

Improvement of Distribution Feeder Loss and Voltage Profile (Case Study: Bella Substation Distribution Feeder)

By

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A Thesis Submitted to School of Graduate Studies of Addis Ababa University in Partial Fulfilment of the Requirements for the Degree of Masters of Science in Electrical Power System Engineering



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October, 2019

Addis Ababa, Ethiopia



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School of Electrical and Computer Engineering

Improvement of Distribution Feeder Loss and Voltage Profile.

(Case Study: Bella Substation Distribution Feeder, Addis Ababa, Ethiopia)

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Declaration

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

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

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Abstract

Distribution feeders are components of distribution system which transfer power from distribution substation to distribution transformers located near to customer's premises. Distribution substation feeders which have poor power factor, large loads beyond its' carrying capacity and which travel long distance to feed costumers are not efficient in transferring electrical power to the connected costumers. To improve the efficiency of distribution feeders in terms of power loss and voltage profile, loss minimization and voltage profile improvement techniques are required.

Bella distribution substation is one of the distribution substations found in Addis Ababa Ethiopia which has six outgoing feeders that feed different areas. Among these feeders, feeder four F4 has been selected as test system due to its longest rout length and large loads during a year recorded data. The selected feeder has been modeled in MATLAB computational tool and DlgSILENT simulating software and load flow analysis has been simulated using Newton-Raphson method implemented in MATLAB.

From Newton-Raphson load flow simulation of feeder F4, it has been observed that the feeder has a power loss of 3.86MW and voltage drop up to 0.3pu at peak load. To reduce power loss and voltage drop of this feeder, capacitors and distributed generation units have been suggested and the impact is investigated. To find optimal size and location of the capacitors and DG, particle swarm optimization (PSO) and genetic algorithm (GA) have been implemented in MATLAB. PSO based capacitor placement resulted in a placement of capacitor sizes(kVAr) (970, 290, 2690, 1350, 1110, 120, 370, 1070, 320) on buses of F4(36, 62, 34, 35, 37, 61, 59, 51, 50) respectively. PSO based DG placement resulted in a placement of DG sizes (kw) (530.1, 255.6, 241.5, 355.2, 399.9, 321.9, 176.6, 385) on buses of F4(62, 61, 60, 59, 32, 31, 27, 24) respectively and GA based capacitor placement resulted in a placement of capacitors sizes(kVAr) (1041.8, 540.3, 1599.7, 1930.6, 1415.2, 26.2, 72, 234.2, 767.2, 858.9) on buses (36, 62, 34, 35, 37, 61, 60, 59, 51, 50) respectively. The initial capital investment cost of PSO based capacitor, PSO based DG and GA based capacitor placement on F4 requires 3,317,328 Birr, 184,114,566 Birr and 6,698,160 Birr with respective return of investment 0.1664 year, 6.832 years and 0.3361 year respectively. Peak load Newton-Raphson load flow simulation of F4 after separate placement of PSO based capacitor, PSO based DG and GA based capacitor results in power loss and voltage drop reduction of (37.3%, 15%), (50%, 12%) and (37.2%, 15.7%) respectively. In addition to peak load, the load flow was simulated at load level of 83% of peak load, 60% of peak load and base load.

In general, for power loss reduction and voltage profile improvement of distribution feeders, PSO based capacitor placement is recommended due to the reasonably minimum capital investment and better performance improvement in reduction of power loss and voltage drop.

Key words: Distribution system power loss, voltage drop, PSO based capacitor placement, DG, PSO, GA

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List of Acronyms

DG	Distributed Generation
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
F1	Feeder one
F2	Feeder two
F3	Feeder three
F4	Feeder four
F5	Feeder five
F6	Feeder six
GA	Genetic Algorithm.
NR	Newton-Raphson
PL	Peak Load
PLI	Power Loss Index
PSO	Particle Swarm Optimization
R	Resistance
ROI	Return of Investment
VII	Voltage Improvement Index.
X	Reactance
Z	Impedance

Chapter 1: Introduction

1.1. Background

The electrical energy produced at the generating station is conveyed to the consumers through a network of transmission and distribution systems. Distribution system is a vital link between utility and the consumer. According to scheme of connection, the distribution system may be classified as [1]:

Radial system: only one path between substation or service transformer and customer. the power flow is from substation to customer along single path. Furthermore, radial is cheap and simple to analyze.

Mesh: for mesh, multiple paths between all point in the network. Power flow between any two points is split along several paths. It is the most reliable method of distributing electricity. If failure occurs, power instantaneously reroutes itself. It is usually used in high density urban areas where maintenance and repairs are difficult and costly.

Loop: for loop, two paths exist between substation transformer and customer. Power flow is usually from both sides to the middle. The equipment is rated so that service can be maintained if an open point occurs in the system.

Electricity losses occur at each stage of the power distribution process. When compared with other, distribution loss is very high, since it operates at low voltage. Distribution network losses are conventionally classified into two categories [2]:

Technical losses

Non-technical losses

Technical losses: technical losses in power system are caused by the physical properties of the components of the power system. These type of losses in power systems occur naturally as they consist of energy dissipation in electrical system components such as lines, transformers, connections, measurement systems and other equipment that carry energy to and from customers.

Technical losses are also called ‘Physical losses’ as they refer to energy transformed to heat and noise while distributing electricity and, therefore, physically lost.

They depend on the design of the power distribution network, the voltage and transformation levels and length of the power lines.

Technical losses can be further divided into:

- A. Variable losses (load related)
- B. Fixed losses (not related to load but related to the connection of network components to the live electrical network and depend on the applied voltage)

Variable losses: all conductors, whether they are coils in transformers, aluminum or copper wires in overhead lines or cables and even in switchgear, fuses, or metering equipment, have an internal electrical resistance which causes them to heat when carrying electric current. Since energy losses stemming from the dissipation of heat to the environment vary with the current flowing through conductors in electrical networks, these losses are called ‘variable losses.’

Distribution networks (at lower voltage) are subjected to a higher level of losses. Network imbalance, power factor and power quality can also have an impact on variable losses, as they influence the value of the currents flowing through conductors.

Fixed losses: some electrical energy is dissipated by network components and equipment such as transformers or conductors as a result of being connected to the network and energized. Even if no power is delivered to customers, the system has losses just because it is electrically energized.

Fixed losses do not change with current; they depend on the applied voltage. However, as the applied voltage is relatively stable while the network equipment is energized, they are essentially fixed. Therefore, fixed losses are a function of the network itself and depend mainly on the number of energized components.

Non-technical losses: is primarily relate to unidentified, misallocated, and inaccurate energy flows. They represent the amount of energy that is delivered but not accounted for. This type of losses is caused by actions that are external to the power system. It refers to lost energy that is not directly related to the transportation of electricity and occur

independently of the physical technical characteristics of the network. Non-technical losses can be also viewed as undetected load of customers that the utilities don't know.

Non-technical losses include:

Theft: is defined as any illegal abstraction of electricity for use other than at premises where any metering points or metering systems are registered by a supplier. It can occur where an unauthorized connection to the network is made.

Fraud: is the illegal abstraction of electricity within the boundary of a customer's property. It happens as a result of an ill-intentioned and illegal manipulation of the meter, by tampering or bypassing the meter.

Measurement errors: is the difference between the amount of energy actually delivered through the meter and the amount registered by the meter. Measurement errors may occur due to: uncertainty of measurement equipment, errors in manual or automatic meter reading, defective measurement equipment and incorrect installation or configuration of measurement equipment. At last the errors lost energy.

Network information issues: situations arise where energy is delivered and consumed but is not accurately recorded due to inaccuracies in the distribution network database. This is effectively becoming lost energy.

Voltage drop in the distribution network

The other problem of the distribution networks is voltage drop problem. Depending on the load current, distribution feeders either absorb or supply reactive power. At loads below surge impedance loading, feeders produce net reactive power while at loads above surge impedance load, it absorbs reactive power. As a result, voltage drop problem may arise when using distribution feeders with long distance or feeding large loads

The equipment connected to the distribution system is designed to operate at a specific voltage level. For efficient and reliable operation of distribution power systems, the control of voltage and reactive power should satisfy the following objectives [3];

Voltage at the terminals of all the equipment in the system are within acceptable limits. Reactive power flow is minimized so as to reduce active and reactive line loss of the distribution system to a practical minimum and system stability is enhanced to maximize utilization of the distribution system.

1.2. Problem Statement

Nowadays, demand of electrical power is increasing from time to time. As a result, the distribution feeders which transfer power from substation to the customers are overloaded beyond their carrying capacity. Overloaded distribution feeders that travel long distances have large losses and voltage drop problems. Utility and connected customers both suffer from these loss and voltage drop problems. The equipment used by utility and customers are designed to operate at a certain voltage level. If they operate below that level, it will draw large current. This has dangerous effect on the life of the connected equipment.

In this regard, finding loss reduction and voltage profile improvement mechanisms for the distribution networks is a pressing issue. There are different such mechanisms as shunt capacitor placement, Distributed Generation (DG) placement, conductor upgrading and feeder reconfiguration, to list a few. Loss reduction and voltage profile improvement mechanism for distribution feeders need feasibility analysis. In addition to the feasibility issue, proper sizing and locating of the selected mechanism in the distribution system is another problem.

Therefore, finding feasible mechanism for loss reduction and voltage profile improvement of distribution feeders with appropriate size and location of capacitor and distribution generation placement is a challenging problem for utility company.

To solve this challenging problem, Particle Swarm Optimization (PSO) based separate DG and capacitor placement has been investigated. To test the validity, Bella distribution feeder four has been used as a test system. In addition, Genetic Algorithm (GA) based capacitor placement on Bella distribution feeder(F4) also has been analyzed.

1.3. Objective of the Thesis

General Objective

The general objective of this thesis is to analyze methods of power loss reduction and voltage profile improvement for Bella distribution substation outgoing feeder F4.

Specific Objectives

The specific objectives of this thesis are:

- ✓ To collect and analyze distribution feeder data from Bella distribution feeder F4 (i.e. line impedance data, active and reactive power loading data, routes of the distribution feeder)
- ✓ To perform load flow analysis of Bella distribution feeder F4 for determination of power loss and voltage drop
- ✓ To investigate the potential loss reduction and voltage profile improvement mechanism for Bella distribution feeder F4.
- ✓ To model and simulate Bella distribution feeder F4 for potential loss minimization and voltage drop reduction.
- ✓ To compare results obtained using PSO based capacitor placement and PSO based DG placement as well as GA based capacitor placement at different load levels.
- ✓ To draw conclusions and recommend appropriate techniques for practical implementation.

1.4. Scope of the Thesis

The scope of this thesis work covers, studying power loss and voltage drop minimization mechanisms for the distribution feeders (Bella distribution feeder four). (from distribution substation to distribution transformers). This thesis, does not include the investigation on impacts of DG injection on protection coordination of distribution systems, impacts of harmonics on power loss and voltage profile of the distribution network and impacts of phase load unbalance on power loss and voltage drop of distribution system.

1.5. Research Methodology

The research methodology followed in this thesis is described by the block diagram, as given in Fig. 1.1

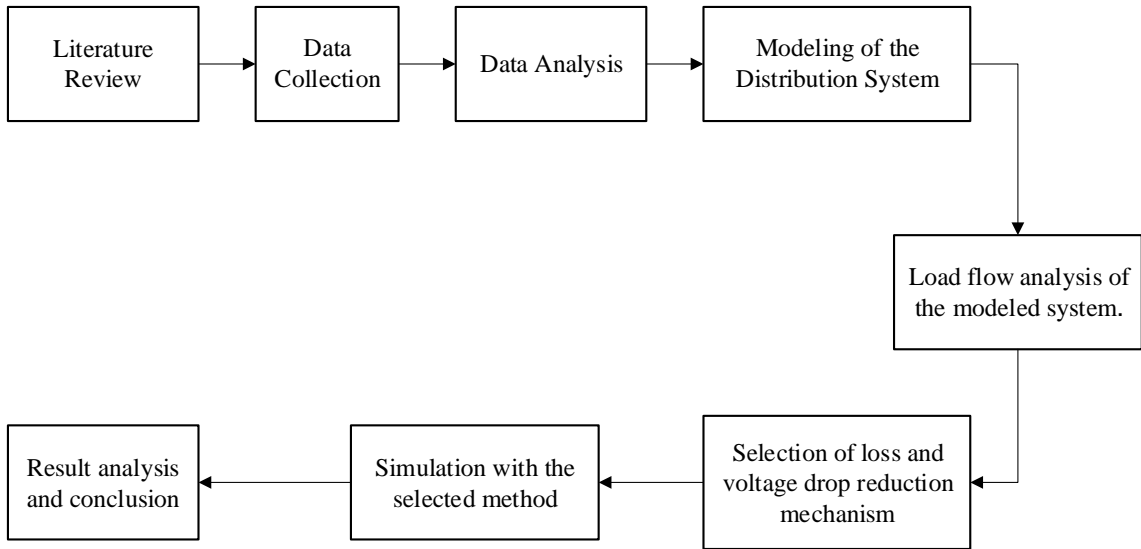


Figure 1. 1 Block diagram of the research methodology

Due to the nature of the study, this thesis has been started by reviewing literatures related to the investigation of loss and voltage drop of power distribution systems. Recent, unpublished important information and data (line data, bus data and current tariff of electric sales of the country, peak and hourly recorded loading data of the feeder...) have been collected for the power distribution system under study (Bella distribution feeder) from Ethiopian Electric Utility (EEU). Random field data collection has also been done by the authors. This includes measuring voltage readings of the secondary side of the farthest transformer, with the help of clampmeter to check the voltage profile of the distribution network under study.

Using the collected data, the base case network model was developed with the help of MATLAB and DlgSILENT software’s. Selection of suitable method (NR) for performing power flow analysis of the distribution system has been done. After the selection of suitable method, a power flow analysis was carried out to determine the initial loss and

voltage drop of the distribution network. Feasible loss reduction and voltage profile improvement mechanism of the distribution network have been assessed.

Separate PSO based capacitor and DG placement and GA based capacitor placement was selected and tested. The load flow analysis was carried out at different load level of the distribution feeder. The compensated system with uncompensated system and cost analysis of the selected mechanism also has been compared.

1.6. Organizations of the Thesis

This thesis is organized as follows:

Chapter one deals with a brief introduction of the thesis background, problem statement, objectives, scope, description of the methodology and thesis outline.

Chapter two gives the detail of theoretical background and review of different literatures related to voltage drop and power loss minimization in the distribution network and optimization techniques used to solve voltage drop and power loss reduction in the distribution network.

Chapter three describes data collection process, the type of data collected from Bella distribution feeder, modeling of the distribution network, load flow analysis, candidate bus selection process, objective function of the PSO and GA, flow chart of Candidate bus selection and PSO.

Chapter four covers simulation result analysis of PSO based DG and capacitor placement, GA based capacitor placement at different load levels and cost analysis of the respective method.

Chapter five deals with conclusions, recommendation and suggestion for future work.

Chapter 2: Voltage Drop and Power Loss Minimization in Distribution Systems

2.1 Introduction

Electrical distribution system is almost the final stage in the delivery of electricity to end users as said before. It carries electric power from substation transformer to distribution transformer and as it operates with large current as compared to transmission system i.e. low voltage, voltage drop and loss problem is very high. Loss and voltage drop problem have its own impact on the distribution system. Both utility and customer equipment's that are connected to the distribution system may not operate properly since they are designed to work at a certain rating. The life of the connected equipment's also will be very short.

2.2 Factors Affecting Voltage Drop and Power Loss of Distribution Feeders

Voltage deviation and loss of the distribution feeders are increasing in distribution network due to various factors. Some of them are listed below [4].

Poor jointing and termination: poor jointing and termination on the distribution networks are resulted from loose contact, there will be high opposition to current flow which generates heat at that point. This leads to an increase in resistance and subsequently result to voltage drop at that point.

Use of undersized conductors: voltage can be considered as the pressure pushing charges along a conductor, while resistance of the conductor is a measure of how difficult it is to push the charges along. The small size conductors have high resistance consequently large voltage drop.

Use of different types of conductor material: corrosion is an important factor to be considered in the selection of conductor materials. The two types of corrosion which exhibit greatest influence on the electrical properties of a metal are oxidation and galvanic corrosion. Galvanic corrosion, which is caused by the difference in electrical potential

between two or more metals, has to be given careful consideration when selecting conductor materials.

Hot spots: whenever a mechanically joint or termination is made, high resistance point is created. Thus, the joint or termination will undergo a progressive failure. High resistance creates localized heating and since heating increases oxidation and creep, the connection become less tight and further heating occurs, until the contact tends glow.

Loads on the main feeder: the currents in a feeder segment along the distribution feeder are function of the loads connected to the downstream portion of the feeder. Although the current will not affect the feeder impedance, it does affect voltage deviation [5].

Length of distribution feeder: the series impedance of a feeder is linearly proportional to the length of the feeder. Therefore, the length of the feeder has a significant effect on voltage deviation.

Phase imbalance: a network which does not have its load evenly distributed across all three phases will have higher currents in at least one phase meaning it is not optimized for losses [6]. There will also be currents flowing in the neutral conductors if they are present. Therefore, due to the quadratic dependence of losses on current, this load imbalance across the three phases will increase losses.

Harmonics: harmonic effects are essentially distortions to an AC current profile. They can occur in transformer windings because the AC magnetizing current is not perfectly sinusoidal. However, this usually occurs on the triple harmonics(3rd,6th,9th). So, on normal three phase system they are all in phase and do not result in any real harmonics. However, if other equipment connected to the network produces harmonics they will not cancel in the neutral conductor. Therefore, these can cause additional loss the distribution system.

Power factor: the power factor is the ratio of real power to apparent power. For two power factor systems distributing the same amount of real power, the system with the lower power factor will have the higher reactive power current which should cause the higher voltage drop and produce the higher loss.

Rated capacity of substation transformer: the variance of node voltage along the feeder can be lessened by increasing the rated capacity of their feeding substation transformer. The larger the transformer capacity have minimum voltage variation effect on the system. However, one of the major disadvantages for increasing rated capacity of substation transformer is the rise in the short-circuit fault current level on the secondary side of a substation transformer.

Location of distribution transformer: in appropriate location of distribution transformer may leads to energy loss in the distribution system. The farthest consumer will get an extremely low voltage as compared to the consumer nearer to distribution transformer.

2.3 Distribution Network Power Loss and Voltage Drop Minimization Techniques

There are different techniques to reduce loss and voltage deviation of a distribution feeder [7]. Some of the power loss and voltage drop reduction techniques are: network reconfiguration, network re conducting (conductor grading), distribution transformer locating and sizing, reactive power compensation, using highly efficient transformer, using high voltage distribution system, using distributed generation and building new substation. The power loss and voltage drop reduction techniques have been discussed in the following section.

Network Reconfiguration

Network reconfiguration is the process of operating switches to change the circuit topology so that operating costs are reduced while satisfying the specified constraints [8]. Network reconfiguration is one of the possible method in distribution system for reducing loss in which the power flow is altered by the formation of new links with a feeder to form tree structure or by opening or closing the appropriate switches on the feeder. Feeder reconfiguration allows the transfer of loads from heavily-loaded feeders to relatively lightly-loaded feeders and form higher-resistance routs to lower resistance routs to obtain the least loss, where the resistance route is the total resistance from the source to the load

point. Such transfers are effective not only in terms of altering the level of loads on the feeder being switched, and reducing the losses, but also in improving the voltage profile along the feeders and affecting reductions in the overall system power losses [9].

But feeder reconfiguration is effective if distribution feeders are automated and not fare apart to each other. For an unautomated and fare apart feeders, feeder reconfiguration may not be cost effective.

Conductor Grading

Conductor grading is the technique of replacing the existing conductor on the feeder by conductor of optimal size for optimal (in terms of cost) length of feeder to reduce the resistance. This can be achieved by replacing the small size conductors with a larger cross-sectional area, or by installing auxiliary conductors to work in parallel with the existing ones. So that the equivalent resistance is reduced. Although these methods could give a large loss reduction, it is not cost effective, and it is not used unless there is a special need, as the cost of conductors and their installation are usually in excess of the cost of the energy saved [9].

This technique is used when existing conductor is no more optimal because of rapid growth of load [8]. This technique is also good for the developing countries where annual Population (energy demand) growth rates are high and the conductors are chosen to minimize power loss and voltage drop of the distribution system.

Distribution Transformer Locating and Sizing

If distribution transformers are not located centrally with respect to consumers, the farthest consumers will obtain extremely low voltage even though a reasonably good voltage level is maintained at secondary of transformer. This leads to higher losses in distribution system. So, distribution transformers should be located nearer to the load center as possible and replace large transformers by the transformers of small rating such that it serves small number of consumers so that optimum voltage level is maintained.

Reactive Power Compensation

Reactive power compensation is defined as the management of reactive power to improve the performance of ac power system.

The beer mug analogy [10] is useful to understand the theory of reactive power compensation. If the mug capacity is the apparent power (kVA) that we can transmit through a system, then the foam is the reactive power (kVAr) and the beer is the real power (kw). If we use capacitors to provide the foam (kVAr) when we drink the beer, then we free up mug capacity so you don't have to buy a bigger mug and/or so you can pay less for your beer.

The benefits of reactive power compensation in the transmission and distribution system include [10]: voltage profile improvement, increase power flow capacity (by decreasing feeder impedance), increase system capacity (the distribution system capacity can be increased by controlling reactive power flow using capacitors) and reduce power losses.

In general, reactive power compensation is an important method to improve voltage profile and loss of a distribution network if the size and location has done optimally.

Using Highly Efficient Transformers

The use of highly efficient transformers will reduce losses of the distribution system. Like amorphous core transformers which have high magnetic susceptibility and high electrical resistance. The high resistance in transformers leads to low losses by eddy currents.

High Voltage Distribution System

Using high voltage distribution system will reduce the loss and voltage deviation of the distribution system. This technique aims extending high voltage lines as nearer to the load as possible and replacing large transformers with various small rating transformers. Also, conversion of existing low voltage distribution systems to high voltage distribution system is done. This technique is most effective and efficient in reducing the technical losses and improving the power quality in distribution system. Because the current is low in high

voltage system. But the initial investment cost is very high for this reason it may not be feasible.

Using Distributed Generation

The concept of DG, which can be traced back to the early 1900s, is based on small scale power plants that are connected to the electricity system close to customers [11].

Distributed generation (DG) is small-scale power generation that is usually connected to distribution system. The Electric Power Research Institute (EPRI) defines DG as generation from a few kilowatts up to 50 MW [12]. Ackermann et.al. have given the recent definition of DG as: “DG is an electric generation source connected directly to the distribution network on the customer side of the meter.”

DG units can be classified into three major types based on their terminal characteristics in terms of real and reactive power delivering capability [13]:

Type 1 DG: distributed generations that supply real power to the network without demanding any reactive power. Few examples of type 1 DG are photovoltaic cell, fuel cell, battery storage and micro-turbines.

This type of DG unit maximizes MWh profit [14]. However, it may lack of voltage support depending on characteristics of distribution network in providing the required reactive power.

Type 2 DG: distributed generation that supply both active and reactive power to the network. e.g. wind generation, combustion engines and synchronous generators.

Type 3 DG: distributed generation unit that inject real power but consuming reactive power. e.g. induction generators used in wind farms.

In [15] the author also classified DG in to four:

Type 1 DG: DG which injects real power only, that is DG at unity power factor.

Type 2 DG: DG which injects reactive power only for voltage profile improvement, that is DG at zero power factor (KVAR) such as capacitors, synchronous condenser,

Type 3 DG: DG which injects both real and reactive power, that is DG at 0.9 power factor lag (KVA) such as synchronous generators.

Type 4 DG: DG which injects real power but consumes reactive power, that is DG at 0.9 power factor lead (KVA) such as induction generators used with turbines.

In general, the feasibility, type, size and location, protection coordination effect of DG and initial investment cost should be investigated in detail.

2.4 Optimization Techniques to Solve Voltage Drop and Power Loss Problems

Researchers used different optimization algorithms to solve distribution loss and voltage deviation of distribution feeders. The theoretical background of mostly used optimization algorithms is discussed below.

2.4.1 Tabu Search

Tabu search was developed by F.Glover and has been used to solve a wide range of hard optimization problems, financial analysis, scheduling, space planning, and energy distribution [16]. Tabu search is a meta-heuristic that guides a local heuristic search strategy to explore the solution space beyond local optimality.

The basic idea behind the search is a move from a current solution to its neighborhood by effectively utilizing a memory to provide an efficient search for optimality. The memory is called, Tabu list, which stores attributes of solutions. In the search process, the solutions are in the Tabu list cannot be a candidate of the next iteration. As a result, it helps inhibit choosing the same solution many times and avoid being trapped into cycling of the solutions [17]. The quality of a move in solution space is assessed by aspiration criteria that provide a mechanism for overriding the Tabu list.

Tabu search algorithm is time consuming one as author [33] has explained. For this reason, it may not be effective for large distribution networks.

2.4.2 Simulated Annealing

The name and inspiration come from annealing process in metallurgy, a technique involving heating and controlled cooling of a material to increase the size of its crystals and reduce their defects [1]. The heat causes the atoms to become unstuck from their initial

positions (a local minimum of the internal energy) and wander randomly through states of higher energy; the slow cooling gives them more chances of finding configurations with lower internal energy than the initial one. In the simulated annealing method, each point of the search space is compared to a state of some physical system, and the function to be minimized is interpreted as the internal energy of the system in that state. Therefore, the goal is to bring the system, from an arbitrary initial state, to a state with the minimum possible energy.

2.4.3 Genetic Algorithm

A Genetic Algorithm is a search heuristic that inspired by Charles Darwin's theory of natural evolution [18]. This algorithm reflects the process of natural selection where the fittest individuals are selected for reproduction in order to produce offspring of the next generation.

The process of natural selection starts with the selection of fittest individuals from a population [19]. They produce offspring which inherit the characteristics of the parents and will be added to the next generation. If parents have better fitness, their offspring will be better than parents and have a better chance of surviving. This process keeps on iterating and at the end, a generation with the fittest individual will be found.

GA works on population consisting of some solutions where population size is the number of solutions. Each solution is called individual. Each individual solution has chromosome. The chromosome is represented as a set of parameters that defines the individual. Each chromosome has a set of genes. Each gene is represented by somehow such as being represented as a string of 0s and 1s.

Each individual also has a fitness value. To select the best individuals, a fitness function is used. The result of the fitness function is the fitness value representing the quality of the solution. The higher the fitness value the higher the quality of the solution.

Genetic algorithm optimization process

Genetic algorithm is a type of optimization algorithm, meaning it is used to find the optimal solution(s) to a given computational problem that maximizes or minimizes a particular function.

Since genetic algorithms are designed to simulate a biological process, much of the relevant terminology is borrowed from biology. The basic components common to almost all genetic algorithms are [20]:

A fitness function for optimization: the fitness function is the function that the algorithm is trying to optimize.

A population of chromosomes: the term chromosome refers to a numerical value or values that represent a candidate solution to the problem that the algorithm is trying to solve. Each candidate solution encoded as an array of parameter values.

Selection of which chromosomes will reproduce: selection operator chooses some of the chromosomes for reproduction based on a probability distribution defined by the user. The fitter a chromosome is, the more likely it is to be selected.

Crossover to produce next generation of chromosomes: the crossover operator resembles the biological crossing over and recombination of chromosomes in cell meiosis. This operator swaps subsequence of two of the chosen chromosomes to create two offspring.

Random mutation of chromosomes in new generation: the mutation operator randomly flips individual bits in the new chromosomes (turning a 0 into 1 and vice versa).

Outline of MATLAB built in genetic algorithm optimization process

The algorithm begins by creating a random initial population. The algorithm then creates a sequence of new population. At each step, the algorithm uses the individuals in the current generation to create the next population. To create the new population, the algorithm performs the following steps:

- ✓ Score each member of the current population by computing its fitness value.
- ✓ Scales the raw fitness scores to convert them into a more usable range of values.

- ✓ Selects members, called parents, based on their fitness.
- ✓ Some of the individuals in the current population that have lower fitness are chosen as elite. These elite individuals are passed to the next population. The genetic algorithm creates three types of children for the next generation: elite children, are the individuals in the current generation with the best fitness values. Crossover children, created by combining the vectors of a pair of parents. Mutation children, created by introducing random changes, or mutations, to a single parent.
- ✓ Produces children from the parents. Children are produced either by making random changes to a single parent-mutation-or by combining the vector entries of pair of parents- crossover.
- ✓ Replaces the current population with the children to form the next generation.

The algorithm stops when one of the stopping criteria is met. Genetic algorithm uses the following conditions to determine when to stop.

Generations- the algorithm stops when the number of generations reaches the value of **Generations**.

Time limit-the algorithm stops after running for an amount of time in seconds equal to **Time limit**.

Fitness limit- the algorithm stops when the value of the fitness function for the best point in the current population is less than or equal to **Fitness limit**.

Stall generations- the algorithm stops the average relative change in the fitness function value over **Stall generation** is less than **Function tolerance**.

Stall time limit- the algorithm stops if there is no improvement in the objective function during an interval of time in seconds equal to **Stall time limit**.

Function tolerance- the algorithm runs until the average relative change in the fitness function value over **Stall generation** is less than **Function tolerance**

The algorithm stops as soon as any of these conditions is met. The values of these criteria can be specified in the **Stopping criteria** pane in the Optimization app.

In this thesis, for comparison purpose, MATLAB built in multi objective genetic algorithm is used to simulate capacitor placement problem for Bella distribution feeder four power loss reduction and voltage profile improvement.

2.4.4 Ant Colony Optimization Method

Ant Colony Optimization (ACO) imitates the behaviors of real ants which are capable of finding the shortest path from food sources to the nest without using visual cues [21]. Also, they are capable of adapting to changes in the environment, for example, finding a new shortest path once the old one is no longer feasible due to a new obstacle. Moreover, the ants manage to establish shortest paths through the medium that is called “pheromone”. The pheromone is the material deposited by the ants, which serves as critical communication information among ants, thereby guiding the detection of the net movement. By the guidance of the pheromone intensity, the ants select preferable path. Finally, the favorite path rich of pheromone became the best tour, the solution to the problem.

2.4.5 Particle Swarm Optimization Process

Particle swarm optimization is one of the swarm intelligence optimization techniques based on social behavior of swarming animals, introduced by Kennedy and Eberhart in 1995 [22], When they mathematically imitate the social behavior of bird flock and fish schools searching for corn, introducing this metaheuristic optimization method. Particles ‘birds’ move through the search space adjusting their positions and their velocities with respect to their own experience and to their neighboring particles experience to find the optimal solution [23].

The PSO algorithm starts with a population of particles with random positions in the search space. Each particle is a solution of the problem and has a fitness value. The fitness is evaluated and is to be optimized. A velocity is defined which directs each particle’s position and gets updated in each iteration. Particles gradually move toward the optima due to their best position they have ever experienced and the best solution which group has experienced [24]. The velocity of a particle is updated due to three factors: the past

velocity of the particle, the best position particle has experienced so far and the best position the entire swarm has experienced so far.

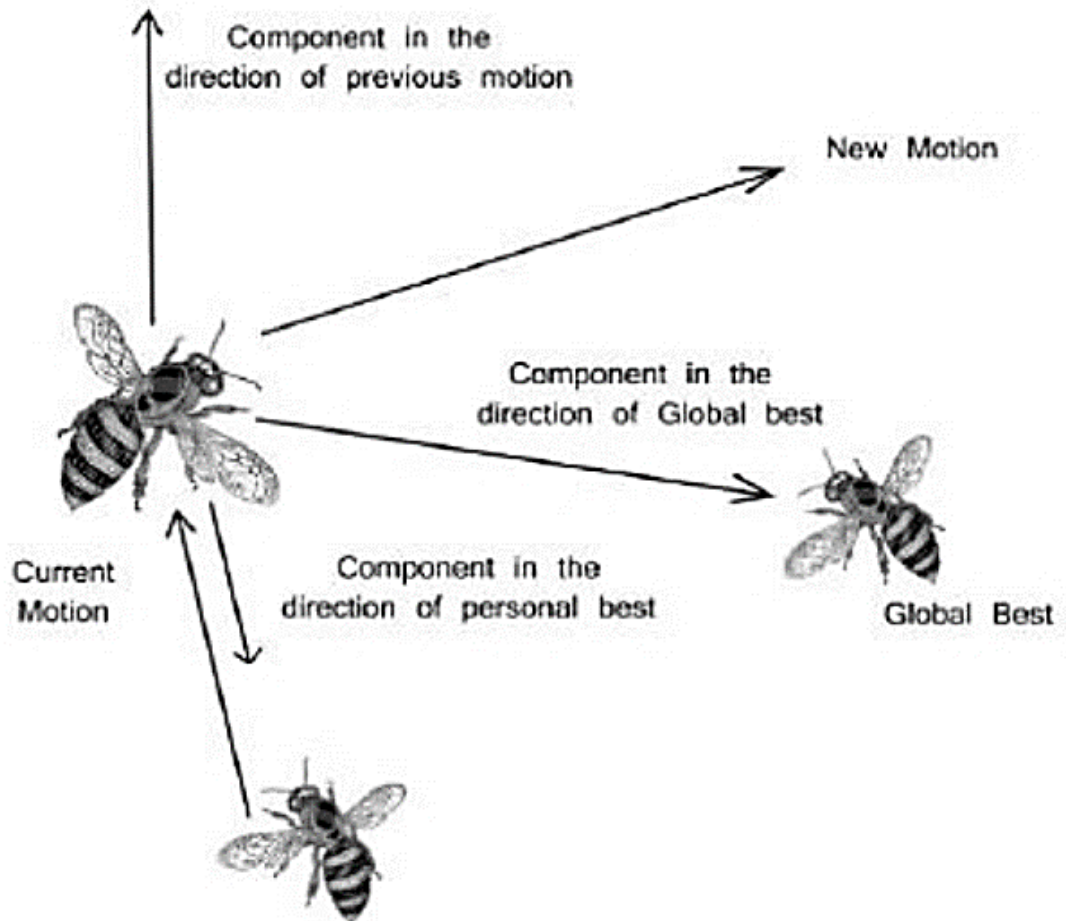


Figure 2. 1 Concept of searching point by PSO [24]

This method is capable handling continuous state variables easily and search a solution space effectively. In addition, the method can be extended to treat continues and discrete variables [25].

Particle Swarm Optimization has the advantage of parallel computation and robustness, and it can find the global optimal solution with a higher probability and efficiency than traditional methods. It is also easy to realize, fast converging, intelligent and capable of

determining near global solution with lesser computational burden [26]. It is suitable to solve the capacitor placement problem [27].

Elements of Particle Swarm Optimization

The general elements of the PSO have been briefly explained as follows [28]:

Particle $\mathbf{X}(t)$: it is a K -dimensional real valued vector which represents the candidate solution. For an i^{th} particle at a time t , the particle is described as

$$x_i(t) = \{x_{i,1}(t), x_{i,2}(t), \dots, x_{i,K}(t)\}. \quad (2.1)$$

Population: it is a set of 'n' number of particles at a time t described as

$$\{x_1(t), x_2(t), \dots, x_n(t)\} \quad (2.2)$$

Swarm: it is n apparently disorganized population of moving particles that tend to cluster together while each particle seems to be moving in random direction.

Particle velocity $\mathbf{V}(t)$: it is the velocity of the moving particle represented by a k -dimensional real valued vector

$$V_i(t) = \{v_{i,1}(t), v_{i,2}(t), \dots, v_{i,K}(t)\}. \quad (2.3)$$

Inertia weight $\mathbf{W}(t)$: it is a control parameter that is used to control the impact of the previous velocity on the current velocity.

Particle Best (P_{best}): conceptually P_{best} resembles autobiographical memory, as each particle remembers its own experience. When a particle moves through the search space, it compares its fitness value at the current position to the best value it has ever attained at any time up to the current time. The best position that is associated with the best fitness arrived so far is termed as individual best or particle best. For each particle in the swarm its P_{best} can be determined and updated during the search.

Global best (g_{best}): it is the best position among all the individual P_{best} of the particles achieved so far.

Velocity updating: using the global best and individual best, the i^{th} particle velocity in k^{th} dimension is updated according to the following equation.

$$V[i][j] = k \times (w \times v[i][j] + c_1 \times rand_1 \times (P_{best} X[i][j] - X[i][j]) + c_2 \times rand_2 \times (g_{best} X[j] - X[i][j])) \quad (2.4)$$

Where, k constriction factor

c_1, c_2 weight factors

w inertia weight parameter

i particle number

j control variable

$rand_1$ and $rand_2$ random numbers between 0 and 1.

Stopping criteria: this is the condition to terminate the search process.

Particle swarm optimization algorithm used here in this work is the built-in MATLAB `particleswarm` algorithm, which is used to locate and size the capacitor and DG separately to minimize loss and voltage deviation.

Particle Swarm Optimization Algorithm in MATLAB

The built in MATLAB particle swarm optimization algorithm begins by creating the initial particles, and assigning them initial velocities. It evaluates the objective function at each particle location, and determines the best (lowest) function value and the best location. It chooses new velocities, based on the current velocity, the particles' individual best locations, and the best locations of their neighbors. It then iteratively updates the particle locations (the new location is the old one plus the velocity, modified to keep particles within bounds), velocities, and neighbors. Iteration proceeds until the algorithm reaches a stopping criterion.

Initialization

By default, `particleswarm` creates particles at random uniformly within bounds. If there is an unbounded component, `particleswarm` creates particles with a random uniform distribution from -1000 to 1000. If you have only one bound, `particleswarm` shifts the creation to have the bound as an endpoint, and a creation interval 2000 wide. Particle i has position $x(t)$, which is a row vector with $nvars$ elements. The span of the initial swarm can be controlled using `InitialSwarmSpan` option.

Similarly, *particleswarm* creates initial particle velocities v at random uniformly within the range $[-r, r]$, where r is the vector of initial ranges. The range of component i is $ub(i)-lb(i)$, but for unbounded or semi-bounded components the range is *InitialSwarmSpan* option.

Particleswarm evaluates the objective function at all particles. It records the current position $p(i)$ of each particle i . in subsequent iterations, $p(i)$ will be the location of the best objective function that particle i has found and b is the best overall particles:

$b = \min(fun(p(i))). d$ is the location such that $b = fun(d)$.

Particleswarm initializes the neighborhood size N

to $minNeighborhoodSize = \max(1, floor(SwarmSize * minNeighborsFraction))$.

Particleswarm initializes the inertia $W = \max(InertiaRange)$, or if *InertiaRange* is negative, it sets

$W = \min(InertiaRange)$ and initialize stall counter $c=0$.

For convenience of notation, set the variable

$$y_1 = SelfAdjustmentWeight, \text{ and}$$

$$y_2 = SocialAdjustmentWeight,$$

Where; *SelfAdjustmentWeight* and *SocialAdjustmentWeight* are options.

Iteration steps

The algorithm updates the swarm as follows. For particle i , which is at position $x(i)$:

1. choose a random subset S of N particles other than i .
2. find $fbest(S)$, the best objective function among the neighbors, and $g(S)$, the position of the neighbor with the best objective function.
3. for u_1 and u_2 uniformly (0,1) distributed random vectors of length $nvars$, update the velocity

$$v = W \times v + y_1 \times u_1 \times (p - x) + y_2 \times u_2 \times (g - x). \quad (2.5)$$

This update uses a weighted sum of:

- ✓ the previous velocity v

- ✓ the difference between the current position and the best position the particle has seen $p - x$
 - ✓ the difference between the current position and the best position in the current neighborhood $g - x$
4. update the position $x = x + v$.
 5. Enforce the bounds. If any component of x is outside a bound, set it equal to that bound. For those components that were just set to a bound, if the velocity v of that component points outside the bound, set that velocity component to zero.
 6. Evaluate the objective function $f = \text{fun}(x)$.
 7. If $f < \text{fun}(p)$, then set $p = x$. this step ensures p has the best position the particle has seen. The next steps of the algorithm apply to parameters of the entire swarm, not the individual particles. Consider the smallest $f = \min(f(i))$ among the particles j in the swarm.
 8. If $f < b$, then set $b = f$ and $d = x$. this step ensures b has the best objective function in the swarm, and d has the best location.
 9. If, in the previous step, the best function value was lowered, then set $\text{flag} = \text{true}$. Otherwise, $\text{flag} = \text{false}$. The value of flag is used in the next step.
 10. Update the neighborhood. If $\text{flag} = \text{true}$:
 - ✓ Set $c = \max(0, c - 1)$.
 - ✓ Set N to $\text{minNeighborhoodSize}$.
 - ✓ If $c < 2$, then set $w = 2 \times w$.
 - ✓ If $c > 5$, then set $w = w/2$.
 - ✓ Ensure that w is in the bounds of the *InertiaRange* option.
- If $\text{flag} = \text{false}$:
- ✓ Set $c = c + 1$.
 - ✓ Set $N = \min(N + \text{minNeighborhoodSize})$.

Stopping criteria

Particleswarm iterates until it reaches a stopping criterion.

Table 2. 1: Stopping criteria of MATLAB built in PSO algorithm

Stopping options	Stopping test	Exit flag
<i>maxStalliterations</i> and Function Tolerance	Relative change in the best objective function value g over the last <i>MaxStallIterations</i> iteration is less than Function Tolerance.	1
<i>MaxIterations</i>	Number of iterations reaches <i>MaxIterations</i> .	0
<i>OutputFcn</i> or <i>PlotFcn</i>	<i>OutputFcn</i> or <i>PlotFcn</i> Can halt the iteration	-1
<i>ObjectiveLimit</i>	Best objective function value g is less than or equal to <i>ObjectiveLimit</i>	-3
<i>MaxStallTime</i>	Best objective function value g did not change in the last <i>MaxStallTime</i> seconds.	-4
<i>MaxTime</i>	Function run time exceeds <i>MaxTime</i> seconds.	-5

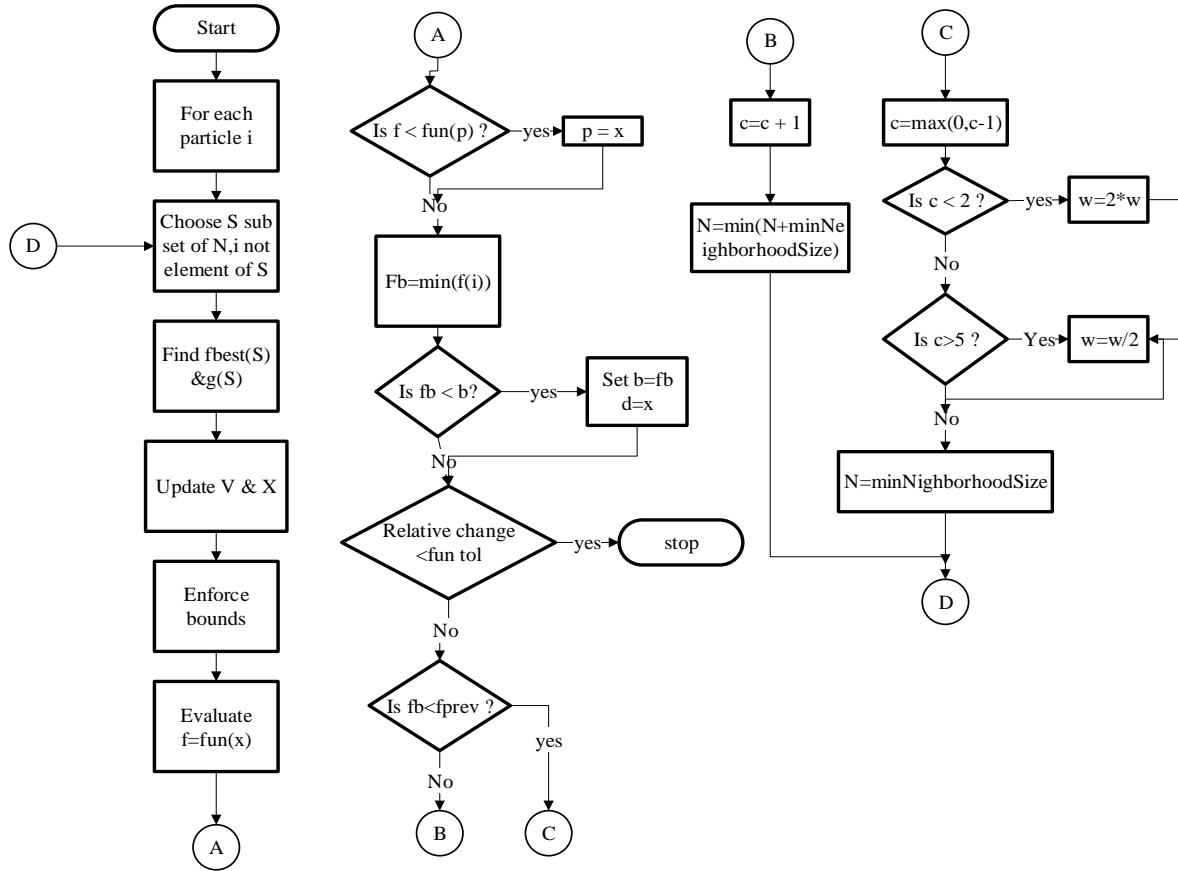


Figure 2. 2 Flow chart of MATLAB built-in Particle Swarm Optimization algorithm

Figure 2.2 is a flow chart of Particle Swarm Optimization algorithm process drawn in micro soft Visio.

2.4.6 Teaching Learning Based Optimization

Teaching Learning Based Optimization (TLBO) is one of the swarm intelligence-based algorithms developed by Rao et al.2011 [29]. TLBO is a teaching-learning process inspired algorithm based on the effect of the teacher on the output of learners in a class. The algorithm describes two basic modes of learning: (i) via a teacher (known as the teacher phase) and (ii) via interacting with the other learners (known as the learner phase). In this optimization algorithm, a group of learners are considered as population, and different subjects offered to the learners are considered as design variables of the optimization problem. The learners result is analogous to the fitness value of the

optimization problem [30]. The best solution in the entire population is the teacher. The design variables are the parameters involved in the objective function of the given optimization problem, and the best solution is the best value of the objective function.

2.5 Literature Review on Power Loss and Voltage Drop reduction of a Distribution System

Different researchers have proposed different ways for solving the problem of voltage drop and power loss in distribution systems.

In [4] the author proposed feeder reconfiguration with addition of new distribution transformer for reduction of voltage drop and distribution loss. In this method, the loss and voltage drop are reduced to some extent but the cost of the added transformers and tie switches is not considered. The payback period may be very large due to the cost of transformers. Therefore, it may not cost effective.

In [11] the author studied impact of distributed generation (diesel generator, wind turbine and photovoltaic) on distribution networks' voltage profile and power loss. He used NEPLAN software and the extended Newton Raphson method in the analysis. He concludes that different types of DG influence the distribution network differently and their precise location and size are vital in reducing power losses and improving the voltage stability. But he did not consider the intermittent nature of the loads and the wind turbine.

In [13] the author studied effects of distribution generation on distribution loss and voltage profile. Voltage stability index-based approach is used to identify the candidate buses. The author tried to show distribution losses are reduced and voltage profile is improved more by type 2 DG (generating both real and reactive power) than type 1 DG (generating real power only). The objective function has not written clearly and not include voltage deviation, he did not use optimizing tool, feasibility issue of the type of DG did not considered and during candidate bus selection loss sensitivity index was not used.

In [31] the author presented a GA-IPSO based approach which utilizes combined sensitivity factor analogy to locate and size multi-type DG in IEEE 57-bus test system

with the aim of reducing power loss and improving voltage profile. The author showed that the system power loss and voltage drop is reduced with the introduction of DGs in to the network up to an optimal number where any further DG inclusion resulted to an increase in system loss and voltage deviation outside the acceptable limits. Even though, the loss and voltage drop are reduced, the effect of DG on the protection coordination, the type of DG and feasibility issue have not considered yet.

In [32],the author proposed capacitor placement with feeder reconfiguration to reduce distribution loss and voltage deviation. The author showed that by using DIgSILENT simulation tool, capacitor placement with feeder reconfiguration improve the loss and voltage drop of the distribution system. But the cost of tie switches and the separation distance between each feeder have not considered. This has significant impact on the initial investment cost of the suggested solution.

In [33], the author studied the improvement of voltage profile of radial distribution system by capacitor placement using plant growth simulation algorithm. Loss sensitivity factor is used to identify the candidate buses then plant growth simulation algorithm is used to select the size of the capacitors. The author tested his solution on IEEE 9 bus system and got a considerable voltage profile improvement. The author assumed a constant load model but in reality, the distribution load is variable. Switchable type capacitors are not also considered. If the compensating capacitor are not switchable type, the voltage rise problem may be occurred during off peak periods.

Chapter 3: Modeling and Analysis of Bella Substation

Distribution Feeder

3.1 Introduction

The distribution network is almost the last stage of power system as said before. Distribution feeders, depending on the load current, either absorb or supply reactive power [34]. At loads below the natural (surge impedance) load, the feeders produce net reactive power; at loads above the natural load, the feeder absorb reactive power. Both the utility equipment and customer equipment connected to the distribution network are designed to operate at a certain voltage rating. One of this problem is voltage drop problem that must be reduced to keep the voltage within acceptable limit. The other problem is real power loss, which increases due to current flowing in the feeder and the resistance of the feeder i.e. I^2r loss. Load flow is used to get the loss and voltage drop of the distribution system.

3.2 Data Collection

The necessary data for this thesis work has been collected from Bella substation distribution feeders. The data have been gathered from, past recorded feeders loading (peak load and each hour load) data of the substation and distribution feeder routs, from Ethiopian Electric Utility (EEU) and Ethiopian Electric Power (EEP) Engineering office. From EEU and EEP, the AutoCAD drawing of the feeders, the type and impedance of the conductors, loading status of the feeder, bus and line data of the feeders have been collected. These data have been used to model the distribution system both in MATLAB and DlgSILENT. To check the presence of voltage drop on the selected distribution feeder, voltage has been measured with the help of clampometer in the secondary side of some of the last transformers. The general information of Bella distribution feeders has been explained below.

Bella substation has two 132kV incoming feeders, one from Cotebie substation and the other from Addis north substation. This 132kV two incoming feeders are converted to

15kV by the two 25MVA transformers. From the two 25MVA transformers, there are six 15kV outgoing feeders which feed different areas in the surrounding of the substations. The direction of the six 15kV out going feeders have been explained below.

Feeder one (F1): from the substation it goes to the switching station underground. Then, it feeds embassy of Germany, Kebena bel Air besides football field, Aware Monaliza Hotel.

Feeder two (F2): feeds embassy of Kenya, residentials in front of British embassy, Misrak TEVT school up to Yeka sub city.

Feeder three (F3): feeds Janmeda behind Feres bet, Addis Ababa institute of technology, Arat killo, up to St. Gebriel church.

Feeder four (F4): feeds Ferency Abo church, Karamara school, residentials to the right of film maekel, to the left of French embassy, behind French embassy towards Eyesus church, Ferncy Mazoriya taxi station, Beret Dildy, Gurara, residentials around Gurara St.K/Mihret Church, Gurara tele tower and new residentials in Ankorcha. Feeder four feeds large area among other feeders and travel long distance.

Feeder five(F5): feeds Birhan school, residentials around Selam Maskeber squire, supreme court, up to St. Mary church.

Feeder six (F6): dedicated to feed American Embassy only.

The substation has one earthing transformer for protection purpose, voltage transformer, current transformer, circuit breaker and operation and protection panel that operate both manually and automatically. But the substation has no any capacitor bank for reactive power control. Reactive power control has significant impact on voltage profile of the distribution feeders.

During the site visit, it has been observed that the transformers and switch boards around Gurara have aged, which has significant effect on the efficiency of the distribution network. Fig. 3.1 taken by the authors around Gurara during feeder routes observation, which indicates how equipment is aged.



Figure 3. 1 Photo taken by the authors to show aged line connections

Table 3.1 and 3.2 shows the line data and bus data of Bella feeder 4 outgoing line.

Table 3. 1: Bella 15kV distribution feeder F4 line data collected from EEU

From Bus	To Bus	R(ohm)	X(ohm)	From Bus	To Bus	R(ohm)	X(ohm)
1	2	0.05201	0.0312	32	33	0.1572	0.04253
2	3	0.0614	0.068	13	34	0.0410	0.01333
3	4	0.0818	0.0906	34	35	0.0520	0.03121
4	5	0.0886	0.0982	35	36	0.0410	0.02464
5	6	0.0546	0.0327	36	37	0.0136	0.00821
6	7	0.1284	0.08	37	38	0.1573	0.08
7	8	0.0955	0.1057	38	39	0.2097	0.05671
8	9	0.10369	0.1148	39	40	0.2622	0.07088
9	10	0.0682	0.0755	37	41	0.0545	0.06044
10	11	0.14128	0.088	41	42	0.0341	0.03777
11	12	0.25688	0.16	42	43	0.0545	0.06044
10	13	0.06822	0.0755	43	44	0.0614	0.068
13	14	0.17982	0.1057	44	45	0.1091	0.12088
14	15	0.08991	0.0544	45	46	0.0886	0.09822
15	16	0.4192	0.1134	46	47	0.0409	0.04533
16	17	0.524	0.1417	47	48	0.1364	0.15111
17	18	0.6288	0.1701	48	49	0.1091	0.12088
18	19	0.262	0.0708	49	50	0.0682	0.07555
19	20	0.3614	0.12	50	51	0.0899	0.056
20	21	0.32	0.1066	51	52	0.1027	0.064
21	22	0.28	0.0933	52	53	0.0719	0.0448
22	23	0.36	0.12	53	54	0.2055	0.128
23	24	0.6	0.2	52	55	0.0256	0.016
19	25	0.4	0.1333	55	56	0.1541	0.096
25	26	0.6293	0.2133	56	57	0.44178	0.28444
26	27	0.1048	0.0355	57	58	0.524	0.14177
27	28	0.2622	0.1333	58	59	0.30392	0.08223
26	29	0.1156	0.06	59	60	0.262	0.07088
29	30	0.0513	0.0266	60	61	0.2096	0.05671
30	31	0.1027	0.0533	61	62	0.2882	0.07797
31	32	0.4192	0.1134	62	63	0.4192	0.11342

Table 3. 2 :Bella distribution feeder F4 peak load data collected from EEU.

Bus	load P(MW)	Load Q(MVAr)	Bus	Load at Bus P(MW)	Load at Bus Q(MVAr)
2	0.15	0.07	33	0.15	0.06
3	0.28	0.1	34	0.07	0.02
4	0.09	0.02	35	0.22	0.1
5	0.15	0.06	36	0.22	0.1
6	0.25	0.11	38	0.25	0.1
7	0.15	0.06	39	0.24	0.1
8	0.07	0.03	40	0.09	0.01
9	0.07	0.02	41	0.22	0.1
11	0.15	0.06	42	0.14	0.06
12	0.25	0.11	43	0.22	0.1
13	0.25	0.11	44	0.13	0.05
14	0.15	0.06	45	0.07	0.02
15	0.25	0.11	46	0.28	0.13
16	0.07	0.02	47	0.28	0.13
17	0.07	0.02	48	0.28	0.13
18	0.25	0.1	49	0.28	0.13
19	0.03	0.01	50	0.28	0.13
20	0.07	0.02	51	0.28	0.13
21	0.25	0.11	53	0.25	0.12
22	0.25	0.1	54	0.25	0.12
23	0.25	0.1	55	0.25	0.11
24	0.25	0.1	56	0.16	0.06
25	0.03	0.01	57	0.25	0.11
27	0.25	0.1	58	0.17	0.06
28	0.15	0.06	59	0.25	0.11
29	0.15	0.06	60	0.25	0.11
30	0.15	0.06	61	0.25	0.11
31	0.25	0.11	62	0.45	0.25
32	0.25	0.11	63	0.08	0.03

3.3 Modeling of Distribution Network

In order to accurately simulate the distribution network problem, it is vitally important to take into account all the practical parameters (line data, bus data, loading condition and...) of the distribution network. Therefore, in this thesis, the real parameters of the conductors (line data) on the distribution network and bus data have been used to model the distribution feeder in MATLAB simulation tool and DIgSILENT simulation software.

Modeling of the Distribution System on DIgSILENT

DIgSILENT software is large integrated power system simulation software designed by Germany DIgSILENT company. It is an integrated power analysis tool that combines reliable and flexible system modeling capabilities with state-of-the-art solution algorithm and unique object-oriented data base management [35]. It provides the function of all aspect of power system analysis, including load flow calculation, fault analysis, optimal power flow, power distribution network optimization, optimal capacitor placement etc.

“DIgSILENT” is an acronym for “**D**igital **S**imuLation of **E**lectrical **N**eTworks”. DIgSILENT version 7 was the world’s first power system analysis software with an integrated graphical single-line interface. That interactive single-line diagram included drawing functions, editing capabilities and all relevant static and dynamic calculation features.

After understanding the network structure and working principle of DIgSILENT, by using the collected datum single line diagram Bella distribution feeder four(F4) is modeled. Figure 3.2 shows the single line representation of Bella outgoing distribution feeders modeled in DIgSILENT.

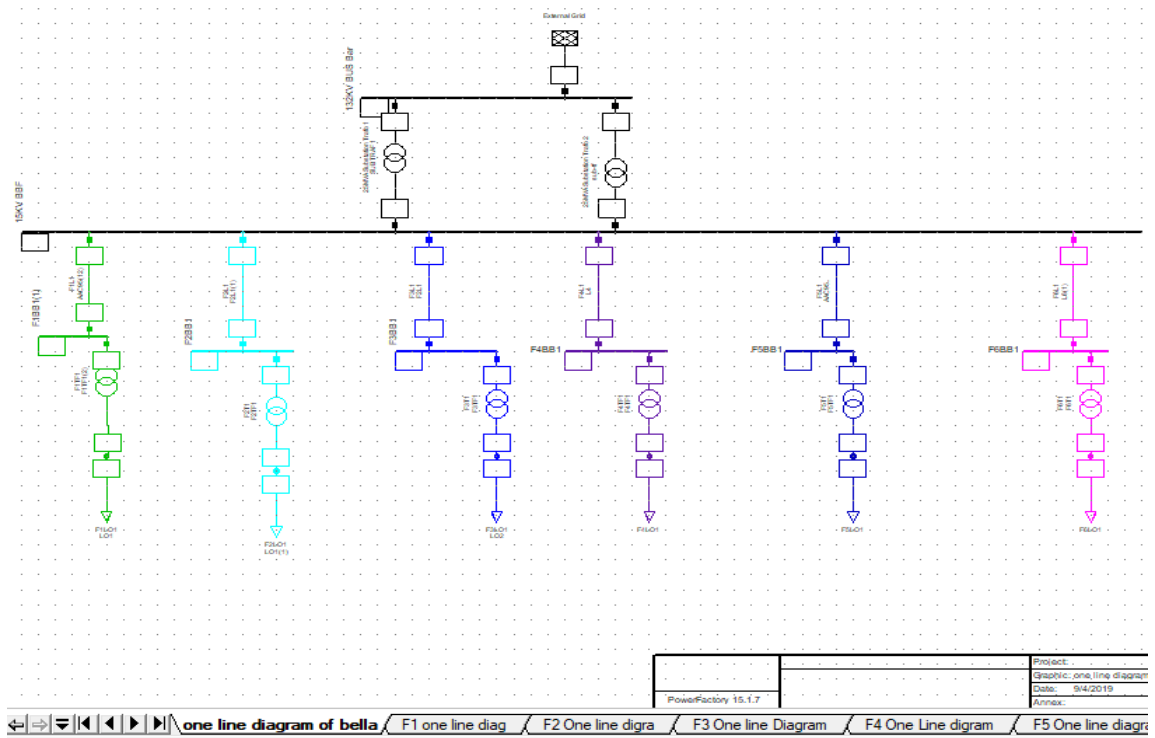


Figure 3. 2 Bella outgoing distribution feeders one-line diagram modeled in DIGSILENT

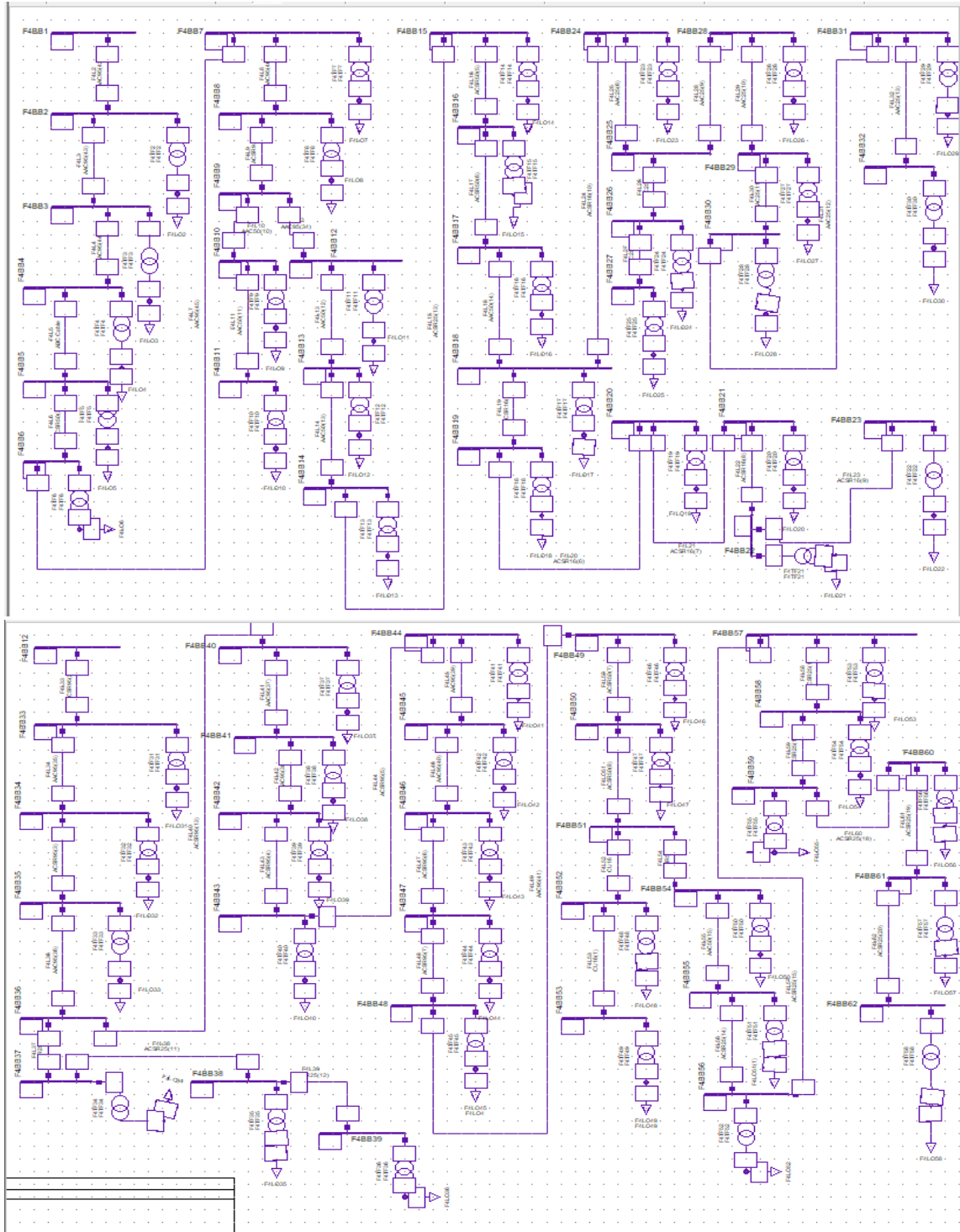


Figure 3. 3 Bella distribution feeder four(F4) single line diagram modeled in DIGSILENT

Modeling of Bella Distribution feeder(F4) Loads

The load variations in Bella distribution system for one-year period of time are taken into account. In this thesis the following assumption has been taken to model Bella distribution feeder loads. It is assumed that the load variation can be approximated in discrete levels and all loads vary in a conforming way, i.e. the k^{th} load level at the i^{th} bus can be expressed in terms of peak load by

$$(P_{ik}, Q_{ik}) = x_k(P_{i1}, Q_{i1}) \quad (3.1)$$

Where: P_{ik} is active power loading of the i^{th} bus at k^{th} load level.

Q_{ik} is reactive power loading of i^{th} bus at k^{th} load level.

P_{i1} is active power loading of the i^{th} bus at peak load.

Q_{i1} is reactive power loading of the i^{th} bus at peak load.

x_k is a number between 0 and 1 including 0 and 1.

Each hour recorded active power loading condition of feeder 4 has been taken from the substation hourly. The average hourly recorded data is summarized with the help of excel. To express the load level of Bella distribution feeder(F4) according to equation (3.1), the following analysis has been done in excel. The average hourly summarized data of the feeder is normalized by the peak load (i.e. dividing hourly average summarized data by the peak load). The normalized values are multiplied by 100 to change it into percentage value. Figure 3.4 shows percentage load variation of Bella distribution feeder(F4).

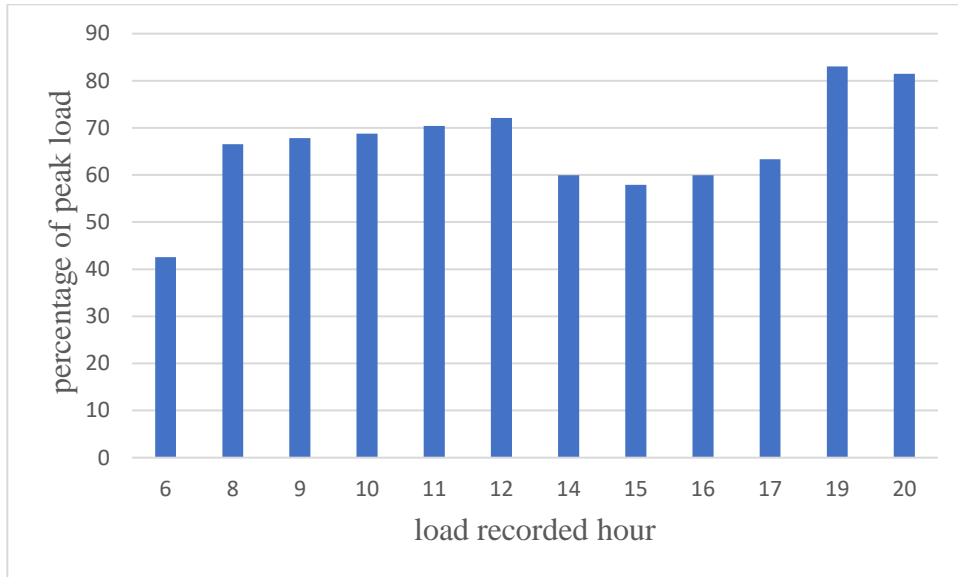


Figure 3. 4 Percentage of load variation in terms of peak load

As shown from figure 3.4, percentage load variation of the distribution system varies between 42 and 83 percent of the peak load. This percentage load variation data is used in separate PSO based DG and capacitor placement and GA based capacitor placement simulation for power loss reduction and voltage profile improvement of Bella distribution feeder four(F4).

3.4 Load Flow Calculation to Determine Distribution System

Parameters

Load flow calculations are used to analyze power systems under steady state conditions. The load flow calculates the voltage magnitude and the voltage angle of the nodes, as well as the active and reactive power flow on branches. Usually, the network nodes are represented by specifying two of these four quantities. Depending on the quantities specified, nodes can be classified as [36]:

PV bus: constant active power and voltage magnitude are specified. This type of node is used to represent generators whose active power and voltage magnitude are controlled, and synchronous condensers.

PQ bus: active and reactive powers are specified. This type of node is used to represent loads and generators with fixed dispatch.

Slack bus: This bus is distinguished from the other two types by the fact that real and reactive powers at this bus are not specified. Instead, voltage magnitude and phase angle are specified.

The complex power injected by a source into a bus, say i^{th} bus of a power system is given by;

$$S_i = P_i + jQ_i = V_i \times I_i^*; \quad i = 1, 2, 3 \dots \quad (3.2)$$

where; V_i is the voltage at the i^{th} bus with respect to ground.

I_i is the source current injected into the bus

So as to handle the load flow problem more conveniently the use of I_i rather than I_i^* is encouraged. As a result, the complex conjugate of the above equation is considered.

That is:

$$S_i^* = P_i - jQ_i = V_i^* \times I_i; \quad i = 1, 2, \dots, n \quad (3.3)$$

The source current is given by;

$$I_i = \sum_{j=1}^n Y_{ij} \times V_j \quad i = 1, 2 \dots n \quad (3.4)$$

Where, ij is branch number and

n is total number of branches in the distribution system.

The expansion of equation (3.4) resulted in equation (3.5).

$$I_i = \sum_{j=1}^n Y_{ij} \times V_j = Y_{i1}V_1 + Y_{i2}V_2 + \dots + Y_{ii}V_i + Y_{i(i+1)}V_{(i+1)} + \dots + Y_{in}V_n \quad (3.5)$$

Thus, substituting this equation into the complex conjugate equation of power injection we have:

$$P_i - jQ_i = V_i^* \left(\sum_{j=1}^n Y_{ij} \times V_j \right) \quad i = 1, 2 \dots n \quad (3.6)$$

Equating real and imaginary parts of equation (3.6), it gives equation (3.7) and (3.8).

$$P_i(\text{real power}) = \text{Re} \left\{ V_i^* \left(\sum_{j=1}^n Y_{ij} \times V_j \right) \right\} \quad (3.7)$$

$$Q_i(\text{reactive power}) = -\text{Im} \left\{ V_i^* \left(\sum_{j=1}^n Y_{ij} \times V_j \right) \right\} \quad (3.8)$$

In polar form V_i and Y_{ij} of Eq (3.5) can be expressed as:

$$V_i = |V_i| e^{j\delta_i} \quad (3.9)$$

$$Y_{ij} = |Y_{ij}| e^{j\theta_{ij}} \quad (3.10)$$

Expressing equation (3.9) and (3.10) in rectangular form and substituting in to equation (3.6) gives the next equations.

$$P_i(\text{real power}) = |V_i^*| \left(\sum_{j=1}^n |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \right) \quad (3.11)$$

$$Q_i(\text{reactive power}) = -|V_i^*| \left(\sum_{j=1}^n |V_j| |Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \right) \quad (3.12)$$

From equation (3.3) the source current can be also expressed as follows:

$$I_i = \frac{(P_i - jQ_i)}{V_i^*} \quad i = 2, 3, \dots, n \quad (3.13)$$

Using equation (3.13) and equation (3.5) the bus voltage V_i is calculated as follows.

$$V_i = \frac{1}{Y_{ii}} \left[I_i - \sum_{j=1 \& j \neq i}^n (Y_{ij} V_j) \right] = \frac{1}{Y_{ii}} \left[\frac{(P_i - jQ_i)}{V_i^*} - \sum_{j=1 \& j \neq i}^n (Y_{ij} V_j) \right] \quad (3.14)$$

To solve the load flow problem for Bella distribution feeder (F4), Newton-Raphson load flow method is implemented in MATLAB computational tool. Newton-Raphson is a

powerful method of solving non-linear algebraic equations. It works faster and sure to converge in most cases as compared to other methods [37]. It is indeed the practical method of load flow solution of large power networks. Newton-Raphson load flow algorithm is explained in Appendix A

Description of DIgSILENT Built-in Load Flow Analysis

DIgSILENT built-in AC load flow method

In DIgSILENT the nodal equations used to represent the analyzed networks are implemented using two different formulations [35]:

- ✓ Newton-Raphson (current Equations)
- ✓ Newton-Raphson (power Equations)

In both formulations, the resulting non-linear equation system solved by an iterative method. DIgSILENT uses the Newton-Raphson as its non-linear equation solver [35]. The selection of the method used to formulate the nodal equation is user-defined, and selected based on a type of network to be calculated. For large transmission systems, especially when heavily loaded, the standard Newton-Raphson algorithm using the “power equation” formulation usually converges best. Distribution systems, especially unbalanced distribution systems, usually converge better using the “Current Equation” formulation.

DIgSILENT built-in DC load flow method

Some occasions may require performing fast analysis in complex transmission networks where only a reasonable approximation of the active power flow of the system is needed. For such situations the DC load flow can be used. Other applications of the DC load flow method include situations where the AC load flow trouble converging.

DIgSILENT Built-in Optimization Mechanisms

The function of Tie Open Point Optimization (TOPO) (ComTieopt) is to optimize a radial system of connected feeders by determining the best location for network open points. An open point can be moved by the TOPO tool by opening and closing switches on the networks to be optimized. Feeder reconfiguration of the distribution network can be done by the TOPO tool.

DIgSILENT built-in voltage profile optimization: The Voltage Profile Optimization (VPO) command (`ComVoltplan`) is used to optimize distribution transformer taps over the expected range of network load and generation conditions.

DIgSILENT built-in optimal capacitor placement for power loss and voltage drop reduction

Optimal Capacitor Placement (OCP) is an automatic algorithm that minimize the cost of losses and voltage constraints(optional) in a distribution network by proposing the installation of new capacitors at terminals along the selected feeder/s. The optimal size and type of capacitor is selected from a list of available capacitors entered by the user. The algorithm also considers the annual cost of such capacitors and only proposes new capacitors for installation when the reduction of energy loss and voltage constraint costs exceeds the annual cost of the capacitor (investment, maintenance, insurance etc.).

Objective function of DIgSILENT Built-in optimal capacitor placement problem for power loss and voltage drop minimization.

The OCP optimization algorithm minimizes the total annual network cost. This is the sum of the cost of grid losses, the cost of installed capacitors and optionally the fictitious penalty cost of voltage violations:

$$\text{Total costs} = C_{Losses} + \sum_{i=1}^m C_{capi} + \sum_{i=1}^N C_{voltvioli}$$

C_{Losses} is the annual cost of grid losses (i.e. including the grid losses, not only the feeder/s for which the optimal capacitor placement is performed). Essentially, this is the current squared loss of all elements in the network.

C_{capi} is the annual cost of a capacitor (investment, maintenance, insurance), as entered by the user in the list of possible capacitors. where m is the total number of installed capacitors.

$C_{voltvioli}$ corresponds to a fictitious cost used to penalize a bus (terminal) voltage violation. N is the total number of feeder terminals with voltage violations.

3.5 Minimization of Power Loss and Voltage Drop

In order to minimize power loss and voltage drop of Bella substation distribution feeder(F4), Separate Particle Swarm Optimization (PSO) based capacitor and DG placement at different load level has been performed. In addition to separate PSO based capacitor placement, Genetic Algorithm (GA) based capacitor placement simulation at different load level also performed on Bella distribution feeder(F4) using MATLAB computational tool. In this section, the objective function of PSO based capacitor and DG placement and GA based capacitor placement has been discussed. Candidate bus (potential node) analysis of distribution substation feeders also explained.

Identification of Candidate Buses for Capacitor (DG) Placement.

In order to get the potential node, the capacitor placement was performed by making the reactive power zero at each node or load at a time. After compensating reactive power at each bus, load flows have been run again. From this load flow, the new real power loss and voltage deviation will be evaluated.

Power loss reduction index and voltage profile improvement index for each bus will be calculated by using equation (3.15) and (3.17). From this value the potential buses for capacitor/DG placement will be identified.

Power Loss reduction Index (PLI) of the i^{th} bus can be calculated as follows [38]:

$$PLI(i) = \frac{Loss\ Reduction[i] - Min.\ Reduction}{Max.\ Reduction - Min.\ Reduction} \quad (3.15)$$

$$Plred = Loss\ Reduction[i] = P_{uncomp} - P(i) \quad (3.16)$$

Where: $Plred$ is power loss reduction

P_{uncomp} is the uncompensated active power loss.

$P(i)$ is the active power loss obtained by making the reactive power at bus i zero.

$PLI(i)$ is normalized loss reduction weight due to compensation at bus i

$Loss\ Reduction[i]$ is the total power loss reduction resulting from compensating bus i

Min.Reduction is the minimum loss reduction of all individual bus compensation

Max.Reduction is the maximum loss reduction of all individual bus compensation.

The voltage improvement index is calculated in the same manner.

$$VII = \frac{\text{Voltage drop reduction}[i] - \text{Min.Voltage drop reduction}}{\text{Max.Voltage drop reduction} - \text{Min.Voltage drop reduction}} \quad (3.17)$$

Where: *VII* is normalized voltage profile improvement weight measured due to compensation at bus *i*

Voltage drop reduction[i] is the total voltage drop reduction due to compensation at bus *i*

Min.Voltage drop reduction is the minimum voltage drop reduction of all individual bus compensation.

Max.Voltage drop reduction is the maximum voltage drop reduction of all individual bus compensation.

The algorithm for potential node (candidate bus) identification is explained below.

1. Read distribution system data
2. Run the load flow and calculate the uncompensated active power loss and voltage deviation.
3. By compensating the reactive power injection (Q_c) at each node and run the load flow, to calculate the active power loss and voltage deviation in each case.
4. Calculate the power loss reduction and voltage deviation reduction, power loss index (PLI) and voltage improvement index (VPI)
5. Select the candidate node whose PLI and VII in the top.
6. Stop

The above algorithm identifies the candidate buses. Then, to locate and size the capacitors (DG) on the candidate buses, PSO and GA optimizers has been used in MATLAB separately.

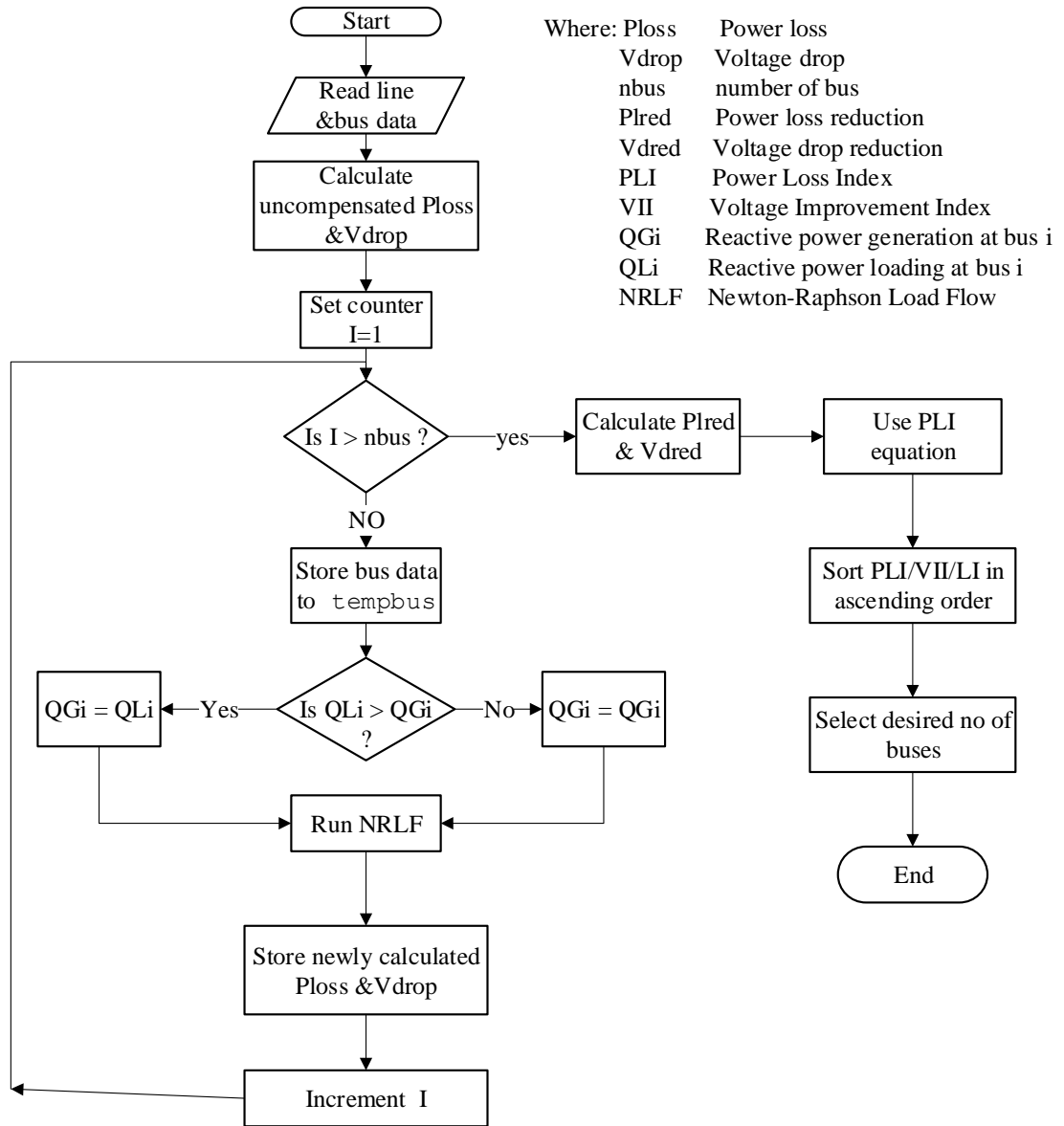


Figure 3. 5 Flow chart of candidate bus selection

Capacitor (DG) Placement and Sizing Using PSO

First, the potential nodes (candidate buses) have been identified using combined sensitivity factor (both power loss indices and voltage improvement indices). Then, the PSO has been used to locate and size the capacitor (DG) on the potential buses.

Objective function of PSO Capacitor (DG) Placement

The objective is to reduce voltage deviation and total energy losses of the distribution system while striving to minimize the cost of capacitors (DG) installed in the system. The objective function consists of two terms. The first is the cost of the capacitor placement and the second is the cost of the total energy losses.

$$F = \text{Minimize}\{\text{cost of yearly power loss} \\ + \text{cost of yearly capacitor(DG) cost}\} \quad (3.18)$$

Subjected to:

$$\text{Cost of yearly power loss} = K_p \times P_{loss} \quad (3.19)$$

$$\text{Cost of yearly capacitor cost} = \sum_{i=1}^n (K_i^c \times Q_i^c) \quad (3.20)$$

Where n is the number of candidate locations for capacitor placement.

K_p , the equivalent annual cost per unit of power loss(\$/(Mw-year)),

K_i^c , is the annual capacitor installation cost.

And $i = 1, 2, \dots, n$ are the indices of the buses selected for compensation.

Capacitor Placement and Sizing Using GA

In order to size and locate capacitors on Bella distribution feeder (F4), in the same way to PSO capacitor placement, the potential nodes have been analyzed first. The potential nodes are candidates for capacitor placement to minimize loss and voltage drop of the distribution system.

Objective function of GA for capacitor placement

MATLAB built in multi objective genetic algorithm is used to simulate capacitor placement problem to reduce Bella distribution feeder (F4) power loss and voltage drop.

The objective is to reduce the loss and voltage drop while minimizing the cost of installed capacitors. The objective function given to the GA algorithm to improve performance of Bella distribution feeder (F4) is explained below.

$$\text{Objective function (F1)} = \text{minimize yearly power loss cost} \quad (3.21)$$

$$\text{objective function(F2)} = \text{minimize yearly capacitor or DG cost} \quad (3.22)$$

Constraints of capacitor Placement problem

Constraints for the optimal solution is explained as follows:

- ✓ Bus voltage magnitude constraint

$$V_{i \min} \leq V_i \leq V_{i \max}$$

Where: $V_{i \min}$ and $V_{i \max}$ are the minimum and maximum permissible per unite voltages of bus i

- ✓ Size of installed capacitor constraint: the total reactive power injection Q_t^c is not to exceed the total reactive power demand Q_t^d in the distribution system.

$$Q_t^c \leq Q_t^d$$

- ✓ Branch current constraint:

$$I_i \leq I_{i \max}$$

Where I_i is the current of feeder I and $I_{i \max}$ is the maximum permissible current of branch i

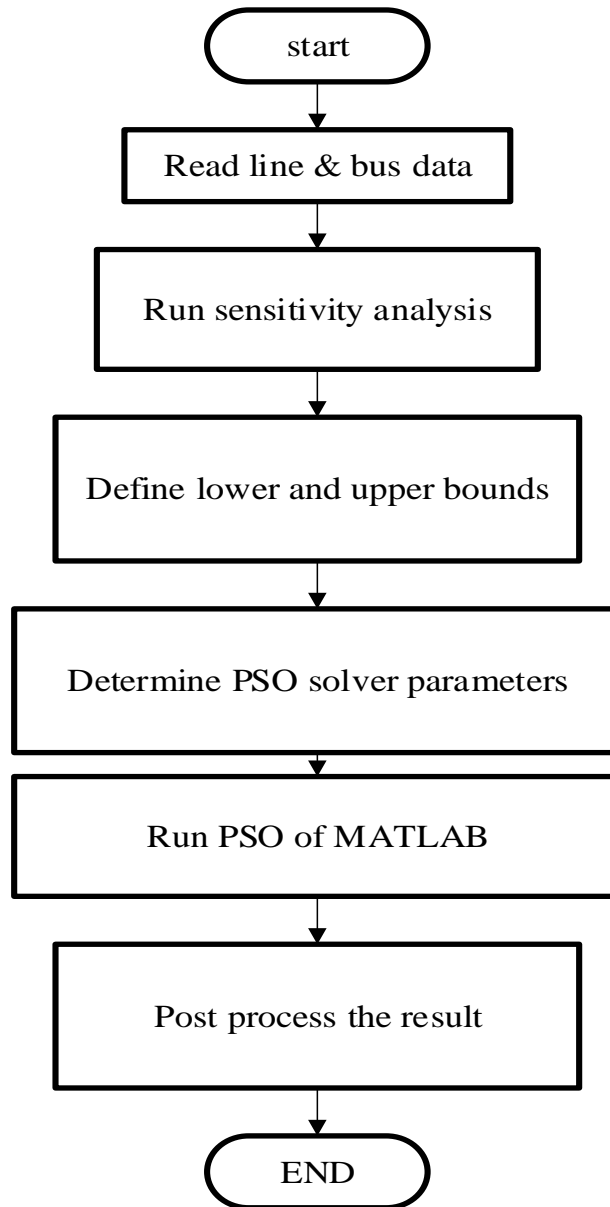


Figure 3. 6 Overall flow chart of the PSO

As explained in the above flow chart, using the collected data the sensitivity analysis has been done. The sensitivity analysis is used to select the candidate buses. MATLAB built in PSO has been used to size and locate DG/capacitors. Load flow simulation result after the placement of PSO based capacitor (DG) on Bella distribution feeder also has been analyzed.

Chapter 4: Simulation Studies and Analysis of Results

4.1 Introduction

In this chapter the results obtained from the simulations performed in MATLAB using the PSO and GA algorithms are presented. The PSO optimization uses the built-in MATLAB function `particleswarm` while the GA is implemented using the multi-objective optimization algorithm `gamultiobj`. The load flow simulations were run at different load levels to investigate the impact of the selected sizes of the compensating capacitors/DG on power loss and voltage drop of Bella distribution feeder(F4).

4.2 Simulation Studies

The load-flow analysis has been performed using the Newton-Raphson algorithm coded in MATLAB, the source code of which is provided in Appendix C. Using the line and peak load bus data of the distribution network under study (Bella F4), the MATLAB Newton-Raphson load flow has been simulated. The peak load base case simulation result of the distribution network is shown in Appendix D.

From simulation result in Appendix E, it has been observed that Bella distribution feeder(F4) has a loss of 3.86MW/3.286Mvar at peak load. To reduce the loss and voltage drop, separate GA and PSO based capacitor and DG placement has been used.

PSO Based Capacitor Placement Result at Different Load Level.

The candidate bus selection process and the objective function of the PSO is explained in chapter 3 section 3.5. The potential node selection has been coded by using the algorithm explained in section 3.5. The candidate bus selection algorithm and PSO code is shown in Appendix E & F. Using this code, the result in Table 4.1 was generated which shows the reactive power sensitivity values at each node for Bella distribution feeder(F4). Reactive power sensitivity values indicate the effect that a change (variation) in the node's reactive power demand has on the total power loss of the system. This is done by calculating the loss reduction resulting from injecting a reactive power equal to that of the load at a given node.

Table 4. 1: F4 Reactive power Sensitivity index result

Bus no	Sensitivity index	Bus no	Sensitivity index	Bus no	Sensitivity index	Bus no	Sensitivity index
36	1	31	0.2105	13	0.123	17	0.0296
62	0.5285	47	0.201	33	0.1182	16	0.0266
34	0.4984	55	0.1994	30	0.1163	5	0.0228
35	0.3885	46	0.1976	29	0.116	8	0.0224
37	0.3076	21	0.1973	28	0.1155	25	0.0183
61	0.2426	27	0.1896	56	0.1125	9	0.0182
60	0.2398	24	0.1848	12	0.1117	19	0.0176
59	0.2352	23	0.1838	42	0.0792	3	0.0139
51	0.2287	22	0.1821	14	0.071	40	0.0127
50	0.2239	18	0.1645	44	0.0701	2	0.0093
49	0.2193	43	0.1352	63	0.069	4	0.0051
54	0.217	15	0.1327	11	0.0611	1	0
57	0.2168	41	0.1289	6	0.0487	10	0
53	0.2166	58	0.1266	20	0.036	26	0
32	0.2123	39	0.1256	7	0.0359	52	0
48	0.2115	38	0.1254	45	0.0297		

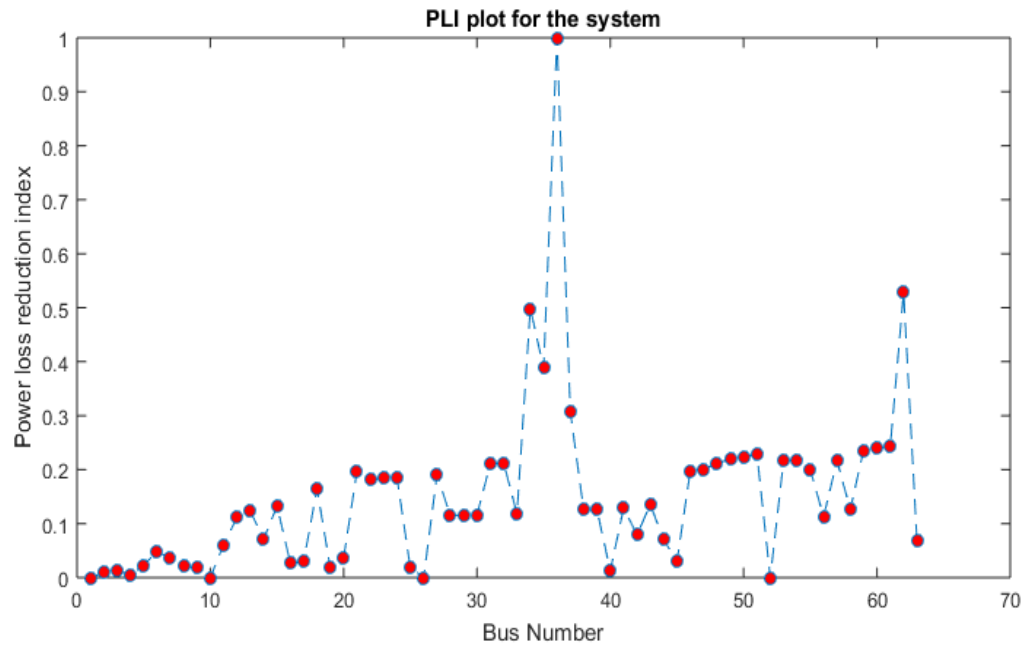


Figure 4. 1 Sensitivity index plot for the buses

The top 10 sensitive buses from Table 4.1 are: 36, 62, 34, 35, 37, 61, 60, 59, 51 and 50 respectively. These buses have been selected for the optimal capacitor placement and using these candidate buses the PSO performed optimal sizing of the capacitors for each and every node. The peak load PSO based simulation has resulted the following size and location of capacitors (see Table 4.2).

Table 4. 2: PSO based capacitor placement simulation result

Bus no	Capacitor size (MVar)	Bus no	Capacitor size (MVar)
36	0.97	61	0.12
62	0.29	60	0
34	2.69	59	0.37
35	1.35	51	1.07
37	1.11	50	0.32

Case I: Load flow simulation result after placement of PSO capacitor at Peak load

By placing the above capacitors at peak load, the real power loss has been reduced from 3.86MW to 2.42MW which is 37.27%. and the voltage profile have been improved up to 15%. Figure 4.2 and 4.3 shows the voltage profile improvement of the distribution network at peak load drawn in excel and MATLAB respectively.

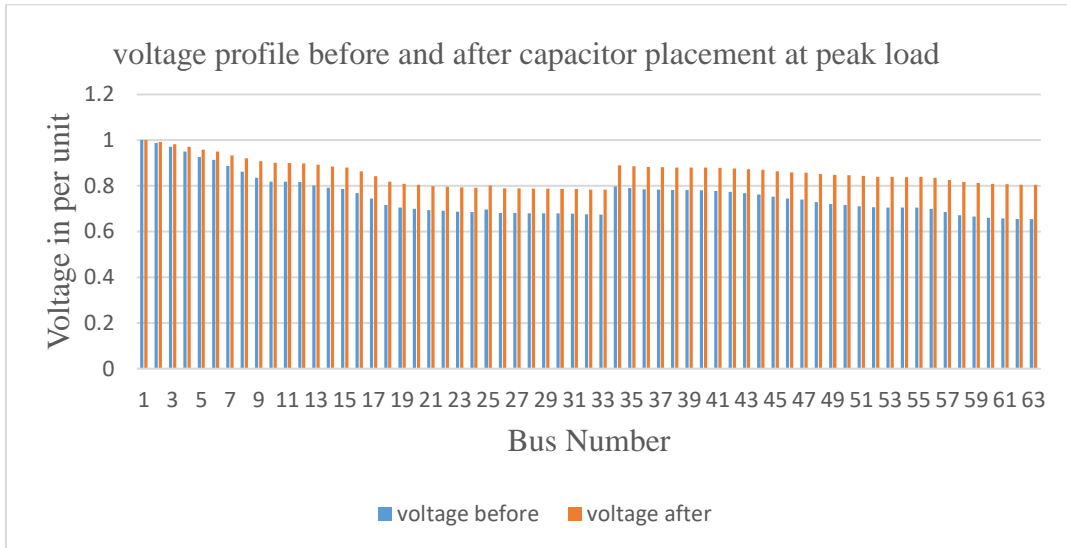


Figure 4. 2 Voltage profile improvement before and after capacitor placement at peak load

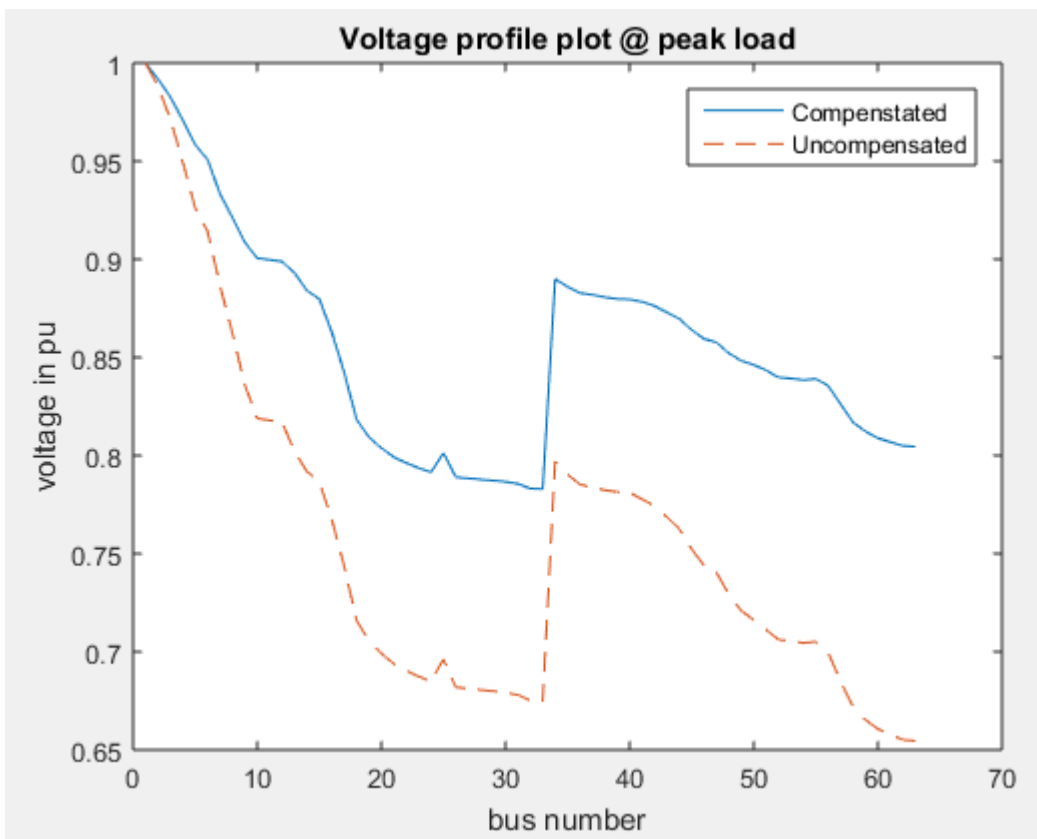


Figure 4. 3 Voltage profile plot in MATLAB before and after capacitor placement

The above Figure 4.2 and 4.3 shows the improvement in the voltage profile of the system as a result of putting the compensating capacitors provided by the PSO algorithm at peak load. In Figure 4.4, it is clearly observed that a maximum of 15% increase in voltage profile has been achieved as a result of the optimization.

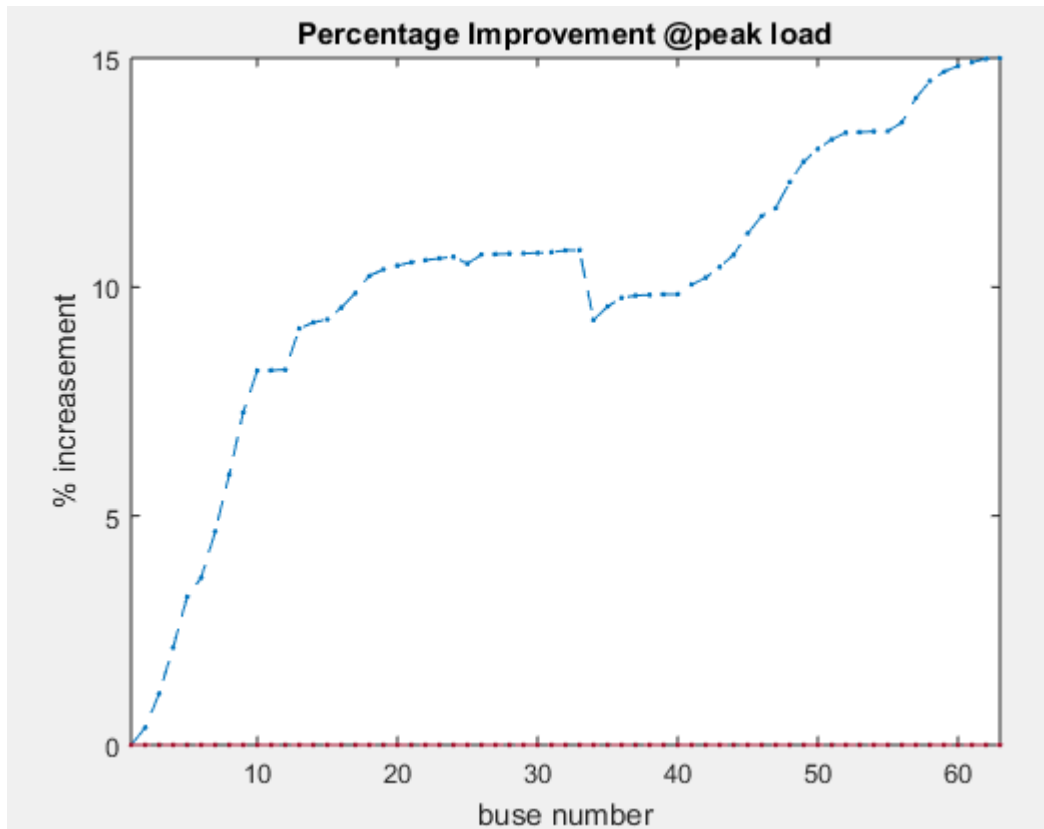


Figure 4. 4 Percentage voltage profile after capacitor placement at peak load

Case II: Load flow simulation result after placement of PSO capacitor at $0.83P_L$

Capacitor placement Particle Swarm Optimization has been simulated at different scenarios. when the load variation is taken at 83% of peak load, the real power loss is reduced from 2.2154MW to 1.5635MW, which is 29% loss reduction and the voltage profile is improved up to 14%.

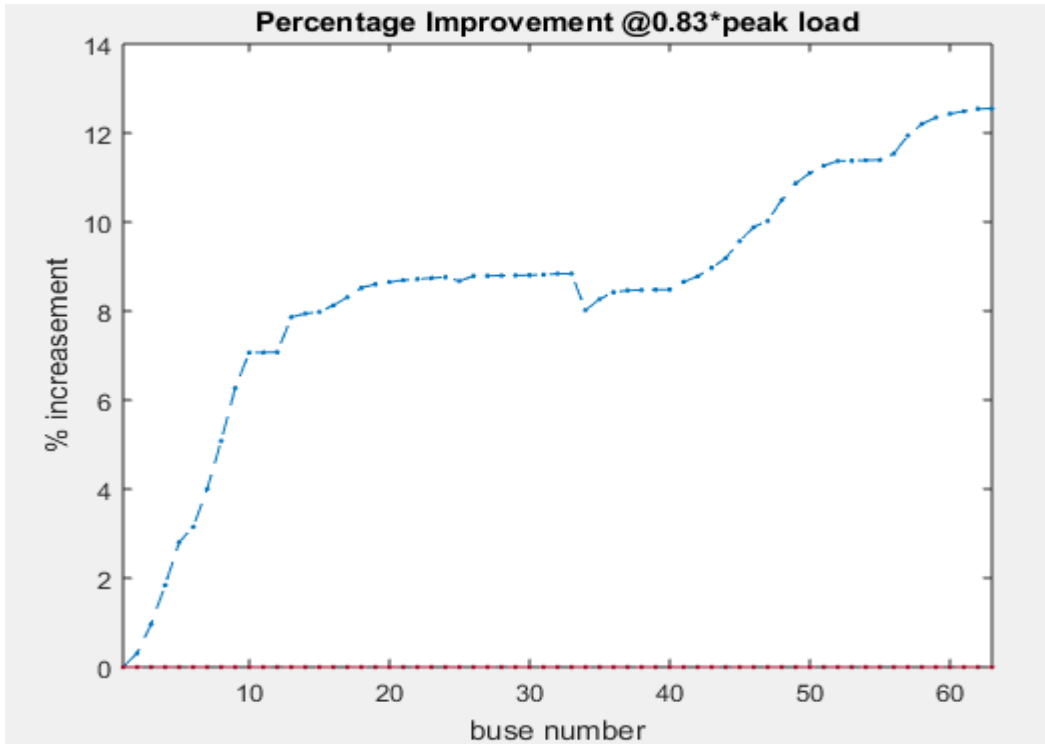


Figure 4. 5 Percentage voltage profile improvement after capacitor placement at $0.83 \cdot P_L$
 Where: P_L is peak Load.

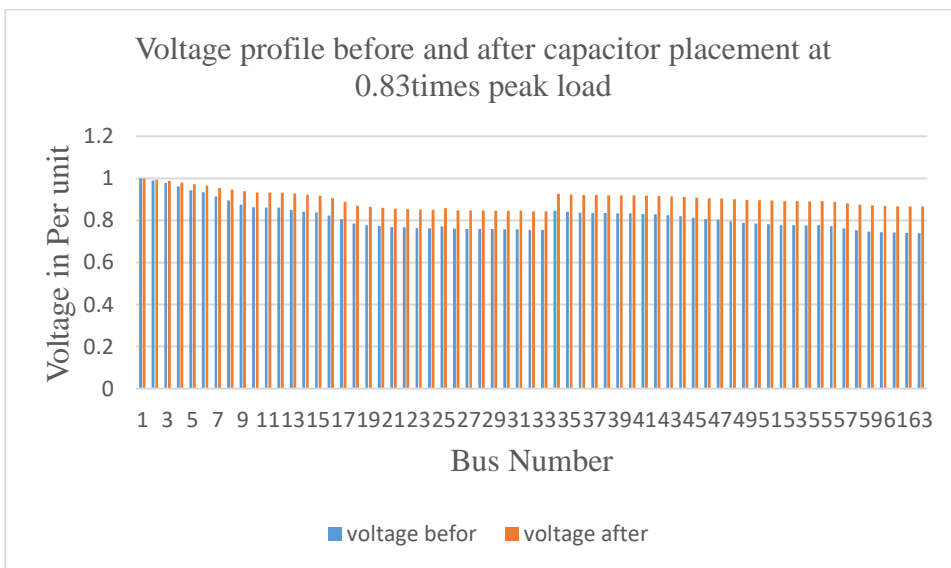


Figure 4. 6 Voltage profile improvement before and after capacitor placement at $0.83 \cdot P_L$

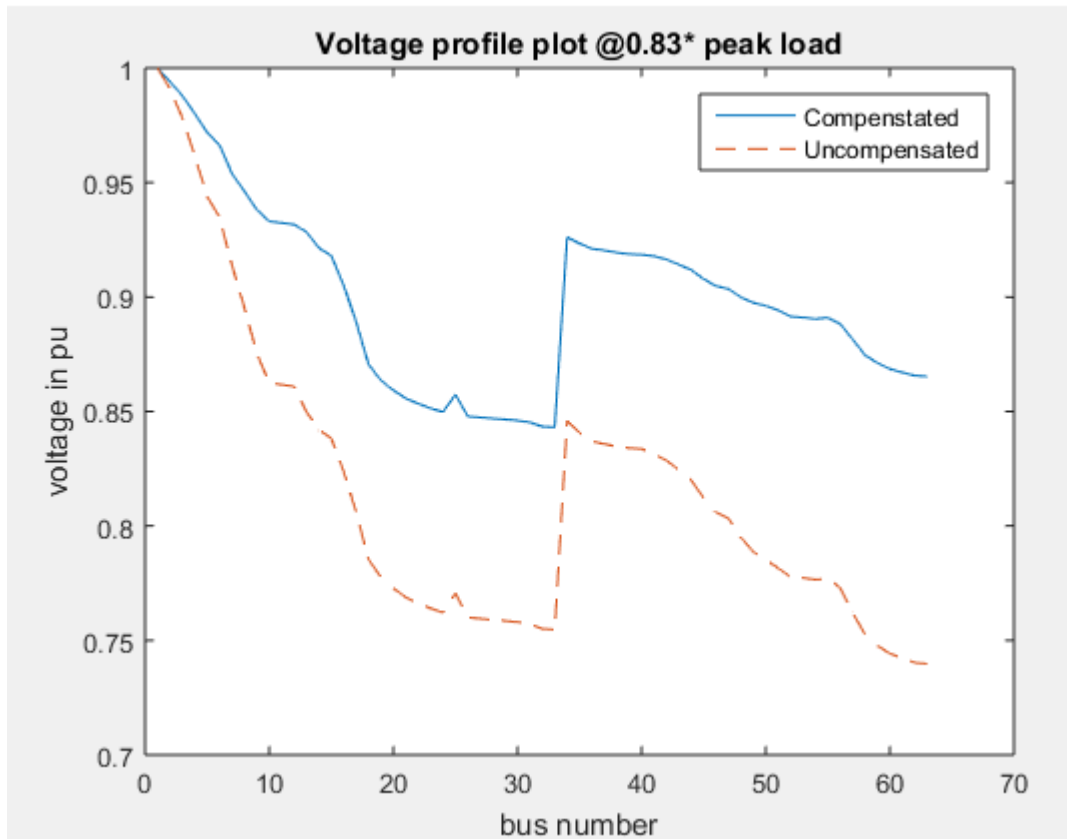


Figure 4. 7 Voltage variation in MATLAB before and after capacitor placement at $0.83*P_L$

Case III: Load flow simulation result after placement of PSO capacitor at $0.6P_L$

When load variation is taken at 60% of the peak load, the real power loss is reduced from 0.974MW to 0.8841MW, which is 9.2% loss reduction. The voltage profile is also improved by 11%.

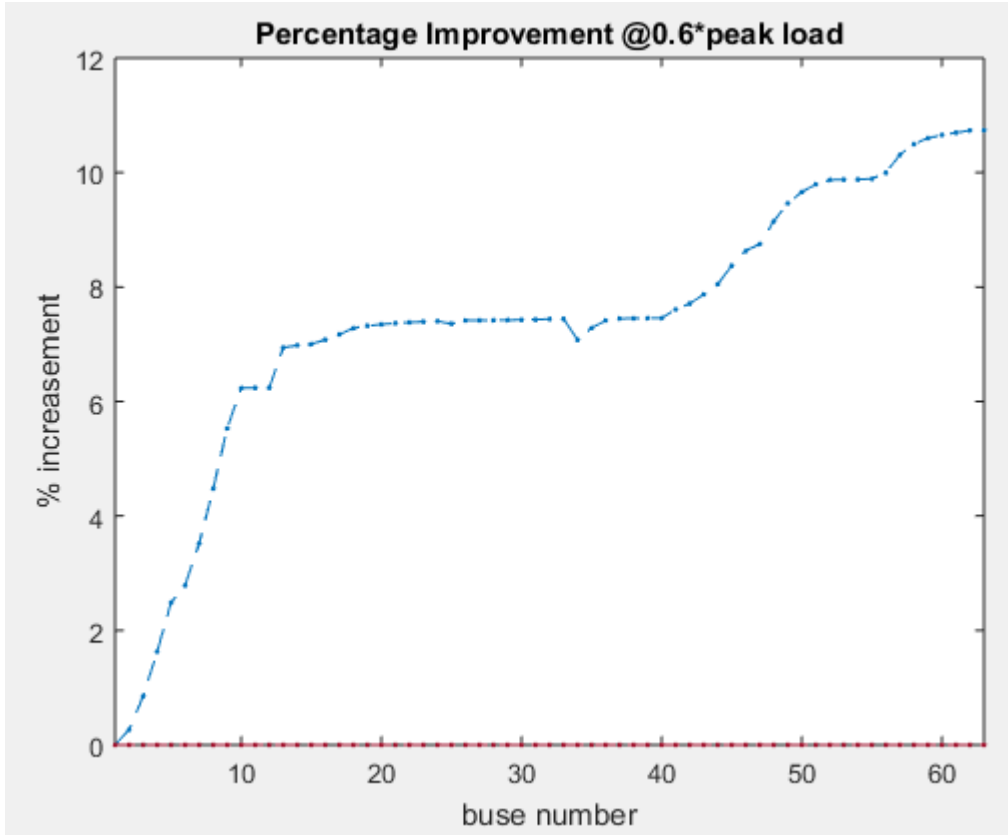


Figure 4. 8 Percentage voltage variation of each bus after capacitor placement at $0.6 \cdot P_L$

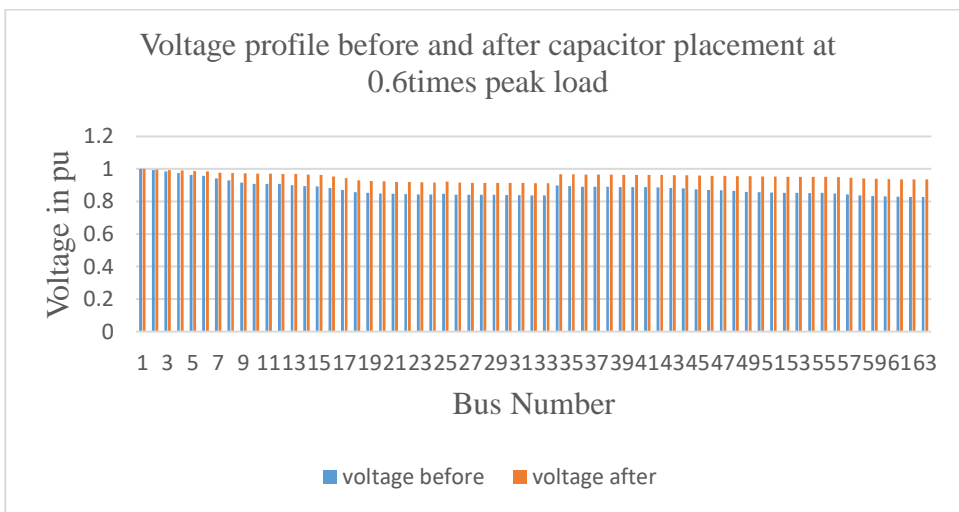


Figure 4. 9 Voltage profile plot before and after capacitor placement at $0.6 \cdot P_L$

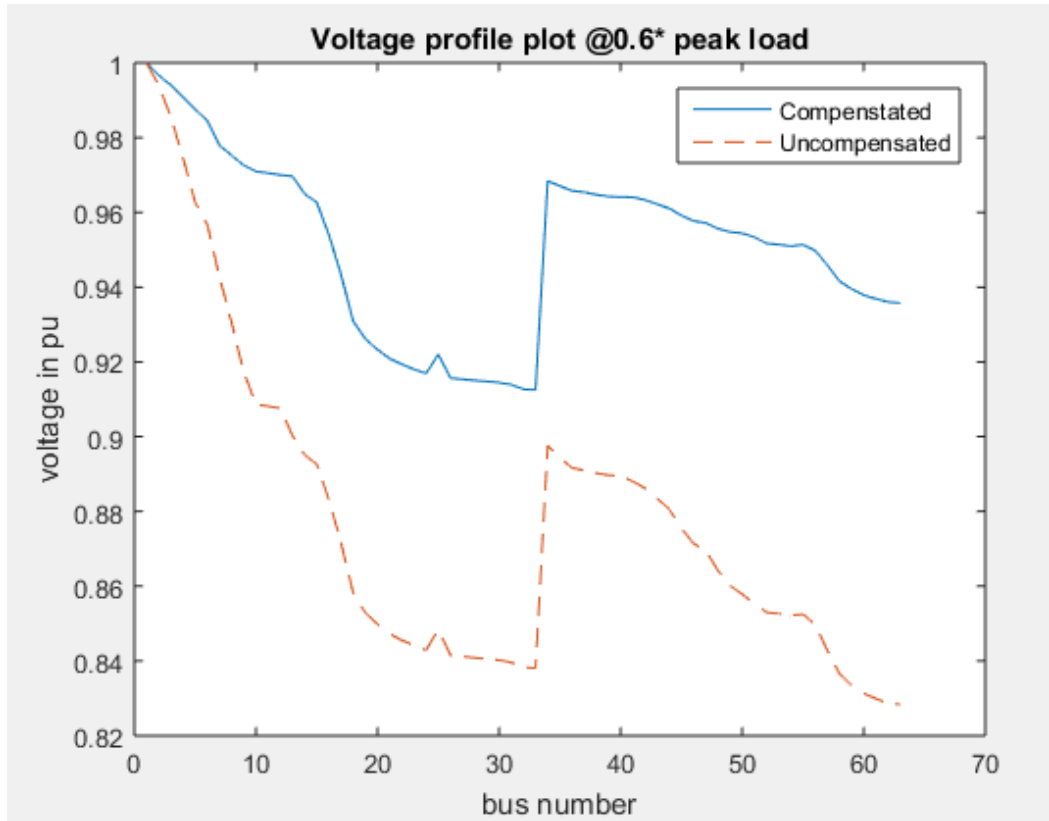


Figure 4. 10 Voltage variation in MATLAB before and after capacitor placement at $0.6 \cdot P_L$

Case IV: Load flow simulation result after placement of PSO capacitor at base load

Capacitor banks may cause over voltage during base load periods. To check the voltage profile, the load flow simulation is run after capacitor placement at base load and gives the following result (see Figure 4.11&4.12).

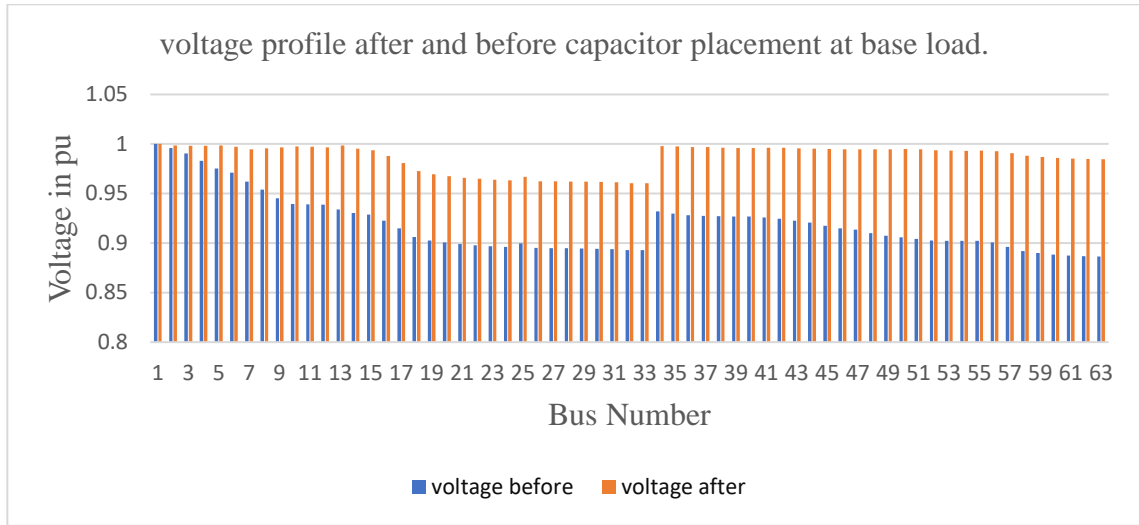


Figure 4. 11 Voltage profile improvement before and after capacitor placement at base load

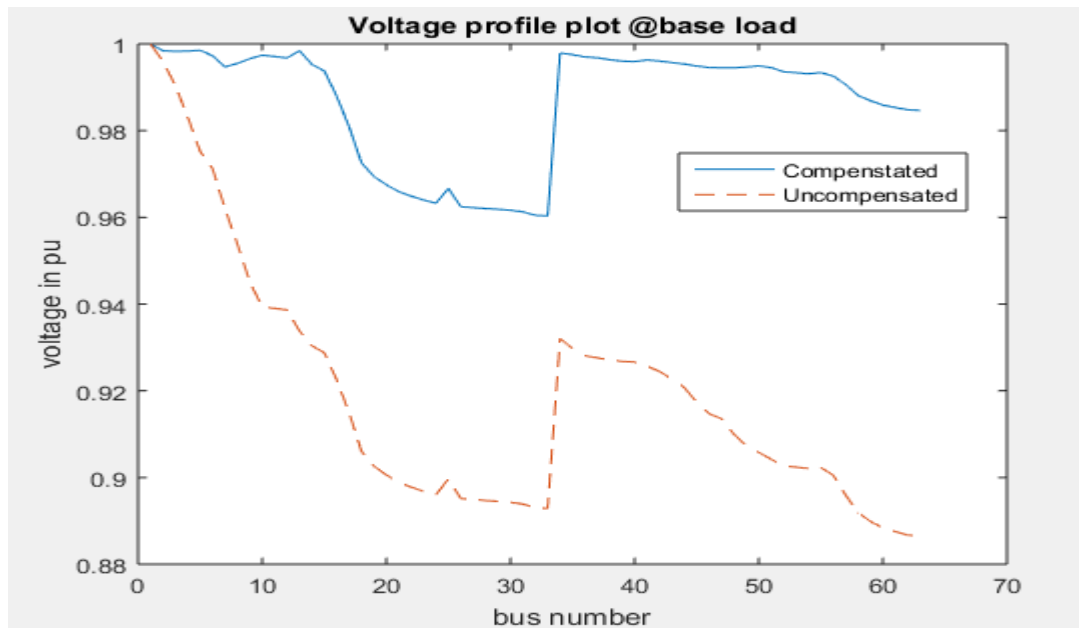


Figure 4. 12 Voltage variation in MATLAB before and after capacitor placement at base load

In general, PSO based capacitor placement resulted in a loss reduction of 37.27% up to 9.2% and a voltage profile improvement of 15% up to 11% at different load levels of the feeder and the selected size of capacitors does not cause any over voltage problem on the buses during off peak load periods.

Particle Swarm Optimized Capacitor Placement Result Cost Analysis

After placement and sizing of capacitor has been accomplished, cost analysis of the selected size of capacitors for peak load have been done. From Table 4.2 and Appendix B, the cost of the selected size of capacitor is calculated as follows:

Table 4. 3: Costs of capacitors selected using PSO

Size of capacitor in KVAR	Location of capacitors (Bus no)	Cost of capacitor in US Dollar [39]
970	36	13400
290	62	6300
2690	34	25550
1350	35	16500
1110	37	14400
120	61	4500
370	59	7600
1070	51	14400
320	50	7050
Sub total cost in US Dollar		109700
installation cost (10%)		10970
Annual maintenance cost (2%)		2194
Total cost in US Dollar		122864
Total cost in Ethiopian Birr		3317328

The revised tariff of Ethiopian Electric Utility is used to calculate the cost of loss [40]. From the revised tariff, average of the general tariff is used, which is 1.58Birr/kwh. Power loss before capacitor placement was 3.86MW and after capacitor placement is reduced to 2.42MW.

Therefore, power loss reduction due to capacitor placement is:

$$3.86MW - 2.42MW = 1.44MW$$

After capacitor placement total energy saved for one year is:

$$1.44MW * 24 * 365 = 12614.4Mwh.$$

Saving in terms of Ethiopian Birr is:

$$12614.4Mwh * 1000 \left(\frac{K}{M}\right) * 1.58 \left(\frac{Birr}{Kwh}\right) = 19930752Birr.$$

Return of investment for capacitor placement is calculated as follows:

$$ROI = \frac{3317328}{19930752} = 0.1664year. \text{ where } ROI; \text{ return of investment}$$

The cost analysis indicates that PSO based capacitor placement needs initial capital investment cost of 3,317,328Birr with return of investment 0.1664year.

Simulation Result of PSO Based DG Location and Sizing

As explained in chapter 2 section 2.3., there are different types of DG technologies. Among those technologies, the selection of a specific DG to a certain area depends on availability of resources, suitability to the environment and cost of DG [41]. Although the PV and wind turbines are free energy sources with low cost and low emission level, it is not feasible to implement in Bella distribution feeders due to the area requirement. Hence, to estimate the cost, microturbine was selected owing to its feasibility to the area and limited cost. To determine the candidate bus for DG placement, first the active power sensitivity index of the distribution system was analyzed in MATLAB.

Active power sensitivity values indicate the effect that a change (variation) in the node's active power demand has on the total power loss of the system. This is done by calculating the loss reduction resulting from injecting active power equal to that of the load at a given node.

Table 4. 4: F4 Active power sensitivity index result

Bus no.	Sensitivity index	Bus no	Sensitivity index	Bus no	Sensitivity index	Bus no	Sensitivity index
62	1	51	0.497	38	0.3007	6	0.0986
36	0.7552	50	0.4841	15	0.2954	16	0.0971
61	0.5921	49	0.4725	39	0.2901	7	0.0837
60	0.5853	18	0.4621	43	0.2883	25	0.0649
59	0.5737	55	0.4606	41	0.2731	19	0.0617
32	0.5611	54	0.4604	13	0.264	9	0.0596
31	0.5558	53	0.4593	12	0.2388	5	0.0493
27	0.5481	48	0.4527	63	0.1984	8	0.0487
37	0.5427	47	0.4267	42	0.1789	3	0.035
24	0.533	46	0.4185	44	0.1781	4	0.0199
34	0.5309	58	0.3773	14	0.1726	2	0.0198
23	0.5296	33	0.3482	20	0.1475	1	0
22	0.5236	30	0.342	11	0.1439	10	0
35	0.5215	29	0.3409	17	0.1136	26	0
21	0.5159	28	0.3394	40	0.1107	52	0
57	0.5098	56	0.3085	45	0.1025		

The top 10 most sensitive buses (62, 36, 61, 60, 59, 32, 31, 27, 37, 24) have been selected and the candidate Buses are given to PSO for DG placement and sizing.

Table 4. 5: PSO based DG sizing and location simulation result

Bus no	DG size in (MW)	Bus no	DG size in (MW)
62	0.5301	32	0.3999
36	0	31	0.3219
61	0.2556	27	0.1766
60	0.2415	37	0
59	0.3552	24	0.385

Case I: Load flow simulation result after placement of PSO based DG at peak load

By locating and sizing DGs at peak load, the real power loss is reduced from 3.86MW to 1.913MW and the voltage drop is reduced up to 12%. Figure 4.13 and 4.14 shows DG voltage profile improvement of the distribution network at peak load drawn in excel and MATLAB respectively.

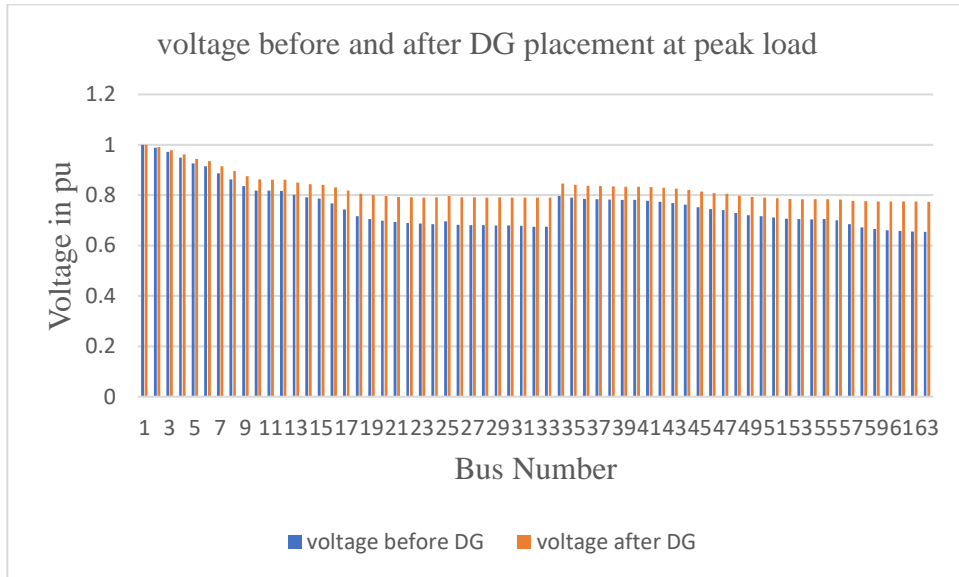


Figure 4. 13 Voltage profile plot before and after DG placement

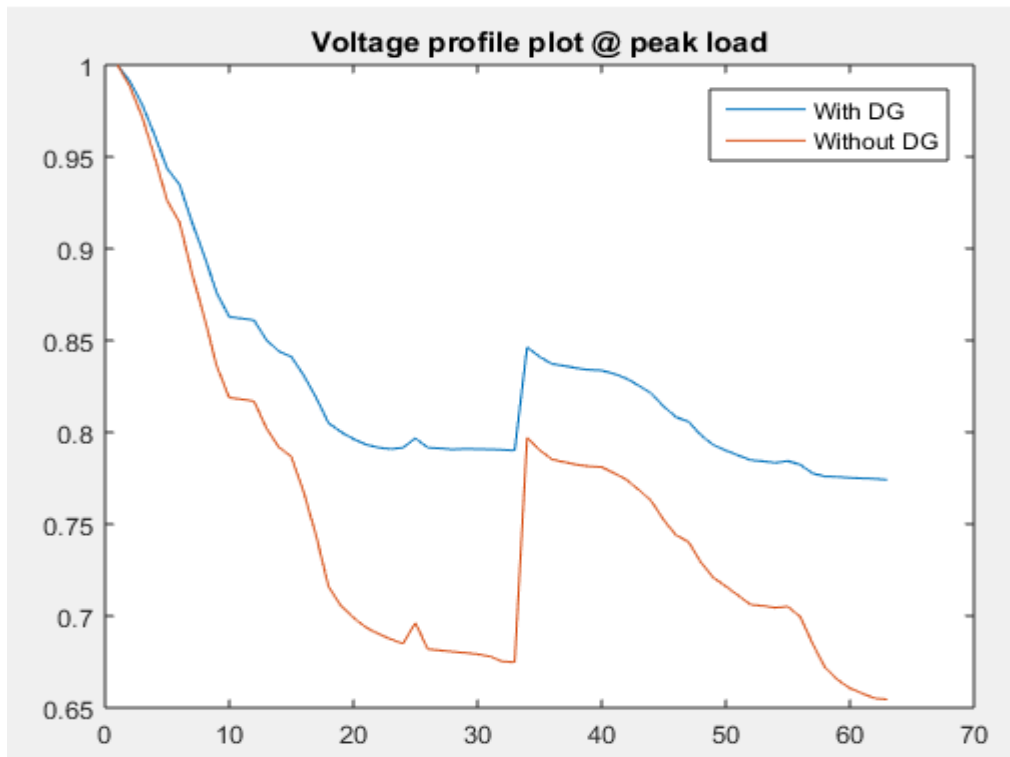


Figure 4. 14 MATLAB voltage profile plot before and after DG placement

Case II: Load flow simulation result after placement of PSO based DG at $0.83P_L$

DG placement at different scenarios has been done for comparison purpose. In this section, the simulation result of DG placement at 83% of peak load is discussed. At this scenario, the distribution feeder active power loss has been reduced from 2.2154MW to 1.0685MW and the voltage drop has been reduced up to 9%.

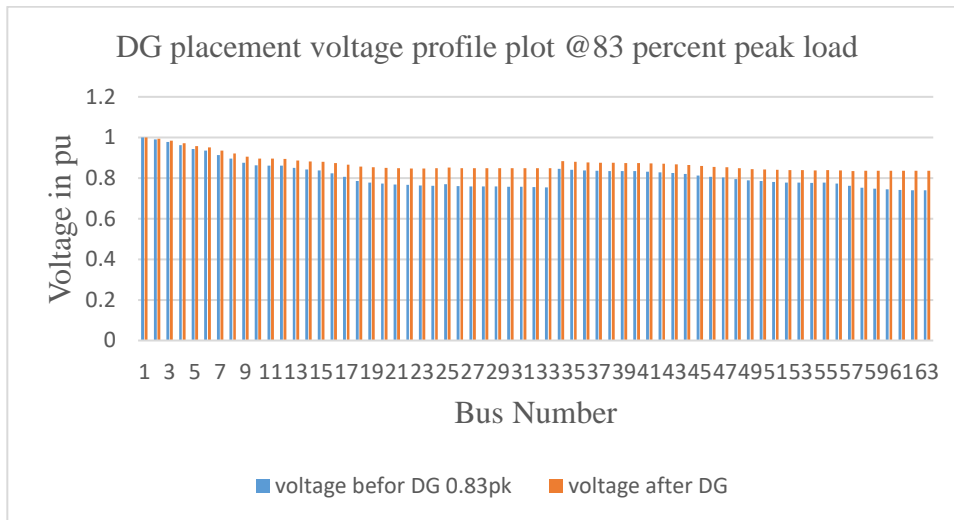


Figure 4. 15 Voltage variation before and after placement of DG at $0.83*P_L$

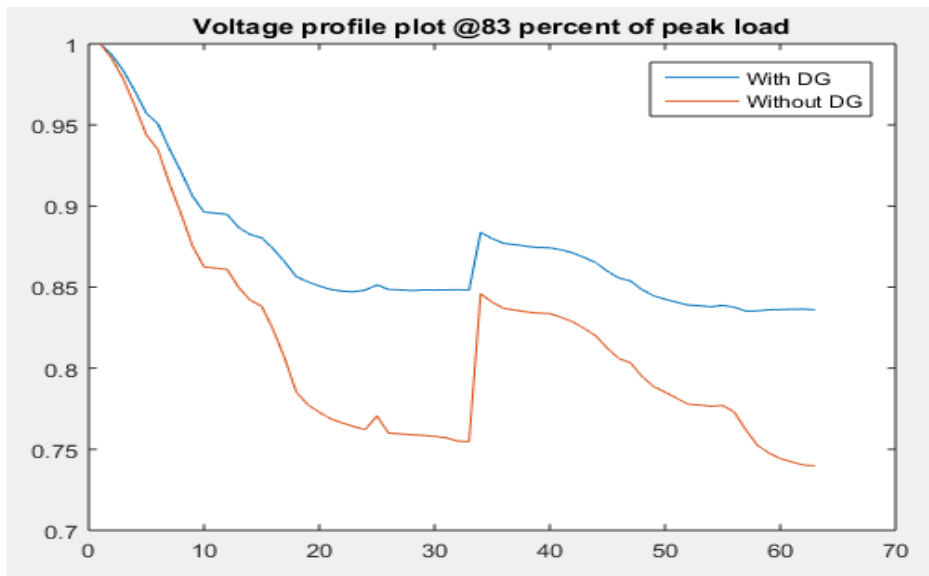


Figure 4. 16 MATLAB plot of bus voltage variation at $0.83*P_L$ DG placement.

Case III: Load flow simulation result after placement of PSO based DG at $0.6P_L$

DG placement at 60% of peak load simulation results in loss reduction from 0.974MW to 0.4051MW and the voltage drop is reduced up to 8%.

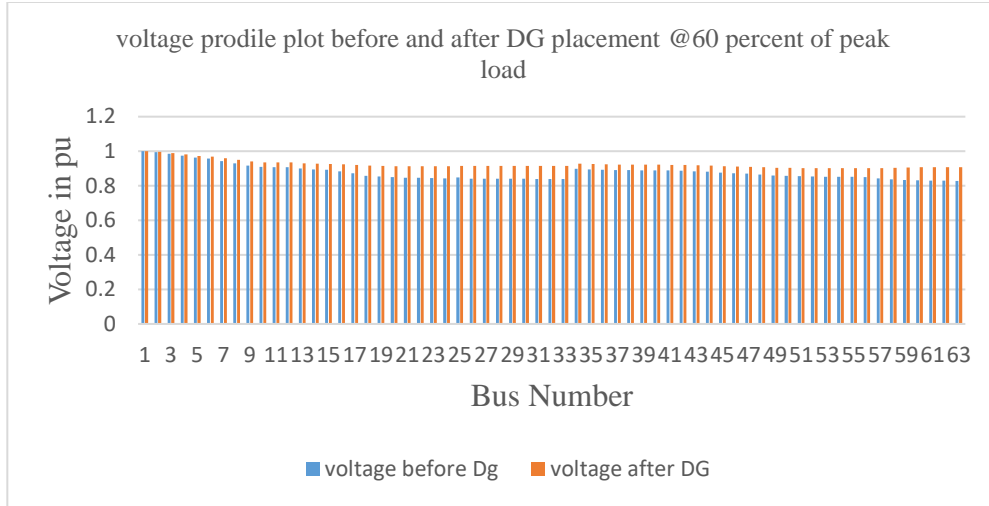


Figure 4. 17 Voltage profile plot after and before placement of DG at $0.6*P_L$

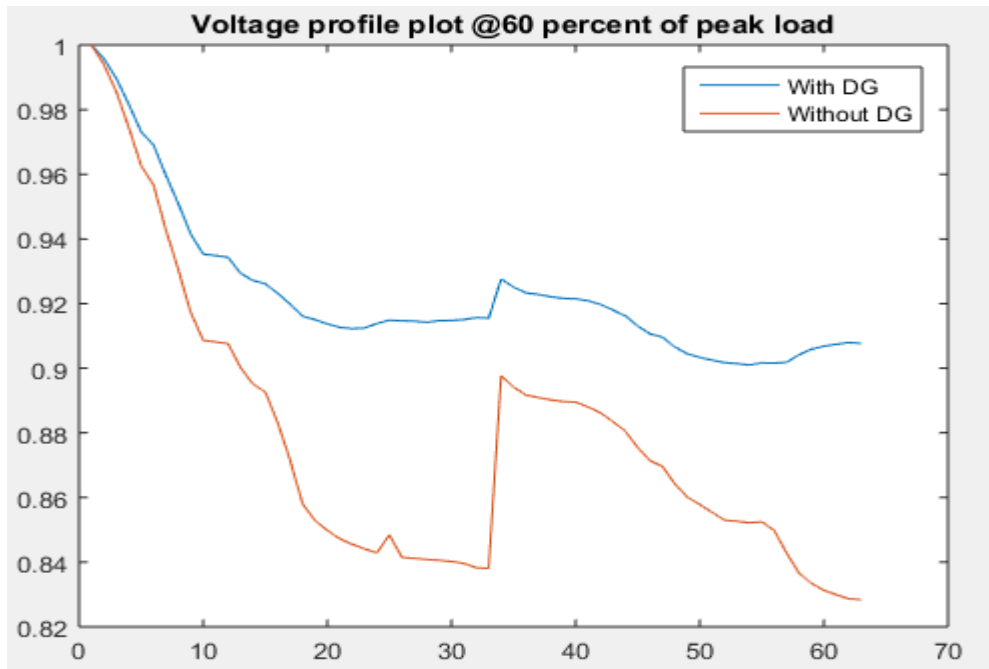


Figure 4. 18 MATLAB voltage profile plot before and after placement of DG at $0.6*P_L$

Case IV: Load flow simulation after placement of PSO based DG at base load

To check the impact of DG at base load, the simulation is tested at base load and gives the following result (see Fig.4.19 &4.20 below).

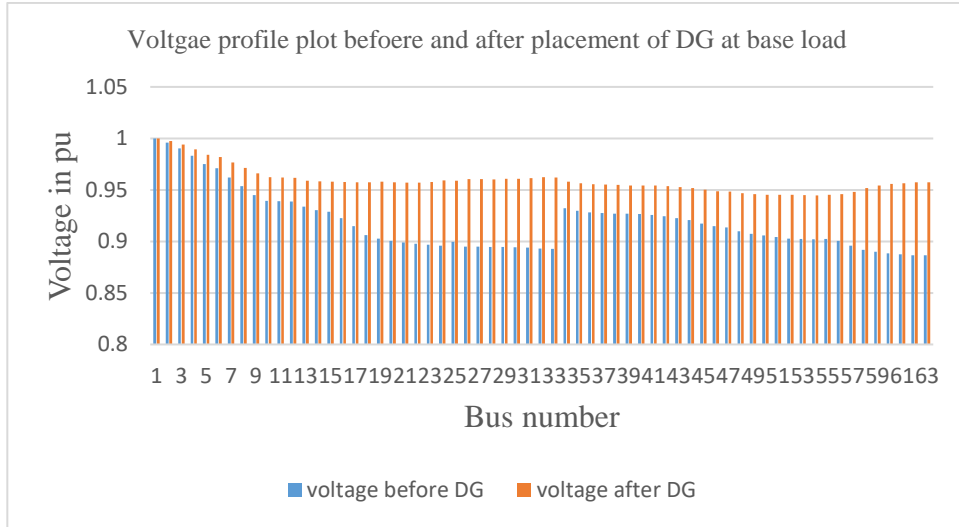


Figure 4. 19 Impact of DG placement on base load power flow

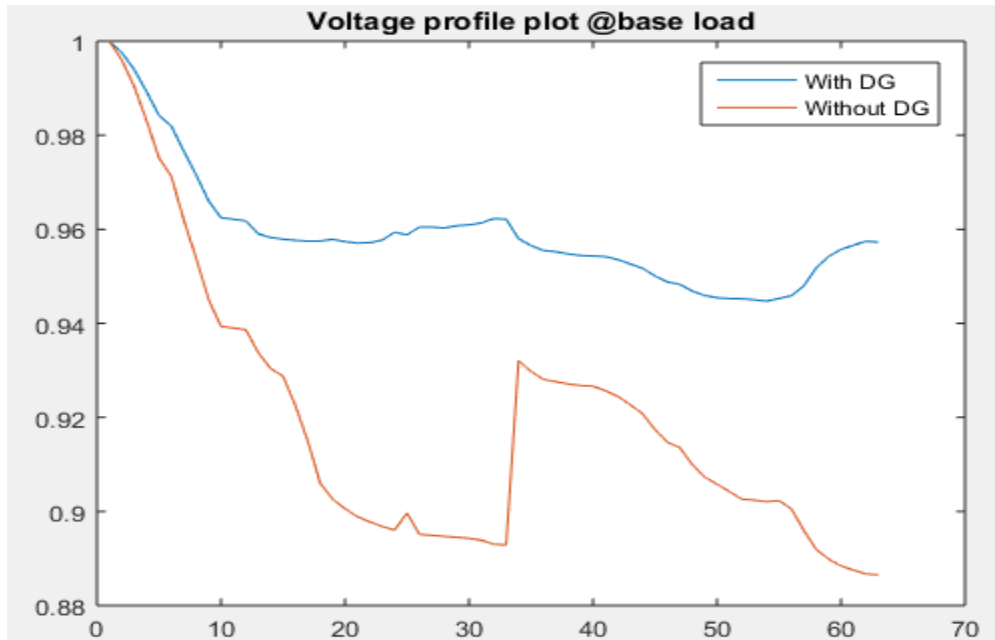


Figure 4. 20 MATLAB plot of DG impact on base load power flow of the distribution system.

In general, PSO based DG placement resulted in a loss reduction up to 50% and voltage profile improvement up to 12%. Even though the loss reduction in PSO based DG placement is better than PSO based capacitor placement, the voltage profile improvement is not as good as the PSO based capacitor placement.

Particle Swarm Optimized DG Placement Result Cost Analysis

After the determination of DG site and size, cost estimation of the obtained DG size has followed. As explained in chapter two, there are different technologies or resources of distribution generation. Among those resources, the selection of a specific DG technology to a certain area depends on availability of resources, suitability to environment, and cost of DG technology [41]. DG technologies also differ in their impacts that they impose on the surrounding environment. Hence, to estimate the cost of DG, the DG technologies selected in this thesis work was Microturbine owing to their low emission level and feasibility to the selected site under study. From Table 5.4 and Appendix G, the cost of the selected DG is calculated as follows.

Table 4. 6:Costs of DGs selected by PSO

Size of DG(KW)	Location of DG (Bus no.)	Cost in (\$/KW)	Sub cost in (\$)
530.1	62	2500	1325250
255.6	61	2580	659448
241.5	60	2580	623070
355.2	59	2500	888000
399.9	32	2500	999750
321.9	31	2500	804750
176.6	27	3150	556290
385	24	2500	962500
Total cost in US Dollar			6819058
Total cost in Ethiopian Birr by taking a currency rate of (27 Birr/Dollar)			184114566

To calculate power loss cost, the revised current tariff of Ethiopian Electric Utility is used [40]. From the revised tariff, average of the general tariff is taken, which is 1.58Birr/kwh. Power loss before placement of DG is 3.86MW and after the placement of DG is 1.913MW. So, power loss reduction due to the placement of DG is:

$$3.86MW - 1.913MW = 1.947MW$$

After DG placement total energy saved for one year is:

$$1.947MW * 24 * 365 = 17055.72Mwh$$

Saving in terms of Ethiopian Birr is:

$$17055.72Mwh * 1000 \left(\frac{K}{M} \right) * 1.58 \left(\frac{Birr}{kwh} \right) = 26948038Birr.$$

Now let's calculate return of investment, payback period is calculated as the initial cost divided by the saving in one year.

$$\frac{\text{total cost of DG (equipment + installation)}}{\text{energy saving per year}} = \frac{184114566Birr}{(26948038) \left(\frac{Birr}{year} \right)} = 6.832year.$$

As per the cost analysis, the PSO based DG placement needs initial capital investment cost of 184,114,566Birr with return of investment around seven years. This also indicate that PSO based DG placement is more expensive than PSO based capacitor placement.

Simulation Result of Capacitor Placement and Sizing Using GA

The working principle of Genetic algorithm is explained in appendix B. The candidate bus selection process (sensitivity analysis) is the same to that of PSO and for the reactive power sensitivity index see Table 4.1 above. From the sensitivity index the candidate buses have been selected. After the candidate bus selection, the candidate buses are given to the genetic algorithm optimizer for sizing and locating capacitor for loss and voltage drop reduction. The Genetic Optimizer gives the following candidate capacitor size and locations on the potential nodes. The code for GA is shown in Appendix H.

Table 4. 7: GA based capacitors placement simulation result in MVar.

Candidate Buses Cap. Options	36	62	34	35	37	61	60	59	51	50
1	0.9094	0.5557	0.5885	1.0299	0.8738	0.1199	0.1563	0.2889	0.8140	0.7168
2	0.9123	0.5578	0.8054	1.2496	0.9346	0.1283	0.1523	0.2876	0.8119	0.7201
3	1.0418	0.5403	1.5997	1.9306	1.4152	0.0262	0.0720	0.2342	0.7672	0.8589
4	1.0328	0.5341	1.5482	1.5393	1.3173	0.0350	0.1028	0.2271	0.8797	0.8155
5	1.0380	0.5366	1.5683	1.7468	1.3600	0.0343	0.0742	0.2243	0.8762	0.8162
6	1.0350	0.5381	1.5991	1.9272	1.4116	0.0262	0.0733	0.2372	0.7740	0.8396
7	0.9567	0.5523	1.2247	1.3267	1.1007	0.1248	0.1218	0.2833	0.8516	0.7648
8	1.0348	0.5380	1.6018	1.9237	1.4116	0.0280	0.0741	0.2378	0.7734	0.8396
9	1.0235	0.5360	1.0515	1.5006	1.2322	0.1233	0.1101	0.2534	0.8587	0.7710
10	0.9210	0.5385	0.8043	1.4587	1.0107	0.1004	0.1030	0.2883	0.8256	0.7333
11	1.0169	0.5399	1.5853	1.7777	1.3632	0.0439	0.1016	0.2526	0.8319	0.7825
12	0.9699	0.5511	1.2426	1.8072	1.2515	0.1107	0.1100	0.2844	0.8246	0.7872
13	0.9255	0.5518	1.1865	1.6753	1.2034	0.1117	0.1316	0.2845	0.8213	0.7391
14	0.9194	0.5543	0.9357	1.3505	1.0056	0.1263	0.1783	0.3090	0.8235	0.7208
15	0.9245	0.5519	0.7339	1.4609	0.8753	0.1185	0.1311	0.2859	0.8220	0.7841
16	0.9113	0.5557	0.7870	1.0375	0.8803	0.1349	0.1381	0.2893	0.8158	0.7167
17	1.0176	0.5346	1.5841	1.7240	1.3606	0.0385	0.1026	0.2390	0.8531	0.8059
18	1.0143	0.5297	1.4393	1.6634	1.2174	0.0405	0.1018	0.2664	0.8755	0.8036
19	0.9036	0.5557	0.6048	1.0299	0.8738	0.1324	0.1116	0.3071	0.8243	0.7168
20	0.9279	0.5520	1.0034	1.4817	1.0550	0.1163	0.1278	0.2582	0.8077	0.8003
21	0.9079	0.5537	1.0269	1.4703	0.9652	0.1176	0.1097	0.3071	0.8366	0.7549

Cap.Options are results of GA based capacitor placement in MVar

From Table 4.7, a single row of capacitor size represents one option of the genetic optimizer result. Each row has been tested and row three gives the most optimized result and used to run the load flow at different load levels.

Case I: Load flow simulation after GA based capacitor placement at peak load.

After the placement of Table 4.7 row three capacitors on the candidate buses (36,62,34, 35,37,61,60,59,51,50) which are taken from Table 4.1, the load flow analysis has been run at peak load. The placement of the capacitors on buses resulted in reduction of loss from 3.86MW to 2.42MW, which is 37% and voltage drop reduction up to 15.7%.

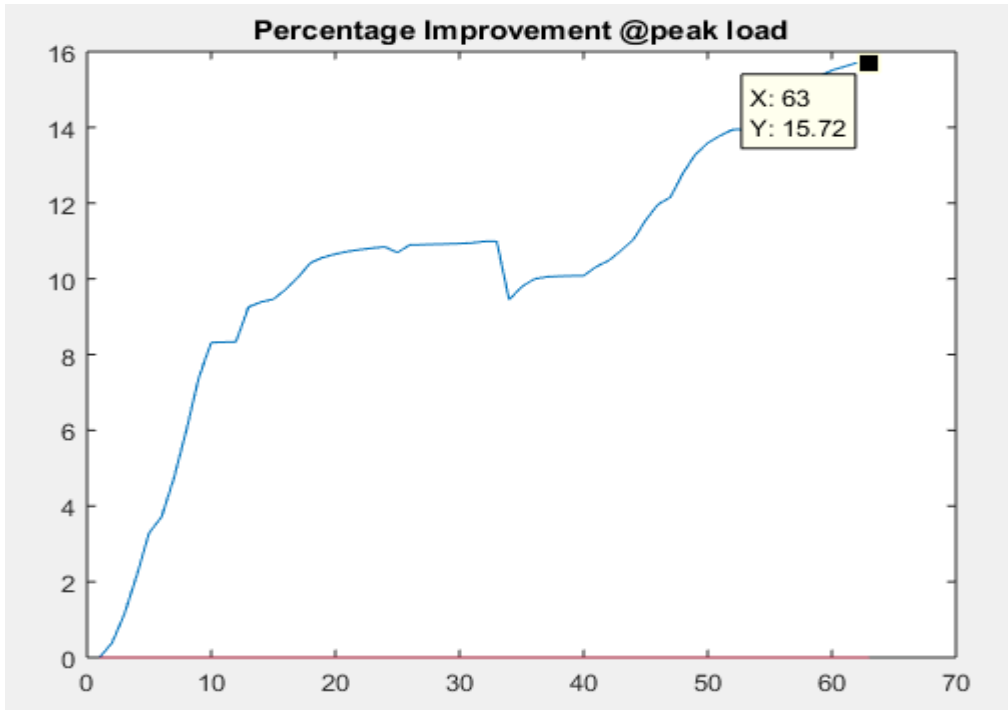


Figure 4. 21 GA capacitor placement percentage voltage drop reduction.

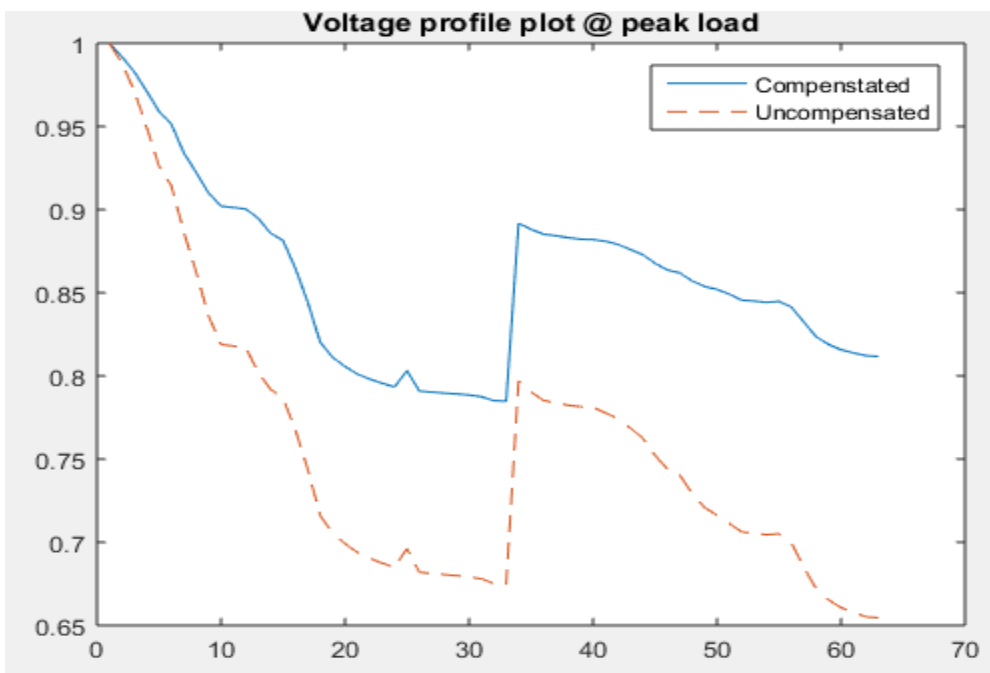


Figure 4. 22 MATLAB plot voltage profile before and after capacitor placement by GA

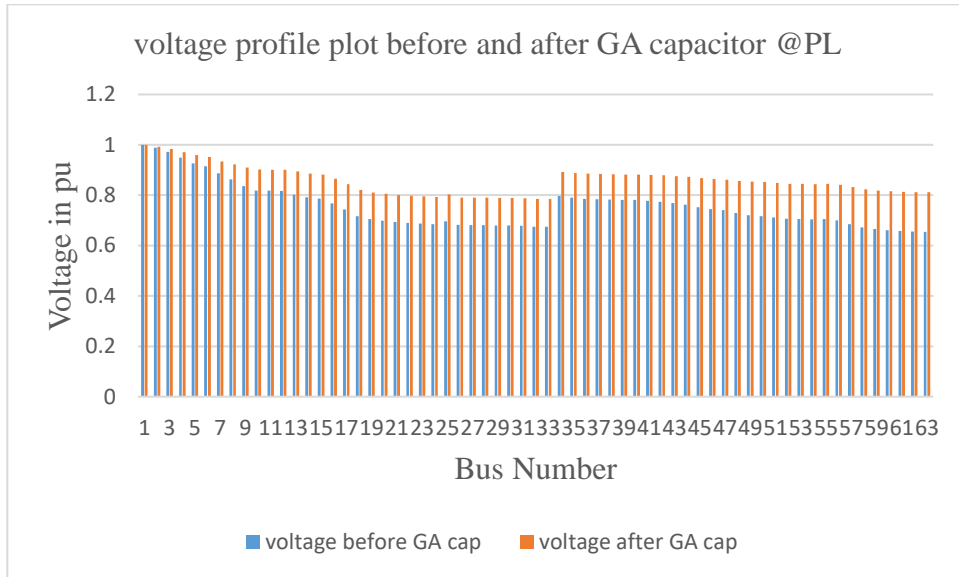


Figure 4. 23 Voltage profile comparison before and after GA capacitor placement.

Case II: Load flow simulation after GA based capacitor placement at 0.83 P_L .

Load flow analysis after the placement of the capacitors at 82% of peak load results in a reduction of loss from 2.1433MW to 1.5436MW and a voltage drop reduction up to 14%

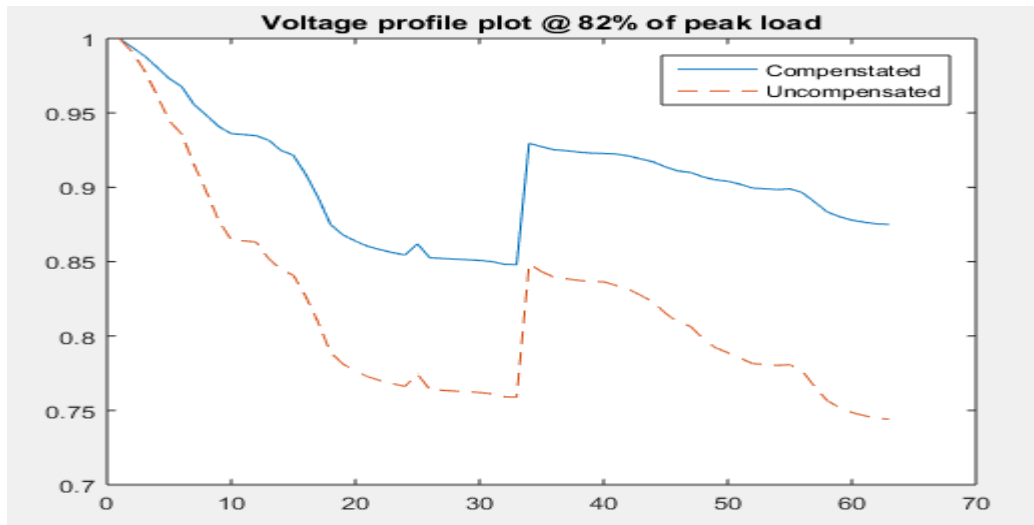


Figure 4. 24 MATLAB voltage profile plot before and after GA capacitor placement.

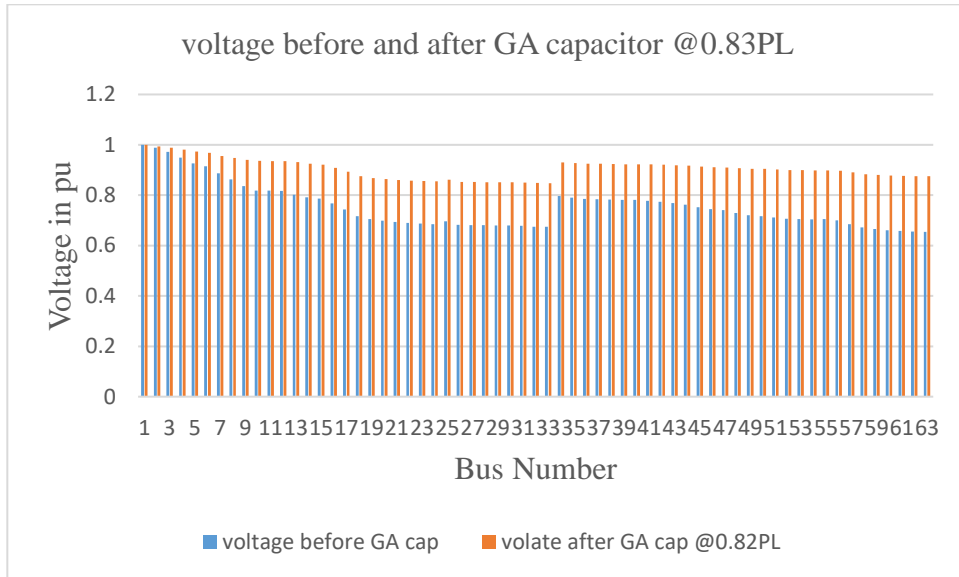


Figure 4. 25 Voltage profile plot before and after GA cap at $0.83 \cdot P_L$

Case III: Load flow simulation after GA based capacitor placement at $0.6P_L$.

The load flow analysis has been run after the GA based capacitor placement at 60% loading condition of the peak load and results in reduction of voltage drop up to 12%.

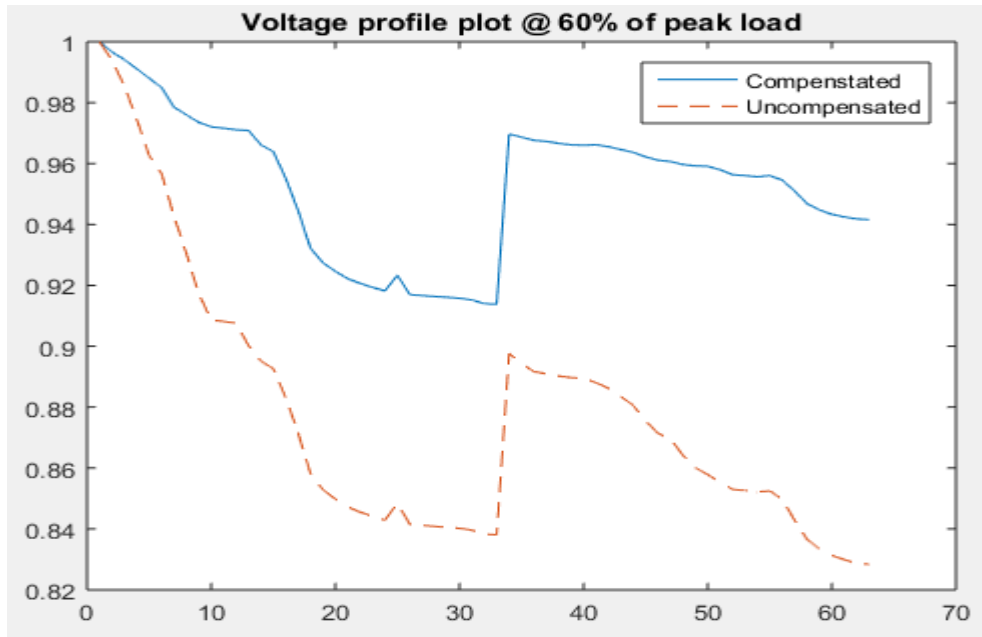


Figure 4. 26 Voltage profile after the placement of GA capacitor at $0.6 \cdot P_L$

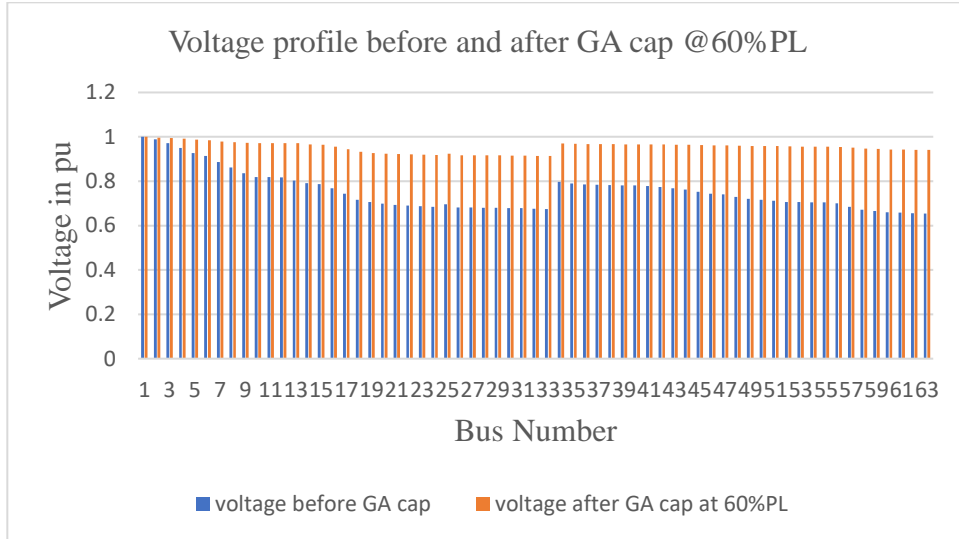


Figure 4. 27 Voltage profile after GA capacitor placement @ $0.6 \cdot P_L$

Case IV: Load flow simulation after GA based capacitor placement at base load.

Capacitors may result in over voltage during off load periods. To check this issue, the load flow has been run at base load after the placement of GA based capacitor sizes.

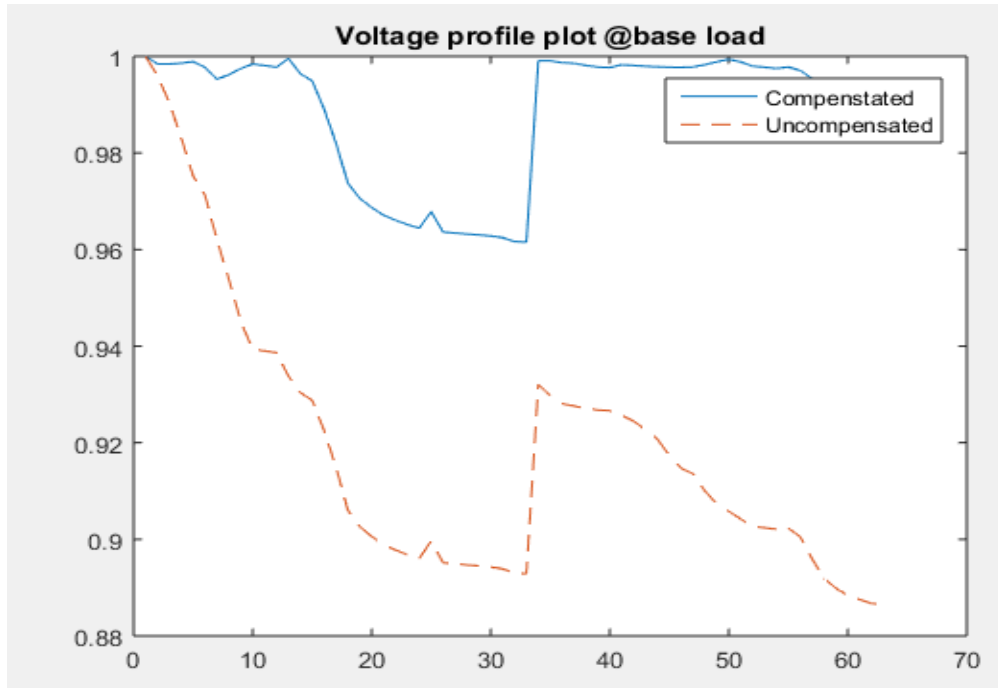


Figure 4. 28 Impact of GA capacitor placement on base load voltage profile.

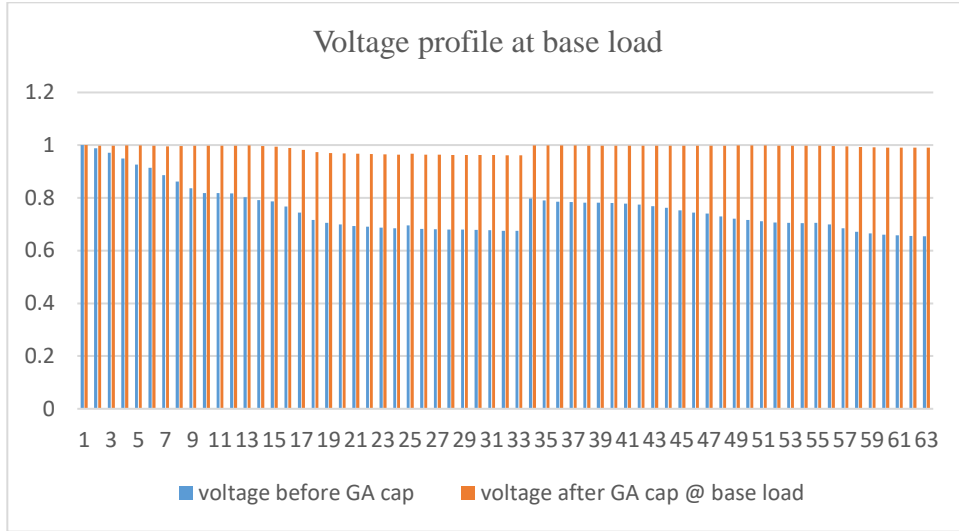


Figure 4. 29 Voltage profile at base load.

Fig 4.28 and 4.29 shows, the impact of GA capacitor placement on the node voltages at base load. As we can see from the figure, all node voltages are within acceptable limit.

GA Based Capacitor Placement Cost Analysis.

Table 4. 8 :Cost breakdown of GA based capacitor sizes

Size of capacitor in (kVAr)	Location of capacitors (bus no)	Cost of capacitor in US Dollar
1041.8	36	13950
540.3	62	9100
1599.7	34	18000
1930.6	35	20800
1415.2	37	16500
26.2	61	1850
72	60	2950
234.2	59	5700
767.2	51	11250
858.9	50	11700
Sub total cost in US Dollar		109700
installation cost (10%)		22150
Annual maintenance cost (2%)		4430
Total cost in US Dollar		248080
Total cost in Ethiopian Birr (taking currency rate 27Birr/\$)		6698160

Therefore, power loss reduction due to capacitor placement is:

$$3.86MW - 2.42MW = 1.44MW$$

After capacitor placement total energy saved for one year is:

$$1.44MW * 24 * 365 = 12614.4Mwh.$$

Saving in terms of Ethiopian Birr is:

$$12614.4Mwh * 1000 \left(\frac{K}{M}\right) * 1.58 \left(\frac{Birr}{Kwh}\right) = 19930752Birr.$$

Return of investment for capacitor placement is calculated as follows:

$$ROI = \frac{6698160}{19930752} = 0.3361year. \text{ where } ROI; \text{ Return of Investment}$$

This cost analysis indicates that GA capacitor placement result is more expensive than PSO capacitor placement but cheaper than PSO based DG placement and Particle Swarm Optimization gives better reduction in active power loss with lesser value of capacitor sizes than GA.

Table 4. 9 :Selection of buses using sensitivity and capacitors using GA and PSO techniques

No.	Bus No. selected using sensitivity analysis	Capacitor size in (MVar)	
		Selected based on GA	Selected based on PSO
1	36	1.0418	0.97
2	62	0.5403	0.29
3	34	1.5997	2.69
4	35	1.9306	1.35
5	37	1.4152	1.11
6	61	0.0262	0.12
7	60	0.0720	0
8	59	0.2342	0.37
9	51	0.7672	1.07
10	50	0.8589	0.32

Table 4. 10: Summary of results showing improvement of power loss and voltage profile

No.	Techniques Adopted	% Power Loss Reduction			% Voltage profile improvement		
		At peak load (11.14MW)	At 83% of PL (9.24MW)	At 60% of PL (6.68MW)	At Peak load (11.14MW)	At 83% of PL (9.24MW)	At 60% of PL (6.68MW)
1	PSO based capacitor placement	37.27%	29%	9.2%	15%	14%	11%
2	PSO based DG placement	50%	51%	58%	12%	9%	8%
3	GA based capacitor placement	37%	28%	6%	15.7%	14%	12%

Table 4. 11: Comparison of costs for the capacitors selected based on PSO, GA and DG based on PSO techniques

No.	Techniques Adopted	Total cost needed in (Birr)	Payback Period in(year)	Cost Comparison
1	PSO based capacitor placement	3,317,328	0.1664	Cheapest one among the three
2	PSO based DG placement	184,114,566	6.832	55.5 times expensive than No.1
3	GA based capacitor placement	6,698,160	0.3361	2.02 times expensive than No.1

Chapter 5: Conclusions, Recommendations and Future Work

5.1 Introduction

In this chapter, conclusions, recommendations and future work of the thesis in titled improvement of distribution feeder loss and voltage profile are presented.

5.2 Conclusions

With the objective of loss reduction and voltage profile improvement of distribution substation feeders, the study was initiated. The feeder F4 of Bella distribution substation was chosen owing to its large loss and voltage drop problem compared to the rest of the feeders, as the selected feeder has long route length and large increasing loads. Based on the collected data, the modeling and the base case simulation of the selected feeder was carried out with the help of MATLAB. The base case simulation results indicate that the feeder encountered a total real power loss of 3.86MW with major bus voltages being out of the acceptable range. In order to reduce the total loss and improve voltage profile of the system, separate PSO based capacitor and DG placement and GA based capacitor placement has been proposed. To size and locate the capacitors and DG on the system, sensitivity analysis was carried out to identify the candidate buses. Separate PSO and GA optimizer has been used to select the optimum size and location of capacitors and DG on the candidate buses. The PSO based capacitor and DG placement showed a loss reduction from 3.86MW to 2.42MW with voltage profile improvement up to 15% and loss reduction from 3.86MW to 1.913MW with voltage profile improvement up to 12% respectively. The GA based capacitor placement also showed a loss reduction from 3.86Mw to 2.42MW with voltage profile improvement of 15.7%. The results are comparable indicating the validity of the result.

Shunt capacitor placement may cause over voltage problem on the distribution networks during off peak periods. To check over voltage impact of DG and capacitor placement on Bella distribution network, the load flow analysis was carried at Peak load, 83% of peak

load, 60% of peak load and base load. The load flow simulation after DG and capacitor placement at base load have no any over voltage problem on the buses.

Cost analysis is mandatory during generating a solution to a problem. In this regard, cost analysis of the generated solution has been done. The cost analysis showed that, PSO based capacitor placement needs initial capital cost of 3,317,328Birr with ROI of 0.1664year, PSO based DG placement needs initial capital cost of 184,114,566Birr with ROI of 6.832year and GA based capacitor placement needs initial capital cost of 6,698,160Birr with ROI of 0.3361year.

5.3 Recommendations

In this thesis, it has been determined that PSO based capacitor placement on Bella distribution feeder resulted in a loss reduction of 37.27% and voltage profile improvement of 15% at peak load with initial capital investment cost of 3,317,328 Birr with ROI of 0.1664 year, PSO based DG placement on Bella distribution feeder resulted in a loss reduction of 50% and voltage profile improvement of 12% at peak load with initial capital investment cost of 184,114,566Birr with ROI of 6.832 year and GA based capacitor placement on Bella distribution feeder resulted in a loss reduction of 37% and voltage profile improvement of 15.7% at peak load with initial capital investment cost of 6,698,160 Birr with ROI of 0.3361 year. PSO based capacitor placement on Bella distribution feeder solve power loss and voltage drop problem with small capital investment cost and short payback period by increasing system capacity and improving power factor of the system. So, PSO based capacitor placement should be implemented to optimize power loss and voltage drop of distribution systems. The implementation of this study is highly recommended to Ethiopian Electric Utility company.

5.4 Suggestion for Future work

In this thesis, the loss reduction and voltage profile improvement of the distribution system has been done by considering phase balanced loading condition. However, impacts harmonics and phase load unbalance on power loss and voltage drop of distribution systems have not been considered

Loss reduction and voltage profile improvement of the distribution network considering phase load unbalance and harmonics is suggested as a future work.

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Appendices

Appendix A: Newton-Raphson load flow solution.

Newton Raphson method is an iterative technique for solving a set of various nonlinear equations with an equal number of unknowns. There are two methods of solutions for the load flow using Newton Raphson method. The first method uses rectangular coordinates for the variables while the second method uses the polar coordinate form. Out of these two methods the polar coordinate form is used widely [37].

Consider a set of n non-linear algebraic equations

$$f_i(x_1, x_2, \dots, x_n) = 0; \quad i = 1, 2, \dots, n \quad (0.1)$$

Assume initial values of unknowns as $x_1^0, x_2^0, \dots, x_n^0$. Let $\Delta x_1^0, \Delta x_2^0, \dots, \Delta x_n^0$ be the corrections, which on being added to the initial guess, give the actual solutions. Therefore,

$$f_i(x_1^0 + \Delta x_1^0, x_2^0 + \Delta x_2^0, \dots, x_n^0 + \Delta x_n^0) = 0; \quad i = 1, 2, \dots, n \quad (0.2)$$

Expanding these equations in Taylor series around the initial guess, we have

$$f_i(x_1^0, x_2^0, \dots, x_n^0) + \left[\begin{array}{c} \left(\frac{\partial f_i}{\partial x_1}\right)^0 \Delta x_1^0 + \left(\frac{\partial f_i}{\partial x_2}\right)^0 \Delta x_2^0 + \dots \\ + \left(\frac{\partial f_i}{\partial x_n}\right)^0 \Delta x_n^0 \end{array} \right] + \text{higher order term} = 0. \quad (0.3)$$

where $\left(\frac{\partial f_i}{\partial x_1}\right)^0, \left(\frac{\partial f_i}{\partial x_2}\right)^0, \dots, \left(\frac{\partial f_i}{\partial x_n}\right)^0$ are the derivatives of f_i with respect to x_1, x_2, \dots, x_n evaluated at $(x_1^0, x_2^0, \dots, x_n^0)$.

Neglecting higher order terms, we can write Eq(A-3) in matrix form.

$$\begin{bmatrix} f_1^0 \\ f_2^0 \\ \cdot \\ \cdot \\ \cdot \\ \vdots \\ f_n^0 \end{bmatrix} + \begin{bmatrix} \left(\frac{\partial f_1}{\partial x_1}\right)^0 & \left(\frac{\partial f_1}{\partial x_2}\right)^0 & \dots & \left(\frac{\partial f_1}{\partial x_n}\right)^0 \\ \left(\frac{\partial f_2}{\partial x_1}\right)^0 & \left(\frac{\partial f_2}{\partial x_2}\right)^0 & \dots & \left(\frac{\partial f_2}{\partial x_n}\right)^0 \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \left(\frac{\partial f_n}{\partial x_1}\right)^0 & \left(\frac{\partial f_n}{\partial x_2}\right)^0 & \dots & \left(\frac{\partial f_n}{\partial x_n}\right)^0 \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \\ \cdot \\ \cdot \\ \cdot \\ \vdots \\ \Delta x_n^0 \end{bmatrix} \cong \begin{bmatrix} 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ \vdots \\ 0 \end{bmatrix} \quad (0.4)$$

Or in vector form

$$f^0 + J^0 \Delta x^0 \cong 0 \quad (0.5)$$

J^0 is known as the Jacobian matrix (obtained by differentiating the function vector f with respect to x and evaluating it at x^0).

Equation (A-5) can be written as

$$f^0 \cong [-J^0] \Delta x^0 \quad (A.6)$$

Approximate values of corrections Δx^0 can be obtained from Eq(A-6).

Updated values of x are then

$$x^1 = x^0 + \Delta x^0$$

Or, in general, for the $(r + 1)^{th}$ iteration

$$x^{r+1} = x^r + \Delta x^r \quad (A.7)$$

Iterations are continued till Eq. A-1 is satisfied to any desired accuracy, i.e.

$$|f_i(x^{(r)})| < \varepsilon (\text{a specified value}); i = 1, 2 \dots n \quad (A.8)$$

Appendix B: Size and cost of capacitors [39]

Capacitor (KVAR)	10	20	30	40	50	60	70	80	90
Cost (\$)	1750	1800	1850	1925	2050	2200	2650	2950	3450
Capacitor (KVAR)	100	150	200	250	300	350	400	450	500
Cost (\$)	4200	4500	5250	5700	6300	7050	7600	8150	8650
Capacitor (KVAR)	550	600	650	700	750	800	850	900	950
Cost (\$)	9100	9450	10000	10450	10800	11250	11700	12350	12850
Capacitor (KVAR)	1000	1050	1100	1200	1300	1400	1500	1600	1700
Cost (\$)	13400	13950	14400	15250	15850	16500	17250	18000	18700
Capacitor (KVAR)	1800	1900	2000	2100	2200	2300	2400	2500	2600
Cost (\$)	19450	20125	20800	21550	22200	22950	23600	24350	24900
Capacitor (KVAR)	2700	2800	2900	3000	3100	3200	3300	3400	3500
Cost (\$)	25550	26400	27125	27800	28550	29200	29950	30650	31400
Capacitor (KVAR)	3600	3700	3800	3900	4000	4100	4200	4300	4400
Cost (\$)	32100	32850	33500	34250	35000	35775	36500	37300	3800
Capacitor (KVAR)	4500	4600	4700	4800	4900	5000	5100	5200	5300
Cost (\$)	38750	39400	40050	40800	41425	42550	43000	43350	43700
Capacitor (KVAR)	5400	5500	5600	5700	5800	5900	6000	6100	6200

Cost (\$)	44150	44500	44950	45350	45900	46300	46750	47050	47350
Capacitor (KVAR)	6300	6400	6500	6600	6700	6800	6900	7000	7100
Cost (\$)	47700	48150	48400	48750	4900	49350	49450	49750	50050
Capacitor (KVAR)	7200	7300	7400	7500	7600	7700	7800	7900	8000
Cost (\$)	50300	50650	51025	51250	51700	51850	52000	52200	52550
Capacitor (KVAR)	8100	8200	8300	8400	8500	8600	8700	8800	8900
Cost (\$)	52800	53050	53150	53300	53550	53650	53850	53900	54000
Capacitor (KVAR)	9000	9100	9200	9300	9400	9500	9600	9700	9800
Cost (\$)	54150	54350	54500	54675	54800	54950	55100	55250	55400
Capacitor (KVAR)	9900	10000							
Cost (\$)	55650	55800							

Appendix C: Code for Newton-Raphson load flow.

```

nbus = 63; % bella-63..
Y = ybusppg(nbus); % Calling ybusppg.m to get Y-Bus Matrix..
busd = busdatas(nbus); % Calling busdatas..
busd(:,7) = 1*busd(:,7);
busd(:,8) = 1*busd(:,8);
BMva = 100; % Base MVA..
bus = busd(:,1); % Bus Number..
type = busd(:,2); % Type of Bus 1-Slack, 2-PV, 3-PQ..
V = busd(:,3); % Specified Voltage..
del = busd(:,4); % Voltage Angle..
Pg = busd(:,5)/BMva; % PGi..
Qg = busd(:,6)/BMva; % QGi..
Pl = busd(:,7)/BMva; % PLi..
Ql = busd(:,8)/BMva; % QLi..
Qmin = busd(:,9)/BMva; % Minimum Reactive Power Limit..
Qmax = busd(:,10)/BMva; % Maximum Reactive Power Limit..
P = Pg - Pl; % Pi = PGi - PLi..
Q = Qg - Ql; % Qi = QGi - QLi..
Psp = P; % P Specified..
Qsp = Q; % Q Specified..
G = real(Y); % Conductance matrix..
B = imag(Y); % Susceptance matrix..

pv = find(type == 2 | type == 1); % PV Buses..
pq = find(type == 3); % PQ Buses..
npv = length(pv); % No. of PV buses..
npq = length(pq); % No. of PQ buses..

Tol = 1;
Iter = 1;
while (Tol > 1e-3) % Iteration starting..

    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) +
B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) -
B(i,k)*cos(del(i)-del(k)));
        end
    end

    % Checking Q-limit violations..
    if Iter <= 7 && Iter > 2 % Only checked up to 7th iterations..
        for n = 2:nbus
            if type(n) == 2
                QG = Q(n)+Ql(n);
            end
        end
    end
end

```

```

        if QG < Qmin(n)
            V(n) = V(n) + 0.01;
        elseif QG > Qmax(n)
            V(n) = V(n) - 0.01;
        end
    end
end
end

% Calculate change from specified value
dPa = Psp-P;
dQa = Qsp-Q;
k = 1;
dQ = zeros(npq,1);
for i = 1:nbus
    if type(i) == 3
        dQ(k,1) = dQa(i);
        k = k+1;
    end
end
dP = dPa(2:nbus);
M = [dP; dQ];           % Mismatch Vector

% Jacobian
% J1 - Derivative of Real Power Injections with Angles..
J1 = zeros(nbus-1,nbus-1);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J1(i,k) = J1(i,k) + V(m) * V(n) * (-G(m,n) * sin(del(m) -
del(n)) + B(m,n) * cos(del(m) - del(n)));
            end
            J1(i,k) = J1(i,k) - V(m)^2 * B(m,m);
        else
            J1(i,k) = V(m) * V(n) * (G(m,n) * sin(del(m) - del(n)) -
B(m,n) * cos(del(m) - del(n)));
        end
    end
end

% J2 - Derivative of Real Power Injections with V..
J2 = zeros(nbus-1,npq);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus

```

```

                J2(i,k) = J2(i,k) + V(n)*(G(m,n)*cos(del(m)-del(n))
+ B(m,n)*sin(del(m)-del(n)));
            end
            J2(i,k) = J2(i,k) + V(m)*G(m,m);
        else
            J2(i,k) = V(m)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
        end
    end
end

% J3 - Derivative of Reactive Power Injections with Angles..
J3 = zeros(npq,nbus-1);
for i = 1:npq
    m = pq(i);
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J3(i,k) = J3(i,k) + V(m)* V(n)*(G(m,n)*cos(del(m)-
del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
            J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
        else
            J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) -
B(m,n)*sin(del(m)-del(n)));
        end
    end
end

% J4 - Derivative of Reactive Power Injections with V..
J4 = zeros(npq,npq);
for i = 1:npq
    m = pq(i);
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-del(n))
- B(m,n)*cos(del(m)-del(n)));
            end
            J4(i,k) = J4(i,k) - V(m)*B(m,m);
        else
            J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
        end
    end
end

J = [J1 J2; J3 J4];    % Jacobian Matrix..

```

```

X = J\M;                % Correction Vector
dTh = X(1:nbus-1);      % Change in Voltage Angle..
dV = X(nbus:end);       % Change in Voltage Magnitude..

% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus); % Voltage Angle..
k = 1;
for i = 1:nbus
    if type(i) == 3
        V(i) = dV(k) + V(i); % Voltage Magnitude..
        k = k+1;
    end
end

Iter = Iter + 1;
Tol = max(abs(M));      % Tolerance..

end
loadflow(nbus,V,del,BMva); % Calling Loadflow.m..

```

Appendix D: Base case Newton-Raphson load flow result

```
#####
```

Line FLOW and Losses

From Bus	To Bus	P MW	Q MVar	From Bus	To Bus	P MW	Q MVar	Line Loss	
								MW	MVar
1	2	16.870	9.816	2	1	-16.671	-9.697	0.198	0.119
2	3	16.321	9.527	3	2	-16.097	-9.279	0.225	0.249
3	4	15.817	9.179	4	3	-15.527	-8.857	0.290	0.321
4	5	15.437	8.837	5	4	-15.125	-8.493	0.311	0.345
5	6	14.975	8.433	6	5	-14.787	-8.320	0.188	0.113
6	7	14.537	8.210	7	6	-14.109	-7.943	0.428	0.267
7	8	13.959	7.883	8	7	-13.647	-7.537	0.312	0.346
8	9	13.577	7.507	9	8	-13.241	-7.135	0.336	0.372
9	10	13.171	7.115	10	9	-12.953	-6.873	0.219	0.242
10	11	0.401	0.170	11	10	-0.400	-0.170	0.000	0.000
11	12	0.250	0.110	12	11	-0.250	-0.110	0.000	0.000
10	13	12.552	6.703	13	10	-12.346	-6.474	0.206	0.228
13	14	3.759	1.480	14	13	-3.713	-1.453	0.046	0.027
14	15	3.563	1.393	15	14	-3.542	-1.380	0.021	0.013
15	16	3.292	1.270	16	15	-3.208	-1.247	0.084	0.023
16	17	3.138	1.227	17	16	-3.037	-1.200	0.101	0.027
17	18	2.967	1.180	18	17	-2.851	-1.149	0.116	0.031

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7	8	13.959	7.883	8	7	-13.647	-7.537	0.312	0.346
8	9	13.577	7.507	9	8	-13.241	-7.135	0.336	0.372
9	10	13.171	7.115	10	9	-12.953	-6.873	0.219	0.242
10	11	0.401	0.170	11	10	-0.400	-0.170	0.000	0.000
11	12	0.250	0.110	12	11	-0.250	-0.110	0.000	0.000
10	13	12.552	6.703	13	10	-12.346	-6.474	0.206	0.228
13	14	3.759	1.480	14	13	-3.713	-1.453	0.046	0.027
14	15	3.563	1.393	15	14	-3.542	-1.380	0.021	0.013
15	16	3.292	1.270	16	15	-3.208	-1.247	0.084	0.023
16	17	3.138	1.227	17	16	-3.037	-1.200	0.101	0.027
17	18	2.967	1.180	18	17	-2.851	-1.149	0.116	0.031
18	19	2.601	1.049	19	18	-2.561	-1.038	0.040	0.011
19	20	1.095	0.438	20	19	-1.085	-0.435	0.010	0.003
20	21	1.015	0.415	21	20	-1.007	-0.412	0.008	0.003
21	22	0.757	0.302	22	21	-0.753	-0.301	0.004	0.001
22	23	0.503	0.201	23	22	-0.501	-0.200	0.002	0.001
23	24	0.251	0.100	24	23	-0.250	-0.100	0.001	0.000
19	25	1.436	0.589	25	19	-1.416	-0.583	0.019	0.006
25	26	1.386	0.573	26	25	-1.357	-0.563	0.029	0.010
26	27	0.401	0.160	27	26	-0.400	-0.160	0.000	0.000
27	28	0.150	0.060	28	27	-0.150	-0.060	0.000	0.000
26	29	0.956	0.403	29	26	-0.954	-0.402	0.003	0.001
29	30	0.804	0.342	30	29	-0.803	-0.341	0.001	0.000
30	31	0.653	0.281	31	30	-0.652	-0.280	0.001	0.001
31	32	0.402	0.170	32	31	-0.400	-0.170	0.002	0.000

Improvement of distribution feeder loss and voltage profile by Temesgen T.

32	33	0.150	0.060	33	32	-0.150	-0.060	0.000	0.000
13	34	8.338	4.885	34	13	-8.278	-4.865	0.060	0.019
34	35	7.798	4.445	35	34	-7.732	-4.406	0.066	0.040
35	36	7.282	4.076	36	35	-7.236	-4.048	0.046	0.027
36	37	6.586	3.198	37	36	-6.574	-3.191	0.012	0.007
37	38	0.581	0.211	38	37	-0.580	-0.210	0.001	0.000
38	39	0.330	0.110	39	38	-0.330	-0.110	0.000	0.000
39	40	0.090	0.010	40	39	-0.090	-0.010	0.000	0.000
37	41	5.543	2.731	41	37	-5.509	-2.693	0.034	0.038
41	42	5.289	2.593	42	41	-5.269	-2.571	0.020	0.022
42	43	5.129	2.511	43	42	-5.100	-2.479	0.030	0.033
43	44	4.880	2.379	44	43	-4.849	-2.345	0.031	0.034
44	45	4.719	2.295	45	44	-4.667	-2.237	0.052	0.057
45	46	4.597	2.217	46	45	-4.556	-2.172	0.041	0.045
46	47	4.276	2.042	47	46	-4.260	-2.024	0.017	0.018
47	48	3.980	1.894	48	47	-3.931	-1.840	0.048	0.054
48	49	3.651	1.710	49	48	-3.618	-1.673	0.033	0.037
49	50	3.338	1.543	50	49	-3.320	-1.524	0.018	0.020
50	51	3.040	1.394	51	50	-3.021	-1.381	0.020	0.012
51	52	2.741	1.251	52	51	-2.722	-1.240	0.018	0.011
52	53	0.501	0.240	53	52	-0.500	-0.240	0.000	0.000
53	54	0.250	0.120	54	53	-0.250	-0.120	0.000	0.000

Improvement of distribution feeder loss and voltage profile by Temesgen T.

52	55	2.222	0.999	55	52	-2.218	-0.998	0.003	0.002
55	56	1.968	0.888	56	55	-1.954	-0.879	0.014	0.009
56	57	1.794	0.819	57	56	-1.759	-0.796	0.035	0.023
57	58	1.509	0.686	58	57	-1.478	-0.678	0.031	0.008
58	59	1.308	0.618	59	58	-1.294	-0.614	0.014	0.004
59	60	1.044	0.504	60	59	-1.036	-0.502	0.008	0.002
60	61	0.786	0.392	61	60	-0.782	-0.391	0.004	0.001
61	62	0.532	0.281	62	61	-0.530	-0.280	0.002	0.001
62	63	0.080	0.030	63	62	-0.080	-0.030	0.000	0.000
Total Loss								3.860	3.286

#####

Appendix E: MATLAB code for candidate bus selection.

```

nbus = 63; % IEEE-14, IEEE-30, bella-63..

%tempBus = busdatas(nbus);
P_loss = zeros(nbus,1);
Q_loss = zeros(nbus,1);
v_dev = zeros(nbus,1);

for count=1:nbus+1
    tempBus = busdatas(nbus);
    if count~=nbus+1
        diff = tempBus(count,8)-tempBus(count,6);
        if diff>0
            tempBus(count,6) =+ diff;
        end
    end
    Y = ybusppg(nbus); % Calling ybusppg.m to get Y-Bus
Matrix..
    busd = tempBus; % Calling busdatas..
    BMva = 100; % Base MVA..
    bus = busd(:,1); % Bus Number..
    type = busd(:,2); % Type of Bus 1-Slack, 2-PV, 3-PQ..
    V = busd(:,3); % Specified Voltage..
    del = busd(:,4); % Voltage Angle..
    Pg = busd(:,5)/BMva; % PGi..
    Qg = busd(:,6)/BMva; % QGi..
    Pl = busd(:,7)/BMva; % PLi..
    Ql = busd(:,8)/BMva; % QLi..
    Qmin = busd(:,9)/BMva; % Minimum Reactive Power Limit..
    Qmax = busd(:,10)/BMva; % Maximum Reactive Power Limit..
    P = Pg - Pl; % Pi = PGi - PLi..
    Q = Qg - Ql; % Qi = QGi - QLi..
    Psp = P; % P Specified..
    Qsp = Q; % Q Specified..
    G = real(Y); % Conductance matrix..
    B = imag(Y); % Susceptance matrix..

    pv = find(type == 2 | type == 1); % PV Buses..
    pq = find(type == 3); % PQ Buses..
    npv = length(pv); % No. of PV buses..
    npq = length(pq); % No. of PQ buses..

    Tol = 1;
    Iter = 1;
    while (Tol > 1e-3) % Iteration starting..

        P = zeros(nbus,1);
        Q = zeros(nbus,1);
        % Calculate P and Q
        for i = 1:nbus

```

```

        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) +
            B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) -
            B(i,k)*cos(del(i)-del(k)));
        end
    end

    % Checking Q-limit violations..
    if Iter <= 7 && Iter > 2    % Only checked up to 7th
iterations..
        for n = 2:nbus
            if type(n) == 2
                QG = Q(n)+Ql(n);
                if QG < Qmin(n)
                    V(n) = V(n) + 0.01;
                elseif QG > Qmax(n)
                    V(n) = V(n) - 0.01;
                end
            end
        end
    end

    % Calculate change from specified value
    dPa = Psp-P;
    dQa = Qsp-Q;
    k = 1;
    dQ = zeros(npq,1);
    for i = 1:nbus
        if type(i) == 3
            dQ(k,1) = dQa(i);
            k = k+1;
        end
    end
    dP = dPa(2:nbus);
    M = [dP; dQ];    % Mismatch Vector

    % Jacobian
    % J1 - Derivative of Real Power Injections with Angles..
    J1 = zeros(nbus-1,nbus-1);
    for i = 1:(nbus-1)
        m = i+1;
        for k = 1:(nbus-1)
            n = k+1;
            if n == m
                for n = 1:nbus
                    J1(i,k) = J1(i,k) + V(m)* V(n)*(-
                    G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
                end
                J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
            else

```

```

                J1(i,k) = V(m)* V(n)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
            end
        end
    end

    % J2 - Derivative of Real Power Injections with V..
    J2 = zeros(nbus-1,npq);
    for i = 1:(nbus-1)
        m = i+1;
        for k = 1:npq
            n = pq(k);
            if n == m
                for n = 1:nbus
                    J2(i,k) = J2(i,k) + V(n)*(G(m,n)*cos(del(m)-
del(n)) + B(m,n)*sin(del(m)-del(n)));
                end
                J2(i,k) = J2(i,k) + V(m)*G(m,m);
            else
                J2(i,k) = V(m)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
            end
        end
    end

    % J3 - Derivative of Reactive Power Injections with Angles..
    J3 = zeros(npq,nbus-1);
    for i = 1:npq
        m = pq(i);
        for k = 1:(nbus-1)
            n = k+1;
            if n == m
                for n = 1:nbus
                    J3(i,k) = J3(i,k) + V(m)*
V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
                end
                J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
            else
                J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) -
B(m,n)*sin(del(m)-del(n)));
            end
        end
    end

    % J4 - Derivative of Reactive Power Injections with V..
    J4 = zeros(npq,npq);
    for i = 1:npq
        m = pq(i);
        for k = 1:npq
            n = pq(k);
            if n == m

```

```

        for n = 1:nbus
            J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-
del(n)) - B(m,n)*cos(del(m)-del(n)));
        end
        J4(i,k) = J4(i,k) - V(m)*B(m,m);
    else
        J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
    end
end
end

J = [J1 J2; J3 J4];    % Jacobian Matrix..

X = J\M;              % Correction Vector
dTh = X(1:nbus-1);    % Change in Voltage Angle..
dV = X(nbus:end);     % Change in Voltage Magnitude..

% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus);    % Voltage Angle..
k = 1;
for i = 1:nbus
    if type(i) == 3
        V(i) = dV(k) + V(i);        % Voltage Magnitude..
        k = k+1;
    end
end

Iter = Iter + 1;
Tol = max(abs(M));    % Tolerance..

end
% Calling loadflow2.m..
if count~=nbus+1
    [P_loss(count), Q_loss(count)] =
loadflow2(nbus,V,del,BMva,Y,busd);
    v_dev(count) = 1-min(V);
elseif count==nbus+1
    [PlossN, QlossN] = loadflow2(nbus,V,del,BMva,Y,busd);
    v_devN = 1-min(V);
end
end

P_reduct = PlossN - P_loss;
Q_reduct = QlossN - Q_loss;
V_imprv = v_devN-v_dev;

minP_loss = min(P_reduct);
maxP_loss = max(P_reduct);
minV_imprv = min(V_imprv);

```

```
maxV_imprv = max(V_imprv);

loss_diff = maxP_loss-minP_loss;
imprv_diff = maxV_imprv - minV_imprv;

PLI = (P_reduct - minP_loss)/loss_diff;
VLI = (V_imprv - minV_imprv)/imprv_diff;

LI = PLI + VLI;

[sortedPLI, I] = sort(PLI, 'descend');
candidateBuses = I(1:10);
```

Appendix F: Code for capacitor placement by PSO

Main program for capacitor placement by PSO

```
clear all
Sensitivity
candidateBuses
nbus = 63;
nb = nbus;
Y = ybusppg(nb);
nvars = length(candidateBuses);
busd = busdatas(nb);
lb = zeros(nvars,1);
ubMag = sum(busd(candidateBuses,8));
ub = ubMag*ones(nvars,1);
f = @(x)objectiveWithParams(x,nb,Y,candidateBuses);
options = optimoptions('particleswarm');
options.Display = 'iter';
x = particleswarm(f,nvars,lb,ub,options)
save('solPSO.mat', 'x');
```

code for objective function of PSO.

```
function F = objectiveWithParams(x,nb,Y,candBus)

nbus = nb; % IEEE-14, IEEE-30, bella-63..

%candidateBuses = [62, 61, 60, 59, 51, 57, 50, 54, 53, 49];
candidateBuses = candBus;

tempBus = busdatas(nbus);

for count=1:length(candidateBuses)
    diff = tempBus(candidateBuses(count),8) -
tempBus(candidateBuses(count),6);
    if diff>0
        tempBus(candidateBuses(count),6) =+ x(count);
    end
end
tempBus(:,7) = 0.42*tempBus(:,7);
tempBus(:,8) = 0.42*tempBus(:,8);
%Y = ybusppg(nbus); % Calling ybusppg.m to get Y-Bus
Matrix..
busd = tempBus; % Calling busdatas..
BMva = 100; % Base MVA..
bus = busd(:,1); % Bus Number..
type = busd(:,2); % Type of Bus 1-Slack, 2-PV, 3-PQ..
```

```

V = busd(:,3);           % Specified Voltage..
del = busd(:,4);        % Voltage Angle..
Pg = busd(:,5)/BMva;    % PGi..
Qg = busd(:,6)/BMva;    % QGi..
Pl = busd(:,7)/BMva;    % PLi..
Ql = busd(:,8)/BMva;    % QLi..
Qmin = busd(:,9)/BMva;  % Minimum Reactive Power Limit..
Qmax = busd(:,10)/BMva; % Maximum Reactive Power Limit..
P = Pg - Pl;           % Pi = PGi - PLi..
Q = Qg - Ql;           % Qi = QGi - QLi..
Psp = P;               % P Specified..
Qsp = Q;               % Q Specified..
G = real(Y);           % Conductance matrix..
B = imag(Y);           % Susceptance matrix..

pv = find(type == 2 | type == 1); % PV Buses..
pq = find(type == 3);          % PQ Buses..
npv = length(pv);             % No. of PV buses..
npq = length(pq);             % No. of PQ buses..

Tol = 1;
Iter = 1;
while (Tol > 1e-3)           % Iteration starting..

    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) +
B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) -
B(i,k)*cos(del(i)-del(k)));
        end
    end

    % Checking Q-limit violations..
    if Iter <= 7 && Iter > 2 % Only checked up to 7th
iterations..
        for n = 2:nbus
            if type(n) == 2
                QG = Q(n)+Ql(n);
                if QG < Qmin(n)
                    V(n) = V(n) + 0.01;
                elseif QG > Qmax(n)
                    V(n) = V(n) - 0.01;
                end
            end
        end
    end
end
end

```

```

% Calculate change from specified value
dPa = Psp-P;
dQa = Qsp-Q;
k = 1;
dQ = zeros(npq,1);
for i = 1:nbus
    if type(i) == 3
        dQ(k,1) = dQa(i);
        k = k+1;
    end
end
dP = dPa(2:nbus);
M = [dP; dQ];           % Mismatch Vector

% Jacobian
% J1 - Derivative of Real Power Injections with Angles..
J1 = zeros(nbus-1,nbus-1);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J1(i,k) = J1(i,k) + V(m)* V(n)*(-
G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
            end
            J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
        else
            J1(i,k) = V(m)* V(n)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
        end
    end
end

% J2 - Derivative of Real Power Injections with V..
J2 = zeros(nbus-1,npq);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J2(i,k) = J2(i,k) + V(n)*(G(m,n)*cos(del(m)-
del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
            J2(i,k) = J2(i,k) + V(m)*G(m,m);
        else
            J2(i,k) = V(m)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
        end
    end
end

```

```

end
% J3 - Derivative of Reactive Power Injections with Angles..
J3 = zeros(npq,nbus-1);
for i = 1:npq
    m = pq(i);
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J3(i,k) = J3(i,k) + V(m)*
V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
            J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
        else
            J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) -
B(m,n)*sin(del(m)-del(n)));
        end
    end
end

% J4 - Derivative of Reactive Power Injections with V..
J4 = zeros(npq,npq);
for i = 1:npq
    m = pq(i);
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-
del(n)) - B(m,n)*cos(del(m)-del(n)));
            end
            J4(i,k) = J4(i,k) - V(m)*B(m,m);
        else
            J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
        end
    end
end

J = [J1 J2; J3 J4];           % Jacobian Matrix..

X = J\M;                     % Correction Vector
dTh = X(1:nbus-1);          % Change in Voltage Angle..
dV = X(nbus:end);           % Change in Voltage Magnitude..

% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus); % Voltage Angle..
k = 1;
for i = 1:nbus
    if type(i) == 3
        V(i) = dV(k) + V(i); % Voltage Magnitude..
    end
end

```

```
        k = k+1;
    end
end

Iter = Iter + 1;
Tol = max(abs(M));           % Tolerance..

end
% Calling loadflow2.m..
[Fp, Fq] = loadflow2(nbus,V,del,BMva,Y,busd);

capCost = costOf(x);
yr = 1;

F = yr*78403*Fp+0.1*capCost/yr;
%F = Fp;
end
```

Appendix G: Microturbine Cost Table

Table A-A.1 Equipment and Installation costs of Microturbine [42]

Description	System					
	1	2	3	4	5	6
Generator Capacity						
Nominal capacity (kW)	30	65	200	250	333	1000
Net capacity (kW)	28	61	190	240	320	950
Equipment costs						
Gen set package	\$53,100	\$112,900	\$359,300	\$441,200	\$566,400	\$1,188,600
Heat recovery	\$13,500	\$0	\$0	\$0	\$0	\$275,000
Fuel gas compression	\$8,700	\$16,400	\$42,600	\$0	\$0	\$164,000
Interconnection	\$0	\$0	\$0	\$0	\$0	\$0
Total equipment cost	\$75,300	\$129,300	\$401,900	\$441,200	\$566,400	\$1,627,600
\$/kW	\$2,689	\$2,120	\$2,120	\$1,840	\$1,770	\$1,710
Installation costs						
Labor/materials	\$22,600	\$28,400	\$80,400	\$83,800	\$101,900	\$293,000
Project & construction Mgmt.	\$9,000	\$15,500	\$48,200	\$52,900	\$68,000	\$195,300
Engineering and fees	\$9,000	\$15,500	\$48,200	\$52,900	\$68,000	\$195,300
Project contingency	\$3,800	\$6,500	\$20,100	\$22,100	\$28,300	\$81,400
Financing (int. during const.)	\$700	\$1,200	\$3,700	\$4,100	\$5,100	\$14,800
Total other costs	\$45,100	\$67,100	\$196,400	\$211,400	\$259,900	\$747,300
\$/kW	\$1,611	\$1,100	\$1,035	\$881	\$812	\$787
Total installed cost (\$)	\$120,400	\$196,400	\$598,500	\$652,600	\$826,300	\$2,374,900
\$/kW	\$4,300	\$3,220	\$3,150	\$2,720	\$2,580	\$2,500

Appendix H: Code of Genetic Algorithm for capacitor placement.

Sub code for objective function.

```

function F = objectiveWithParams(x,nb,Y,candBus)

    nbus = nb; % IEEE-14, IEEE-30, bella-63..

    %candidateBuses = [62, 61, 60, 59, 51, 57, 50, 54, 53, 49];
    candidateBuses = candBus;

    tempBus = busdatas(nbus);

    for count=1:length(candidateBuses)
        diff = tempBus(candidateBuses(count),8)-
tempBus(candidateBuses(count),6);
        if diff>0
            tempBus(candidateBuses(count),6) =+ x(count);
        end
        %tempBus(candidateBuses(count),6) =+ x(count); % Inject a
reactive power
    end
    tempBus(:,7) = 1*tempBus(:,7);
    tempBus(:,8) = 1*tempBus(:,8);
    %Y = ybusppg(nbus); % Calling ybusppg.m to get Y-Bus
Matrix..
    busd = tempBus; % Calling busdatas..
    BMva = 100; % Base MVA..
    bus = busd(:,1); % Bus Number..
    type = busd(:,2); % Type of Bus 1-Slack, 2-PV, 3-PQ..
    V = busd(:,3); % Specified Voltage..
    del = busd(:,4); % Voltage Angle..
    Pg = busd(:,5)/BMva; % PGi..
    Qg = busd(:,6)/BMva; % QGi..
    Pl = busd(:,7)/BMva; % PLi..
    Ql = busd(:,8)/BMva; % QLi..
    Qmin = busd(:,9)/BMva; % Minimum Reactive Power Limit..
    Qmax = busd(:,10)/BMva; % Maximum Reactive Power Limit..
    P = Pg - Pl; % Pi = PGi - PLi..
    Q = Qg - Ql; % Qi = QGi - QLi..
    Psp = P; % P Specified..
    Qsp = Q; % Q Specified..
    G = real(Y); % Conductance matrix..
    B = imag(Y); % Susceptance matrix..

    pv = find(type == 2 | type == 1); % PV Buses..
    pq = find(type == 3); % PQ Buses..
    npv = length(pv); % No. of PV buses..
    npq = length(pq); % No. of PQ buses..

```

```

Tol = 1;
Iter = 1;
while (Tol > 1e-3)           % Iteration starting..

    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) +
B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) -
B(i,k)*cos(del(i)-del(k)));
        end
    end

    % Checking Q-limit violations..
    if Iter <= 7 && Iter > 2    % Only checked up to 7th
iterations..
        for n = 2:nbus
            if type(n) == 2
                QG = Q(n)+Ql(n);
                if QG < Qmin(n)
                    V(n) = V(n) + 0.01;
                elseif QG > Qmax(n)
                    V(n) = V(n) - 0.01;
                end
            end
        end
    end

    % Calculate change from specified value
    dPa = Psp-P;
    dQa = Qsp-Q;
    k = 1;
    dQ = zeros(npq,1);
    for i = 1:nbus
        if type(i) == 3
            dQ(k,1) = dQa(i);
            k = k+1;
        end
    end
    dP = dPa(2:nbus);
    M = [dP; dQ];           % Mismatch Vector

    % Jacobian
    % J1 - Derivative of Real Power Injections with Angles..
    J1 = zeros(nbus-1,nbus-1);
    for i = 1:(nbus-1)
        m = i+1;
        for k = 1:(nbus-1)

```

```

        n = k+1;
        if n == m
            for n = 1:nbus
                J1(i,k) = J1(i,k) + V(m)* V(n)*(-
G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
            end
            J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
        else
            J1(i,k) = V(m)* V(n)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
        end
    end
end

% J2 - Derivative of Real Power Injections with V..
J2 = zeros(nbus-1,npq);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J2(i,k) = J2(i,k) + V(n)*(G(m,n)*cos(del(m)-
del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
            J2(i,k) = J2(i,k) + V(m)*G(m,m);
        else
            J2(i,k) = V(m)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
        end
    end
end

% J3 - Derivative of Reactive Power Injections with Angles..
J3 = zeros(npq,nbus-1);
for i = 1:npq
    m = pq(i);
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J3(i,k) = J3(i,k) + V(m)*
V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
            J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
        else
            J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) -
B(m,n)*sin(del(m)-del(n)));
        end
    end
end
end

```

```

% J4 - Derivative of Reactive Power Injections with V..
J4 = zeros(npq,npq);
for i = 1:npq
    m = pq(i);
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-
del(n)) - B(m,n)*cos(del(m)-del(n)));
            end
            J4(i,k) = J4(i,k) - V(m)*B(m,m);
        else
            J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
        end
    end
end

J = [J1 J2; J3 J4];      % Jacobian Matrix..

X = J\M;                % Correction Vector
dTh = X(1:nbus-1);      % Change in Voltage Angle..
dV = X(nbus:end);       % Change in Voltage Magnitude..

% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus); % Voltage Angle..
k = 1;
for i = 1:nbus
    if type(i) == 3
        V(i) = dV(k) + V(i); % Voltage Magnitude..
        k = k+1;
    end
end

Iter = Iter + 1;
Tol = max(abs(M));      % Tolerance..

end
% Calling loadflow2.m..
[Fp, Fq] = loadflow2(nbus,V,del, BMva, Y, busd);

capCost = costOf(x);
yr = 5;

%F = yr*78403*Fp+capCost;
F(1) = Fp*1000;
F(2) = capCost;
end

```

main code of Genetic Algorithm which calls all sub codes.

```
clear all
Sensitivity
candidateBuses
nbus = 63;
nb = 63;
Y = ybusppg(nb);
nvars = length(candidateBuses);
busd = busdatas(nb);
lb = zeros(nvars,1);
lbMag = sum(busd(candidateBuses,8));
ub = lbMag*ones(nvars,1);
f = @(x)objectiveWithParams(x,nb,Y,candidateBuses);
%options = optimoptions('particleswarm');
options = gaoptimset('PopulationSize',60,'PlotFcns',@gaplotpareto);
options.Display = 'iter';
[x,f,exitflag] = gamultiobj(f,nvars,[],[],[],[],lb,ub,options);
%x = gaoptimset(f,nvars,lb,ub,options)
save('solGA', 'x');
save('solGAf', 'f');
```