Optimal Placing and Sizing of Distributed Generation Units in Radial Distribution Networks

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ABSTRACT

In today's world, the lion's share of electricity demand is met by thermal power plants globally. Thermal power plants, mainly coal fired and in some cases gas fired come with some major issues. The first and foremost issue is, fossil fuels come with limited stockpile. Extensive usage of coal is leading to rapid declination of the stock. The second major problem is the massive amount of pollution caused by burning the fossil fuels especially coal. The third issue is these plants generate electricity in a centralized fashion, dispatching the energy to distant areas leads to losses in transmission and distribution. The concept of Distributed Generation is capable of dealing with all three aforementioned major issues. By implementing Distributed Generation (DG)s, small scale decentralized generation of electricity is possible by installing small sized renewable energy sources like solar panels, small wind turbines, biomass plants or non polluting non-renewable sources such as small seized gas turbines directly to the low voltage side of the distribution system.

In this research, the attempt has been made to find the optimal locations to place single DG units as well as multiple DG units having optimal size of each DG unit so that the system loss becomes minimized using a fairly new optimization algorithm. The outcomes show effectiveness of the proposed method and the results have been compared to recent works of similar fashion.

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NOMENCLATURE

$\mathbf{I_k}$	Current through branch 'k'
$\mathbf{p_{loss}}$	Net real powr loss
$\mathbf{P_N}$	Nominal real power at a node
$\mathbf{P(q)}$	Real power load at node 'q'
$\mathbf{P_s}$	Real power flow through a branch
$\mathbf{Q_{eff}}$	Net reactive power supplied beyond node 'q'
$\mathbf{Q_{loss}}$	Net reactive power loss
$\mathbf{Q_N}$	Nominal reactive power at a node
$\mathbf{Q(q)}$	Reactive power load at node 'q'
$\mathbf{Q_s}$	Reactive power flow through a branch
$\mathbf{V_p}$	Voltage magnitude at node 'p'
$\mathbf{V_q}$	Voltage magnitude at node 'q'
$\mathbf{X'_{j,k,i}}$	Updated solution
$\mathbf{X_{j,best,i}}$	Best solution
$\mathbf{X_{j,worst,i}}$	Worst solution

ABBREVIATIONS

ABC Artificial Bee Colony

AC Alternating Current

CHP Combined Heat and Power

DC Dircect Current

DE Differential Evolution

DFIG Doubly-Fed Induction Generator

DG Distributed Generation

EP Evolution Programming

ES Evolution Strategy

FF Firefly Algorithm

GA Genetic Algorithm

GSA Gravitational Search Algorithm

LBP Loop Break Point

LSF Loss Sensitivity Factor

MV Medimum Voltage

NSGA Non-dominated Sorting Genetic Algorithm

PSO Particle Swarm Optimization

RDN Radial distribution Network

TLBO Teaching-Learning Based Optimization

VSI Voltage Stability Index

CHAPTER 1

INTRODUCTION

> *If you want to find the secrets of the universe, think in terms of energy, frequency and vibration*
>
> NIKOLA TESLA

1.1 Overview

In the late 19th century, benefits and importance of electricity started to make and impact in European and American socio-economical lifestyle. With development in dynamos, bulk amount of energy generation became possible and power stations were built in Europe and America. A hydroelectric power station was established in "Cragside, England" in 1878. Commercial grade Generator was established in Belgium. In 1882, coal fired power stations were set up in both London and New York driven by inventions of Thomas Alva Edison. These systems were Dircect Current (DC) systems with various limitations. George Westinghouse started to develop Alternating Current (AC) systems based on the groundbreaking inventions by Nikola Tesla. AC had the characteristics needed to overcome the problem associated with DC, mainly the problem of long distance transmission where DC systems faced severe Ohmic Loss over long distance. Invention of transformer gave AC the edge over long distance transmission making AC less expensive and more efficient. Factors like this led to the infamous "*War of Currents*" between Edison backed General Electric and Tesla backed Westinghouse Corporation, which eventually swung toward Westinghouse and AC systems.

As power stations became capable of generating more and more power, it became absolute necessary to develop system to dispatch the generated electricity to the consumers. This necessity eventually has led to the complex system of electricity system network consisting of numerous elements regarding generation, transmission and distribution. These elements are briefly classified.

1.1.1 The Electrical Network

The electrical network is broadly classified into three categories.

1. ***Generation System:*** Generation system consists of Power Stations where electricity is generated mainly by thermal powered, hydro powered, gas powered or nuclear powered turbine propelled alternators and more recently by the means of renewable and non conventional sources. The range of generated voltage varies in the range of 2.5 kV to 25kV.
2. ***Transmission System:*** The transmission system serves the purpose of carrying electricity to the remote locations of load centres from the localized Power Stations. The voltage level of transmission system is stepped up up-to 750 kV to reduce Ohmic Losses.
3. ***Distribution System:*** Distribution system delivers electricity to the consumers from the load centres. The voltage level is stepped down to typically 11 kV and then further 440 kV level for direct consumption.

The whole process of generation-transmission-distribution is purposefully executed by numerous components, which work as the building blocks of the entire electricity network. The key components are hereby classified.

- ***Alternators:*** Alternators are electrical generators, which generate electric energy from mechanical energy in the form of AC. Alternating current is generated by the interaction of fixed armature magnetic field and rotating field. The rotational motion is provided by the means of steam, gas or hydro turbines.
- ***Transformers:*** Transformers are the instrumental component of AC transmission system. The purpose of a transformer is to step-up the voltage level after generation so that Ohmic loss is minimized in long distance transmission and then stepping it down at the distribution end at a consumable level.

- ***Conductors:*** Conductors are the means of moving electrical energy from generating end to consumer end. Conductors are made of copper, copper and steel composite, copper and aluminium composite or aluminium. Constructions of conductors vary according to voltage level and whether it is overhead cable or underground cable.

- ***Protection:*** Protection schemes in an electrical system are integral parts in order to prevent fatal accident and save costly equipments from being damaged or destroyed. Protection scheme comprises of ”Relays” to sense a fault, and “Switchgears” made of fuses and circuit breakers to isolate the healthy circuit from the faulty circuit upon sensing a fault.

This work focuses solely on distribution system as the purpose of the dissertation is optimal allocation of single DG unit and multiple DG units in Radial distribution Network (RDN).

1.1.2 Distribution System Types

Electrical distribution systems are classified on the basis of their feeder connection topology. The main types are as follows.

- ***Radial Distribution System:*** Radial systems consist of a single sub-station. Feeder branches radiate from the substation connecting the loads. In this system, flow of current is unidirectional.

- ***Parallel Distribution System:*** In parallel distribution system, sub-station and load centres are connected by parallel feeders to ensure connectivity in case of a faulty feeder.

- ***Ring Main Distribution System:*** In ring main structure, each distribution transformer is fed from two different paths, hence developing a ring like architecture, starting from and ending at the substation bus connecting all the load centres.

- ***Interconnected Distribution System:*** Interconnected systems and ring main systems are same in architecture except interconnected systems have multiple substations connected to the system.

In this work, analysis and computations of DG unit placement are done only on radial distribution networks as these networks are the most commonly found distribution network type all over the world.

A brief understanding of DG is as follows.

1.1.3 Distributed Generation

Distributed Generation (DG), also termed as *Dispersed Generation* or *Embedded Generation* are "small scale electric power source connected directly to the distribution network or on the customer side of the meter"(Ackermann ***et al.*** (2001)).

There is no clear definition of Distributed generation and many researches and scientific and engineering organizations has come up with their own definition. According to Ackermann ***et al.*** (2001), to define distributed generation, several aspects such as "the purpose, the location, rating, power delivery area, the technology, the environmental impact, mode of operation, ownership, penetration level" are to be defined separately.

- ***Purpose:*** The purpose of DG is to provide a source of active electric power.
- ***Location:*** The location of DG is defined as the installation and operation of electric power generation units connected directly to the distribution network or connected to the network on the customer site of the meter.(Sharma and Bartels (1997)).
- ***Rating of distributed generation:*** Different organizations define DG rating in different ways, such as
    1. As per the Electric-Power-Research-Institute (1998), DG is a generation from "a few kilowatts up to 50 MW."
    2. As per *Gas Research Institute,* ,DG is "typically [between] 25 and 25 MW."(Gas-Research-Institute (1998))

3. Preston and Rastler (1996) define the size as “ranging from a few kilowatts to over 100 MW.”
4. Cardell and Tabors (1997) give the definition of DG as“generation between 500 kW and 1 MW.”
5. As per *International Conference on Large High Voltage Electric Systems*(CIGRE) DG rating is “smaller than 50–100 MW.” (CIGRE (1997))

- ***Types of DG:*** After thorough review of researches by Linden ***et al.*** (1998), Kliman (1997) and Duffie and Beckman (2013) a detailed categorization of distributed generation units are hereby presented.

Table 1.1: Classification of DG units

DG Technology	**Size**
Combined cycle gas	35-400 MW
Internal combustion engines	5 kW-10 MW
Combustion turbine	1-250 MW
Micro-Turbines	35 kW-1 MW
Renewable Sources	
Small hydro	1-100 MW
Micro hydro	25 kW-1 MW
Wind turbine	200 Watt-3 MW
Photovoltaic arrays	20 Watt-100 kW
Solar thermal, central receiver	1-10 MW
Solar thermal, Lutz system	10-80 MW
Biomass e.g. based on gasification	100 kW-20 MW
Fuel cells, phosacid	200 kW-2 MW
Fuel cells, molten carbonate	250 kW-2 MW
Fuel cells, proton exchange	1 kW-250 kW
Fuel cells, solid oxide	250 kW-5 MW
Geothermal	5-100 MW
Ocean energy	100 kW-1 MW

Stirling engine	2-10 kW
Battery storage	500 kW-5 MW

Based on this classification, Ackermann ***et al.*** (2001) broadly classified DGs into three categories, Renewable units, Modular units and Combined Heat and Power (CHP) units.

1.1.4 Advantages of DG

Like every other technology DG technology comes with various advantages and disadvantages as described.

- Improvement in system reliability.
- Decrement in peak power demands.
- Emergency source of energy.
- Power quality improvement.
- Reduced land use effect and Rights of Way (ROI) acquisition expenses.
- Reduced overall system loss.

1.2 Literature Survey

A distribution network is considered as ill-conditioned networks. The conventional load-flow methods such as 'Gauss Seidel' or 'Newton Raphson' methods fail to converge in case of distribution networks. So special computational methodologies had been developed to solve power-flow problems for distribution networks. Kersting and Mendive (1976) suggested a technique where voltage and current values were updated using forward and backward sweeps using the ladder-network theory. One of the very initial work was done by Iwamoto and Tamura (1981). The method proposed by them was very straight forward and free of mathematical approximations. The method, the solution never diverged and it was possible to judge the existence of a final solution from the initial guess only. IEEE 11 and 43 bus systems were studied to to understand the effectiveness of the methodology.

Research by Shirmohammadi ***et al.*** (1988) proposed a new solution methodology to solve weakly meshed distribution network load-flow problems alongside radial networks. They used basic formulas of KCL and KVL and a multi-port compensation technique. That method proved to be very robust and showed excellent convergence characteristics. The peer presented load-flow solutions to several practical weakly meshed and radial distribution networks using a computer program. The method was also capable of solving both the single phase(balanced) networks and three-phase(unbalanced) networks.

Luo and Semlyen (1990) proposed another novel load-flow method for loosely meshed networks. The key advantages of that method over the method of Shirmohammadi ***et al.*** (1988) were (a) Active and reactive powers were the flow variables in place of complex current, leading to major simplification in handling P-V buses and reduction of computational complexity to half. (b) their method implements advanced tree labelling technique which further reduced the computational complexity. (c) An improved solution strategy had been implemented, which reduced the tedious task of mismatch calculations. Authors had validated the proposed method by successfully testing it with 30, 243, 1380 and 4130 node test networks.

Load-flow solution of distribution network by implementing decoupled load-flow analysis method was first proposed by Chiang (1991). In his research, the author investigated various solution algorithms to find a viable solution to the load-flow problem of RDN. His proposed algorithms achieved computational efficiency by utilizing the special characteristics of the distribution power network. His proposed algorithms showed excellent convergence characteristic when applied to various real world networks. Numerical properties and the robustness issues of the methods were also discussed.

Hatziargyriou ***et al.*** (1993) developed a probabilistic load-flow method for distribution networks with distributed generations embedded into in the form of wind turbines. The probabilistic model accounts for the generated active power and consumed reactive power induction generator driven turbines taking into consideration short-term wind velocity forecasts which had probabilistic nature. Radial load-flow solution was achieved using their model. It allowed probabilistic load modelling at the Medium Voltage/Low Voltage substations. It also modelled voltage regulator effects at the starting of medium voltage distribution feeder.

Haque (1996) proposed another new and potent way of solving the power-flow problem of a radial or mesh distribution network. If the given network was a mesh network, the network in transformed into a Radial Network by breaking the meshes using dummy buses. Computation of power injections at loop break points was executed using reduced ordered bus impedance matrix. In his algorithm, shunt admittances were considered unlike other methods and impact of load admittances were also taken into account while calculating power injection at the Loop Break Point (LBP)s. As that solution methodology was capable of incorporating shunt admittances, some special case networks could also be solved using his method.

Expósito and Ramos (1999) came up with a method to solve load-flow or radial distribution networks. In the proposed algorithm, load-flow equations were formulated as new variables resulting in a set of 3N equations(N number of quadratic and 2N number of liner equations) for a system with (N+1) buses. A Newton-Raphson based efficient solution methodology was proposed in their work.

Ghosh and Das (1999) devised an easy and efficient way of finding out power-flow problem of radial distribution networks. The method comprised of only calculation of simple receiving end voltages of the network nodes. Computational efficiency of the proposed method was very high as shown by the authors in three examples.

load-flow solution for a mesh network with multiple feeder node could be achieved by a simple method proposed by Haque (2000). The mesh system was transformed into an equivalent radial network with single source so that *"DistFlow branch equations"* could be deployed to solve the network. Because of the conversion, some break points and dummy buses were generated. To preserve the original characteristic of the network, appropriate complex power was in the break points of the equivalent radial network.

Teng (2003) proposed a direct approach to solve unbalanced three-phase distribution network load-flow problems. To make simple calculation possible, the special topological characteristics of radial networks had been well implemented. Bus-injection to branch-current matrix and the branch-current to bus-voltage matrix— and a simple matrix multiplication were the only three computational elements used to obtain load-flow solution. their solution methodology eradicated the need of time taking LU decomposition and forward/backward substitution of Jacobian or bus admittance matrix.

Another paper presented a simple and productive methodology to evaluate the power-flow problem of radial distribution networks(Ranjan and Das (2003)). The solution methodology dealt with the evaluation of the magnitude of basic algebraic recursive equation of voltage and the data was accumulated in vector form. Basic circuit theory being the method's building block, it was very easy to understand. The paper presented a comparative study with two other existing methods after applying it to various distribution networks. Two examples had been utilized to demonstrate the functionality of the method.

Eminoglu and Hocaoglu (2005) proposed a method which used line charging capacitance and voltage dependency of static loads into account for the purpose of power-flow calculation. The proposed methodology functioned by forward and backward voltage updating by polynomial equations of voltages of every branch and "DistFlow branch equations". Reliability and Convergence capability of the proposed method had been established to be viable enough by drawing comparisons with forward-backward sweep based Ratio-Flow method subjected to various kinds of R/X Ratios, loading conditions and source voltages for a substantial range of exponents of loads. The results establish the functionality of the proposed method.

In further researches Ghosh and Sherpa (2008) proposed a solution methodology which came along with minimum amount of data preparation and higher accuracy. Moreover, the algorithm did not require sequential numbering of the nodes and branches unlike other methods. Simple mathematical equations were used to equate voltage magnitude. The algorithm was also capable of handling composite load models. The method functions on the basis of nodes of feeder branch, lateral branch(s) and sub lateral branch(s). The advantage of the proposed method was demonstrated with the help of two examples.

Optimal DG placement was a relatively new concept of generation of power where small scale generation technology was implemented to generate electricity usually on a close proximity to the end user. The generation felicities were usually small scale domestic sized wind turbine, solar photovoltaic panels or other means of small scale energy generation technology(Rau and Wan, 1994). However, the benefits of these distributed generations set ups were location specific. The paper proposed a procedure to spot the optimal locations to place the DGs in a meshed distribution network. The required amount of resources in selected node to compensate the drops was computed by the proposed second order algorithm. Any kind of network such as transmission, sub-transmission or even distribution network could be taken under consideration.

Another research Kim ***et al.*** (2002) presented a hybrid system of fuzzy and Genetic Algorithm method to evaluate optimum dispersed generator placement for distribution systems.The problem was formulated considering objective of reducing power loss and number and size of the dispersed generators and load voltage deviation were considered as the constraints. In their method, fuzzy non-linear programming had been implemented to transfer the main objective function to multi-objective optimization problem. The fuzzy logic was a perfect tool to evaluate the imprecise nature of the objective function. Thereafter the problem was solved using Genetic Algorithm.

Chiradeja and Ramakumar (2004) discussed the benefits in changes in electrical power infrastructure. They further set indices to assess the developments in a quantitative manner. The indices included voltage profile improvement index, line loss reduction index, environmental impact reduction index and DG benefit reduction index. They had validated their findings with simulation results.

Another analytical approach for optimal placement of DG Sources was presented by Wang and Nehrir (2004). Demand of DG had skyrocketed in recent times because of deregulation in power system and shortage of transmission capacities. So, spotting an appropriate location to place a DG was the network had opened up a new window for researchers to obtain their maximum benefits their method focused on analytical methodologies to find optimum placement of DGs in both radial systems and meshed systems to decrease power loss of the system. Simulation results had also been presented to support the functionality of the analytical approaches.

Acharya ***et al.*** (2006) presented another analytical approach to solve optimal placing of DG problem, which solely focused on placing the DGs in primary distribution network. An analytical expression had been proposed to evaluate the optimal size and placement in order to minimize the power loss in the primary distribution network. Exact loss formula was the base of the derived analytical expression presented in the work. Their research focused on the impact of size and location of the DG on the loss in the network with great detail. Three test system of varying size and detailing had been examined by the proposed methodology and the results were compared with existing studies which uses comprehensive power-flow studies and loss-sensitivity method. Their method establishes that the approach based on Loss Sensitivity Factor (LSF) might not always yield to the spotting of the best placement location.

Jahromi ***et al.*** (2007) had developed an algorithm based on Genetic Algorithm (GA) to establish the optimal distributed generator allocation on a Medimum Voltage (MV) distribution network. They had taken indices namely *SARFIx* which was average number of RMS frequency variations, the net sag performance, average RMS Frequency index and overall voltage drop to understand the effects of DG placement on a network.

Their results showed appropriate allocations of DGs in a network.

Prakash and Sydulu (2007) had formulated a method of determining the optimal size and locations of capacitors in a radial distribution system. The capacitor sizing and placement was achieved by LSF and Particle Swarm Optimization (PSO) techniques. In the area of distribution network, the concept of *LSF* had been considered to be new. The factors were evaluated by running base case power-flow. Their proposed method had been applied on 10 node, 15 node, 34 node, 69 node and 85 node RDNs.

Celli ***et al.*** (2008) had classified energy saving in networks in the form of a multi-objective optimization problem. They had developed a Non-dominated Sorting Genetic Algorithm (NSGA) to simultaneously place various types of generators in the network. They had considered the energy saving goals as greenhouse gas emission reduction, characterizing generation technology based on CO_2 emission per kWh production. Probabilistic modelling had been used to determine load demand and DG production.

Haghifam ***et al.*** (2008) had presented a way to place the DG units in the network in an ambiguous environment. A multi objective model based approach had been taken up. The objectives had been defined as minimization of cost, technical risk and economic risk owing to volatility of electricity market price. Pareto-optimal front was achieved by multi-objective Genetic Algorithm (GA) and the final solution was obtained through a min-max approach.

Keane ***et al.*** (2009) had analysed the appropriate planning and operational complexities caused by non-firm access. To realize the probability of breach of constraints, coincidence was used through past generations and load profiles. A novel approach had been proposed through coordinated operation minimize the expense of non-firm access of generators.

A more recent work by Hung ***et al.*** (2010) came up with a method to compute optimal size and optimal power factor of DG units of four categories using analytical expressions. The types are as follows, DG supplying real power(Type 1), DG supplying both real and reactive power(Type 2), DG supplying real power but absorbing reactive power(Type 3) and DG delivering reactive power only(Type 4). The goal of the DG placement was to reduce the amount of loss in the RDN. Their technique had been put to test on three different test networks and results had been compared with readily available results from previous methods. The research established that the method had computational simplicity providing the optimal solution.

Khalesi ***et al.*** (2011). had presented the optimal placing of DGs in a distribution system by using a multi-objective function. Their main aim was to enhance reliability of the distribution system and improve the voltage profile across the distribution network. A time varying load had been applied so as to achieve pragmatic results. They had used a novel dynamic programming approach to solve the multi-objective problem.

Kalantari and Kazemi (2011) had taken three indices i.e., active power loss, reactive power loss and voltage profile and had reduced it by the GA. They had conducted their power-flow using forward and backward sweep method and the simulation had been conducted on a 28 node Radial distribution Network (RDN). Their results had shown significant cutback in losses and major increment of voltage profile.

Dixit ***et al.*** (2011) had presented an optimal allocation and sizing of DG in radial distribution network for power loss minimization and to enhance voltage profile of the system. They had divided their study into two parts namely, optimal allocation of the DG and optimal sizing of the DG. The location were identified by the Index Vector method and the Artificial Bee Colony method was used to find the optimal size of the DG. Their proposed method had been tested on the 15 node and 33 node RDNs.

Abu-Mouti and El-Hawary (2011) presented a new optimization approach, which used another Evolutionary Programming Method called “Artificial Bee Colony (ABC)” algorithm to find optimal number of DG units, size of the units and power factor and location. ABC Algorithm was a meta-heuristic optimization algorithm inspired by the foraging of of bees. The effectiveness of the algorithm was justified by applying the method on three test cases and had been compared with results obtained by other existing methods. The results verify the robustness, efficiency and capability of handling mixed integer non linear optimization problems. The ABC algorithm needed only two parameters to be adjusted. So the simplicity of the tuning process naturally enhanced the capability of the algorithm as compared to other meta heuristic optimization algorithms.

Amanifar and Golshan (2012) had applied PSO in order to determine the optimal size and location of DG units in a distribution network. The objective function used in their research was cost oriented- comprising of the net amount of cost of DG energy injection, fixed installation cost and percentage of buses going through voltage sag. Their results showed proper placement of DG leads to improvement of the above mentioned indices.

Mahari and Babaei (2012) had used an imperialistic competition algorithm to compute the optimal size and location of DG units. Their cost function was based on minimizing network power losses. Better voltage regulation was achieved by optimal sizing and allocation. The analysis of the performance was executed on 33 node and 69 node RDN and the performance was compared with other algorithms.

Rueda-Medina and Padilha-Feltrin (2012) had proposed a settlement procedure for the reactive power market for DGs in a distribution network. Wind turbines connected to the network through permanent magnet alternators and Doubly-Fed Induction Generator (DFIG) was where key attention had been paid in their work. The generation uncertainty was depleted by applying a Monte-Carlo based multi-objective optimization tool considering several probabilistic frameworks. Markov Models were used to represent the real power delivered by the units. The proposed methodology had been tested on a modified IEEE 37-bus distribution system.

Al Abri ***et al.*** (2012) had proposed a method to optimally spot and size DG units to increase voltage stability. The two key aspects, which were taken under consideration were probabilistic characteristic of load and DGs powered by renewable sources. The mathematical formulation for sizing and placing was executed by mixed integer nonlinear programming.

Doagou-Mojarrad ***et al.*** (2013) had used the particle swarm optimization algorithm to solve the DG sizing and placement problem. Usefulness of PSO had been established by applying it to the IEEE 34 node test network. Results showed loss reduction and voltage profile improvement.

Alinezhad ***et al.*** (2015) had defined a multi-objective problem formulated by cost function to reach to all objectives like optimal positioning and sizing of DG units, real and reactive power loss reduction, improvement of system voltage, cost reduction and reliability improvement. Several Evolutionary programming and swarm based algorithms were implemented such as GA, PSO, Gravitational Search Algorithm (GSA). Results had proven acceptability of GSA over other methods.

Nagaballi and Kale (2017) had proposed an optimal placement and sizing of DG based on modified teaching learning based algorithm (MTLBO) in radial distribution network. Their main aim was to reduce the real power loss. IEEE 33 bus test system had been chosen to prove the functionality of their algorithm. Simulation studies had been carried out using MATLAB environment.

In order to find optimal sizes of DG units, optimization algorithm was implemented. Optimization algorithm could be broadly classified into two categories, Evolutionary Algorithms and Swarm Intelligence based methods. Genetic Algorithm (GA), Evolution Programming (EP), Evolution Strategy (ES), Differential Evolution (DE) were some of the Evolution based algorithms. Particle Swarm Optimization(PSO), Tabu Search Firefly Algorithm (FF), Teaching-Learning Based Optimization (TLBO), Shuffled Frog Leap (SFL) were examples of Swarm based methods.

History of Evolutionary Algorithms dates back to 1950 when British mathematician and computer scientist Alan Turing (1950) proposed the idea of a ‘Learning Machine’ which would work on the principles of evolution. During 1970s, Lawrence J. Fogel proposed the concept of evolutionary programming to generate artificial intelligence.(Fogel ***et al.***, 1975). Genetic Algorithm in particular was made famous by John Holland (1975) in his book *Adaptation in Natural and Artificial Systems.* Genetic Algorithm was the pioneering method of Evolutionary programming.

Storn and Price (1997) proposed a new heuristic approach, which could effectively minimize non-linear and non-differentiable continuous space functions. Using extensive test beds, it was established that the proposed method had faster convergence rate than other existing methods. The key advantages of their method was it had lesser control variables, that was robust, easy to apply and most importantly, it was very friendly to parallel computing.

1.3 Objectives

After thorough examination of the available researches and exploring the research opportunities, two potential objectives has been identified.

1. To find the sensitive nodes of networks for DG placement.
2. To compute size of DG by a suitable optimization algorithm.

A readily available suitable load-flow analysis and Voltage Stability Index will be used in the study.

In the next chapter, detailed explanation of the theoretical methodologies used to execute the objective are explained thoroughly.

CHAPTER 2

THEORY AND FORMULATION

> *I have not failed. I've just found 10,000 ways that won't work.*
>
> THOMAS ALVA EDISON

The DG allocation problem can be subdivided into two parts. One is to spot the optimal location where the DG unit is to be placed, the other one is to find the exact size of the unit for which the loss will be minimal. Another very important and absolutely integral part of this work is the Load-Flow or power-flow analysis which gives the steady state operating conditions of a network. This chapter consists of detailed discussion of the all three key points.

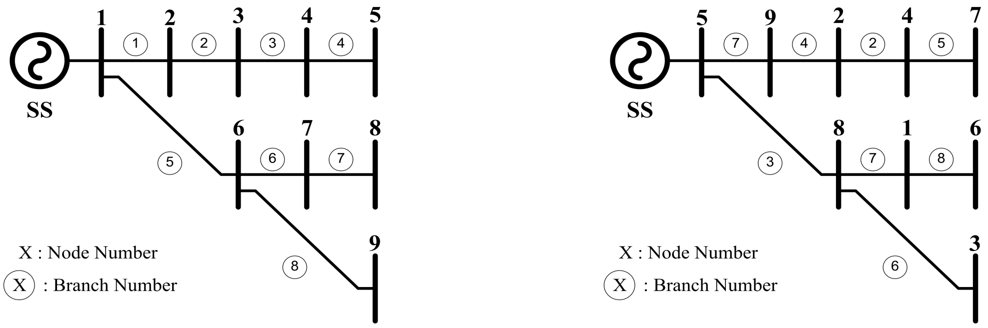
This work also includes another parameter called **Voltage Stability Index (VSI)** for monitoring system performance. VSI will be briefly addressed in this chapter.

Furthermore, a cost analysis has also been presented in this study. Both cost of energy produced by DG and cost of energy lost in the system is analysed. A simple mathematical formulation to calculate cost of energy lost is provided by Murty and Kumar (2015) and Gautam and Mithulananthan (2007) provided analytical data and a quadratic cost function to calculate the energy cost generated by DG.

2.1 Load-Flow Solution

load-flow or power-flow solution is an integral part of most of the power system related problem. load-flow analysis is done to know the steady state operating condition of a networks i.e. node voltages, power-flow through lines and losses in line et cetera, depending upon the network structure and a specific generating state.

A novel load-flow solution methodology has been implemented in this work, accuracy and minimized data preparation being its key advantages.



(a) RDN with sequential node numbering. (b) RDN with non-sequential node numbering.

Figure 2.1: Sample Radial Distribution Networks

Radial distribution network consists of one source, which is a substation. The main branch coming out of the substation is called feeder line, branches coming out of the feeder branch are called lateral branches and branches coming out of laterals are termed as sub-lateral branches.

For example, in the sample network given in Figure 2.1(a), branches 1 to 5 are feeder branches, branches 5 to 8 are lateral branches and branch number 9 is sub-lateral branch. For network in Figure 2.1(b), branches 7,4,2,5 are feeders, 3,7,8 are laterals and 6 is sub-lateral branch. In some cases branches come out of sub-laterals, those branches are termed as minors.

Node numbering scheme for network in Figure 2.1(a) is:

FN={1,2,3,4,5};

LN={1,6,7,8};

SLN={6,9};

Branch numbering scheme for network in Figure 2.1(a) is:

FB={1,2,3,4};

LB={5,6,7};

SLB={8};

Branch numbering scheme for network in Figure 2.1(b) is:

FN={5,9,2,4,7};

LN={5,8,1,6};

SLN={8,3};

Branch numbering scheme for network in Figure 2.1(b) is:

FB={7,4,2,5};

LB={3,7,8};

SLB={6};

To denote the branch types mathematically, a number is assigned to each branch type. feeder is denoted by 1, lateral is denoted by 2 and sub-lateral is denoted by 3. A 2-dimensional array $FN(x, y)$ is used to store nodes of feeder branches, lateral branches and sub-lateral branches. The first element of the array denotes branch type, the second one represents branch number. So, for network in Figure 2.1(a),

FN(1,1)=1; FN (1,2)=2; FN (1,3)=3; FN (1,4)=4; FN (1,5)=5;

FN (2,1)=1; FN (2,2)=6; FN (2,3)=7; FN (2,4)=8

FN (3,1)=6; FN (3,2)=9.

For network in Figure 2.1(b),

FN(1,1)=5; FN(1,2)=9; FN(1,3)=2; FN(1,4)=4; FN(1,5)=7;

FN(2,1)=5; FN(2,2)=8; FN(2,3)=1; FN(2,4)=6

FN(3,1)=8; FN(3,2)=3.

Similarly, branches are also denoted by a two dimensional array $FB(x, y)$. For network in Figure 2.1(a),

FB (1,1)=1; FB (1,2)=2; FB (1,3)=3; FB (1,4)=4;

FB (2,1)=5; FB (2,2)=6;

FB(2,3)=7;

FB(3,1)=8.

For network in Figure 2.1(b) ,

FB (1,1)=7; FB (1,2)=4; FB (1,3)=2; FB (1,4)=5;

FB (2,1)=3; FB (2,2)=7;

FB (2,3)=8;

FB (3,1)=6.

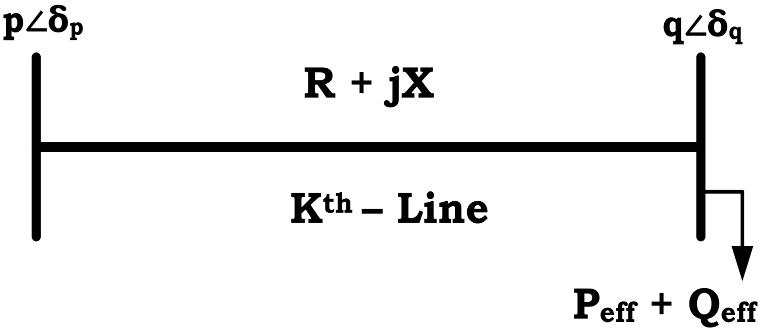


Figure 2.2: A typical segment of a distribution line

Figure 2.2 displays a typical section of a radial distribution network with two adjacent nodes 'p' and 'q' and a line 'k' in between those.

Voltage magnitude at node 'q' is given by Equation (2.1).

$$|V_q| = |V_p| - \frac{[P_{eff}^2 + Q_{eff}^2]^{\frac{1}{2}} \times |Z_k|}{|V_p|} \tag{2.1}$$

Where

P_{eff}= Net real power supplied beyond node 'q'.

Q_{eff}= Net reactive power supplied beyond node 'q'.

$|V_p|$= Voltage magnitude at node 'p'.

$|V_q|$= Voltage magnitude at node ‘q’.

Current magnitude through branch ‘k’ is calculated by Equation (2.2).

$$|I_k| = \frac{|V_p| - |V_q|}{|Z_k|} \tag{2.2}$$

Real and Reactive power loss at branch ‘k’ is calculated by Equation (2.3) and Equation (2.4) respectively.

$$P_{loss} = |I_K|^2 \times R_k \tag{2.3}$$

$$Q_{loss} = |I_K|^2 \times X_k \tag{2.4}$$

Now, in order to calculate Voltage magnitude, current and losses, real and reactive power flows P_{eff} and Q_{eff} are to be calculated. Procedure of calculating power flow is hereby described.

Power flow through any branch in a network is addition of the nominal power at the receiving end node of the branch, power loss in the branch and power flow in the next branch.If the branch is the last branch of the line, power flow is addition of loss in the branch and nominal power at the receiving end node of the branch. For example, Power flow in the k^{th} branch of sample Figure 2.2 is the addition of nominal power at node ‘q’, power flow at $(k+1)^{th}$ branch and power loss at k^{th} branch.

For the sample network in Figure 2.2, real power flow calculation starts from the sub-lateral branch, given by Equation (2.5).

$$P_s[FB(3,1)] = P_N[FN(3,2)] + P_{loss}[FB(3,1)] \tag{2.5}$$

For laterals real power flow through each branch is given by Equation (2.6).

$$\left.\begin{aligned} P_s[FB(2,3)] &= P_N[FN(2,4)] + P_{loss}[FB(2,3)] \\ P_s[FB(2,2)] &= P_N[FN(2,3)] + P_{loss}[FB(2,2)] + P_s[FB(2,3)] \\ P_s[FB(2,1)] &= P_N[FN(2,2)] + P_{loss}[FB(2,1)] + P_s[FB(2,2)] \end{aligned}\right\} \tag{2.6}$$

For Feeders, real power flow through each branch is given by Equation (2.7).

$$\left.\begin{aligned} P_s[FB(1,4)] &= P_N[FN(1,5)] + P_{loss}[FB(1,4)] \\ P_s[FB(1,3)] &= P_N[FN(1,4)] + P_{loss}[FB(1,3)] + P_s[FB(1,4)] \\ P_s[FB(1,2)] &= P_N[FN(1,3)] + P_{loss}[FB(1,2)] + P_s[FB(1,3)] \\ P_s[FB(1,1)] &= P_N[FN(1,2)] + P_{loss}[FB(1,1)] + P_s[FB(1,2)] \end{aligned}\right\} \tag{2.7}$$

Generalizing the equation, power flow for end branches can be expressed as Equation (2.8).

$$P_s[FB(x,y)] = P_N[FN(x,y+1)] + P_{loss}[FB(x,y)] \tag{2.8}$$

For other branches, power flow is given by Equation (2.9).

$$P_s[FB(x,y)] = P_N[FN(x,y+1)] + P_{loss}[FB(x,y)] + P_s[FB(x,y+1)] \tag{2.9}$$

P_s= Real power flow through a branch.
P_N= Nominal real power at a bus.
P_{loss}= Real power Loss in a branch.

Similarly, for reactive power flow, generalized formulae can be formed. For end branches, reactive power flow is given by Equation (2.10).

$$Q_s[FB(x,y)] = Q_N[FN(x,y+1)] + Q_{loss}[FB(x,y)] \tag{2.10}$$

For other branches, reactive power flow is given by Equation (2.11).

$$Q_s[FB(x,y)] = Q_N[FN(x,y+1)] + Q_{loss}[FB(x,y)] + Q_s[FB(x,y+1)] \tag{2.11}$$

Q_s= Reactive power flow through a branch.
Q_N= Nominal Reactive power at a bus.
Q_{loss}= Reactive power Loss in a branch.

Now, sub-lateral branch $FB(3,1)$ is connected to lateral node $FN(2,2)$ and lateral branch $FB(2,1)$ is connected to feeder node $FN(1,1)$.

Therefore, net real power flow in the branch $FB(2,1)$ is calculated by Equation (2.12)

$$P_s[FB(2,1)] = P_N[FN(2,2)] + P_{loss}[FB(2,1)] + P_s[FB(2,2)] + P_s[FB(3,1)] \tag{2.12}$$

Similarly, reactive power flow through the branch $FB(2,1)$ is calculated by Equation (2.13)

$$Q_s[FB(2,1)] = Q_N[FN(2,2)] + Q_{loss}[FB(2,1)] + Q_s[FB(2,2)] + Q_s[FB(3,1)] \quad (2.13)$$

Therefore, in order to successfully evaluate power-flow in a radial distribution network using the above described , it is essential to find the common nodes between laterals and sub-laterals, feeders and laterals and the subsequent branches behind the common nodes.

In the load-flow study, another important aspect is load modelling.

2.1.1 Load Modelling

A balanced load can be generally represented by 4 types, constant power, constant current, constant impedance type and composite type. Two commonly used load models are **Polynomial Load Model** and **Exponential Load Model**.

Polynomial Load Model

The general expression of real and reactive load for Polynomial Load Model is expressed as Equation (2.14) and Equation (2.15) respectively.

$$P(q) = P_N[a_0 + a_1 * V_q + a_2 * V_q^2] \quad (2.14)$$

$$Q(q) = Q_N[b_0 + b_1 * V_q + b_2 * V_q^2] \quad (2.15)$$

$P(q), Q(q)$= Real and Reactive load at bus ‘q’.
P_N, Q_N= Nominal Real and Reactive power at bus ‘q’.
V_q= Voltage at bus ‘q’.
For constant power(CP) load, $a_0, b_0 = 1$ and $a_1, b_1 = 0, a_2, b_2 = 0$.
For constant current(CI) load, $a_1, b_1 = 1$ and $a_0, b_0 = 0, a_2, b_2 = 0$.
For constant impedance(CZ) load, $a_2, b_2 = 1$ and $a_0, b_0 = 0, a_1, b_1 = 0$.
For composite load, $a_0 + a_1 + a_2 = 1$ and $b_0 + b_1 + b_2 = 1$.

Exponential Load Model

The General expression of real and reactive load for exponential load model is as expressed as Equation (2.16) and (2.17) respectively.

$$P(q) = P_N * (\frac{V_q}{V_{q0}})^{np} \tag{2.16}$$

$$Q(q) = Q_N * (\frac{V_q}{V_{q0}})^{nq} \tag{2.17}$$

V_{q0}= Voltage at bus 'q' at nominal power P_N.
np, nq= Exponent factors.
For CP load, $np, nq = 0$.
For CI load, $np, nq = 1$.
For CZ load, $np, nq = 2$.

Algorithm for load-flow

In order to calculate node voltages and branch currents, initially, losses at all the branches are taken as 0, calculation is initiated with flat voltage profile i.e (1+j0) pu. To determine termination criteria, change in voltage in two consecutive iterations has to be less than a pre determined value. ΔV=$[V_{new} - V_{old}]$<ϵ for all the buses, where ϵ is a pre determined value called termination criterion. The steps to calculate load-flow are as follows.

Step 1: Read total number of Feeder(F), lateral(L) and sub-lateral(S) branches.

Step 2: Calculate $TL = F + L + S$

Step 3: Read number of Branches(TB) and number of Nodes(TN).

Step 4: Read Bus data and Line data.

Step 5: Read all the initial node voltages as 1.0 pu and all the line losses as 0 pu.

Step 6: Find the common nodes between lateral and sub-lateral and store them in an array. Store the branch of the lateral which is in front of the node.

Step 7: Find the common nodes between feeder and lateral and store them in an array. Store the branch of the feeder which is in front of the node.

Step 8: Convert bus data and line data into P.U form and calculate impedance of each branch.

Step 9: Start iterative voltage calculation with a flat voltage profile.

Step 10: Determine the appropriate load type and calculate real and reactive power at each node using Equations (2.14) and (2.15) or Equations (2.16) and (2.17).

Step 11: Calculate real and reactive power-flow through all the branches using Equations 2.8, 2.9, 2.10, 2.11.

Step 12: Calculate voltage at each node except node 1, which is taken as slack bus with constant voltage 1.0 pu, using Equation (2.1).

Step 13: Calculate difference ΔV of voltage between previous iteration and current iteration.

Step 14: Calculate current flowing through each branch using Equation (2.2).

Step 15: Calculate real and reactive power loss in every branch using Equations (2.3) and (2.4).

Step 16: Check if ΔV is less than termination criterion ϵ. Value of ϵ is set to be 0.000001.

Step 17: Repeat steps 9 to step 13 until termination criteria is met.

Step 18: Calculate net loss by adding losses of each line.

2.2 Optimal Placing of DG Units

To find the optimal positions, a node ranking method named **Loss Sensitivity Factor** is implemented in this work.

2.2.1 Loss Sensitivity Factor

LSF is a useful tool to find out suitable nodes of the distribution system for compensation.

Active power loss in k^{th} line can be written as Equation (2.18)

$$(I_k^2)R(k) = P_{lineloss}(q) = \frac{(P_{eff}^2(q) + Q_{eff}^2(q)) \times R(k)}{V(q)^2} \tag{2.18}$$

Similarly, reactive power loss in k^{th} line can be written as Equation (2.19)

$$(I_k^2)X(k) = Q_{lineloss}(q) = \frac{(P_{eff}^2(q) + Q_{eff}^2(q)) \times X(k)}{(V(q))^2} \tag{2.19}$$

Where

P_{eff}= Net real power supplied beyond node ‘q’.

Q_{eff}= Net reactive power supplied beyond node ‘q’.

Now, for real power compensation, LSF is defined as change in real and reactive power with respect to change in real power loss. So, both loss sensitivity factor indices can be formulated as Equation (2.20) and Equation (2.21) respectively.

$$\frac{\delta P_{lineloss}}{\delta P_{eff}} = \frac{2 \times P_{eff}(q) \times R(k)}{V(q)^2} \tag{2.20}$$

$$\frac{\delta Q_{lineloss}}{\delta P_{eff}} = \frac{2 \times P_{eff}(q) \times X(q)}{V(q)^2} \tag{2.21}$$

For reactive power compensation, LSF is defined as change in real and reactive power loss with respect to change in reactive power flow.

So, both loss sensitivity factor indices can be formulated as Equation (2.22) and Equation (2.23).

$$\frac{\delta P_{lineloss}}{\delta Q_{eff}} = \frac{2 \times Q_{eff}(q) \times R(k)}{V(q)^2} \tag{2.22}$$

$$\frac{\delta Q_{lineloss}}{\delta Q_{eff}} = \frac{2 \times Q_{eff}(q) \times X(k)}{V(q)^2} \tag{2.23}$$

Node Selection by LSF Method

The implementation of above mentioned four types of Loss Sensitivity Factors are described below

- $(\delta P_{lineloss} \big/ \delta P_{eff})$ is suitable for real power loss minimization problems using real power compensations.
- $(\delta Q_{lineloss} \big/ \delta P_{eff})$ is suitable for reactive power loss minimization problems using real power compensation.
- $(\delta P_{lineloss} \big/ \delta Q_{eff})$ is suitable for real power loss minimization problems using reactive power compensation.
- $(\delta Q_{lineloss} \big/ \delta Q_{eff})$ is suitable for reactive power loss minimization problems using reactive power compensation.

Algorithm

For any certain type of DG and optimization problem, the algorithm to implement LSF method is as follows.

Step 1: Loss Sensitivity Factor of each line is calculated from base case load-flow.

Step 2: Values are arranged in descending order and corresponding lines are ordered.

Step 3: Sending end nodes of each line are stored in order.

Step 4: Voltages of each node is normalized by dividing each p.u valued base case voltages by 0.95.

Step 5: Nodes of which normalized voltages are less than 1.01 are eligible for compensation and hence stored separately in ‘rank bus’ vector.

Step 6: Separated nodes which are eligible for compensation are arranged according to previously stored order fixed using “LSF” values.

Step 7: Node node in the highest position is given the highest priority for compensation.

To study the system performance, VSI has been calculated and studied. Brief mathematical background of VSI is hereby analysed.

2.2.2 Voltage Stability Index

For the section of distribution network segment given in Figure 2.2, real and reactive power flow through the kth branch is given by Equation (2.24) and Equation (2.25) respectively.

$$P_{eff} = \frac{V_pV_q}{|Z_k|} cos(\theta_z - \delta_p + \delta_q) - \frac{V_q^2}{|Z_k|} cos(\theta_z) \tag{2.24}$$

$$Q_{eff} = \frac{V_pV_q}{|Z_k|} sin(\theta_z - \delta_p + \delta_q) - \frac{V_q^2}{|Z_k|} sin(\theta_z) \tag{2.25}$$

Where $\theta_z = tan^{-1}(\frac{R_k}{X_k})$ i.e the impedance angle of the transmission line segment.

Rearranging Equation (2.24) and Equation (2.25),

$$cos(\theta_z - \delta_p + \delta_q) = \frac{P_{eff}|Z_k|}{V_pV_q} + \frac{V_s}{V_r} cos(\theta_z) \tag{2.26}$$

$$sin(\theta_z - \delta_p + \delta_q) = \frac{Q_{eff}|Z_k|}{V_pV_q} + \frac{V_s}{V_r} sin(\theta_z) \tag{2.27}$$

Now, Equation (2.28) by Trigonometric Identity,

$$sin(\theta_z - \delta_p + \delta_q) + cos^2(\theta_z - \delta_p + \delta_q) = 1 \tag{2.28}$$

By putting equation (2.26) and (2.27) into equation (2.28),

$$V_q^4 + V_q^2[2(PR + QX) - V_p^2] + (P_{eff}^2 + Q_{eff}^2)|Z^2| = 0 \tag{2.29}$$

The given equation is in the form of a bi-quadratic equation, solutions of which are Equation (2.30) and Equation (2.31).

$$P = \frac{-cos(\theta_z)V_q^2 \pm \sqrt{cos^2(\theta_z)V_q^4 - |Z|^2Q^2 - 2V_q^2QX + V_p^2V_q^2}}{|Z|} \tag{2.30}$$

$$Q = \frac{-sin(\theta_z)V_q^2 \pm \sqrt{sin^2(\theta_z)V_q^4 - |Z|^2P^2 - 2V_q^2PR + V_p^2V_q^2}}{|Z|} \tag{2.31}$$

So, for real value of real and reactive power to exist, following conditions expressed by Equation (2.32) and Equation (2.33) must hold:

$$cos^2(\theta_z)V_q^4 - |Z|^2Q^2 - 2V_q^2QX + V_p^2V_q^2 > 0 \tag{2.32}$$

$$sin^2(\theta_z)V_q^4 - |Z|^2P^2 - 2V_q^2PR + V_p^2V_q^2 > 0 \tag{2.33}$$

Summing (2.32) and (2.33), the following Equation (2.34) is formulated.

$$2V_p^2V_q^2 - V_q^4 - 2V_q^2(PR + QX) - |Z|^2(P^2 + Q^2) > 0 \tag{2.34}$$

If transferred power and impedance of the transmission line increases, the value of equation 2.34 decreases. Equation (2.34) is used as the mathematical expression to calculate VSI.

2.3 Optimal Sizing of DG Units

Finding optimum DG size is a complex minimizing optimization problem. For solving optimization problems, using Evolutionary Programming or Swarm Intelligence based methods are widely accepted. For Optimal Seizing, a new optimization algorithm named **Jaya Algorithm** is used.

2.3.1 Jaya Algorithm

Jaya Algorithm, developed in 2016, is an algorithm specific parameter-less optimization algorithm. The algorithm works on the basis of a very simple logic-in a pool of potential solutions, move a solution towards the best possible solution and away from the worst solution. The biggest benefit of this algorithm is its simplicity and ease of implementation. The mathematical formulation is briefly described below.

Mathematical Formulation

Suppose, $f(x)$ is an objective function to be optimized(maximize or minimize). At a random iteration i, suppose there are $'m'$ number of variables in the function, and $'n'$ populations or candidate solutions.

Suppose, the candidate *best* results in the best solution of $f(x)$ i.e $f(x)_{best}$ and the candidate *worst* results in the worst solution $f(x)_{worst}$. If, value of j^{th} variable for k^{th} candidate at i^{th} iteration is $X_{j,k,i}$, then that certain candidate is updated as Equation (2.35):

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i} \times (X_{j,best,i} - |X_{j,k,i}|) - r_{2,j,i} \times (X_{j,worst,i} - |X_{j,k,i}|) \tag{2.35}$$

$X'_{j,k,i}$= Updated solution

$X_{j,best,i}$= Best solution.

$X_{j,worst,i}$= Worst solution.

$r_{1,j,i}$, $r_{2,j,i}$= Two random numbers ranging between 0 and 1.

The tendency of this algorithm is to move towards success and avoid failure. The aim of the algorithm is to become victorious and hence the name Jaya Algorithm is given. $\{r_{1,j,i}(X_{j,best,i} - |X_{j,k,i}|)\}$ moves a solution toward the best solution and $\{r_{2,j,i}(X_{j,worst,i} - |X_{j,k,i}|)\}$ moves the solution away from the worst solution.

Algorithm for Jaya Algorithm

Algorithm to implement Jaya Algorithm is hereby explained.

Step 1: Initiate population size, total number of iterations and number of design variables.

Step 2: Find *best* and *worst* solutions. For minimization problems, solution which gives minimum value of objective function is the *best* solution and solution which gives maximum value is the worst solution. For maximization problems, solution which gives maximum value of objective function is the *best* solution and solution which gives minimum value is the worst solution.

Step 3: Update every solution using Equation (2.35).

Step 4: Check if the updated solution is better than the original solution.

Step 5: If updated solution gives better result, accept the solution, otherwise, keep the original solution.

Step 6: Check if termination criterion is met. If met, declare the optimum solution. Otherwise repeat step 2 through step 5 until termination criterion is met.

2.3.2 Objective Function

Objective function for any optimization algorithm is a mathematical function which is to be optimized(to maximize or minimize). Objective function can be single or multiple(multi-objective optimization). For multi-objective optimizations, EP or SI algorithm comes in handy because simultaneously optimizing two or more different functions by algebraic methods is almost impossible or inefficient.

Constrained and Unconstrained Optimization

Constraints are restrictions on various parameters of the objective function.

- In *Unconstrained Optimization Problems*, the aim is to find global optimum point of an objective function without any kind of restrictions or limitations on the variables.
- In *Constrained Optimization Problems*, the aim is to find the optimum solution within some constraints on the parameters. These constraints make some points or ranges in the solution set illegal.

Objective Function for DG Allocation Problem

In this work, net real power loss of the network is taken as the objective function.

Constraints

Two constraints which are used in this work are,

- Size of the DG Units. Each DG units must be within a certain size. Roughly, net DG injection capacity should not exceed the net power flowing through the system.
- Position of the DG units are used as a second constraint. If a DG unit is placed too close to the substation,

In the following section, the formulations for cost analysis of the power loss and generated power by DGs are analysed.

2.4 Cost analysis

Cost effectiveness being a very integral part of almost all engineering problems, this research looks into the cost of both energy generated by the DG units and cost of lost energy in the system. Both techniques are hereby briefly described.

2.4.1 Annual Cost of Energy Loss

Cost of energy losses annually is calculated by the following Equation (2.36):

$$Cost_{Ploss} = P_{loss_{net}} \times Cost_{energy} \times t \qquad \$ \tag{2.36}$$

$Cost_{Ploss}$= Total cost of energy loss.

$P_{loss_{net}}$= Net power loss of the network.

$Cost_{energy}$= Energy cost.

t= Time of consumption.

Here,

$Cost_{energy}$= 0.06 \$/kWh.

t=8760 Hours.

2.4.2 Cost of DG

Cost of DG is calculated by a quadratic function expressed by Equation (2.37).

$$Cost_{DG} = P_{DG}^2 * a + P_{DG} * b + c \tag{2.37}$$

P_{DG}= Power generated by DG.

a, b, c= Cost coefficients.

Values of cost coefficients are taken as,

a= 0, b= 20, c=0.25.

In the following chapter, results obtained by implementing the above mentioned formulations has been explained in details.

CHAPTER 3

RESULTS AND DISCUSSION

When something is important enough, you do it even if the odds are not in your favor.

Elon Musk

3.1 System Configuration

All the simulation has been executed on a Personal Computer manufactured by Dell Inc. powered by Intel® Core™ i5 Processor with 8 GB DDR3 RAM . All the programming related tasks are executed in MATLAB® R2019a software.

3.2 33 Node RDN

Figure 3.1 shows the schematic of IEEE 33 Bus test network. The network has base voltage level of 12.66 kV and base power of 100 MVA. The bus and line data of the network is given in Appendix A.

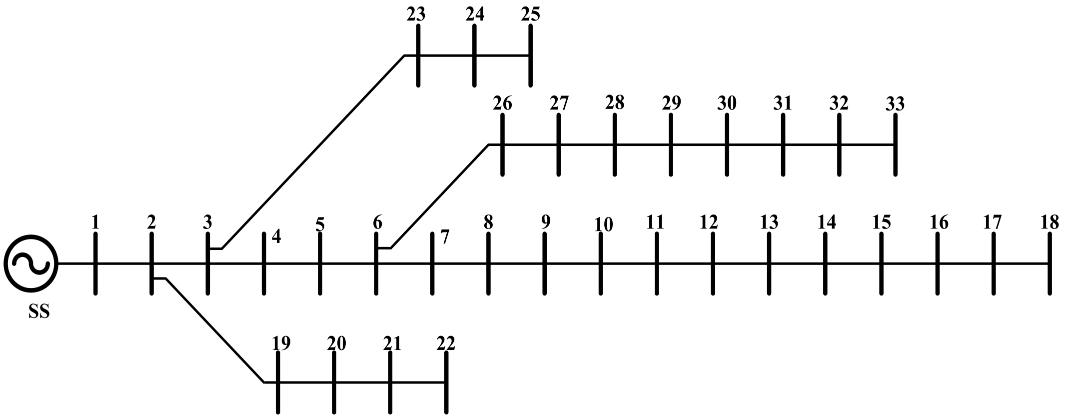


Figure 3.1: Single line diagram of 33 node RDN

3.2.1 Base Case Comparison

To obtain steady state power flow and losses in the networks, load-flow analysis has been done in this work as well as in the researches used to obtain comparative study.

Due to difference of methodologies, the results differ from one another. In the following Table 3.1, the base case load-flow results are given.

Due to the differences in load-flow approach, DG sizes given in the existing works for each cases are used in the load-flow method used in this work and losses are recalculated and shown in Table 3.2, Table 3.3 and Table 3.4.

Table 3.1: Simulation Results for one type 1 DG placement on 33 node RDN

Methods **Value**	**Proposed Method**	**Das *et al.* (2016)**	**Kansal *et al.* (2016)**
Real Power Loss (kW)	202.8617	202.6711	211

3.2.2 Optimal Seizing and Placing

In the shown network, up to three DG units are placed and results are compared with existing researches.

1 DG Placement

Table 3.2: Simulation Results for one type 1 DG placement on 33 node RDN

Methods **Parameters**	**Proposed Method**	**Kansal *et al.* (2016)**
Node No.	6	6
DG Size (kW)	2505.68	2490.00

Net Size (kW)	2505.68	2490.00
Real Power Loss (kW)	-	111.17
	106.0773	**106.0810**
Reactive Loss (kVAr)	79.4026	-
	-	-
Minimum Voltage (p.u)	0.93205	0.93207
VSI	0.7557	-
Energy Cost ($)	55754.22	55756.17
DG Cost ($)	50113.85	49800.25

Measuring parameters for single DG placement on a 33 node RDN is given in Table 3.2. Gathered data is compared with an existing work of same category. A comparative DG cost and energy cost analysis is also presented.

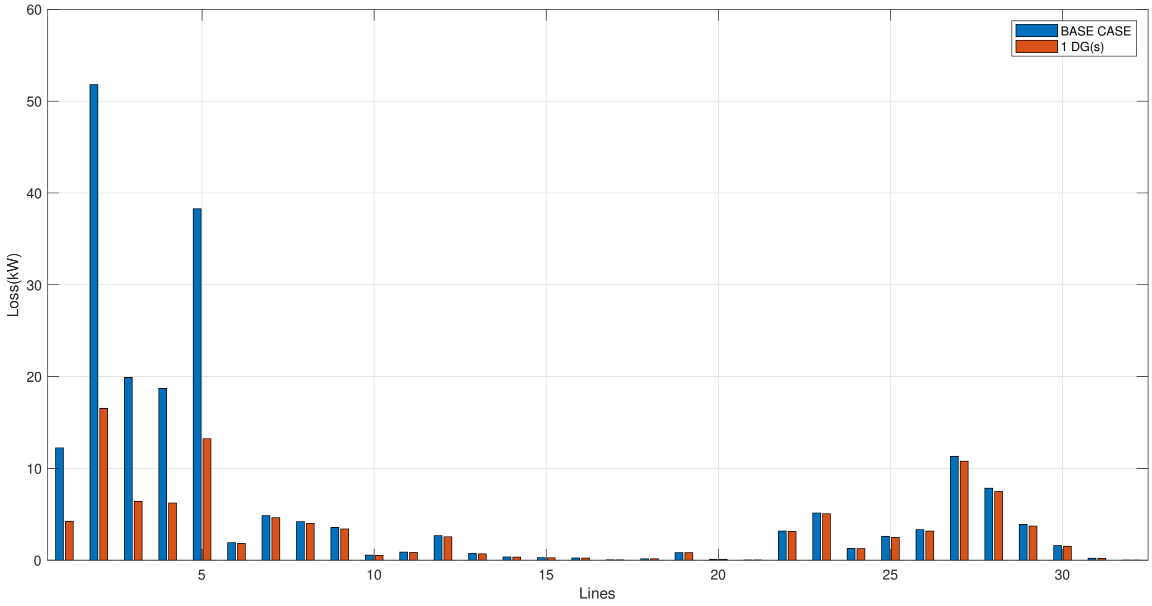


Figure 3.2: Branch wise real power loss reduction after single DG placement

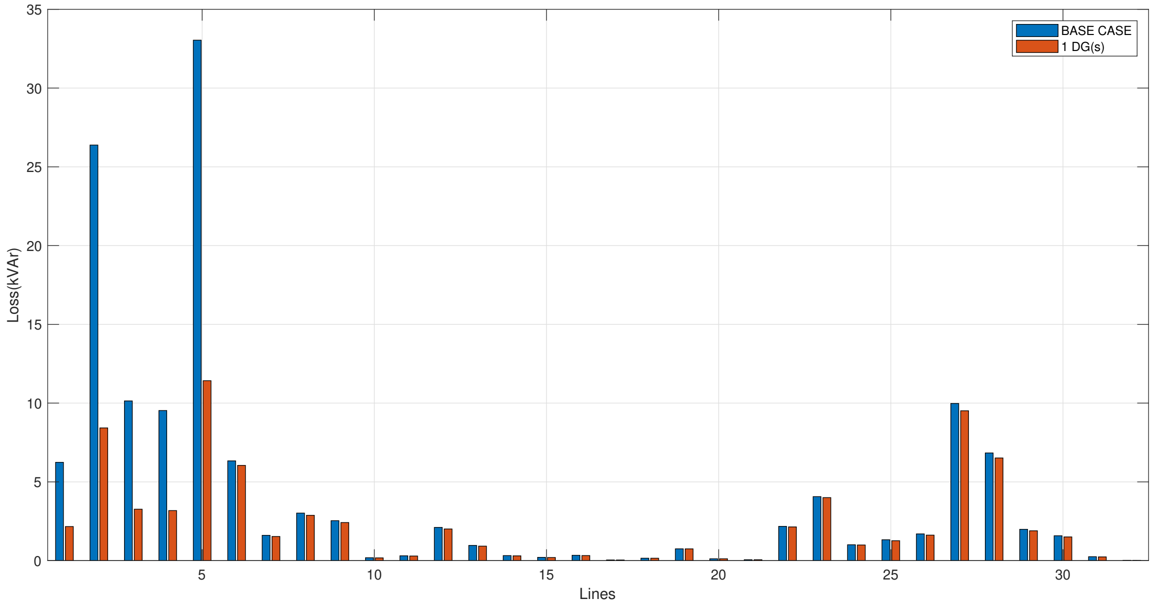


Figure 3.3: Branch wise reactive power loss reduction after single DG placement

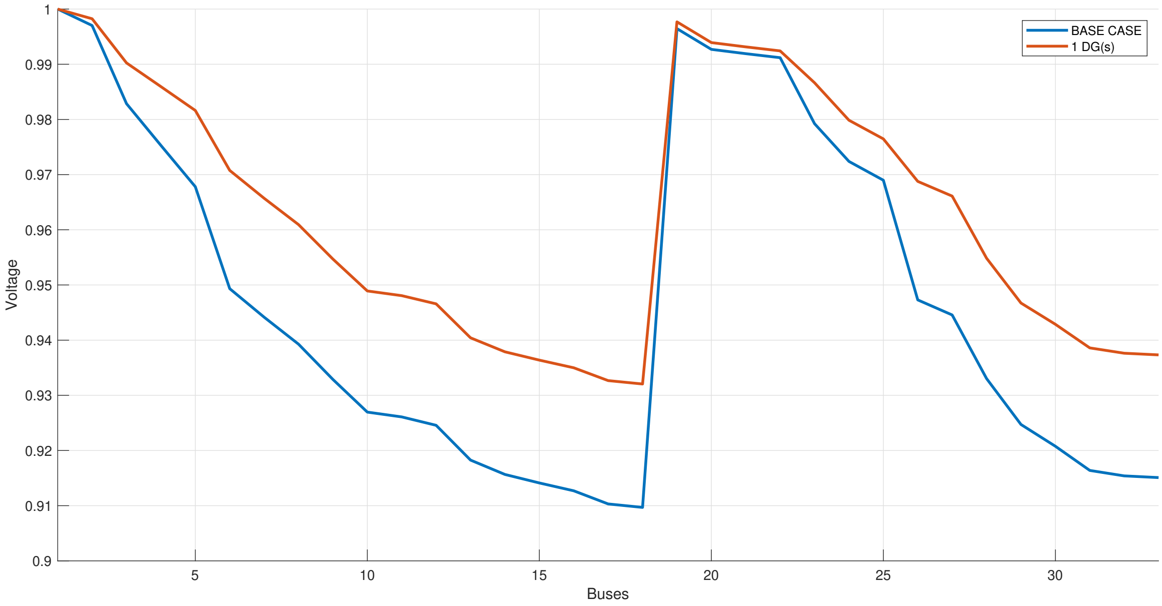


Figure 3.4: Voltage profile improvement after single DG placement

Real power loss reduction, reactive power loss reduction and voltage profile improvement due to single DG placement in the network is graphically presented in

Figure 3.2, Figure 3.3 and Figure 3.4 respectively.

2 DG Placement

Table 3.3: Simulation Results for two type 1 DG placement on 33 node RDN

Methods **Parameters**	**Proposed Method**	**Kansal *et al.* (2016)**
Node No.	30, 13	30, 13
DG Size (kW)	1236.36, 701.23	1110, 830
Net Size (kW)	1937.59	1940.00
Real Power Loss (kW)	-	87.28
	87.03	**87.07**
Reactive Loss (kVAr)	-	-
	59.34	-
Minimum Voltage (p.u)	0.9423	-
VSI	0.7891	-
Energy Cost ($)	45742.96	45763.99
DG Cost ($)	38752.05	38800.25

Measuring parameters for double DG placement on a 33 node RDN is given in Table 3.3. Gathered data is compared with an existing work of same category. A comparative DG cost and energy cost analysis is also presented.

Real power loss reduction, reactive power loss reduction and voltage profile improvement due to three DG placement in the network is graphically presented in Figure 3.5, Figure 3.6 and Figure 3.7 respectively.

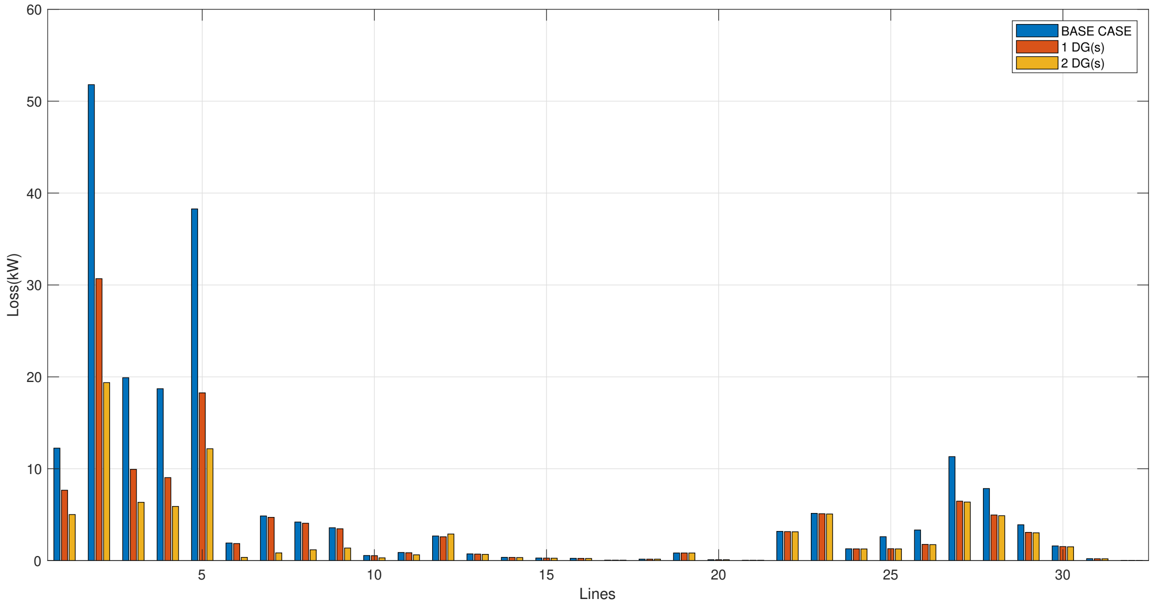


Figure 3.5: Branch wise real Power Loss reduction after double DG placement

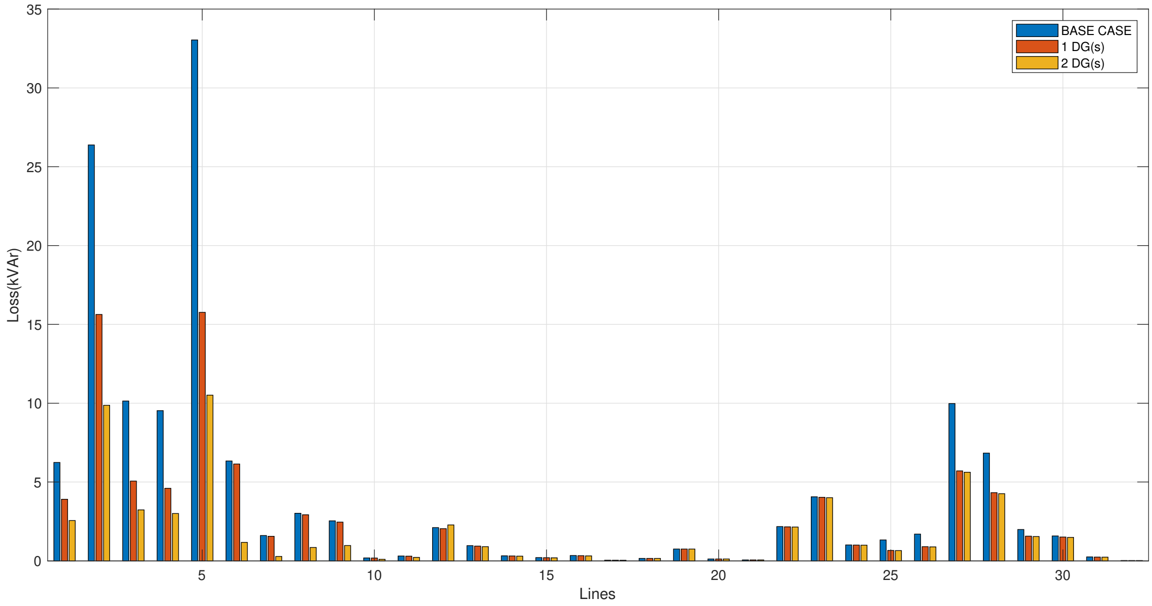


Figure 3.6: Branch wise reactive Power Loss reduction after double DG placement

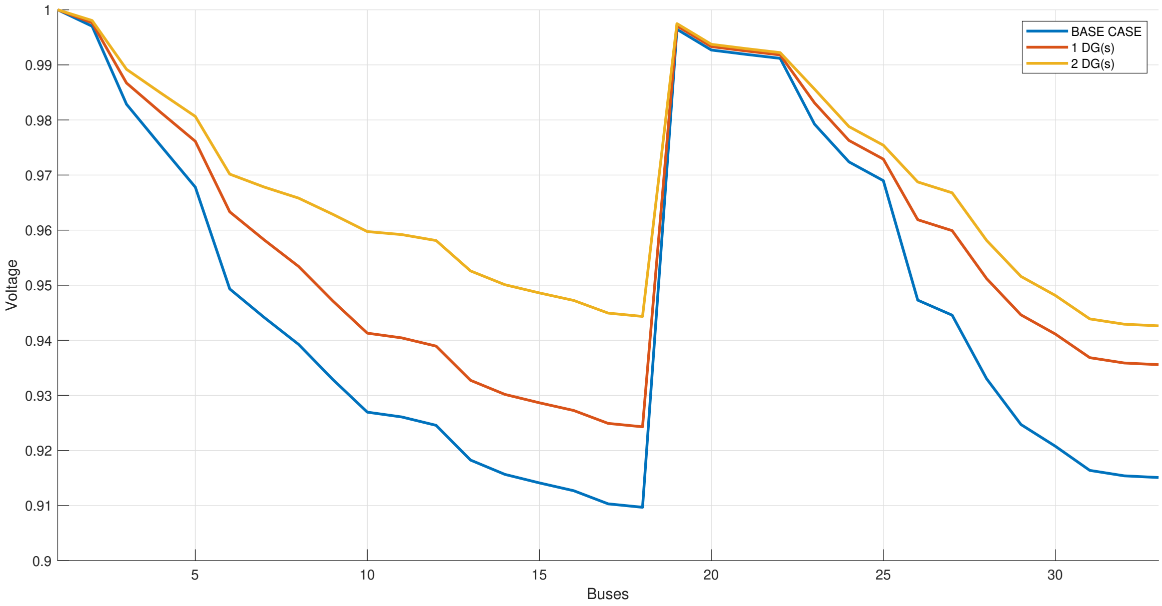


Figure 3.7: Voltage Profile improvement after double DG placement

3 DG Placement

Table 3.4: Simulation Results for three type 1 DG placement on 33 node RDN

Methods / **Values**	**Proposed Method**	**Das *et al.* (2016)**	**Kansal *et al.* (2016)**
Node No.	30, 24, 14	30, 24, 14	13, 24, 30
DG Size (kW)	1121.38, 1091.32, 684.75	1071.42, 1099.44, 753.98	790.00, 1070.00, 1010.00
Net Size (kW)	2897.45	2924.84	2870.00
Real Power Loss (kW)	-	71.46	72.89
	72.25	**72.58**	**72.66**
Reactive Loss (kVAr)	54.41	-	-
		-	-
Minimum Voltage (p.u)	0.9474	-	-

VSI	0.8121	-	-
Energy Cost ($)	37974.6	38148.048	38190.09
DG Cost ($)	57949.25	58497.05	57400.25

Measuring parameters for three DG placement on a 33 node RDN is given in Table 3.4. Gathered data is compared with an existing work of same category. A comparative DG cost and energy cost analysis is also presented.

Real power loss reduction, reactive power loss reduction and voltage profile improvement due to three DG placement in the network is graphically presented in Figure 3.8, Figure 3.9 and Figure 3.10 respectively.

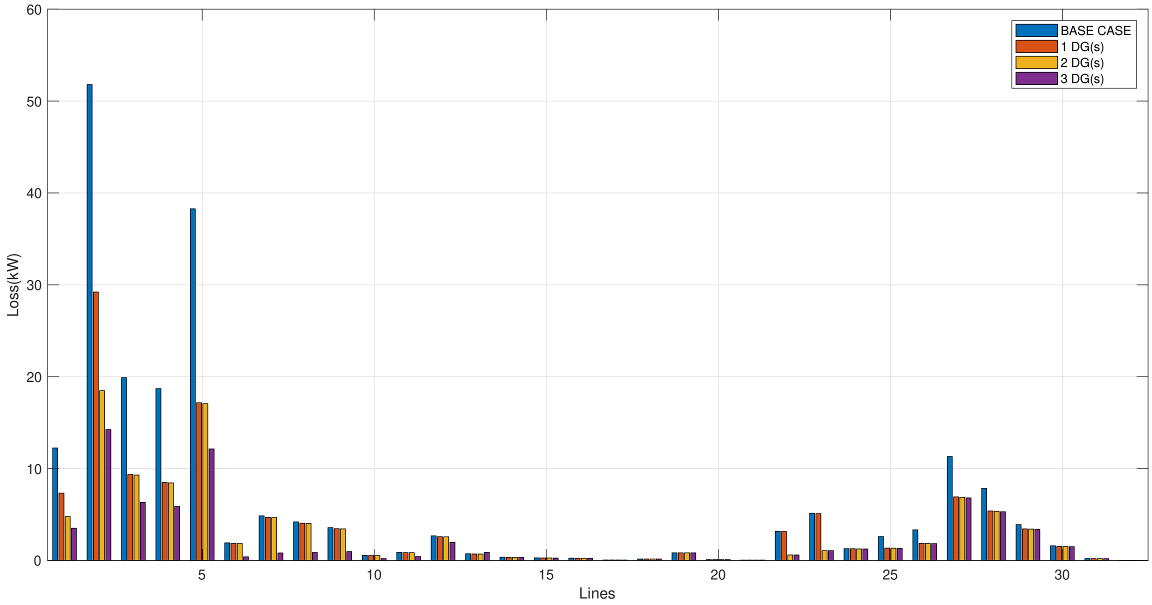


Figure 3.8: Branch wise real Power Loss reduction after three DG placement

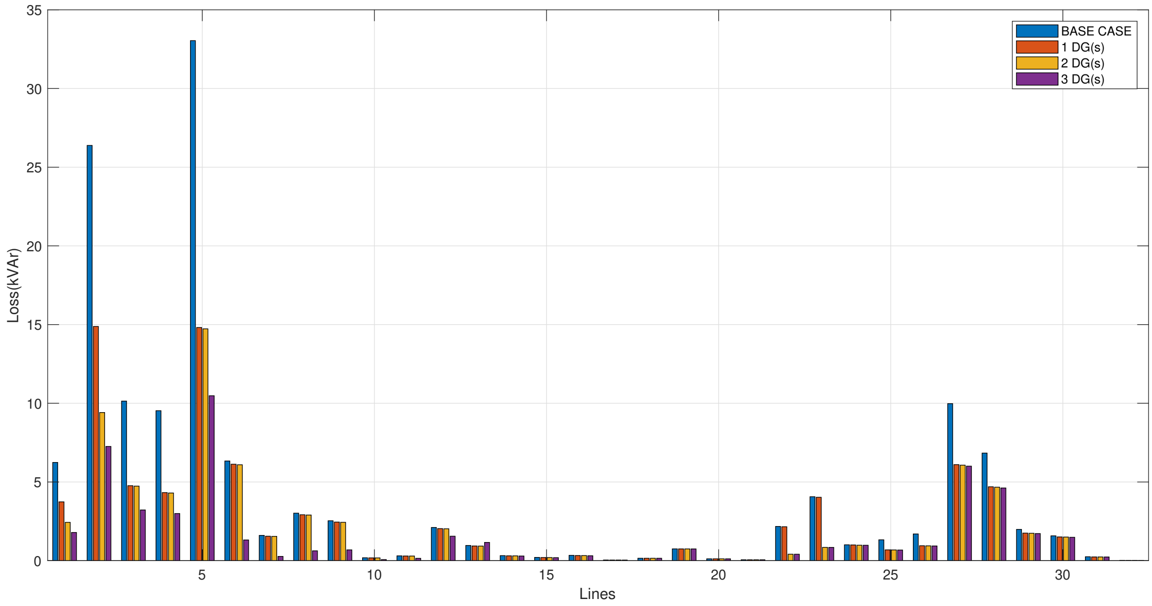


Figure 3.9: Branch wise reactive Power Loss reduction after three DG placement

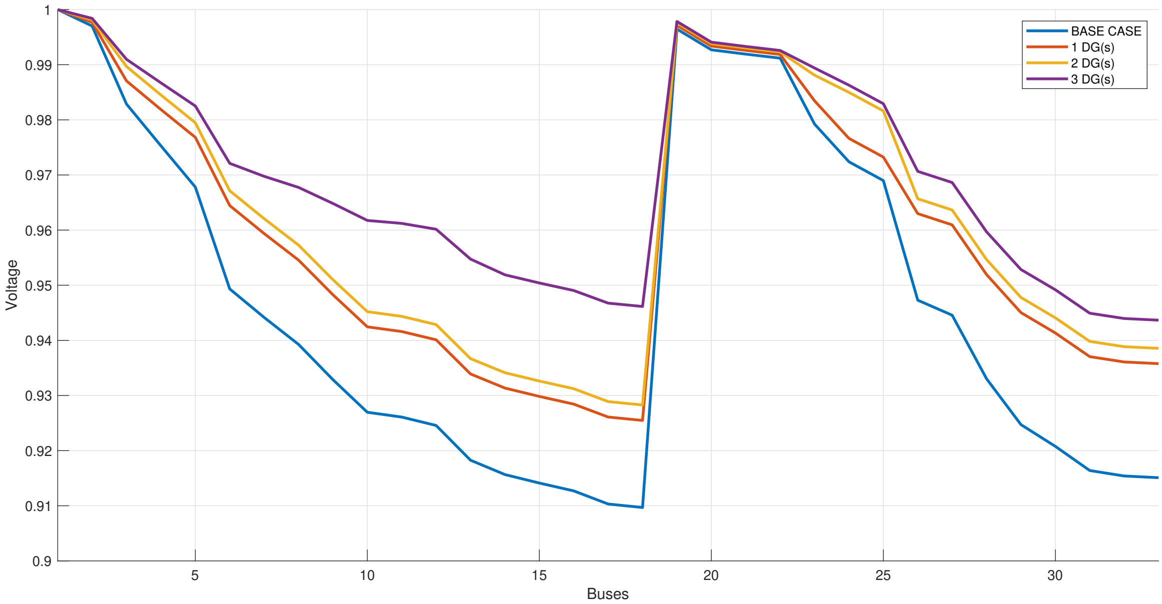


Figure 3.10: Voltage Profile improvement after three DG placement

3.3 69 Node RDN

Figure 3.11 shows the schematic of IEEE 69 node test network. The network has base voltage level of 12.66 kV and base power of 100 MVA. The bus and line data of the network is given in Appendix B.

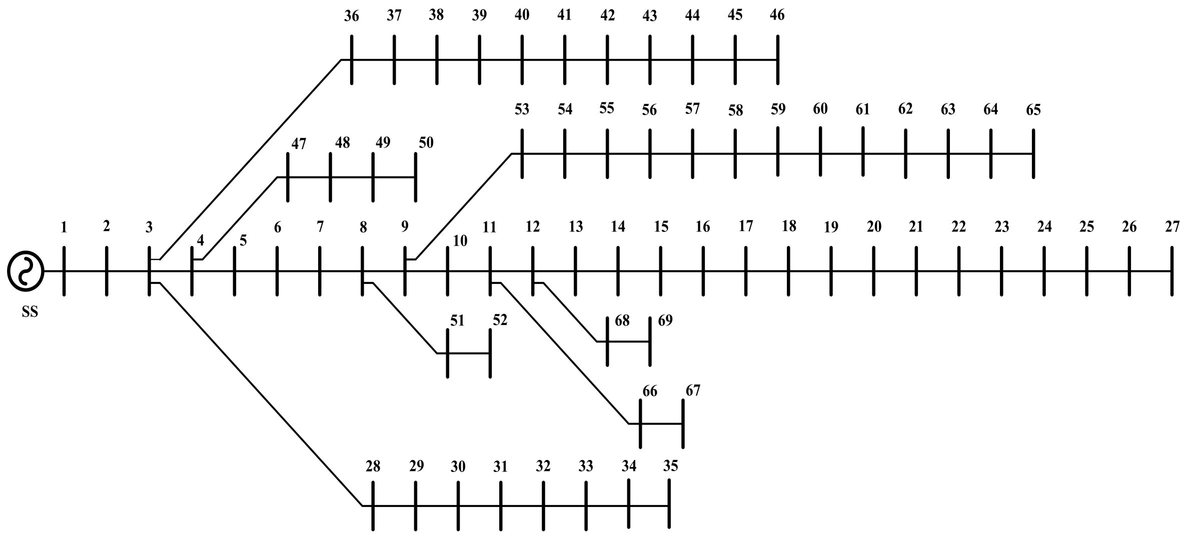


Figure 3.11: Single line diagram of 69 node RDN

3.3.1 Base Case Comparison

Due to the differences in load-flow approach, in the following Table 3.5, the base case load-flow results are given. DG sizes given in the existing works for each cases are used in the load-flow method used in this work and losses are recalculated and shown in Table 3.6, Table 3.7 and Table 3.8.

Table 3.5: Comparison of base case load flow data for 69 node RDN of proposed method and existing methods

Methods / **Value**	**Proposed Method**	**Das *et al.* (2016)**	**Kansal *et al.* (2016)**
Real Power Loss (kW)	225.3132	225.0028	225.00

3.3.2 Optimal Seizing and Placing

In the shown network, up to three DG units are placed and results are compared with existing researches.

1 DG Placement

Table 3.6: Simulation Results for one type 1 DG placement on 69 node RDN

Methods **Parameters**	**Proposed Method**	**Kansal *et al.* (2016)**
Node No.	61	61
DG Size (kW)	1846.40	1810.00
Net Size (kW)	1846.40	1810.00
Real Power Loss (kW)	-	83.37
	84.64	**84.70**
Reactive Loss (kVAr)	-	-
	42.12	42.21
Minimum Voltage (p.u)	0.9456	-
VSI	0.8006	-
Energy Cost ($)	44486.784	44518.32
DG Cost ($)	36928.25	36200.25

Measuring parameters for single DG placement on a 69 node RDN is given in Table 3.6. Gathered data is compared with an existing work of same category. A comparative DG cost and energy cost analysis is also presented.

Real power loss reduction, reactive power loss reduction and voltage profile improvement due to single DG placement in the network is graphically presented in

Figure 3.12, Figure 3.13 and Figure 3.14 respectively.

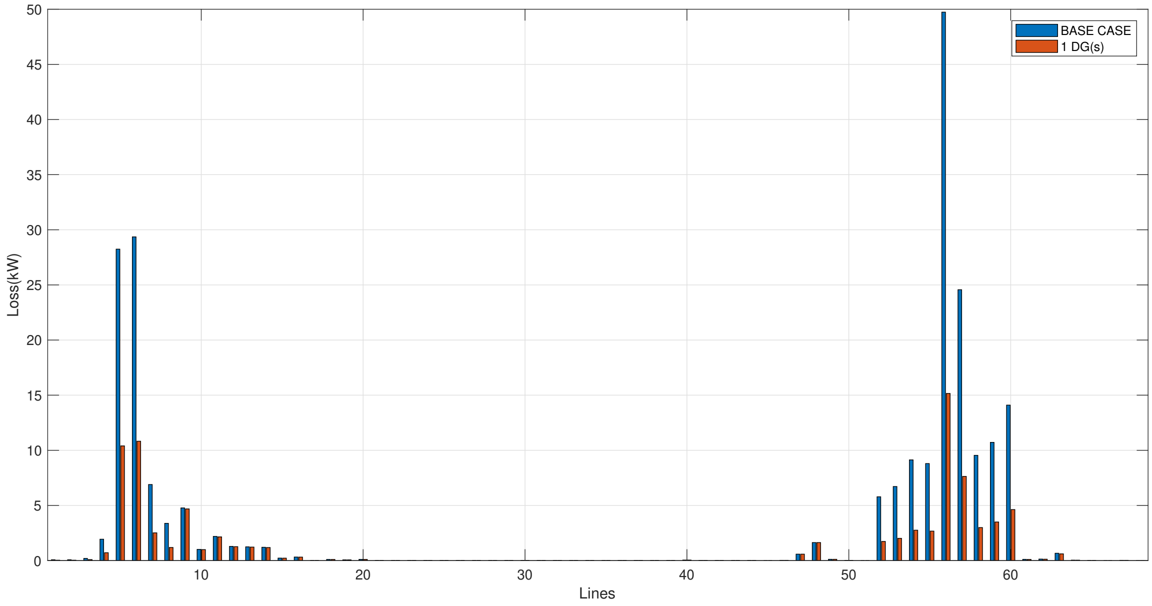


Figure 3.12: Branch wise real power loss reduction after single DG placement

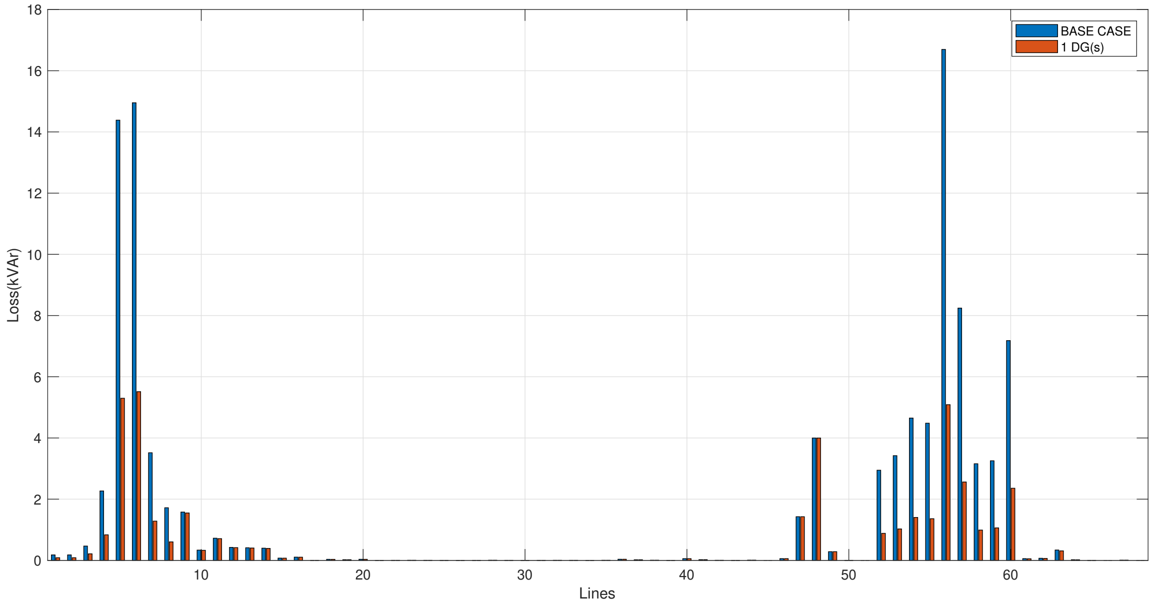


Figure 3.13: Branch wise reactive power Loss reduction after single DG placement

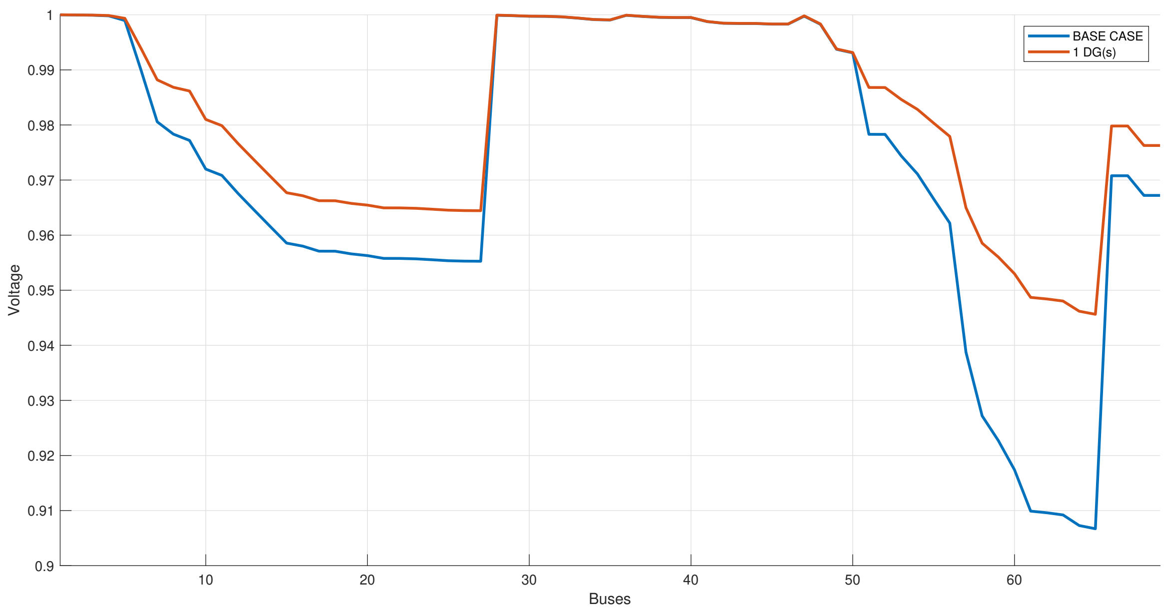


Figure 3.14: Voltage profile improvement after single DG placment

2 DG Placement

Table 3.7: Simulation Results for two type 1 DG placement on 69 node RDN

Methods **Parameters**	**Proposed Method**	**Kansal *et al.* (2016)**
Node Number	61, 17	17, 61
DG Size (kW)	1736.47, 528.73	520.00, 1720.00
Net Size (kW)	2265.20	2240.00
Real Power Loss (kW)	-	71.80
	73.15	**73.19**
Reactive Loss (kVAr)	-	-
	36.55	-
Minimum Voltage (p.u)	0.9443	-
VSI	0.7960	

Energy Cost ($)	38447.64	38468.66
DG Cost ($)	45304.25	44800.25

Measuring parameters for two DG placement on a 69 node RDN is given in Table 3.7. Gathered data is compared with an existing work of same category. A comparative DG cost and energy cost analysis is also presented.

Real power loss reduction, reactive power loss reduction and voltage profile improvement due to single DG placement in the network is graphically presented in Figure 3.15, Figure 3.16 and Figure 3.17 respectively.

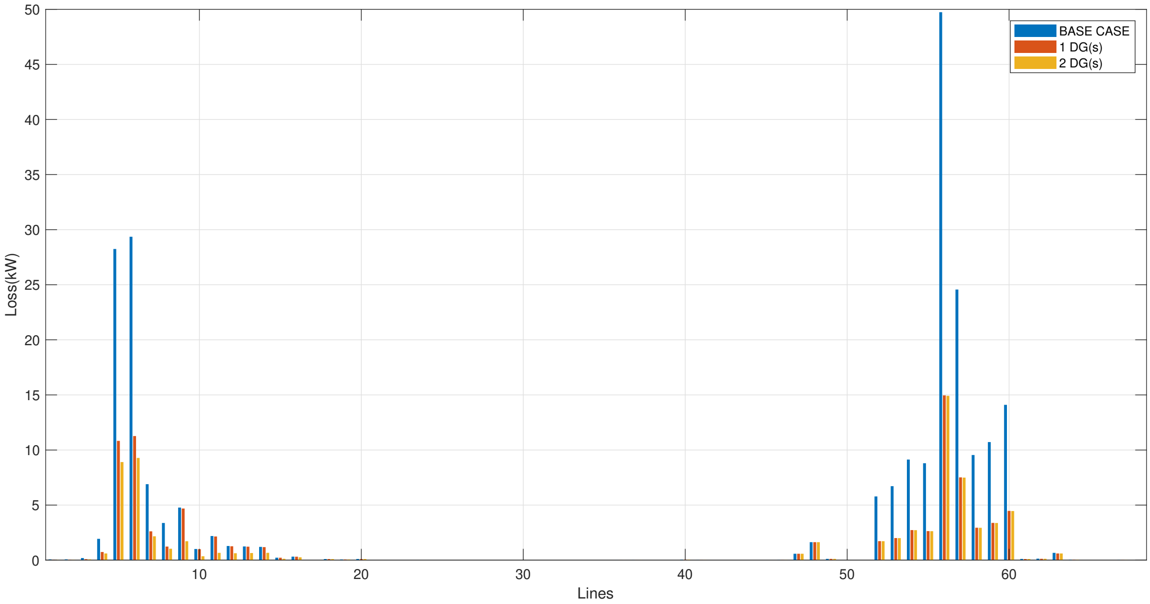


Figure 3.15: Branch wise real Power Loss reduction after double DG placement

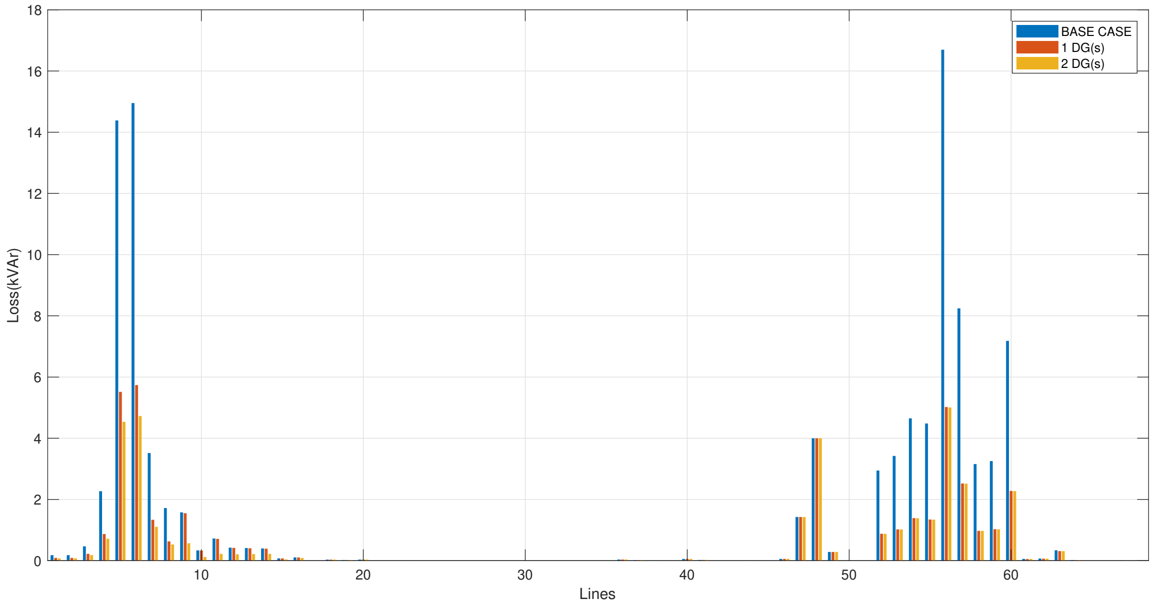


Figure 3.16: Branch wise reactive power loss reduction after double DG placement

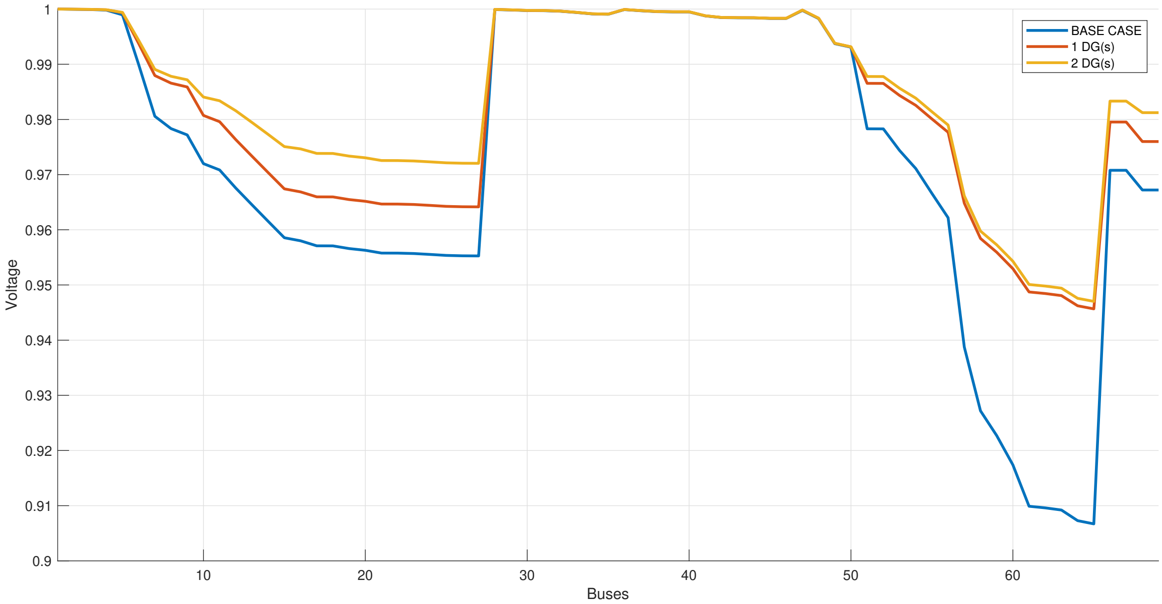


Figure 3.17: Voltage profile improvement after double DG placement

3 DG Placement

Table 3.8: Simulation Results for three type 1 DG placement on 69 node RDN

Methods **Values**	**Proposed Method**	**Das *et al.* (2016)**	**Kansal *et al.* (2016)**
Node Number	61, 18, 11	61, 18, 11	11, 17, 61
DG Size (kW)	1698.47, 351.72 545.15	1719.12, 380.50, 526.70	510.00, 380.00, 1670.00
Net Size (kW)	2595.34	2626.32	2560
Real Power Loss (kW)	-	69.43	69.54
	70.41	**70.98**	**71.09**
Reactive Loss (kVAr)	35.44	-	-
		-	-
Minimum Voltage (p.u)	0.9469	-	-
VSI	0.8141	-	-
Energy Cost ($)	37007.49	37307.08	37364.90
DG Cost ($)	51907.05	52526.65	51200.25

Measuring parameters for three DG placement on a 69 node RDN is given in Table 3.8. Gathered data is compared with an existing work of same category. A comparative DG cost and energy cost analysis is also presented.

Real power loss reduction, reactive power loss reduction and voltage profile improvement due to single DG placement in the network is graphically presented in Figure 3.18, Figure 3.19 and Figure 3.20 respectively.

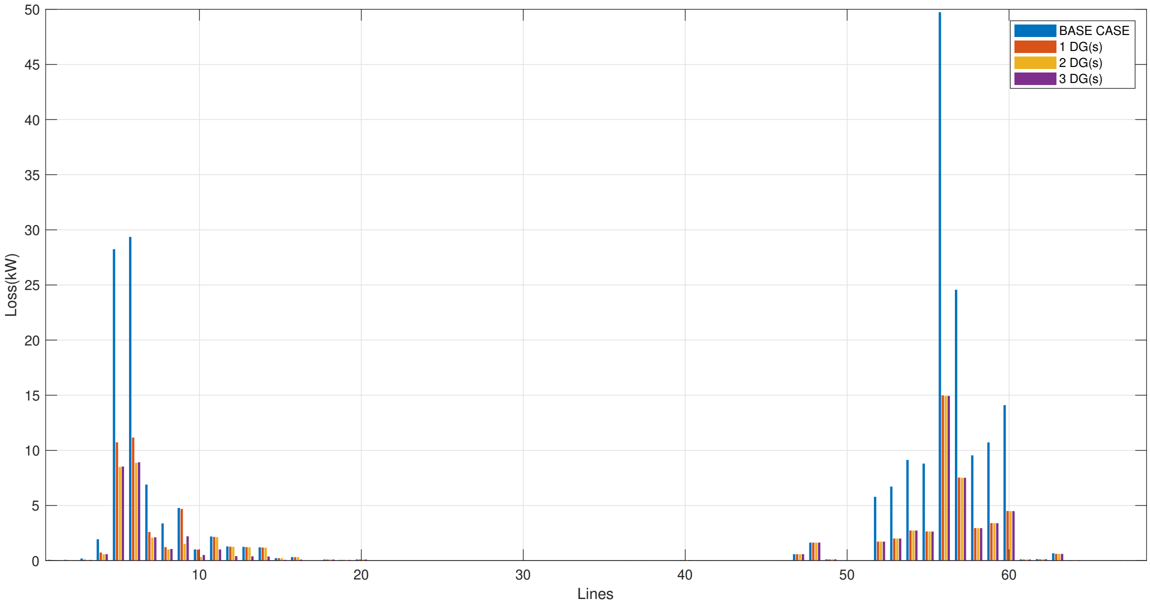


Figure 3.18: Branch wise real Power Loss reduction after three DG placement

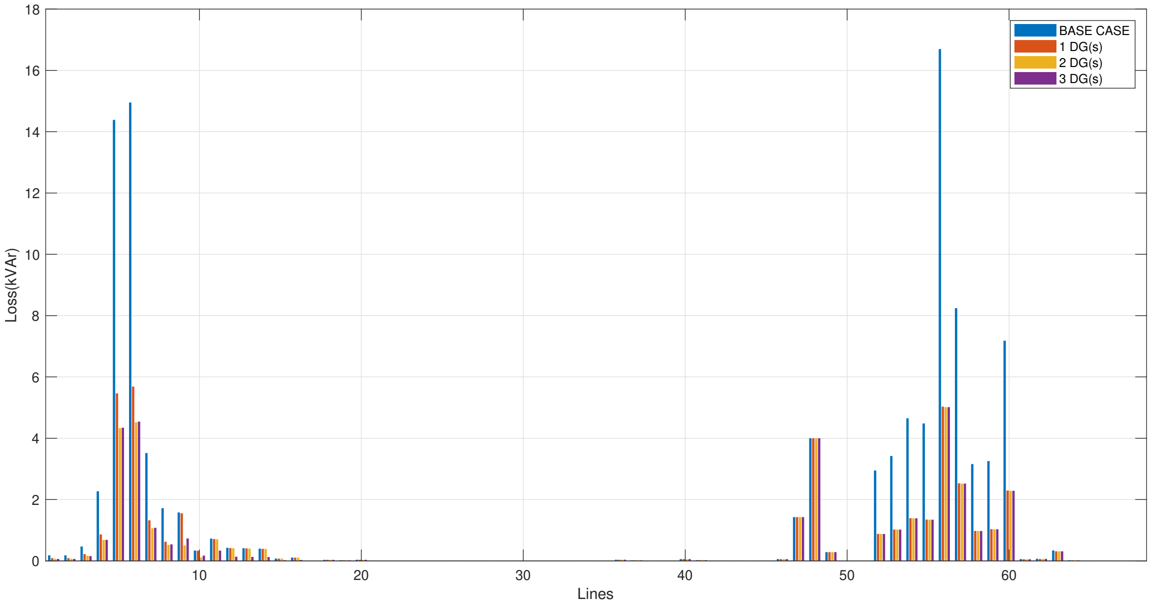


Figure 3.19: Branch wise reactive power loss reduction after three DG placement

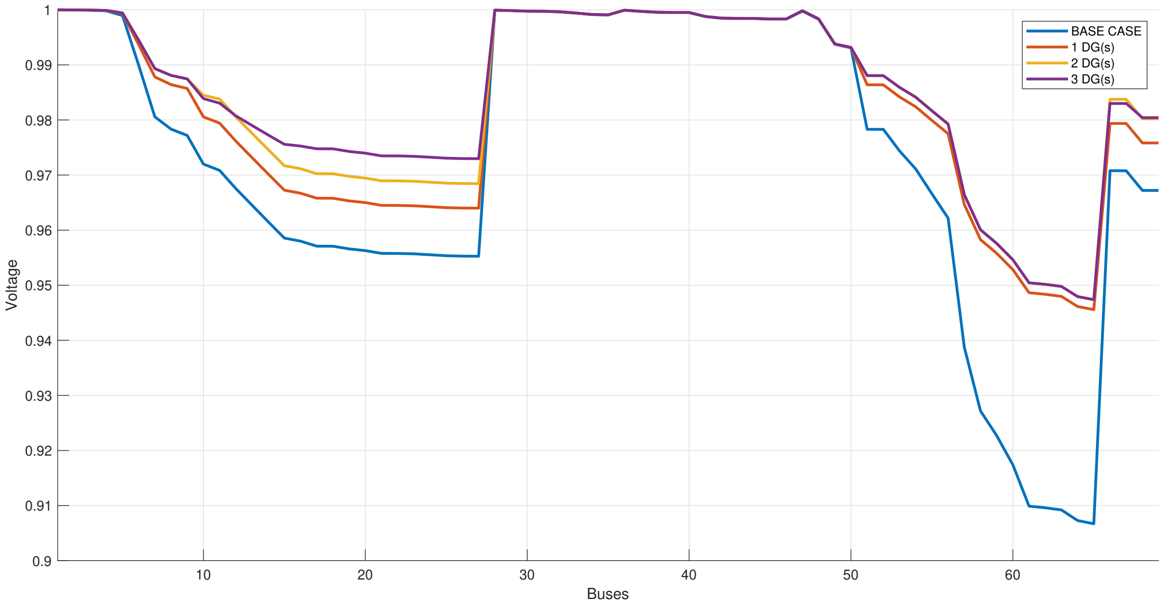


Figure 3.20: Voltage profile improvement after three DG placement

3.4 Conclusion

From the above results, it can be concluded that,

- Jaya Algorithm has been successfully implemented to optimally size DG units in a RDN.
- Real power loss is reduced.
- Voltage profile is improved.
- VSI is also improved to make the system more stable.
- LSF method is capable of finding best locations for DG placement.

3.5 Future Scope

The existing work opens door to various aspects for future research. Some are enlisted below.

- DG placement can be done with consideration of load uncertainty.
- The load growth can be considered and DG placement can be done.
- Existing network structure can be modified if the additional nodes exist and the DG can be placed on the final network configuration.

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APPENDIX A

33 Node RDN

Table A.1: Bus Data and Line data for 33 Node Radial Distribution System

Node Number	**Real Power**	**Reactive Power**	**Line Number**	**Resistance**	**Reactance**
2	100	60	1	0.0922	0.047
3	90	40	2	0.493	0.2511
4	120	80	3	0.366	0.1864
5	60	30	4	0.3811	0.1941
6	60	20	5	0.819	0.707
7	200	100	6	0.1872	0.6188
8	200	100	7	0.7114	0.2351
9	60	20	8	1.03	0.74
10	60	20	9	1.044	0.74
11	45	30	10	0.1966	0.065
12	60	35	11	0.3744	0.1298
13	60	35	12	1.468	1.155
14	120	80	13	0.5416	0.7129
15	60	10	14	0.591	0.526
16	60	20	15	0.7463	0.545
17	60	20	16	1.289	1.721
18	90	40	17	0.732	0.574
19	90	40	18	0.164	0.1565
20	90	40	19	1.5042	1.3554
21	90	40	20	0.4095	0.4784
22	90	40	21	0.7089	0.9373
23	90	50	22	0.4512	0.3083
24	420	200	23	0.898	0.7091

25	420	200	24	0.896	0.7011
26	60	25	25	0.203	0.1034
27	60	25	26	0.2842	0.1447
28	60	20	27	1.059	0.9337
29	120	70	28	0.8042	0.7006
30	200	600	29	0.5075	0.2585
31	150	70	30	0.9744	0.963
32	210	100	31	0.3105	0.3619
33	60	40	32	0.341	0.5302

APPENDIX B

69 Node RDN

Table B.1: Bus Data and Line data for 69 Node Radial Distribution System

Node Number	Real Power	Reactive Power	Line Number	Resistance	Reactance
2	0	0	1	0.0005	0.0012
3	0	0	2	0.0005	0.0012
4	0	0	3	0.0015	0.0036
5	0	0	4	0.0251	0.0294
6	2.6	2.2	5	0.366	0.1864
7	40.4	30	6	0.3811	0.1941
8	75	54	7	0.0922	0.047
9	30	22	8	0.0493	0.0251
10	28	19	9	0.819	0.2707
11	145	104	10	0.1872	0.0619
12	145	104	11	0.7114	0.2351
13	8	5	12	1.03	0.34
14	8	5.5	13	1.044	0.345
15	0	0	14	1.058	0.3496
16	45.5	30	15	0.1966	0.065
17	60	35	16	0.3744	0.1238
18	60	35	17	0.0047	0.0016
19	0	0	18	0.3276	0.1083
20	1	0.6	19	0.2106	0.069
21	114	81	20	0.3416	0.1129
22	5	3.5	21	0.014	0.0046
23	0	0	22	0.1591	0.0526
24	28	20	23	0.3463	0.1145

25	0	0	24	0.7488	0.2475
26	14	10	25	0.3089	0.1021
27	14	10	26	0.1732	0.0572
28	26	18.6	27	0.0044	0.0108
29	26	18.6	28	0.064	0.1565
30	0	0	29	0.3978	0.1315
31	0	0	30	0.0702	0.0232
32	0	0	31	0.351	0.116
33	14	10	32	0.839	0.2816
34	9.5	14	33	1.708	0.5646
35	6	4	34	1.474	0.4873
36	26	18.55	35	0.0044	0.0108
37	26	18.55	36	0.064	0.1565
38	0	0	37	0.1053	0.123
39	24	17	38	0.0304	0.0355
40	24	17	39	0.0018	0.0021
41	1.2	1	40	0.7283	0.8509
42	0	0	41	0.31	0.3623
43	6	4.3	42	0.041	0.0478
44	0	0	43	0.0092	0.0116
45	39.22	26.3	44	0.1089	0.1373
46	39.22	26.3	45	0.0009	0.0012
47	0	0	46	0.0034	0.0084
48	79	56.4	47	0.0851	0.2083
49	384.7	274.5	48	0.2898	0.7091
50	384.7	274.5	49	0.0822	0.2011
51	40.5	28.3	50	0.0928	0.0473
52	3.6	2.7	51	0.3319	0.1114
53	4.35	3.5	52	0.174	0.0886
54	26.4	19	53	0.203	0.1034

55	24	17.2	54	0.2842	0.1447
56	0	0	55	0.2813	0.1433
57	0	0	56	1.59	0.5337
58	0	0	57	0.7837	0.263
59	100	72	58	0.3042	0.1006
60	0	0	59	0.3861	0.1172
61	1244	888	60	0.5075	0.2585
62	32	23	61	0.0974	0.0496
63	0	0	62	0.145	0.0738
64	227	162	63	0.7105	0.3619
65	59	42	64	1.041	0.5302
66	18	13	65	0.2012	0.0611
67	18	13	66	0.0047	0.0014
68	28	20	67	0.7394	0.2444
69	28	20	68	0.0047	0.0016

BIBLIOGRAPHY

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