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OPTIMAL EXPANSION PLANNING OF DISTRIBUTION NETWORK WITH DISTRIBUTED GENERATION BY UTILIZING GRID-BASED MULTI-OBJECTIVE HARMONY SEARCH ALGORITHM

(CASE STUDY: DEBREMARKOS DISTRIBUTION NETWORK)

BY

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September 25, 2019

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(Case Study: Debre Markos Distribution Network)

By

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DECLARATION

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ABSTRACT

Electrical energy plays a vital role in the socio-economic development. To combat for the power system profile problems, distribution substation needs to be established considering future expansion due to urbanization. Debre Markos (D/M) distribution network needs expansion planning to meet the growing load demand. To evaluate the capability of the existing distribution network and to supply reliable power for future expansion, demand forecast for the years 2017/18-2022/23-2027/28 has been performed by using trend forcasting technigue withl east sequre approximation and evaluating the load flow by using backward-forward sweep load flow. According to the results, the existingnetwork cannot meet the existing load demand and it has major problems of increased voltage deviation and power loss. In this thesis, D/M distribution network expansion planning considering future demand growth and distributed generation placement and sizing is carried out using Grid based Multi-Objective Harmony Search Algorithm (GrMHSA). The total real power loss (Pl), total reactive power loss (Ql) and total voltage deviation (VD) at the target year for the base case by taking the existing line and the projected bus data are 7434.9kw, 7391.8kvar and 58.6952p.u for D/M Feeder 3 and 470.7058kw, 404.5524kvar and 6.4412p.u for D/M Feeder 4 respectively. After applying GrMHSA optimization technique for DG sizing and placement, the total Pl, total Ql and VD at the target year are 95.398kw,124.979kvar and 0.479p.u for D/M Feeder 3 (F3A and F3B) and 30.811kw, 37.727kvar and 0.533p.u for D/M Feeder 4 respectively.

Key-words: Distribution network planning, load forecasting, least-square method, backward-forward sweep load flow, power loss, VD, meta-heuristic algorithm, HSA.

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LIST OF ACRONYMS

AAC	All Aluminum Conductor
ABC	Ant Bee Colony
Ac	Ant Colony
AC	Alternating Current
AVAFL	Average Annual Feeder Loss
AI	Artificial Intelligence
BCBV	Branch Current To Bus Voltage
BCSSO	Binary Chaotic Shark Smell Optimization
BIBC	Bus Injected Branch Current
DC	Direct Current
DLF	Distribution Load Flow
DM	Debre Markos
DG	Distribution Generation
DSM	Demand Side Management
DSP	Distribution System Planning
DDSP	Dynamic Distribution System Planning
DNSP	Distribution Network Service Providers
DT	Distribution Transformer
EEPCO	Ethiopian Electric Power Corporation
EMTP	Electromagnetic Transient Program
EEU	Ethiopian Electric Utility
END	Energy Not Distributed
GA	Genetic Algorithm
GA-IPSO	Genetic Algorithm-Imperialist Particle Swarm Optimization
GRMHSA	Grid Based Multi-Objective Harmony Search Algorithm
HMCR	Harmony Memory Consideration Rate
HAS	Harmony Search Algorithm
HV	High Voltage
ICA	Imperialist Competitive Algorithm

IP	Integer Programming
KM	Kilo Meter
KV	Kilo Volt
KVA	Kilo Volt Ampere
KVAR	Kilo Volt Ampere Reactive
KVL	Kirchhoff's Voltage Law
KW	Kilo Watt
KVARH	Mega Volt Ampere Reactive Per Hour
KWH	Mega Watt Hour
LF	Load Factor
LP	Linear Programming
LV	Low Voltage
MV	Medium Voltage
MDEP	Multi-Stage Distribution Expansion Planning
MOPSO	Multi-Objective Particle Swarm Optimization
MPSO	Modified Particle Swarm Optimization
MEPDN	Multi-Year Expansion Planning Of Distribution Network
MILP	Mixed Integer Linear Programming
MVA	Mega Volt-Ampere
MW	Mega Watt
NLP	Non-Linear Optimization Problem
NSGA-II	Non Dominated Sorting Genetic Algorithm-II
OPF	Optimal Power Flow
PAR	Pitch Adjustment Rate
PF	Power Factor
PU	Per Unit
PS	Particl Swarm
PSO	Particle Swarm Optimization
PV	Photovoltaic
PVDG	Photovoltaic Distributed Generation
SFL	Shuffled Frog Leaping

SCC	Short Circuit Capacity
SA	Simulated Annealing
TS	Tabu Search
TFL	Total Feeder Loss

CHAPTER ONE

INTRODUCTION

1.1. Background

A power system commonly includes generation, transmission, sub-transmission system, and distribution system. An electric power utility prioritizes on satisfying system load as well as the requirement of its customers by ensuring minimum operation cost on the condition that is acceptable to continuity and quality of electricity supply should be attained [1]. Power distribution network contains a number of distribution substations connected to each other through feeders; an electric conductor carrying power from a substation to meet load demands along its path. This is part of the power system which distributes power to end users. It is the most extensive part of the electrical system as a result; mainly responsible for energy losses. Several Studies have indicated that as much as 13% of total power generated is lost in the form of losses at the distribution network level [2].

Long-term distribution system planning involves a series of study with an aim to assess time and place of installing new equipment. The common planning horizon is 10 years or more. It is acknowledged that besides combinatorial nature, the complexity of the problem is increased with the inclusion of a wide variety of cases, both for intermediate years and the horizon year. Some important practical cases are raised regarding the expansion of the network, which is not only related to the reinforcement of the existing system but also involved in substantial changes to the network topology. Moreover, when expansion planning is concerned, the solution for disconnected networks at the initial point of the planning process should also be dealt [3].

Expansion planning of distribution networks pursues the greatest reinforcement strategies while minimizing the overall power losses as well as the cost subject to several operational and consistency constraints. Also, it is one of the complex problems with several decades 'history of continuous efforts and contributions for improved solutions. Distribution Expansion Planning is an important dispute in developing countries all over the world, whose electricity demand has been increasing up in recent years. However, significant efforts in energy management realm have recently dumped the increasing rate of electricity demand.

Nonetheless, the need for continuous expansion looks inevitable in the near future. The expansion planning of distribution network comprises of determining the capacity of installation and reinforcement of distribution substation units, installing Distributed Generation units, additional or replacement of distribution feeders to attend future increasing load demand [4].

1.2. Statement of the Problem

Ethiopian Electricity network is not well established and will continue to be a critical part of the country's energy infrastructure. The electricity utility company has a responsibility to ensure that the network is developed consistently and in a manner that encounters the future demands of the customers. Ethiopia is currently a developing country with one of the fastest growth rate in Africa, although energy consumption per capita still ranks among the lowest in the world, it has begun increasing faster due to socio-economic development and improvement of living standard.

The number of households is growing by 2.6% (0.42 million) every year. This is in contrast to EEU's maximum yearly residential connection rate attained in the past decade, 0.23 million every year, which is only about half of the growth in a number of families. This means the population is not getting connected by EEU is increasing in complete terms and only somewhat deteriorating in terms of percent connected [5].

The main problem facing the electric power utilities in Ethiopia today is that the power demand is growing rapidly where supply growth is constrained by economic, environmental problems and other common concerns. This has resulted in a need for more wide justifications of the new system facilities, and improvements in fabrication and use of electricity. Distribution network system planning and operation based on a consistency assessment approach provides an opportunity to justify one of the inspected and susceptible economic sectors in Ethiopia. This causes the existing problems in D/M distribution networks are a high frequency of interruptions, power losses and voltage drops at the end user. Major reasons are; the power grid conductor size and transformer capacity is too small and old; networks were constructed without good planning.

To overcome these problems and delivering reliable & continuous power with agood quality of power system profile,itisnecessaryto haveagood expansion plan for Debre Markosdistribution network consideringthe optimalsizing and placement of distributed generationthatmeetsthe existing and future electricity demand.

1.3. Objective

1.3.1. General Objective

The general objective of the study is to carry out the optimal expansion planning of distribution network with distributed generation to meet the future demand by using meta-heuristic optimization technique.

1.3.2. Specific Objectives

- ✓ Collect the connected load data for the existing power distribution network.
- ✓ Survey network infrastructure in thesystem.
- ✓ Forecast the load demand in the power distribution network
- ✓ Load flow analysis for existing and expanded distribution network
- ✓ Calculate the optimal size of conductors and number and capacity of transformers for target years of 2027/28.
- ✓ Determine the optimal size and location of DG to the expanded power distribution network using GrMHSA (meta-heuristic optimization technique).
- ✓ Compare the results of GrMHSA with other meta-heuristic optimization techniques.
- ✓ Evaluate the performance of the expanded network in terms of voltage deviation and power losses with respect to the conductor and transformer overloading conditions.

1.4. The significance of the study

This work provides meta-heuristic optimization techniques based distribution network expansion planning considering DG for power loss and voltage deviation minimization. Optimally placing and sizing of distributed generation in the distribution network has a significant role for the local distribution company as well as the end users. Some of the significances are:

- ✓ Since load forecasting has been accomplished very well, it can be used as a basis for future distribution expansion works
- ✓ Damage of distribution feeder lines and distribution transformers due to overload can be avoided.
- ✓ Devise mechanisms for power loss and voltage deviation reduction.
- ✓ It is the basis for future researchers on distribution network expansion planning for the growing field of distribution system automation.

1.5. Scope and limitation of the thesis

The scopes for this study focuses on to minimize power loss and voltage deviation by performing distribution network expansion planning considering DG using GrMHSA to make sure that the objectives of this study is successfully achieved. Technical data is collected from D/M substation and electric power utility in D/M distribution network and is used for planning the distribution network from 2013/14 to 2017/18. The planning is done for two stages that are 2017/18-2021/22 and 2022/23-2027/28.

The limitations of the study are:

- ✓ The study considers only technical data of primary distribution feeders and does not focus on technical and non-technical data in the secondary system, because the secondary distribution system network is too large and data is not available.
- ✓ Electricity tariff is regulated by government and demand side management isn't included.
- ✓ The implementation of this thesis is limited to computer simulation and has no practical implementation as they all are done by using MATLAB simulation software.

1.6. Thesis outline

The contents of this thesis are organized into five chapters. These chapters are overviewed as:

Chapter-1: deals with an introduction about distribution network expansion planning. It also focuses on the statements of problems, objectives, methodologies, significance, scopes, and limitation of the work.

Chapter-2: introduces some literature surveys on Distribution network expansion planning, load demand forecasting techniques, DG penetration limit, and distributed generation.

Chapter-3: Materials & Methodology and planning techniques are presented and also Energy demand forecast for the study area is estimated.

Chapter-4: shows simulations results and discussion and comparative analysis for each case of the expanded network for the feeder with DG and without DG were explained.

Chapter-5: It gives conclusions and recommendations. And at the end reference and appendix are also included.

CHAPTER TWO

LITERATURE REVIEW

The fundamental objective of distribution system planning is to supply the load in maximum profit and minimum operational costs and to solve the common problem of power losses and voltage deviation. Research on the optimal expansion planning of the distribution network has been an active topic. In recent years in Ethiopia especially in Debre Markos due to fast-growing electric power consumption, new circuits must be added to the existing Distribution networks. Distribution network expansion planning (DNEP) facilitate finding a plan that must specify the number, size, and location of lines and transformers where power system can operate in a reliable as well as secure manner.

The Distribution Expansion Planning is carried out to provide a distribution infrastructure that encounters the electricity customer requirements in terms of capacity, reliability, and quality in the most cost effective manner. This entails the need to mould, reinforce, and develop the existing infrastructure in a phase wise manner so that infrastructure expansions are appropriate with the evolving electricity requirements. Distribution planners must ensure that there is tolerable substation capacity (i.e. distribution transformer)and feeder capacity to meet the load forecasts bounded by the planning horizon [6].

2.1. Distribution Network Demand Forecasting

Electrical load demand forecasting is the prediction of future load demand for industries, utility companies, and costumes for a specified period of time. An energy demand forecast is a measurement and estimate of historic, current and projected patterns of energy demand within a state. Precise models for electric power load forecasting are crucial to the operation and planning of a utility company. There are three classes of load forecasting and these are long term forecasting (covering a period of 20 years), Medium-term forecasts (a period of 5 to 6) and Short-term forecasts (a period of 1 to 2 years) [7]. In Ethiopia, demand forecasting studied for distribution system rehabilitation. However, the study considers only trend analysis of historical consumption demand.

2.1.1. Demand forecasting techniques

These models are useful for medium and long-term forecasting. The three types of electricity demand forecasting methods are:

Trend Analysis: Trend forecasting technique uses the past growth rates of electrical load demand and extends to the future using various techniques from the simplest to the complex one. This technique considers the electrical load demand changes in the past to forecast the electrical load demand changes in the future and it is modified frequently informed judgment based on the knowledge of the future developmental aspects that makes the future electrical demand behaves differently than the past one. The trend analysis is simple, quick and cheap to perform and it is useful when there is not enough data to use more sophisticated methods. The disadvantage of a trend forecast technique is producing only one result which is the future electrical power demand and it relies on past patterns of electrical power demand to project future patterns of electricity demand.

End-Use Analysis: The end use analysis uses the electrical demand usage at the end users and it has the advantages of identifying where the electricity goes, how much is used and the potential for the conservation of each end user by dividing the electrical demand as residential, commercial and industrial demands. This forecasting technique can be used for forecasting the load changes which can be caused by the change in one sector resulting indirectly from load changes in other sectors. The disadvantages of this technique is that a constant relationship between electrical power demand and end-use is assumed even if it is true for few years but it will not hold constant for 10 to 20 years since energy savings technology or energy prices will undoubtedly change.

Econometric or Simulation approach: This approach is a combination of trend analysis and end-user analysis which uses economics, mathematics, and statistics for its electrical demand forecasting, but it does not take the trend analysis's assumption that future electricity demand can be projected based on past demand. Moreover, unlike the end use model, econometrics can permit variations in the relationship between electrical power input and end use.

Econometrics uses complex mathematical equations to describe the past relationships between electricity demand and the factors that have a great effect on that electrical demand and it is capable of providing electrical load demand forecasting for residential, commercial, and industrial sectors. This approach is flexible for analyzing load growth under different cases in which it is defined in terms of a mass of factors such as policy factors, price factors, end-use factors but it has a disadvantage of the forecast to be accurate, the changes in electricity demand caused by changes in the factors influencing that demand must remain the same in the forecast period as in the past [8].

2.2. Distribution Expansion Planning

Many researchers have been investigated and proposed by different approaches to solving the distribution network expansion planning problem.

Robert H. Fletcher et al[9] proposed a solution for optimal Distribution System Horizon Planning. The model uses a feeder layout viewed as a treelike circuit serving a circular sector of a round or hexagonal service area of uniform load density. This arrangement reduces the input data requirements. Ten distribution design parameters include distance of main feeder, number of consumers per secondary line, the number of feeders per substation, number of secondary lines per distribution transformer, size of primary lateral conductor, size of primary main feeder conductor, size of secondary conductor, size of distribution transformers, and size of substation power transformer, and primary voltage class rating, is defined as decision variables. The horizon distribution design can be assessed for changing consumer densities, consumer load characteristics, the cost of energy, and economic factors. The optimal conductor size, primary voltage class, the number of feeders, cost of service, and voltage drop regulation are evaluated. This generalized approach to horizon planning enables electric utilities to evaluate a complete set of optimal future designs, perform sensitivity analyses of alternative futures and link short-range planning decisions with strategic horizon design standards.

Aghaei and Azizivahed [10] proposed a new multi-objective, multi-stage expansion planning of distribution networks using Modified Particle Swarm Optimization (MPSO) algorithm. In this paper, DG units are included in the Multi-Stage Distribution Expansion Planning (MDEP) problem. Investment and Operation (I&O) costs, energy not distributed, electrical power losses, and voltage stability based on short circuit capacity (SCC) were used to develop the objective functions. Additionally, a new approach based on graph theory for checking the radial structure of the distribution network is developed. Accordingly, the contributions of this study with respect to earlier ones in the area can be concise as follows:

- ✓ Including reliability index, i.e., energy not supplied (END) and voltage stability index (VSI) based on SCC as new extra objective functions in the MDEP formulation;
- ✓ using MPSO as optimization solution algorithm;
- ✓ Using graph theory to assess the radial structure of the network;
- ✓ including AC power flow constraints in MDEP problem; and
- ✓ Implementing some indices to evaluate the Pareto solutions.

Sedghi, et al [11] has presented Distribution Network Expansion Using Hybrid Simulated annealing / Tabu search(SA/TS) Algorithm. In this paper distribution network expansion based on hybrid simulated annealing and Tabu search algorithm to solve the combinatorial problem by minimizing the total cost of the objective function with technical constraints and reliability limits since the Optimal expansion of medium-voltage power, network is carried as a common issue. The proposed hybrid algorithm in which the TS was the main and SA was the auxiliary algorithm which controls the tabu list and improves the result without increasing the convergence time since TS algorithm has a good convergence time but the result might be a local optimum. The auxiliary algorithm provides modification which lets the main algorithm wider zones of solution space, so the final solution is more accurate and a strengthening which makes the local searches more efficient and decreases required local search numbers at each iteration, so the computational time is less.

Ahmad, et al [12] have tried to develop a new multi-objective framework for planning studies of the modern distribution networks integrated with the DG technologies and considering a predetermined the capacity penetration level of the EVs. Total losses of the distribution network along with the annualized total enforced the cost of expansion plans are presented as two important criteria which should be optimized in these studies. These criteria effectively present the requirements of system planners and operators from planning studies. The NSGA II algorithm is applied to solve the gained MO optimization framework. The obtained solutions confirmed that the simultaneous presence of the DG units and EVs can be considered as an opportunity for the distribution system operators to more effectively alleviate the bad effects of EVs charging load.

Gitizadeh, et al [13] have proposed Multistage distribution system expansion planning considering distributed generation using hybrid evolutionary algorithms and described the minimization of investment and operation costs and the maximization of the reliability index are carried on and the proposed optimization model is solved subject to AC power flow constraints to obtain the optimal configuration of feeders (adding and removing lines) including the optimal capacity of conductor, replacement of conductor for backup feeders, and generated power of DGs. Also, in this paper, in order to identify Pareto optimal solutions of the multi-objective MDEP problem, a hybrid Particle Swarm Optimization (PSO) and Shuffled Frog Leaping (SFL) algorithm are implemented and for the MDEP problem in a 4-year planning horizon, a synthetic distribution test system is considered and conducted.

Nayeripour, etal [14] explained as the distributed generation (DG) is a new option to meet the electrical demand growth as well as conservative methods such as substation establishment and feeder replacement. This study delivers a new approach to solve single and multi-objective distribution system expansion planning problem including DG and conservative method simultaneously. Subsequently, this optimization problem has a nonlinear complex nature; the classical mathematical method cannot guarantee to achieve the global optimum solution. So, to overcome this burden, a heuristic evolutionary algorithm based on binary particle swarm optimization (PSO) is projected. The model determines the decision variables as follows: placement and size of the DG units, new transformers, and upgraded feeders are performed in detail.

Chandrashekara, et al [15] proposed a neuro-expert system for planning and load forecasting of distribution systems and the problem domain is divided into three parts as planning module, load forecasting module, and expansion planning module. Planning module uses optimization and knowledge-based expert system (ES) for finding optimal substation location and uses the concentric circle relaxation techniques. The load forecasting module uses artificial neural networks (ANN) and expert system for forecasting the yearly peak loads at the load centers of the formerly planned system for a lead time of ten years, which is taken as the year at which expansion planning has to be done. The expansion planning component uses a planning module, reconfiguration module, and an expert system, and attempts to modify the system plan in agreement with the new load demand.

Saeed, et al [16] proposed the Implementation of the distribution automation system with such features significantly reduces the outage time and the consequence of the costs. In this study, the expansion planning model assumes that the distribution network is equipped with the automation system with such capabilities. With this supposition, among several substitutes for network expansion, a plan that fulfills the problem constraints and also maximizes the company's profits will be selected as the network expansion final plan. So, in this work, a model for expansion planning of distribution networks is suggested that is useful in the new competitive environment and it is also capable of modeling the impressions of distribution automation.

Ganguly, et al [17] described a Pareto-based multi-objective optimization algorithm using Comprehensive Learning Particle Swarm Optimization (CLPSO) is suggested for expansion planning of electrical distribution networks. The two conflicting objectives are installation and operational cost, and fault/failure cost. A novel cost-biased particle encoding/decoding scheme, along with heuristics-based conductor size selection, for CLPSO is planned to obtain optimum network topology. Simultaneous optimization of network topology, reserve-branch installation and conductor sizes are the key features of the suggested algorithm. Results on a practical power system are presented along with statistical hypothesis tests to validate the stated algorithm.

Yousefpour, et al [18] proposed A Dynamic Approach for Distribution System Planning (DSP) Using Particle Swarm Optimization. In this paper, modified particle swarm optimization (PSO) algorithm is used for the proposed model on DG solution to solve DSP problem by implementing optimal power flow (OPF) for minimizing operation and maintenance cost and losses costs to handle the increased load. This model is a dynamic distribution system planning (DDSP) since the planning horizon is provided over the whole period and feeder reinforcement, substation expansion, and new DGs installation are considered instantaneously as alternatives to load growth and it was chosen for its high effectiveness due to shorter computational time and better convergence compared to other approaches.

Khator and Leung [19] discussed the general issues of power distribution system planning with an overview of some relevant models and prior work. They classified distribution-planning problems into two categories: planning under normal conditions and planning considering contingencies. In their work, the authors also justified the superiority of multi-period (dynamic) models over single-period models (and their variations) in achieving optimal solutions.

Yeh, et al [20] discussed the integration of a Geographic information system (GIS) into distribution planning. The concept of long range and short range planning are introduced and the coordination between them is discussed. In essence, long-range planning sets a direction for short-range planning exercise to follow. In the long range (10 years), the location of installation is determined, while short range (3 years) size and the year of installation are finalized (from initial solutions obtained in the long-range plan.

Duc [21] proposed the load demand forecasting for Phanthiet city during the period of 2008-2015 to reduce power losses and improve voltage profiles, two scenarios have proposed for the primary distribution systems planning by Phanthiet city. Scenario 1 is to upgrade the system along with capacitor addition. Scenario 2 is to upgrade and combine with DG and capacitor placement. Each scenario consists of two stages i.e. stage 1 (2008-2010) and stage 2 (2011-2015). Scenario 1 has selected to meet economic evaluation while satisfying technical constraints.

Hemmati,et al [22] have presented DNEP is frequently carried out through reinforcement or installation of new modules. The study provided how to use a new and combined methodology is used to consider numerous practical features in DNEP such as uncertainty, distributed generation (DG), load growth, electricity market, and multi-stage dynamic expansion are involved in the planning. So that DNEP is addressed in the incidence of distributed generation (DG), in view of load and price uncertainties under electricity market environment and also aims to minimize investment and operational costs instantaneously. Subsequently, DNEP in coordination with DG planning leads to decrease planning cost, therefore, the coordinated DNEP and DG planning are presented and implemented by the particle swarm optimization (PSO) technique.

Asakura et al [23] have presented a distribution network expansion planning method by network reconfiguration and distributed generation construction plans. The method evaluates several items containing new equipment installation cost, equipment utilization rate, and reliability of the target distribution system by incident analysis, and loss minimization. It also comes with yearly load growth during the target term. It generates various construction plans using an expert system and reactive tabu search techniques.

Gregorio Mu˜noz-Delgado, et al [24] have proposed joint expansion planning of distributed generation and distribution networks aims to address the multistage expansion planning problem of the electrical distribution system by which the investment in the distribution network and in the DG are taken together. The multistage expansion planning model consists of several alternatives for feeders, transformers, and DG by which the optimal expansion plan categorizes the best alternative, location, and installationtimeforthe candidate assets. The model is realized by reducing the net present value of the total cost including investment, maintenance, production, losses, and unserved energy costs and radially situations to accommodate the incidence of DG in order to avoid the isolation of distributed generators and the issues related with transfer nodes.

2.3. Distribution Network Expansion Techniques

There are many optimization techniques have been established to solve power system difficulties. These are Mathematical Algorithms, Heuristic algorithms, Meta-heuristics algorithms, etc. Among this method, Meta-heuristics optimization techniques have been broadly applied to solve problems. Meta-heuristics algorithms are a powerful knowledge-based optimization approach that can address the nonlinearity of practical systems. Meta-heuristics algorithms can decrease the mathematical complexity and have a rapid response [25], [26].

2.3.1. Mathematical Algorithms

A mathematical optimization formulates the problem in a mathematical equation to provide the objective function and nonlinear constraints to designate the problem as a nonlinear optimization problem (NLP) which is quadratic programming with a quadratic function of x and it suffers from numerical problems and complex in implementation. The nature of this approach is dependent on the nature of variables (x). If the objective function and the constraints both are linear functions of x, the problem is considered as a linear programming problem. For occurrence, if x is an integer, the problem is integer programming. Mixed types such as MILP which is mixed integer linear programming may also occur in which while the variables may be both real and integer, the problem is also of LP type [27].

2.3.2. Heuristic Algorithms

Heuristic algorithms describe the step by step techniques to generate, evaluate and select the expansion options. A component of the solution is added at each stage until a good quality solution is found. It is robust random and guided search that converges quickly to the optimal solution to any case whether simple or complex [28], but for very large scale and the highlycomplex problem it may converge very far away from the optimal solution. Global optimality may be only reached, checked or guaranteed for simple cases. If the problem is highly complex as most practical cases it cannot be easily solved through mathematical algorithms [29]. Heuristic algorithms are developed to tackle the above-mentionedpoints and they are used to solve the combinatorial problems which are very complex.

For the Heuristic methods sensitivity analysis is the main criteria whereby the sensitivity index can be built based on the algorithm that employs the electrical system performance like least effort criteria the relaxed version of their own mathematical model, load supply capability, optimal power flow in the circuit [29], use of expert systems, and guide numbers that build up the new expanded network one branch at a time. Tree formats have been also employed in order to decompose the original probleminto subproblems.

2.3.3. Meta-heuristics

Some modified heuristic algorithms (meta-Heuristic algorithms) are developed in the literature by which improved behaviors are attained, claiming that the optimal solutions are guaranteed. They combine characteristics of both the mathematical and heuristic modes [27], [28], [30], [31], [32]. Basically, all start from either a point or a set of points,moving towards a better solution; through a guided search and few are listed below.

Genetic Algorithm (GA) based on genetics and evolution: GA has been widely implemented to solve combinatorial optimization problems. GA applies to the population of individuals; each individual is a potential solution to a given problem and is typically encoded as a fixed length binary string that is the representation of the actual chromosome. After the initial population is generated, the algorithm can generate new generation at the end of each iteration through the sequential and iterative applications of selection, crossover and mutation operators [27], [31].

Particle Swarm (PS) based on bird and fish movements: It is an optimization technique started at the beginning of 1990 by Kennedy and Eberhart through simulationof bird flocking in two-dimensional space [27], [28], [31].

Tabu search (TS) based on memory response: This approach tends to move to the new solution space in a more aggressive or greedier way than that of GA or SA but it is not related to physical phenomena to search and consider like other combinatorial approaches. TS optimization algorithminvolves the following steps;

- ✓ Generate an initial solution,
- ✓ Select move,
- ✓ Update the solution.

The next solution for this approach is chosen from the list of neighbors which are either considered as desired or not tabu and for which the objective function problem is optimum and the process is repeated based on any stopping rule proposed [27]**,** [25]**.**

Ant Colony (AC), based on how ants behave: This approach is based on the behaviors of insects, especially the ants with the following steps Initialization, Evaluation, Trail adding, Ants sending in and Evaporation with the steps being repeated to get the best solution [26]**,** [25]**.** Another meta-heuristic may include simulated Annealing, based on some thermodynamics principles and etc.

2.4. Distributed Generations

The DG can be clearly defined as "electric power generation within distribution networks or on the end user side of the network" or the process of producing electricity through the systems that are located on the distribution network or at the end user side [33]. The DG units in power systems get increased due to the dramatical increment in using green energy sources to replace fossil fuel sources. The integration of the DG unit has a great effect on the whole power system operation and its performance and there are several technical issues that are still not well understood and addressed [34].

2.4.1. Impact of DG on the Distribution Power System

Interconnecting a DG to the power system can have significant effects on the system such as power flow, voltage regulation, reliability enhancement, and power loss, etc. DG changes the traditional characteristics of the distribution system. Most of the distribution systems are that the power flows in one direction. When the DG power is more than the downstream load, it sends power upstream reversing the direction of power flow and at some point between the DG and substation; the real power flow is zero due to backflow of power from DG.

The central power plants are located at specific remote sites and are connected to an extended transmission system which transfers bulk electrical power to the distribution system. This way of power system operation is often called a vertically-operated power system. The decentralized power generation sources are small in size and mainly connected to the distribution system. Because of the implementation of DG in the distribution system the power is generated closer to the load which will affect the local power flow [35]. An increasing penetration level of DG is expected and the total amount of generated electric power can exceed the total connected load. As a consequence, the distribution grid can start exporting electrical power to neighboring distribution grids that converts the power system into a horizontally operated power system [36].

2.4.2. Distributed Generation Model

Distributed generation units can be modeled as induction generators for wind and micro hydropower units, as synchronous generators for small hydropower, geothermal power, combined cycles, and combustion turbine units and as power electronic inverter generators for micro gas turbine, solar power, photovoltaic power, and fuel cell units. So based on the source of generation of active and reactive power or both, DG can be classified into four types.

Type 1: DG unit supplying or injecting constant real power only (PV)

Certain DG types will produce real power only. For instance, photovoltaic systems convert solar energy into electricity giving DC power output.

Type 2: DG units supplying or delivering reactive power only(Synchronous condenser)

Certain DG types provide only the reactive power to improve the power system conditions and they are synchronous condensers.

Type 3: DG units supplying or injecting constant real power and consuming reactive power (Wind Turbine)

This type of DG can supply real power and it can absorb the reactive power and the wind turbines which are the induction generators are categorized in this type

Type 4: DG units supplying or injecting both real and reactive power (Gas Turbine)

This type of DG use interfaced power electronics to produce both real and reactive power and it can include fuel cell, current controlled photovoltaic and Synchronous generator [37], [38].

2.4.3. Optimal DG Placement and Sizing

Different approaches have been implemented for optimizing the objectives of the distributionnetwork through the placement and sizing of DG units such as analytical methods, genetic algorithm (GA), Ant Bee Colony (ABC), Particle Swarm Optimization (PSO), Fuzzy System, Evolutionary Programming, Tabu Search and Dynamic Programming, etc. ThesePSOand GA are mostly used [38].

Arash Afraz et al. [39] has presented PSO based approach to optimize the sizing and sitting of DGs in radial distribution systems with an objective function of dropping line losses and improving voltage profile and also the objective functions were multi-objective one considering active and reactive power losses of the system and the voltage profile but the authors considered the DG generating is only active power.

M. Padma, et al [40] presented a new method using Artificial Bee Colony algorithm for the location of DG in the radial distribution systems to decrease the real power losses and to improve the voltage profile. The outcomes verified that the ABC algorithm is simple in nature than GA and PSO so it takes less calculation period.

S. Kayalvizhi and D.M. Vinod Kumar, [41] have described optimal planning of dispatch able Distributed Generation (DG) connected to distribution networks. Pareto based multi-objective optimization using Harmony Search Algorithm have been used for optimizing the siting and size of DGs and a fuzzy set theory approach has been used to find the best solution from the obtained Pareto solutions. Optimally placing these DG units from the existing distribution networks seems to be challenging in planning and operation of DG connected distribution network. Since the objectives such as real power loss, voltage deviation, and costs, etc. are more than one and are conflicting with each other, this problem of optimal placement and sizing should be attempted as a multi-objective model by using any of the heuristic techniques. The proposed approach is tested on IEEE-33 bus and IEEE 69-bus distribution systems and the results are validated with well-known NSGA-II technique. The comparison has shown that the proposed technique resulted better compared to NSGA-II.

T. N. Shukla, et al [42] have presented by using GA for optimal location of DG for minimum system losses in radial distribution networks. The problem is articulated as an optimization problem with the reduction of real power loss subject to equality and inequality constraints and solution is attaining by using GA. The appropriate location is decided on the basis of active power loss sensitivity to real power injection through DG. The authors demonstrated that the benefit increases with an increased number of locations within certain locations beyond which it is uneconomical. This formulation considered only active power losses.

B. Poornazaryan, et al [43] have proposed a new index to attain the optimal sitting and sizing of DG unit, in order to decrease losses and improve voltage stability consider the load variation. To resolve this optimization problem, a new imperialist competitive algorithm (ICA) based has been introduced and utilized. The results of the ICA-based algorithm, a new framework based on cuckoo search have been implemented and the results of both algorithms have been computed and compared. Loads of the buses are varied from 50% to 150% of the existing load in the steps 1%. The Simulation result shows that the optimal location of a DG unit is fixed during load variation scenarios. Also, the optimal DG sizes are varying linearly with respect to load variation. The set of general expressions have been obtained to calculate DG sizes as the function of load levels. The result shows that three main concern of this study has been definitely resolving. Active power losses in all the load variation scenarios have been evidently decreased. The voltage stability index of all the buses has been enhanced for the load variation scenarios. Besides, the voltage profile of the system and reactive power losses have been improved by the optimal DG unit placement.

2.4.4. Optimal DG Capacity/ Penetration/ limit

Heslop, Simon, et al [44] have presented method for determining a PV generation limit on low voltage feeders for evenly distributed PV and Load. This method is to assess the acceptable maximum PV generation in low voltage feeders by considering/ Identifying the load, total feeder impedance, terminal count and PV generation for which the upper voltage limit of the feeder line is broken/ breached to provide Distribution Network Service Providers (DNSPs) to execute load flow calculations on a case by case basis. For the evenly distributed PV and load, the feeder voltage profile is analyzed in Matlab to decide PV generation limits and the result shows that the PV generation limit can be determined for a given load, terminal count and total feeder impedance.

Sheikh, A., et al [45] have proposed Distributed Generation Penetration Impact on Distribution Networks Loss. In this paper, the influence of DG units' penetration on distribution networks worth of loss is examined, the power delivered to the distribution network from the source to directly connected loads and no transmission cost is involved. The proposed method covered the difference between centralized and decentralized generation and it shows that distribution worth of loss follows a U-shape trajectory by an increase in distributed generation units' capacity.

Mahmud, et al [46] have proposed the analysis of voltage rise effect on distribution network with distributed generation and aims to address the effect of DG penetration on the voltage rise in the distribution network and detail analysis is conducted for how the voltage rise affects the connection of DG on the distribution network. In this paper, the analysis is done on a two-bus radial distribution network with and without DG by taking the worst case scenario (minimum load maximum generation) to approximation the maximum distributed generation that can be connected to the distribution system.

Chen, Po-Chen, et al [47] presented Analysis of Voltage Profile Problems Due to the Penetration of Distributed Generation in Low-Voltage Secondary Distribution Networks. This paper studies the possible impacts of different DG penetration levels on the voltage profile of low voltage distribution network by considering all system components to be performed in several time-domain simulations using Electromagnetic Transients Program (EMTP).

This paper contributes that the determination of maximum allowable DG that the distribution network can withstand without exhibiting under voltage, over voltage and unexpected load disconnected. The result shows that the placement, type, and capacity of the installed DGs, minimum amounts of DG may cause overvoltage problems. However, large amounts of DG may not cause any voltage problems when appropriately chosen.

Morren, et al [48] presented maximum penetration level of distributed generation without violating voltage limits and addresses reactive power compensation (DG unit itself) and numerous methods are investigated to achieve raise in allowable maximum penetration level especially in networks with a high X/R ratio. In this paper, the results show that as the maximum allowable voltage increase, this can limit the allowable greatest penetration limit of DG.

Najafi, Soroush, et al [49] proposed A New DG Planning Approach to Maximize Renewable-Based DG Penetration Level and Minimize Annual Loss. In this paper, reactive power planning and network reconfiguration are involved to maximize the penetration level of DG and to minimize the annual loss of DGs by taking into account feeder capacity, short circuit level, and investment cost constraints. The PSO algorithm multi-objective method is implemented to resolve the optimization problem and 96 scenarios and 10 different load levels are calculated.

Safigianni, et al [50] have explained distributed generation effects on large-scale distribution networks. The results of distributed generation penetration by taking a case study consisting of 21 lines fed by three power stations in large-scale medium voltage power distribution networks. The power injected from PV units and results of DG on the distribution branch currents, losses, voltage profile and short circuit level at the medium voltage distribution buses are examined based on standards. As general conclusions concerning the extended distributed generation penetration in real power distribution networks are performed.

Charles, et al [51] have presented Effects of Distributed Generation penetration on system power losses and voltage profiles. This paper stands to address GA-IPSO optimization approach for sinking power losses and improving the voltage profile by using the joint sensitivity factor analogy to site and size multi DG type optimally tested in IEEE 57-bus system. In this study, the result shows that eventhough the system losses are reduced and the voltage profile improved with the placement of the first DG, as the number of DGs increases this is not the case and it reaches a point where an enlarge in power losses and distortion in bus voltage profile.

Abdul Kadir, et al [52] have developed Integrating Photovoltaic Systems in Power System: Power Quality Impacts and Optimal Planning Challenges. This paper aims to present harmonic distortion formed by photovoltaic distributed generation units, the maximum allowable penetration level of photovoltaic distributed generation in the distribution system, optimal planning for photovoltaic distributed generation placement and sizing and challenges for integrating photovoltaic distributed generation in the power systems. Moreover, power quality, voltage fluctuation of the integrated photovoltaic distributed generation and reverse power low and protection of power system with integrated photovoltaic distributed generation are studied. In this paper, results show that photovoltaic distributed generation with high penetration can lead the propagation of harmonics into the power system and that can reduce the reliability of the power system and thus protection scheme is required to withstand this problem.

Shayani [53] has presented Photovoltaic Generation Penetration Limits in Radial Distribution Systems. This paper presents that when PVDG is increased more than the existing load and the extra power is injected into the feeder which results in a rise in voltage and feeder overloading. This study presents the situations in which the feeder overloads are more resistive than voltage rises and it discusses the conductor ampacity and voltage rise are the limiting factors that manifest themselves under various conditions. Variation in substation voltage, load, and its power factor was simulated in a simplified radial distribution system model, and the amount of distributed generation that may be installed was obtained.

2.4.5. Advantages of DGs in power systems applications

DG units have various advantages in power system applications which are the major reason behind its widespread acceptance. Some major technical benefits include:

- ✓ Reducing power losses and Improve voltage profile
- ✓ Increasing energy efficiency and Improving reliability
- ✓ Improving power quality and Enhanced productivity
- ✓ DG is closer to customers than central power station so they can avoid Transmission and distribution cost (investment cost, operating and maintenance cost). Besides, the net demand to be supplied through transmission and distribution networks may decrease, allowing postponing reinforcement of existing networks
- ✓ DG affects less to the environment than central power station: there is no effect of transmission and distribution routes,
- ✓ DG can have great value in a highly crowded area where the site of the market prices is higher than elsewhere. In such situation, it can serve the local load and effectively reduce the power flow in the system, thus improving the system voltage profile, minimizing the system losses, and relieving the heavy loaded feeders and extending the equipment’s lifetime. The location of DG, however, should be carried out with due attention to its size and location. The location should be optimal in order for the maximum benefit of DG executed in the network. Improper location in some situations can reduce benefits and even jeopardize the system operation [54], [55].

For this study, an efficient multi-objective approach is proposed by integrating grid-based strategy into multi-objective harmony search algorithm. The main aim is to enhance the optimization process for minimizing the distribution systems power loss and voltage deviation by adding optimally sized DGs placing it at optimal locations in the existing distribution network system.

CHAPTER THREE

METHODOLOGY

3.1. Introduction

In this chapter the methods which is used to perform the optimal expansion planning, implementation of the optimization techniques and Materials which have been used in this work are articles, theses, and dissertations, reference and text books, recognized and regulated documents, media as references and MATLAB software for analysis and simulation.

3.2. Overall Methodology

The methods exercised on optimal expansion planning of the radial distribution network are data collection, including transformers, conductors, and voltage level, and power demand and energy consumption of each customer's load. From the data collected in the distribution network, a single line diagram has been prepared with Microsoft Visio Software.

A base case power flow analysis of the system has been done with MATLAB Software by using Backward/Forward Sweeping algorithm. From the analysis, voltage profile at each node, total voltage deviation and active and reactive power loss for the existing system has been found.

Load forecasting has been done for the system under consideration for the targeted year 2027/28. For the system expansion plan for the aforementioned years the system is evaluated for three different scenarios:

- ✓ **Scenario 1: Separated feeders-**a branch is disconnected from the original major feeder and become separate standalone feeder. Therefore, in this research work, feeder 3 is separated into two main feeders due to covering maximum loads and distances.
- ✓ **Scenario 2: Upgraded feeder-**conductor size and transformer capacity upgrading
- ✓ **Scenario 3: Upgraded feeder with DG-**feeder upgrade with distributed generation

For each scenario, a backward/forward power flow analysis has been performed to find voltage profile at each node, total voltage deviation; active and reactive power loss and comparison has been performed among the three scenarios.

In the third scenario, optimal DG sizing and placement have been performed according to the objective function and constraints by using Grid Based Multi-Objective Harmony Search (GrMHS) Algorithm.

All the procedure followed for conducting this thesis work is presented with the flow chart presented below.

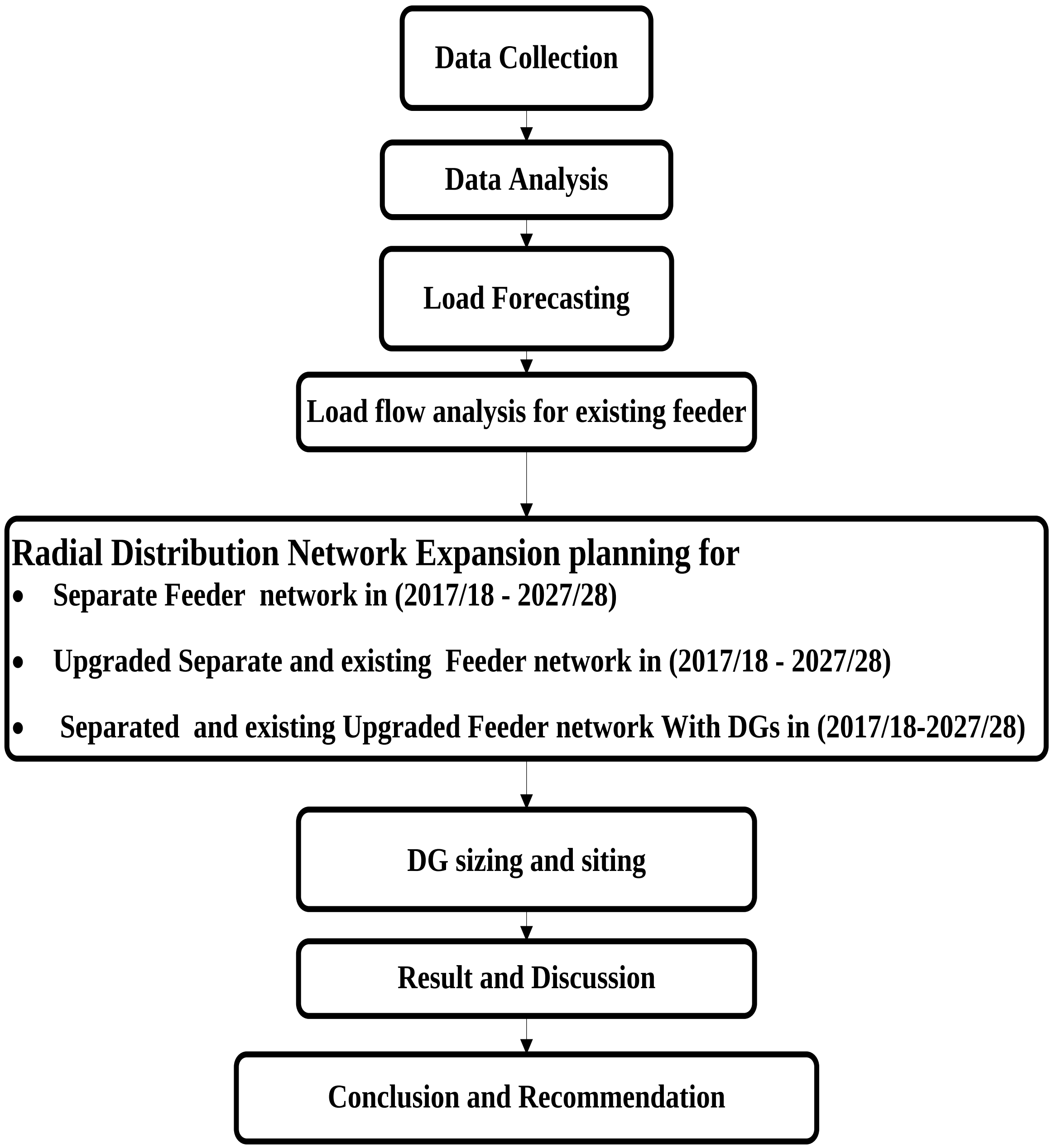

Figure 3.1: The Overall steps of the thesis.

3.3. Data Collection

Collected data related to the study area of the D/M distribution network consisting of

- ✓ Size of distribution transformers.
- ✓ Conductor size of primary distribution lines of all feeders.
- ✓ The voltage level of feeders.
- ✓ Feeders peak load.
- ✓ Current demand for each feeder

Detail of each collected data is found in Appendix A.

3.4. Demand Forecasting

An accurate electrical load demand forecasting improves a lot of challenges and supports in making proper decisions including the electrical power load and infrastructure development. The trend forecasting technique with least square approximation method is used as a distribution load forecasting technique to forecast and estimate the total electrical load demand for D/M distribution network in a period of 2017/18-2022/23-2027/28.

Fundamentally, the existing load demand at all load buses or feeders and its future load demand at the end of the year n^{th} can be calculated based on the following equation.

$$P_n = P_o(1+g)^n \tag{3.1}$$

Where,

P_n**:** Load demand at the end of the nth year

P_o**:** Initial load

n**:** Number of years

g**:** Annual load growth rate, expressed as

$$g = \frac{P_i - P_{i-1}}{P_{i-1}} \tag{3.2}$$

Where; i is the current year and i-1 is the previous year.

3.5. Backward/Forward Sweep Method for Radial Distribution Networks

Load flow is a vital tool for analyzing electrical power system network performance and almost all distribution networks are radial in nature having high R/X value that causes problems in the convergence of conventional load flow algorithms which makes it ill-condition. The study distribution network system is possible to consider as the primary distribution feeder of a 3 phase system which is operating in balanced load condition.

For this study backward-forward sweep load flow method is proposed as distribution load flow for, ituses simple algebraic equations to calculate the outgoing power and voltage magnitudes at different nodes, very robust and numerically efficient for convergence over the wide variations in the voltages of radial distribution system, Suitable for online and offline problems,computational efficiencies and system accuracies are some of the advantageous and unsuccessful for heavy load and large scale network are disadvantageous for this methods.

3.5.1. Algorithm for Forward-Backward Sweep Load Flow

In this algorithm, the equivalent current injections (ECI), the bus-injection to the branch-current matrix (BIBC) and the branch-current to the bus-voltage matrix (BCBV) are utilized.

For bus-i, the complex load S_i is expressed as,

$$S_i = P_i + jQ_i \qquad (3.3)$$

Where, $\boldsymbol{S_i}$ is the complex power at the i^{th}bus, $\boldsymbol{P_i}$ is the real power at thei^{th}bus and $\boldsymbol{Q_i}$**:** is the reactive power at bus i^{th}, i = 1, 2, 3... N

3.5.1.1. Equivalent Current Injection

From the specified complex power S_i at bus-i which is expressed in equation (3.3), the respective equivalent current injection which is practical.

From equation 3.3, the equivalent current injection is expressed as

$$\boldsymbol{I_i} = \boldsymbol{I_i^r}(\boldsymbol{V_i}) + \boldsymbol{J}\boldsymbol{I_i^i}(\boldsymbol{V_i}) = \left(\frac{\boldsymbol{P_i} + \boldsymbol{jQ_i}}{\boldsymbol{V_i}}\right)* \qquad (3.4)$$

For the load flow solution, the equivalent current injection at the k^{th} iteration at the i^{th} node is expressed as

$$I_i^k = I_i^r\left(V_i^k\right) + jI_i^i\left(V_i^k\right) = \left(\frac{P_i + jQ_i}{V_i^k}\right)* \qquad (3.5)$$

Where,

$\boldsymbol{S_i}$: is the complex power at the i^{th}bus
$\boldsymbol{P_i}$**:** is the real power at thei^{th}bus

$\boldsymbol{Q_i}$**:** is the reactive power at the i^{th} bus

V_i^k: is the bus voltage at the k^{th} iteration for i^{th} bus

$\boldsymbol{I_i^k}$**:** is equivalent current injection at the k^{th} iteration for i^{th} bus

$\boldsymbol{I_i^r}$**:** is the real part of the equivalent current injection at the k^{th} iteration for i^{th}bus

$\boldsymbol{I_i^i}$**:** is the imaginary part of the equivalent current injection at the k^{th} iteration for i^{th}bus

3.5.1.2. Formation of BIBC Matrix/Backward Sweep

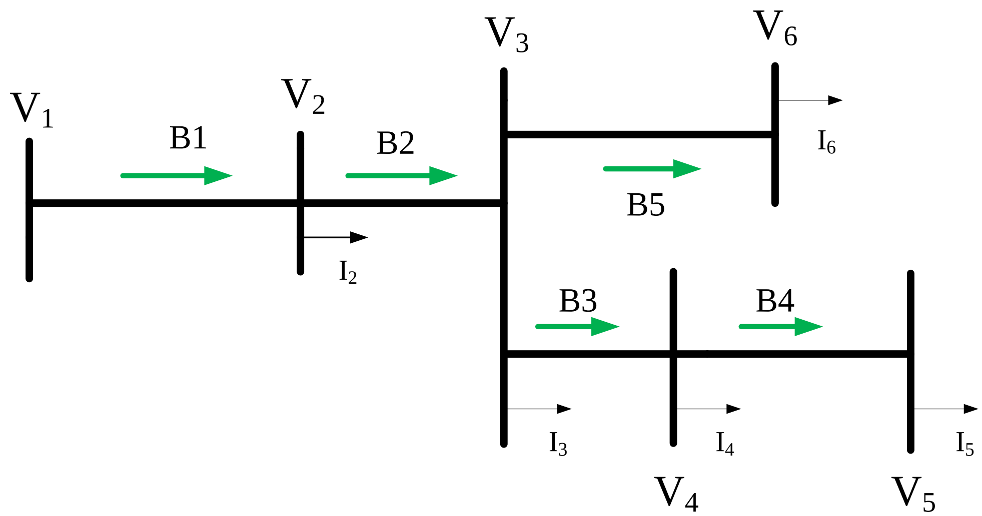

Figure 3.2: Simple radial Distribution network

The branch currents are obtained as a function of injected currents at each bus by applying Kirchhoff's current law (KCL) to the radial distribution network as shown below in figure 3.2. The injected currents at each bus are calculated using equation (3.5) and the branch currents B_5, B_4, B_3, B_2, and B_1 can be formulated as a function of the equivalent current injections and expressed as shown below.

$$B_5 = I_6 \tag{3.6}$$

$$B_4 = I_5 \tag{3.7}$$

$$B_3 = I_4 + I_5 \tag{3.8}$$

$$B_2 = I_3 + I_4 + I_5 + I_6 \tag{3.9}$$

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6 \tag{3.10}$$

Thus, the bus current injections and branch currents (BIBC) matrix can be expressed from the above equations (3.6-3.10) as,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \tag{3.11}$$

The general form of Eq. (3.11) can be expressed as:

$$[B]= [BIBC][I] \tag{3.12}$$

Where, BIBC is the bus injection branch current for the given sample network is given by

$$[BIBC] = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.13}$$

3.5.1.3. Formation of BCBV matrix/Forward Sweep

The Branch-Current to Bus voltage (BCBV) matrix is the relation of branch currents and bus voltages of a radial distribution network that can be obtained by applying Kirchhoff's Voltage Law (KVL). As shown in Figure 3.2, the voltages of Node 2, 3, and 4 for the relationship between branch currents and bus voltages are expressed as:

$$V_2 = V_1 - (Z_{12}B_1) \tag{3.14}$$

$$V_3 = V_2 - (Z_{23}B_2) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) \tag{3.15}$$

$$V_4 = V_3 - (Z_{34}B_3) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) - (Z_{34}B_3) \tag{3.16}$$

$$V_5 = V_4 - (Z_{45}B_4) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) - (Z_{34}B_3) - (Z_{45}B_4) \tag{3.17}$$

$$V_6 = V_3 - (Z_{36}B_5) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) - (Z_{36}B_5) \tag{3.18}$$

Where;

V_i: Is the voltage at bus i and

Z_{ij}: Is the line impedance between bus i and bus j.

From equations (3.14-3.18), the node voltage of the network can be expressed as a function of the branch currents, line parameters,and main substation voltage.

$$\begin{bmatrix} V2 \\ V3 \\ V4 \\ V5 \\ V6 \end{bmatrix} = \begin{bmatrix} V1 \\ V1 \\ V1 \\ V1 \\ V1 \end{bmatrix} - \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{56} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \tag{3.19}$$

$$[BCBV] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & 0 & 0 \\ 0 & 0 & 0 & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \tag{3.20}$$

$$[BCBV] = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & 0 & 0 \\ 0 & 0 & 0 & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \tag{3.21}$$

$$[BCBV] = [BIBC]^T [ZD] \tag{3.22}$$

Equation (3.19) can be expressed as

$$\begin{bmatrix} V1 \\ V1 \\ V1 \\ V1 \\ V1 \end{bmatrix} - \begin{bmatrix} V2 \\ V3 \\ V4 \\ V5 \\ V6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{56} \end{bmatrix} \begin{bmatrix} B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix} \tag{3.23}$$

$$\begin{bmatrix} V1 \\ V1 \\ V1 \\ V1 \\ V1 \end{bmatrix} - \begin{bmatrix} V2 \\ V3 \\ V4 \\ V5 \\ V6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & 0 & 0 \\ 0 & 0 & 0 & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix} \tag{3.24}$$

$$\Delta V = [\mathrm{BCBV}][\mathrm{B}] \tag{3.25}$$

$$\Delta V = [BCBV][ZD][B] \tag{3.26}$$

$$\Delta V = [\mathrm{BCBV}][ZD][\mathrm{B}] \tag{3.27}$$

$$\Delta V = [BIBC]^T [ZD][\mathrm{B}] \tag{3.28}$$

The general form for the bus voltage at $(k+1)^{th}$ iteration from equation (3.19) can expressed as:

$$[V^{k+1}] = [V_1] - [BCBV][B] \tag{3.29}$$

Equating equations (3.12) and (3.25), the relations between the node current injections and node voltages could be communicated as:

$$\Delta V = [\mathrm{BCBV}][BIBC][\mathrm{I}] \tag{3.30}$$

$$\Delta V = [BIBC]^T[ZD][BIBC][\mathrm{I}] \quad (3.31)$$

And the distribution load flow (DLF) matrixes formed as

$$[DLF] = [\mathrm{BCBV}][BIBC] = [BIBC]^T[ZD][BIBC] \quad (3.32)$$

Substituting equation (3.32) into equation (3.31), we have

$$[\Delta V] = [DLF][I] \quad (3.33)$$

The iterative solution for the distribution system load flow can be obtained as:

$$[\Delta V^{k+1}] = [DLF][I^k] \quad (3.34)$$

$$[V^{k+1}] = [V_1] + [\Delta V^{k+1}] \quad (3.35)$$

3.5.2. Algorithm for distribution network load flow

The backward forward load flow algorithm described above may have the following steps for load flow solution of distribution networks as shown below:

Step 1: Read the line data and bus data of the distribution network.

Step 2: Calculate each node current injection matrix using equation (3.4).

Step 3: Calculate the BIBC matrix by using steps given in section 3.5.1.2 and determine the branch current.

Step 4: Form the BCBV matrix using steps given in section 3.5.1.3.

Step 5: Calculate the DLF matrix by using the equation (3.31).

Step 6: Set Iteration k = 0.

Step 7: Iteration k = k + 1.

Step 8: Update voltages by using equations (3.5), (3.34) and (3.35).

Step 9: If max $((|V^{(k+1)}| - |V^{(k)}|) >$ tolerance, go to step 5.

Step 10: Calculate branch currents, and losses from final node voltages.

Step 11: Display the node voltage magnitudes and angle, branch currents and losses.

Step 12: Stop

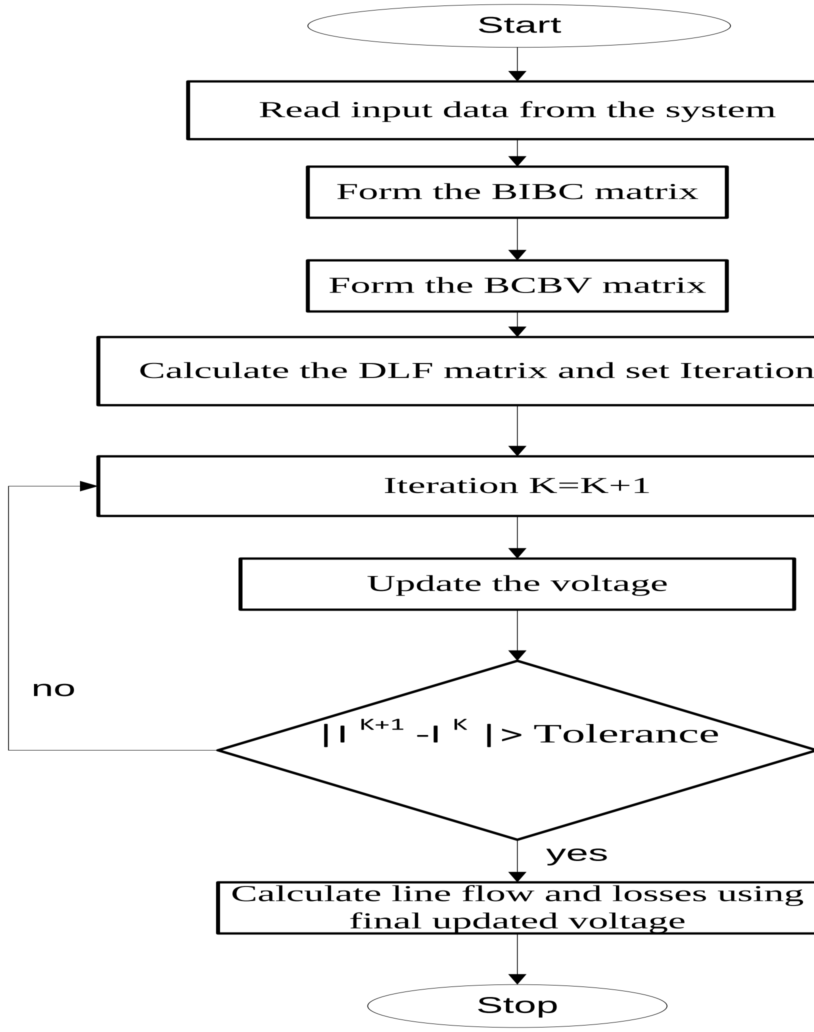

Figure 3.3: Flowchart for load flow solution for radial distribution networks

3.6. Load flow analysis of existing DebreMarkos 15 KV distribution network

For 15 KV load flow analysis, the demand at each distribution transformer is necessary. The demand recorded at the substation on each feeder represents the aggregate of simultaneous demands of all transformers plus the power loss in the feeder segment and the method used was to distribute the feeder loads on the appropriate basis. MV network analysis of load flow comprises the Losses in Primary distribution feeder plus distribution transformer loss.

3.6.1. Loss calculation of transformer

The power losses in the transformer is the sum of core or iron losses (permanent loss as the transformer on regardless of loading or not) and copper losses which are done in the short circuit which can be depends on load when the transformer is energized and it can be calculated as follows [56],[57].

$$P_{loss} = P_{iron\ loss} * T + P_{copper\ loss} * T \tag{3.36}$$

$$P_{loss} = \frac{P_{iron\ loss}}{year} * (365\ days - iT) + \frac{P_{copper\ loss}}{year} * (365\ days - iT) \tag{3.37}$$

Where,

T: Working time per year of the transformer

iT : Interruption duration in days

$P_{iron\ \ loss}$: Iron loss or no load loss at rated power (kVA) of transformer per year.

$P_{copper\ \ loss}$: Copper loss of transformer at rated power (kVA) of transformer per year.

$P_{copper\ \ loss}$ Can be calculated as below:

$$P_{copper\ \ loss} = Copper\ loss\ at\ rated\ KVA\ per\ year * T * (LF^2) \tag{3.38}$$

Where, LF: load factor

In the case of D/M distribution system, the voltage is stepped down to 15 KV from 230kV of 63 MVA 230/66/15 kV transformers and the system is MV network.

The details can be seen on Appendix-D

3.6.2. Loss calculation of conductors of a feeder

In this electrical distribution network, the conductor length of the feeder is long and serves transformer widely spaced, the value of load in the feeder may be considered as a distributed load [58]. Thus the average annual losses of the feeder can be calculated as follows:

$$AVAFL = TFL * L_sF * 8760 \tag{3.39}$$

$$TFL = \sum_{i=1}^{m} {I_i}^2 . R_i \tag{3.40}$$

$$L_sF = 0.2 * LF + 0.8(LF^2) \tag{3.41}$$

$$LF = \frac{Total\ annual\ energy}{Annual\ peak\ load * 8760} \tag{3.42}$$

$$AVAFL = 8760 * \left(0.2 * LF + 0.8(LF^2)\right) * \sum_{i=1}^{m} {I_i}^2 . R_i \tag{3.43}$$

Where:

AVAIL: Average annual feeder losses

TFL: Totalfeeder losses

L_sF: Loss factor

I_i: Current at each branch (A)

R_i: Resistance of each line (Ω)

LF: Load Factor

3.6.3. Voltage Drop in an Electric Power Distribution System

In the radial feeder, the voltage drop exists as a result of the line impedance of the feeder which covers the long distance in the network. This voltage drop may have a negative effect on the equipment or appliances which are connected to the utility due to low voltage and over current resulted from it [21]. When the radial feeder is relatively long and serves non-uniformly distributed loads and as the primary feeder supply from one to many transformers, the voltage drop can be formulated as:

$$\Delta V = \sqrt{3}\sum_{i=1}^{n} I_i(R_i \cos\theta + X_i \sin\theta)L_i \tag{3.44}$$

Where,

I_i: Portion current online (A)

θ: Angle between current and voltage

R_i: Resistance of the line (Ohm/km)

X_i: Reactance of the line (Ohm/km)

n: Number of portions

L_i: Portion length of the line (km)

3.7. Selection of Conductor Size and Transformer Capacity

3.7.1. Selection of Conductor Size

The strands of a conductor made of all aluminum conductors (AAC) were usually used in the distribution network. Their size depended on the following factors:

- ✓ The capacityfor transmitting current.
- ✓ Acceptable voltage drops or line regulation.
- ✓ Breakdown strength of the conductor.

A backward forward sweep load flow study has been conducted using MATLAB to point out the current on the feeders for addressing the selection of conductor sizes for the expansion of the future D/M distribution system and the size of the conductor for distribution line can be chosen on the basis of the allowable current transmitting capacity of the conductors. Then, the size of the conductors for the feeders can be selected based on the permissible current carrying capacity of the conductors ($\boldsymbol{I_p}$) to meet that$\boldsymbol{I} \leq \boldsymbol{I_p}$.

The maximum current in a feeder is calculated as follows:

$$I = \frac{P}{\sqrt{3} * V * cos\,\theta} \tag{3.45}$$

Where,

P: maximum power in the feeder (kW)

V: the base voltage of the feeder (kV)

$\boldsymbol{I_p}$: Peak current (the proposed conductor max. current carrying capacity)

cosθ: Power factor of the feeder

3.7.2. Selection of Transformer Size

The value of demand of the transformers' LV network is calculated taking into account the load which was connected to the second main to find out thesize of the transformer, and usually, the standard-size transformer (KVA) that is the next bigger to the demand (kW) can be chosen. After the load has been calculated, the "the next bigger" EEU standard transformer size is chosen and to permit for further development and not to negative effect to the life of the transformer, the chosen size was usually larger than that of demand[59], [60].

$$\boldsymbol{S}_{selected} \geq \boldsymbol{S}_{demand}(kVA) \tag{3.46}$$

3.8. Problem Formulation

The problem is to determine the optimal allocating and sizing of DGs which minimizes the distribution power losses and the voltage deviation for the expanded distribution network. Proper placement and sizing of DG is a valid solution to the problem if it satisfies certain constraints.

3.8.1. Objective Function

The main objective is to minimize the real power loss and the voltage deviation subject to different constraints. Thus can be expressed mathematically as:

$$F_1 = \sum_{i=1}^{m} I_{i\,real}^2 \,.\, R_i \tag{3.47}$$

$$F_2 = \sum_{i=1}^{m} I_{i\,imag}^2 \,.\, X_i \tag{3.48}$$

$$F_3 = \sum_{i=1}^{m} (1 - V_i)^2 \tag{3.49}$$

Where,

F_1: Objective functions of to minimize the real power loss

F_2: Objective functions of to minimize the reactive power loss

F_3: Objective functions of to minimize the voltage deviation

i: Any feeder branch,

m: The number of network branches

R_i: The resistance of branch i

X_i: The reactance of branch i

I_i: Is the current magnitude flows in branch i.

V_i: Is the voltage of bus i.

3.8.2. Constraints

The objective function for the expansion planning is subjected tosatisfy all of the operational constraints such as limits of node voltages, limits of DG capacity, limits of Branch thermal, and limits of active and reactive power losses before and after DGs as follows:

i. Node Voltage Constraint

$$V_i^{min} \leq V_i \leq V_i^{max.} \tag{3.50}$$

V_i: Bus voltage;

V_i^{min}: Bus minimum voltage;

$V_i^{max.}$: Bus maximum voltage.

ii. Branch Thermal Limit Constraint

$$I_{(i,j)} \leq I_{rated} \tag{3.51}$$

I_{rated} : Thermal Current carrying capacity of line section ij

iii. DG Capacity Limits Constraint

The capacity of the distribution generator to be connected with an expanded feeder should not be too small or too high with respect to the feeder loading for the target year 2027/28. The size of DG in the expanded network should not be more than the feeder loading value**.** The used DG must have the allowable size as the following range:

$$\mathrm{S}_{\mathrm{DG_i}}^{\mathrm{min}} \leq \mathrm{S}_{\mathrm{DG_i}} \leq \mathrm{S}_{\mathrm{DG_i}}^{\mathrm{max}}; \quad \mathrm{i} = 2, \dots \dots, \mathrm{N}, \tag{3.52}$$

Where;

$\mathrm{S}_{\mathrm{DG_i}}^{\mathrm{min}}$: Minimum power output limits of DG at bus i

$\mathrm{S}_{\mathrm{DG_i}}^{\mathrm{max}}$: Maximum power output limits of DG at bus i and

$\mathrm{S}_{\mathrm{DG_i}}$: The power output of DG at bus i.

iv. Active and Reactive Power Losses Constraint

The losses after installing DG in the expanded network should be less than or equal to the losses before installing DG.

$$\begin{pmatrix} P_L withDG \leq P_L withoutDG \\ Q_L withDG \leq Q_L withoutDG \end{pmatrix} \tag{3.53}$$

3.9. HSA Technique for Optimal Sizing and Allocation of DGs

This work incorporates searching (Harmony Search Algorithm) approach for placement and sizing DG determination based on real and reactive power loss and voltage deviation reduction for predicted year 2027/28.

3.9.1. Introduction

The Harmony search algorithm was derived by adopting the idea that the present meta-heuristic algorithms are originated in the pattern of natural phenomena. The algorithm was recently developed in equivalence with music improvisation process, where music players improvise the pitches of their instruments to attain better harmony. As the improvisation pursues the best state in terms of artistic evaluation, the optimization look for the best state in terms of objective function evaluation, as aesthetic evaluation is determined by the set of the sounds played by musical instruments, objective function evaluation is determined by the set of the values assigned to decision variables and as the harmony is improved practice by practice, the vector is improved iteration by iteration [61].This algorithm is a meta-heuristic optimization algorithm inspired by the improvisation process of music in pursuit of perfect harmony. Therefore, like existing meta-heuristic algorithms mimic natural or behavioral phenomena, [62], [63], [64], the HS algorithm intellectualizes the music improvisation process of searching for perfect harmony.

3.9.2. The Basic Model of HS Algorithm

Harmony search (HS) optimization technique is relatively a new meta-heuristic algorithm, which was designed by Geem, et al. [65]. HS algorithm is a heuristic algorithm imitating the improvisation progression of music players, where musicians improvise the pitches of their instruments to search for a perfect state of harmony. In this algorithm, musical performances pursue a perfect state of harmony determined by artistic estimation, as the optimization algorithms pursue a global best determined by objective function value. Specifically, musical instrument x^i(i= 1, 2... n) is analogous to the$\boldsymbol{i^{th}}$decision set of the optimization problems. The harmony $x_{\boldsymbol{j}}$ (j = 1, 2… n) produced by musical instruments is analogous to the $\boldsymbol{j^{th}}$ explanation of the optimization problems. Artistic evaluation is analogous to the objective function [66].

In the process of iteration, each New Harmony vector $\boldsymbol{X^{new}} = (\boldsymbol{X_1^{new}}, \boldsymbol{X_2^{new}}, \dots\dots \boldsymbol{X_n^{new}})$ are generated based on three rules:

- ✓ Memory consideration,
- ✓ Pitch adjustment, and
- ✓ Random selection

Generating a new harmony is called “improvisation” [66]. In memory consideration, the value of each component is updated as follows:

$$X_i^{new} = \begin{cases} x_i^j, & j \in (1, 2, \dots\dots, HMS), rand_1 < HMCR \\ x_i \in X_i, & else, \end{cases} \tag{3.54}$$

Where; $rand_1$ is a random number uniformly distributed in the range of [0,1], HMS is harmony memory size, $HMCR$ is harmony memory consideration rate and X_i is the value space of the i^{th} variable.

Each component obtained by the memory consideration is examined to determine whether it should be pitch adjusted. The PAR parameter is the rate of pitch adjustment. The equation of pitch-adjustment can be described as follows:

$$X_i^{new} = \begin{cases} x_i^j \pm rand_2 * BW, & rand_2 < PAR \ (when\ x_i\ is\ continuous) \\ x_i(k+m), & rand_2 < PAR \ (when\ x_i\ is\ discrete) \\ x_i^{new} \in X_i, & else, \end{cases} \quad (3.55)$$

Where; $rand_2$ is a random number uniformly distributed in the range of [0,1], PAR is pitch adjustment rate, BW is band width and m is a constant, which belongs to the $(-1,1)$.

In the HS Meta heuristic algorithm, an initial population is randomly generated and stored in an HM. New candidate harmony vector is improvised by utilizing memory consideration rule, pitch adjustment rule, and random selection. If candidate harmony is better than the worst harmony, the worst harmony vector is exchanged by the new candidate harmony vector and HM is updated. This progression is repetitive until a specified termination criterion is achieved. In the improvisation process, they used a modified pitch adjustment rule to well inherit good information from the best harmony vector and a modified memory consideration confined optimal solution [67].

3.9.2.1. Improved Harmony Search Algorithm

The main operation in HS is improvising new harmony vector. In this operation, the two main parameters harmony memory consideration rate (HMCR) and pitch adjustment rate (PAR) are used, so that the new harmony vector is generated both from existing HM members as well as arbitrarily selected variables. Each variable value of the new harmony vector is generated by memory consideration with probability HMCR or randomly selected with probability (1-HMCR). Decision variable values generated by memory consideration are subject to pitch adjustment with probability PAR. Having HMCR closer to 1.0 is in favor of choosing from the historic variable values stored in the HM, which results in fast convergence. On the other hand, small HMCR is in favor of increasing the diversity of the HM. A small value of PAR results in passing decision variable values chosen by memory consideration as is which enhances local manipulation around the selected variable, while large PAR helps with the exploration [68].

3.9.2.2. Update Harmony Memory

After the new harmony vector is generated, its fitness value is determined and the worst harmony is replaced in HM if its fitness is better than it.

3.9.2.3. Check Stopping Criteria

If the stopping criteria are met the improvisation process stops and the best harmony vector is retrieved as the optimal or near optimal solution, otherwise the improvisation continues until the system has gotten theoptimal or near optimal solution.

3.9.2.4. Harmony Search Algorithm Parameters

HSA requires a number of parameters to be selected before optimization which may affect its performance for any given optimization problem. The values and choices of these parameters have large, small or no impact on the performance of the HSA method. These parameters are illustrated below.

Harmony Memory considering Rate (HMCR): HMCR ∈ [0, 1] determines whether the value of decision variables to be chosen from HM. In order to ensure that the algorithms can quickly find local optima in the early operation and the solutions obtained in the later are diverse, this paper adopts the following linear decreasing strategy to update HMCR [69].

$$HMCR(t) = HMCR_{max} - \frac{(HMCR_{max} - HMCR_{min}) * t}{T_{max}} \tag{3.56}$$

Where; t is iteration number,T_{max} is maximum total number of iterations,$HMCR_{max}$ ismaximum harmony memory considering rate and $HMCR_{min}$is minimum harmony memory considering rate.

Pitch Adjusting Rate (PAR): PAR plays a role in controlling local search and the appropriate PAR can avoid the search being trapped in local optimum efficiently. Ordinarily, the smaller PAR is beneficial to quickly find the local optimal solution in the initial search stage, while the larger PAR is propitious to jump out the local optimal in the later stage [69]. Therefore, dynamic change strategy for PAR is incorporated into the algorithm in this paper; the mathematical expression for PAR is

$$PAR(t) = \frac{PAR_{max} - PAR_{min}}{\pi/2} * \arctan t + PAR_{min}, \tag{3.57}$$

Where PAR (t) denotes pitch adjusting rate for the tenth generation; PAR_{max} and PAR_{min} represent maximum and the minimum pitch adjusting rate, respectively.

Band Width (BW): The appropriate BW can be potentially useful in adjusting the convergence rate of the algorithm to the optimal solution. In this paper, BW changes from large too small. BW changes dynamically with a generation number as expressed as follows:

$$BW(t) = BW_{max} - \frac{BW_{max} - BW_{min}}{T} * t, \tag{3.58}$$

Where BW (t) denotes pitch bandwidth for the t^{th}generation; BW_{max} and BW_{min}representsthe maximum and the minimum band width, respectively.

Iteration Numbers: Observing significant improvement in the solution based on computational experience, a number of iterations are usually sufficient which is dependent on the problem providing that the initial solutions are feasible. The proper number of iteration number should be taken since taking a small number of iteration may force to stop the searchprocess prematurely and taking a largenumber of iteration may result in unnecessary additional computational complexity and more time.

3.9.3. Advantages of GrHSA

GrHSA technique is a powerful technique for solving non-linear optimization problems.

- ✓ It is applied both in scientific research and engineering problems as the implementation of this algorithm is Simple and easy.
- ✓ It is simple to the calculation.
- ✓ Efficient in searching optimal solution among other heuristic algorithms.
- ✓ Compared to other optimization techniques, this algorithm has less impact of parameters to the optimal solution as it has only less number of parameters.
- ✓ Optimum value can be obtained easily within a short time and faster convergence.

3.9.4. Application of GrMHSA

The following are some of the applications of HSA that are successfully used to:

- ✓ Telecommunications
- ✓ System control

- ✓ Data mining
- ✓ Power systems design
- ✓ Signal processing
- ✓ Network training.

3.10. Implementation of GrMHSA for Optimal sizing and placement of DGs

The grid-based dominance strategy into harmony search algorithm is making an effort in this paper and the outcomes are also found encouraging in terms of quality solutions. Before entering into the procedural steps of the proposed GrMHS algorithm a few necessary definitions (concepts) and Fitness calculation is introduced below slightly.

This paper aims to implement a grid strategy one of the most efficient population based meta-heuristic algorithm for multi-objective DG planning problem. In GrMHSA optimization techniques, grid coordinates are used to locate individuals in the objective space. To set the grid structure of k^{th} objective, the range of k^{th} objective are identified in the entire population P and it is denoted as P_m^{min} and P_m^{max} respectively. Then, the lower and upper limits of the grid in the k^{th} objective are determined as follows:

$$ll_k = P_m^{min} - \left(P_m^{max} - P_m^{min}\right)/2 * div \tag{3.59}$$

$$ul_k = P_m^{max} + \left(P_m^{max} - P_m^{min}\right)/2 * div \tag{3.60}$$

Where; div refers to the number of divisions of the objective space (generally user defined). If there are M objectives, then objective space will be divided into hyper boxes. Thus, the width w_k of hyperbox in the K^{th} objective can be given as:

$$w_k = (ul_k - ll_k)/div \tag{3.61}$$

The grid coordinates of the individual in the k^{th} objective are calculated as

$$G_k(x) = \lfloor (f_k(k) - ll_k)/w_k \rfloor \tag{3.62}$$

Where, $\lfloor . \rfloor$ denotes the floor function, $G_k(x)$ is the grid coordinates of individual x in the k^{th} objective and $f_k(k)$ is the actual objective value in the k^{th} objective.

Fitness calculation: The GrMHS considers three grid-based criteria to rank individual with better fitness. They are grid ranking (GR), grid crowding distance (GCD) and the grid coordinate point distance (GCPD). GR and GCPD are used to evaluate the convergence while GCD concerned with the diversity of entities. This ensures the Pareto of objective values close to the source and blow out of the solutions inside pareto. This spread provides a choice for decision making depends on the application. GR is defined as the summation of its grid coordinates in each objective

$$GR(x) = \sum_{k=1}^{M} G_k(x) \tag{3.63}$$

Density estimation of solutions is taken care of by the GCD by considering the distribution of neighbours of a solution and it was given by

$$GCD(x) = \sum_{y \in N(x)} (M - GD(x, y)) \tag{3.64}$$

Where, N(x) is the set of neighbours of x and solution y is regarded as a neighbour of solution x if GD(x, y) < M.

The Euclidian distance between an individual and the best corner solution of its hyperbox is GCPD and it is calculated as follows:

$$GCPD(x) = \sqrt{\sum_{k=1}^{M} ((F_k(x) - (lb_k + G_k(x) \times d_k))/d_k)^2} \tag{3.65}$$

The problem of optimum determination of DG size and placement with reasonable capacity limits is formulated in the form of GrMHSA optimization. An objective function is formulated considering minimization of the distribution power losses and the voltage deviation for the expanded distribution network and it is given in equation (3.47), (3.48) & (3.49).

Minimize

$$Objective\ function = \text{minimization}(\text{Pl}, \text{Ql}, \text{VD}) \tag{3.66}$$

Where; Pl is the real power loss, Ql is the reactive power loss and VD is the voltage deviation.

The GrMHSA approach for solving the optimal DG allocation and sizing problem for a specified number of DG can be summarized as follows:

Step 1: Read the distribution system's bus data and line data and Set the value of constraints and number of DGs, such as maximum-minimum allowed voltages and DG size range are specified.

Step 2: Choose appropriate Input algorithm parameters such as the Harmony Memory Considering Rate (HMCR), distance Bandwidth (BW) and Pitch

Step 3: Set feeder loading and take total voltage deviation (VD) and total power loss (Pl) from Backward Forward Sweep Load Flow without DG.

Step 4: Randomly initialize a population P Initialize (P) N∗D, Where, N-Population size; D-Number of decision variable and set iteration counter as i = 1.

Step 5: Set bus count n=2.

Step 6: Run backward/forward sweep load flow solution to calculate total real power loss voltage deviation and it is assigned to be a fitness value (objective function) for the initialized populations.

Step 7: Evaluate the objectives for the initialized population and determine the best position among all populations based on minimum fitness value (real power loss and voltage deviation) for bus n.

Step 8: Perform violation check on constraints in which whether the position of the updated to satisfy the constraints or not. If any violation is present on the constraints, randomly assign the feasible solution to the violated; otherwise, go to the next step.

Step 9: Harmony search improvisation process on the decision variables.

For all $p \in P$

For all $d \in D$

Generate random number rand ()

If rand () <HMCR

Select a solution x_i from the existing population

If rand () < PAR

$$x_i^{new} = x_i + rand() * bw \tag{3.67}$$

End if

Else

x_i^{new}Is randomly generated

End if, end for

End for

Evaluate objectives for the newly updated population P^{new}

Step 10: Environmental selection (P') to obtain a well-approximated and well-distributed archive set is implemented by picking out the "best" solutions from the previous population and the newly created population /detailed procedure referred in [70]/.

Step 11: If the number of iteration exceeds the maximum iteration (i exceed imax), then stop and output the optimal location and size of DG otherwise go to step 2 to set i = i + 1, and repeat the steps 4 to 10.

Step 12: If the bus count reaches the maximum limit (total number of the bus), go to Step 7 or else increase the counter by one and go to Step 5.

Step 13: Print out the solution. The optimal location and size of DG, and the related fitness value representing the minimum total real power loss and voltage deviation.

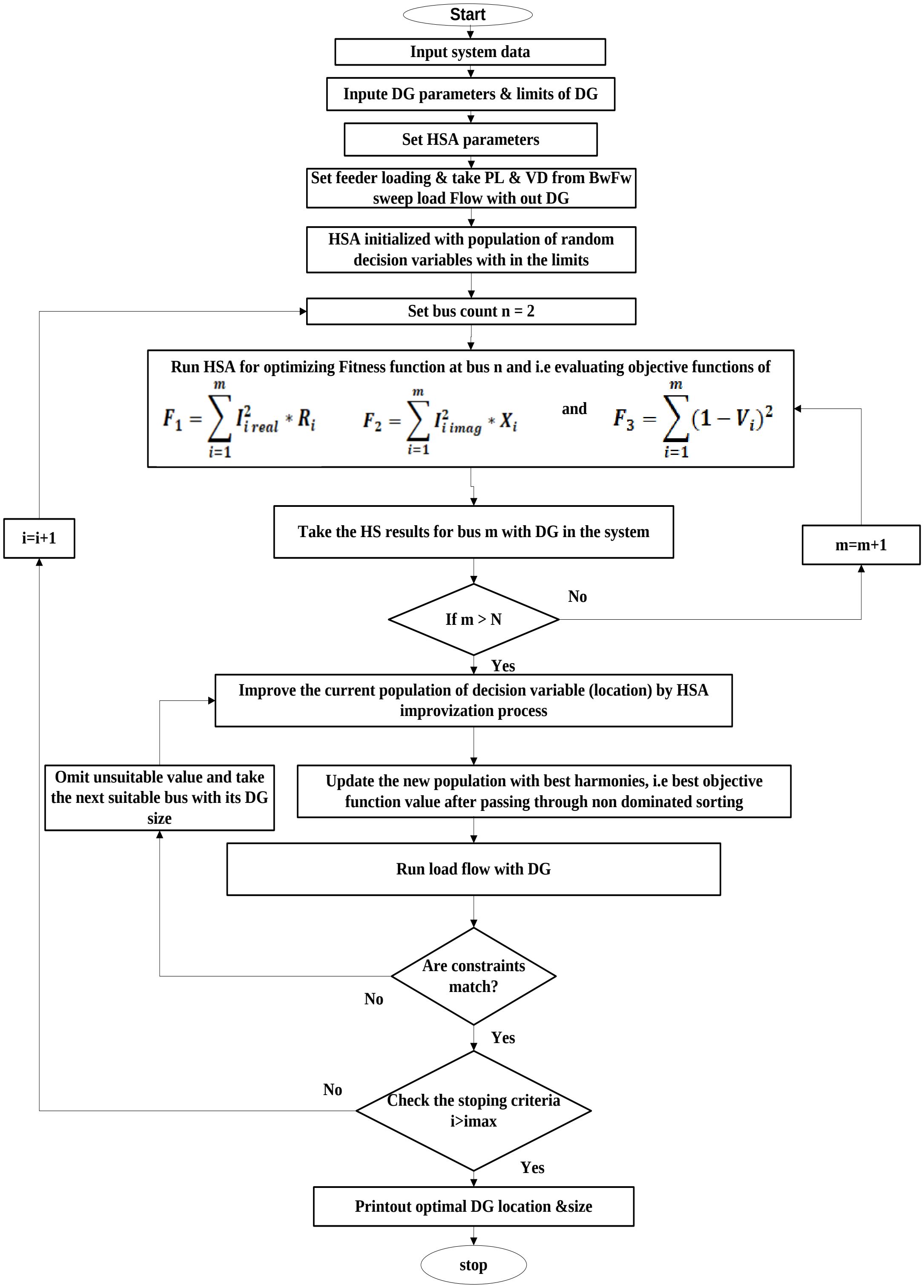

Figure 3.4: GrMHSA algorithm for optimal DG sizing and placement.

3.11. Electrical Load Demand Forecasting and Analysis of Debre Markos Distribution Network

3.11.1. Overview of Study Area

Debre Markos (D/M) town is located in northwestern Ethiopia, in Amhara National regional state, East Gojjam Zone, at a distance of 300 km from Addis Ababa and 265 km from Bahir Dar the regional capital. Its geographical coordinate is 10^{0}21'N latitude and 37^{0}43'E longitude. The total area of D/M city is 6460 hectare. Based on D/M city administration mayor office, the population is about 49,297 in 2002, 107433 persons in 2017/18 and an estimated the population of 262,497 in 2027/28. The population density at the study year, 2017/18, is 1663 people per square kilometer (from Wikipedia, the free encyclopedia) [71], [72].

This Pilot area consists of two feeders which are D/M feeder 3 and D/M feeder 4 and they are projected from D/M substation from a 63 MVA three winding transformer. But there are two additional feeders with 15 KV; Amanuel Feeder and Lumame feeder which is also taken from this transformer that feeds the towns Amanuel and Lumame respectively and there is another line with 66 KV feeding Finote Selam town which is projected from D/M substation from the same 63 MVA three winding transformer.

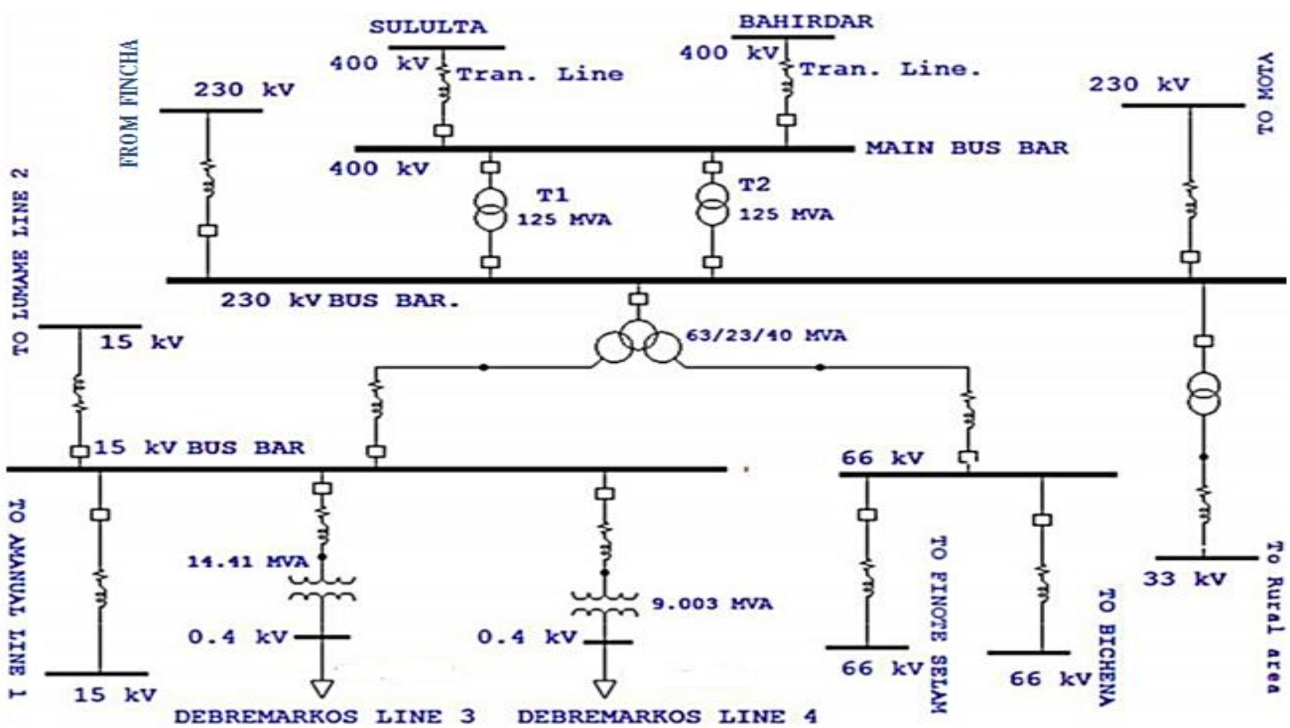

Figure 3.5: Overview of D/M Distribution Substation

For load flow analysis in this thesis work, the 15kV bus bar shown in Figure 3.5 is used as infinite bus ($1\angle 0^{o}$ pu). Therefore, other loads beyond the 15kV buses are considered to have no effect on the voltage deviation and power loss of feeder 3 and 4.

3.11.2. Existing Debre Markos Distribution Network

The medium voltage networks in D/M city are under responsible for the operation, maintaining, management of D/M Power utility department and D/M substation and mainly operating at 15 KV. All of the medium voltage networks in D/M city are overhead line type by 3 phases 3 wires. The medium voltage networks in the pilot area are supplied energy from 230/66/15kV three winding power transformer at D/M substation through 2 feeders. The system data of the study distribution network is described in table 3.1 and the peak load on each feeder recorded from 2013/14 to 2017/18at D/M distribution system are tabulated in table 3.2.

Table 3.1: Existing network description of the study area (D/M Distribution network)

n/o	Substation name	Feeders name/transformer	Description	Voltage level
1	D/M	63 MVA Tr	Supplies all 15 KV feeders and 66 KV outgoing line to Finote Selam.	230KV
2	D/M	Amanuel	Outgoing feeder, which supplies Amanuel town that is about 37 km far from D/M substation.	15KV
3	D/M	Lumame	Outgoing feeder, which supplies Lumame town that is about 37 km far from D/M substation.	15 KV
4	D/M	Debre Markos 3	Outgoing feeder, which supplies larger part of D/M city and the town Rebugebeya that is about 27 km far from D/M substation.	15KV
5	D/M	DebreMarkos 4	Outgoing feeder, which supplies smaller part of D/M city.	15 KV
6	D/M	Finote Selam	Outgoing feeder, which Finote Selam city.	66KV

Table 3.2: The loading condition of the 15 KV feeders from 2013/14 to 2017/18

Feeder Name	Year	Yearly peak Power demand(MW)	Voltage level (KV)	Current(A)	Total number of. transformer	Length (KM)	Total transformer capacity(KVA)
D/M feeder 3	2013/14	2.39	15	106.88	106	63.1601	23260
	2014/15	2.69	15	120.43			
	2015/16	3.1	15	138.42			
	2016/17	3.31	15	165.3			
	2017/18	4.14	15	188.2			
D/M feeder 4	2013/14	1.77	15	79	54	20.1127	13880
	2014/15	2.02	15	90.22			
	2015/16	2.3	15	102.92			
	2016/17	2.2	15	120			
	2017/18	2.73	15	124.9			
Amanuel feeder	2013/14	2.52	15	112.71	No details	No details	No details
	2014/15	2.77	15	123.89			
	2015/16	3.02	15	135.33			
	2016/17	2.2	15	130.7			
	2017/18	3.05	15	140.5			
Lumame feeder	2013/14	2.58	15	115.42	No details	No details	No details
	2014/15	2.83	15	126.78			
	2015/16	2.32	15	103.58			
	2016/17	2.47	15	113.78			
	2017/18	2.99	15	136.9			

Source data: Debre Markos distribution station Power Department

3.11.2.1. Transformer Loss Analysis

According to the specification of the transformer in D/M radial distribution network system, transformer loss analysis can be divided into two main components:

- ✓ No-load losses (iron loss) and
- ✓ On- load losses (copper loss).

The absorbed active power at rated frequency and reference temperature associated with a pair of windings.

Table 3.3: Existing network Transformers ‘loss and capacity analysis

Feeder	Transformer capacity (KVA)	Iron loss (KW)	Copper loss (KW)	No. of Transformer	Total iron loss	Total copper loss	Total loss(KW)	Total transformer capacity(KVA)
D/M feeder 3	25	0.08	0.6	8	0.64	4.04	4.67	200
	50	0.16	1.1	12	1.91	11.09	13.00	600
	100	0.26	1.8	30	7.75	45.40	53.15	3000
	200	0.62	3.7	24	14.78	74.66	89.45	4800
	315	0.8	5.3	18	14.30	80.21	94.52	5670
	630	1.5	6.8	13	19.37	74.33	93.69	8190
	800	1.9	10	1	1.89	8.41	10.29	800
	Total			106	60.64	298.15	358.79	23260
D/M feeder 4	25	0.08	0.6	4	0.32	2.02	2.34	100
	50	0.16	1.1	2	0.32	1.85	2.17	100
	100	0.26	1.8	14	3.62	21.23	24.86	1400
	200	0.62	3.7	11	6.79	34.29	41.09	2200
	315	0.8	5.3	14	11.15	62.52	73.68	4410
	630	1.5	6.8	9	13.44	51.57	65.01	5670
	total			54	35.64	173.51	209.15	13880

Source data: Debre Markos distribution station Power Department

3.11.2.2. Power Factor and Load Factor Analysis of D/M Distribution

The data are available for feeders’ D/M feeder 3 and D/M feeder 4 at the year 2016 /2017 and using it the power factor and load factor can be calculated for the distribution network as described below:

$$\text{Annual Load Factor (LF)} = \text{Total Annual Energy} /(\text{Annual Peak Load} * 8760)$$

$$\text{Monthly Load Factor (LF)} = \text{Total Monthly Energy} /(\text{Monthly Peak Load} * 730)$$

$$\text{Power Factor (Pf)} = \text{Active Energy} /\sqrt{(\text{Active Energy}^2 + \text{Reactive Energy}^2)}$$

Table 3.4: Load Factor and Power Factor of D/M Feeder 3

	Feeder 3 load factor and power factor at 2017/18									
Month	**peak load (A)**	**peak power (MW)**	**Voltage (KV)**	**KVA**	**Outage time (H)**	**Active energy (KWH)**	**KVAR**	**Reactive energy (KVARH)**	**power factor**	**load factor**
September	**168**	**3.9**	**15**	**4364.77**	**78**	**2503800**	**1959.9**	**1258254.49**	**0.89**	**0.88**
October	**179**	**4**	**15**	**4650.56**	**32**	**2752000**	**2372.27**	**1632123.22**	**0.86**	**0.94**
November	**193**	**4**	**15**	**5014.29**	**17**	**2812000**	**3023.75**	**2125697.52**	**0.8**	**0.96**
December	**182**	**4**	**15**	**4728.5**	**58**	**2648000**	**2521.65**	**1669329.84**	**0.85**	**0.91**
January	**189**	**4**	**15**	**4910.36**	**18**	**2808000**	**2848.1**	**1999366.37**	**0.81**	**0.96**
February	**193**	**4.2**	**15**	**5014.29**	**32**	**2889600**	**2739.17**	**1884551.81**	**0.84**	**0.94**
march	**210**	**4.6**	**15**	**5455.96**	**85**	**2921000**	**2933.85**	**1862997.37**	**0.84**	**0.87**
April	**199**	**4.4**	**15**	**5170.17**	**47**	**2961200**	**2714.9**	**1827126.83**	**0.85**	**0.92**
May	**185**	**4**	**15**	**4806.44**	**58**	**2648000**	**2664.93**	**1764186.53**	**0.83**	**0.91**
June	**188.2**	**4.14**	**15**	**4889.58**	**53**	**2761380**	**2601.61**	**1735275.46**	**0.85**	**0.91**
July	**188.2**	**4.14**	**15**	**4889.58**	**107**	**2537820**	**2601.61**	**1594788.39**	**0.85**	**0.84**
August	**184**	**4.3**	**15**	**4780.46**	**108**	**2631600**	**2088.73**	**1278303.78**	**0.9**	**0.84**
Average	**188.2**	**4.14**	**15**	**4889.58**	**57.75**	**2739533**	**2589.21**	**1719333.47**	**0.85**	**0.91**

Table 3.4 shows that the monthly power factor and load factor for D/M feeder 3 in the year 2017/18. Therefore; the monthly average power factor and load factor at 2017/18 for D/M feeder 3 are 0.85 and 0.91 respectively.

Table 3.5: Load Factor and Power Factor of D/M Feeder 4

	Feeder 4 load factor and power factor at 2017/18									
Month	**peak load (A)**	**peak power (MW)**	**Voltage (KV)**	**KVA**	**Outage time(H)**	**Active energy (KWH)**	**KVAR**	**Reactive energy (KVARH)**	**power factor**	**load factor**
September	**110**	**2.5**	**15**	**2857.88**	**79**	**1602500**	**1384.74**	**887617.2**	**0.87**	**0.88**
October	**114**	**2.5**	**15**	**2961.81**	**34**	**1715000**	**1588.18**	**1089488**	**0.84**	**0.94**
November	**119**	**2.4**	**15**	**3091.71**	**8**	**1708800**	**1949.02**	**1387702**	**0.78**	**0.98**
December	**129**	**2.8**	**15**	**3351.52**	**39**	**1906800**	**1841.92**	**1254349**	**0.84**	**0.93**
January	**125**	**2.7**	**15**	**3247.6**	**9**	**1919700**	**1804.68**	**1283128**	**0.83**	**0.97**
February	**162**	**3.5**	**15**	**4208.88**	**19**	**2453500**	**2337.67**	**1638707**	**0.83**	**0.96**
march	**121**	**2.7**	**15**	**3143.67**	**40**	**1836000**	**1610.18**	**1094921**	**0.86**	**0.93**
April	**125**	**2.8**	**15**	**3247.6**	**29**	**1934800**	**1645.26**	**1136874**	**0.86**	**0.95**
may	**125**	**2.7**	**15**	**3247.6**	**52**	**1803600**	**1804.68**	**1205527**	**0.83**	**0.92**
June	**124.9**	**2.73**	**15**	**3245**	**54**	**1818180**	**1754.17**	**1168276**	**0.84**	**0.91**
July	**124.9**	**2.73**	**15**	**3245**	**51**	**1826370**	**1754.17**	**1173539**	**0.84**	**0.92**
August	**119**	**2.7**	**15**	**3091.71**	**50**	**1809000**	**1506.21**	**1009162**	**0.87**	**0.92**
Average	**124.9**	**2.73**	**15**	**3245**	**38.67**	**1861188**	**1748.41**	**1194107**	**0.84**	**0.93**

Table 3.5 shows that the monthly power factor and load factor for D/M feeder 4 in the year 2017/18. Therefore; the monthly average power factor and load factor at 2017/18 for D/M feeder 4 are 0.84 and 0.93 respectively.

Table 3.6: Average Power Factor and a load factor of the System

year	power factor		Load factor	
	F3	F4	F3	F4
2016/17	0.85	0.84	0.91	0.93
Average	0.845		0.92	

At the end of 2017/18, there are 160 existing three-phase distribution transformers in both feeders which are installed in the D/M distribution network. The total capacity of these distribution transformers is 23, 260 KVA and 13,880 KVA for D/M feeder 3 and D/M feeder 4 respectively. The total capacity of all the transformers in both feeders is 37,140 KVA. The existing distribution network in D/M town is the radial distribution network in which the power is delivered from the source to the customer in a straightforward manner and it is cheap in design and protection but it is less reliable since it is subjected to disturbance easily. In these medium voltage 15 KV line feeders, all aluminum conductors are used and the DebreMarkos 15KV existing Distribution network feeders which are D/M Distribution feeder 3 and D/M Distribution feeder 4at 2017/18are shown in Figure 3.6, and Figure 3.7, respectively.

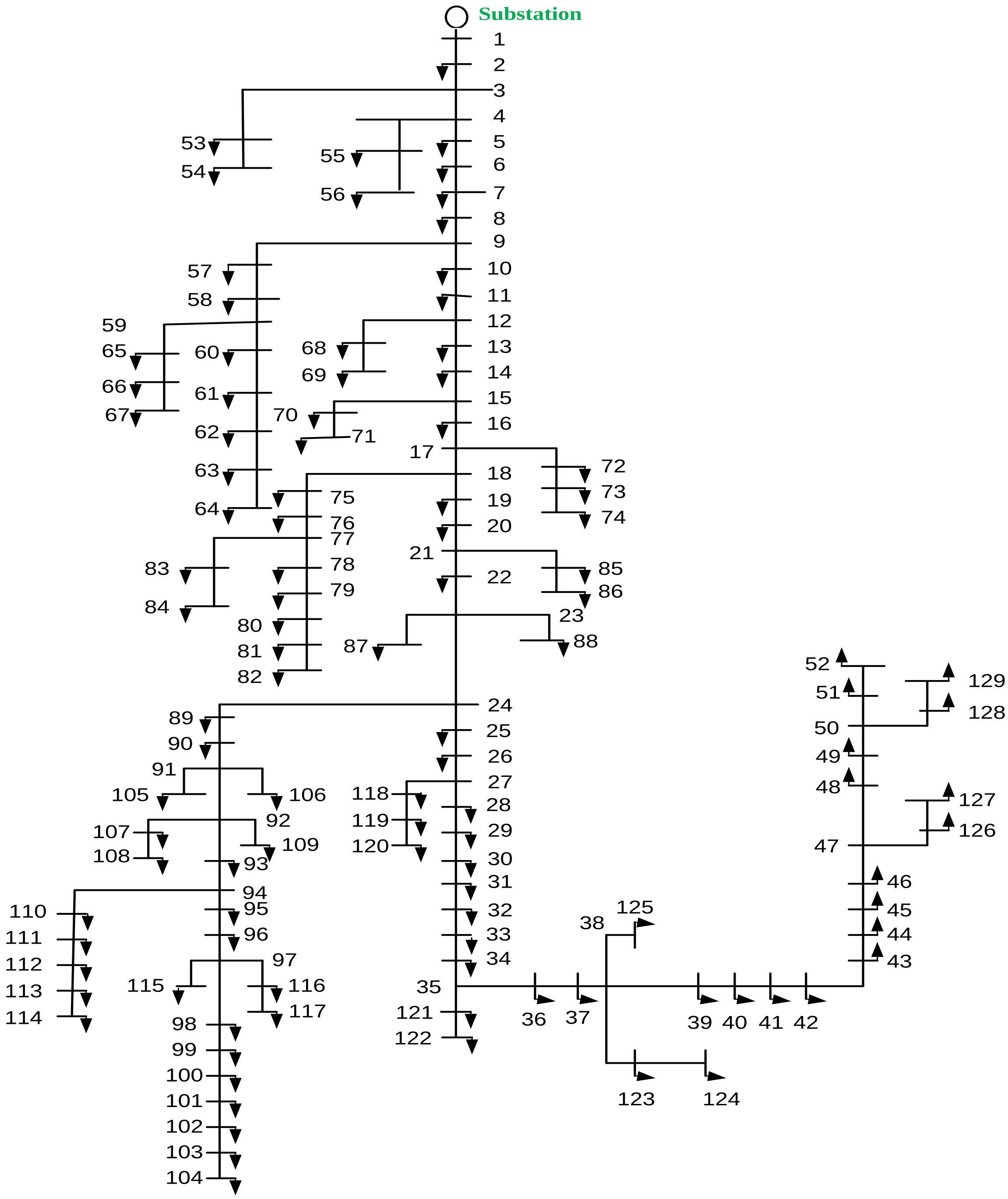

Figure 3.6: Single line diagram of D/M feeder 3

Figure 3.7 shows that the existing D/M feeder 3 with 129 buses which are connected in maximume load and covers maximume distrance around 63 kmwhich is stated in Table 3.1. Due to this reason the power losses and voltage devation became maximume.Therefore, separating and adding new feeders, upgrading and instulling DGs are performing on this feeder to solve seach problmes.

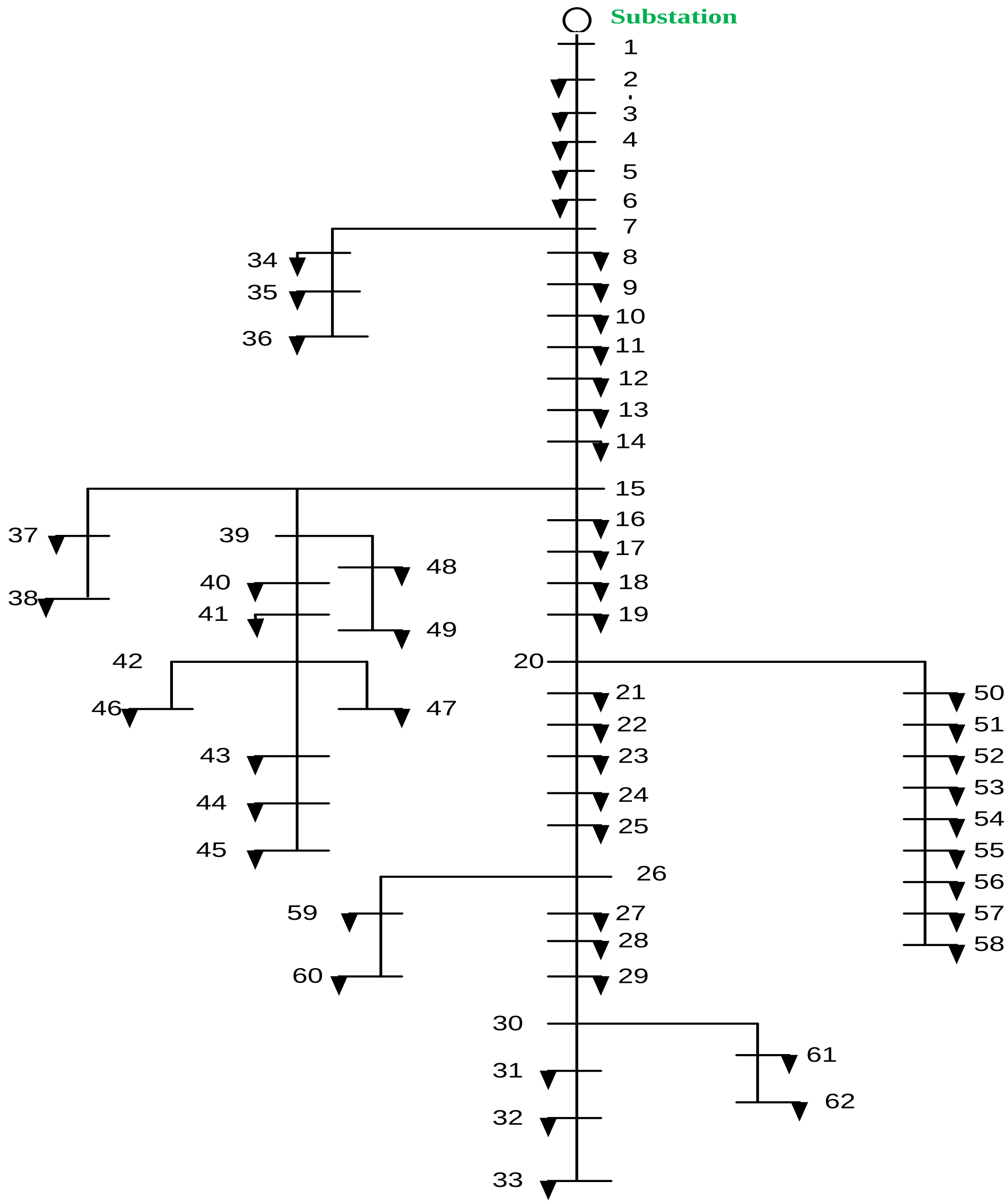

Figure 3.8: Single line diagram of D/M feeder 4

The above Figure 3.7 shows that the existing D/M feeder 4with 62buses which are connected in minimume load and covers minimume distrance around 20 kmcomparing with D/M feeder 3 which is stated in Table 3.2. Due to this reason the power losses and voltage devation in D/M feeder 4 is less than that of D/M feeder 3. Therefore, ruther than separating and adding new feeders, upgrading and instulling DGs are performing on this feeder .

The bus data and line data of existing MV network are enclosed in Appendix A and Electrical Parameters of Conductors and Distribution Transformer Capacities are shown in appendix D.

3.11.3. Electrical Demand Forecasting

Electric power load and electricity demand forecasting are the most important tasks of electrical engineering. Accurate electrical demand forecasting analysis is used to determine the conditions for sustainable energy supplement and this is necessary to satisfy power demands and meet consumer needs in electrical energy during the period future investigation and so as to design the expansion plan.

3.11.3.1. Evaluation of the Current Situation of D/M Distribution Network

The loading profile of the feeders for five successive years is shown in table 4.9 below. The data is taken from Debre Markos substation.

Table 3.7: Peak load on feeders in a period of (2013/14-2017/18)

Year	2013/14	2014/15	2015/16	2016/17	2017/18	Average
Peak load for D/M 3 (MW)	2.39	2.69	3.09	3.31	4.14	3.082
Peak load growth rate (%) of feeder 3	-	12.63	15.05	6.86	25.14	14.92
Peak load for D/M 4 (MW)	1.77	2.02	2.30	2.20	2.73	2.024
Peak load growth rate (%) of feeder 4	-	14.04	14.01	-4.31	24.09	11.96
Peak load for D/M Feeder 3 & 4 (MW)	4.16	4.71	5.39	5.51	6.87	5.106
Peak load growth rate (%) of D/M Feeder 3 &4	-	13.23	14.60	2.100	24.72	13.66

Table 3.9: shows the peak load demand from 2013/14 to 2017/18. Overall, there is increasing in the peak load power with growth rate increases from 12.63% in 2013/14 to 25.14% in 2017/18, 14.04% in 2013/14 to 24.09% in 2017/18 and 13.23% in 2013/14 to 24.72% in 2017/18 for D/M feeder 3, 4 and both feeders respectively. The peak load growth rate for feeder 4 in the year 2016/17 is -4.31%, but, the real cause for the decrease in the peak load is not yet known. Logically there is disconnection of some loads on this feeder that shows reduction of peak load on years of 2015/16 to 2016/17, which shows that negative growth rate.

3.11.3.2. Power Demand Forecast

In this study trend forecasting technique with least square approximation is used to forecast power demand for D/M distribution network in the period of 2017/18-2022/23-2027/28. Based on the collected data, the forecasting of power demand in all the feeders are carried on using the trend forecasting technique with least square approximation method.

The future load demand at the end of the year (n^{th}) can be calculated/forecasted base on the mathematical expression of the exponential trend method using equation (3.1).

Table 3.8: Feeder loading and Power demand forecasting for 2017/18-2027/28(in MW)

Year	Existing feeder Loading @ Feeder (MW)				Forecasted Feeder Loading @ Feeder (MW)			
	D/M 3	D/M 4	Amanu -el	Lum -ame	D/M 3	D/M3 growth rate (%)	D/M 4	D/M 4 growth rate (%)
2013/14	2.39	1.77	2.52	2.58	2.364		1.801	
2014/15	2.69	2.02	2.77	2.83	2.694	13.95840677	1.982	10.04164739
2015/16	3.1	2.3	3.02	2.32	3.070	13.94989174	2.180	10.00841043
2016/17	3.31	2.2	2.20	2.47	3.498	13.95222584	2.398	10.01529052
2017/18	4.14	2.73	3.05	2.99	3.986	13.93520724	2.639	10.04169562
2018/19					4.543	13.96613004	2.904	10.04104831
2019/20					5.176	13.94239589	3.195	10.0143472
2020/21					5.898	13.95910481	3.515	10.01564945
2021/22					6.721	13.94461712	3.866	10.0284495
2022/23					7.659	13.96156231	4.256	10.04093945

2023/24					8.728	13.94842781	4.683	10.02545526
2024/25					9.945	13.95015755	5.152	10.01957644
2025/26					11.333	13.95173454	5.673	10.02911679
2026/27					12.914	13.9569086	6.237	10.02646281
2027/28					14.716	13.95108731	6.862	10.02137894

Table 3.8 shows the forecasted peak load demand from 2013/14 to 2027/28. The demand growth rate is calculated for each year from 2013/14 to 2027/28 based on equation 3.2 and the values are depend on the values of the electrical demand (MW).Using the forecasting technique stated above and equation (3.1), the forecasted electrical load demand of the study area, the D/M distribution network, from the above table 3.8 is as follow:

For D/M Feeder 3

- ✓ For the year 2017/18, the load demand was 3.99MW
- ✓ For the year 2022/23, load demand will be 7.66 MW
- ✓ For the year 2027/28, load demand will be 14.72MW

For D/M Feeder 4

- ✓ For the year 2017/18, the load demand was 2.64MW
- ✓ For the year 2022/23, load demand will be 4.26MW
- ✓ For the year 2027/28, load demand will be 6.86MW

3.11.4. Summary of Demand Forecasting

The forecasting of electrical demand for the study area, D/M distribution network, shows that the electrical demand grows dramatically. The electrical load demand at 2027/28 is about 3.55 times and 2.51 times of the electrical demand at 2017/18 for D/M feeder 3 and D/M feeder 4 respectively.

Therefore; proper expansion planning for the distribution network is fundamental to satisfy the large growth of electrical demand in the study area to improve the power system profile and to avoid the overloaded components in the distribution network.

The dramatically increment of the electrical demand can be shown in figure 3.3 below.

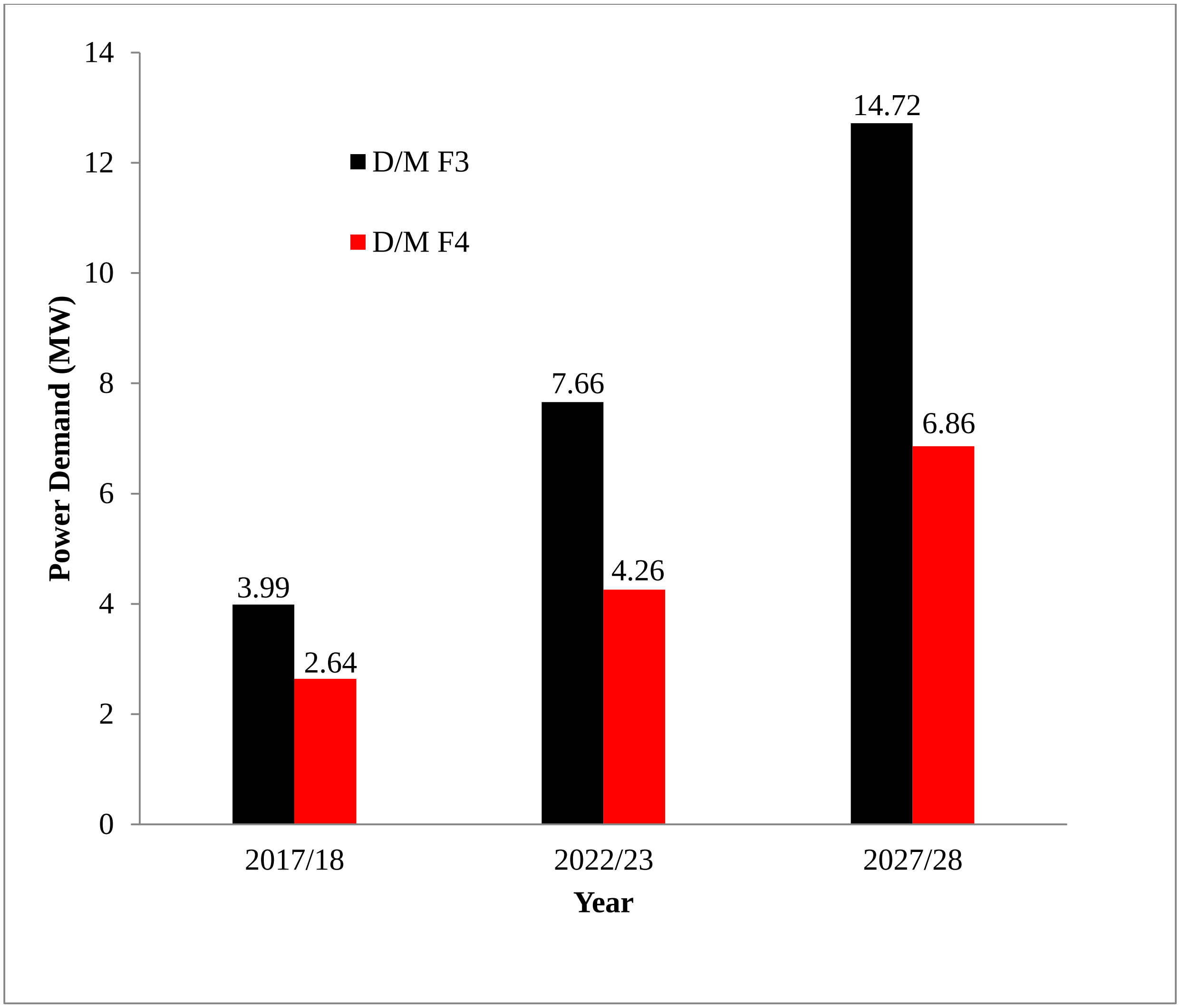

Figure 3.9: Power Demand of D/M feeder 3 and 4 from 2016/17-2026/27

3.12. Resource Assessment

The distributed generation resources are performed/worked in different technologies. Among those resources, the selection of a specific DG technology to a certain area depends on the availability of resources, suitability to the environment, and the cost of DG technology. Different geographical areas have different resources, both renewable and non-renewables.

For instance, the solar and wind energy availability resources are varied due to the difference in solar radiation and wind speed of different areas respectively.

3.12.1. Solar Energy Resource in Ethiopia

Ethiopia located very close to the equator between 3^0 and 15^0 N, receives abundant solar energy potential which can be harnessed and used in the form of both thermal and electrical energy. The average solar radiation is around 5.2 kWh/m^2, which is more or less uniform [73], [74], [75], 76]. The value varies seasonally from a minimum of 4.55kWh/m^2 in July to a maximum of 5.55kWh/m^2 in February and March. With location, the radiation varies more widely between 4.25 kWh/m^2 in extreme western low lands (in the areas of Itang in the Gambella regional state) and 6.25 kWh/m^2 in the northern part of the country (the areas around Adigrat in the Tigray regional state) [74].

Solar Energy Assessment in D/M: There is a sunshine duration data recorded at the nearby D/M distribution station. By using the following equations are stated below with definitions.

Solar declination angle (δ) is the angle between the earth's equatorial plane and the earth-sun line. Solar hour angles have a clear relationship between these angles is described below [76].

$$\delta = 23.45 \sin\left[360 * \left(\frac{248 + n_d}{365}\right)\right] \tag{3.68}$$

Where:

δ: solar declination angle (^{0})

$n_{\,d}$: Day number of the year starting at January 1^{st} as 1

The solar hour angles at sunrise and sunset are very useful quantities to know. Numerically these two values have the same value however the sunrise angle is negative and the sunset angle is positive. Both can be calculated from:

$$\omega_s = cos^{-1}(-tan\varphi tan\delta) \tag{3.69}$$

Where:

δ: Solar declination angle (^{0})

φ: Latitude of the location (10.25^0)

By integrating the solar constant (extraterrestrial irradiance) over the day length gives us the daily solar radiation on the horizontal surface.

$$H_0 = \frac{24 * 360 * G_{SC}}{\pi} * \left[cos\varphi cos\delta sin\omega_s + \frac{\pi\omega_s}{180} sin\varphi sin\delta\right] \tag{3.70}$$

Where:

n_d : Day number starting from January 1^{st} as 1

G_{SC} : 1367 W/m2, the solar constant

φ: Latitude of the location (10.25^0)

δ: Declination angle (^{0})

ω_s: Sunset hour angle (^{0})

The sunshine duration data from the nearby station is used to estimate the monthly average solar radiation using the following angstrom type equation [77], [78].

$$H = H_0 \left(a + b\frac{n}{N}\right) \tag{3.71}$$

Where

H: Monthly average daily radiation on a horizontal surface (MJ/m^2)

H_0: Monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m^2)

N: The maximum possible daily hours of bright sunshine given by equation

n: Monthly average daily number of hours of bright sunshine

a &b: are regression coefficients having average value of a =0.33 and b=0.43 [77].

The day length, N, is the maximum possible daily sunshine hour is given by equation

$$N = \frac{2}{15}\omega_s \tag{3.72}$$

The solar radiation of the study area is estimated as shown in Table 3.9 by using the equations which are listed in equation 3.68 to 3.72. The last two columns of Table 3.9 show solar radiation data obtained from NASA and PVGIS in (kWh/m^2/day).

Table 3.9: Monthly solar radiation around the study area

Month	Date	n_d	δ(°)	ω_s(°)	N (hours)	n	H_0 (kWh/m^2/d)	H (kWh/m^2/d)	NASA	PVGIS
Jan.	**15**	**15**	**-21.3**	**86.01**	**11.47**	**9.90**	**8.82**	**6.1543**	**6.15**	**6.93**
Feb.	**14**	**45**	**-13.7**	**87.53**	**11.67**	**10.17**	**9.53**	**6.6494**	**6.49**	**7.22**
Mar.	**15**	**74**	**-2.89**	**89.52**	**11.94**	**8.40**	**10.22**	**6.5822**	**6.57**	**7.15**
Apr.	**15**	**105**	**9.34**	**91.75**	**12.23**	**8.00**	**10.54**	**6.4651**	**6.48**	**5.99**
May	**15**	**135**	**18.74**	**93.56**	**12.47**	**8.10**	**10.45**	**6.3745**	**6.35**	**5.48**
June	**15**	**166**	**23.30**	**94.51**	**12.60**	**7.30**	**10.29**	**5.9803**	**5.98**	**4.83**
July	**15**	**196**	**21.56**	**94.14**	**12.55**	**5.80**	**10.32**	**5.4493**	**5.24**	**4.16**
Aug.	**15**	**227**	**13.87**	**92.60**	**12.35**	**4.90**	**10.44**	**5.2372**	**5.26**	**4.2**
Sep.	**15**	**258**	**2.33**	**90.47**	**12.06**	**7.90**	**10.30**	**6.3260**	**5.87**	**5.28**
Oct.	**15**	**288**	**-9.49**	**88.31**	**11.78**	**9.10**	**9.74**	**6.4033**	**6.38**	**6.49**
Nov.	**15**	**319**	**-19.1**	**86.46**	**11.53**	**9.50**	**8.99**	**6.1350**	**6.11**	**6.67**
Dec.	**15**	**349**	**-23.3**	**85.58**	**11.41**	**9.70**	**8.58**	**5.8386**	**6**	**6.86**
Average								**6.1322**	**6.0833**	**5.9583**
The Average of calculated, NASA and PVGIS solar radiation								**6.05793 (kWh/m^2/d)**		

3.12.2. Wind Resource in Ethiopia

Ethiopia has an average speed of 3.5 – 5.5 m/s wind energy resources are available, for flowing 6 hours/day. The two basic zones with homogenous periodicity divided by the rift valley and the first one of these cover most of the highland plateaus. There are two known wind speed maximal occurring, between March and May and between September and November respectively in this zone. In the second zone, covering most of the Ogaden and the eastern lowlands, average wind velocity becomes maximum values between May and August [73], [77], [79], [80]. Presently, two projects are being constructed, one Ashegoda wind park (near Mekele) of 120MW and the other Adama Wind Park of nearly 40MW.

Wind Potential Assessment in D/M: Annual average wind speed at a nearby station (D/M) is calculated as 3.5 m/s based on anemometer data collected at 10 m height [77]. NASA has estimated the annual average wind speed of the location to be 3.1 m/s at the same 10 m height [79]. As the author discussed in [77] NMA taken the measurement from 10m among the selected heights.

In general, 10 m height is the one where the most standard measurements are taken. Furthermore, the geographical layout of the study area is different from the nearby stations where the measurements are taken. It is believed that the roughness nature of the upper Blue Nile gorge is a good resource of wind. Hence, the minimum of the 3.5m/sand the 3.1m/s mentioned above are considered for this study and that is data obtained from NASA. This data can be extrapolated to the selected wind turbine height using the equation below [77], [78].

$$V(Z) * \ln\left(\frac{Z_r}{Z_0}\right) = V(Zr) * \ln\left(\frac{Z}{Z_0}\right) \tag{7.73}$$

Where,

Z_r : Reference height (m)

Z: Height where wind speed is to be determined (m)

Z_0 : Measure of surface roughness (0.1 to 0.25 for crop land)

$V(Z)$: Wind speed at height of Z m (m/s)

$V(Z_r)$: Wind speed at the reference height (m/s)

The value of Z_0 is taken as 0.1; Weibull parameters are estimated to be K=2 and c=3.9 m/s [77]. Table 3.10 summarizes the wind speed at 10 m and 70 m heights.

Table 3.10: Monthly average wind speed (m/s) at the site from NASA

	Ja.	Fe.	Ma	Ap	Ma	Ju	Jul	Au	Se	Oc	Nov	Dec	Avr.
NASA @10m	3.5	3.4	3.3	3.1	3.1	3.4	3.5	2.9	2.6	2.6	2.9	3.3	3.1
Calc.@70m	5.0	4.8	4.7	4.4	4.4	4.8	5.0	4.1	3.7	3.7	4.1	4.7	4.5

According to the assessment in the above table, Table 3.10, the wind speed is not enough good to generate power in this area due to this reason the hybrid system is better. Therefore, based on [81], [82] and [83], hybrid wind and photovoltaic is appropriate than the individual one in this area since the hybrid one has complementary result profiles, it suppresses rapid change in its output power of a single source and it provides good and constant supply to the rising load.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Result Assessment of the Existing Power Distribution System up to 2027/28

The system base voltage (V_{base}) and the system base complex power (S_{base}) are 15 KV and 100 MVA respectively and taking the system base load as constant:

$$Z_{base} = \frac{V_{base}^2}{S_{base}} = \frac{(15000)^2}{100000000} = 2.25\Omega$$

$$I_{base} = \frac{S_{base}}{V_{base}} = \frac{100000000}{15000} = 6666.6 \text{ A}$$

The total peak demand taken from the existing networks and the results of load forecasting which is stated above in 2017/18, 2022/23 and 2027/28 will be 82.44 MW, 142.98 MW, and 258.93 MW respectively. For this study, the assessment and expansion planning took account of the existing and the future at 2027/28.

Use Backward/forward Matlab code to analyze load flow on D/M distribution networks in cases of peak demand in 2017/18 and peak forecasted demands in 2022/23 and 2027/28and determines the total voltage deviation, bus voltage, current and power losses in each branch. Analysis results are shown in the table from 4.1 to 4.5.

Table 4.1: Result analysis of the existing network in case of peak load in 2017/18, 2022/23 &2027/28

Feeder Name	Total Curent (A)	Demand (MW)	line data	Demand @	Total Power loss (kw)	Total Reactive Power loss (kvar)	Total Voltage deviation (p.u)	overloaded lines	overloaded Trs
	@2017/18								
D/M feeder 3	188.2	3.99	2017/18	2017/18	519.3944	518.3686	15.6075	Yes	Yes
			2017/18	2022/23	2040.4	2033.9	31.0227	Yes	Yes

			2017/18	2027/28	7434.9	7391.8	58.6952	Yes	Yes
D/M feeder 4	124.9	2.64	2017/18	2017/18	102.5987	88.3432	3.0067	No	Yes
			2017/18	2022/23	246.4414	212.0153	4.6603	Yes	Yes
			2017/18	2027/28	470.7058	404.5524	6.4412	Yes	Yes

From the results of load flow analysis in the above table, the existing distribution network cannot meet the future forecasted demand as well as the existing demand. That is technical problems which are transformer and feeder conductor overloading and large powerloss and voltage deviation are observed in existing demand and forecasted demand at 2022/23 and 2027/28.

Feeder conductors and distribution transformers are overloaded for the forecasted loads at 2022/23 and 2027/28 in both feeders and for existing distribution network data except feeder 4. For D/M feeder 3, the power loss and voltage deviation for existing @ 2017/18 data are 519kW and 16p.u and it is also increased to 7430 kW and 59p.u in 2027/28 respectively.

For D/M feeder 4, the power loss and voltage deviation for existing @ 2017/18 data are 102 kW and 3p.u and it is also increased to 471kw and 6p.u in 2027/28 respectively.

So, if the distribution network is not planned properly, the network will not meet the existing as well as the forecasted future demand with reasonable power system profile. Therefore; proper expansion planning must be carried on as described below.

4.2. Distribution Network Expansion Planning

Considering the demand of forecasted peak load during the target year, 2027/28, and based on geographical location, feeders' capability and to improve power system profile, expansion planning is fundamental. In this study, this expansion planning consists of separating and adding new feeders, upgrading the separated as well as existing feeder lines and transformers and adding DG in the network. These expansion planning techniques are described below.

4.2.1. Separating Existing Feeders and Adding New Additional Feeder

Since D/M feeder 3 covers a large area of the city and feeds loads at a long distance which is about 27 KM from the source, it has high power loss and voltage deviation for existing and forecasted load demand. So, this feeder is separated into two and the new feeder line is added. These separated feeders are F3A and F3B.

Table 4.2: Newly Installed Conductor Line for Separate Feeder2017/18

newly installed conductors		
New conductor for separated feeder	type	Length(km)
F3B	AAC-95	12.1042 km from source to node 24 of F3

Details are shown in Table A.4: of Appendix-A.

Table 4.3: Result Analysis of the Separated Network in Case of Peak Load 2017/18, 2022/23 and 2027/28

Feeder Name	line data	Demand @	Total Power loss(kw)	Total Reactive Power loss(kvar)	Total Voltage deviation(p.u)	overloaded lines	overloaded Trs
D/M feeder 3 F3A	2017/18	2017/18	55.8534	57.6111	2.0526	No	No
	2017/18	2022/23	170.3977	175.7524	3.5880	Yes	Yes
	2017/18	2027/28	376.6690	388.3507	5.5438	Yes	Yes
D/M feeder 3 F3B	2017/18	2017/18	93.1044	96.6836	4.0442	No	Yes
	2017/18	2022/23	296.3975	307.7846	7.2267	Yes	Yes
	2017/18	2027/28	665.1067	690.6386	10.8442	Yes	Yes

Table 4.3 shows that when the feeders are separated, even the voltage drop and power loss are improved as shown in the above table, the power loss and voltage deviation still have maximum numerical values and there are overloading conditions on transformers and feeder lines. So, the separated feeders should be upgraded.

4.2.2. Upgrade and Add New Conductor Lines and Distribution Substations (Transformers)

Based on the amount of current through the conductors resulted from the load flow, the appropriate conductor's size is selected.

Table 4.4: Upgraded conductors of separated feeders in Case of demand of 2027/28

feeder name	Existing conductor type	length (KM)	upgraded conductor type
F3A	AAC-95	6.867	AAC-200
		1.802	AAC-150
F3B	AAC-95	12.1042	AAC-200
F4	AAC-95	6.691	AAC-200
	AAC-95	0.71	AAC-150
	AAC-50	2.25	AAC-150

Details of upgraded separated feeders and upgraded feeder conductors are shown in Table C.1 to Table C.3 in Appendix C and the single line diagrams of the expanded separated feeders, F3A and F3B, and the expanded feeder, F4 with their DG locations are shown in Appendix E.

In this stage, most of the transformers are overloaded and they have to be replaced by with new ones, in which their capacities are computed that they will operate with a full load in 2027/28. Based on the forecasted load in 2027/28, the new capacity of distribution substations (transformers) can be selected as stated in section 3.7.2, using equation (3.45).

Details of the upgraded transformers for the target year 2027/28 in each expanded feeders and upgraded feeder are enclosed in Table B.1 to Table B.3 in Appendix B.

Table 4.5: Load Flow Results for Upgraded separated and upgraded existing Network in Case of Peak Load in 2027/28

Feeder	line data	Demand @	Total Power loss(kw)	Total reactive Power loss(kw)	Total Voltage deviation(p.u)	overloaded lines	overloaded Trs
Upgraded separated Feeder D/M F3	Upgraded F3A	2027/28	206.6084	303.3365	3.6971	No	Yes
	Upgraded F3B	2027/28	334.5744	508.9150	6.9729	No	Yes
	Total	2027/28	541.1828	812.2515	10.67		
Upgraded existing Feeder D/M F4	Upgraded F4	2027/28	215.8598	300.3384	3.7972	No	Yes

From the result of load flow analysis which is tabulated in table 4.5, the power loss and voltage deviation are reduced dramatically but the system faces the overloading condition for the target year, 2027/28. So, DG should be incorporated in upgraded separated feeders for the case D/M feeder 3 and upgraded existing feeder for the case of D/M feeder 4 with the appropriate DG capacity limit for the target year, 2027/28, for further improvement in power loss and voltage deviation.

4.2.3. Incorporating DG in Upgraded Separated and Upgraded Existing Network Feeders

GrMHSAtechnique is implemented on the three expanded distribution network feeders for optimal place and size of the distributed generation (DG) which are used to improve system voltage profile and power loss minimization. Figure 3.6 and 3.7 represents the existing D/M feeder 3 with 129 buses andDebre Markos feeder 4 with 62 buses respectively. The necessary codes are developed and simulated using MATLAB release 2016a with Toshiba i3 processor equipped with 8 GB RAM to solve the DG sizing and location based on Grid-based multi-objective Harmony Search algorithm. To find the optimal DG location and size, the objective function (explained in Section 3.9.1) is computed by satisfying the constraints for each expanded feeders using GrMHSA based on the set parameters. Table 4.10 registers the optimum location, optimum size, and real power losses before and after DG placement in the existing two feeders, D/M feeder 3 and Debre Markos feeder 4.

In this case, the upgraded separated and upgraded existing network Feeders expanded distribution network feeders to place and size the distribution generation (DG) which can be performed by using GrMHSA optimization technique.

Table 4.6 : Result Analysis of upgraded separated and upgraded existing feeders with DG in Case of Peak Load in 2027/28.

Feeder	line data	Demand @	Total Power loss(kw)	Total Reactive Power loss(kvar)	Total Voltage deviation(p.u)	overloaded lines	overloaded Trs
Upgraded Separated Feeder	Upgraded F3A	2027/28	206.6084	303.3365	3.6971	No	Yes
	Upgraded F3B	2027/28	334.5744	508.9150	6.9729	No	Yes

Upgraded separated Feeder with DG	Upgraded F3Awith DG at bus 15 (1.8028MVA)	2027/28	21.382	20.878	0.176	No	No
	Upgraded F3B with DG at bus 18 (1.9997 MVA)	2027/28	74.016	104.101	0.303	No	No

D/M feeder 4 is not separated since it covers small area and feeds minimum customers and as it is seen in table 4.1, even though the power loss, as well as the voltage deviation, is minimum, there are overloaded lines and distribution transformers and thus the network is upgraded before DG placement and then the proper DG size and location with acceptable DG capacity limit can be performed using GrMHSA optimization technique and the result is tabulated in table 4.10.

Table 4.7: Results Analysis of upgraded existing feeders and upgraded existing feeders with DG in Case of Peak Load in 2027/28

Feeder	line data	Demand @	Total Power loss(kw)	Total Reactive Power loss (kvar)	Total Voltage deviation(p.u)	overloaded lines	overloaded Trs
Upgraded D/M feeder 4	Upgraded @2027/28	2027/28	215.8598	300.3384	3.7972	No	Yes
Upgraded D/M F4 with DG at bus 22 (2.990MVA)	Upgraded @2027/28	2027/28	30.811	37.727	0.533	No	No

4.3. Overall Result Analysis After and Before DG is Placed

In this part, the whole analysis of the study can be tabulated as shown in Table 4.8 and Table 4.9 for D/M feeder 3 and D/M feeder 4 respectively.

Table 4.8: Comparison of Result Analysis for all cases of Feeder 3 In Case Of Peak Load in 2017/18, 2022/23 and 2027/28

case		Feeder 3					
	line data@	bus data@	Total Power loss(kw)	Total Reactive Power loss(kvar)	Total Voltage deviation (p.u)	overloaded lines	overloaded Trs
Existing /base	2017/18	2017/18	519.3944	518.3686	15.6075	Yes	Yes
	2017/18	2022/23	2040.4	2033.9	31.0227	Yes	Yes
	2017/18	2027/28	7434.9	7391.8	58.6952	Yes	Yes
Separate feeder	F3A 2017/18	2017/18	55.8534	57.6111	2.0526	No	Yes
	F3A 2017/18	2022/23	170.3977	175.7524	3.5880	Yes	Yes
	F3A 2017/18	2027/28	376.6690	388.3507	5.5438	Yes	Yes
	F3B 2017/18	2017/18	93.1044	96.6836	4.0442	No	Yes
	F3B 2017/18	2022/23	296.3975	307.7846	7.2267	Yes	Yes
	F3B 2017/18	2027/28	665.1067	690.6386	10.8442	Yes	Yes
	Total for 2027/28		1041.776	1078.9893	16.388		
Upgraded separated Feeder	Upgraded F3A	2027/28	206.6084	303.3365	3.6971	No	Yes
	Upgraded F3B	2027/28	334.5744	508.9150	6.9729	No	Yes
	Total		541.1828	812.2515	10.67		
Upgraded separated Feeder with DG	Upgraded F3A@bus	2027/28	21.382	20.878	0.176	No	No
	Upgraded F3B	2027/28	74.016	104.101	0.303	No	No
	Total		95.398	124.979	0.479		

As shown on table 4.8, performance comparison is made among the base case, and three other scenarios, namely a system with separated feeder, upgraded separated feeder and upgraded separated feeder with DG. According to the performance measurements of total active, reactive power loss and total voltage deviation, a system with upgraded separated feeder with DG results in lowest total active and reactive power losses and minimum total voltage deviation.

Table 4.9: Results Analysis for all cases of Feeder 4 In Case of Peak Load in 2017/18, 2022/23 and 2027/28

case		Feeder 4					
	line data@	bus data@	Total Power loss(kw)	Total reactive Power loss(kvar)	Total Voltage deviation (p.u)	Over loded lines	Over loaded Trs
existing/base	2017/18	2017/18	102.5987	88.3432	3.0067	No	Yes
	2017/18	2022/23	246.4414	212.0153	4.6603	Yes	Yes
	2017/18	2027/28	470.7058	404.5524	6.4412	Yes	Yes
Upgraded existing	Upgraded @2027/28	2027/28	215.8598	300.3384	3.7972	No	Yes
Upgraded existing with DG	Upgraded @2027/28	2027/28	30.811	37.727	0.533	No	No

As shown on table 4.9, performance comparison is made among the base case, and two other scenarios, namely a system with upgraded existing feeder and upgraded existing feeder with DG. According to the performance measurements of total active, reactive power loss and total voltage deviation, a system with upgraded existing feeder with DG results in lowest total active and reactive power losses and minimum total voltage deviation.

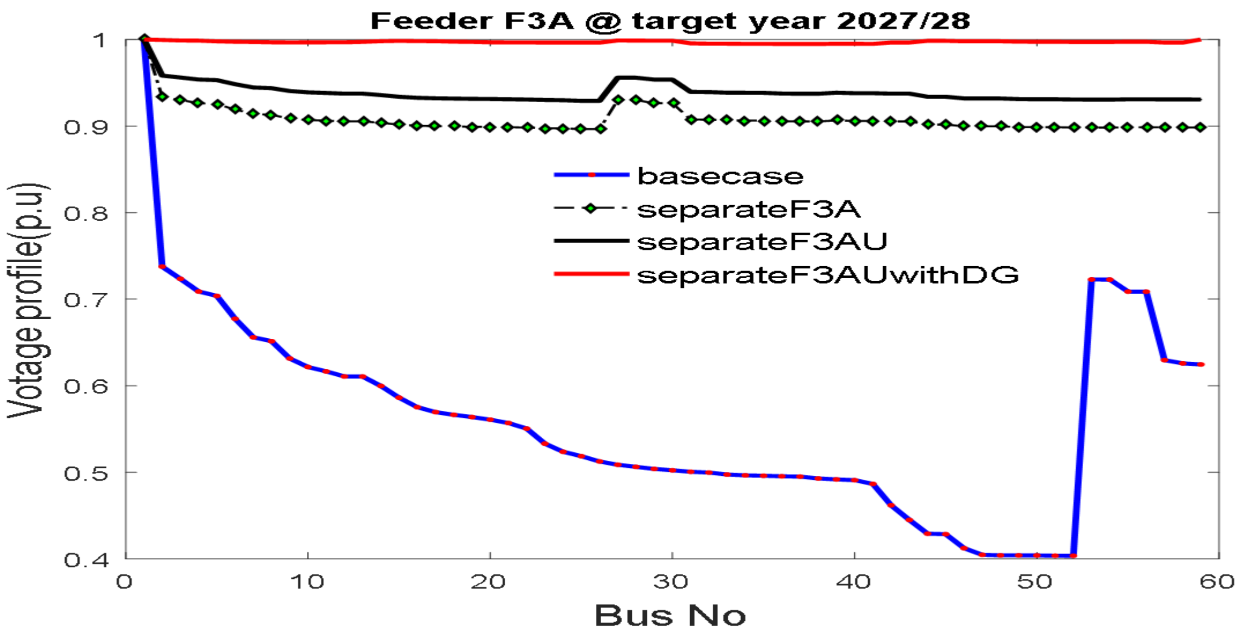

Figure 4.1: Voltage Profile of separated feeder F3A for different cases

Figure 4.1 shows the voltage profile for the base case, and other three other scenarios, namely a system with separated feeder, upgraded separated feeder and upgraded separated feeder with DG. A system with upgraded separated feeder with DG results the best voltage profile (which is shown in red line on the graph) among the other scenarios.

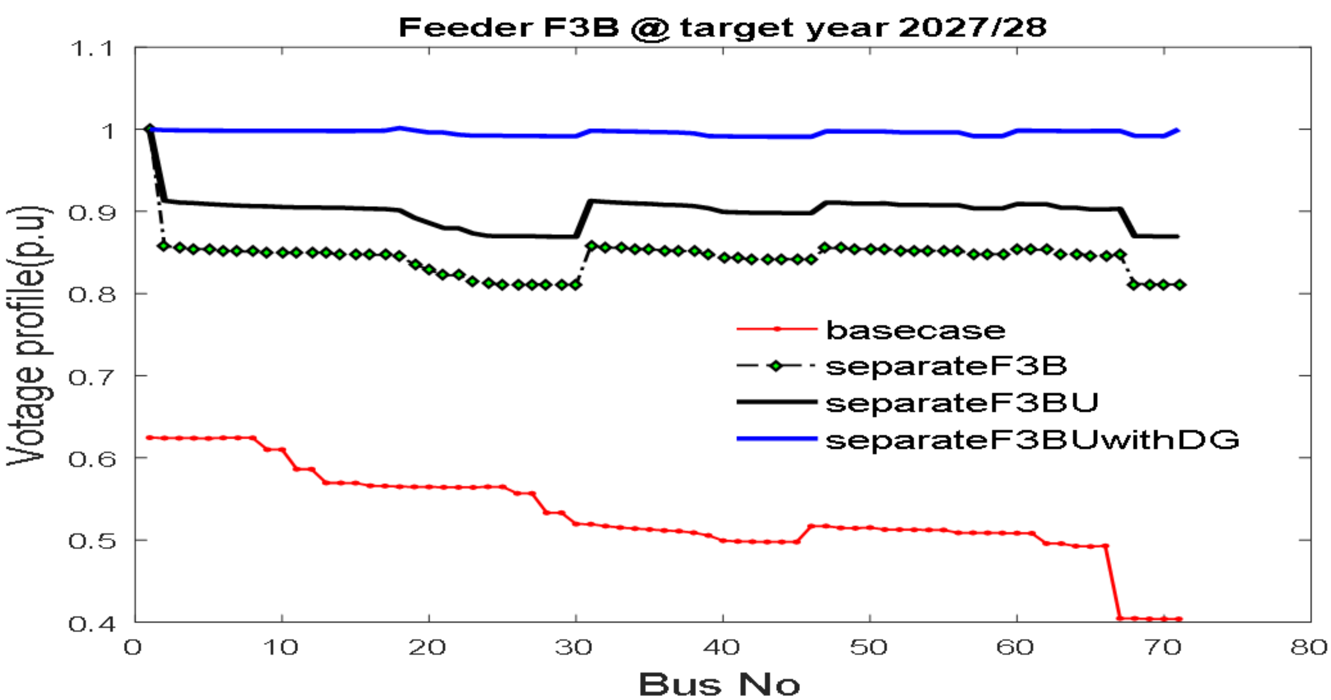

Figure 4.2: Voltage Profile of separated feeder F3B for different cases

Figure 4.2 shows the voltage profile for the base case, and other three other scenarios, namely a system with separated feeder, upgraded separated feeder and upgraded separated feeder with DG. A system with upgraded separated feeder with DG results the best voltage profile (which is shown in blue line on the graph) among the other scenarios.

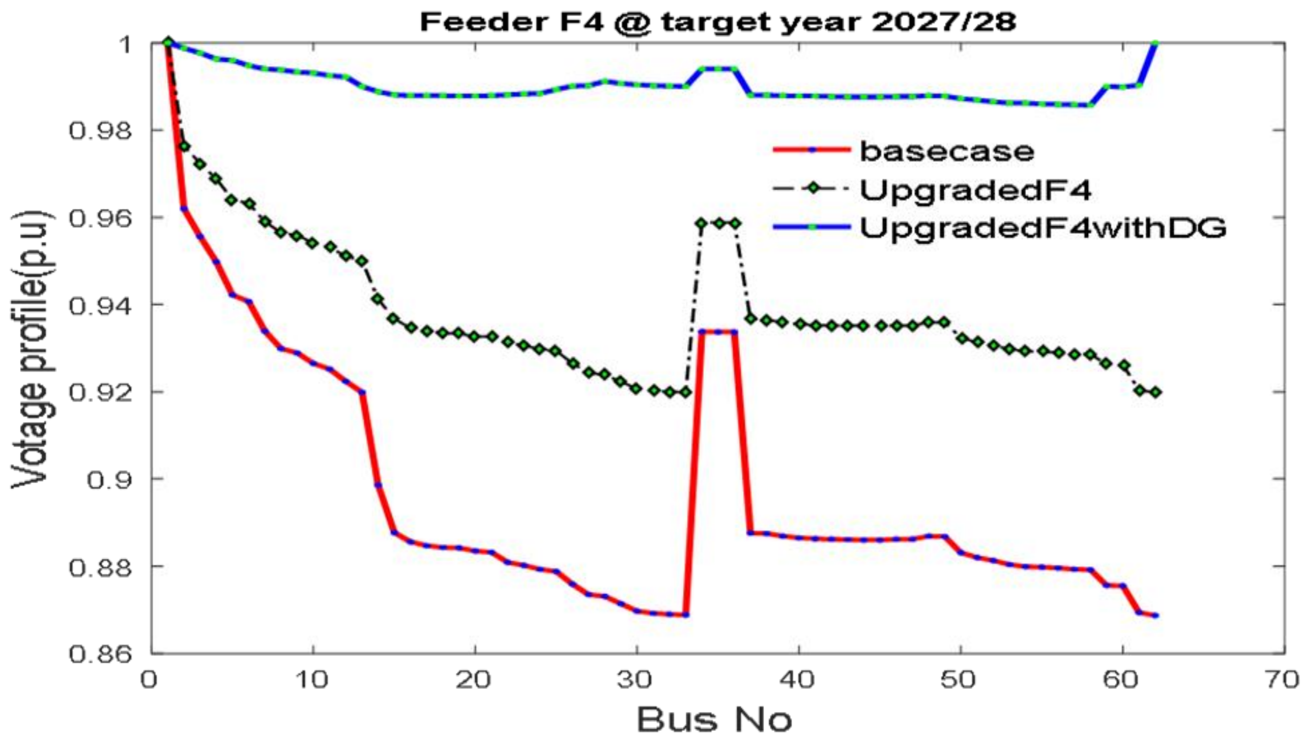

Figure 4.3: Voltage Profile of feeder F4 for different cases

Figure 4.3 shows the voltage profile for the base case, and other two scenarios, namely a system with separated feeder, upgraded separated feeder and upgraded separated feeder with DG. A system with upgraded separated feeder with DG results the best voltage profile (which is shown in blue with green strip line on the graph) among the other scenarios.

4.4. Performance Comparison of GrMHSA with HSA & MOPSO

HSA&MOPSO are selected for comparison since they are more popular due to their ability to obtain fast convergence and easy implementation as GrMHSA.

Table 4.10: Result comparison of GrMHSA, Weighted sum HSA and MOPSO on reduction in real & reactive power loss and voltage deviation with DG

Feeder Name	Optimization techniques	Optimal DG location	Optimal DG size (MVA)	Real Power loss (kW)	Reactive Power loss (kvar)	Voltage deviation (p.u)
F3AU	MOPSO	16	1.8271	23.780	23.019	0.198
	HS	17	2.000	21.858	21.334	0.185
	GrMHS	15	1.8028	21.382	20.878	0.176
F3BU	MOPSO	21	2.000	79.453	112.089	0.348
	HS	19	2.000	75.539	107.954	0.337
	GrMHS	18	1.9959	74.016	104.101	0.303
F4U	MOPSO	26	3.000	38.480	39.991	0.559
	HS	24	3.000	32.147	38.117	0.567
	GrMHS	28	2.990	30.811	37.727	0.533

As it is shown in table 4.10 above, the optimal placement and size of DG with a minimum value of active power loss, reactive power loss and voltage deviation which is tabulated in diffrente optimization techniques. The GrMHSA technique as selected an optimal size and location of DG with the lowest total real power loss, total reactive power loss and total voltage deviation and also the computational time is minimum as compared to HAS and MOPSO, where thus are using after the distribution network is expanded with incorporating the appropriate DG.

Table 4.11: Result comparison of GrMHSA, HSA & MOPSO on reduction in real & reactive power loss and voltage deviation with DG

Case	Total Real Power loss (kw)			Total Reactive Power loss (kvar)			Total Voltage deviation (p.u)		
	F3AU	F3BU	F4U	F3AU	F3BU	F4U	F3AU	F3BU	F4U
Without DG	206.68	334.57	215.86	303.34	508.92	300.34	3.69	6.97	3.79
WithDGby GrMHSA	21.38	74.02	30.81	20.88	104.10	37.73	0.176	0.30	0.53
Reduction (%)	89.66	77.87	85.73	93.12	79.54	87.44	95.23	95.70	86.02
WithDG by HSA	21.858	75.54	32.15	21.33	107.95	38.12	0.185	0.34	0.57
Reduction (%)	89.42	77.42	85.12	92.97	78.79	87.31	94.98	95.12	84.96
WithDG by MOPSO	23.78	79.45	38.48	23.02	112.09	39.99	0.198	0.35	0.56
Reduction (%)	88.50	76.25	82.17	92.41	77.97	86.69	94.62	94.98	85.22

As result in table 4.11, the total real power loss reduction, total reactive power loss reduction and total voltage deviation reduction are tabulated in different selected optimization techniques. These results are figured out in figure 4.4, figure 4.5 and figure 4.6 are shown for F3A, F3B, and F4 respectively.

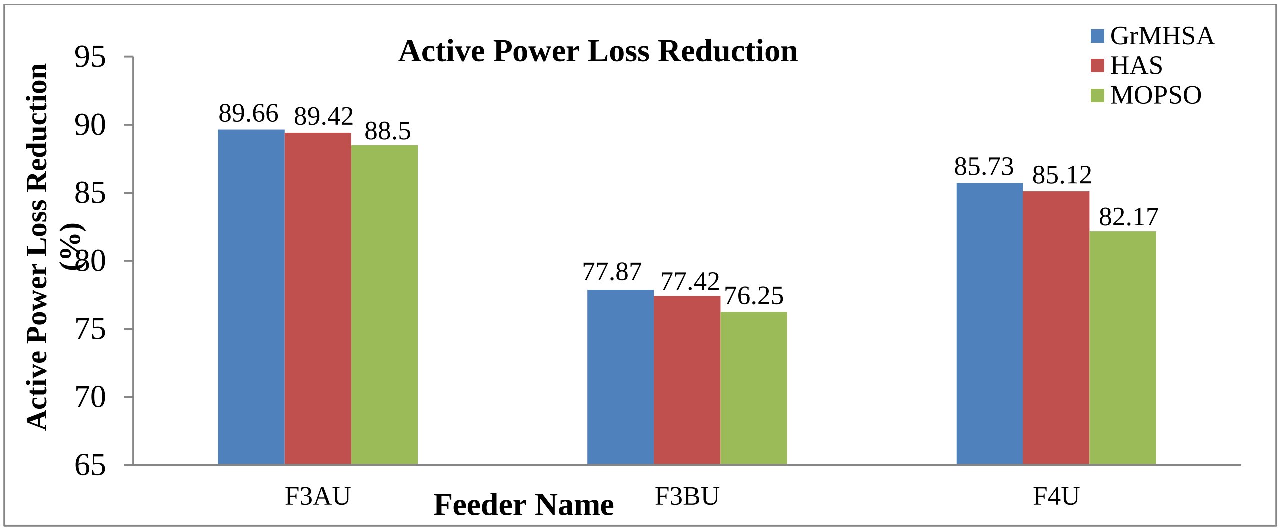

Figure 4.4: Total active power loss reduction of F3AU, F3BU, and F4U under selected optimization techniques

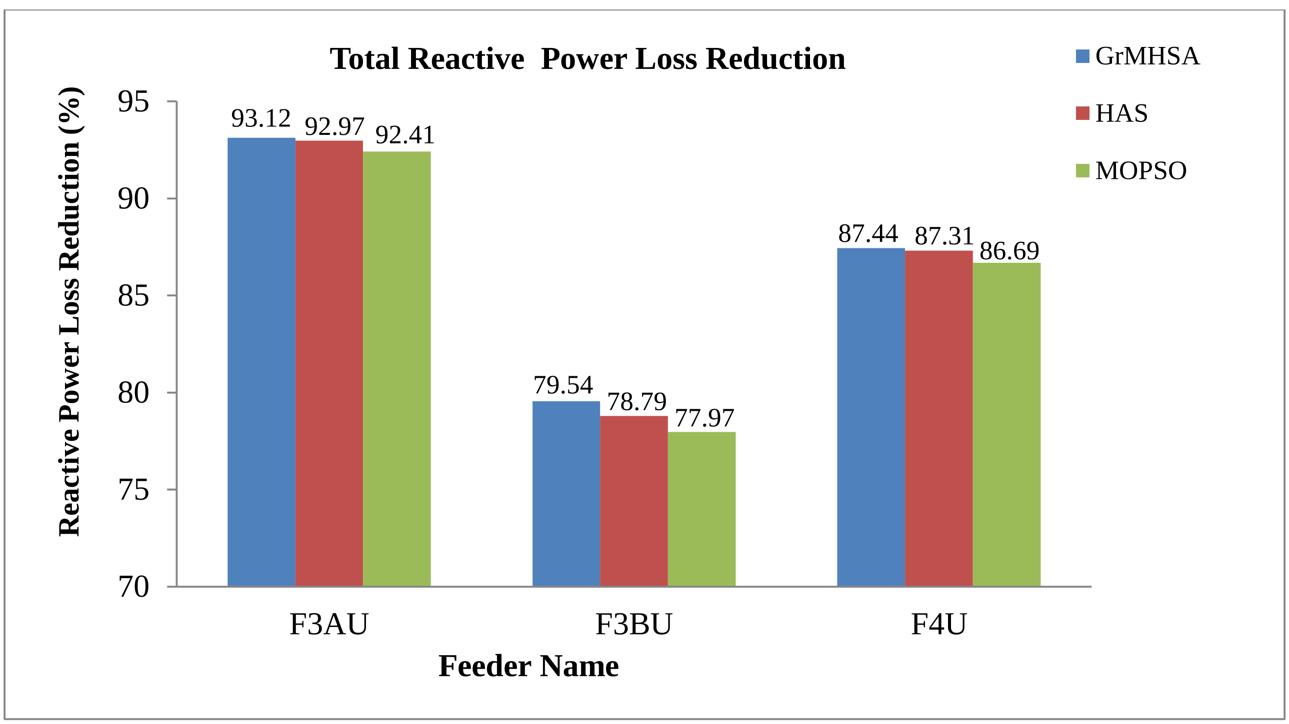

Figure 4.5: Total reactive power loss reduction of F3AU, F3BU, and F4U under selected optimization techniques

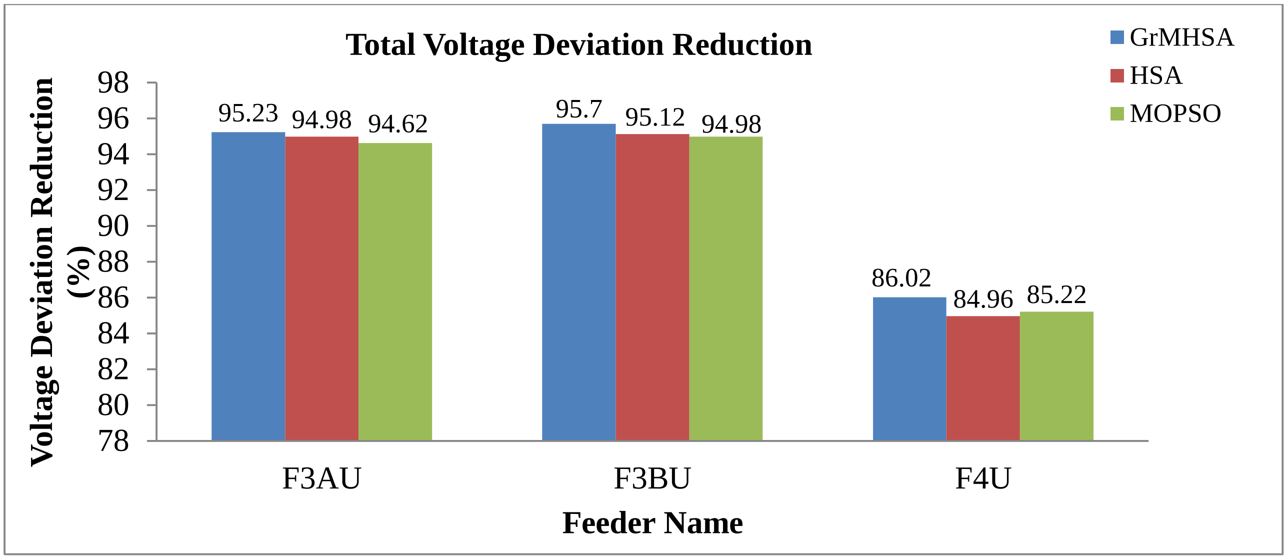

Figure 4.6: Total active power loss reduction of F3AU, F3BU, and F4U under selected optimization techniques

As the results shown in fig. 4.7, fig. 4.8 and fig. 4.9, using GrMHS optimization technique resulted best voltage profile than using MOPSO and HS for feeder F3A, F3B and F4 after the distribution network is expanded with incorporating the appropriate DG size. The comparisons of results indicated that the proposed GrMHSA based optimization technique is effective for solving the problem of optimal placement and sizing of distributed generation than the above mentioned optimization methods.

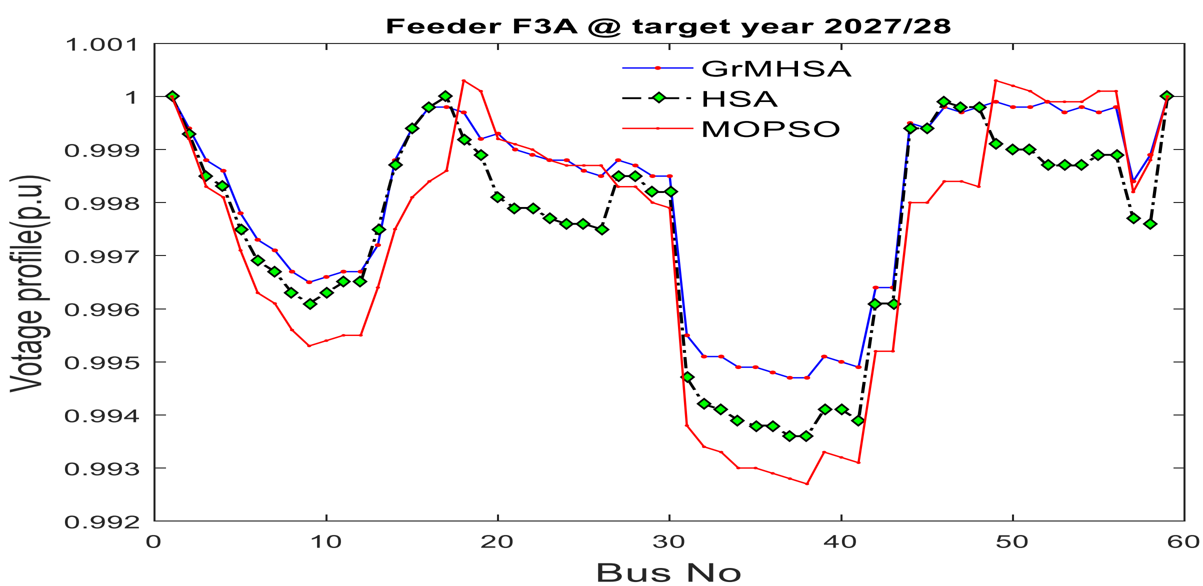

Figure 4.7: Voltage profile of separate upgraded feeder F3A under selected optimization techniques

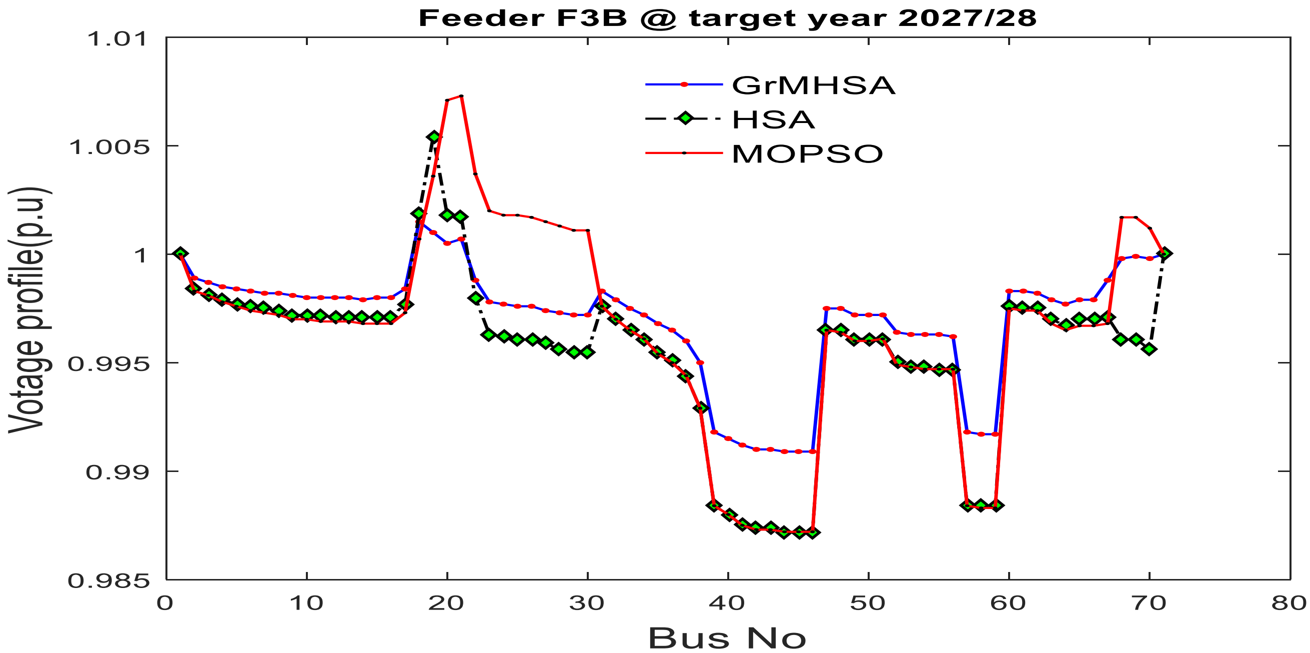

Figure 4.8: Voltage profile of separate upgraded feeder F3B under selected optimization techniques

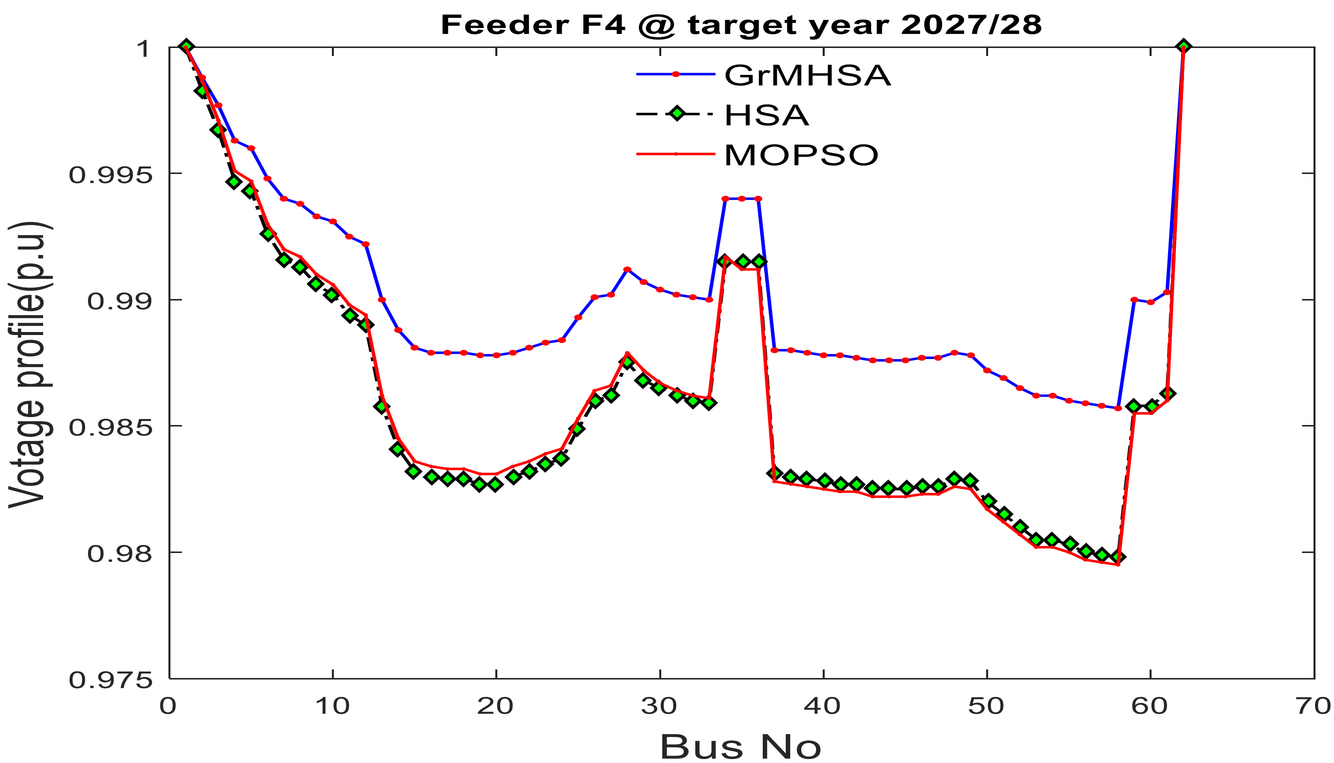

Figure 4.9: Voltage profile of separate upgraded feeder F4 under selected optimization techniques

4.5. ECONOMIC ANALYSIS

A major attribute of planning in almost all endeavors is reduction of cost. Every alternative plan contains or implies certain limits of costs such as equipment, installation labor, losses, and many others as well. Estimating cost of transformers, lines and DGs. The total investment cost is calculated and summarized as below.

Table 4.12: Summary quantity of material and equipment's with total investment cost for upgrading network

No	Item type	Description	Unit	Qty	unit price (Birr)	Total price (Birr)	Remark
1	conductor	AAC-50	meter	780	25.81	20131.8	These items are required for feeder and transformer upgrading
		AAC-95	meter	1314.6	49.26	64757.196	
		AAC-100	meter	7,770	55.01	427427.7	
		AAC-150	meter	12,351	87.25	1077624.75	
		AAC-200	meter	38,919	112.35	4372549.65	
	Transformer 15kV/0.4kV	630kva	Pcs	12	529,713.1	6356556.96	
		800kva	Pcs	20	649,347.5	12986950.4	
		1250kva	Pcs	9	1,015,856	9142706.25	
	Labor					1,000,010.2	
2	Concrete pole	Suspension concert pole (10m)	Pcs	119	4999.32	594919.08	Line constr-uction
		Suspension concert pole (11m)	Pcs	2	5387.75	10,775.5	
3	insulator	15kV pin type insulator	Pcs	363	134.79	48,928.77	
4	Tiy strap		Pcs	242	28.81	6,972.02	
5	Long bolet		Pcs	121	68.9	8,336.9	
6	colar		Pcs	121	13.42	1,623.82	
7	Cross arm		Pcs	121	853.2	103,237.2	
8	connector	M-10	Pcs	242	13.79	3,337.18	
9	Conductor	AAC-200	meter	36,312	112.35	4,079,653.2	
10	labor	Pole erection (labor cost)	Pcs	121	1,065.98	128,983.58	
		Conductor stringing(labor cost)	km	12.104	2,106.55	25,497.6812	
11	DG-6.8MVA	DG based on solar-75%=5.1MVA	KW	4309.5	30450	131,224,275	DG constr-uction
		DG based on wind-25%-1.7MVA	KW	1436.5	40380	58,005,870	
Total investment costs						349,863,021.2	

The cost is estimated based on the following:

- ✓ Distribution transformers 15/0.4kV for the three feeders
- ✓ Medium voltage overhead lines

✓ Construction of Newly added lines & DGs installation costs

Investment cost is considered as the estimation of the budget needed for expansion that has to be planned in the future. The cost estimation must be done to allow the planning to go on.

In this distribution networks expansion planning the cost is analyzed due to power. The rule of EEU billing system which is incremental rate is shown in table 4.4: below.

Table 4.13 : EEU's incremental rate billing system (new updated tariff system).

Tariff Category	KWH/month	Birr/KWH
Block 1	0-50	0.273
lock 2	50-100	0.4591
Block 3	100-200	0.7807
Block 4	200-300	0.9125
Block 5	300-400	0.975
Block 6	400-500	1.0423
Block 7	>500	1.141

Source data: Debre Markos distribution station Power Department

Table 4.14: Feeders power losses before and after separating, upgrading and installing DGs.

Feeder Name	losses in kw	
	Before Separating, Upgrading and installing DGs	After Separating, Upgrading and installing DGs
F3	7434.9	-
F4	470.7058	30.811
F3A	-	21.382
F3B	-	74.016
Total losses	7905.6058	126.209

The difference of the power loss between power loss Before Separating, Upgrading and installing DGs and After Separating, Upgrading and installing DGs from Table 4.14 is 7779.3968 Kw (i.e.7905.6058kw -126.209kw). According to the saving power, Energy is calculated the product of this saving at the targeted year 2027/28(i.e.7779.3968 Kw * 8760 hrs.) is 68,147,515.968 kwh and the cost is estimated based on the incremental rate of EEU's electricity tariff as shown in Table 4.13.

Table 4.15: The cost calculation by using the difference of power losses after and before separating, upgrading and installing DGs

Kwh	Birr/kwh	Total Birr
0-50	0.273	13.65
50-100	0.4591	22.955
100-200	0.7807	78.07
200-300	0.9125	91.25
300-400	0.975	97.5
400-500	1.0423	104.23
68,147,015.97	1.141	77,755,745.22
Total Birr		77,756,152.88

Therefore, the total saving of the expanded distribution networks is 77756152.88 birr in the target year, 2028 G.C.

Determining the relative worth of a new project by calculating the time it will take to pay back what it cost is the single most popular method of project screening. If we assume that all projects have equal annual benefit the payback period can be calculated using the formula

$$Payback\ period = \frac{Totral\ investment\ cost}{Annual\ saving}$$

$$Payback\ period = \frac{349{,}863{,}021.15}{77756152.88} = 4.49949 \cong 4.5\ years$$

So, the expanded networks are profitable by separating, upgrading and installing DGs and the total investment cost is paid back in 4.5 years.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

In this study, electrical load demand forecasting, backward-forward sweep load flow analysis, distribution network expansion planning, and appropriate DG capacity limit determination for the proper size and placement of DG using GrMHSA to improve the power loss and voltage deviation of the radial D/M distribution feeders have been conducted and promising results are obtained. In expanding the distribution network, feeder separation, upgrading the components and incorporating DG with proper capacity level are conducted. Incorporation of DG unit in D/M distribution feeders considering its capacity limit is prominent due to the benefits including reducing power losses, improving voltage profiles, reducing emission impacts. The optimal selection of nodes for the placement and size of the DG is obtained using GrMHSA technique and voltage profile improvement and power loss reduction is analyzed in a detailed manner. GrMHSA efficiently minimizes the total real power loss, total reactive power loss, total voltage deviation with satisfying the objective function constraints.

The total real power loss, total reactive power loss and total voltage deviation at the target year for the base case by taking the existing line data and the projected bus data are 7434.9kw, 7391.8kvar and 58.6952p.u for D/M F3 and 470.7058kw, 404.5524kvar and 6.4412p.u for D/M F4 respectively. After applying GrMHSA optimization technique for DG sizing and placemnt, the total real power loss, total reactive power loss and total voltage deviation at the target year are 95.398 kw, 124.979kvar and 0.479p.u for D/M F3 (F3A and F3B) and 30.811kw, 37.727kvar and 0.533p.u for D/M F4 respectively.

As the result comparison indicates, GrMHSA achieved best results in total real power loss reduction, total reactive power loss reduction, total voltage deviation reduction and voltage profile improvement as compared with MOPSO and HSA. The reduction of total real power loss, total reactive power loss and total voltage deviation with and without DG by using GrMHSA is 89.66%, 93.12% and 95.23% for feeder F3A, 77.87%, 79.54% and 95.70% for feeder F3B and 85.73%, 87.44% and 86.02% for feeder F4 have been achieved respectively.

5.2. RECOMMENDATION

The proposed research can be further expanded to include some possible future research areas as advancement:

- ✓ The forward/backward power flow model and the algorithm can be extended to undertake an unbalanced three phase and the DG allocation and sizing problem can be extended to unbalanced distribution networks.
- ✓ The developed GrMHSA model and algorithm can be extended for the integration of multiple DG units considering DG penetration level.
- ✓ Extending the proposed objective function to include technical evaluation of upgrading the network and DG placement and sizing should be considered in all respects. The researcher can also include reliability and deferment issues in upgrading the existing lines and substations.

The proposed research can be further expanded to include some possible expected recommendation to the stakeholders, D/M substation and distribution utility.

- ✓ The results in this thesis work highly recommends
  - Feeder separation by adding one more feeder for feeder 3.
  - Upgrading conductor size for feeder 3 and feeder 4.
  - Installing DG at bus 15, 18 and 28 of feeder F3A, F3B, and F4 respectively.
- ✓ These stakeholders have to consider electrical load demand forecasting approach based on economic growth and they make sure the existence of spatial data for the network.
- ✓ D/M substation should provide a power source to specific distribution network or feeder only from a single substation transformer to make ease of upgrading the transformer, avoiding total outage and to monitor easily.

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APPENDICES

Appendix A: D/M distribution network data

Table A. 1:D/M Feeder 3 Bus and Line Data.

D/M feeder 3 line data @-year 2017/18							bus data @-year 2017/18			
Branch no	sending	receiving	conductor type	Length (km)	Resistance (pu)	Reactance (pu)	Node no	Existing Trs (KVA)	Active power (pu)	Reactive power (pu)
1	1	2	AAC-95	6.065	0.836	0.873	1	0	0	0
2	2	3	AAC-95	0.327	0.045	0.047	2	100	0.015	0.01
3	3	4	AAC-95	0.35	0.048	0.05	3		0	0
4	4	5	AAC-95	0.125	0.017	0.018	4		0	0
5	5	6	AAC-95	0.65	0.09	0.094	5	200	0.031	0.019
6	6	7	AAC-95	0.53	0.073	0.076	6	100	0.015	0.01
7	7	8	AAC-95	0.112	0.015	0.016	7	630	0.097	0.061
8	8	9	AAC-95	0.51	0.07	0.073	8	200	0.031	0.019
9	9	10	AAC-95	0.28	0.039	0.04	9		0	0
10	10	11	AAC-95	0.15	0.021	0.022	10	315	0.048	0.031
11	11	12	AAC-95	0.17	0.023	0.024	11	200	0.031	0.019
12	12	13	AAC-50	0.001	0.002	0.0005	12		0	0
13	13	14	AAC-50	0.22	0.066	0.035	13	100	0.015	0.01
14	14	15	AAC-50	0.282	0.085	0.045	14	630	0.097	0.061
15	15	16	AAC-95	0.35	0.048	0.05	15		0	0
16	16	17	AAC-95	0.18	0.025	0.026	16	100	0.015	0.01
17	17	18	AAC-95	0.1	0.014	0.014	17		0	0
18	18	19	AAC-95	0.09	0.012	0.013	18		0	0
19	19	20	AAC-95	0.102	0.014	0.015	19	315	0.048	0.031
20	20	21	AAC-95	0.12	0.017	0.02	20	315	0.048	0.031
21	21	22	AAC-95	0.23	0.032	0.033	21		0	0
22	22	23	AAC-95	0.51	0.127	0.073	22	315	0.048	0.031
23	23	24	AAC-95	0.35	0.048	0.05	23		0	0
24	24	25	AAC-95	0.3	0.041	0.043	24		0	0
25	25	26	AAC-95	0.36	0.05	0.052	25	200	0.031	0.019
26	26	27	AAC-50	0.16	0.048	0.026	26	200	0.031	0.019
27	27	28	AAC-50	0.105	0.032	0.017	27		0	0
28	28	29	AAC-50	0.112	0.034	0.018	28	200	0.031	0.019
29	29	30	AAC-95	0.11	0.015	0.016	29	630	0.097	0.061

30	30	31	AAC-95	0.12	0.017	0.017	30	200	0.031	0.019
31	31	32	AAC-95	0.07	0.01	0.01	31	630	0.097	0.061
32	32	33	AAC-95	0.19	0.026	0.027	32	630	0.097	0.061
33	33	34	AAC-95	0.08	0.011	0.012	33	315	0.048	0.031
34	34	35	AAC-95	0.04	0.006	0.006	34	25	0.004	0.002
35	35	36	AAC-95	0.06	0.008	0.009	35		0	0
36	36	37	AAC-95	0.04	0.006	0.006	36	630	0.097	0.061
37	37	38	AAC-95	0.25	0.034	0.036	37	630	0.097	0.061
38	38	39	AAC-95	0.18	0.025	0.026	38		0	0
39	39	40	AAC-95	0.17	0.023	0.024	39	800	0.123	0.078
40	40	41	AAC-95	0.93	0.128	0.134	40	200	0.031	0.019
41	41	42	AAC-95	5.49	0.756	0.791	41	100	0.015	0.01
42	42	43	AAC-95	4.31	0.594	0.621	42	315	0.048	0.031
43	43	44	AAC-95	4.49	0.619	0.647	43	200	0.031	0.019
44	44	45	AAC-95	0.2	0.028	0.029	44	315	0.048	0.031
45	45	46	AAC-95	5.64	0.777	0.812	45	100	0.015	0.01
46	46	47	AAC-95	2.78	0.383	0.4	46	25	0.004	0.002
47	47	48	AAC-95	0.3	0.041	0.043	47		0	0
48	48	49	AAC-95	0.04	0.006	0.006	48	315	0.048	0.031
49	49	50	AAC-50	0.09	0.027	0.014	49	315	0.048	0.031
50	50	51	AAC-50	0.44	0.133	0.071	50		0	0
51	51	52	AAC-50	0.62	0.187	0.1	51	315	0.048	0.031
52	3	53	AAC-50	0.42	0.127	0.068	52	100	0.015	0.01
53	53	54	AAC-50	0.035	0.011	0.006	53	315	0.048	0.031
54	4	55	AAC-50	0.05	0.015	0.008	54	630	0.097	0.061
55	55	56	AAC-50	0.152	0.046	0.024	55	630	0.097	0.061
56	9	57	AAC-95	0.4	0.055	0.058	56	200	0.031	0.019
57	57	58	AAC-95	0.87	0.12	0.125	57	100	0.015	0.01
58	58	59	AAC-95	0.29	0.04	0.042	58	200	0.031	0.019
59	59	60	AAC-50	0.03	0.009	0.005	59		0	0
60	60	61	AAC-50	0.15	0.045	0.024	60	630	0.097	0.061
61	61	62	AAC-50	0.05	0.015	0.008	61	315	0.048	0.031
62	62	63	AAC-50	0.045	0.014	0.007	62	630	0.097	0.061
63	63	64	AAC-50	0.45	0.136	0.072	63	50	0.008	0.005
64	59	65	AAC-50	0.12	0.036	0.019	64	315	0.048	0.031
65	65	66	AAC-50	0.027	0.008	0.004	65	630	0.097	0.061
66	66	67	AAC-50	0.032	0.01	0.005	66	200	0.031	0.019
67	12	68	AAC-25	0.31	0.184	0.052	67	315	0.048	0.031
68	68	69	AAC-25	0.367	0.218	0.062	68	630	0.097	0.061
69	15	70	AAC-95	0.05	0.007	0.007	69	25	0.004	0.002
70	70	71	Cu -16	0.065	0.055	0.011	70	25	0.004	0.002

71	17	72	AAC-25	0.003	0.002	0.0005	71	200	0.031	0.019
72	72	73	AAC-25	0.12	0.071	0.02	72	315	0.048	0.031
73	73	74	AAC-25	0.102	0.061	0.017	73	100	0.015	0.01
74	18	75	AAC-50	0.33	0.1	0.053	74	200	0.031	0.019
75	75	76	AAC-50	0.21	0.063	0.034	75	100	0.015	0.01
76	76	77	AAC-50	0.76	0.23	0.122	76	25	0.004	0.002
77	77	78	AAC-50	0.2	0.06	0.032	77		0	0
78	78	79	AAC-50	0.1	0.03	0.016	78	100	0.015	0.01
79	79	80	AAC-50	0.75	0.227	0.121	79	50	0.008	0.005
80	80	81	AAC-50	0.325	0.098	0.052	80	50	0.008	0.005
81	81	82	AAC-50	0.163	0.049	0.026	81	100	0.015	0.01
82	77	83	AAC-50	0.35	0.106	0.056	82	100	0.015	0.01
83	83	84	AAC-50	0.6	0.181	0.097	83	50	0.008	0.005
84	21	85	AAC-50	0.1	0.03	0.016	84	50	0.008	0.005
85	85	86	AAC-50	0.093	0.028	0.015	85	630	0.097	0.061
86	23	87	AAC-50	0.003	0.001	0.0004	86	315	0.048	0.031
87	23	88	AAC-50	0.023	0.007	0.004	87	100	0.015	0.01
88	24	89	AAC-95	0.45	0.062	0.065	88	100	0.015	0.01
89	89	90	AAC-95	0.026	0.004	0.004	89	200	0.031	0.019
90	90	91	AAC-95	0.262	0.036	0.038	90	315	0.048	0.031
91	91	92	AAC-95	0.22	0.03	0.032	91		0	0
92	92	93	AAC-95	0.18	0.025	0.026	92		0	0
93	93	94	AAC-95	0.18	0.025	0.026	93	200	0.031	0.019
94	94	95	AAC-95	0.333	0.046	0.048	94		0	0
95	95	96	AAC-95	0.2	0.028	0.029	95	100	0.015	0.01
96	96	97	AAC-95	0.554	0.076	0.08	96	100	0.015	0.01
97	97	98	AAC-95	1.23	0.169	0.177	97		0	0
98	98	99	AAC-95	3.77	0.519	0.543	98	630	0.097	0.061
99	99	100	AAC-95	0.58	0.08	0.084	99	100	0.015	0.01
100	100	101	AAC-95	0.79	0.109	0.114	100	630	0.097	0.061
101	101	102	AAC-95	0.59	0.081	0.085	101	100	0.015	0.01
102	102	103	AAC-95	0.04	0.006	0.006	102	100	0.015	0.01
103	103	104	AAC-95	0.68	0.094	0.098	103	100	0.015	0.01
104	91	105	AAC-50	0.162	0.049	0.026	104	50	0.008	0.005
105	91	106	AAC-50	0.027	0.008	0.004	105	200	0.031	0.019
106	92	107	AAC-50	0.145	0.044	0.023	106	100	0.015	0.01
107	107	108	AAC-50	0.19	0.057	0.031	107	315	0.048	0.031
108	92	109	AAC-25	0.015	0.009	0.002	108	800	0.123	0.078
109	94	110	AAC-50	0.04	0.012	0.006	109	100	0.015	0.01
110	110	111	AAC-50	0.04	0.012	0.006	110	25	0.004	0.002
111	111	112	AAC-50	0.12	0.036	0.019	111	800	0.123	0.078

112	112	113	AAC-50	0.28	0.085	0.045	112	200	0.031	0.019
113	113	114	AAC-50	0.13	0.039	0.021	113	200	0.031	0.019
114	97	115	AAC-50	0.17	0.051	0.027	114	200	0.031	0.019
115	97	116	AAC-50	0.175	0.053	0.028	115	315	0.048	0.031
116	116	117	AAC-50	0.25	0.076	0.04	116	200	0.031	0.019
117	27	118	AAC-50	0.26	0.079	0.042	117	100	0.015	0.01
118	118	119	AAC-50	0.091	0.028	0.015	118	315	0.048	0.031
119	119	120	AAC-50	0.4	0.121	0.064	119	25	0.004	0.002
120	35	121	AAC-95	0.33	0.045	0.048	120	200	0.031	0.019
121	121	122	AAC-95	0.222	0.031	0.032	121	315	0.048	0.031
122	38	123	AAC-50	0.21	0.063	0.03	122	315	0.048	0.031
123	123	124	AAC-50	1.1	0.332	0.158	123	630	0.097	0.061
124	38	125	AAC-95	0.113	0.016	0.016	124	200	0.031	0.019
125	47	126	AAC-95	0.2	0.028	0.029	125	630	0.097	0.061
126	126	127	AAC-95	0.06	0.008	0.009	126	315	0.048	0.031
127	50	128	AAC-95	0.38	0.052	0.055	127	315	0.048	0.031
128	128	129	AAC-95	0.34	0.047	0.049	128	100	0.015	0.01
							129	100	0.015	0.01

Table A. 2: D/MFeeder 4 Bus and Line Data.

D/M feeder 4 line data @-year 2017/18							bus data @-year 2017/18			
Branch no	sending	receiving	conductor type	Length (km)	Resistance (pu)	Reactance (pu)	Node number	Existing Transformer (KVA)	Active power (pu)	Reactive power (pu)
1	1	2	AAC-95	3.47	0.478	0.5	1		0	0
2	2	3	AAC-95	0.59	0.081	0.085	2	200	0.031	0.019
3	3	4	AAC-95	0.56	0.077	0.081	3	630	0.096	0.061
4	4	5	AAC-95	0.74	0.102	0.107	4	100	0.015	0.01
5	5	6	AAC-95	0.15	0.021	0.022	5	100	0.015	0.01
6	6	7	AAC-95	0.67	0.092	0.096	6	100	0.015	0.01
7	7	8	AAC-95	0.401	0.055	0.058	7		0	0
8	8	9	AAC-95	0.11	0.015	0.016	8	200	0.031	0.019
9	9	10	AAC-95	0.26	0.036	0.037	9	630	0.096	0.061
10	10	11	AAC-95	0.14	0.019	0.02	10	200	0.031	0.019
11	11	12	AAC-95	0.31	0.043	0.045	11	315	0.048	0.031
12	12	13	AAC-50	0.16	0.048	0.026	12	100	0.015	0.01
13	13	14	AAC-50	1.37	0.414	0.22	13	25	0.004	0.002
14	14	15	AAC-50	0.72	0.218	0.116	14	315	0.048	0.031
15	15	16	AAC-95	0.34	0.047	0.049	15		0	0
16	16	17	AAC-95	0.14	0.019	0.02	16	200	0.031	0.019
17	17	18	AAC-95	0.06	0.008	0.009	17	315	0.048	0.031
18	18	19	AAC-95	0.03	0.004	0.004	18	630	0.096	0.061
19	19	20	AAC-95	0.12	0.017	0.017	19	100	0.015	0.01
20	20	21	AAC-25	0.03	0.018	0.005	20		0	0
21	21	22	AAC-25	0.23	0.137	0.039	21	50	0.008	0.005
22	22	23	AAC-25	0.08	0.048	0.014	22	315	0.048	0.031
23	23	24	AAC-25	0.1	0.059	0.017	23	200	0.031	0.019
24	24	25	AAC-25	0.05	0.03	0.008	24	25	0.004	0.002
25	25	26	AAC-25	0.35	0.208	0.059	25	100	0.015	0.01
26	26	27	AAC-25	0.29	0.172	0.049	26		0	0
27	27	28	AAC-25	0.06	0.036	0.01	27	315	0.048	0.031
28	28	29	AAC-25	0.3	0.178	0.051	28	630	0.096	0.061
29	29	30	AAC-25	0.31	0.184	0.052	29	100	0.015	0.01
30	30	31	AAC-25	0.15	0.089	0.025	30		0	0
31	31	32	AAC-25	0.16	0.095	0.027	31	630	0.096	0.061
32	32	33	AAC-25	0.218	0.13	0.037	32	315	0.048	0.031
33	7	34	AAC-25	0.3	0.178	0.051	33	315	0.048	0.031

34	34	35	AAC-25	0.14	0.083	0.024	34	100	0.015	0.01
35	35	36	AAC-25	0.12	0.071	0.02	35	25	0.004	0.002
36	15	37	AAC-95	0.24	0.033	0.035	36	100	0.015	0.01
37	37	38	AAC-95	0.29	0.04	0.042	37	315	0.048	0.031
38	15	39	AAC-95	0.45	0.062	0.065	38	315	0.048	0.031
39	39	40	AAC-95	0.3	0.041	0.043	39		0	0
40	40	41	AAC-95	0.13	0.018	0.019	40	200	0.031	0.019
41	41	42	AAC-95	0.08	0.011	0.012	41	630	0.096	0.061
42	42	43	AAC-95	0.12	0.017	0.017	42		0	0
43	43	44	AAC-95	0.26	0.036	0.037	43	630	0.096	0.061
44	44	45	AAC-95	0.213	0.029	0.031	44	100	0.015	0.01
45	42	46	AAC-25	0.0017	0.001	0.0003	45	200	0.031	0.019
46	42	47	AAC-95	0.24	0.033	0.035	46	100	0.015	0.01
47	39	48	AAC-95	0.18	0.025	0.026	47	100	0.015	0.01
48	48	49	AAC-95	0.27	0.037	0.039	48	50	0.008	0.005
49	20	50	AAC-50	0.11	0.033	0.018	49	200	0.031	0.019
50	50	51	AAC-50	0.373	0.113	0.06	50	315	0.048	0.031
51	51	52	AAC-50	0.271	0.082	0.044	51	315	0.048	0.031
52	52	53	AAC-50	0.36	0.109	0.058	52	200	0.031	0.019
53	53	54	AAC-50	0.36	0.109	0.058	53	630	0.096	0.061
54	54	55	AAC-50	0.04	0.012	0.006	54	25	0.004	0.002
55	55	56	AAC-50	0.19	0.057	0.031	55	315	0.048	0.031
56	56	57	AAC-50	0.45	0.136	0.072	56	200	0.031	0.019
57	57	58	AAC-50	0.36	0.109	0.058	57	315	0.048	0.031
58	26	59	AAC-25	0.445	0.265	0.075	58	200	0.031	0.019
59	59	60	AAC-25	0.58	0.345	0.098	59	100	0.015	0.01
60	30	61	AAC-25	0.14	0.083	0.024	60	100	0.015	0.01
61	61	62	AAC-25	0.43	0.256	0.073	61	315	0.048	0.031
							62	630	0.096	0.061

Table A. 3:D/MSeparate Feeder F3A Bus and Line Data.

Separate F3A line data @-year 2017/18							bus data @-year 2017/18			
Branch no	sending	receiving	conductor type	Length (km)	Resistance (pu)	Reactance (pu)	Node number	Existing Transformer (KVA)	Active power (pu)	Reactive power (pu)
1	1	2	(AAC-95)	6.065	0.836	0.836	1		0	0
2	2	3	(AAC-95)	0.327	0.045	0.045	2	100	0.015	0.01
3	3	4	(AAC-95)	0.35	0.048	0.048	3		0	0
4	4	5	(AAC-95)	0.125	0.017	0.017	4		0	0
5	5	6	(AAC-95)	0.65	0.09	0.09	5	200	0.031	0.019
6	6	7	(AAC-95)	0.53	0.073	0.073	6	100	0.015	0.01
7	7	8	(AAC-95)	0.112	0.015	0.015	7	630	0.097	0.061
8	8	9	(AAC-95)	0.51	0.07	0.07	8	200	0.031	0.019
9	9	10	(AAC-95)	0.28	0.039	0.039	9		0	0
10	10	11	(AAC-95)	0.15	0.021	0.021	10	315	0.048	0.031
11	11	12	(AAC-95)	0.17	0.023	0.023	11	200	0.031	0.019
12	12	13	(AAC-50)	0.0012	0	0	12		0	0
13	13	14	(AAC-50)	0.22	0.066	0.066	13	100	0.015	0.01
14	14	15	(AAC-50)	0.282	0.085	0.085	14	630	0.097	0.061
15	15	16	(AAC-95)	0.35	0.048	0.048	15		0	0
16	16	17	(AAC-95)	0.18	0.025	0.025	16	100	0.015	0.01
17	17	18	(AAC-95)	0.1	0.014	0.014	17		0	0
18	18	19	(AAC-50)	0.33	0.1	0.1	18		0	0
19	19	20	(AAC-50)	0.21	0.063	0.063	19	200	0.031	0.019
20	20	21	(AAC-50)	0.76	0.23	0.23	20	100	0.015	0.01
21	21	22	(AAC-50)	0.2	0.06	0.06	21		0	0
22	22	23	(AAC-50)	0.1	0.03	0.03	22	100	0.015	0.01
23	23	24	(AAC-50)	0.75	0.227	0.227	23	50	0.008	0.005
24	24	25	(AAC-50)	0.325	0.098	0.098	24	50	0.008	0.005
25	25	26	(AAC-50)	0.163	0.049	0.049	25	100	0.015	0.01
26	3	27	(AAC-50)	0.42	0.127	0.127	26	100	0.015	0.01
27	27	28	(AAC-50)	0.035	0.011	0.011	27	315	0.048	0.031
28	4	29	(AAC-50)	0.05	0.015	0.015	28	630	0.097	0.061
29	29	30	(AAC-50)	0.152	0.046	0.046	29	630	0.097	0.061
30	9	31	(AAC-95)	0.4	0.055	0.055	30	200	0.031	0.019
31	31	32	(AAC-95)	0.87	0.12	0.12	31	100	0.015	0.01
32	32	33	(AAC-95)	0.29	0.04	0.04	32	200	0.031	0.019
33	33	34	(AAC-50)	0.03	0.009	0.009	33		0	0
34	34	35	(AAC-50)	0.15	0.045	0.045	34	630	0.097	0.061

35	35	36	(AAC-50)	0.05	0.015	0.015	35	315	0.048	0.031
36	36	37	(AAC-50)	0.045	0.014	0.014	36	630	0.097	0.061
37	37	38	(AAC-50)	0.45	0.136	0.136	37	50	0.008	0.005
38	33	39	(AAC-50)	0.12	0.036	0.036	38	315	0.048	0.031
39	39	40	(AAC-50)	0.027	0.008	0.008	39	630	0.097	0.061
40	40	41	(AAC-50)	0.032	0.01	0.01	40	200	0.031	0.019
41	12	42	(AAC-25)	0.31	0.184	0.184	41	315	0.048	0.031
42	42	43	(AAC-25)	0.367	0.218	0.218	42	630	0.097	0.061
43	15	44	(AAC-95)	0.05	0.007	0.007	43	25	0.004	0.002
44	44	45	Cu -16	0.065	0.055	0.055	44	25	0.004	0.002
45	17	46	(AAC-25)	0.0027	0.002	0.002	45	200	0.031	0.019
46	46	47	(AAC-25)	0.12	0.071	0.071	46	315	0.048	0.031
47	47	48	(AAC-25)	0.102	0.061	0.061	47	100	0.015	0.01
48	18	49	(AAC-95)	0.09	0.012	0.012	48	315	0.048	0.031
49	49	50	(AAC-95)	0.102	0.014	0.014	49	315	0.048	0.031
50	50	51	(AAC-25)	0.12	0.017	0.017	50	315	0.048	0.031
51	51	52	(AAC-95)	0.23	0.032	0.032	51		0	0
52	52	53	Cu-16	0.51	0.127	0.127	52	315	0.048	0.031
53	53	54	(AAC-50)	0.0026	0.001	0.001	53		0	0
54	53	55	(AAC-50)	0.023	0.007	0.007	54	315	0.048	0.031
55	51	56	(AAC-50)	0.1	0.03	0.03	55	50	0.015	0.01
56	56	57	(AAC-50)	0.093	0.028	0.028	56	100	0.008	0.005
57	21	58	(AAC-50)	0.35	0.106	0.106	57	630	0.097	0.061
58	58	59	(AAC-50)	0.6	0.181	0.181	58	100	0.015	0.01
							59	100	0.008	0.005

Table A. 4:D/M Separate Feeder F3B Bus and Line Data.

Separate F3B line data @-year 2017/18							bus data @-year 2017/18			
Branch no	sending	receiving	conductor type	Length (km)	Resistance (pu)	Reactance (pu)	Node number	Existing Transformer (KVA)	Active power (pu)	Reactive power (pu)
1	1	2	(AAC-95)	12.104	1.668	1.743	1		0	0
2	2	3	(AAC-95)	0.3	0.041	0.043	2		0	0
3	3	4	(AAC-95)	0.36	0.05	0.052	3	200	0.031	0.019
4	4	5	(AAC-50)	0.16	0.048	0.026	4	200	0.031	0.019
5	5	6	(AAC-50)	0.105	0.032	0.017	5		0	0
6	6	7	(AAC-50)	0.112	0.034	0.018	6	200	0.031	0.019
7	7	8	(AAC-95)	0.11	0.015	0.016	7	630	0.097	0.061
8	8	9	(AAC-95)	0.12	0.017	0.017	8	200	0.031	0.019
9	9	10	(AAC-95)	0.07	0.01	0.01	9	630	0.097	0.061
10	10	11	(AAC-95)	0.19	0.026	0.027	10	630	0.097	0.061
11	11	12	(AAC-95)	0.08	0.011	0.012	11	315	0.048	0.031
12	12	13	(AAC-95)	0.04	0.006	0.006	12	25	0.004	0.002
13	13	14	(AAC-95)	0.06	0.008	0.009	13		0	0
14	14	15	(AAC-95)	0.04	0.006	0.006	14	630	0.097	0.061
15	15	16	(AAC-95)	0.25	0.034	0.036	15	630	0.097	0.061
16	16	17	(AAC-95)	0.18	0.025	0.026	16		0	0
17	17	18	(AAC-95)	0.17	0.023	0.024	17	800	0.123	0.078
18	18	19	(AAC-95)	0.93	0.128	0.134	18	200	0.031	0.019
19	19	20	(AAC-95)	5.49	0.756	0.791	19	100	0.015	0.01
20	20	21	(AAC-95)	4.31	0.594	0.621	20	315	0.048	0.031
21	21	22	(AAC-95)	4.49	0.619	0.647	21	200	0.031	0.019
22	22	23	(AAC-95)	0.2	0.028	0.029	22	315	0.048	0.031
23	23	24	(AAC-95)	5.64	0.777	0.812	23	100	0.015	0.01
24	24	25	(AAC-95)	2.78	0.383	0.4	24	25	0.004	0.002
25	25	26	(AAC-95)	0.3	0.041	0.043	25		0	0
26	26	27	(AAC-95)	0.04	0.006	0.006	26	315	0.048	0.031
27	27	28	(AAC-50)	0.09	0.027	0.014	27	315	0.048	0.031
28	28	29	(AAC-50)	0.44	0.133	0.071	28		0	0
29	29	30	(AAC-50)	0.62	0.187	0.1	29	315	0.048	0.031
30	2	31	(AAC-95)	0.45	0.062	0.065	30	100	0.015	0.01
31	31	32	(AAC-95)	0.026	0.004	0.004	31	200	0.031	0.019
32	32	33	(AAC-95)	0.262	0.036	0.038	32	315	0.048	0.031
33	33	34	(AAC-95)	0.22	0.03	0.032	33		0	0

34	34	35	(AAC-95)	0.18	0.025	0.026	34		0	0
35	35	36	(AAC-95)	0.18	0.025	0.026	35	200	0.031	0.019
36	36	37	(AAC-95)	0.333	0.046	0.048	36		0	0
37	37	38	(AAC-95)	0.2	0.028	0.029	37	100	0.015	0.01
38	38	39	(AAC-95)	0.554	0.076	0.08	38	100	0.015	0.01
39	39	40	(AAC-95)	1.23	0.169	0.177	39		0	0
40	40	41	(AAC-95)	3.77	0.519	0.543	40	630	0.097	0.061
41	41	42	(AAC-95)	0.58	0.08	0.084	41	100	0.015	0.01
42	42	43	(AAC-95)	0.79	0.109	0.114	42	630	0.097	0.061
43	43	44	(AAC-95)	0.59	0.081	0.085	43	100	0.015	0.01
44	44	45	(AAC-95)	0.04	0.006	0.006	44	100	0.015	0.01
45	45	46	(AAC-95)	0.68	0.094	0.098	45	100	0.015	0.01
46	33	47	(AAC-50)	0.162	0.049	0.026	46	50	0.008	0.005
47	33	48	(AAC-50)	0.027	0.008	0.004	47	200	0.031	0.019
48	34	49	(AAC-50)	0.145	0.044	0.023	48	100	0.015	0.01
49	49	50	(AAC-50)	0.19	0.057	0.031	49	315	0.048	0.031
50	34	51	(AAC-25)	0.015	0.009	0.002	50	800	0.123	0.078
51	36	52	(AAC-50)	0.04	0.012	0.006	51	100	0.015	0.01
52	52	53	(AAC-50)	0.04	0.012	0.006	52	25	0.004	0.002
53	53	54	(AAC-50)	0.12	0.036	0.019	53	800	0.123	0.078
54	54	55	(AAC-50)	0.28	0.085	0.045	54	200	0.031	0.019
55	55	56	(AAC-50)	0.13	0.039	0.021	55	200	0.031	0.019
56	39	57	(AAC-50)	0.17	0.051	0.027	56	200	0.031	0.019
57	39	58	(AAC-50)	0.175	0.053	0.028	57	315	0.048	0.031
58	58	59	(AAC-50)	0.25	0.076	0.04	58	200	0.031	0.019
59	5	60	(AAC-50)	0.26	0.079	0.042	59	100	0.015	0.01
60	60	61	(AAC-50)	0.091	0.028	0.015	60	315	0.048	0.031
61	61	62	(AAC-50)	0.4	0.121	0.064	61	25	0.004	0.002
62	13	63	(AAC-95)	0.33	0.045	0.048	62	200	0.031	0.019
63	63	64	(AAC-95)	0.222	0.031	0.032	63	315	0.048	0.031
64	16	65	(AAC-50)	0.21	0.063	0.03	64	315	0.048	0.031
65	65	66	(AAC-50)	1.1	0.332	0.158	65	630	0.097	0.061
66	16	67	(AAC-95)	0.1126	0.016	0.016	66	200	0.031	0.019
67	25	68	(AAC-95)	0.2	0.028	0.029	67	630	0.097	0.061
68	68	69	(AAC-95)	0.06	0.008	0.009	68	315	0.048	0.031
69	28	70	(AAC-95)	0.38	0.052	0.055	69	315	0.048	0.031
70	70	71	(AAC-95)	0.34	0.047	0.049	70	100	0.015	0.01
							71	100	0.015	0.01

Appendix B: Upgraded transformer capacity

Table B. 1: Distribution substation proposed in 2027/28- feeder F3A.

Node No	Installed capacity (kVA)	Peak load 2027/28-P (kW)	Peak load 2027/28-Q (kVAR)	Overload of Trans. (%)	Peak load 2027/28(kVA)	New capacity (kVA)	Tr Location
1		0	0		0		
2	100	183.556	116.216	117.25	217.254	315	catolic school
3		0	0		0		
4		0	0		0		
5	200	367.113	232.432	117.25	434.507	630	Edetibebakababitawula
6	100	183.556	116.216	117.25	217.254	315	Yetebaberutmadeya
7	630	1156.405	732.162	117.25	1368.698	2000	hospital condominum
8	200	367.113	232.432	117.25	434.507	630	arogew hospital condo
9		0	0		0		
10	315	578.203	366.081	117.25	684.349	800	hospital mill
11	200	367.113	232.432	117.25	434.507	630	Hospital
12		0	0		0		
13	100	183.556	116.216	117.25	217.254	315	polic college surrounding
14	630	1156.405	732.162	117.25	1368.698	2000	hospitalmesmercondomi
15		0	0		0		
16	100	183.556	116.216	117.25	217.254	315	zone admin front
17		0	0		0		
18		0	0		0		
19	200	367.113	232.432	117.25	434.507	630	Gozamin hotel
20	100	183.556	116.216	117.25	217.254	315	Ambasel building
21		0	0		0		
22	100	183.556	116.216	117.25	217.254	315	nehase 30 front
23	50	47.778	14.108	-0.36	49.818	50	wutrn pump near forest
24	50	47.778	14.108	-0.36	49.818	50	wutrn pump near daligaw
25	100	183.556	116.216	117.25	217.254	315	getermenged
26	100	183.556	116.216	117.25	217.254	315	getermengedcondomi 1
27	315	578.203	366.081	117.25	684.349	800	getermrngedcondomi 2
28	630	1156.405	732.162	117.25	1368.698	2000	getermengercondomiakababi
29	630	1156.405	732.162	117.25	1368.698	2000	Kidanemihiret front
30	200	367.113	232.432	117.25	434.507	630	Maremiya corner
31	100	183.556	116.216	117.25	217.254	315	marmiya flour factory1
32	200	367.113	232.432	117.25	434.507	630	marmiya oil factory
33		0	0		0		
34	630	1156.405	732.162	117.25	1368.698	2000	marmiya flour factory2

35	315	578.203	366.081	117.25	684.349	800	marmiya near tawula
36	630	1156.405	732.162	117.25	1368.698	2000	den enteprise
37	50	91.778	58.108	117.25	108.627	200	marmiya water pump
38	315	578.203	366.081	117.25	684.349	800	marmiya oil factory
39	630	1156.405	732.162	117.25	1368.698	2000	marmiya flour factory3
40	200	1156.405	732.162	117.25	1368.698	2000	police college
41	315	578.203	366.081	117.25	684.349	800	police college tele
42	630	1156.405	732.162	117.25	1368.698	2000	Police college
43	25	23.889	7.054	-0.36	24.909	25	police college tele
44	25	23.889	7.054	-0.36	24.909	25	Tele near Tv
45	200	367.113	232.432	117.25	434.507	630	admin
46	315	578.203	366.081	117.25	684.349	800	palace
47	100	183.556	116.216	117.25	217.254	315	tawula near T/haymanot
48	315	578.203	366.081	117.25	684.349	800	tele in T/Haymanot
49	315	578.203	366.081	117.25	684.349	800	Near Aderaw house
50	315	578.203	366.081	117.25	684.349	800	wutrn water pump forest
51		0	0		0		
52	315	578.203	366.081	117.25	684.349	800	wutrn water pump daligaw
53		0	0		0		
54	315	578.203	366.081	117.25	684.349	800	Medhanialem church
55	50	47.778	14.108	-0.36	49.818	50	water pump near coridor
56	100	91.778	58.108	117.25	108.627	200	pump daligawcoridor
57	630	1156.405	732.162	117.25	1368.698	2000	tele office
58	100	183.556	116.216	117.25	217.254	315	Tilik hotel front
59	100	91.778	58.108	117.25	108.627	200	Tlik hotel

Table B. 2: Distribution substation proposed in 2027/28- feeder F3B.

Node No.	Installed capacity (kVA)	Peak load 2027/28-P (kW)	Peak load 2027/28-Q (kVAR)	Overload Of Trans. (%)	Peak load 2027/28(kVA)	New capacity (kVA)	Tr Location
1		0	0		0		
2		0	0		0		
3	200	367.113	232.432	117.25	434.507	630	Gizachew mill
4	200	367.113	232.432	117.25	434.507	630	kuteba
5		0	0		0	0	
6	200	367.113	232.432	117.25	434.507	630	pickok
7	630	1156.405	732.162	117.25	1368.698	2000	Dr.Tebkew front
8	200	578.203	366.081	117.25	684.349	800	Agriculture biro
9	630	1156.405	732.162	117.25	1368.698	2000	Enmaymenafesha
10	630	1156.405	732.162	117.25	1368.698	2000	stadium front
11	315	578.203	366.081	117.25	684.349	800	human bridge college
12	25	23.889	7.054	-0.36	24.909	25	Technic tele
13		0	0		0		
14	630	1156.405	732.162	117.25	1368.698	2000	gozamn union
15	630	1156.405	732.162	117.25	1368.698	2000	techniqe school
16		0	0		0		
17	800	183.556	116.216	117.25	217.254	315	Bole condomi
18	200	91.778	58.108	117.25	108.627	200	Jaika school
19	100	183.556	116.216	117.25	217.254	315	Bole water reservoir
20	315	578.203	366.081	117.25	684.349	800	enerat
21	200	367.113	232.432	117.25	434.507	630	enerata2
22	315	578.203	366.081	117.25	684.349	800	yeted
23	100	23.889	7.054	-0.36	24.909	25	yetedtele
24	25	23.889	7.054	-0.36	24.909	25	Tele
25		0	0		0		
26	315	578.203	366.081	117.25	684.349	800	near robgebeyatele
27	315	578.203	366.081	117.25	684.349	800	behind gebeyarobgebeya

28		0	0		0		
29	315	578.203	366.081	117.25	684.349	800	robgebyamichael front
30	100	183.556	116.216	117.25	217.254	315	robgebeya preparatory
31	200	367.113	232.432	117.25	434.507	630	Dibza condo front
32	315	578.203	366.081	117.25	684.349	800	Dibza condo 1
33		0	0		0		
34		0	0		0		
35	200	367.113	232.432	117.25	434.507	630	College gebeyaakababi
36		0	0		0		
37	100	95.556	29.216	-0.08	99.923	100	water well nearcollege
38	100	183.556	116.216	117.25	217.254	315	water well near road
39		0	0		0		
40	630	1156.405	732.162	117.25	1368.698	2000	water booster gotera
41	100	183.556	116.216	117.25	217.254	315	megenteyawofcho
42	630	1156.405	732.162	117.25	1368.698	2000	water booster wonka
43	100	183.556	116.216	117.25	217.254	315	water well nea river
44	100	183.556	116.216	117.25	217.254	315	water well yetjan side
45	100	183.556	116.216	117.25	217.254	315	water well yetjan front
46	50	47.778	14.108	-0.36	49.818	50	water well end
47	200	183.556	116.216	117.25	217.254	315	protestant
48	100	183.556	116.216	117.25	217.254	315	veternary front
49	315	578.203	366.081	117.25	684.349	800	tawulabet dibzcodo2
50	800	183.556	116.216	117.25	217.254	315	dibza condo2
51	100	183.556	116.216	117.25	217.254	315	near yetebaberut
52	25	23.889	7.054	-0.36	24.909	25	tele in college
53	800	183.556	116.216	117.25	217.254	315	college1
54	200	183.556	116.216	117.25	217.254	315	college2
55	200	183.556	116.216	117.25	217.254	315	college near driving
56	200	367.113	232.432	117.25	434.507	630	near DM academy
57	315	578.203	366.081	117.25	684.349	800	gotera
58	200	91.778	58.108	117.25	108.627	200	goteratele
59	100	183.556	116.216	117.25	217.254	315	gozamin school

60	315	578.203	366.081	117.25	684.349	800	fasika school
61	25	23.889	7.054	-0.36	24.909	25	hidasietele
62	200	367.113	232.432	117.25	434.507	630	dibza primary school
63	315	578.203	366.081	117.25	684.349	800	tawulabet right of road
64	315	578.203	366.081	117.25	684.349	630	green area
65	630	1156.405	732.162	117.25	1368.698	2000	technic wofcho
66	200	578.203	366.081	117.25	684.349	800	T/Haymanot church
67	630	367.113	232.432	117.25	434.507	630	bole codomi front
68	315	578.203	366.081	117.25	684.349	800	robgebyawofcho on left
69	315	578.203	366.081	117.25	684.349	800	robgebya near oil on left
70	100	183.556	116.216	117.25	217.254	315	robgebyawofcho
71	100	183.556	116.216	117.25	217.254	315	choke front

Table B. 3: Distribution substation proposed in 2027/28- feeder F4.

NodeNo.	Installed capacity (kVA)	Peak load 2027/28-P (kW)	Peak load 2027/28-Q (kVAR)	Overload of Trans. (%)	Peak load 2027/28(kVA)	New capacity (kVA)	Tr Location
1		0	0		0		
2	200	315.827	199.961	86.9	373.807	630	chemoga
3	630	994.855	629.879	86.9	1177.491	1250	kajima(2*630)
4	100	157.914	99.981	86.9	186.903	200	fm
5	100	157.914	99.981	86.9	186.903	200	yerabamesk≈
6	100	157.914	99.981	86.9	186.903	200	kela school
7		0	0		0		
8	200	315.827	199.961	86.9	373.807	630	condo front(selam f1)
9	630	994.855	629.879	86.9	1177.491	1250	factory(selamf2)
10	200	315.827	199.961	86.9	373.807	630	curve(blocket f)
11	315	497.428	314.939	86.9	588.745	630	blocket factory(raye)
12	100	157.914	99.981	86.9	186.903	200	menkorer taxi front(pole)
13	25	23.889	7.054	-0.36	24.909	25	yetebaruttele
14	315	497.428	314.939	86.9	588.745	630	gozamn police
15		0	0		0		
16	200	315.827	199.961	86.9	373.807	630	k2(newman college)
17	315	497.428	314.939	86.9	588.745	630	zeyas mill(motasfer)
18	630	994.855	629.879	86.9	1177.491	1250	630kva@zeyas
19	100	157.914	99.981	86.9	186.903	200	100KVA@fana college
20		0	0		0		
21	50	78.957	49.99	86.9	93.452	100	above kebt beret
22	315	497.428	314.939	86.9	588.745	630	Dom clinc front(animal)
23	200	315.827	199.961	86.9	373.807	630	timiket front community
24	25	23.889	7.054	-0.36	24.909	25	25KVA@semersland tele
25	100	157.914	99.981	86.9	186.903	200	near semersland
26		0	0		0		
27	315	497.428	314.939	86.9	588.745	630	DMU Endmata
28	630	994.855	629.879	86.9	1177.491	1250	DMU store
29	100	157.914	99.981	86.9	186.903	200	Endmata church
30		0	0		0		
31	630	994.855	629.879	86.9	1177.491	1250	digital lab DMU
32	315	497.428	314.939	86.9	588.745	630	techno college
33	315	497.428	314.939	86.9	588.745	630	males doorm
34	100	157.914	99.981	86.9	186.903	200	police collge1 or era
35	25	23.889	7.054	-0.36	24.909	25	police college tele

36	100	157.914	99.981	86.9	186.903	200	police college front
37	315	497.428	314.939	86.9	588.745	630	road tadele
38	315	497.428	314.939	86.9	588.745	630	shebel front
39		0	0		0		
40	200	315.827	199.961	86.9	373.807	630	near abayikuno
41	630	994.855	629.879	86.9	1177.491	1250	abayikuno condo1
42		0	0		0		
43	630	994.855	629.879	86.9	1177.491	1250	abayikuno condo2(left)
44	100	95.556	29.216	-0.08	99.923	100	habitat tele
45	200	315.827	199.961	86.9	373.807	630	habitat community
46	100	157.914	99.981	86.9	186.903	200	abayikuno (central)
47	100	157.914	99.981	86.9	186.903	200	airport
48	50	47.778	14.108	-0.36	49.818	50	Near DMU tele
49	200	315.827	199.961	86.9	373.807	630	timiket(wuseta)
50	315	497.428	314.939	86.9	588.745	630	tayezeeyt
51	315	497.428	314.939	86.9	588.745	630	Marsilas
52	200	315.827	199.961	86.9	373.807	630	enkutatashtorno
53	630	994.855	629.879	86.9	1177.491	1250	M.kidusan
54	25	39.478	24.995	86.9	46.726	50	A.mariyamtele
55	315	497.428	314.939	86.9	588.745	630	abma school
56	200	315.827	199.961	86.9	373.807	630	below ama school
57	315	497.428	314.939	86.9	588.745	630	filklk end/630
58	200	315.827	199.961	86.9	373.807	630	aba temeenchettera end
59	100	157.914	99.981	86.9	186.903	200	wuseta water well1
60	100	157.914	99.981	86.9	186.903	200	wuseta water well2
61	315	497.428	314.939	86.9	588.745	630	dorm(female)
62	630	994.855	629.879	86.9	1177.491	1250	treatment plant DMU

Appendix C: Upgraded line data

Table C. 1: Expanded network Line Data for (upgraded F3A).

Separate f3A line data @-year 2017/18								Upgraded line data		
Branch no	sending	receiving	conductor type	Length (km)	Resistance (pu)	Reactance (pu)	Current flow(A) during 2027/28	Upgraded conductor	R (pu)	X (pu)
1	1	2	(AAC-95)	6.065	0.836	0.836	368.663	AAC-200	0.445	0.72
2	2	3	(AAC-95)	0.327	0.045	0.045	365.996	AAC-200	0.024	0.039
3	3	4	(AAC-95)	0.35	0.048	0.048	339.997	AAC-150	0.026	0.042
4	4	5	(AAC-95)	0.125	0.017	0.017	330.663	AAC-150	0.009	0.015
5	5	6	(AAC-95)	0.65	0.09	0.09	324.663	AAC-150	0.065	0.08
6	6	7	(AAC-95)	0.53	0.073	0.073	321.33	AAC-150	0.053	0.065
7	7	8	(AAC-95)	0.112	0.015	0.015	301.33	AAC-150	0.011	0.014
8	8	9	(AAC-95)	0.51	0.07	0.07	295.33	AAC-100	0.051	0.063
9	9	10	(AAC-95)	0.28	0.039	0.039	176.665	(AAC-95)	0.039	0.04
10	10	11	(AAC-95)	0.15	0.021	0.021	166.665	(AAC-95)	0.021	0.022
11	11	12	(AAC-95)	0.17	0.023	0.023	159.998	(AAC-95)	0.023	0.024
12	12	13	(AAC-50)	0.0012	0	0	153.332	AAC-95	0.0004	0.0002
13	13	14	(AAC-50)	0.22	0.066	0.066	149.999	AAC-95	0.066	0.035
14	14	15	(AAC-50)	0.282	0.085	0.085	129.999	(AAC-50)	0.085	0.045
15	15	16	(AAC-95)	0.35	0.048	0.048	116.666	(AAC-95)	0.048	0.05
16	16	17	(AAC-95)	0.18	0.025	0.025	113.332	(AAC-95)	0.025	0.026
17	17	18	(AAC-95)	0.1	0.014	0.014	103.332	(AAC-95)	0.014	0.014
18	18	19	(AAC-50)	0.33	0.1	0.1	87.332	(AAC-50)	0.012	0.013
19	19	20	(AAC-50)	0.21	0.063	0.063	77.333	(AAC-50)	0.014	0.015
20	20	21	(AAC-50)	0.76	0.23	0.23	77.333	(AAC-50)	0.017	0.017
21	21	22	(AAC-50)	0.2	0.06	0.06	46.666	(AAC-50)	0.032	0.033
22	22	23	(AAC-50)	0.1	0.03	0.03	36.666	(AAC-50)	0.07	0.073
23	23	24	(AAC-50)	0.75	0.227	0.227	33.333	(AAC-50)	0.048	0.05
24	24	25	(AAC-50)	0.325	0.098	0.098	30	(AAC-50)	0.127	0.068
25	25	26	(AAC-50)	0.163	0.049	0.049	20	(AAC-50)	0.011	0.006
26	3	27	(AAC-50)	0.42	0.127	0.127	26	(AAC-50)	0.015	0.008
27	27	28	(AAC-50)	0.035	0.011	0.011	6	(AAC-50)	0.046	0.024
28	4	29	(AAC-50)	0.05	0.015	0.015	9.333	(AAC-50)	0.055	0.058
29	29	30	(AAC-50)	0.152	0.046	0.046	6	(AAC-50)	0.12	0.125
30	9	31	(AAC-95)	0.4	0.055	0.055	118.665	(AAC-95)	0.04	0.042
31	31	32	(AAC-95)	0.87	0.12	0.12	118.665	(AAC-95)	0.009	0.005
32	32	33	(AAC-95)	0.29	0.04	0.04	98.666	(AAC-95)	0.045	0.024

33	33	34	(AAC-50)	0.03	0.009	0.009	57.999	(AAC-50)	0.015	0.008
34	34	35	(AAC-50)	0.15	0.045	0.045	38	(AAC-50)	0.014	0.007
35	35	36	(AAC-50)	0.05	0.015	0.015	36.666	(AAC-50)	0.136	0.072
36	36	37	(AAC-50)	0.045	0.014	0.014	26.666	(AAC-50)	0.036	0.019
37	37	38	(AAC-50)	0.45	0.136	0.136	6.667	(AAC-50)	0.008	0.004
38	33	39	(AAC-50)	0.12	0.036	0.036	30.666	(AAC-50)	0.01	0.005
39	39	40	(AAC-50)	0.027	0.008	0.008	20.666	(AAC-50)	0.184	0.052
40	40	41	(AAC-50)	0.032	0.01	0.01	0.667	(AAC-50)	0.218	0.062
41	12	42	(AAC-25)	0.31	0.184	0.184	7.333	(AAC-25)	0.007	0.007
42	42	43	(AAC-25)	0.367	0.218	0.218	6.667	(AAC-25)	0.039	0.011
43	15	44	(AAC-95)	0.05	0.007	0.007	13.333	(AAC-95)	0.002	0
44	44	45	Cu -16	0.065	0.055	0.055	3.333	Cu -16	0.071	0.02
45	17	46	(AAC-25)	0.0027	0.002	0.002	10.667	(AAC-25)	0.061	0.017
46	46	47	(AAC-25)	0.12	0.071	0.071	4	(AAC-25)	0.1	0.053
47	47	48	(AAC-25)	0.102	0.061	0.061	0.667	(AAC-25)	0.063	0.034
48	18	49	(AAC-95)	0.09	0.012	0.012	16	(AAC-95)	0.23	0.122
49	49	50	(AAC-95)	0.102	0.014	0.014	16	(AAC-95)	0.06	0.032
50	50	51	(AAC-25)	0.12	0.017	0.017	12.667	(AAC-25)	0.03	0.016
51	51	52	(AAC-95)	0.23	0.032	0.032	8	(AAC-95)	0.227	0.121
52	52	53	Cu-16	0.51	0.127	0.127	6.667	Cu-16	0.098	0.052
53	53	54	(AAC-50)	0.0026	0.001	0.001	3.333	(AAC-50)	0.049	0.026
54	53	55	(AAC-50)	0.023	0.007	0.007	3.333	(AAC-50)	0.106	0.056
55	51	56	(AAC-50)	0.1	0.03	0.03	1.333	(AAC-50)	0.181	0.097
56	56	57	(AAC-50)	0.093	0.028	0.028	30	(AAC-50)	0.03	0.016
57	21	58	(AAC-50)	0.35	0.106	0.106	10	(AAC-50)	0.028	0.015
58	58	59	(AAC-50)	0.6	0.181	0.181	12	(AAC-50)	0.019	0.052

Table C. 2: Expanded network Line Data for (upgraded F3B).

Separate f3B line data @-year 2017/18								Upgraded line data		
Branch no	sending	receiving	conductor type	Length (km)	Resistance (pu)	Reactance (pu)	Current flow(A) during 2027/28	Upgraded conductor	R (pu)	X (pu)
1	1	2	(AAC-95)	12.104	1.668	1.743	402.663	AAC-200	0.888	1.436
2	2	3	(AAC-95)	0.3	0.041	0.043	211.331	AAC-100	0.05	0.052
3	3	4	(AAC-95)	0.36	0.05	0.052	204.665	AAC-100	0.022	0.023
4	4	5	(AAC-50)	0.16	0.048	0.026	204.665	AAC-100	0.032	0.017
5	5	6	(AAC-50)	0.105	0.032	0.017	189.998	AAC-95	0.034	0.018
6	6	7	(AAC-50)	0.112	0.034	0.018	179.332	AAC-95	0.033	0.018
7	7	8	(AAC-95)	0.11	0.015	0.016	175.998	(AAC-95)	0.017	0.017
8	8	9	(AAC-95)	0.12	0.017	0.017	165.332	(AAC-95)	0.01	0.01
9	9	10	(AAC-95)	0.07	0.01	0.01	154.665	(AAC-95)	0.026	0.027
10	10	11	(AAC-95)	0.19	0.026	0.027	147.999	(AAC-95)	0.011	0.012
11	11	12	(AAC-95)	0.08	0.011	0.012	147.332	(AAC-95)	0.006	0.006
12	12	13	(AAC-95)	0.04	0.006	0.006	147.332	(AAC-95)	0.008	0.009
13	13	14	(AAC-95)	0.06	0.008	0.009	119.332	(AAC-95)	0.006	0.006
14	14	15	(AAC-95)	0.04	0.006	0.006	108.666	(AAC-95)	0.034	0.036
15	15	16	(AAC-95)	0.25	0.034	0.036	108.666	(AAC-95)	0.025	0.026
16	16	17	(AAC-95)	0.18	0.025	0.026	65.999	(AAC-95)	0.023	0.024
17	17	18	(AAC-95)	0.17	0.023	0.024	62.666	(AAC-95)	0.128	0.134
18	18	19	(AAC-95)	0.93	0.128	0.134	60.666	(AAC-95)	0.756	0.791
19	19	20	(AAC-95)	5.49	0.756	0.791	53.999	(AAC-95)	0.594	0.621
20	20	21	(AAC-95)	4.31	0.594	0.621	50.666	(AAC-95)	0.619	0.647
21	21	22	(AAC-95)	4.49	0.619	0.647	43.333	(AAC-95)	0.028	0.029
22	22	23	(AAC-95)	0.2	0.028	0.029	42	(AAC-95)	0.777	0.812
23	23	24	(AAC-95)	5.64	0.777	0.812	40.666	(AAC-95)	0.383	0.4
24	24	25	(AAC-95)	2.78	0.383	0.4	40.666	(AAC-95)	0.041	0.043
25	25	26	(AAC-95)	0.3	0.041	0.043	24.666	(AAC-95)	0.006	0.006
26	26	27	(AAC-95)	0.04	0.006	0.006	18	(AAC-95)	0.012	0.013
27	27	28	(AAC-50)	0.09	0.027	0.014	18	(AAC-50)	0.133	0.071
28	28	29	(AAC-50)	0.44	0.133	0.071	8.667	(AAC-50)	0.187	0.1
29	29	30	(AAC-50)	0.62	0.187	0.1	7.333	(AAC-50)	0.136	0.072
30	2	31	(AAC-95)	0.45	0.062	0.065	184.665	(AAC-95)	0.004	0.004
31	31	32	(AAC-95)	0.026	0.004	0.004	173.998	(AAC-95)	0.036	0.038
32	32	33	(AAC-95)	0.262	0.036	0.038	173.998	(AAC-95)	0.03	0.032
33	33	34	(AAC-95)	0.22	0.03	0.032	159.998	(AAC-95)	0.025	0.026

34	34	35	(AAC-95)	0.18	0.025	0.026	121.999	(AAC-95)	0.025	0.026
35	35	36	(AAC-95)	0.18	0.025	0.026	121.999	(AAC-95)	0.046	0.048
36	36	37	(AAC-95)	0.333	0.046	0.048	80.666	(AAC-95)	0.028	0.029
37	37	38	(AAC-95)	0.2	0.028	0.029	77.333	(AAC-95)	0.076	0.08
38	38	39	(AAC-95)	0.554	0.076	0.08	77.333	(AAC-95)	0.169	0.177
39	39	40	(AAC-95)	1.23	0.169	0.177	44	(AAC-95)	0.519	0.543
40	40	41	(AAC-95)	3.77	0.519	0.543	40.666	(AAC-95)	0.08	0.084
41	41	42	(AAC-95)	0.58	0.08	0.084	18.666	(AAC-95)	0.109	0.114
42	42	43	(AAC-95)	0.79	0.109	0.114	15.333	(AAC-95)	0.081	0.085
43	43	44	(AAC-95)	0.59	0.081	0.085	12	(AAC-95)	0.006	0.006
44	44	45	(AAC-95)	0.04	0.006	0.006	8.667	(AAC-95)	0.094	0.098
45	45	46	(AAC-95)	0.68	0.094	0.098	6.667	(AAC-95)	0.022	0.023
46	33	47	(AAC-50)	0.162	0.049	0.026	3.333	(AAC-50)	0.008	0.004
47	33	48	(AAC-50)	0.027	0.008	0.004	10.667	(AAC-50)	0.044	0.023
48	34	49	(AAC-50)	0.145	0.044	0.023	30.666	(AAC-50)	0.057	0.031
49	49	50	(AAC-50)	0.19	0.057	0.031	3.333	(AAC-50)	0.005	0.002
50	34	51	(AAC-25)	0.015	0.009	0.002	0.667	(AAC-25)	0.024	0.006
51	36	52	(AAC-50)	0.04	0.012	0.006	38	(AAC-50)	0.012	0.006
52	52	53	(AAC-50)	0.04	0.012	0.006	16.667	(AAC-50)	0.036	0.019
53	53	54	(AAC-50)	0.12	0.036	0.019	13.333	(AAC-50)	0.085	0.045
54	54	55	(AAC-50)	0.28	0.085	0.045	10	(AAC-50)	0.039	0.021
55	55	56	(AAC-50)	0.13	0.039	0.021	6.667	(AAC-50)	0.051	0.027
56	39	57	(AAC-50)	0.17	0.051	0.027	3.333	(AAC-50)	0.053	0.028
57	39	58	(AAC-50)	0.175	0.053	0.028	8.667	(AAC-50)	0.076	0.04
58	58	59	(AAC-50)	0.25	0.076	0.04	6.667	(AAC-50)	0.079	0.042
59	5	60	(AAC-50)	0.26	0.079	0.042	10.667	(AAC-50)	0.028	0.015
60	60	61	(AAC-50)	0.091	0.028	0.015	10	(AAC-50)	0.121	0.064
61	61	62	(AAC-50)	0.4	0.121	0.064	6.667	(AAC-50)	0.1	0.053
62	13	63	(AAC-95)	0.33	0.045	0.048	17.333	(AAC-95)	0.031	0.032
63	63	64	(AAC-95)	0.222	0.031	0.032	10.667	(AAC-95)	0.029	0.03
64	16	65	(AAC-50)	0.21	0.063	0.03	14	(AAC-50)	0.332	0.158
65	65	66	(AAC-50)	1.1	0.332	0.158	10.667	(AAC-50)	0.034	0.016
66	16	67	(AAC-95)	0.1126	0.016	0.016	6.667	(AAC-95)	0.028	0.029
67	25	68	(AAC-95)	0.2	0.028	0.029	8.667	(AAC-95)	0.008	0.009
68	68	69	(AAC-95)	0.06	0.008	0.009	2	(AAC-95)	0.052	0.055
69	28	70	(AAC-95)	0.38	0.052	0.055	2	(AAC-95)	0.047	0.049
70	70	71	(AAC-95)	0.34	0.047	0.049	2	(AAC-95)	0.047	0.049

Table C. 3: Expanded network Line Data for (upgraded F4).

Branch no	Sending	Receiving	Length (km)	Existing conductor type	Current flow(A) during 2027/28	Upgraded conductor	Upgraded line data	
							R (pu)	X (pu)
1	1	2	3.47	(AAC-95)	376.663	AAC-200	0.254	0.412
2	2	3	0.59	(AAC-95)	371.33	AAC-200	0.043	0.07
3	3	4	0.56	(AAC-95)	355.996	AAC-200	0.041	0.066
4	4	5	0.74	(AAC-95)	353.33	AAC-200	0.054	0.088
5	5	6	0.15	(AAC-95)	350.663	AAC-200	0.011	0.018
6	6	7	0.67	(AAC-95)	347.997	AAC-200	0.049	0.08
7	7	8	0.401	(AAC-95)	341.997	AAC-200	0.029	0.048
8	8	9	0.11	(AAC-95)	336.663	AAC-150	0.008	0.013
9	9	10	0.26	(AAC-95)	320.663	AAC-150	0.026	0.032
10	10	11	0.14	(AAC-95)	315.33	AAC-150	0.014	0.017
11	11	12	0.31	(AAC-95)	307.33	AAC-150	0.031	0.038
12	12	13	0.16	(AAC-50)	304.664	AAC-150	0.016	0.02
13	13	14	1.37	(AAC-50)	303.997	AAC-150	0.136	0.169
14	14	15	0.72	(AAC-50)	295.33	AAC-100	0.072	0.089
15	15	16	0.34	(AAC-95)	217.998	AAC-100	0.047	0.049
16	16	17	0.14	(AAC-95)	212.665	AAC-100	0.019	0.02
17	17	18	0.06	(AAC-95)	203.998	AAC-100	0.008	0.009
18	18	19	0.03	(AAC-95)	186.665	(AAC-95)	0.004	0.004
19	19	20	0.12	(AAC-95)	183.998	(AAC-95)	0.017	0.017
20	20	21	0.03	(AAC-25)	114.666	AAC-50	0.009	0.005
21	21	22	0.23	(AAC-25)	113.332	AAC-50	0.07	0.037
22	22	23	0.08	(AAC-25)	104.666	(AAC-25)	0.048	0.014
23	23	24	0.1	(AAC-25)	99.332	(AAC-25)	0.059	0.017
24	24	25	0.05	(AAC-25)	98.666	(AAC-25)	0.03	0.008

25	25	26	0.35	(AAC-25)	95.999	(AAC-25)	0.208	0.059
26	26	27	0.29	(AAC-25)	89.999	(AAC-25)	0.172	0.049
27	27	28	0.06	(AAC-25)	81.333	(AAC-25)	0.036	0.01
28	28	29	0.3	(AAC-25)	63.999	(AAC-25)	0.178	0.051
29	29	30	0.31	(AAC-25)	61.333	(AAC-25)	0.184	0.052
30	2	31	0.15	(AAC-25)	35.333	(AAC-25)	0.089	0.025
31	31	32	0.16	(AAC-25)	17.333	(AAC-25)	0.095	0.027
32	32	33	0.218	(AAC-25)	8.667	(AAC-25)	0.13	0.037
33	33	34	0.3	(AAC-25)	6	(AAC-25)	0.178	0.051
34	34	35	0.14	(AAC-25)	3.333	(AAC-25)	0.083	0.024
35	35	36	0.12	(AAC-25)	2.667	(AAC-25)	0.071	0.02
36	36	37	0.24	(AAC-95)	17.333	(AAC-95)	0.033	0.035
37	37	38	0.29	(AAC-95)	8.667	(AAC-95)	0.04	0.042
38	38	39	0.45	(AAC-95)	59.999	(AAC-95)	0.062	0.065
39	39	40	0.3	(AAC-95)	53.333	(AAC-95)	0.041	0.043
40	40	41	0.13	(AAC-95)	48	(AAC-95)	0.018	0.019
41	41	42	0.08	(AAC-95)	30.666	(AAC-95)	0.011	0.012
42	42	43	0.12	(AAC-95)	25.333	(AAC-95)	0.017	0.017
43	43	44	0.26	(AAC-95)	8	(AAC-95)	0.036	0.037
44	44	45	0.213	(AAC-95)	5.333	(AAC-95)	0.029	0.031
45	45	46	0.0017	(AAC-25)	2.667	(AAC-25)	0	0
46	33	47	0.24	(AAC-95)	2.667	(AAC-95)	0.033	0.035
47	33	48	0.18	(AAC-95)	6.667	(AAC-95)	0.025	0.026
48	34	49	0.27	(AAC-95)	5.333	(AAC-95)	0.037	0.039
49	49	50	0.11	(AAC-50)	69.333	(AAC-50)	0.033	0.018
50	34	51	0.373	(AAC-50)	60.666	(AAC-50)	0.113	0.06
51	36	52	0.271	(AAC-50)	51.999	(AAC-50)	0.082	0.044
52	52	53	0.36	(AAC-50)	46	(AAC-50)	0.109	0.058
53	53	54	0.36	(AAC-50)	29.333	(AAC-50)	0.109	0.058
54	54	55	0.04	(AAC-50)	28	(AAC-50)	0.012	0.006
55	55	56	0.19	(AAC-50)	19.333	(AAC-50)	0.057	0.031

56	39	57	0.45	(AAC-50)	14	(AAC-50)	0.136	0.072
57	39	58	0.36	(AAC-50)	5.333	(AAC-50)	0.109	0.058
58	58	59	0.445	(AAC-25)	5.333	(AAC-25)	0.265	0.075
59	5	60	0.58	(AAC-25)	2.667	(AAC-25)	0.345	0.098
60	60	61	0.14	(AAC-25)	26	(AAC-25)	0.083	0.024
61	61	62	0.43	(AAC-25)	17.333	(AAC-25)	0.256	0.073

Appendix D: Electrical specification of conductors and transformers

Table D. 1: Electrical Parameters of Conductors [84], [85]

No.	Conductor Size (mm^2)	Current carrying capacity (A)	R (Ω/ km)	X (Ω/ km)
1	AAC-25	110	1.338	0.38
2	AAC-50	139	0.68	0.362
3	AAC- 95	197	0.31	0.324
4	AAC-100	297	0.366	0.296
5	AAC-150	342	0.224	0.277
6	AAC-200	412	0.165	0.267
7	AAC-250	471	0.133	0.26
8	AAC-300	530	0.11	0.254
9	AAC-400	616	0.086	0.245

Table D. 2: Distribution Transformer Capacities with R X Values [57],[85]

Transformer capacity (kVA)	Iron Loss(KW)	Copper Loss(KW)	Impedance (%)
25	0.08	0.6	4.5
50	0.16	1.1	4.5
100	0.26	1.8	5
200	0.62	3.7	5
315	0.8	5.3	5.5
630	1.5	6.8	6
800	1.9	10	6
1000	2.2	12	6
1250	2.5	15	6
2000	6	24	6
5000	8.19	32.3	6.92

Appendix E: Single line diagrams of expanded feeders with the proposed DG locations

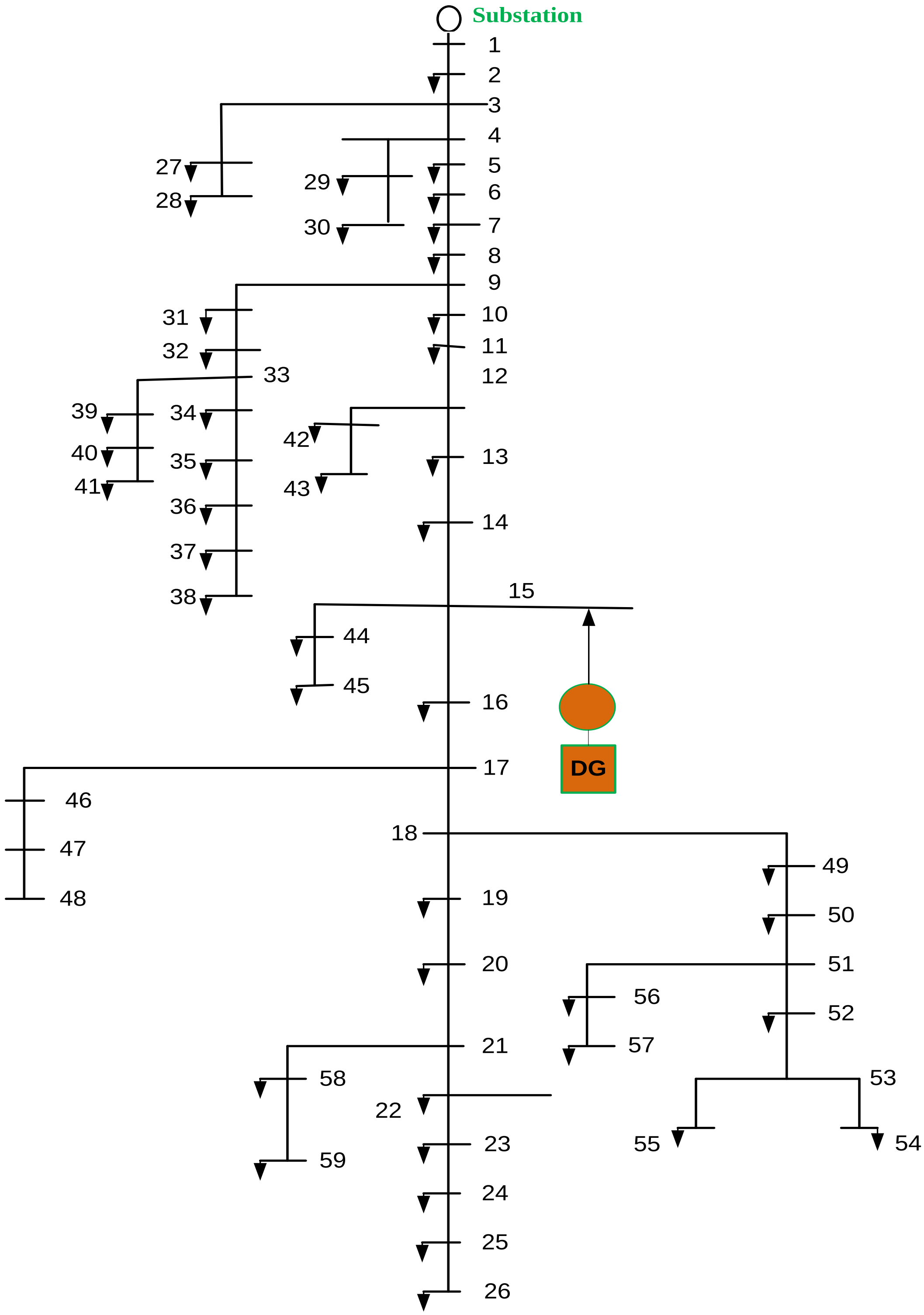

Figure E.1: Single line diagram of separated feeder F3A with its DG location by using GrMHSA.

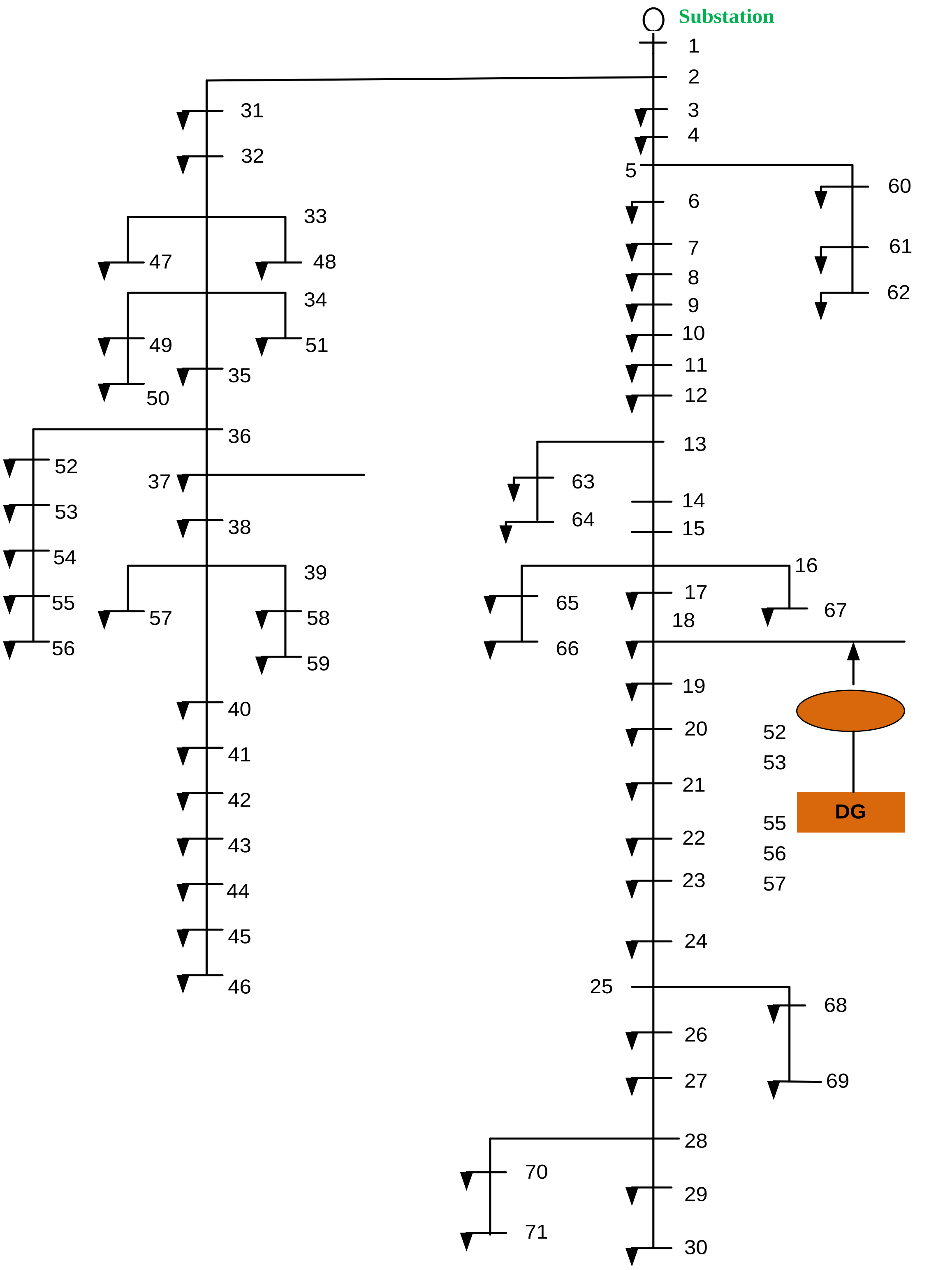

Figure E.2: Single line diagram of separated feeder F3B with its DG location by using GrMHSA.

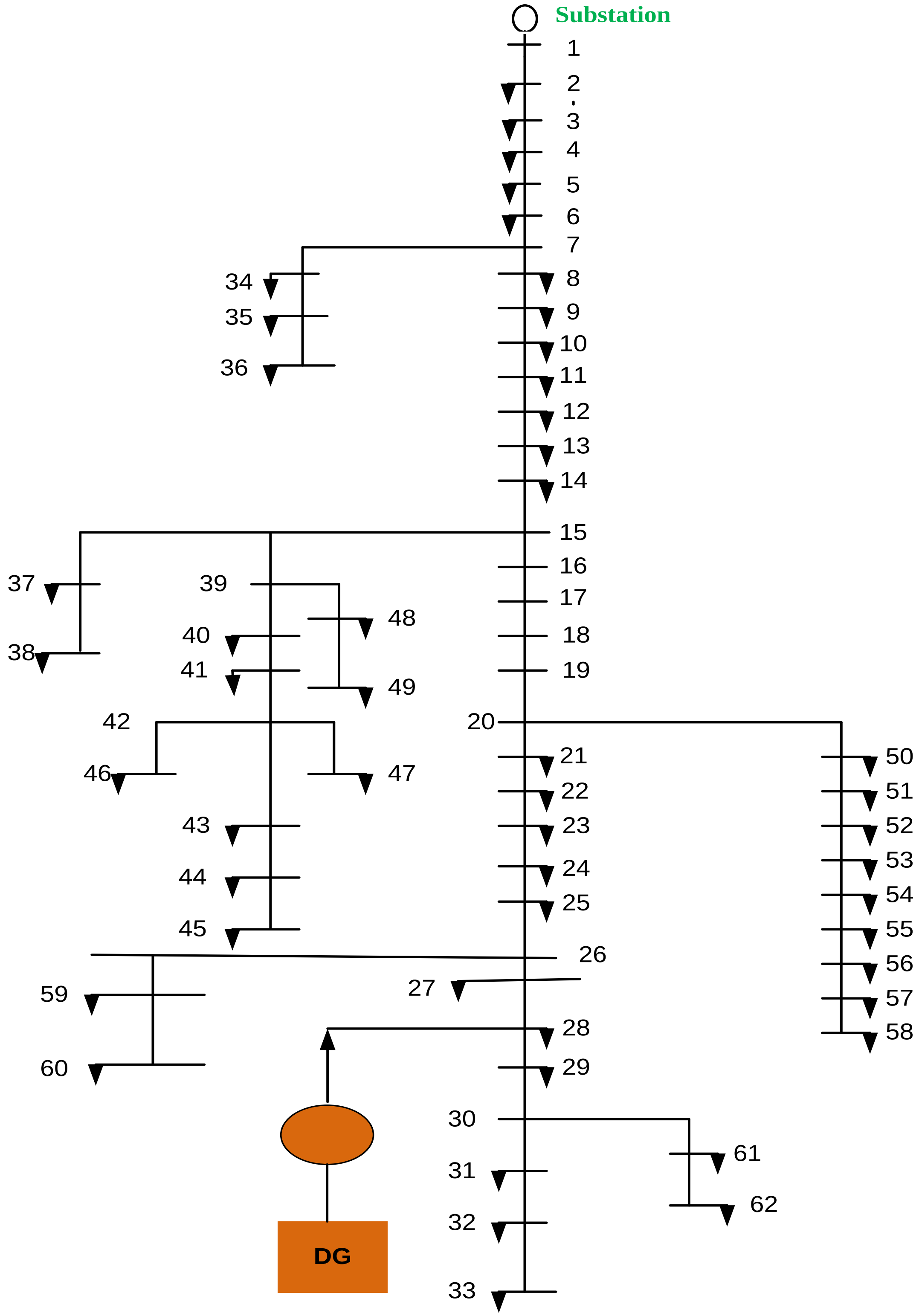

Figure E. 3: Single line diagram of expanded feeder F4 with its DG location by using GrMHSA.

Appendix F: Sample Matlab Codes

F.1: Sample Matlab Code for Optimal Placement and Sizing of DG

```
% Optimal placement and sizing of DGs in distribution networks using Grid-
based Multi-objective Harmony Search Algorithm (GrMHS)
% Basic code of GrMHS was developed

%% The GrMHS code was addapted for the problem of optimal placement and sizing
of DGs in distribution network

function [Solution,OptimumValue,Solutions,Frontiers,X,P]=GrMHS()
clc;
%% Step 1: Input algorithm parameters (GrMHS Parametters)
HMCR=0.9;% Harmony Memory Considering Rate
PAR=0.1;  % Pitch Adjustment Rate
bw=0.2;   % distance Bandwidth
N=50;     % Harmony Memory Size (Population Size)
Div=10;   % Number of Divisions of the Objective Space
MaxItr=200;% Maximum Number of Iteration
% Problem Prameters
[~,~,dg]=Data_Bus59;   % distribution system data
ndg=length(dg(:,1));  % number of DGs
Sdgmin=dg(:,2)';
Sdgmax=dg(:,3)';
Busmin=zeros(1,ndg);
Busmax=zeros(1,ndg);
Busmin(1:ndg)=1;
Busmax(1:ndg)=59;
Low=[Busmin Sdgmin];
% Low=[52 10 7  Sdgmin];
rng(0)
High=[Busmax Sdgmax];
% High=[41 25 32   Sdgmax];
D=2*ndg;

Fun={@Fobj1; @Fobj3};
% Fobj1 - calculation of active power loss
% Fobj2 - calculation of reactive power loss
% Fobj3 - calculation of voltage deviation
%% Step 2: Initialization of randomly generated population.
Low=repmat(Low,N,1);
Range=repmat(High,N,1)-Low;
X=Low+Range.*rand(N,D);
%% Step 3: Evaluate the objectives for the initialized population
P=Obj(X,Fun);
RandomizeIndex=zeros(N,D);
%% Step 4: While termination criteria is not met do Iteration Loop
for Itr=1:MaxItr
    fprintf('Runing GrMHS : % 3.0f %%\n',Itr/MaxItr*100);
%% Step 5: Harmony search improvisation process on the decisionvariables.
for d=1:D
        RandomizeIndex(:,d)=randperm(N);
end
    CMMask=rand(N,D)<HMCR;   % Memory Considering Harmonies Mask
    NHMask=~CMMask;          % New Harmonies Mask
```

```
    PAMask=(rand(N,D)<PAR) & CMMask;% Pitch Adjusted Harmonies Mask
    CMMask=CMMask & (~PAMask);
    XNew=CMMask.* X(RandomizeIndex) + ... Memory Considering
         PAMask.*(X(RandomizeIndex) + bw*(2*rand(N,D)-1)) + ...Pitch Adjusted
Harmonies
         NHMask.*(Low+Range.*rand(N,D));% New Harmonies
% Evalute Objective Function
    PNew=Obj(XNew,Fun);
%% Step 6: Intermediate population
    XHat=[X;XNew];
    PHat=[P;PNew];
%% Step 7: Environmental selection
    [X,P]=EnvironmentalSelection(XHat,PHat,N,Div);
%% Step 8: end iter
end
%% Step 9: Fuzzy set theory to select the best solution from the pareto set
n=size(P,1);
Mu=(repmat(max(P),n,1)-P)./...
    repmat(max(P)-min(P),n,1);
MuHat=sum(Mu,2)/sum(sum(Mu));

[~,Best]=max(MuHat);
Solution=X(Best,:);
OptimumValue=P(Best,:);
fprintf(['\nSolution is [ ',sprintf('%4.3f ',Solution),']\n','Objective
Function Value = [ ',sprintf('%4.3f ',OptimumValue),']\n']);
%% Generate final results based on optimal control variables
Lbest=Solution;
Lbest(1:ndg)=round(Lbest(1:ndg));
BWFWSLF(Lbest);
end
function P=Obj(X,Fun)
M=length(Fun);
N=size(X,1);
P=zeros(N,M);
for i=1:N
for k=1:M
        P(i,k)=Fun{k}(X(i,:));
end
end
end
function [XSelected,PSelected]=EnvironmentalSelection(X,P,N,Div)
NN=size(X,1);
Q=zeros(N,1);
F=1:NN;
for i=1:N
    [GR,GCD,GCPD]=ExtractGridRelatedValues(P(F,:),Div);
    Best=find(GR==min(GR));
if length(Best)>1
        Best=Best(GCD(Best)==min(GCD(Best)));
if length(Best)>1
            [~,BestHat]=min(GCPD(Best));
            Best=Best(BestHat);
end
end
    Q(i)=F(Best);
    F(Best)=[];
```

```
end
XSelected=X(Q,:);
PSelected=P(Q,:);
end
function [GR,GCD,GCPD]=ExtractGridRelatedValues(P,Div)
[N,M]=size(P);
ll= min(P)-(max(P)-min(P))/(2*Div); % Eq1 [1]
ul= max(P)+(max(P)-min(P))/(2*Div); % Eq2 [1]
w =(ul-ll)/Div;
LL=repmat(ll,N,1);
W =repmat(w ,N,1);
G=floor((P-LL)./W);
 [A,B]=meshgrid(1:N,1:N);
GD=zeros(N,N);
for k=1:M
    GD(:)=GD(:)+abs(G(A(:),k)-G(B(:),k));
end
GR=sum(G,2); %Eq7 [1]
FGD=GD;% Filtered GD
FGD(GD>M)=M; % This solutions are not the neighbors and this filter rule out
them from summation
GCD=sum(M-FGD,2); %Eq8 [1]
GCPD=sqrt(sum(((P-(LL+G.*W))./W).^2,2)); %Eq9 [1]
End
```

F.2: Sample Matlab Code to Calculate Total Active Power Loss

```
function y=Fobj1(x)
% Calculate objective function. Fobj1 is total active power loss (sum_ploss)
for given x
% Fobj1 is evaluated by power flow calculation for x which define locations
and powers of DGs
%=========================================================================
[branch,bus,dg]=Data_Bus59;
% Branch data
%-------------------------------------------------------------------------
[ngr,~]=size(branch);
bus_i=branch(:,1);
bus_j=branch(:,2);
element=branch(:,3);
rbr=branch(:,4);
xbr=branch(:,5);
zbr=(rbr+1i*xbr);

%bus incidence matrix
for k=1:ngr
    inc(bus_i(k),bus_j(k))=1;
    inc(bus_j(k),bus_i(k))=1;
end

% Bus data
%-------------------------------------------------------------------------
[nbus,~]=size(bus);
Bus=bus(:,1);
typebus=bus(:,2);
V0=bus(:,3);
```

```
theta0=bus(:,4);
pgen=bus(:,5);
qgen=bus(:,6);
pload=bus(:,7);
qload=bus(:,8);
Sload=pload+1i*qload;

%DG
ndg=length(dg(:,1));
cosfidg=dg(:,4);

xlok=zeros(1,ndg);
xpow=zeros(1,ndg);
xlok=round(x(1:ndg));    %location of DG as result from PSO
xpow=x(ndg+1:2*ndg);     %size (npominal power) of DG at determined location as
result from PSO
for k=1:ndg
    pgen(xlok(k))=xpow(k)*cosfidg(k);
    qgen(xlok(k))=pgen(xlok(k))*tan(acos(cosfidg(k)));
end
Sgen=pgen+1i*qgen;
%----------------------------------------------------------------------------

% Initialization
U=V0.*(cos(theta0)+1i*sin(theta0));
Ipot=zeros(1,nbus-1);
Igen=zeros(1,nbus-1);
%============================================================================
% Iterative procedure
%============================================================================
% Converegence conditions
iter=0; itermax=1000;
epsilon=0.0001;
maxraz=epsilon+1;
while (iter < itermax) && (maxraz > epsilon)
    iter=iter+1;
    Unew=U;
    qgennew=qgen;
for k=1:nbus-1
if typebus(k)==21
            Ipot(k)=conj(Sload(k))/conj(Unew(k));
            Igen(k)=conj(pgen(k)+1i*qgen(k))/conj(Unew(k));
elseif typebus(k)==22
            Ipot(k)=abs(conj(Sload(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sload(k))));
            Igen(k)=abs(conj(Sgen(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sgen(k))));
elseif typebus(k)==23
            Ipot(k)=Unew(k)*conj(Sload(k))/abs(V0(k)^2);
elseif typebus(k)==11
            Igen(k)=conj(pgen(k)+1i*qgennew(k))/conj(Unew(k));
            Ipot(k)=conj(Sload(k))/conj(Unew(k));
end
end
%----------------------------------------------------------------------------
%Backward sweep:
```

```
for k=1:nbus-1
        I(k)=Ipot(k)-Igen(k);
end
    J(nbus)=0;
for k=1:nbus-1
        sumi=0;
for kk=1:k
if inc(nbus-k,nbus-k+kk)==1
                sumi=sumi+J(nbus-k+kk);
end
end
        J(nbus-k)=I(nbus-k)+sumi;
end
    J0=0;
for k=1:nbus
if inc(nbus,k)==1
            J0=J0+J(k);
end
end
    J(nbus)=J0;
%-------------------------------------------------------------------------
% Forward sweep:
for k=1:nbus-1
if inc(k,nbus)==1
            U(k)=Unew(nbus)-zbr(k)*J(k);
end
end
for k=2:nbus-1
for kk=1:k-1
if inc(k,kk)==1
                U(k)=U(kk)-zbr(k)*J(k);
end
end
end
%----------------------------------------------------------------------
% Checking the convergence criteria:
    maxraz=max(abs(Unew-U));
end% End of iterative procedure
%==========================================================================

% Power loss in branches and voltage deviation at buses
for k=1:nbus-1
    ploss(k)=real(zbr(k))*(abs(J(k)))^2;
    qloss(k)=imag(zbr(k))*(abs(J(k)))^2;
    deltaV(k)=abs(abs(U(k))-1);
end
% Total power loss:
sum_ploss=sum(ploss);
sum_qloss=sum(qloss);
% Total voltage deviation
sum_deltaV=sum(deltaV);
y=sum_ploss;
end
```

F.3: Sample Matlab Code to Calculate Total Reactive Power Loss

```
function y=Fobj2(x)
% Calculate objective function.  Fobj2 is total reactive power loss
(sum_qloss) for given x
% Fobj2 is evaluated by power flow calculation for x which define locations
and powers of DGs
%==========================================================================
[branch,bus,dg]=Data_Bus59;
% Branch data
%--------------------------------------------------------------------------
[ngr,~]=size(branch);
bus_i=branch(:,1);
bus_j=branch(:,2);
element=branch(:,3);
rbr=branch(:,4);
xbr=branch(:,5);
zbr=(rbr+1i*xbr);

%bus incidence matrix
for k=1:ngr
    inc(bus_i(k),bus_j(k))=1;
    inc(bus_j(k),bus_i(k))=1;
end

% Bus data
%--------------------------------------------------------------------------
[nbus,~]=size(bus);
Bus=bus(:,1);
typebus=bus(:,2);
V0=bus(:,3);
theta0=bus(:,4);
pgen=bus(:,5);
qgen=bus(:,6);
pload=bus(:,7);
qload=bus(:,8);
Sload=pload+1i*qload;

%DG
ndg=length(dg(:,1));
cosfidg=dg(:,4);

xlok=zeros(1,ndg);
xpow=zeros(1,ndg);
xlok=round(x(1:ndg));    %location of DG as result from PSO
xpow=x(ndg+1:2*ndg);     %size (npominal power) of DG at determined location as
result from PSO
for k=1:ndg
    pgen(xlok(k))=xpow(k)*cosfidg(k);
    qgen(xlok(k))=pgen(xlok(k))*tan(acos(cosfidg(k)));
end
Sgen=pgen+1i*qgen;
%--------------------------------------------------------------------------

% Initialization
U=V0.*(cos(theta0)+1i*sin(theta0));
Ipot=zeros(1,nbus-1);
Igen=zeros(1,nbus-1);
```

```
%==========================================================================
% Iterative procedure
%==========================================================================
% Converegence conditions
iter=0; itermax=1000;
epsilon=0.0001;
maxraz=epsilon+1;
while (iter < itermax) && (maxraz > epsilon)
    iter=iter+1;
    Unew=U;
    qgennew=qgen;
for k=1:nbus-1
if typebus(k)==21
            Ipot(k)=conj(Sload(k))/conj(Unew(k));
            Igen(k)=conj(pgen(k)+1i*qgen(k))/conj(Unew(k));
elseif typebus(k)==22
            Ipot(k)=abs(conj(Sload(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sload(k))));
            Igen(k)=abs(conj(Sgen(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sgen(k))));
elseif typebus(k)==23
            Ipot(k)=Unew(k)*conj(Sload(k))/abs(V0(k)^2);
elseif typebus(k)==11
            Igen(k)=conj(pgen(k)+1i*qgennew(k))/conj(Unew(k));
            Ipot(k)=conj(Sload(k))/conj(Unew(k));
end
end
%--------------------------------------------------------------------------
%Backward sweep:
for k=1:nbus-1
        I(k)=Ipot(k)-Igen(k);
end
    J(nbus)=0;
for k=1:nbus-1
        sumi=0;
for kk=1:k
if inc(nbus-k,nbus-k+kk)==1
                sumi=sumi+J(nbus-k+kk);
end
end
        J(nbus-k)=I(nbus-k)+sumi;
end
    J0=0;
for k=1:nbus
if inc(nbus,k)==1
            J0=J0+J(k);
end
end
    J(nbus)=J0;
%--------------------------------------------------------------------------
% Forward sweep:
for k=1:nbus-1
if inc(k,nbus)==1
            U(k)=Unew(nbus)-zbr(k)*J(k);
end
end
for k=2:nbus-1
```

```
for kk=1:k-1
if inc(k,kk)==1
                U(k)=U(kk)-zbr(k)*J(k);
end
end
end
% Checking the convergence criteria:
    maxraz=max(abs(Unew-U));
end% End of iterative procedure
%===========================================================================
% Power loss in branches and voltage deviation at buses
for k=1:nbus-1
    ploss(k)=real(zbr(k))*(abs(J(k)))^2;
    qloss(k)=imag(zbr(k))*(abs(J(k)))^2;
    deltaV(k)=abs(abs(U(k))-1);
end
% Total power loss:
sum_ploss=sum(ploss);
sum_qloss=sum(qloss);
% Total voltage deviation
sum_deltaV=sum(deltaV);

y=sum_qloss;
end
```

F.4: Sample Matlab Code to Calculate Total Voltage Deviation

```
function y=Fobj3(x)
% Calculate objective function. Fobj3 is total voltage deviation at buses
(sum_deltaV) for given x
% Fobj3 is evaluated by power flow calculation for x which define locations
and powers of DGs
%==========================================================================
[branch,bus,dg]=Data_Bus59;
% Branch data
%---------------------------------------------------------------------------
[ngr,~]=size(branch);
bus_i=branch(:,1);
bus_j=branch(:,2);
element=branch(:,3);
rbr=branch(:,4);
xbr=branch(:,5);
zbr=(rbr+1i*xbr);
%bus incidence matrix
for k=1:ngr
    inc(bus_i(k),bus_j(k))=1;
    inc(bus_j(k),bus_i(k))=1;
end
% Bus data
[nbus,~]=size(bus);
Bus=bus(:,1);
typebus=bus(:,2);
V0=bus(:,3);
theta0=bus(:,4);
pgen=bus(:,5);
qgen=bus(:,6);
```

```
pload=bus(:,7);
qload=bus(:,8);
Sload=pload+1i*qload;
%DG
ndg=length(dg(:,1));
cosfidg=dg(:,4);
xlok=zeros(1,ndg);
xpow=zeros(1,ndg);
xlok=round(x(1:ndg));    %location of DG as result from PSO
xpow=x(ndg+1:2*ndg);     %size (npominal power) of DG at determined location as
result from PSO
for k=1:ndg
    pgen(xlok(k))=xpow(k)*cosfidg(k);
    qgen(xlok(k))=pgen(xlok(k))*tan(acos(cosfidg(k)));
end
Sgen=pgen+1i*qgen;
%--------------------------------------------------------------------------

% Initialization
U=V0.*(cos(theta0)+1i*sin(theta0));
Ipot=zeros(1,nbus-1);
Igen=zeros(1,nbus-1);
%==========================================================================
% Iterative procedure
%==========================================================================
% Converegence conditions
iter=0; itermax=1000;
epsilon=0.0001;
maxraz=epsilon+1;
while (iter < itermax) && (maxraz > epsilon)
    iter=iter+1;
    Unew=U;
    qgennew=qgen;
for k=1:nbus-1
if typebus(k)==21
            Ipot(k)=conj(Sload(k))/conj(Unew(k));
            Igen(k)=conj(pgen(k)+1i*qgen(k))/conj(Unew(k));
elseif typebus(k)==22
            Ipot(k)=abs(conj(Sload(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sload(k))));
            Igen(k)=abs(conj(Sgen(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sgen(k))));
elseif typebus(k)==23
            Ipot(k)=Unew(k)*conj(Sload(k))/abs(V0(k)^2);
elseif typebus(k)==11
            Igen(k)=conj(pgen(k)+1i*qgennew(k))/conj(Unew(k));
            Ipot(k)=conj(Sload(k))/conj(Unew(k));
end
end
%Backward sweep:
for k=1:nbus-1
        I(k)=Ipot(k)-Igen(k);
end
    J(nbus)=0;
for k=1:nbus-1
        sumi=0;
for kk=1:k
```

```
if inc(nbus-k,nbus-k+kk)==1
                sumi=sumi+J(nbus-k+kk);
end
end
        J(nbus-k)=I(nbus-k)+sumi;
end
    J0=0;
for k=1:nbus
if inc(nbus,k)==1
            J0=J0+J(k);
end
end
    J(nbus)=J0;
%---------------------------------------------------------------------------
% Forward sweep:
for k=1:nbus-1
if inc(k,nbus)==1
            U(k)=Unew(nbus)-zbr(k)*J(k);
end
end
for k=2:nbus-1
for kk=1:k-1
if inc(k,kk)==1
                U(k)=U(kk)-zbr(k)*J(k);
end
end
end
%-----------------------------------------------------------------------
% Checking the convergence criteria:
    maxraz=max(abs(Unew-U));
end% End of iterative procedure
%===========================================================================
% Power loss in branches and voltage deviation at buses
for k=1:nbus-1
    ploss(k)=real(zbr(k))*(abs(J(k)))^2;
    qloss(k)=imag(zbr(k))*(abs(J(k)))^2;
    deltaV(k)=abs(abs(U(k))-1);
end
% Total power loss:
sum_ploss=sum(ploss);
sum_qloss=sum(qloss);
% Total voltage deviation
sum_deltaV=sum(deltaV);
% Vp=abs(U)
y=sum_deltaV;
end
```

F.5: Line and Bus Data

```
function [branch,bus,dg,Sbase,Vbase,Ibase,loadlevel]=Data_Bus59
%---------------------------------------------------------------------------
Sbase=1; %MVA
Vbase=15; %kV
Zbase=Vbase^2/Sbase;  %Base impendance in (Om)
Ibase=Sbase/(sqrt(3)*Vbase)*1e3;  %Base current in (A)
%===========================================================================
% branch - data on netwotk elements (given in per unit system)
%---------------------------------------------------------------------------
```

```
% bus_i -> bus_j - indexes of buses conected by a branch (line or transformer)
% |bus_i  -> bus_j  | element  |     r   |          x     |
branch=[2         1          1      1.88015           1.96506
        3         2          2      0.101369999       0.105948
        4         3          3      0.1085            0.1134
        5         4          4      0.03875           0.0405
branch(:,4)=branch(:,4)/Zbase;  % for r in p.u.
branch(:,5)=branch(:,5)/Zbase;  % for x in p.u.
%--------------------------------------------------------------------------
% bus - data on network buses
%--------------------------------------------------------------------------
%| busNo|type |  V   | angle | Pgen | Qgen | Pload | Qload |
| busNo    |  type  |     V    |   angle  |  Pgen    |  Qgen  |Pload  Qload
bus=[1           21         1         0         0        0    0       0
     2           21         1         0         0        0    0.015   0.01
     3           21         1         0         0        0    0       0
     4           21         1         0         0        0    0       0
     5           21         1         0         0        0    0.031   0.019
```

F.6: Sample Matlab Code for Load Flow Using BackwardForward Sweep

```
function [] = BWFWSLF(Lbest)
% ========================================================================
% Generate final results based on optimal control variables
% Power flow computation in radial symetrical dustribution networks
considering DG
% method: backward/forward sweep (BW/FWSLF)
% per unit system
%=========================================================================
[branch,bus,dg,Sbase,~,~]=Data_Bus59;  %testsystem data
% Branch data
%--------------------------------------------------------------------------
[ngr,~]=size(branch);
bus_i=branch(:,1);
bus_j=branch(:,2);
element=branch(:,3);
rbr=branch(:,4);
xbr=branch(:,5);
zbr=(rbr+1i*xbr);
rng(0)
%bus incidence matrix
for k=1:ngr
    inc(bus_i(k),bus_j(k))=1;
    inc(bus_j(k),bus_i(k))=1;
end
% Bus data
%--------------------------------------------------------------------------
[nbus,~]=size(bus);
Bus=bus(:,1);
typebus=bus(:,2);
V0=bus(:,3);
theta0=bus(:,4);
pgen=bus(:,5);
qgen=bus(:,6);
pload=bus(:,7);
qload=bus(:,8);
```

```
Sload=pload+1i*qload;
% DG
ndg=length(dg(:,1));
cosfidg=dg(:,4);
opti_loc_DG=zeros(1,ndg);
opti_pow_DG=zeros(1,ndg);
opti_loc_DG=Lbest(1:ndg);          %optimal locations of DGs as result from
PSO
opti_pow_DG=Lbest(ndg+1:2*ndg);    %optimal sizes (nominal power) of DGs at
determined location as result from PSO
for k=1:ndg
    pgen(opti_loc_DG(k))=opti_pow_DG(k)*cosfidg(k);
    qgen(opti_loc_DG(k))=pgen(opti_loc_DG(k))*tan(acos(cosfidg(k)));
end
Sgen=pgen+1i*qgen;
%% Initialization
U=V0.*(cos(theta0)+1i*sin(theta0));
Ipot=zeros(1,nbus-1);
Igen=zeros(1,nbus-1);
itermax=1000;
epsilon=0.00001;
maxraz=epsilon+1; % Converegence conditions
iter=0;
%% Iterative procedure
while (iter < itermax) && (maxraz > epsilon)
    iter=iter+1;
    Unew=U;
for k=1:nbus-1
if typebus(k)==21        % modeled by constant power
            Ipot(k)=conj(Sload(k))/conj(Unew(k));
            Igen(k)=conj(pgen(k)+1i*qgen(k))/conj(Unew(k));
elseif typebus(k)==22    % modeled by constant current
            Ipot(k)=abs(conj(Sload(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sload(k))));
            Igen(k)=abs(conj(Sgen(k))/conj((V0(k))))*exp(1i*(angle(Unew(k))-
angle(Sgen(k))));
elseif typebus(k)==23    % modeled by constant impedance
            Ipot(k)=Unew(k)*conj(Sload(k))/abs(V0(k)^2);
end
end
%Backward sweep: determining the currents flowing in all the system's branches
(starting from the terminal branches and going towards the source bus)
for k=1:nbus-1
        I(k)=Ipot(k)-Igen(k);
end
    J(nbus)=0;
for k=1:nbus-1
        sumi=0;
for kk=1:k
if inc(nbus-k,nbus-k+kk)==1
                sumi=sumi+J(nbus-k+kk);
end
end
        J(nbus-k)=I(nbus-k)+sumi;
end
    J0=0;
for k=1:nbus
```

```
if inc(nbus,k)==1
            J0=J0+J(k);
end
end
    J(nbus)=J0;
% Forward sweep: Bus voltages are updated in a forward sweep starting from
branches connected to the root bus toward those in the last
for k=1:nbus-1
if inc(k,nbus)==1
            U(k)=U(nbus)-zbr(k)*J(k);
end
end
for k=2:nbus-1
for kk=1:k-1
if inc(k,kk)==1
                U(k)=U(kk)-zbr(k)*J(k);
end
end
end
% Checking the convergence criteria:
    maxraz=max(abs(Unew-U));
end% End of iterative procedure
% Power loss in branches and voltage deviation at buses
for k=1:nbus-1
    ploss(k)=real(zbr(k))*(abs(J(k)))^2;
    qloss(k)=imag(zbr(k))*(abs(J(k)))^2;
    deltaV(k)=abs(abs(U(k))-1);
end
% Total power loss:
sum_ploss=sum(ploss);
sum_qloss=sum(qloss);
Vp=abs(U)
% Total voltage deviation
sum_deltaV=sum(deltaV);
%SHOWING THE RESULTS
TABLE_DG=[opti_loc_DG' opti_pow_DG'];
fprintf('\n R E S U L T S:             ')
fprintf('\n---------------------------')
fprintf('\n  Optimal | Optimal rated |')
fprintf('\n location | power of DGs  |')
fprintf('\n  (Bus)   |    (MVA)      |')
fprintf('\n==========|===============|')
for i=1:ndg
fprintf('\n%6d%15.4f',TABLE_DG(i,:));
end
```