0.952
Bus	37	37	16

5.6. Design of PV array for Yirgalem town feeder at suitable buses

The design and calculation of 7.86 MW of PV size placed into Yirgalem distribution feeder at two locations are shown in this section. 6.29 MW of the total SPV DG size is allocated to bus number 9 and 1.57 MW is allocated to bus number 24.

PV modules must be chosen in this design based on their efficiency, price, warranty, and environmental conditions. The best performance, a reasonable price, and reliability are all factors in the decision. The selection was based on the market's two most well-known module types, mono-crystalline and poly-crystalline pv modules. These modules share the same structure as one another, however they differ in terms of cost and efficiency. Poly-crystalline panels are less efficient than mono-crystalline panels in general. Monocrystalline panels, on the other hand, are slightly more expensive than polycrystalline panels.

As a result, mono-crystalline modules are preferred over poly-crystalline modules due to their superior efficiency. The project will make use of Suniva ART245-60 240 Wp solar panel modules which is available in ETAP library. The ART245-60 module is a well-known form of durable solar cell that is intended for use in grid-connected solar projects and power plants. The ART245-properties 60's were measured in a laboratory setting under STC (Standard Test Conditions). 1000W/m2 irradiation, 25°C, and 1.5 solar spectrum air mass are the standard conditions.

Table 5. 3 Features of PV module (Suniva, 2016)

Maximum power	240 W
Voltage @ maximum power point	30.9 V
Current @ maximum power point	7.95 A
Open circuit voltage	37.4 V
Short circuit current	8.44 A
Cells per module	60
β (Voltage de-rating factor (Voc % / °C))	-0.332
α (Current de-rating factor (Isc % / °C))	0.035
γ (Power de-rating factor (Pmax % / °C))	-0.465
Length	165.3 cm
Width	98.2cm
Depth	4.6cm

In order to generate the required power of 7.86 MW, the proposed PV design must be implemented. The sizing of the PV system is done in two locations.

Location1: 6.29 MW SPV DG capacity is integrate at bus 9

The maximum power of each module is 240 W. The total number of modules can be obtained by (Al-Shetwi & Zahim, 2016).

$$\text{Requierd number of modules} = \frac{\text{Total power}}{\text{Maximum module power}} \tag{5.5}$$

$$\text{Hence, number of modules} = \frac{6.29\times10^{6}\ \text{w}}{240\ \text{w}} \approx 26{,}208 \text{ modules}$$

A 6.92 MW system has 26,208 solar panels each of 240 watts. Hence the area needed to install such amount of power is calculated by:

Area required for solar panels = Total number of solar panel x area of one panel (5.6)

Based on equation (5.6) the total solar panels will be laid out 188.4 m by 225.8 m of rectangular surface.

In this design, the system DC link voltage is rated 600 VDC to minimize the output ripple current and to regulate the DC voltage at the inverter input side. Therefore, number of modules in series is calculated by (Al-Shetwi & Zahim, 2016).

$$\text{Number of modules in series} = \frac{\text{Dc nominal voltage}}{\text{Voltage @ MPPT}} \tag{5.7}$$

$$\text{Number of modules in series} = \frac{600\ \text{V}}{30.9\ \text{V}} \approx 19\ \text{modules}$$

The number of strings of the photovoltaic array is calculated by the following formula (Al-Shetwi & Zahim, 2016).

$$\text{Number of strings} = \frac{\text{Number of array modules}}{\text{Number of modules in series}} \tag{5.8}$$

$$\text{Number of strings} = \frac{26208}{19} \approx 1379\ \text{strings}$$

As a result, the pv system produced 6.29 Mw of power using 26,208 modules, each having a maximum output power of 240 watts. It's necessary to keep in mind that the power ratings given on the solar modules' datasheets are based on standard test conditions that are difficult to achieve in real life. Because of the high temperature and low irradiation levels, the true maximum power generated from the module is usually less than this value. The maximum voltage (Vmp) and maximum current (Imp) of the PV array is calculated by equation (5.9) and (5.10) respectively.

$$\text{Vmp} = \text{Number of series modules} \times \text{Maximum power point voltage} \tag{5.9}$$

$$\text{Vmp} = 19 \times 30.9\ \text{V} = 587\ \text{V DC}$$

$$\text{Imp} = \text{Number of parallel string} \times \text{Maximum power point current} \tag{5.10}$$

$$\text{Imp} = 1379 \times 7.95\ \text{A} = 10{,}963\ \text{A}$$

The PV array's maximum open circuit voltage (Voc) and maximum short circuit current (Isc) are determined using the following equations (5.11) and (5.12).

$$\text{Voc} = \text{Number of series modules} \times \text{Open circuit voltage} \tag{5.11}$$

$$\text{Voc} = 19 \times 37.4\ \text{V} = 710.6\ \text{V DC}$$

$$\text{Isc} = \text{Number of parallel string} \times \text{Short circuit current} \tag{5.12}$$

$$\text{Isc} = 1379 \times 8.44\ \text{A} = 11{,}638.7\ \text{A}$$

BY considering PV system losses the total output power is after the reduction of DC cable loss (97%), inverter loss (98%), and AC cable loss (99%). The mismatch losses due to radiation and temperature changes can be reduced by using maximum power point tracking (MPPT) in the inverter (Taymur, 2009).

Therefore, the output power of the PV array after considering of loss gives

$$\text{Output power of PV} = 6.29\ \text{Mw} \times\ 0.97 \times 0.98 \times 0.99 = 5.92\ \text{Mw}$$

Design and selection of grid-tied Inverter

A power electronic device that transforms DC to AC electrical energy is known as an inverter. The input rating of the inverter for grid-tie or grid-connected systems should be the same as the PV array rating to ensure safe and efficient operation (Ndagijimana, 2019).

A power rating of 5.92 Mw is required for the inverter. However, such a huge inverter does not exist on the market right now. ABB's three-phase central inverter with a 1 MW rating was chosen for this thesis, with a total of 6 inverters, each with a 1 MW rating, being linked to the system. The CORE-500/100-TL model central inverter is used. The main characteristics of this inverter's model are shown in Table 5.4.

Table 5. 4 Features of the ABB 1 MW central inverter (Shah, 2016*)*

Model	CORE-500/100-TL (500-1000 kw)
Input DC	
Maximum DC input voltage	1000 V
MPPT input DC voltage	500 V-850 V
Maximum DC input current	2300 A
Output (AC)	
Nominal AC power	1000 Kw
Maximum AC output power	1100 Kw
Nominal output voltage	300 V
AC voltage range	272 V-368 V
Output current	1984 A
Nominal power factor and adjustable range	0.995 (Adjustable range ± 0.9)
Rated frequency	50 Hz

Taking into account the total number of modules found previously, which will be distributed across six inverters, the total number of modules are 26,208. That means each inverter will have a total of 4368 modules connected to it. If each string has 19 series modules for better performance and security, the number of parallel strings is equal to:

$$\text{String number}/_{\text{One Inverter}} = \frac{\text{Modules per inverter}}{\text{Modules per string}} = \frac{4368}{19} = 230$$

According to the calculations, one inverter requires 230 strings of 19 modules, while the other five inverters are arranged similarly, with the output of each inverter supplied to a single common coupling point.

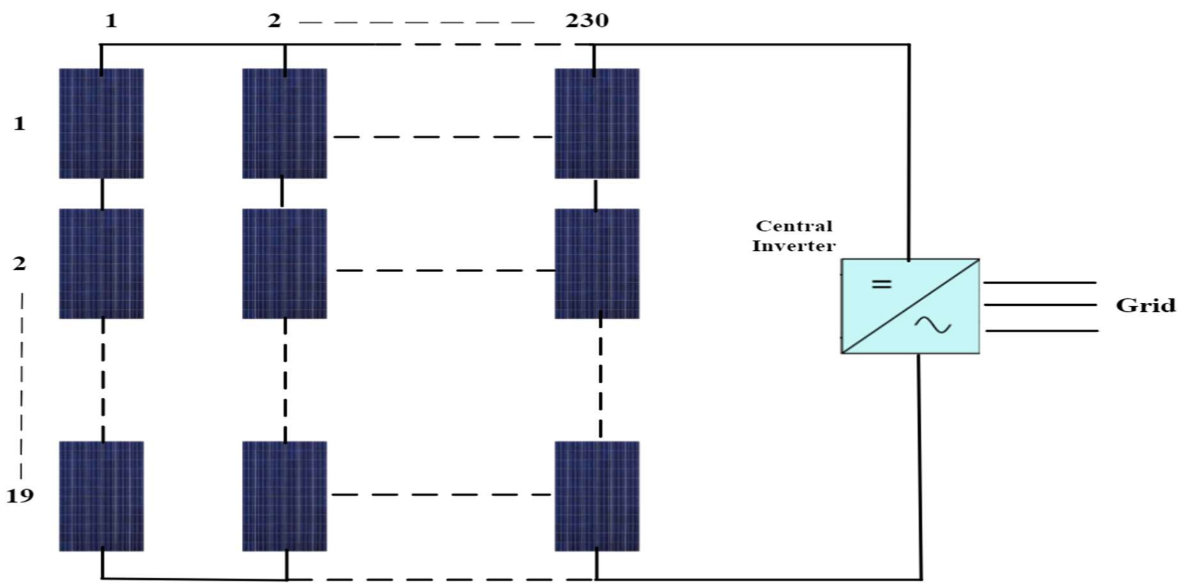

Figure 5. 13 structure of the arrays with the inverters at location 1

Location 2: 1.57 MW SPV DG capacity is integrate at bus 24.

To design and size, the SPV DG at location two have the same procedure and the solar module type, inverter type, and specification is taken from the previous one.

The maximum power of each module is 240 W. The total number of modules can be obtained by:

$$\text{Requierd number of modules} = \frac{\text{Total power}}{\text{Maximum module power}} = \frac{1.57\times10^{6}\,w}{240\text{ w}} = 6542\text{ modules}$$

Based on equation (5.6), A 1.57 MW system has 6542 solar panels each of 240 watts will be laid out 188.4 m by 56.3 m of rectangular surface.

The number of modules in series is calculated by taking DC link voltage 600 V

$$\text{Number of modules in series} = \frac{\text{Dc nominal voltage}}{\text{Voltage @ MPPT}} = \frac{600}{30.9} = 19\text{ modules}$$

The number of strings of the photovoltaic array is calculated by the following formula

$$\text{Number of strings} = \frac{\text{Number of array modules}}{\text{Number of modules in series}} = \frac{6542}{19} = 344 \text{ strings}$$

As a result, to generate 1.57 Mw power from the pv system 6542 modules with 240 W maximum output power of each module is calculated.

The PV array's maximum voltage (Vmp), maximum current (Imp), open circuit voltage (Voc), and short circuit current are computed using equations ranging from 5.9 to 5.12.

$$Vmp = \text{Number of series modules} \times \text{Maximum power point voltage}$$

$$Vmp = 19 \times 30.9 \text{ V} = 587 \text{ V DC}$$

$$Imp = \text{Number of parallel string} \times \text{Maximum power point current}$$

$$Imp = 344 \times 7.95 \text{ A} = 2734.8 \text{ A}$$

$$Voc = \text{Number of series modules} \times \text{Open circuit voltage}$$

$$Voc = 19 \times 37.4 \text{ V} = 710.6 \text{ V DC}$$

$$Isc = \text{Number of parallel string} \times \text{Short circuit current}$$

$$Isc = 344 \times 8.44 \text{ A} = 2903.4 \text{ A}$$

BY considering PV system losses the total output power is after the reduction of DC cable loss (97%), inverter loss (98%) and AC cable loss (99%).

Therefore, the output power of the PV array after consideration of loss gives

$$\text{Output power of PV} = 1.57 \text{ Mw} \times 0.97 \times 0.98 \times 0.99 = 1.47 \text{ Mw}$$

Three phase Central inverter of 1 MW rating with total of 2 inverters each of 1 MW going to be connected to the system.

For each inverter, taking in consideration the total number of modules found to be 6542 modules that will be distributed on two inverters. That means each inverter will be connected to a total of 3271 modules. The number of parallel strings is then given by:

$$\text{String number}/_{\text{One Inverter}} = \frac{\text{Modules per inverter}}{\text{Modules per string}} = \frac{3271}{19} = 172 \text{ Strings}$$

From the above calculation the design must use 172 strings of 19 modules for one inverter and the output of the two inverters are fed to one common coupling points.

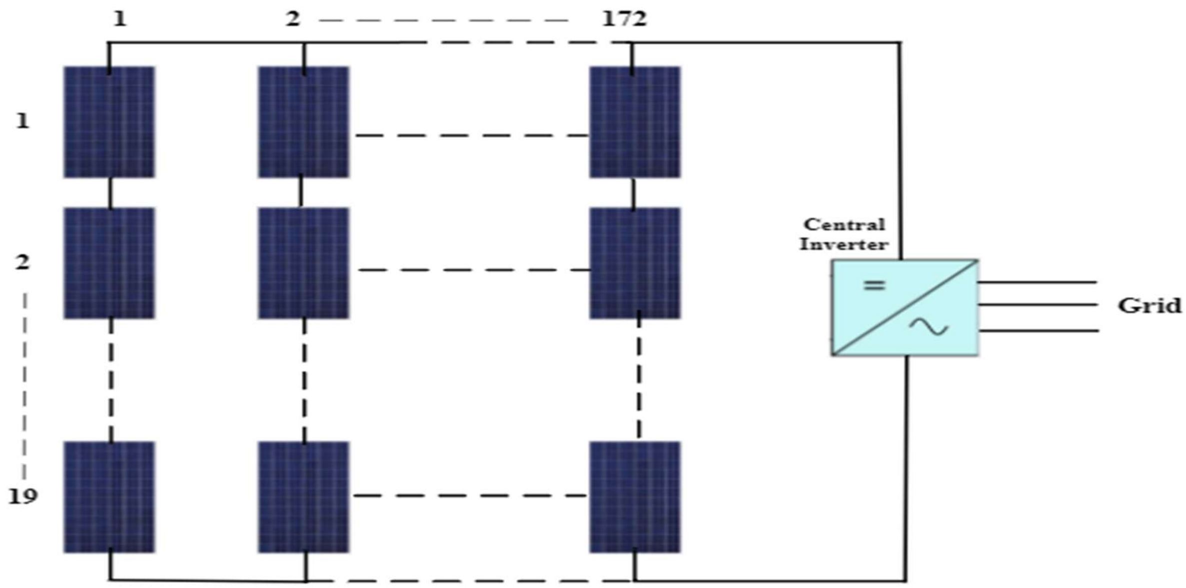

Figure 5. 14 structure of the arrays with the inverters at location 2

5.7. Cost Analysis of the Design System

After the distribution system has been improved, it is necessary to assess the costs of all the alternatives considered, including investment costs, the loss saving cost in the system and cost of Energy supplied by the PV System every year during the life cycle of the PV System is discussed in this section. Hence, an economic analysis was conducted based on total power loss reduction due to the integration of SPV DG and by considering the annual energy sold of SPV DG with two cases had been discussed. The first case involves placing a single SPV DG, whereas the second case involves placing two SPV DG at suitable buses and comparing which one has higher economic benefits.

Due to its technological advancements in solar PV modules, manufacturing advances, economies of scale, reductions in BoS costs, and rapid growth in solar PV deployment to between 1750 and 2500 GW by 2030 (Taylor et al., 2016). The central case examined here identifies that the global average total installed cost of utility-scale PV systems could fall from around USD 1.8/W in 2015 to USD 0.8/W in 2025, a 57% reduction in 10 years. Based on this information, the average cost of a solar PV module in 2015 is 1.8 USD per watt, For the following 10 years, it might drop by 57 percent from 2015, resulting in a price of 0.8 USD per watt in 2025 G.C. Assuming a constant rate of decrease, the expected cost per watt in 2022 G.C will be:

$$1.8 - (57\% \times 1.8 \times \frac{7}{10}) = \$1.08/\text{watt}$$

The cost of installing solar photovoltaic DG varies from time to time, it is difficult to give a specific estimate. When compared to the cost of fossil fuels, however, the cost of solar energy continues to fall year after year. By taking this price the total investment cost of the SPV DG is calculated in the table below.

Table 5. 5 Total costs of solar PV DG

DG type	Total capacity (MW)	Unit cost ($/watt)	Total cost ($)	Total cost in Ethiopian birr ($1=51 ETB) on March 2022	Life time
Solar PV	7.86	1.08	8,488,800	432,928,800	25 yr

Calculating the payback period of the capital invested for DG installation is also extremely significant to determine economic feasibility after estimating the installed cost of SPV-based DG. The payback period is the amount of time it takes to return an investment's cost. It's the ratio of the cost of DG installation to cost of energy supplied by the PV System every year and the total energy saved due to the installation of SPV DG (Lincy, 2018) (Mandefro, 2020).

$$\text{payback period} = \frac{\text{Total installation cost}}{\text{Cost of supplied Energy by DG annually} + \text{cost of annual energy saved}} \quad (5.13)$$

This part of the study estimates cost lost by the utility in the Yirgalem town feeder due to losses and the cost of energy supplied by SPV DG with two cases.

Case-1: At single SPV DG location:

The total power loss reduction after SPV integration at single location as follows;

$$\text{PLR} = \text{Power loss before SPV integration} - \text{Power loss after SPV integration at 1 location} \quad (5.14)$$

$$1.1133\ \text{MW} - 0.1007\text{MW} = 1.0126\ \text{MW}$$

After integration of SPV DG at a single location, the total cost of energy saved for one year is calculated using equation 5.15, by Considering the average residential first block and general tariff which is 1.198 Birr/KWh for electricity in EEU (seen in appendix E),

Cost of energy = power loss*time*electric tariff (5.15)

Cost of energy = 1012.6*8760 hr/yr*1.198 Birr/kwh = 10,626,710 Birr

Case-2: At two SPV DG location:

The total power loss reduction after SPV integration at two locations as follows;

PLR = Power loss before SPV integration – Power loss after SPV integration at two locations

1.1133 MW – 0.0664 MW = 1.0469 MW

Based on equation 5.15 the total cost of energy saved for one year is calculated as

Cost of energy = 1046.9*8760 hr/yr*1.198 Birr/kWh = 10,986,671 Birr

The integration of SPV DG to Yirgalem distribution feeder saves the annual energy wastage by reducing the total power loss. On the other hand, the utility can sell the generated power from solar PV. Hence the cost of energy supplied by SPV DG for one year is calculated as follows:

Cost of energy = power *time*electric tariff

Cost of energy = (7.86*1000) kw*8760 hr/yr*1.198 Birr/kWh = 82,486,613 Birr

Using this equation 5.13, the payback period to return the investment cost for case-1 is

$$\text{payback period} = \frac{\text{Total installation cost}}{\text{Cost of supplied Energy by DG annually+cost of annual energy saved}}$$

$$\text{payback period} = \frac{432,928,800}{82,486,613+10,626,710} = 4.65 \text{ years}$$

The payback period for case 2 can be calculated as:

$$\text{payback period} = \frac{432,928,800}{82,486,613+10,986,671} = 4.63 \text{ years}$$

Table 5. 6 Overall cost analysis result for the two cases

DG Type	Capacity (MW)	Total investment cost	Saving cost (ETB)	Payback period
Solar PV	1DG at Bus 9 =7.86	432,928,800 birr	10,626,710	4.65 years
	2-DG $\begin{cases}\text{at Bus 9} = 6.29\\ \text{at Bus 24} = 1.57\end{cases}$	432,928,800 birr	10,986,671	4.63 years

From the above economic analysis, the saving in terms of money increased from 10.626 million birr to 10.986 million birr for the SPV DG at 1 and 2 locations. Therefore, the same size of SPV DG at two locations saves 359,961 birr per year more than SPV DG at a single location.

CHAPTER SIX

CONCLUSION, RECOMMENDATION, AND FUTURE WORK

6.1. Conclusions

The most essential issue in an electric power system is power loss and voltage profile. It has an impact on distribution system planning and operations. Network reconfiguration, the use of FACTs devices, and distributed generation integration are among the ways used to reduce power loss and enhance voltage profiles. Each method has its own set of integration strategies, each with its own set of benefits and drawbacks. The integration of SPV DG is a unique option for future power distribution systems in sustainability and greenhouse gas reduction, as well as improved distribution system performance.

In this thesis, electrical load demand forecasting, distribution network expansion planning with integration of SPV DG to meet the increment of load demand, voltage profile improvement and power loss reduction of the radial 15 KV Yirgalem town distribution feeder has been conducted. The case study distribution feeder was identified with higher interruption data as compared to other feeders. The modeling and simulation of this feeder were carried out using ETAP software with and without integration SPV DG. The load flow result before integration of SPV DG showed that the total real and reactive power loss was 1.1133 MW and 0.5451 MVAR respectively with the majority of bus voltages being outside the allowable range.

SPV DG was introduced into the system at a suitable location with appropriate capacity to reduce total real loss, reactive power loss, and to improve all node voltages to within an acceptable range. Based on the analytical approach and load flow study, the proper site and size of the SPV DG were located and determined to be at bus 9 with a proper active power size of 7.86 MW and reactive power size 4.03 MVAR. The positive sequence load flow result showed that the total real and reactive power loss reduced to 0.1007 MW and 0.386 MVAR respectively, and the percentage reduction of real and reactive loss was found to be 90.95% and 92.9% respectively with all bus voltages were within the limit and the minimum voltage at bus 24 improved from 0.8428 p.u to 0.9583 p.u.

For further reduction of power loss,enhancement of voltage profile and, economic benefits, the optimal size of SPV DG at multiple location is more essential. Four scenarios have been selected for examination. Results show that scenario 2 is selected with total active power of 7.86 MW and reactive power of 4.03 MVAR is injected into two different buses, namely 6.29 MW plus

3.23 MVAR at bus 9 and 1.57 MW plus 0.8 MVAR at bus 24. Total real and reactive power losses were reduced to 0.0664 MW and 0.0214 MVAR with a percentage reduction 94.03% and 96.07% respectively, and the bus voltage has been improved drastically.

Furthermore, in this study appropriate SPV DG (the PV system) with a power of 7.86MW has also been designed to serve as an additional and alternative power supply for the expected most critical and sensitive society issued load center. The total cost of SPV DG installation was found to be 432,928,800 Ethiopian birr. As it can be seen from economic analysis, the proposed SPV-based MLDG is very cost-effective, resulting in a total annual savings of 10.626 million birr for a single location and 10.986 million birr for SPV DG at two locations.

The author of this thesis paper believes that the SPV-based DG at two locations should be an effective solution for further improvement of distribution system performance and having economic benefits without increasing the DG size.

6.2. Recommendations

According to this study, the Integration of solar photovoltaic-based distributed generation with distribution network expansion planning reduces power loss and improves voltage profile. In addition, DG technology especially solar photovoltaic based expects to have a key role in the future power distribution system for sustainable and emission-free energy supply and due to its technological advancements in solar PV modules, manufacturing advances, economies of scale, and reductions in BoS costs. I recommended that the Ethiopian electric utility may apply Utility-scale solar PV integration into the distribution system to solve the problem associated with the increase in energy demand.

6.3. Future Work

Any scientific study cannot cover all aspects and investigate all significant issues at the same time; some points will need to be addressed in future work. Here are some points to be focused:

- This work suggests using the branch current loss formula to determine the optimal DG sizing in radial systems, but it is ineffective in large distribution networks as an alternative, other optimization approaches can be used to test the robustness and efficiency of a large network.
- The study has been carried out on balanced distribution networks. The DGs placement problem could be extended to unbalanced distribution systems.
- The impact of SPV DG on distribution network in terms of fault level, system stability and protection device coordination will be the future work to be focused on.

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APPENDICES

Appendix A :MATLAB m-file program for SPV DG sizing

```
clc;
clear;
close all;
% parametre definition
N = 47;   i =(1:N);
Vref=15;
IDG =zeros(1,N);
IRDG=zeros(1,N);
PDG=zeros(1,N);
QDG=zeros(1,N);
Psize=zeros(1,N);
Qsize=zeros(1,N);
PFDG=0.89;
ak=tan(acos(PFDG));
%% Parameter Initialization
R = zeros(1,N);
I = zeros(1,N);
IR = zeros(1,N);
%% active Branch Currents Initialization
I24 = zeros(1,24); A24 = zeros(1,24);p = zeros(1,24);
I3 = zeros(1,3); A3 = zeros(1,3);
I29 = zeros(1,29); A29=zeros(1,29); k = zeros(1,29);
I7 = zeros(1,7); A7 = zeros(1,7);
I35 = zeros(1,35); A35 =zeros(1,35); m = zeros(1,35);
b=zeros(1,38); t=zeros(1,36);s=zeros(1,37);
I8 = zeros(1,8); A8=zeros(1,8);
I41 = zeros(1,41); A41 = zeros(1,41); w=zeros(1,41);
I9 = zeros(1,9); A9=zeros(1,9);
I43=zeros(1,43); A43=zeros(1,43); d=zeros(1,43);
h=zeros(1,47); q=zeros(1,44);
I46 = zeros(1,46); A46 = zeros(1,46); u=zeros(1,46);
I12 =zeros(1,12); A12 =zeros(1,12);
v=zeros(1,25);
% % reactive branch currents initialization
IR24 = zeros(1,24); AR24 = zeros(1,24);c = zeros(1,24);
IR3 = zeros(1,3); AR3 = zeros(1,3);
IR29 = zeros(1,29); AR29=zeros(1,29); e = zeros(1,29);
IR7 = zeros(1,7); AR7 = zeros(1,7);
IR35 = zeros(1,35); AR35 =zeros(1,35); f = zeros(1,35);
g=zeros(1,38); j=zeros(1,36);l=zeros(1,37);
IR8 = zeros(1,8); AR8=zeros(1,8);
IR41 = zeros(1,41); AR41 = zeros(1,41); o=zeros(1,41);
IR9 = zeros(1,9); AR9=zeros(1,9);
IR43=zeros(1,43); AR43=zeros(1,43); x=zeros(1,43);
y=zeros(1,47); z=zeros(1,44);
IR46 = zeros(1,46); AR46 = zeros(1,46); a1=zeros(1,46);
IR12 =zeros(1,12); AR12 =zeros(1,12);
b1=zeros(1,25);
%% Input line data
R = [0.06001 0.357236 0.69188 0.7413 0.731416 0.108724 0.06354 0.15179
0.094604 0.481492 0.25416 0.10943 ...
0.186384 0.337468 0.460312 0.149672 0.45184 0.104488 0.13061 0.43419
0.11296 0.2471 0.338174 0.061422...
```

```
0.078366 0.33888 0.073424 0.503378 0.391124 0.146848 0.033888 0.30005
0.204034 0.081896 0.122138 0.205446...
0.196974 0.216742 0.146848 0.156732 0.040948 0.139788 0.4236 0.228744
0.080484 0.061422 0.286636];
Ia = [0.347189 0.33642 0.315327 0.304736 0.301532 0.30082 0.291297 0.233625
0.171948 0.090246 0.084372 0.081435 0.072624 0.066839 0.052332 0.046547
0.03738 0.028302 0.019135 ...
0.018512 0.014418 0.008722 0.002937 0.001958 0.005874 0.010591 0.007298
0.004005 0.000801 0.048416 0.038982 0.03293 0.029993 0.026967 0.025543
0.010146 0.000712 0.009434 0.061677...
0.024831 0.01246 0.078676 0.041741 0.024564 0.018601 0.009345 0.007921];
Ir = [0.1778856 0.172368 0.1615608 0.1561344 0.1544928 0.154128 0.1492488
0.1197 0.0880992 0.0462384 0.0432288 0.041724 0.0372096 0.0342456 0.0268128
0.0238488 0.019152 0.0145008...
0.009804 0.0094848 0.0073872 0.0044688 0.0015048 0.0010032 0.0030096
0.0054264 0.0037392 0.002052 0.0004104 0.0248064 0.0199728 0.016872
0.0153672 0.0138168 0.0130872 0.0051984...
0.0003648 0.0048336 0.0316008 0.0127224 0.006384 0.0403104 0.0213864
0.0125856 0.0095304 0.004788 0.0040584];
%% DG sizing using analytical 'brach current loss' formula
for i =1:24
I24(i) = Ia(i).*R(i);
A24(i) =R(i);
IR24(i) = Ir(i).*R(i);
AR24(i) =R(i);
p(i) =
(sum(I24))./((1+ak.^2).*sum(A24))+(ak*sum(IR24))/((1+ak.^2)*sum(AR24));
end
P=p(:,1:24);
for i = 1:3
I3(i) = Ia(i).*R(i);
A3(i) = R(i);
IR3(i) = Ir(i).*R(i);
AR3(i) = R(i);
end
I3;
A3;
IR3;
AR3;
for i=26:29
I29(i)= Ia(i).*R(i);
A29(i)=R(i);
IR29(i)= Ir(i).*R(i);
AR29(i)=R(i);
k(i)=(sum(I3)+sum(I29))/((1+ak^2)*sum(A3)+(1+ak^2)*sum(A29))...
+(ak*sum(IR3)+ak*sum(IR29))/((1+ak^2)*sum(AR3)+(1+ak^2)*sum(AR29));
end
K=k(:,26:29);
for i = 1:7
I7(i) = Ia(i).*R(i);
A7(i) = R(i);
IR7(i) = Ir(i).*R(i);
AR7(i) = R(i);
end
I7;
A7;
IR7;
```

```
AR7;
for i = 30:35
I35(i) = Ia(i).*R(i);
A35(i) = R(i);
IR35(i) = Ir(i).*R(i);
AR35(i) = R(i);
m(i) = (sum(I7)+sum(I35))/((1+ak^2)*sum(A7)+(1+ak^2)*sum(A35))...
+(ak*sum(IR7)+ak*sum(IR35))/((1+ak^2)*sum(AR7)+(1+ak^2)*sum(AR35));
end
M=m(:,30:35);
for i=38
b(i)=(sum(I7)+sum(I35)+Ia(38)*R(38))/((1+ak^2)*sum(A7)+(1+ak^2)*sum(A35)+R(
38))...
+(ak*sum(IR7)+ak*sum(IR35)+Ir(38)*R(38))/((1+ak^2)*sum(AR7)+(1+ak^2)*sum(AR
35)+R(38));
end
B=b(:,38);
for i=36
t(i)=(sum(I7)+sum(I35)+Ia(36)*R(36))/((1+ak^2)*sum(A7)+(1+ak^2)*sum(A35)+R(
36))...
+(ak*sum(IR7)+ak*sum(IR35)+Ir(36)*R(36))/((1+ak^2)*sum(AR7)+(1+ak^2)*sum(AR
35)+R(36));
end
T=t(:,36);
for i=37

s(i)=(sum(I7)+sum(I35)+Ia(36)*R(36)+Ia(37)*R(37))/((1+ak^2)*sum(A7)+(1+ak^2
)*sum(A35)+R(36)+R(37))...

+(ak*sum(IR7)+ak*sum(IR35)+Ir(36)*R(36)+Ir(37)*R(37))/((1+ak^2)*sum(AR7)+(1
+ak^2)*sum(AR35)+R(36)+R(37));
end
S=s(:,37);
for i=1:8
I8(i)=Ia(i).*R(i);
A8(i)=R(i);
IR8(i)=Ir(i).*R(i);
AR8(i)=R(i);
end
I8;
A8;
IR8;
AR8;
for i=39:41
I41(i)=Ia(i).*R(i);
A41(i)=R(i);
IR41(i)=Ir(i).*R(i);
AR41(i)=R(i);
w(i)=(sum(I8)+sum(I41))/((1+ak^2)*sum(A8)+(1+ak^2)*sum(A41))...
+(ak*sum(IR8)+ak*sum(IR41))/((1+ak^2)*sum(AR8)+(1+ak^2)*sum(AR41));
end
W=w(:,39:41);
for i=1:9
I9(i)=Ia(i).*R(i);
A9(i)=R(i);
IR9(i)=Ir(i).*R(i);
AR9(i)=R(i);
```

```
end
I9;
A9;
IR9;
AR9;
for i=42:43
I43(i)=Ia(i).*R(i);
A43(i)=R(i);
IR43(i)=Ir(i).*R(i);
AR43(i)=R(i);
d(i)=(sum(I9)+sum(I43))/((1+ak^2)*sum(A9)+(1+ak^2)*sum(A43))...
+(ak*sum(IR9)+ak*sum(IR43))/((1+ak^2)*sum(AR9)+(1+ak^2)*sum(AR43));
end
D=d(:,42:43);
for i=47
h(i)=(sum(I9)+sum(I43)+Ia(47)*R(47))/((1+ak^2)*sum(A9)+(1+ak^2)*sum(A43)+R(
47))...
+(ak*sum(I9)+ak*sum(I43)+I(47)*R(47))/((1+ak^2)*sum(AR9)+(1+ak^2)*sum(AR43)
+R(47));
end
H=h(:,47);
for i=44
q(i)=(sum(I9)+sum(I43)+Ia(44)*R(44))/((1+ak^2)*sum(A9)+(1+ak^2)*sum(A43)+R(
44))...
+(ak*sum(IR9)+ak*sum(IR43)+Ir(44)*R(44))/((1+ak^2)*sum(AR9)+(1+ak^2)*sum(AR
43)+R(44));
end
Q=q(:,44);
for i=45:46
I46(i)=Ia(i).*R(i);
A46(i)=R(i);
IR46(i)=Ir(i).*R(i);
AR46(i)=R(i);
u(i)=(sum(I9)+sum(I43)+Ia(44)*R(44)+sum(I46))/((1+ak^2)*sum(A9)+(1+ak^2)*su
m(A43)+R(44)+(1+ak^2)*sum(A46))...
+(ak*sum(IR9)+ak*sum(IR43)+Ir(44)*R(44)+ak*sum(I46))/((1+ak^2)*sum(AR9)+(1+
ak^2)*sum(AR43)+R(44)+(1+ak^2)*sum(AR46));
end
U=u(:,45:46);
for i=1:12
I12(i)=Ia(i).*R(i);
A12(i)=R(i);
IR12(i)=Ir(i).*R(i);
AR12(i)=R(i);
end
I12;
A12;
IR12;
AR12;
for i=25
v(i)=(sum(I12)+Ia(25)*R(25))/((1+ak^2)*sum(A12)+R(25))+(ak*sum(IR12)+Ir(25)
*R(25))/((1+ak^2)*sum(AR12)+R(25));
end
V=v(:,25);
%% OutPut- real and reactive DG
IDG =[P V K M T S B W D Q U H];
PDG=Vref*IDG*sqrt(3);
```

```
idg=IDG';
IRDG=ak*IDG';
Psize=PDG';
QDG=ak*PDG';
PFsize=PFDG';
Qsize=QDG;
sr =(1:N)';
Table =table(sr,Psize,idg,Qsize,IRDG);
bar(1:N,PDG,'b')
hold on
bar(1:N,QDG,'g')
xlabel("Bus Number");
ylabel("Optimum SPV DG Size")
title("SPV DG Sizing at each bus")
legend('PDG','QDG')
grid on;
```

Appendix B: ETAP Load Flow Analysis Input and Output Results

B1: Per-unit Line Impedance of Yirgalem town Feeder

Table A. 1 Per-unit Line Impedance of Yirgalem town Feeder

Project:	Masters Thesis	ETAP		Page:	1
Location:	Yirgalem city	19.0.1C		Date:	28-02-2022
Contract:	-			SN:	
Engineer:	Endalk D	Study Case:	With out SPV	Revision:	Base
Filename:	YIRGALEM FEEDER(02)			Config.:	Normal

Electrical Transient Analyzer Program

Load Flow Analysis

Loading Category (1): Design

Generation Category (1): Design

Load Diversity Factor: None

	Swing	V-Control	Load	Total
Number of Buses:	1	0	47	48

	XFMR2	XFMR3	Reactor	Line/Cable/ Busway	Impedance	Tie PD	Total
Number of Branches:	0	0	0	47	0	0	47

Method of Solution:	Newton-Raphson Method
Maximum No. of Iteration:	99
Precision of Solution:	0.0001000
System Frequency:	50.00 Hz
Unit System:	Metric
Project Filename:	YIRGALEM.FEEDER(02)
Output Filename:	C:\ETAP 1901\YIRGALEM.FEEDER(02)\47 bus LF.lfr

Project:	Masters Thesis	ETAP		Page:	7
Location:	Yirgalem city	19.0.1C		Date:	28-02-2022
Contract:	-			SN:	
Engineer:	Endalk.D	Study Case:	With out SPV	Revision:	Base
Filename:	YIRGALEM.FEEDER(02)			Config.:	Normal

Branch Connections

CKT/Branch		Connected Bus ID		% Impedance, Pos. Seq., 100 MVA Base			
ID	Type	From Bus	To Bus	R	X	Z	Y
L1	Line	Swing bus	Bus1	2.67	1.33	2.98	0.0000639
L2	Line	Bus1	Bus2	15.88	7.91	17.74	0.0003801
L3	Line	Bus2	Bus3	30.75	15.32	34.36	0.0007362
L4	Line	Bus3	Bus4	32.95	16.41	36.81	0.0007888
L5	Line	Bus4	Bus5	32.51	16.20	36.32	0.0007782
L6	Line	Bus5	Bus6	4.83	2.41	5.40	0.0001157
L7	Line	Bus6	Bus7	2.82	1.41	3.16	0.0000676
L8	Line	Bus7	Bus8	6.75	3.36	7.54	0.0001615
L9	Line	Bus8	Bus9	4.20	2.09	4.70	0.0001007
L10	Line	Bus9	Bus10	21.40	10.66	23.91	0.0005123
L11	Line	Bus10	Bus11	11.30	5.63	12.62	0.0002704
L12	Line	Bus11	Bus12	4.86	2.42	5.43	0.0001164
L13	Line	Bus12	Bus13	8.28	4.13	9.25	0.0001983
L14	Line	Bus13	Bus14	15.00	7.47	16.76	0.0003591
L15	Line	Bus14	Bus15	20.46	10.19	22.86	0.0004898
L16	Line	Bus15	Bus16	6.65	3.31	7.43	0.0001593
L17	Line	Bus16	Bus17	20.08	10.01	22.44	0.0004808
L18	Line	Bus17	Bus18	4.64	2.31	5.19	0.0001112
L19	Line	Bus18	Bus19	5.80	2.89	6.49	0.0001390

L20	Line	Bus19	Bus20	19.30	9.61	21.56	0.0004620
L21	Line	Bus20	Bus21	5.02	2.50	5.61	0.0001202
L22	Line	Bus21	Bus22	10.98	5.47	12.27	0.0002629
L23	Line	Bus22	Bus23	15.03	7.49	16.79	0.0003598
L24	Line	Bus23	Bus24	2.73	1.36	3.05	0.0000654
L25	Line	Bus12	Bus25	3.48	1.74	3.89	0.0000834
L26	Line	Bus3	Bus26	15.06	7.50	16.83	0.0003606
L27	Line	Bus26	Bus27	3.26	1.63	3.65	0.0000781
L28	Line	Bus27	Bus28	22.37	11.15	25.00	0.0005356
L29	Line	Bus28	Bus29	17.38	8.66	19.42	0.0004162
L30	Line	Bus7	Bus30	6.53	3.25	7.29	0.0001562
L31	Line	Bus30	Bus31	1.51	0.75	1.68	0.0000361
L32	Line	Bus31	Bus32	13.34	6.64	14.90	0.0003193
L33	Line	Bus32	Bus33	9.07	4.52	10.13	0.0002171
L34	Line	Bus33	Bus34	3.64	1.81	4.07	0.0000871
L35	Line	Bus34	Bus35	5.43	2.70	6.06	0.0001300
L36	Line	Bus35	Bus36	9.13	4.55	10.20	0.0002186
L37	Line	Bus36	Bus37	8.75	4.36	9.78	0.0002096
L38	Line	Bus35	Bus38	9.63	4.80	10.76	0.0002306
L39	Line	Bus8	Bus39	6.53	3.25	7.29	0.0001562
L40	Line	Bus39	Bus40	6.97	3.47	7.78	0.0001668
L41	Line	Bus40	Bus41	1.82	0.91	2.03	0.0000436
L42	Line	Bus9	Bus42	6.21	3.10	6.94	0.0001487
L43	Line	Bus42	Bus43	18.83	9.38	21.03	0.0004507
L44	Line	Bus43	Bus44	10.17	5.07	11.36	0.0002434
L45	Line	Bus44	Bus45	3.58	1.78	4.00	0.0000856
L46	Line	Bus45	Bus46	2.73	1.36	3.05	0.0000654
L47	Line	Bus43	Bus47	12.74	6.35	14.23	0.0003050

B2: Power Loss and Voltage Profile Without SPV DG

Table A. 2 Power Loss and Voltage Profile Without SPV DG

Project:	Masters Thesis	ETAP		Page:	1
Location:	Yirgalem city	19.0.1C		Date:	10-03-2022
Contract:	-			SN:	
Engineer:	Endalk.D	Study Case:	With out SPV	Revision:	Base
Filename:	YIRGALEM.FEEDER(02)			Config.:	Normal

Branch Losses Summary Report

Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
L1	-9.281	-4.034	9.309	4.048	27.5	13.6	99.7	100.0	0.30
L10	2.102	0.910	-2.087	-0.903	14.9	7.0	86.8	86.2	0.63
L11	1.948	0.851	-1.941	-0.848	6.9	3.2	86.2	85.9	0.31
L12	1.876	0.814	-1.873	-0.812	2.8	1.3	85.9	85.8	0.13
L13	1.676	0.714	-1.672	-0.712	3.7	1.7	85.8	85.6	0.20
L14	1.545	0.639	-1.539	-0.636	5.7	2.6	85.6	85.2	0.33
L15	1.192	0.531	-1.187	-0.529	4.8	2.0	85.2	84.9	0.35
L16	1.056	0.468	-1.055	-0.468	1.2	0.5	84.9	84.8	0.10
L17	0.843	0.389	-0.840	-0.388	2.4	0.9	84.8	84.5	0.25
L18	0.631	0.306	-0.630	-0.306	0.3	0.1	84.5	84.5	0.04
L19	0.427	0.210	-0.427	-0.210	0.2	0.0	84.5	84.5	0.04
L2	8.999	3.899	-8.845	-3.823	153.6	76.2	99.7	98.0	1.74
L20	0.409	0.206	-0.409	-0.206	0.6	0.0	84.5	84.3	0.12
L21	0.326	0.149	-0.326	-0.149	0.1	0.0	84.3	84.3	0.02
L22	0.199	0.086	-0.199	-0.086	0.1	-0.2	84.3	84.3	0.03

L23	0.067	0.032	-0.067	-0.032	0.0	-0.2	84.3	84.3	0.01
L24	0.046	0.019	-0.046	-0.019	0.0	0.0	84.3	84.3	0.00
L25	0.132	0.065	-0.132	-0.065	0.0	-0.1	85.8	85.8	0.01
L26	0.274	0.124	-0.274	-0.125	0.2	-0.2	94.8	94.7	0.05
L27	0.193	0.082	-0.193	-0.082	0.0	-0.1	94.7	94.7	0.01
L28	0.114	0.036	-0.114	-0.037	0.0	-0.5	94.7	94.7	0.03
L29	0.025	0.003	-0.025	-0.004	0.0	-0.4	94.7	94.7	0.00
L3	8.280	3.608	-8.019	-3.479	261.4	129.6	98.0	94.8	3.16
L30	1.169	0.423	-1.167	-0.422	1.3	0.5	87.6	87.5	0.10
L31	0.941	0.339	-0.941	-0.339	0.2	0.1	87.5	87.5	0.02
L32	0.798	0.285	-0.797	-0.284	1.3	0.4	87.5	87.3	0.14
L33	0.724	0.261	-0.724	-0.260	0.7	0.2	87.3	87.2	0.09
L34	0.651	0.238	-0.651	-0.238	0.2	0.0	87.2	87.2	0.03
L35	0.615	0.226	-0.614	-0.226	0.3	0.1	87.2	87.2	0.05
L36	0.248	0.089	-0.248	-0.089	0.1	-0.1	87.2	87.1	0.03
L37	0.025	0.003	-0.025	-0.004	0.0	-0.2	87.1	87.1	0.00
L38	0.224	0.084	-0.224	-0.084	0.1	-0.1	87.2	87.1	0.03
L39	1.416	0.674	-1.414	-0.673	2.1	0.9	87.1	86.9	0.13
L4	7.744	3.354	-7.483	-3.225	261.2	129.4	94.8	91.5	3.27
L40	0.528	0.344	-0.528	-0.344	0.4	0.1	86.9	86.9	0.06
L41	0.262	0.176	-0.262	-0.176	0.0	0.0	86.9	86.9	0.01
L42	1.830	0.792	-1.827	-0.791	3.3	1.5	86.8	86.7	0.16
L43	0.942	0.477	-0.939	-0.476	2.8	1.1	86.7	86.4	0.26
L44	0.550	0.283	-0.550	-0.283	0.5	0.1	86.4	86.3	0.08
L45	0.419	0.212	-0.419	-0.212	0.1	0.0	86.3	86.3	0.02
L46	0.208	0.109	-0.208	-0.109	0.0	0.0	86.3	86.3	0.01
L47	0.170	0.105	-0.170	-0.105	0.1	-0.2	86.4	86.4	0.03
L5	7.406	3.193	-7.153	-3.068	252.4	125.1	91.5	88.3	3.20
L6	7.135	3.060	-7.098	-3.042	37.3	18.5	88.3	87.9	0.47
L7	6.873	2.950	-6.852	-2.940	20.5	10.1	87.9	87.6	0.27
L8	5.461	2.423	-5.429	-2.408	31.4	15.5	87.6	87.1	0.51
L9	4.013	1.734	-4.003	-1.729	10.6	5.2	87.1	86.8	0.24
					1113.3	545.1			

* This Transmission Line includes Series Capacitor.

SUMMARY OF TOTAL GENERATION , LOADING & DEMAND

	MW	Mvar	MVA	% PF
Source (Swing Buses):	9.309	4.048	10.151	91.70 Lagging
Source (Non-Swing Buses):	0.000	0.000	0.000	
Total Demand:	9.309	4.048	10.151	91.70 Lagging
Total Motor Load:	0.979	0.582	1.139	85.94 Lagging
Total Static Load:	7.217	2.920	7.785	92.70 Lagging
Total Constant I Load:	0.000	0.000	0.000	
Total Generic Load:	0.000	0.000	0.000	
Apparent Losses:	1.113	0.545		
System Mismatch:	0.000	0.000		

Number of Iterations: 3

B3: Power Loss and Voltage Profile with Single SPV DG

Table A. 3 Power Loss and Voltage Profile with Single SPV DG

Project:	Masters Thesis	ETAP		Page:	1
Location:	Yirgalem city	19.0.1C		Date:	02-04-2022
Contract:	-			SN:	
Engineer:	Endalk.D	Study Case:	With SPV DG	Revision:	Base
Filename:	YIRGALEM.FEEDER(02)			Config.:	Normal

Branch Losses Summary Report

Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
L1	-2.357	-0.304	2.359	0.304	1.5	0.7	99.9	100.0	0.07
L10	2.669	1.149	-2.651	-1.140	18.6	8.8	98.6	97.9	0.70
L11	2.471	1.072	-2.463	-1.068	8.5	4.0	97.9	97.6	0.35
L12	2.378	1.024	-2.375	-1.023	3.4	1.6	97.6	97.5	0.14
L13	2.120	0.895	-2.116	-0.893	4.6	2.1	97.5	97.2	0.22
L14	1.951	0.799	-1.944	-0.796	7.1	3.2	97.2	96.9	0.36
L15	1.495	0.660	-1.489	-0.657	5.8	2.4	96.9	96.5	0.39
L16	1.321	0.579	-1.319	-0.578	1.5	0.6	96.5	96.4	0.11
L17	1.045	0.477	-1.042	-0.476	2.9	1.0	96.4	96.1	0.27
L18	0.771	0.369	-0.771	-0.369	0.4	0.1	96.1	96.1	0.05
L19	0.508	0.246	-0.507	-0.246	0.2	0.0	96.1	96.0	0.04
L2	2.074	0.168	-2.067	-0.165	6.9	3.1	99.9	99.6	0.34
L20	0.485	0.240	-0.485	-0.240	0.6	-0.1	96.0	95.9	0.12
L21	0.402	0.183	-0.402	-0.183	0.1	-0.1	95.9	95.9	0.03
L22	0.237	0.101	-0.237	-0.101	0.1	-0.2	95.9	95.8	0.03

L23	0.067	0.032	-0.067	-0.032	0.0	-0.3	95.8	95.8	0.01
L24	0.046	0.019	-0.046	-0.019	0.0	-0.1	95.8	95.8	0.00
L25	0.170	0.084	-0.170	-0.084	0.0	-0.1	97.5	97.4	0.01
L26	0.290	0.132	-0.290	-0.133	0.2	-0.3	99.1	99.1	0.05
L27	0.203	0.087	-0.203	-0.087	0.0	-0.1	99.1	99.1	0.01
L28	0.117	0.037	-0.117	-0.038	0.0	-0.5	99.1	99.0	0.03
L29	0.025	0.003	-0.025	-0.004	0.0	-0.4	99.0	99.0	0.00
L3	1.483	-0.057	-1.476	0.060	6.8	2.7	99.6	99.1	0.45
L30	1.469	0.533	-1.467	-0.532	1.6	0.7	98.4	98.3	0.12
L31	1.182	0.427	-1.181	-0.427	0.2	0.1	98.3	98.3	0.02
L32	1.001	0.359	-0.999	-0.358	1.6	0.5	98.3	98.1	0.16
L33	0.908	0.328	-0.907	-0.328	0.9	0.2	98.1	98.0	0.10
L34	0.815	0.300	-0.815	-0.300	0.3	0.1	98.0	98.0	0.04
L35	0.769	0.284	-0.769	-0.284	0.4	0.1	98.0	97.9	0.05
L36	0.307	0.111	-0.306	-0.112	0.1	-0.2	97.9	97.9	0.03
L37	0.025	0.003	-0.025	-0.004	0.0	-0.2	97.9	97.9	0.00
L38	0.282	0.106	-0.282	-0.107	0.1	-0.2	97.9	97.9	0.03
L39	1.664	0.766	-1.662	-0.765	2.3	1.0	98.5	98.4	0.14
L4	1.185	-0.192	-1.181	0.194	4.8	1.6	99.1	98.8	0.36
L40	0.528	0.344	-0.528	-0.344	0.3	0.0	98.4	98.3	0.05
L41	0.262	0.176	-0.262	-0.176	0.0	0.0	98.3	98.3	0.01
L42	2.312	0.992	-2.308	-0.990	4.0	1.9	98.6	98.5	0.18
L43	1.166	0.585	-1.162	-0.584	3.3	1.2	98.5	98.2	0.28
L44	0.711	0.365	-0.710	-0.365	0.7	0.1	98.2	98.1	0.09
L45	0.541	0.274	-0.540	-0.274	0.1	0.0	98.1	98.1	0.02
L46	0.268	0.141	-0.268	-0.141	0.0	0.0	98.1	98.1	0.01
L47	0.170	0.105	-0.170	-0.105	0.1	-0.3	98.2	98.2	0.03
L5	1.090	-0.231	-1.086	0.232	4.1	1.3	98.8	98.5	0.32
L6	1.064	-0.242	-1.063	0.242	0.6	0.2	98.5	98.4	0.05
L7	0.781	-0.357	-0.781	0.357	0.2	0.0	98.4	98.4	0.02
L8	-0.969	-1.008	0.970	1.009	1.4	0.5	98.4	98.5	0.10
L9	-2.634	-1.775	2.639	1.777	4.4	2.1	98.5	98.6	0.15
					100.7	38.6			

* This Transmission Line includes Series Capacitor.

B4: Power Loss and Voltage Profile with Two SPV DG

Table A. 4 Power Loss and Voltage Profile with Two SPV DG

Project:	Masters Thesis	ETAP		Page:	1
Location:	Yirgalem city	19.0.1C		Date:	05-04-2022
Contract:	-			SN:	
Engineer:	Endalk.D	Study Case:	With SPV DG	Revision:	Base
Filename:	YIRGALEM.FEEDER(02)			Config.:	Normal

Branch Losses Summary Report

Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
L1	-2.394	-0.316	2.396	0.317	1.6	0.7	99.9	100.0	0.07
L10	1.168	0.372	-1.164	-0.371	3.3	1.2	98.6	98.3	0.29
L11	0.983	0.303	-0.982	-0.303	1.2	0.4	98.3	98.2	0.13
L12	0.897	0.258	-0.896	-0.258	0.4	0.1	98.2	98.1	0.05
L13	0.638	0.129	-0.638	-0.129	0.4	0.0	98.1	98.1	0.06
L14	0.471	0.033	-0.470	-0.034	0.3	-0.2	98.1	98.0	0.07
L15	0.011	-0.106	-0.011	0.105	0.0	-0.5	98.0	98.0	0.01
L16	-0.163	-0.186	0.163	0.186	0.0	-0.1	98.0	98.0	0.02
L17	-0.447	-0.291	0.447	0.291	0.6	-0.2	98.0	98.1	0.12
L18	-0.730	-0.402	0.730	0.402	0.3	0.1	98.1	98.2	0.04
L19	-1.005	-0.531	1.006	0.531	0.8	0.3	98.2	98.2	0.08
L2	2.111	0.180	-2.103	-0.177	7.1	3.2	99.9	99.6	0.35
L20	-1.029	-0.537	1.032	0.538	2.7	0.9	98.2	98.5	0.25
L21	-1.114	-0.595	1.115	0.595	0.8	0.3	98.5	98.6	0.07
L22	-1.289	-0.682	1.291	0.683	2.4	0.9	98.6	98.8	0.18
L23	-1.472	-0.756	1.476	0.758	4.2	1.8	98.8	99.0	0.28
L24	-1.497	-0.772	1.498	0.772	0.8	0.3	99.0	99.1	0.05
L25	0.173	0.085	-0.173	-0.085	0.0	-0.1	98.1	98.1	0.01
L26	0.290	0.132	-0.290	-0.132	0.2	-0.3	99.1	99.1	0.05
L27	0.203	0.087	-0.202	-0.087	0.0	-0.1	99.1	99.1	0.01
L28	0.117	0.037	-0.117	-0.038	0.0	-0.5	99.1	99.0	0.03
L29	0.025	0.003	-0.025	-0.004	0.0	-0.4	99.0	99.0	0.00
L3	1.519	-0.044	-1.512	0.047	7.2	2.8	99.6	99.1	0.46
L30	1.467	0.532	-1.466	-0.532	1.6	0.7	98.3	98.2	0.11
L31	1.180	0.426	-1.180	-0.426	0.2	0.1	98.2	98.2	0.02
L32	1.000	0.358	-0.998	-0.358	1.6	0.5	98.2	98.0	0.16
L33	0.907	0.328	-0.906	-0.327	0.9	0.2	98.0	97.9	0.10
L34	0.814	0.300	-0.814	-0.300	0.3	0.1	97.9	97.9	0.04
L35	0.768	0.284	-0.768	-0.284	0.4	0.1	97.9	97.9	0.05
L36	0.306	0.111	-0.306	-0.111	0.1	-0.2	97.9	97.8	0.03
L37	0.025	0.003	-0.025	-0.004	0.0	-0.2	97.8	97.8	0.00
L38	0.282	0.106	-0.282	-0.106	0.1	-0.2	97.9	97.8	0.03
L39	1.663	0.765	-1.660	-0.764	2.3	1.0	98.4	98.3	0.14
L4	1.222	-0.179	-1.217	0.181	5.1	1.8	99.1	98.7	0.38
L40	0.528	0.344	-0.528	-0.344	0.3	0.0	98.3	98.3	0.05

L41	0.262	0.176	-0.262	-0.176	0.0	0.0	98.3	98.2	0.01
L42	2.310	0.991	-2.306	-0.989	4.0	1.9	98.6	98.4	0.18
L43	1.165	0.584	-1.161	-0.583	3.3	1.2	98.4	98.1	0.28
L44	0.710	0.365	-0.709	-0.365	0.7	0.1	98.1	98.0	0.09
L45	0.540	0.273	-0.540	-0.273	0.1	0.0	98.0	98.0	0.02
L46	0.268	0.141	-0.268	-0.141	0.0	0.0	98.0	98.0	0.01
L47	0.170	0.105	-0.170	-0.105	0.1	-0.3	98.1	98.1	0.03
L5	1.127	-0.218	-1.122	0.220	4.4	1.4	98.7	98.4	0.33
L6	1.100	-0.229	-1.099	0.230	0.6	0.2	98.4	98.4	0.05
L7	0.817	-0.345	-0.817	0.345	0.2	0.0	98.4	98.3	0.02
L8	-0.931	-0.995	0.932	0.995	1.3	0.5	98.3	98.4	0.10
L9	-2.595	-1.761	2.599	1.763	4.3	2.0	98.4	98.6	0.15
					66.4	21.4			

* This Transmission Line includes Series Capacitor.

B5: Power Loss and Voltage profile with SPV DG after one-year demand increase

Table A. 5 Power Loss and Voltage profile with SPV DG after one-year demand increase

Project:	Masters Thesis	ETAP	Page:	1
Location:	Yirgalem city	19.0.1C	Date:	14-04-2022
Contract:	-		SN:	
Engineer:	Endalk.D	Study Case: LF	Revision:	Base
Filename:	YIRGALEM FEEDER CASE 2		Config.:	Normal

Branch Losses Summary Report

Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
L1	-2.485	-0.326	2.487	0.327	1.7	0.8	99.9	100.0	0.07
L10	1.213	0.387	-1.210	-0.385	3.6	1.3	98.5	98.2	0.31
L11	1.021	0.315	-1.020	-0.314	1.3	0.4	98.2	98.1	0.14
L12	0.931	0.268	-0.931	-0.268	0.5	0.1	98.1	98.1	0.05
L13	0.662	0.133	-0.662	-0.133	0.4	0.0	98.1	98.0	0.06
L14	0.488	0.034	-0.487	-0.034	0.4	-0.2	98.0	97.9	0.08
L15	0.009	-0.111	-0.009	0.111	0.0	-0.5	97.9	97.9	0.01
L16	-0.172	-0.195	0.172	0.195	0.0	-0.1	97.9	97.9	0.02
L17	-0.468	-0.304	0.468	0.304	0.7	-0.1	97.9	98.1	0.13
L18	-0.762	-0.419	0.763	0.420	0.4	0.1	98.1	98.1	0.05
L19	-1.049	-0.554	1.049	0.554	0.8	0.3	98.1	98.2	0.08
L2	2.190	0.184	-2.182	-0.181	7.7	3.4	99.9	99.6	0.36
L20	-1.074	-0.561	1.077	0.562	2.9	1.0	98.2	98.5	0.27

L21	-1.163	-0.621	1.164	0.621	0.9	0.3	98.5	98.5	0.08
L22	-1.345	-0.711	1.347	0.712	2.6	1.0	98.5	98.7	0.19
L23	-1.536	-0.789	1.540	0.791	4.6	1.9	98.7	99.0	0.29
L24	-1.562	-0.805	1.563	0.806	0.9	0.4	99.0	99.1	0.05
L25	0.180	0.089	-0.180	-0.089	0.0	-0.1	98.1	98.0	0.01
L26	0.302	0.138	-0.302	-0.138	0.2	-0.3	99.1	99.0	0.06
L27	0.211	0.091	-0.211	-0.091	0.0	-0.1	99.0	99.0	0.01
L28	0.122	0.039	-0.122	-0.040	0.0	-0.5	99.0	99.0	0.03
L29	0.026	0.003	-0.026	-0.004	0.0	-0.4	99.0	99.0	0.00
L3	1.573	-0.050	-1.566	0.053	7.7	3.1	99.6	99.1	0.48
L30	1.528	0.554	-1.526	-0.553	1.8	0.7	98.3	98.2	0.12
L31	1.229	0.444	-1.229	-0.444	0.3	0.1	98.2	98.1	0.02
L32	1.041	0.373	-1.039	-0.372	1.7	0.5	98.1	98.0	0.17
L33	0.944	0.341	-0.943	-0.341	1.0	0.3	98.0	97.9	0.10
L34	0.847	0.312	-0.847	-0.312	0.3	0.1	97.9	97.8	0.04
L35	0.800	0.296	-0.799	-0.296	0.4	0.1	97.8	97.8	0.05
L36	0.319	0.116	-0.319	-0.116	0.1	-0.2	97.8	97.8	0.04
L37	0.026	0.003	-0.026	-0.004	0.0	-0.2	97.8	97.7	0.00
L38	0.294	0.111	-0.294	-0.111	0.1	-0.2	97.8	97.8	0.03
L39	1.732	0.798	-1.730	-0.796	2.5	1.1	98.4	98.2	0.14
L4	1.263	-0.191	-1.258	0.193	5.5	2.0	99.1	98.7	0.39
L40	0.550	0.359	-0.550	-0.359	0.3	0.0	98.2	98.2	0.05
L41	0.273	0.183	-0.273	-0.183	0.0	0.0	98.2	98.2	0.01
L42	2.406	1.032	-2.401	-1.030	4.4	2.0	98.5	98.4	0.18
L43	1.213	0.609	-1.209	-0.607	3.6	1.4	98.4	98.1	0.29
L44	0.739	0.380	-0.738	-0.380	0.7	0.1	98.1	98.0	0.10
L45	0.562	0.285	-0.562	-0.285	0.1	0.0	98.0	97.9	0.03
L46	0.279	0.146	-0.279	-0.146	0.0	0.0	97.9	97.9	0.01
L47	0.177	0.110	-0.177	-0.110	0.1	-0.3	98.1	98.0	0.03
L5	1.164	-0.232	-1.159	0.233	4.7	1.6	98.7	98.4	0.35
L6	1.136	-0.243	-1.135	0.243	0.7	0.2	98.4	98.3	0.05
L7	0.842	-0.363	-0.841	0.363	0.2	0.1	98.3	98.3	0.02
L8	-0.979	-1.040	0.980	1.041	1.4	0.6	98.3	98.4	0.10
L9	-2.712	-1.838	2.717	1.841	4.7	2.2	98.4	98.5	0.16
					71.8	24.1			

* This Transmission Line includes Series Capacitor.

B6: Power Loss and Voltage Profile with SPV DG after Five-Year Demand Increase

Table A. 6 Power Loss and Voltage Profile with SPV DG after Five-Year Demand Increase

Project:	Masters Thesis	ETAP		Page:	1
Location:	Yirgalem city	19.0.1C		Date:	14-04-2022
Contract:	-			SN:	
Engineer:	Endalk.D	Study Case:	With SPV DG	Revision:	Base
Filename:	YIRGALEM.FEEDER(02)			Config.:	Normal

Branch Losses Summary Report

Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
L1	-4.124	-1.065	4.129	1.068	4.9	2.4	99.9	100.0	0.12
L10	1.577	0.551	-1.570	-0.548	6.5	2.7	96.2	95.8	0.41
L11	1.362	0.470	-1.359	-0.469	2.6	1.0	95.8	95.6	0.19
L12	1.261	0.417	-1.260	-0.417	0.9	0.4	95.6	95.5	0.07
L13	0.964	0.268	-0.963	-0.268	0.9	0.3	95.5	95.4	0.10
L14	0.771	0.159	-0.770	-0.158	1.0	0.2	95.4	95.3	0.13
L15	0.243	-0.001	-0.243	0.001	0.1	-0.4	95.3	95.2	0.05
L16	0.044	-0.094	-0.044	0.094	0.0	-0.1	95.2	95.2	0.00
L17	-0.281	-0.214	0.281	0.214	0.3	-0.3	95.2	95.3	0.08
L18	-0.604	-0.340	0.605	0.340	0.2	0.0	95.3	95.4	0.04
L19	-0.919	-0.488	0.920	0.488	0.7	0.2	95.4	95.4	0.07
L2	3.780	0.901	-3.756	-0.889	24.0	11.6	99.9	99.2	0.67
L20	-0.946	-0.496	0.949	0.496	2.4	0.8	95.4	95.7	0.24
L21	-1.049	-0.565	1.049	0.565	0.8	0.3	95.7	95.7	0.07
L22	-1.248	-0.664	1.251	0.665	2.4	1.0	95.7	95.9	0.18
L23	-1.457	-0.749	1.462	0.751	4.4	1.9	95.9	96.2	0.29
L24	-1.487	-0.768	1.488	0.768	0.8	0.4	96.2	96.3	0.05
L25	0.198	0.098	-0.198	-0.098	0.0	-0.1	95.5	95.5	0.01
L26	0.347	0.158	-0.347	-0.159	0.2	-0.2	98.2	98.1	0.07
L27	0.243	0.105	-0.243	-0.105	0.0	-0.1	98.1	98.1	0.01
L28	0.141	0.045	-0.141	-0.046	0.1	-0.5	98.1	98.0	0.04
L29	0.030	0.004	-0.030	-0.004	0.0	-0.4	98.0	98.0	0.01
L3	3.053	0.622	-3.023	-0.608	30.3	14.4	99.2	98.2	1.04
L30	1.698	0.616	-1.695	-0.615	2.3	1.0	96.1	95.9	0.14
L31	1.366	0.493	-1.365	-0.493	0.3	0.1	95.9	95.9	0.03
L32	1.157	0.414	-1.154	-0.414	2.2	0.8	95.9	95.7	0.19
L33	1.049	0.379	-1.048	-0.379	1.2	0.4	95.7	95.6	0.12
L34	0.942	0.346	-0.941	-0.346	0.4	0.1	95.6	95.6	0.04
L35	0.889	0.328	-0.888	-0.328	0.5	0.1	95.6	95.5	0.06
L36	0.355	0.129	-0.355	-0.129	0.1	-0.1	95.5	95.5	0.04
L37	0.030	0.004	-0.030	-0.004	0.0	-0.2	95.5	95.5	0.00
L38	0.326	0.123	-0.326	-0.123	0.1	-0.1	95.5	95.5	0.04
L39	1.951	0.904	-1.947	-0.903	3.3	1.5	96.1	95.9	0.16
L4	2.676	0.450	-2.650	-0.438	25.2	11.8	98.2	97.2	0.97
L40	0.640	0.417	-0.640	-0.417	0.4	0.1	95.9	95.9	0.06

L41	0.317	0.213	-0.317	-0.213	0.0	0.0	95.9	95.8	0.01
L42	2.674	1.149	-2.668	-1.147	5.7	2.7	96.2	96.0	0.21
L43	1.352	0.680	-1.348	-0.678	4.7	1.9	96.0	95.6	0.33
L44	0.817	0.420	-0.816	-0.420	0.9	0.2	95.6	95.5	0.11
L45	0.622	0.315	-0.622	-0.315	0.2	0.0	95.5	95.5	0.03
L46	0.308	0.162	-0.308	-0.162	0.0	0.0	95.5	95.5	0.01
L47	0.206	0.128	-0.206	-0.128	0.1	-0.2	95.6	95.6	0.04
L5	2.545	0.394	-2.522	-0.383	22.8	10.6	97.2	96.3	0.92
L6	2.496	0.372	-2.493	-0.371	3.3	1.5	96.3	96.1	0.13
L7	2.166	0.237	-2.164	-0.237	1.5	0.7	96.1	96.1	0.07
L8	0.142	-0.516	-0.141	0.516	0.2	0.0	96.1	96.1	0.01
L9	-1.809	-1.420	1.812	1.421	2.4	1.1	96.1	96.2	0.11
					161.6	69.3			

* This Transmission Line includes Series Capacitor.

B7: Power Loss and Voltage Profile with SPV DG Seven -Year Demand Increase

Table A. 7 Power Loss and Voltage Profile with SPV DG Seven -Year Demand Increase

Project:	Masters Thesis	ETAP		Page:	1
Location:	Yirgalem city	19.0.1C		Date:	14-04-2022
Contract:	-			SN:	
Engineer:	Endalk.D	Study Case:	With SPV	Revision:	Base
Filename:	YIRGALEM.FEEDER(02)			Config.:	Normal

Branch Losses Summary Report

Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
L1	-4.796	-1.358	4.802	1.362	6.6	3.2	99.9	100.0	0.15
L10	1.728	0.617	-1.720	-0.613	7.9	3.5	95.3	94.8	0.46
L11	1.502	0.531	-1.499	-0.530	3.2	1.3	94.8	94.6	0.21
L12	1.396	0.476	-1.395	-0.476	1.2	0.5	94.6	94.5	0.08
L13	1.084	0.320	-1.083	-0.320	1.2	0.4	94.5	94.4	0.11
L14	0.882	0.205	-0.880	-0.205	1.4	0.4	94.4	94.2	0.16
L15	0.329	0.037	-0.329	-0.038	0.3	-0.3	94.2	94.2	0.08
L16	0.120	-0.060	-0.120	0.060	0.0	-0.1	94.2	94.2	0.01
L17	-0.220	-0.185	0.220	0.185	0.2	-0.3	94.2	94.2	0.07
L18	-0.558	-0.317	0.558	0.317	0.2	0.0	94.2	94.3	0.04
L19	-0.886	-0.472	0.887	0.472	0.7	0.2	94.3	94.3	0.07
L2	4.428	1.182	-4.395	-1.166	33.5	16.3	99.9	99.1	0.80
L20	-0.915	-0.480	0.917	0.480	2.3	0.7	94.3	94.6	0.24
L21	-1.024	-0.554	1.025	0.554	0.8	0.3	94.6	94.6	0.07
L22	-1.233	-0.658	1.235	0.659	2.4	1.0	94.6	94.8	0.18

L23	-1.452	-0.747	1.456	0.748	4.5	1.9	94.8	95.1	0.29
L24	-1.483	-0.766	1.484	0.767	0.8	0.4	95.1	95.2	0.05
L25	0.208	0.102	-0.208	-0.102	0.0	-0.1	94.5	94.5	0.01
L26	0.370	0.169	-0.370	-0.169	0.3	-0.2	97.8	97.7	0.07
L27	0.259	0.111	-0.259	-0.111	0.0	-0.1	97.7	97.7	0.01
L28	0.151	0.048	-0.151	-0.049	0.1	-0.5	97.7	97.7	0.04
L29	0.032	0.004	-0.032	-0.005	0.0	-0.4	97.7	97.7	0.01
L3	3.645	0.882	-3.601	-0.860	44.1	21.2	99.1	97.8	1.27
L30	1.784	0.647	-1.781	-0.646	2.6	1.2	95.2	95.0	0.14
L31	1.435	0.518	-1.434	-0.518	0.4	0.2	95.0	95.0	0.03
L32	1.215	0.435	-1.213	-0.434	2.5	0.9	95.0	94.8	0.20
L33	1.102	0.398	-1.100	-0.398	1.4	0.5	94.8	94.7	0.12
L34	0.989	0.364	-0.989	-0.364	0.5	0.1	94.7	94.6	0.04
L35	0.934	0.345	-0.933	-0.345	0.6	0.2	94.6	94.6	0.06
L36	0.373	0.135	-0.373	-0.135	0.2	-0.1	94.6	94.5	0.04
L37	0.032	0.004	-0.032	-0.005	0.0	-0.2	94.5	94.5	0.00
L38	0.342	0.129	-0.342	-0.129	0.1	-0.1	94.6	94.5	0.04
L39	2.061	0.958	-2.057	-0.956	3.7	1.7	95.2	95.0	0.17
L4	3.231	0.692	-3.193	-0.674	37.6	18.0	97.8	96.6	1.20
L40	0.685	0.446	-0.685	-0.446	0.5	0.1	95.0	94.9	0.07
L41	0.339	0.228	-0.339	-0.228	0.0	0.0	94.9	94.9	0.01
L42	2.810	1.209	-2.804	-1.206	6.4	3.1	95.3	95.0	0.22
L43	1.423	0.716	-1.418	-0.714	5.3	2.2	95.0	94.7	0.35
L44	0.857	0.441	-0.856	-0.440	1.1	0.3	94.7	94.6	0.12
L45	0.652	0.330	-0.652	-0.330	0.2	0.0	94.6	94.5	0.03
L46	0.323	0.170	-0.323	-0.170	0.0	0.0	94.5	94.5	0.01
L47	0.221	0.136	-0.221	-0.137	0.1	-0.2	94.7	94.6	0.04
L5	3.081	0.627	-3.047	-0.611	34.5	16.4	96.6	95.4	1.14
L6	3.020	0.599	-3.015	-0.597	5.0	2.4	95.4	95.3	0.17
L7	2.671	0.457	-2.669	-0.456	2.3	1.1	95.3	95.2	0.09
L8	0.544	-0.335	-0.543	0.335	0.3	0.0	95.2	95.2	0.03
L9	-1.517	-1.293	1.519	1.293	1.8	0.8	95.2	95.3	0.10
					218.6	97.9			

* This Transmission Line includes Series Capacitor.

Appendix C: Distribution Feeder Data

C1: Medium Voltage Design of Yirgalem City with AUTOCAD.

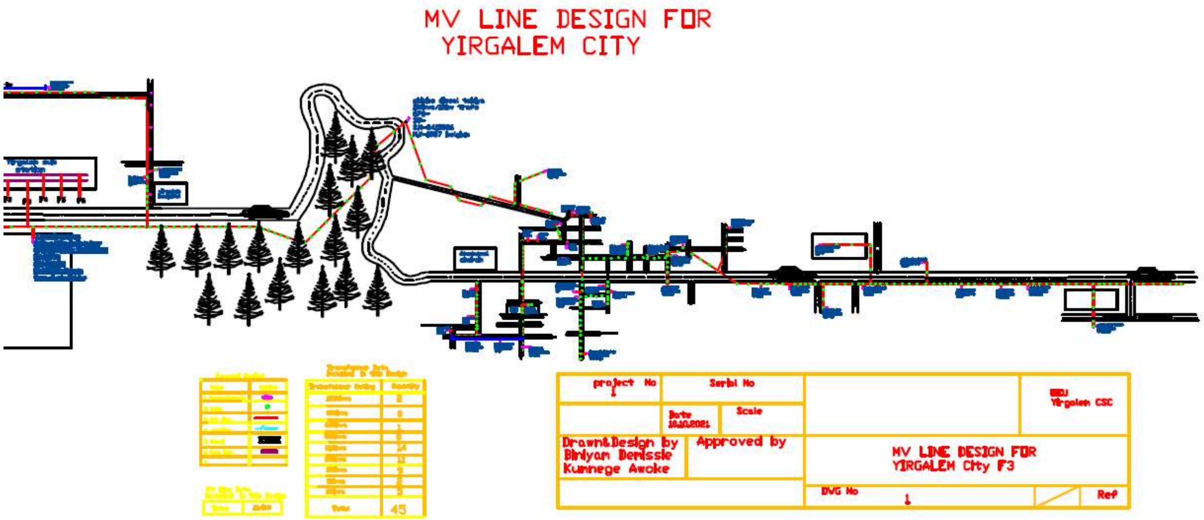

Figure A. 1 Medium Voltage Design of Yirgalem City Sketched with AUTOCAD

C2: Load Data of the Feeder

Table A. 8 Load Data of the Feeder

Bus	Load in (MW)	Load in (MVAR)	Load in (MVA)
Bus1	0.284	0.136	0.315
Bus2	0.589	0.223	0.63
Bus3	0	0	0
Bus4	0.092	0.038	0.1
Bus5	0.023	0.010	0.025
Bus6	0.292	0.119	0.315
Bus7	0.290	0.122	0.315
Bus8	0	0	0
Bus9	0.094	0.035	0.1
Bus10	0.187	0.070	0.2
Bus11	0.089	0.046	0.1
Bus12	0.089	0.046	0.1
Bus13	0.174	0.099	0.2
Bus14	0.479	0.145	0.5
Bus15	0.181	0.085	0.2
Bus16	0.295	0.109	0.315
Bus17	0.293	0.115	0.315
Bus18	0.285	0.134	0.315
Bus19	0.024	0.007	0.025
Bus20	0.083	0.057	0.1

Bus21	0.179	0.089	0.2
Bus22	0.185	0.076	0.2
Bus23	0.021	0.014	0.025
Bus24	0.046	0.019	0.05
Bus25	0.179	0.088	0.2
Bus26	0.089	0.046	0.1
Bus27	0.086	0.05	0.1
Bus28	0.094	0.035	0.1
Bus29	0.025	0.004	0.025
Bus30	0.295	0.109	0.315
Bus31	0.187	0.070	0.2
Bus32	0.095	0.031	0.1
Bus33	0.096	0.029	0.1
Bus34	0.047	0.016	0.05
Bus35	0.188	0.069	0.2
Bus36	0.294	0.113	0.315
Bus37	0.025	0.004	0.025
Bus38	0.295	0.111	0.315
Bus39	1.172	0.435	1.25
Bus40	0.266	0.168	0.315
Bus41	0.262	0.176	0.315
Bus42	1.178	0.418	1.25
Bus43	0.292	0.118	0.315
Bus44	0.176	0.095	0.2
Bus45	0.283	0.138	0.315
Bus46	0.279	0.146	0.315
Bus47	0.170	0.105	0.2

C3: Line parameters of the Feeder (line impedance data)

Table A. 9 Line parameters of the Feeder (line impedance data)

Name of the line	Length of the line			Impedance of the line in (Ω/km)		Impedance of the line in (Ω)	
	From node	To node	Distance b/n buses in (KM)	Resistance in (Ω/km)	Reactance in (Ω/km)	Resistance (Ω)	Reactance (Ω)
L1	Swing bus	B1	0.085	0.706	0.351749	0.06001	0.029899
L2	B1	B2	0.506	0.706	0.351749	0.357236	0.177985
L3	B2	B3	0.98	0.706	0.351749	0.69188	0.344714
L4	B3	B4	1.05	0.706	0.351749	0.7413	0.369336
L5	B4	B5	1.036	0.706	0.351749	0.731416	0.364412
L6	B5	B6	0.154	0.706	0.351749	0.108724	0.054169
L7	B6	B7	0.09	0.706	0.351749	0.06354	0.031657

L8	B7	B8	0.215	0.706	0.351749	0.15179	0.075626
L9	B8	B9	0.134	0.706	0.351749	0.094604	0.047134
L10	B9	B10	0.682	0.706	0.351749	0.481492	0.239893
L11	B10	B11	0.36	0.706	0.351749	0.25416	0.12663
L12	B11	B12	0.155	0.706	0.351749	0.10943	0.054521
L13	B12	B13	0.264	0.706	0.351749	0.186384	0.092862
L14	B13	B14	0.478	0.706	0.351749	0.337468	0.168136
L15	B14	B15	0.652	0.706	0.351749	0.460312	0.22934
L16	B15	B16	0.212	0.706	0.351749	0.149672	0.074571
L17	B16	B17	0.64	0.706	0.351749	0.45184	0.225119
L18	B17	B18	0.148	0.706	0.351749	0.104488	0.052059
L19	B18	B19	0.185	0.706	0.351749	0.13061	0.065074
L20	B19	B20	0.615	0.706	0.351749	0.43419	0.216326
L21	B20	B21	0.16	0.706	0.351749	0.11296	0.05628
L22	B21	B22	0.35	0.706	0.351749	0.2471	0.123112
L23	B22	B23	0.479	0.706	0.351749	0.338174	0.168488
L24	B23	B24	0.087	0.706	0.351749	0.061422	0.030602
L25	B12	B25	0.111	0.706	0.351749	0.078366	0.039044
L26	B3	B26	0.48	0.706	0.351749	0.33888	0.16884
L27	B26	B27	0.104	0.706	0.351749	0.073424	0.036582
L28	B27	B28	0.713	0.706	0.351749	0.503378	0.250797
L29	B28	B29	0.554	0.706	0.351749	0.391124	0.194869
L30	B7	B30	0.208	0.706	0.351749	0.146848	0.073164
L31	B30	B31	0.048	0.706	0.351749	0.033888	0.016884
L32	B31	B32	0.425	0.706	0.351749	0.30005	0.149493
L33	B32	B33	0.289	0.706	0.351749	0.204034	0.101655
L34	B33	B34	0.116	0.706	0.351749	0.081896	0.040803
L35	B34	B35	0.173	0.706	0.351749	0.122138	0.060853
L36	B35	B36	0.291	0.706	0.351749	0.205446	0.102359
L37	B36	B37	0.279	0.706	0.351749	0.196974	0.098138
L38	B35	B38	0.307	0.706	0.351749	0.216742	0.107987
L39	B8	B39	0.208	0.706	0.351749	0.146848	0.073164
L40	B39	B40	0.222	0.706	0.351749	0.156732	0.078088
L41	B40	B41	0.058	0.706	0.351749	0.040948	0.020401
L42	B9	B42	0.198	0.706	0.351749	0.139788	0.069646
L43	B42	B43	0.6	0.706	0.351749	0.4236	0.211049
L44	B43	B44	0.324	0.706	0.351749	0.228744	0.113967
L45	B44	B45	0.114	0.706	0.351749	0.080484	0.040099
L46	B45	B46	0.087	0.706	0.351749	0.061422	0.030602
L47	B43	B47	0.406	0.706	0.351749	0.286636	0.14281

C4: Distribution transformer data of Yirgalem town feeder

Table A. 10 Distribution transformer data of Yirgalem town feeder

S/NO	Specific location of transformers	Transformer capacity (KVA)	GPS location	Manufacturer
1	Hawassa university (Awada campus)	315	N6.748721, E38.389859	Ethiopia
2	Hawassa university (Awada campus)	630	N6.745529, E38.387810	Ethiopia
3	Gidabo (diesel tabya)	100	-	Belgium
4	Tele kera trafo	25	N6.752157, E38.405395	India
5	Asnakech nigus trafo	315	-	Ethiopia
6	Kefyalew trafo	315	-	Ethiopia
7	Weynuma real state	100	N6.748199, E38.407242	Ethiopia
8	Muluwengel trafo	200	N6.752093, E38.409646	Ethiopia
9	betemetsaft sefer trafo	100	N6.749946, E38.413276	-
10	Tele biro	100	N6.750014, E38.414232	Belgium
11	Tena tibeka	200	N6.750829, E38.416176	-
12	Hartl trafo	500	N6.752564, E38.418536	Ethiopia
13	Arada trafo	200	N6.750718, E38.424229	India
14	Fikadu trafo	315	N6.750787, E38.426143	India
15	Arada gebeya	315	N6.748238, E38.430887	China
16	Arada mesgid	315	N6.748323, E38.432346	India
17	Ras desta tele tower	25	N6.749256, E38.431927	-
18	Tesfaye gebre weficho	100	N6.746913, E38.437336	-
19	Ali abdulshekur trafo	200	N6.746289, E38.438658	-
20	Aregash lodge	200	N6.745594, E38.441737	Ethiopia
21	Abebayew weficho	25	N6.746933, E38.445628	-
22	Abebayew site wuha limat	50	N6.746399, E38.446049	Ethiopia

23	Fura college trafo	200	N6.749432, E38.41415	Croatia
24	Hospital trafo	100	N6.749882, E38.393111	-
25	Hospital fistula gibi	100	N6.750554, E38.392547	India
26	Docteroch menoria	100	N6.753226, E38.391007	Ethiopia
27	Filwuha trafo	25	N6.754880, E38.388100	-
28	03 condominium 1	315	-	India
29	03 condominium 2	200	-	India
30	Aderash school	100	N6.745021, E38.403418	-
31	Degefa trafo	100	N6.742960, E38.403665	India
32	Radio tabya	50	N6.742783, E38.40267	-
33	Yirgalem maremiya	200	N6.742723, E38.401137	Ethiopia
34	Stadium	315	N6.743038, E38.398988	Ethiopia
35	Deraro adarash	25	N6.744735, E38.400850	India
36	Tekaken (stadium jerba)	315	-	Ethiopia
37	Gebeya (gugsa fitlefit)	1250	N6.750190, E38.407827	-
38	Weficho sefer1	315	N6.749964, E38.406428	Ethiopia
39	Wefcho sefer 2 (Gebeya)	315	N6.749445, E38.406478	Ethiopia
40	05 condominium 1	1250	N6.746447, E38.407756	-
41	05 condominium 2	315	N6.746234, E38.408190	-
42	06 sefer trafo	200	N6.746673, E38.410812	Italy
43	Kagnew trafo	315	N6.747570, E38.411076	India
44	06 condominium trafo	315	N6.747937, E38.410274	-
45	Arsema duket factory	200	N6.742897, E38.409433	Ethiopia
Total	-	11165		

Appendix D: Annual solar radiation of Yirgalem Town in Kwh/m^2

Table A. 11 Annual solar radiation of Yirgalem Town in Kwh/m2

Month	Annual solar radiation (Kwh/m^2)				Average
	2017	2018	2019	2020	
January	7.09	6.76	6.97	6.05	6.72
February	6.39	6.42	6.83	6.50	6.54
March	6.89	5.64	6.99	5.99	6.38
April	6.17	5.1	5.98	5.62	5.72
May	5.36	5.45	5.73	5.66	5.55
June	5.16	4.51	4.68	4.97	4.83
July	4.14	4.23	4.65	3.73	4.19
August	4.35	4.79	4.6	4.25	4.50
September	4.54	5.64	4.96	4.75	4.97
October	5.02	5.56	5.57	5.44	5.40
November	5.83	5.58	5.41	6.14	5.74
December	6.88	6.18	5.76	6.43	6.31
Average	**5.57**				

Appendix E: Ethiopian electricity tariff amendment according to customer class

Table A. 12 Ethiopian electricity tariff amendment according to customer class

Tariff amendment		As of Dec. 18 onward	As of Dec. 19 onward	As of Dec. 20 onward	As of Dec. 21 onward
Tariff Category	kwh/month	Birr/kwh	Birr/kwh	Birr/kwh	Birr/kwh
1.Residential tariff block					
1.1 1st block	Up to 50 kwh	0.2730	0.2730	0.2730	0.2730
1.2 2nd block	Up to 100	0.4591	0.5617	0.6644	0.7670
kwh		0.7807	1.0622	1.3436	1.6250
1.3 3rd block	Up to 200 kwh	0.9125	1.2750	1.6375	2.0000
1.4 4th block	Up to 300 kwh	0.9750	1.3833	1.7917	2.2000
1.5 5th block	Up to 400 kwh	1.0423	1.4965	1.9508	2.4050
1.6 6th block	Up to 500 kwh	1.1410	1.5877	2.0343	2.4810
1.7 7th block	Above 500 kwh				
2. General Tariff					
2.1 Flat Rate		1.0352	1.3982	1.7611	2.1240
3. Low Voltage Industry Tariff					
3.1 Flat Rate		0.8161	1.0544	1.2927	1.5310
3.2 Demand Charge rate		50.0000	100.00	150.0000	200.0000
4. Medium Voltage Industry Tariff. 15kv & 33kv					
4.1 Flat Rate		0.6047	0.8008	0.9969	1.1930
4.2 Demand Charge rate		36.8850	73.7700	110.6550	147.5400
5. High Voltage Industry Tariff. Above 66kv					
5.1 Flat Rate		0.5174	0.6540	0.7911	0.9280
5.2 Demand Charge rate		21.9100	43.8200	65.7300	87.6400
6. Street Light Tariff					
6.1 Flat Rate		1.0352	1.3982	1.7611	2.1240
7. Bulk Supply Tariff					
7.1 Demand Charge rate per kw		39.2908	78.5815	117.8723	157.1600
7.2 Generation Tariff. Monthly per kwh		0.2218	0.4435	0.6653	0.8870