FUZZY BASED DG ALLOCATION FOR LOSS MINIMIZATION IN RADIAL DISTRIBUTION SYSTEM

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled **"Fuzzy based DG Allocation for Loss Minimization in Radial Distribution System"** in the partial fulfillment of the requirement for the degree of **Master of Engineering** in **Power Systems** submitted in Electrical and Instrumentation Engineering department, Thapar University, Patiala is an authentic work carried out under the guidance of **Dr. Smarajit Ghosh**, Professor EIED, Thapar University. It refers other researcher's work, which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, either in part or in full to any other degree to any other university or institute except as reported in text and references.

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(AVIK METIA)

DEDICATED TO MY PARENTS

ABSTRACT

In recent years, the penetration level of distributed generator into a distribution system has been increasing rapidly in many parts of the world due to the liberalization of the electricity markets, constraints on building new distribution and transmission lines and environmental concerns. Technological advances in small generators, power electronics and energy storage devices have accelerated the penetration of DG unit. DG units are smaller generating units, which are placed closer to the point of consumption. The utilization of a DG unit in the system can made many benefits such as power losses reduction, stability enhancement, environmental sustainability and also voltage profile improvement. The impact of DG unit on the system depends on the size and location of DG unit. Therefore, it is very important to obtain the optimal size and site for DG placement. This thesis work focuses on the power loss minimization and voltage profile improvement of a radial distribution network by proper placing a suitable DG unit. A 33-node radial distribution system has been selected as the test system. In this thesis work a fuzzy expert system has been implemented to find the optimal location of DG unit and an analytical method has been implemented to obtain the optimal size of DG to reduce the network power losses. This thesis presents two types of DG allocation in radial distribution system to minimize losses. A comparison has been done for power loss reduction, voltage profile improvement for the two cases and a backward /forward sweep method of load-flow has been used as a load-flow solution methodology.

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NOMENCLATURE

P_L	Total real power loss
z_{ij}	*ij* th element of impedance matrix
$V_i\angle\delta_i$	Complex voltage at the *i* th bus
P_i	Active power injection at *i* th bus
P_j	Active power injection at *j* th bus
Q_i	Reactive power injection at *i* th bus
Q_j	Reactive power injection at *j* th bus
N	Number of buses
V_{imin}	Minimum values of voltage of *i* th bus
V_{imax}	Maximum values of voltage of *i* th bus
V_i	Voltage of *i* th bus
I_{imax}	Maximum permissible value of current in *i* th branch
I_i	Current flow in *i* th branch
N_{br}	Number of branches
P_{iG}	Total active power generation at node 'i'
Q_{iG}	Total reactive power generation at node 'i'
P_L	Total active power loss
Q_L	Total reactive power loss
P_{Load}	Total active load
Q_{Load}	Total reactive load
N_{no}	Number of nodes
$V(i)$	Voltage of node 'i'
$V(i-1)$	Voltage of node '(i−1)'
$Z(i)$	Impedance of branch 'i'
$I(i)$	Current flow in branch 'i'
$P_L(i)$	Active power of load connected to node 'i'
$Q_L(i)$	Reactive power of load connected to node 'i'

$R(i)$	Resistance of *i* th branch
$X(i)$	Reactance of *i* th branch
μ_s	DG suitability membership function
μ_p	Power loss factor membership function
μ_v	Voltage index membership function
PF_{dg}	Power factor of DG
P_{dgi}	Real power injection by DG at node 'i'
Q_{dgi}	Reactive power injection by DG at node 'i'
P_{di}	Real power demand at node 'i'
Q_{di}	Reactive power demand at node 'i'
PF_d	Power factor of load

ABBREVIATIONS

DG	Distributed Generators
PV	Photo Voltaic
MT	Micro-Turbine
FC	Fuel Cell
FES	Fuzzy Expert System
PSO	Particle Swarm Optimization
OPF	Optimal Power Flow
ANM	Active Network Management
GA	Genetic Algorithm
EP	Evolutionary Programing
MTLBO	Modified Teaching Learning based Optimization
BSOA	Backtracking Search Optimization algorithm
ABC	Artificial Bee colony
MINLP	Mixed Integer Nonlinear Programing
SA	Simulate Annealing
PLF	Power Loss Factor
VI	Voltage Index

CHAPTER-1

INTRODUCTION

Power system is undoubtedly the oldest and most conventional of the various aspects of electrical systems. In spite of this fact no other system of modern technology is currently experiencing a more dramatic revolution in terms of both technological and industrial structure. Future development and present operation of electric power system must pursue a number of different aims. Above all, the most important aim is to make power system economically efficient, it should provide a reliable energy supply without any detrimental impact on environment. In addition to these global aims there are various supplementary aims and objectives. However, many challenges are faced by the design engineers in designing an economical and stable system that operates efficiently and increasing the reliability of the power system network.

1.1 ELECTRICAL POWER SYSTEMS

The process of generating, transmitting and distributing a large amount of power required for an urban or remote area is highly complex. However, each system, regardless of its complexity, is composed of the same basic elements with the same basic goal: deliver AC power where it is needed by customers or industry.

In general electric utility system is divided into three following categories as shown in Fig. 1.1.

- Generation system
- Transmission system
- Distribution system

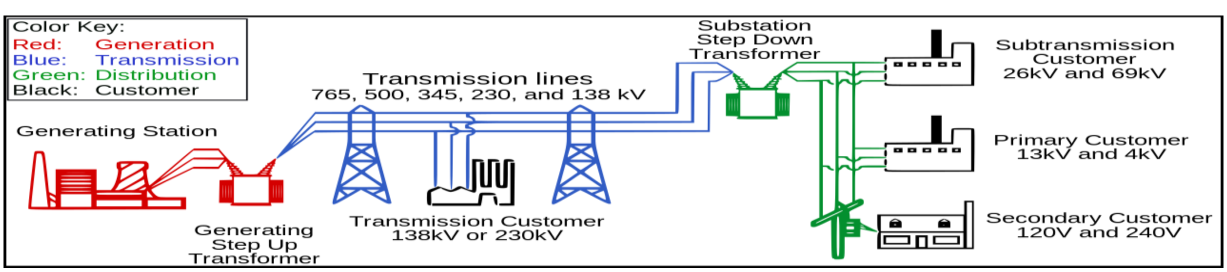


Figure 1.1 Basic structure of an electric power system [1].

1.1.1 Typical Power Network

An understanding of basic design principle is essential in the operation as well as control of electric power systems. Although there is no typical diagram of electric power system but a schematic representation is necessary for understanding the design and control of the electric power system. Figure 1.2 shows a single line diagram of a typical electrical power generation, transmission and distribution system.

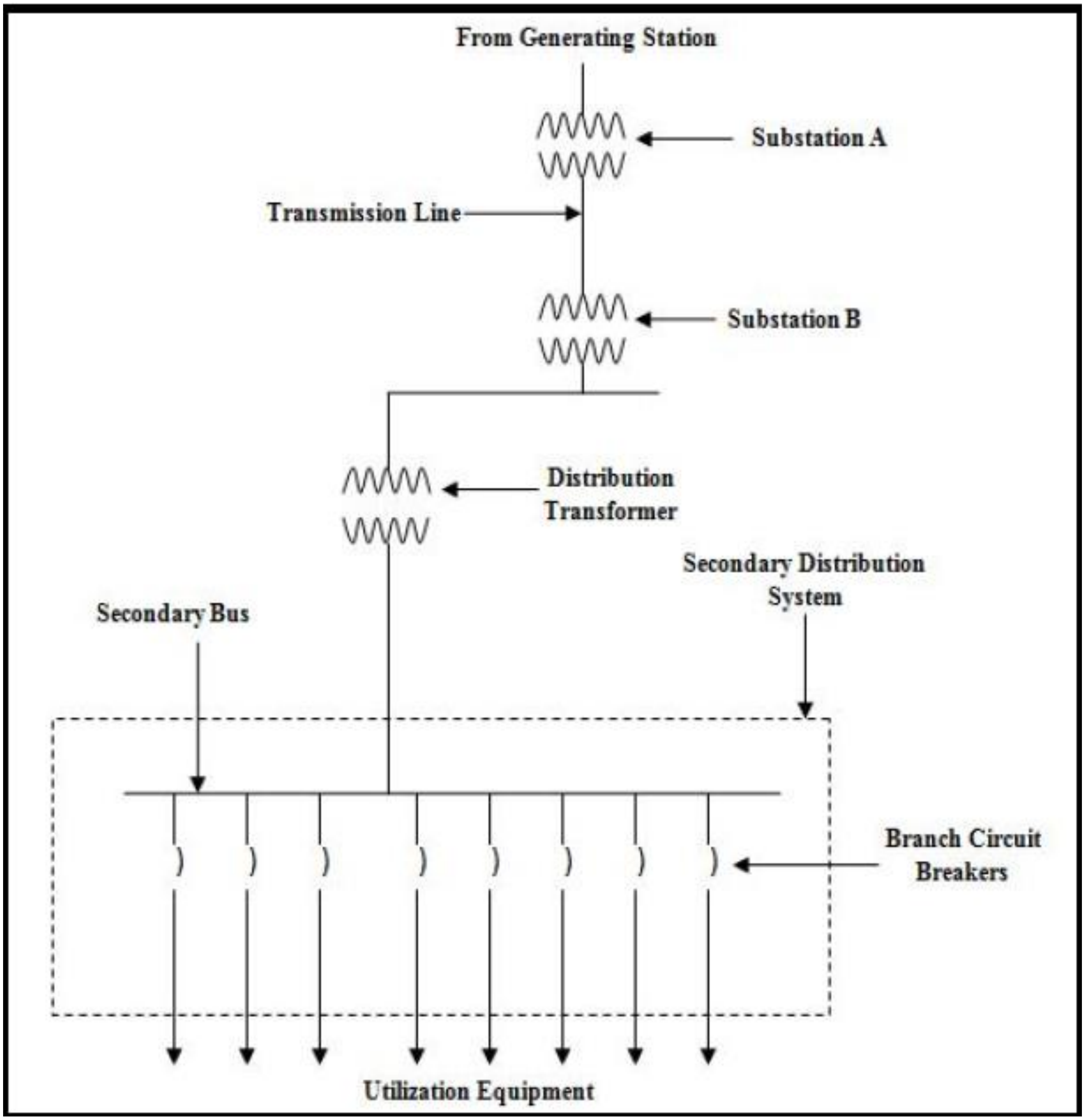


Figure 1.2 Electric power generation, transmission and distribution system.

1.2 OVERVIEW OF DISTRIBUTION SYSTEM

Distribution system can be defined as a tying system between transmission system and consumer service points to provide power to individual consumer premises. Distribution of electric power to consumer is fed at very low level of voltage. In general distribution of electric power is done using distribution network which is consists of substation, transformers, feeders, distributors and the service mains. Figure 1.3 shows the elements of distribution system.

(i) Substation: Distribution system is always fed through substation. These substations has so many numbers of designs based on consideration such as load density, high side voltage and low side voltage, land availability, reliability, load growth, voltage drop, cost and losses. For a typical substation the high side voltage is in the range of 34.5 kV to 345 kV. The average high side voltage is about 6.6 kV to 66 kV. Two or more than two feeders are connected to the low voltage side bus through breaker.

(ii) Distribution Transformers: The purpose of distribution transformer is to step down the primary voltage to a level which can be useful for consumers. Single phase transformers size is in the range of 10 kVA to about 300 kVA out of which 25 kVA and 37.5 kVA sizes are the most common transformer size used for residential customers. In India the secondary transformer voltage is in the range of 220-240 V. Low wattage devices such as lights are connected in line-to-neutral with both the sides of transformer's secondary and high wattage devices such as electric ovens, cloth dryers etc. are connected with the approximate voltage of 240 V.

(iii) Feeders: A feeder is essentially a conductor which is used to connect the sub-station to the area where power is to be distributed. Generally, no tapping are taken from the feeder so that the current throughout the feeder remains same. The most important consideration in the design of a feeder is its current carrying capacity.

(iv) Distributor: A distributor is a conductor which is used to transfer power from distributor to consumer centers from the distributors. From the distributors tappings are taken to supply consumers. In Fig. 1.3 AB, BC, CD and DA are the distributors. The current through a distributor is not a constant value because tappings are taken at various points along its length. At the time of designing a distributor, voltage drop along its length is taken as the main consideration since the statutory limit of voltage variations is ± 10% of rated value of the consumer's terminals.

(v) Service mains: Service mains are the cables between the distributors and the consumer premises.

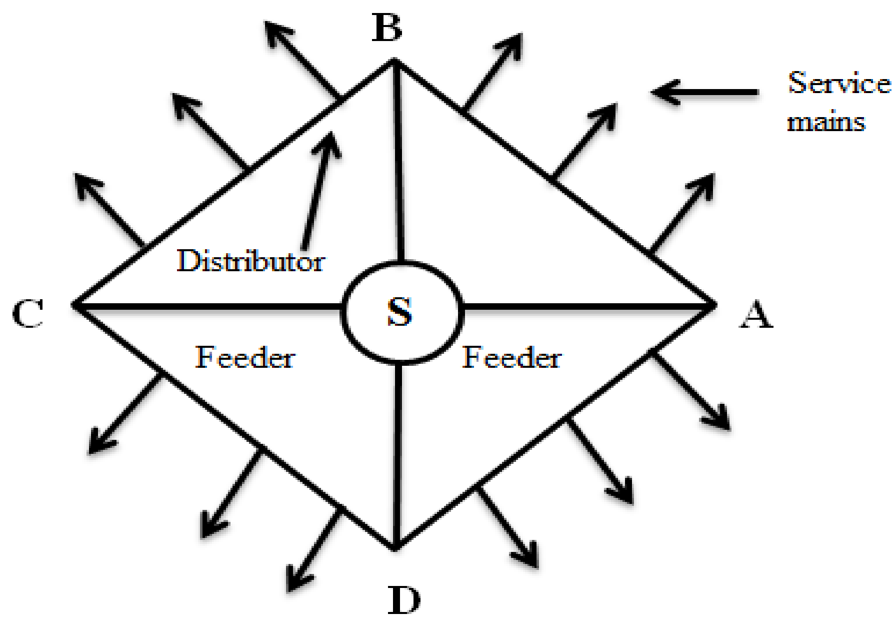


Figure 1.3 Elements of distribution system.

1.3 CLASSIFICATION OF DISTRIBUTION SYSTEM

A distribution system can be classified in the following way

(i) Nature of current: According to the nature of current distribution system can be classified into two categories they are as follows

(a) AC distribution system.

(b) DC distribution system.

AC distribution system is generally employed as compared to DC distribution system because of its simplicity and economy.

(ii) Type of construction: According to the type of construction distribution system is classified into two

(a) Overhead system

(b) Underground system

Generally overhead system is used for distribution because it is 5 to 10 times cheaper than the underground system. Underground system is used there where overhead system is impracticable and limited by local constraints.

(iii) Scheme of connection: All distribution of electrical energy is done based on constant voltage. According to the scheme of connection distribution system is classified into three sub categories as follows

(a) Radial system.

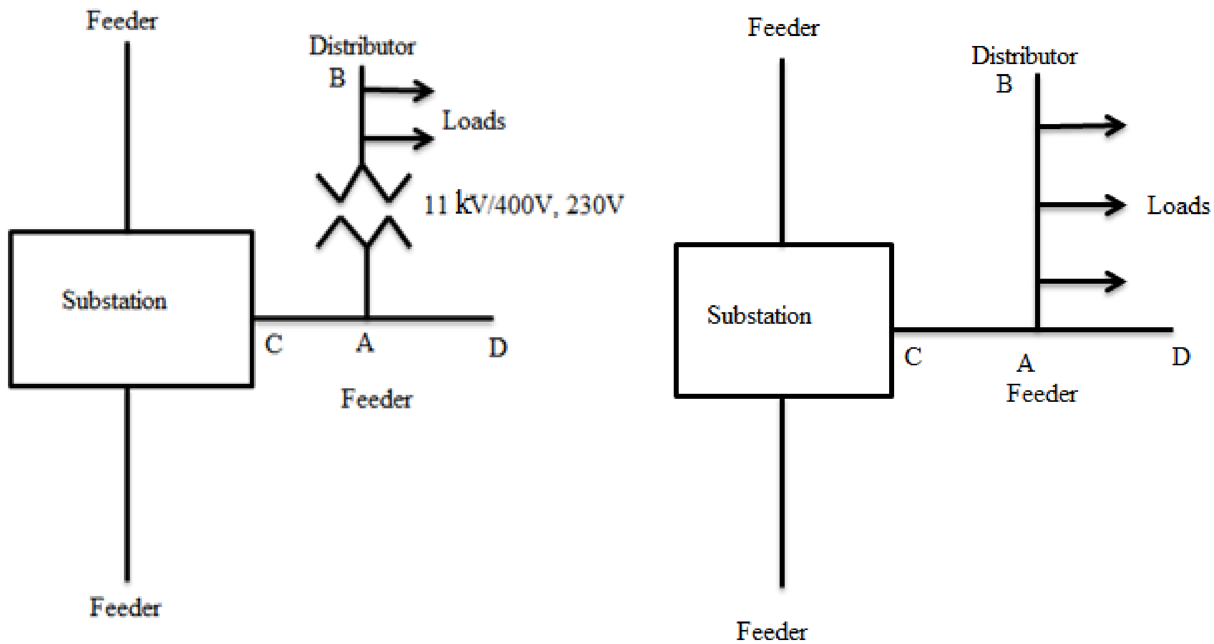
(b) Ring main system.

(c) Inter-connected system.

1.4 CONNECTION SCHEME OF DISTRIBUTION SYSTEM

All power distribution systems are designed based on constant voltage criterion. The connection scheme of distribution systems are classified in the following categories

1.4.1 Radial System: In a radial distribution system separate feeders are radiating from a single substation and feed the distributors at one end only. Figure 1.4 (a) and Fig.1.4 (b) shows the DC radial distribution system and AC radial distribution system respectively. In this system primary feeders take power from the distribution substation and fed to the load areas by sub-feeders and lateral branches. It is basically used in sparsely populated area. This scheme of connection is simple and less expensive as compared to other connection. A radial distribution system has only one source of energy for a group of consumers. Figure 1.4 (a) shows a single line diagram of a DC radial distribution system where a feeder CD supplies a distributor AB at point A. So it is clear that the distribution system is fed from one point i.e. A.



(a) DC radial distribution system (b) AC radial distribution system

Figure 1.4 Radial distribution systems.

This is the simplest and less expensive distribution connection scheme. However this connection scheme suffers from the following drawbacks:

(i) The end of the distributor as compared to nearest of the feeding point will be heavily loaded.

(ii) The consumers should dependent on single distributor and single substation. If there is a fault occurred then who are on the end of the distributor must experiences cut-off of power supply.

(iii) The distributors who are at the far end of distributor are subjected to serious voltage fluctuation when there is a change of load.

1.4.2 Ring Main System: In this system the primaries of distribution transformers make a loop (or ring). The loop circuit starts from substation bus bars and make a loop through the area to be served and return to the substation again. Figure 1.5 shows single line diagram of a ring main distribution system where substation supplies to closed feeders LMNOPQRS. M, O and Q are the different points through which distributors are fed. Ring main distribution system is more expensive as compared to radial distribution system. However these connection arrangement is more reliable and convenient to those consumers, where continuity of power is important such as medical centers, railways etc. In the loop system circuit breakers sectionalize the loop on both sides of distribution transformer which is connected to the loop. The fault is cleared by the circuit breaker nearest to the loop and the power is supplied other way by the loop without interruption of most of the connected loads.

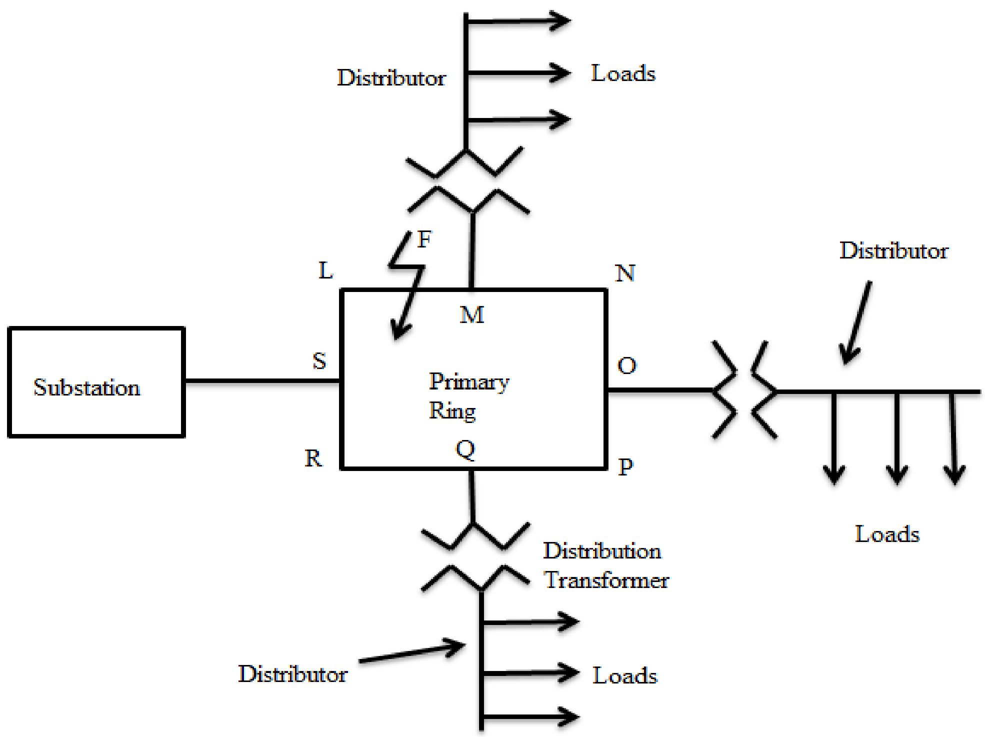


Figure 1.5 Ring main distribution system.

The ring main distribution system has the following advantages:

(a) It causes very less fluctuation of voltage at the consumer's terminal.

(b) The system is very reliable as the power is supplied to the consumers with two feeders. If one feeder is suffering from any fault then the other feeder feed the consumers.

1.4.3 Interconnected System: When feeder ring is energized by more than one generating stations or substations then it is called inter-connected system. As the feeder ring is supplied by more than one generating stations or substations so this arrangement provides best service reliability to the load centers. Power can flow from any substation to the load centers. Service can be extended to more of the load centers without much additional arrangements. As this kind of arrangement requires large amount of equipment so this arrangements are more expensive and complex as compared to radial distribution system. These kinds of arrangements are generally employed in high load density areas or downtown areas. Figure 1.6 represents a single line diagram of interconnected system where closed feeder ring ABCD is supplied by two source of energy S1 and S2 through the point D and C respectively.

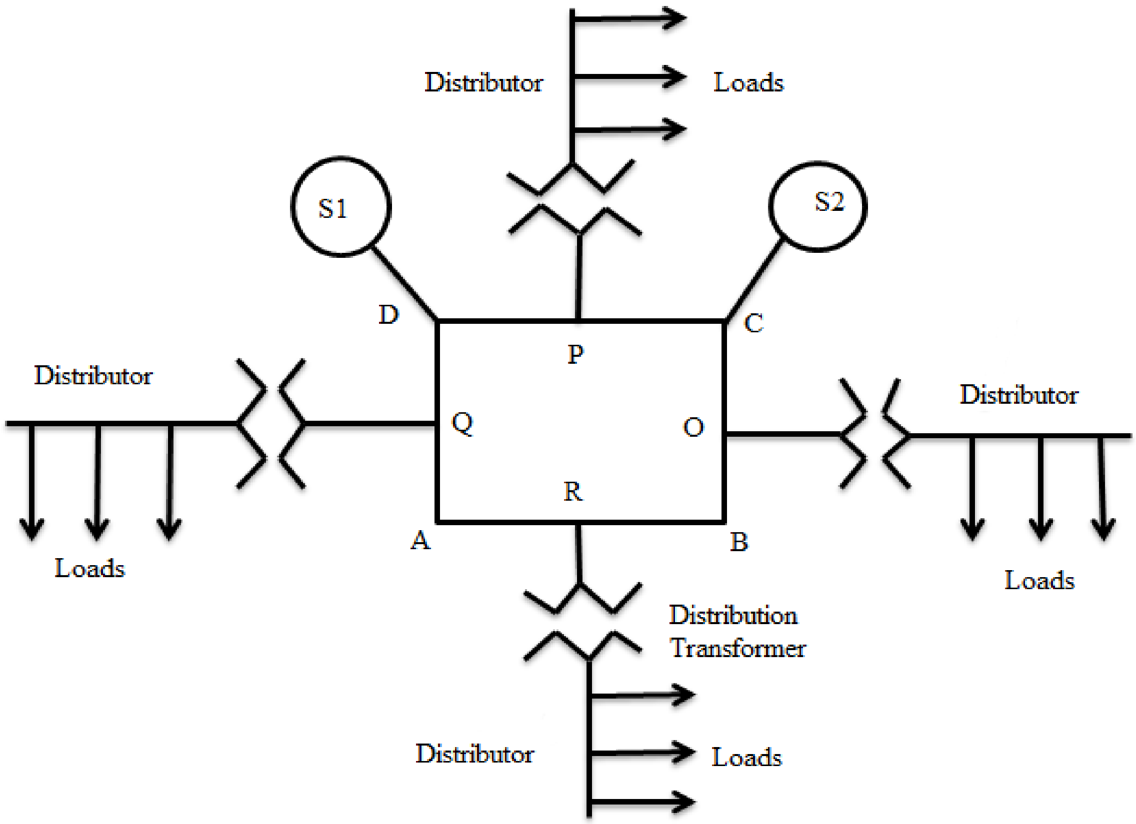


Figure 1.6 Interconnected system.

The advantages of an interconnected system are described as:

(a) It improves the service reliability.

(b) Any area fed by one generating station can also be supplied with power by another generating station during the peak hours and it reduces the generating capacity and improves system efficiency.

1.5 DISTRIBUTED GENERATION

Distributed generation (DG) refers to the very small scale (typically 1 kW to 50 MW) electric power generators that produces electricity located near to the consumers or to the nearby distribution system. Distributed generators are not only limited to synchronous generators, induction generators, reciprocating engines but it also includes micro-turbines (combustion turbines that operate on high efficiency fossil fuels such as oil, natural gas, propane, gasoline or diesel) combustion gas turbines, solar photo voltaic, fuel cells, wind turbines. The DG technologies efficiency for fuel cell is high i.e. 40% to 55% compared to the efficiency of traditional generators whose efficiency is 28% to 35%.

1.5.1 Distributed Generation: Definition

Distributed generation (DG) is a one of the new trends that support the increased energy demands. Different countries used different definitions and notations for distributed generation such as ‘embedded generation’, ‘dispersed generation’ and ‘decentralized generation’. Furthermore a number of definitions have been defined by different organizations such as IEEE, CIGRE, etc.

Distributed generation can be defined as *“Electric generation that feeds into the distribution grid, rather than the bulk transmission grid, whether on the utility side of the meter or on the customer side.”*

(or)

Distributed generation is considered as an electrical source, connected to the power system, in a point very close to/or customer site which is small enough compared with the centralized power plants.

The motivation for using these definitions is that the connection of generation unit to the transmission system is done traditionally by the industry. However the central idea is to locate distributed generator unit close to the load hence on the distribution system or near to the consumer side meter.

1.5.2 Rating of the Distributed Generator

The technical issues related with the distributed generator unit may lead to a significant variation with their ratings. Therefore, it is necessary to categorize them in an appropriate way. The distributed generation units are categorized as follows

Table 1.1 Category of distributed generator unit based on capacity [41]

Categories	Ratings
Micro-distributed generation	~1 W < 5 kW
Small-distributed generation	5 kW< 5 MW
Medium-distributed generation	5 MW< 50 MW
Large-distributed generation	~50 MW< 300 MW

1.5.3 Distributed Generation Technologies

Various DG technologies have been used in power system, some of them have been used for long time and some are newly emerging. The DG technologies are commonly employed to reduce the system losses as well as to improve the voltage profile and efficiency of the system. DG technologies are generally categorized into two types:

(a) Renewable technologies (e.g. solar or photovoltaic, wind turbines etc.)

(b) Non-renewable technologies (e.g. reciprocating engines, micro-turbines, combustion turbines, fuel cells etc.)

The following section provides most of the DG technologies used in the recent years.

1.5.3.1 Solar or Photovoltaic

A solar or photovoltaic is made of a special semiconductor material such as silicon crystal. This photo voltaic cell is designed to convert light energy into the electric energy. It is a special type of diode which is an electric component with positively and negatively charged fields that force the movement of electric current in one direction. When the cell’s surfaces are exposed on light, a portion of the light energy is being absorbed by the semiconductor material. Hence the electrons are allowed to flow freely. By placing metal wires on the two sides of photovoltaic cell, current can be drawn-off for external use. Obviously the current as well as voltage drawn from the cell is low and they must be connected in large series and parallel arrays to obtain useful amount of energy. When the solar cells are exposed to the sunlight they generate 0.5V DC for each solar cell. The PV systems are divided into three sizes based on the power they produce (small size which is less than 10 kW; medium size which is in between 10 kW to 100 kW; large size which is more than the 100 kW). The large size can be employed for distribution level.

1.5.3.2 Wind Turbines

Another source of energy is wind turbines. Modern wind turbines consists of three basic components a tower: on which the wind is mounted; a rotor: This is rotated by the wind; and the nacelle. The nacelle is capsule shape equipment, which helps in housing the equipment. It also includes the generator, which converts mechanical energy into electrical energy. The rotor blades must be light and strong in order to be aerodynamically efficient. The generator used in wind turbines are induction generators mostly. World power capacity had been expanded to 336 GW in June 2014, and the total wind energy generation is 4% of the total worldwide energy usage. Wind turbine manufacturers offer the range of wind turbine from 5 kW to more than 1000 kW. Sometimes these wind turbines are connected with the distribution system and operates as a DG unit. Like solar energy wind turbines are not responsible for emitting greenhouse gases and it helps in exploiting renewable energy sources.

1.5.3.3 Reciprocating Engines

Reciprocating engines has been developed over a hundred years ago and can be implemented as DG technologies integrate with distribution system. Reciprocating engines are subset of internal combustion engines, which also includes rotary engines. Reciprocating engines are currently available in large size, which can be connected with the distribution system. When reciprocating engines are operated as a DG unit, it offers low cost and increased efficiency. However, it has high maintenance cost and high emissions if the engine is diesel fueled.

1.5.3.4 Micro-Turbines

Micro-turbines are scaled down turbine engines, which are integrated with generators and power electronics. Micro-turbines can operate on a wide variety of gaseous or liquid fuels such as natural gas, propane and have extremely low emissions of nitrogen oxides. Electrical efficiency of micro-turbine is in the range of 25% to 30%. So micro-turbines are also very important for utilization as DG unit in distribution system. The capacity of micro-turbine is in the range of 20 kW to 500 kW and they can also give maximum efficiency 80% integrated with combined heat power unit.

1.5.3.5 Fuel Cells

A fuel cell is an electrochemical engine that release energy when hydrogen and oxygen are combined. In principle a fuel cell is operating like a battery and it does not require any recharging. It produces electricity and heat as long as the fuel is supplied to it. Fuel cells are rated generally from 1 W to less than 100 MW. Some efficient fuel cells are Reformed methanol fuel cell (5 W to 100 kW), Proton member exchange fuel cell (1 W to 500 kW) and Molten carbonate fuel cell (less than 100 MW).

1.5.4 Benefits of Distributed Generators

Distributed generation offers several positive potential impacts on distribution system, both economic and technical. Integration of a DG unit with a distribution network gives the following benefits.

- Installed DG units in a distribution network can inject both active and reactive power which further improves voltage profile as well as load factor. This reduces the number of capacitors and voltage regulators and their maintenance costs.
- In a radial distribution system DG units are installed near to the load site that helps in replacing transmission power by injecting DG power, causing a reduction in transmission and distribution losses, which further reduces cost related to loss.
- Increased load growth needs increased amount of generation, which can be fulfilled by installing a DG unit in a distribution system without increasing the generating capacity of the conventional generating unit.
- DGs are flexible devices, DGs can be easily installed near the load side rather than substation where difficulties due to geographical constraints and availability of land are occurred.

- DG technologies are available in a wide capacity range i.e. from few kW to 15 MW, which leads its flexibility to install medium or small distribution networks.
- DG units require a small period of time to install and it reduces the investment risk due to their modular characteristics, which helps them to install easily anywhere such as FC-MT and MT-batteries. Each unit can be operated after its installation and they are not affected by other unit's operation failure. Total capacity can be increased or reduced by adding or removing number of DG unit in distribution system respectively.
- DG unit also helps in service continuity and service reliability as there are many generating units, which can be started very easily as compared to one large centralized unit.
- DG units can be started-up without any external source of electricity that helps in restoring power to the Independent System Operator (ISO) controlled grid following system or local area blackouts.

On the other side a large size of DG unit may lead negative impact on a distribution network if it is not optimally sized and sited. DG size more than the optimal size may increase the line current and that may exceed thermal limit and may lead to harmonic problem, voltage fluctuation and instability of voltage for some customers nearby DG unit. In addition to this a bi-directional power flow due to DG unit causes improper voltage profile and leads to change short-circuit level of distribution network

1.6 OPTIMAL SIZING AND SITING OF DG IN DISTRIBUTION SYSTEM

DG can be a solution of a today's power system network considering environmental and economic challenges. Installing a DG unit influences system voltage profile and losses. However, improper sizing and siting of a DG unit may lead negative impact on distribution system. So it is very important to allocate a DG unit with optimal size and optimal position with respect to the distribution system. Solution techniques of DG placement can be obtained using various optimization methods to get maximum benefits. Several optimization methods have been employed by the researchers for optimal sizing and siting of DG unit. These methods can be classified into two categories: deterministic methods, which includes analytical method and the other is heuristic methods such as Artificial Bee colony algorithm (ABC), Mixed integer non-linear programming (MINLP), Particle swarm optimization (PSO), Ant colony search algorithm, Differential evolution approach (DE), fuzzy expert system (FES). Most of the researchers used all these optimization methods to reduce system losses, some of them also employed these methods to improve voltage profile, reliability and to reduce overall cost of the system.

1.7 RESEARCH GAP

Literature survey of the previous research work regarding the effect of distributed generation in distribution system has been carried in **Chapter 2**. There is a still possibility to obtain optimum location of DG unit to be placed in radial distribution system using fuzzy expert system and a suitable analytical method can be implemented to obtain optimal size with less number of iteration.

1.8 PURPOSE AND CONTRIBUTIONS OF THIS RESEARCH WORK

The purpose of the thesis work is to contribute the method for optimal sizing and siting of a DG unit in order to minimize the total power losses as well as to improve the voltage profile of the distribution system. To achieve the purpose, the following steps have been carried out in this Thesis work.

- The load-flow method is run to get the solution of radial distribution network.
- The method for optimal siting and sizing of DG unit is presented. For different problem different optimization techniques are used. In this thesis work fuzzy expert system is chosen for optimal siting of DG unit and an analytical method has been used for optimal sizing of DG unit.

1.9 ORGANIZATION OF THE THESIS

The thesis is organized as follows:

Chapter 1 presents introduction of distribution system, different connection scheme of distribution system. It also presents different distributed generator technologies and benefits of distributed generation in distribution system.

Chapter 2 presents survey of past research works for DG allocation in distribution system.

Chapter 3 presents the problem formulation in terms of mathematical model and solution methodology by providing a suitable method.

Chapter 4 presents the discussion and analysis of the results obtained from the proposed method and compares these results with existing results.

Chapter 5 presents the conclusion and future scope of the thesis work.

CHAPTER-2
LITERATURE REVIEW

DG exploitation is one of the challenging and traditional characteristics in power system to support the increased energy demands. It also supports unidirectional active power flows from the supply end to the load ends. For proper planning and design purposes, many DG resources may uses modular technology, paving the way to the formulation of optimization problems to select the best location and size for higher efficiency. The DG siting and sizing impacts on evolution of the distribution systems.

In the last two decades many researchers had analyzed the effects of the penetration level of different DG technologies in distribution systems on the perspective of annual energy losses, and they showed that inappropriate sizing and siting of DG unit might lead to system losses greater than the losses without DG. So many solution methodologies were proposed to address optimal DG location and sizing.

Rau *et al.* [2] presented a concept of installing dispersed generators in a distribution system for minimization of real power losses, VAr losses and also loading in selected lines. The method was proposed for optimal placement of dispersed resources to maximize the potential benefits.

Kim *et al.* [3] developed a new approach based on Hereford Ranch Algorithm for the dispersed generation planning in a sub-transmission system. The proposed method was used to optimally allocate dispersed generation in a meshed network for maximizing potential benefits. The benefit, which was expressed as performance index, was to minimize the losses. The proposed method was tested on three test system and the results were compared with those of classical genetic algorithm and conventional second order method.

Willis [4] proposed $2/3$ rule for determining DG location and sizing on the radial feeder with uniformly distributed load. The proposed method showed that a DG unit located at $2/3$ distance out on the feeder minimized the MW-miles power flow on the feeder. The concept of zero point was also studied, which helped to characterize the impact of DG unit in a distribution system.

Nara *et al.* [5] implemented a Tabu Search application for the optimal placement of DG unit to reduce the losses in a distribution system. Several techniques like decomposition/coordination techniques were introduced to implement Tabu Search method. From the numerical examples it was found that the calculation results were better than those of the results obtained by using Simulated Annealing (SA) method and the method was applicable to the problem.

Kim *et al.* [6] presented a Fuzzy-GA based approach for the optimal placement of Distributed generators in a distribution system. The objective of this method was reduction of power loss costs with considering number or size of DG and the deviation of bus voltage as a constraint. They proposed a satisfying method to solve constrained multiple objective problems. They also concluded that by using this algorithm a dispatcher could get a compromised or satisfied solution of multi-objectives.

Mao and Miu [7] proposed a new switch placement scheme to improve the system reliability and also to minimize the active and reactive power losses by DG placement. The algorithm presented by them was graph based algorithms and that method was useful for unbalanced distribution system with single or multiple DG units.

Wang and Nehrir [8] suggested an analytical method to compute the optimal location to place a DG unit in radial as well as meshed distribution networks to minimize the power loss of the system. That method was developed for optimal placement of DG unit in a networked system based on bus admittance matrix, generation information and load distribution of the system. The suggested method was quite fast and it was not suffered from any convergence problem.

El-Khattam *et al.* [9] developed a new integrated model to solve distribution system planning problem by using distributed generators. A comprehensive optimization model and planner's experience were integrated to achieve optimal size and site of distributed generation. The proposed framework optimization computation was based on planning cost minimization. The results obtained in this paper showed that DG minimized total system cost of DISCOs; improve the voltage profile of the system, reducing system losses and increasing feeder lifetime by reducing their loading.

Keane and O'Malley [10] proposed a new method, which explained the technical constraints behind the embedded generation projects. In this research paper a new linear programming based method was also developed for optimal placement of embedded generation with these constraints. The final result obtained from these research papers showed that the proper placement and sizing of embedded generation was crucial to accommodate the increasing level of embedded generation on distribution network.

Acharya *et al.* [11] proposed an analytical expression to compute an effective size and also suggested an effective methodology for corresponding optimum location for DG in distribution system to minimize both active and reactive power loss. The proposed analytical expression was based on exact loss formula. This proposed method was efficient for convergence problem and the calculation of losses was fast.

Victor *et al.* [12] formulated an analytical approach to compute annual energy losses variations when different penetration and concentration levels of DG were connected to a distribution network. They also presented that the energy losses variation was a function of DG penetration level.

Teng *et al.* [13] proposed a value based methods to enhance reliability and to obtain benefits for DG placement. The proposed value based method was used to find out best trade-off between costs and advantages of DG placement considering their types, optimal location and optimal size. The generalized formulation was solved using genetic algorithm. Test results showed that with proper size installation and site selection of DG placement was the best method to improve system reliability, reducing system losses in a distribution system.

Gautam and Mithulananthan [14] presented two new methods for optimal placement of distributed generators in a deregulated market. The optimal sizing and siting of DG unit was formulated for the two objectives namely social welfare maximization and profit maximization. The optimal node for DG allocation was achieved on the basis of locational marginal price (LMP). A large reduction in central generation dispatch was observed with high DG penetration.

Hedayati *et al.* [15] suggested a method for optimal placement of DG units in distribution system which was based on the analysis of power flow continuation and a direct method, also determined the most sensitive buses for voltage collapse. The improvement of voltage profile, reduction of power losses, enhancement of power transfer capacity were carried out by the given suggested method. The proposed method could also be implemented for optimal placement of compensators and large size DG units in distribution system.

Gozel and Hocaoglu [16] developed an analytical method based on sensitivity factor for the determination of the optimal size and location of distributed generation in a distribution system to minimize the total power losses. This method was based on analytical method without use of admittance matrix, inverse of admittance matrix or Jacobian matrix. In this research paper the loss sensitivity factor was formulated based on equivalent current injection and this loss sensitivity factor was employed for the determination of optimal size and optimal location of DG unit to be placed in distribution system to minimize losses.

Kumar and Gao [17] suggested a mixed integer nonlinear programming (MINLP) for optimal location and number of distributed generators to be placed in a hybrid electricity market and pool model. Based on real power nodal price and real power loss sensitivity index suitable zone for allocation of distributed generators was obtained. After the identification of suitable zone non-linear approach had been applied to allocate DG in suitable position as well as the number of DG units to be placed in the zone. The non-linear optimization approach consisted of minimization of fuel cost of DG unit and minimization of line loss in the network. They also showed that four DG should be placed in pool model and three DG should be placed in hybrid model to reduce maximum fuel cost as well as line losses.

Atwa *et al.* [18] proposed a probabilistic base planning technique for determining the optimal fuel mix of different types of renewable DG units in order to minimize the annual energy losses in the distribution system. The planning problem was formulated as mixed integer nonlinear programming with an objective function for minimizing the systems annual losses. This method was subjected to lack of accuracy problem when high quality solution was required.

Hung *et al.* [19] successfully developed an analytical expressions based on exact loss formula for finding optimal size and power factor of four type of distributed generator units. The proposed analytical expressions were based on an improvement to the method that was limited to DG type, which was capable of delivering real power only. Three other types could also be identified with their optimal size and location using the proposed method. The method had been tested in three test distribution systems with varying size and complexity. Results obtained in this paper showed that the proposed method could lead optimal solution very fast, and required less computational time as compared to exhaustive load flow method.

Ghosh *et al.* [20] developed a simple method for optimal sizing and optimal placement of generators. A simple conventional iterative search technique along with Newton Raphson load flow method had been implemented on three different bus systems. The objective of this research paper was to lower down both cost and loss very effectively. This paper also focused on optimization on weighting factor, which balanced both cost and the loss factors. It helped to build up desired objectives with potential benefit. It was observed that after the optimal placement and sizing of DG unit the voltage at the load buses were improved and loss was also minimized.

Shukla *et al.* [21] presented a multi-location distributed generation problem to reduce active power losses of the radial distribution system using genetic algorithm based solution. The loss sensitivity to the change in active power injection was used to select optimal node for DG placement. The results obtained in this method showed that with appropriate DG placement energy loss costs were reduced significantly and saving was increased and there was also a noticeable improvement in voltage profile after installation of DG unit. The computational time was dependent on the system size and the number of location in the system.

Ochoa *et al.* [22] suggested a multi-period AC optimal power flow (OPF) based technique for evaluating maximum capacity of new variable distributed generation, which was connected in distribution system in the presence of active network management (ANM) strategies. The active network management (ANM) strategies embedded coordinated voltage control, adaptive power factor, energy curtailment in to the optimal power flow (OPF). The results showed that very high penetration levels of generating capacity was reached by strategically adopting active network management scheme (ANM).

Dent *et al.* [23] explained how voltage step limits influence the amount of DG that could be connected in distribution network. In this method voltage step constraints had been incorporated with the optimal power flow (OPF) based method to determine capacity of the network to accommodate DG unit. The analysis showed that strict voltage step constraint had comparatively more impact on the capability of the network to accommodate DG than the same bound on voltage rise. The results further showed that progressively wider step change gave much more capability to accommodate DG in the network.

Khodr *et al.* [24] presented a probabilistic approach to assist system planning engineers in the selection of distributed generator location considering hourly load changes or the daily load cycle. The location points were weighted according to their load magnitude, and used to calculate best fit probability distribution. The proposed methodology had been applied to a real cases considering three bivariate probability distribution. The application of the proposed method demonstrated the efficiency and effectiveness of the method to solve the problem of DG sizing and siting corresponding to the network in an isolated electric market.

Singh and Goswami [25] suggested a new methodology based on nodal pricing for optimally allocating distributed generator unit for loss reduction and voltage profile improvement. The study was carried out for time variant as well as time invariant loads incorporating single and multiple DG units in existing Indian rural distribution network. The results showed that a small DG unit was more beneficial as compared to the large size DG unit that was not optimally located.

Koutroumpezis and Safigianni [26] presented a suitably modified and optimized method. A real network with already installed DG unit was taken as case study. The problems solved by applying required modification in the network structure. The proposed method was also used to determine the optimal allocation of multiple DG units in the predetermined bus as well as the other buses without changing network structures. The results were suitably extended to obtain estimated network structures.

Akorede *et al.* [27] proposed an effective method to guide electric utility distribution companies in determining the optimal location and appropriate size of DG unit used in distribution system. This proposed approach took care of system constraints, maximizes the system loading margin as well as the distribution companies profit. Authors had used a Fuzzy expert system to convert the objective functions in a single multi-objective function and this multi-objective function was solved by genetic algorithm (GA). The fuzzy controller used in this method had reduced the chance of premature convergence of simple genetic algorithm (GA). The result obtained in this study showed that DG was a viable economic alternative as compared to upgrading substations and feeders facilities whenever incremental cost of serving additional cost was considered.

Abu-Mouti and El-Hawary [28] suggested a new optimization approach using artificial bee colony (ABC) algorithm to obtain optimal size, location and power factor of DG unit to be placed so that the losses of distribution system would be minimized. The ABC algorithm was a new metaheuristic, population based optimization technique, which was inspired by the behavior of honey bee swarm. The outcomes showed that the ABC algorithm was robust, efficient and it would be capable of handling mixed integer optimization problem. The results obtained from this ABC method were compared with the results attained by other methods. Among all the test case number two had maximum real power loss reduction as well as voltage profile improvements.

Moradi and Abedini [29] proposed in this paper a novel genetic algorithm (GA) / particle swarm optimization (PSO) to find the optimal size and location of DG units in a distribution system. The objective of this paper was to minimize network power losses, better voltage regulation and improve voltage stability within a certain specified frame-work of system operation and system constraints in a radial distribution system. The main advantage of this proposed method was uniform answers with negligible value for the variances and at the same time it was able to find optimal solution for the system.

Khatod *et al.* [30] presented an Evolutionary programming (EP) based technique for optimal placement of distributed generation units as a renewable sources in a radial distribution system. To handle uncertainties associated with load and renewable resources, probabilistic techniques had been adopted. Two operation strategies were employed for the restriction of wind power to a specified part of load for the stability consideration. To reduce the search space and computational burden, a sensitivity analysis had also been employed that gave a set of locations suitable for DG placemen. For the proposed Evolutionary Programming (EP) based approach, an index based scheme had been developed to generate the population ensuring the feasibility of each individual and also it reduced the computational time. They showed in this research paper that allocation of several DG units of smaller sizes in the distribution system was more beneficial of the system performance as compared to the allocation of more number of large size DG units in distribution system. They also employed the technique to place other renewable technologies in the distribution system by selecting suitable probability distribution functions.

Garcia and Mena [31] employed a Modified Teaching Learning Based Optimization (MTLBO) algorithm to determine optimal size and optimal location of distributed generators in a distribution system. The objective function considered was to minimize total electric power losses although the problem could be easily configured as multi-objective where optimal locations along with their sizes were simultaneously obtained. The optimal sizing and siting problem was considered as mixed integer non-linear programming problem. Evolutionary methods were used to solve this kind of problem because of their independence of type of objective function and constraints. In this article a comparison of proposed algorithm and brute forced algorithm was performed.

Dehghanian *et al.* [32] applied a comprehensive multi-objective optimization approach by which all the influences of DG placement process were accounted. The objectives of the main scheme were total imposed costs, total network losses and customer outage costs. The non-dominated sorted genetic algorithm II had been employed for the optimization problem. At last a fuzzy application was used to find final optimal solutions. It was concluded that optimal placement of DG could be obtained with the trade-off between the addressed objective function and an optimal solution was obtained.

Sajjadi *et al.* [33] presented simultaneous placement of distributed generators and capacitors for reducing active and reactive power loss reduction in a radial distribution network. Voltage stability was also considered as objective function. The improvement of voltage profile was also carried out in this research paper. The memetic algorithm, which was the combinatorial form of local search and genetic algorithm, had been used to get optimal solution. The results gave a significant loss reduction of the network and improvement in the voltage profile.

Hung *et al.* [34] developed three analytical expressions for optimal sizes, location and operating strategy of distributed generation. The analytical expressions were adopted by considering time varying demand and an appropriate operating condition of distributed generator units. The obtained result showed that these analytical expressions were adequate to find out optimal sizes, location and power factor of distributed generator unit to reduce losses in a distribution system.

Mistry and Roy [35] applied a particle swarm optimization with constriction factor to determine the optimal sizes, location of multiple DG units. A predetermined load growth with voltage regulation for five year was considered as constraints in this research paper. The results proved that by the incorporation of multiple DG units in distribution system reduced real power loss, reactive power loss, purchase cost of energy and voltage deviation in the distribution system.

Karimyan *et al.* [36] proposed a long term scheduling for optimal sizing and siting of DG unit for loss reduction and voltage profile improvement of distribution system. A particle swarm optimization (PSO) and an analytical method had been employed to obtain reliable solution. The feeder loads were increased from 50% to 150% in 1% steps and according to that the optimal size of DG unit had been changed linearly as load changes. The results showed that by optimal placement of DG unit in a distribution system active and reactive power losses were minimized and voltage profile of the system was also improved.

El-Fergany [37] applied a backtracking search optimization algorithm (BSOA) to assign distributed generator units in a radial distribution network. The objective function was adopted with weighting factor to reduce real power loss and also to improve the voltage profile improvement. A set of fuzzy expert rules were employed to identify the initial DG location. In this article two types of DGs were studied. The numerical results described that the proposed method was more applicable in comparisons with the analytical and other heuristics methods.

CHAPTER-3
PROBLEM FORMULATION

3.1 PROBLEM FORMULATION

Radial distribution system loss minimization is done by appropriate siting and sizing of a DG unit. This loss minimization method not only minimizes the network losses but also improves the voltage profile of the system. On the account of some inherent features of distribution systems such as radial distribution system structure, large number of nodes, high R/X ratios; the conventional techniques developed for load-flow solution of transmission systems failed to give the reliable and optimal solution. Therefore, many load-flow solution methodologies had been developed to overcome the limitation of conventional load-flow method while determining power flow solution of distribution system. It is also quite important to define the size and location of distributed generator (DG) units in a radial structure because a size of a DG unit more than optimal size may lead negative impact on loss minimization. The size of the DG unit should be such that it is consumable within the distribution system sufficiently. Any attempt to install a high capacity DG unit with the purpose of exporting power beyond the substation will lead very high losses in the system.

3.1.1 Objective Function

The total real power loss in a system can be represented by 'exact loss' formula [38] in Eq. (3.1).

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}(Q_iP_j - P_iQ_j)] \tag{3.1}$$

where $\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i - \delta_j)$,

$\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right)$,

And $r_{ij} + jx_{ij} = z_{ij}$ is *ij* th element of impedance matrix

$V_i\angle\delta_i$ is complex voltage at the bus *i* th;

P_i and P_j active power injection at *i* th and *j* th buses respectively.

Q_i and Q_j reactive power injection at *i* th and *j* th buses respectively.

N is the number of buses.

3.1.2 Constraints

The objective function in Eq. (3.1) is subjected to the following inequality and equality constraints

(a) Bus voltage limits:

A small change in voltage leads to a wide change of reactive power of a system whereas active power practically does not change. So the operating voltage of each node must be within the safety range.

$V_{imin} \leq V_i \leq V_{imax}$ Where $i \in \{1, 2, 3 \ldots N\}$ (3.2)

where V_{imin}, V_{imax} are the minimum and maximum values of voltage of *i* th bus.

V_i is the voltage of *i* th bus.

N is the number of bus.

(b) Feeder capacity limits:

Current flows through each feeder must be within the maximum capacity.

$I_i \leq I_{imax}$ $i \in \{1, 2, 3, \ldots\ldots\ldots N_{br}\}$ (3.3)

where I_{imax} is the maximum permissible value of current in *i* th branch.

I_i is the current flow in *i* th branch.

N_{br} is the number of branches.

(c) Power flow equations:

The active power generation must be equal to the total active power loss and the active power load. Similarly, the reactive power generation must be equal to total reactive power loss and the reactive power load.

$$\sum P_{iG} = \sum P_L + \sum P_{Load} \tag{3.4}$$

$$\sum Q_{iG} = \sum Q_L + \sum Q_{Load} \tag{3.5}$$

where,

P_{iG} = Total active power generation.

Q_{iG} = Total reactive power generation.

P_L = Total active power loss.

Q_L = Total reactive power loss.

P_{Load} = Total active load.

Q_{Load} = Total reactive load.

3.2 LOAD-FLOW ANALYSIS

Load-flow is one of the most important and basic method for operation, planning studies, and analysis of any power system studies under steady state condition. Most of the distribution systems are of radial structure and they are fed from one source point. There are many methods of load-flow for radial distribution system but out of them the most efficient one is backward/forward sweep method. This load flow method is based on the concept of backward/ forward sweeps of radial network.

3.3 BACKWARD/FORWARD SWEEP METHOD

The backward/ forward sweep is an iterative method of load flow in which at each iteration two computations are performed. The first sets of equations are for calculation of currents through the branches starting from the last branch and proceeding in the backward direction towards the starting node. The other set of equations are used for the calculation of voltage magnitude and angle of each node starting from the root node and proceeding in forward direction towards the end node. The backward/forward sweep method has been described below.

3.3.1 Assumptions

1) It is assumed that the three phase distribution networks are balanced and can be represented by their equivalent single-line diagram.

2) Distribution feeders are of medium level voltage so there are no shunt capacitance effect and no charging current flowing through the distribution network.

3) The loads are modeled as constant power.

3.3.2 Node and Branch Numbering

For a radial distribution system, the number of branches is N_{br} and the number of nodes is N_{no} and they are related as

$$N_{no} = N_{br} + 1 \tag{3.6}$$

The node numbering process is started at 1 from source node and it is increased for other nodes. The Fig. 3.1 shows the single line diagram of a balanced radial distribution system with 10 number of nodes and 9 branches.

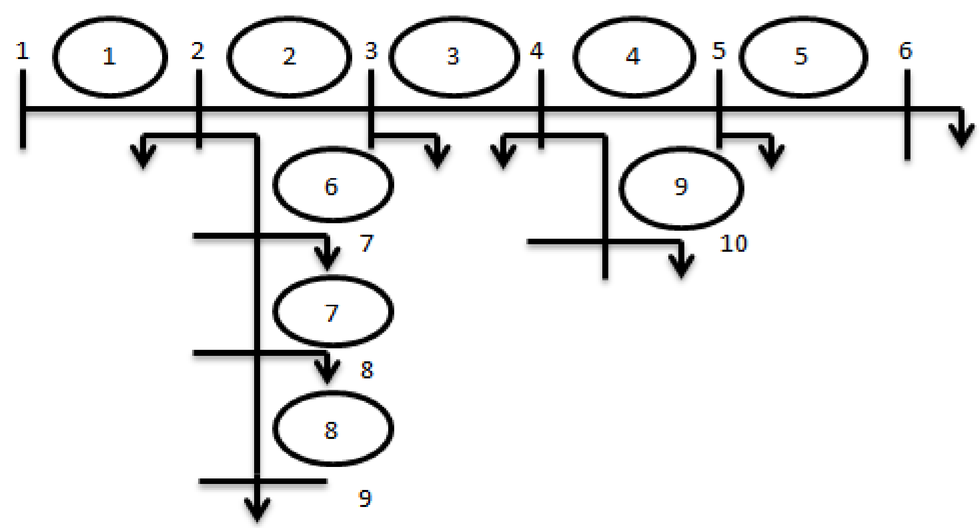


Figure 3.1 A simple radial distribution system.

3.3.3 Load-flow Equations/ Solution Methodology

It is already assumed that the three phase radial distribution system is balanced so that the three phase system can be represented as a single line diagram. A direct load-flow can be used for the radial distribution system [39]. Now consider branch-1. The receiving end node voltage can be calculated as

$$V(2) = V(1) - I(1)Z(1) \tag{3.7}$$

Similarly, for branch-2

$$V(3) = V(2) - I(2)Z(2) \tag{3.8}$$

So as the substation voltage $V(1)$ is known so if we can determine the branch current $I(1)$ then it will be very easy to calculate $V(2)$ from Eq. (3.7). So in the same way by calculating the branch current $I(2)$ we can easily determine the node voltage $V(3)$. Similarly, we can determine the node voltages of node 1, 2 …N_{no} in forward sweep.

So based on the above equation the voltage of node 'i' can be written as

$$V(i) = V(i-1) - I(i)Z(i) \tag{3.9}$$

where $V(i)$ = voltage of node 'i'

$V(i-1)$ = voltage of node '(i-1)'

$Z(i)$ = impedance of branch 'i'

$I(i)$ = current flow in branch 'i'

The load current of node 'i'; $I_L(i)$ can be calculated as

$$I_L(i) = \frac{P_L(i) - jQ_L(i)}{V(i)^*}; \quad \text{for i= 1,2……..}N_{no} \tag{3.10}$$

where $P_L(i)$ = active power of load connected to node 'i'.

$Q_L(i)$ = reactive power of load connected to node ‘i’.

The current through a branch ‘i’ i.e. $I(i)$ is the sum of load current $I_L(i)$ of node ‘i’ and the branch currents connected to this line

$$I(i) = I_L(i) + \sum_{k\in\gamma_i} I(k) \tag{3.11}$$

where γ_i is the set consisting of all the branches connected to node ‘i’ and thus γ_i is empty for each end node.

So the current $I(i)$ connected to **end node** ‘i’ can be expressed as

$$\mathrm{I(i)} = \mathrm{I_L}(i) \tag{3.12}$$

So Eq. (3.11) and Eq. (3.12) are utilized in backward sweeps from all end nodes towards the root node. Therefore, end nodes and branches of the path connected to the source node and adjacent downstream nodes of an interested node must be determined. The algorithm of determination of these parameters is described in the next subsection.

3.3.4 Node Determination after Branch [40]

It is already assumed that the distribution system has N_{no} number of nodes so the parameters to be determined are the end nodes and the branches of the path connected to the source node, and the adjacent downstream nodes of an interested node. The steps of the algorithm are described as below

Step-1) In the first step a node-to-branch matrix S is obtained, which has N_{no} columns and $(N_{no} - 1)$ number of rows. In this matrix the row numbers identify the branches and the column numbers identify nodes. In each row of S, a column corresponding to a sending-end is equal to -1 and a column corresponding to a receiving-end node is equal to $+1$, while the other elements of this row are 0. Thus each row contains only one 1 and one -1 and the rest elements are 0. The generic elements S (i, j) can be expressed as

$$S(i,j) = \begin{cases} -1 & \text{column corresponding to sending end} \\ +1 & \text{column corresponding to receiving end} \\ 0 & \text{other elements of the row} \end{cases}$$

Step-2) In this step the branches of the path, which is connected to node 'i', are determined. An example is illustrated here in which the branches of path connecting node 6 to the source node are determined in a step by step. At first in the *i* th column of S (6 th column) an element equal to 1 is determined. Then the row, which is determined element (1), belongs to is determined. This row is the first branch of interested path. Now in the determined row *i*, we find an element equal to -1 and the column which belongs to -1 is found (column 5). After that in this column an element, which is equal to 1 is determined and the number of the row of its location in the matrix S is the second element of the interested path (4). This search continues until the algorithm reaches a column, which has no element equal to 1(source node). Table 3.1 shows the node-to-branch matrix S of the radial system in Fig. 3.1. The process of branches determination located between node 6 and the source node is shown in Table 3.1. The mentioned process shows that branches 5,4,3,2 and 1 are respectively determined as the branches connecting to node 6 to the source node.

Step-3) In this step all the end nodes of the radial system are determined. First we have to find columns, which have only one element equal to 1 but no element is equal to -1. For example it can be seen from the Table 3.1 that the nodes 6, 9 and 10 are the end nodes, which satisfy the above mentioned procedures.

Step-4) In this step the adjacent downstream nodes of an interested node has been determined. After the identification of end nodes, for each end node, the path connecting to the source node must be determined and order is increased accordingly. After that for all the paths including the interested node, the first element after the interested node is an adjacent node of it. The nodes which are repeated more than one times among the adjacent nodes are eliminated and we reach the set γ used in Eq. (3.11). This procedure is done for all the nodes in distribution system. Table 3.2 shows all the paths of the end node and the method helps in achieving the nodes connected to node 2. In all rows of the Table 3.2 node 2 is found and the first element after node 2 is selected. It can be seen that node 3 is repeated 2 times. Thus set γ for node 2 includes node 3 and node 7.

Table 3.1 Node and branch matrix for 10 node radial distribution system

Branch Number	**Node Number**									
	1	2	3	4	5	6	7	8	9	10
1	−1	1	0	0	0	0	0	0	0	0
2	0	−1	1	0	0	0	0	0	0	0
3	0	0	−1	1	0	0	0	0	0	0
4	0	0	0	−1	1	0	0	0	0	0
5	0	0	0	0	−1	1	0	0	0	0
6	0	−1	0	0	0	0	1	0	0	0
7	0	0	0	0	0	0	−1	1	0	0
8	0	0	0	0	0	0	0	−1	1	0
9	0	0	0	−1	0	0	0	0	0	1

Table 3.2 Path of end node to the source node

End Node	**Path of the end node to the source node**					
6	1	2^*	3^{**}	4	5	6
9	1	2^*	7^{**}	8	9	
10	1	2^*	3^{**}	4	10	

$*$ Interested node, $**$ The node connected to node 2.

3.3.5 Calculation of Real and Reactive Power Loss

The real and reactive power loss for branch-*i* of a distribution system can be expressed below

$$P_L(i) = |I(i)|^2 R(i) \quad (3.13)$$

$$Q_L(i) = |I(i)|^2 X(i) \quad (3.14)$$

3.3.6 Backward/ Forward Sweeps in Load-flow and Criterion of Convergence

Initially a constant voltage of magnitude $1\angle 0$ p.u. is assumed for all nodes. Then all nodes current can be computed using the Eq. (3.10). After the computation of node current branch currents are computed using the Eq. (3.11) and Eq. (3.12) in a backward sweeps. Thereafter voltage of each node is determined by Eq. (3.9) in forward sweeps. Once the new value of voltage is calculated the convergence criterion of solution is checked. The convergence criterion is such that in each successive iteration the maximum difference in voltage magnitudes must be less than 1×10^{-4} p.u.

3.4 FUZZY EXPERT SYSTEM FOR DISTRIBUTED GENERATION OPTIMAL PLACEMENT

For a given particular configuration of a single source radial distribution network the loss associated with the active and reactive component of branch currents cannot be minimized because all the active and reactive power must be supplied by the source at the root bus of the radial distribution system. This limitation can be overcome by placing DG units at different nodes of the system for loss reduction. That means real as well as reactive power can be supplied locally by using DG units of optimal size. The location of DG is chosen based on fuzzy expert system. The location must be one that gives minimum losses along with the best voltage profile.

3.4.1 FES Implementation

The fuzzy expert system (FES) contains a set of rules, which are developed according to the qualitative descriptions. In a DG allocation problem, rules are defined to determine the suitability of a node in which the DG could be installed. In the fuzzification process, the power loss factor (PLF) and voltage index (VI) are converted into fuzzy. Power loss factor (PLF) is described by the linguistic terms very low (VL), low (L), medium low (ML), medium (M), medium high (MH), high (H), very high (VH) and voltage index is described by the linguistic terms low (L), medium low (ML), medium (M), medium high (MH), high (H). All these linguistic terms are represented by membership functions. The membership functions of trapezoidal type are used in the following fuzzy expert system and they are graphically shown in the Fig. 3.2 and in Fig. 3.3. The power loss factor (PLF) and the voltage index (VI) are the two inputs to the fuzzy Inference system (FIS), which determines the optimal position for allocation of DG by fuzzy inferencing. The inference involves heuristic rules for the determination of output decisions. In this fuzzy inference system there are two input variables (PLF, VI) and (7, 5) fuzzified variables respectively so that the fuzzy inference system has a set of 35 rules.

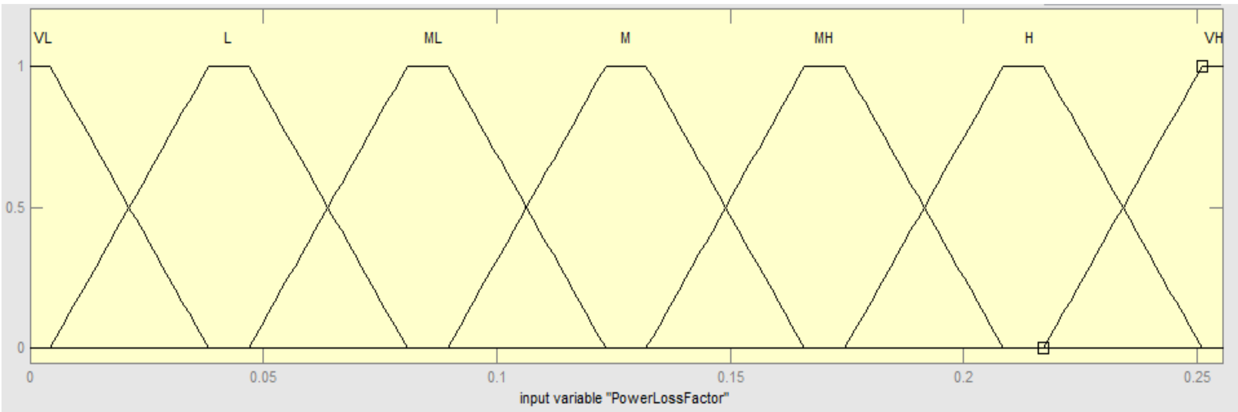


Figure 3.2 Power loss factor membership functions.

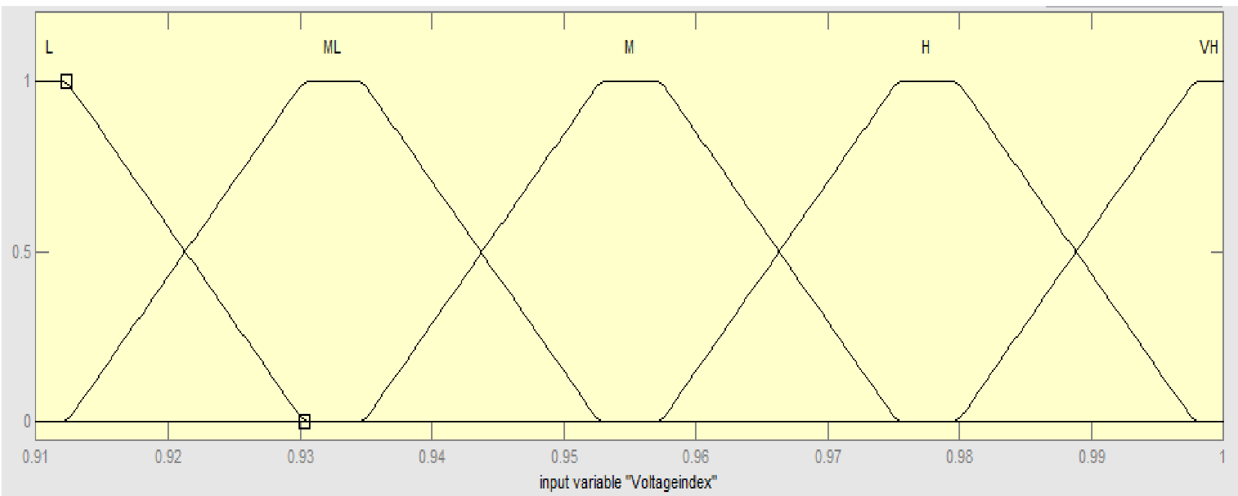


Figure 3.3 Voltage index membership functions.

The DG unit is to be placed in the optimal position such that power loss factor should be maximum and the voltage index should be minimum. These two objectives are more important while designing the heuristic rules for fuzzy inference system (FIS). Such rules are expressed as the following way

IF premise (antecedent).THEN conclusion (consequent).

For the determination of DG suitability at a particular node a set of multiple-antecedent fuzzy rules have been established. The rule base for optimal DG placement is summarized in the fuzzy decision matrix shown in Table 3.3 and illustrated in Fig. 3.5. The output of fuzzy inference system is DG placement suitability index and it is also described by the linguistic terms very low (VL), low (L), medium low (ML), medium (M), medium high (MH), high (H) and very high

(VH). These linguistic terms are also represented by membership functions and it is shown in Fig. 3.4.

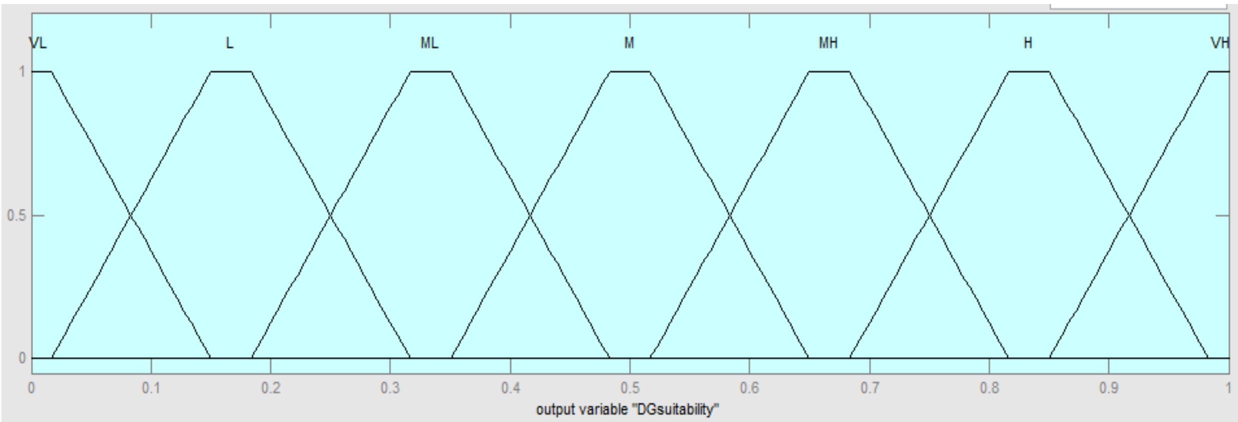


Figure 3.4 DG placement suitability index membership functions.

Table 3.3 Fuzzy Decision Matrix

AND	**Voltage index (VI)**					
		Low (L)	Medium Low (ML)	Medium (M)	Medium High (MH)	High (H)
Power loss factor (PLF)	Very Low (VL)	VL	VL	VL	VL	VL
	Low (L)	VL	VL	VL	VL	VL
	Medium Low (ML)	M	ML	L	VL	VL
	Medium (M)	MH	M	ML	L	L
	Medium High (MH)	H	MH	MH	ML	L
	High (H)	H	MH	M	M	ML
	Very High (VH)	VH	H	MH	M	L

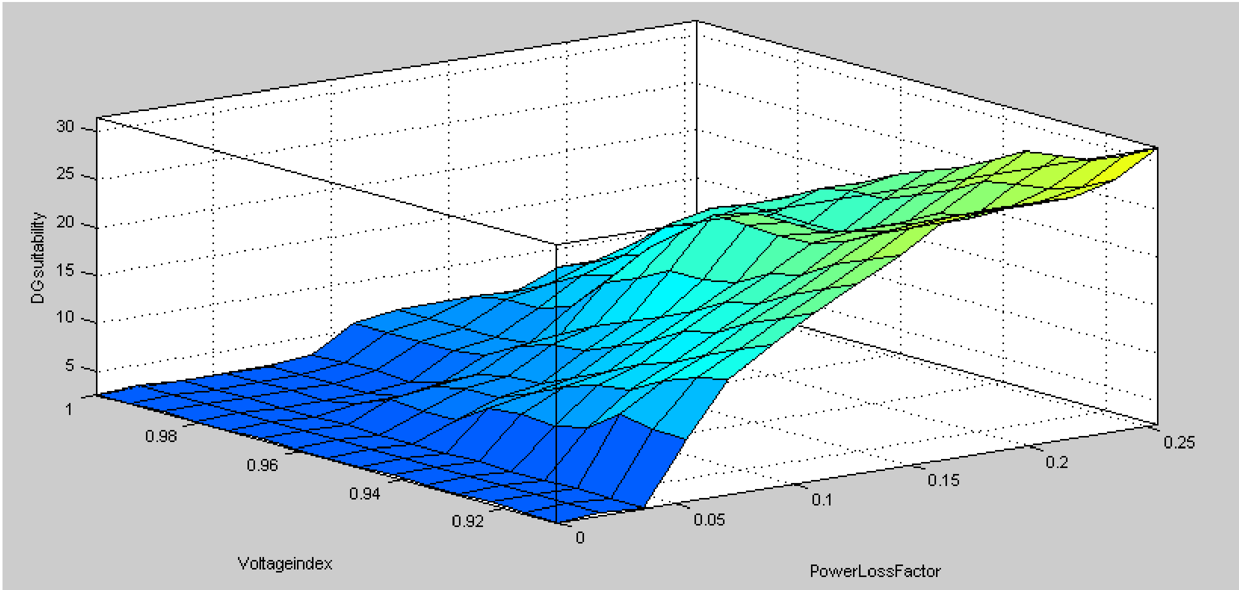


Figure 3.5 Fuzzy rules

3.4.2 Fuzzy Inference and Defuzzification Techniques

After the inputs are given to the fuzzy expert system (FES) from the load flow program, several rules are fired with some degree of membership. In this method Mamdani's maximum-minimum implication method of inference involves in truncating the consequent membership function of each fired rules at the minimum membership value of all antecedents. After that a final aggregated membership function is achieved by taking the union of all truncated consequent membership functions of fired rules. For the DG allocation problem, the resulting DG placement suitability membership function, μ_s of node *i* for *k* fired rules are given by

$$\mu_s(i) = \max[\min[\mu_p(i), \mu_v(i)]] \tag{3.15}$$

where μ_p and μ_v are the two membership functions of power loss factor and voltage index respectively.

Once the DG suitability membership function of a node is calculated, it must be defuzzified in order to determine the node's suitability ranking. The centroid method of defuzzification is used to defuzzify the fuzzified values. This method of defuzzification finds the center of area of the membership function. Thus the DG suitability index is determined by

$$S = \frac{\int \mu_s(z).zdz}{\int \mu_s(z)dz} \tag{3.16}$$

3.5 SIZING OF DG UNIT AT VARIOUS LOCATIONS

For optimal sizing of a DG unit we are considering $a = (sign)\tan(\cos^{-1} PF_{dg})$ [19], where the reactive power of DG can be expressed as:

$$Q_{\boldsymbol{dgi}} = aP_{dgi} \tag{3.17}$$

In which

$sign$ = +1: DG injecting reactive power

$sign$ = -1: DG consuming reactive power

PF_{dg} = Power factor of DG

Now the active power and reactive power injected at bus 'i' in a distribution system, where the DG is installed are given by the following Eq. (3.18) and Eq. (3.19).

$$P_i = P_{dgi} - P_{di} \tag{3.18}$$

$$Q_i = Q_{dgi} - Q_{di} = aP_{dgi} - Q_{di} \tag{3.19}$$

From Eq. (3.1), Eq. (3.18) and Eq. (3.19) the active power loss can be written in the following way

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}[(P_{dgi} - P_{di})P_j + (aP_{dgi} - Q_{di})Q_j] + \beta_{ij}[(aP_{dgi} - Q_{di})P_j - (P_{dgi} - P_{di})Q_j]] \tag{3.20}$$

The total active power loss of a system will be minimum if the partial derivative of Eq. (3.20) with respect to the active power injection from DG at bus 'i' becomes zero. After simplification and rearrangement Eq. (3.20) can be expressed as

$$\frac{\partial P_L}{\partial P_{dgi}} = 2\sum_{j=1}^{N}[\alpha_{ij}(P_j + aQ_j) + \beta_{ij}(aP_j - Q_j)] = 0 \tag{3.21}$$

Equation (3.21) can be expressed in the following way:

$$\alpha_{ii}(P_i + aQ_i) + \beta_{ii}(aP_i - Q_i) + \sum_{\substack{j=1 \\ j\neq i}}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right) + a\sum_{\substack{j=1 \\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j) = 0 \tag{3.22}$$

Let, $X_i = \sum_{\substack{j=1 \\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)$ and $Y_i = \sum_{\substack{j=1 \\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j)$ (3.23)

From the Eq. (3.18), Eq. (3.19), Eq. (3.22) and Eq. (3.23) , Eq. (3.24) can be obtained as given below

$$\alpha_{ii}\left(P_{dgi} - P_{di} + a^2P_{dgi} - aQ_{di}\right) + \beta_{ii}(Q_{di} - aP_{di}) + X_i + aY_i = 0 \tag{3.24}$$

Rearranging Eq. (3.24) we can obtain optimal size of DG at each bus 'i' for minimizing loss i.e.

$$P_{dgi} = \frac{\alpha_{ii}(P_{di}+aQ_{di})+\beta_{ii}(aP_{di}-Q_{di})-X_i-aY_i}{a^2\alpha_{ii}+\alpha_{ii}} \tag{3.25}$$

The power factor of a DG depends on the operating condition as well as the type of DG. When the power factor of a DG is given, the optimal size of DG at each bus 'i' for minimizing losses can be obtained in the following way.

(a) Type 1 DG: This kind of DG is capable of injecting only active power such as fuel cells, photovoltaic system. For type 1 DG power factor is unity i.e. $PF_{dg} = 1$, $a = 0$. So the optimal size of DG at each bus 'i' for minimization of losses can be obtained by reducing the Eq. (3.26).

$$P_{dgi} = P_{di} - \frac{1}{\alpha_{ii}}\left[\beta_{ii}P_{di} + \sum_{\substack{j=1 \\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)\right. \tag{3.26}$$

(b) Type 2 DG: This kind of DG is capable of injecting both active and reactive power such as DG units which are based on synchronous machine and VSC based DG units. For type 2 DG unit power factor belong to the range $0 < PF_{dg} < 1, sign = +1$ and 'a' is a constant. The optimal size of DG at each bus 'i' for loss minimization can be obtained by the Eq. (3.25) and Eq. (3.19) respectively.

(c) Type 3 DG: This kind of DG is capable of generating active power and consuming reactive power such as induction generators. So for type 3 DG power factor is in the range $0 < PF_{dg} <$

$1, sign = -1$ and 'a' is a constant. The optimal size of DG at each bus 'i' for minimum loss can be obtained from the Eq. (3.25) and Eq. (3.19) respectively.

(c) Type 4 DG: This kind of DG capable of injecting only reactive power. For this kind of DG power factor $PF_{dg} = 0$ and $a = \infty$. From Eq. (3.17) and Eq. (3.25) the optimal size of DG for loss minimization can be obtained by the Eq. (3.27).

$$Q_{dgi} = Q_{di} + \frac{1}{\alpha_{ii}}[\beta_{ii}P_{di} - \sum_{\substack{j=1 \\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j) \quad (3.27)$$

3.6 OPTIMAL POWER FACTOR

Let consider a simple distribution system with two buses, a source, a load and DG unit connected through a transmission line as shown in Fig. 3.6.

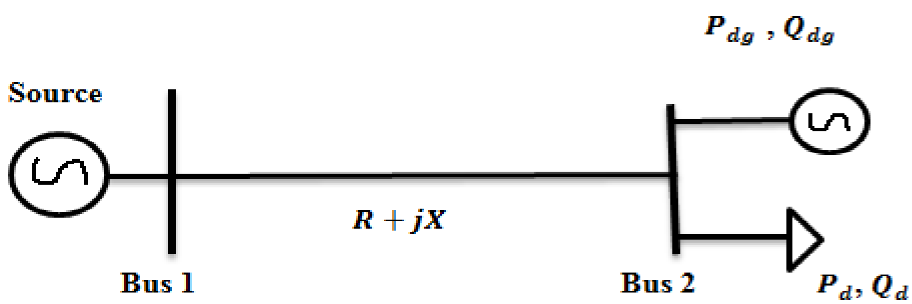


Figure 3.6 Distribution system with single DG.

The power factor of a single DG (PF_{dg}) connected to a simple distribution system can be obtained as

$$PF_{dg} = \frac{P_{dg}}{\sqrt{P_{dg}^2 + Q_{dg}^2}} \quad (3.28)$$

The power factor of the single load (PF_d) can be obtained as

$$PF_d = \frac{P_d}{\sqrt{P_d^2 + Q_d^2}} \quad (3.29)$$

The minimum loss will occur when power factor of a single DG is equal to power factor of single load. The power factor of combined load of the system can be expressed by Eq. 3.29 at that calculation the total active and reactive power load can be obtained as

$$P_d = \sum_{i=1}^{N} P_{di} \tag{3.30}$$

$$Q_d = \sum_{i=1}^{N} Q_{di} \tag{3.31}$$

The possible minimum loss will be obtained if the power factor of DG (PF_{dg}) is equal to power factor of total load (PF_d). That can be expressed as

$$PF_{dg} = PF_d \tag{3.32}$$

3.7 PROCEDURES

The procedure to allocate DG unit for loss minimization in a radial distribution system can be expressed as follows:

Step 1) Run the forward/ backward sweep load flow for base case and find each branch losses as well as total losses and node voltages for the specified test system.

Step 2) Find the optimal node to allocate a DG unit using fuzzy expert system.

(a) Develop the two input membership functions based on branch losses and node voltages and one output membership function of DG suitability index.

(b) Develop fuzzy rules (5×7) using Mamdani's method and defuzzify that to get optimal node for DG placement.

Step 3) Find the optimal power factor using Eq. (3.32).

Step 4) Find the optimal size of DG and calculate the losses using the following steps:

(a) Place the DG unit at the optimal position obtained from step 2, and change this DG size in small step using Eq. (3.19), Eq. (3.25), Eq. (3.26), Eq. (3.27) by updating the values of 'α' and 'β' and compute the loss for each case using load flow used in step 1.

(b) Select and store the DG size which gives minimum losses and discard other results.

Step 5) Update the load data after placing DG unit with optimal size obtained in step 3.

Step 6) Stop the procedure if

(a) the voltage at a particular node violate its upper limit.

(b) the total DG size is over the total load and loss.

(c) the loss which is obtained in new iteration if greater than the previous iteration loss. The previous iteration loss is saved (or) repeat steps 1 to 5.

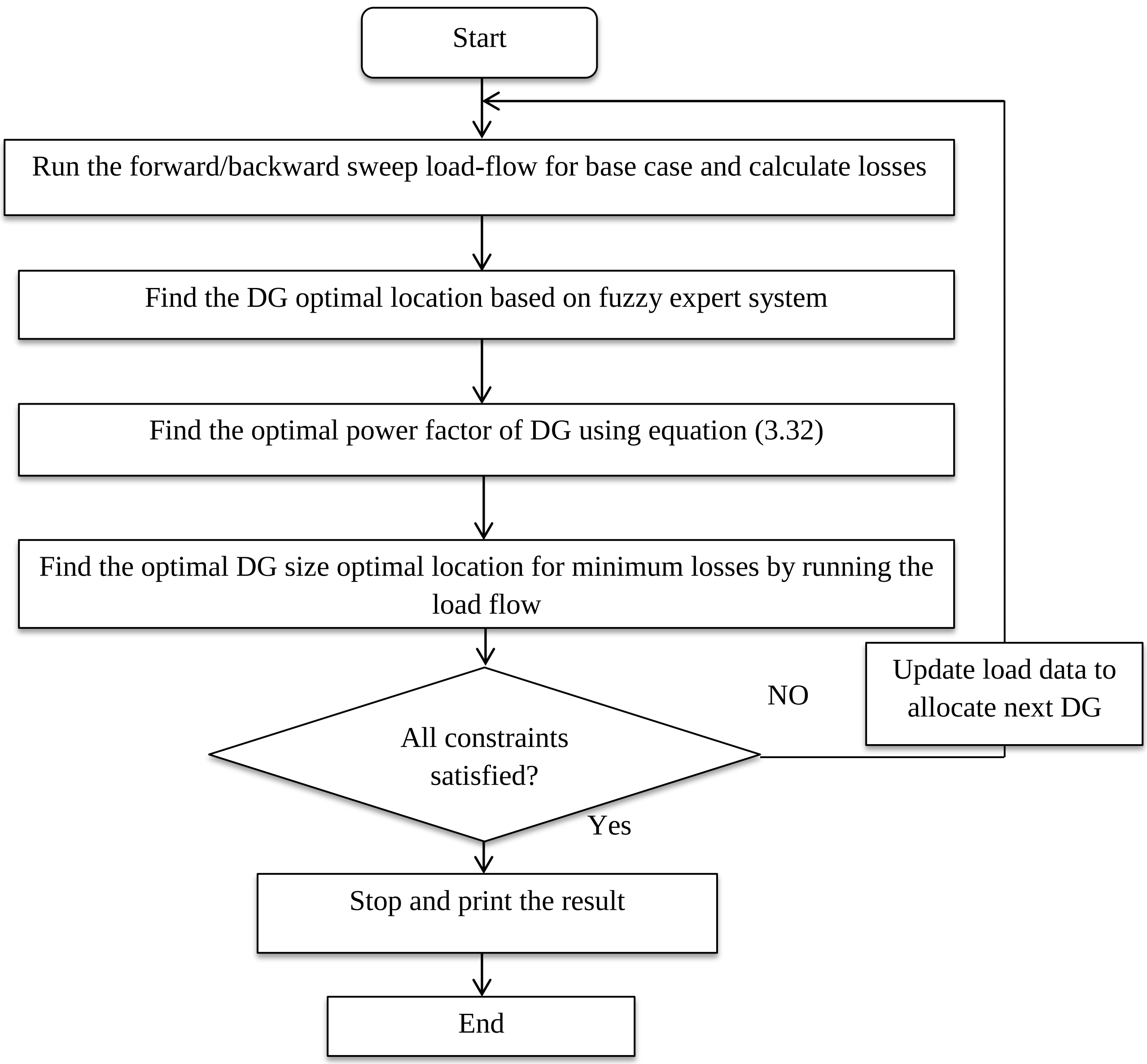


Figure 3.7 Flowchart of the proposed method.

3.8 TEST SYSTEM

For this thesis work an IEEE-33-node radial distribution system has been taken as test system. The line data and load data are given in the following Appendix A.1 and A.2 respectively. The base kV and base MVA are 12.66 and 100 respectively. The total real and reactive power loads on the system are 3.715 MW and 2.3 MVAr respectively.

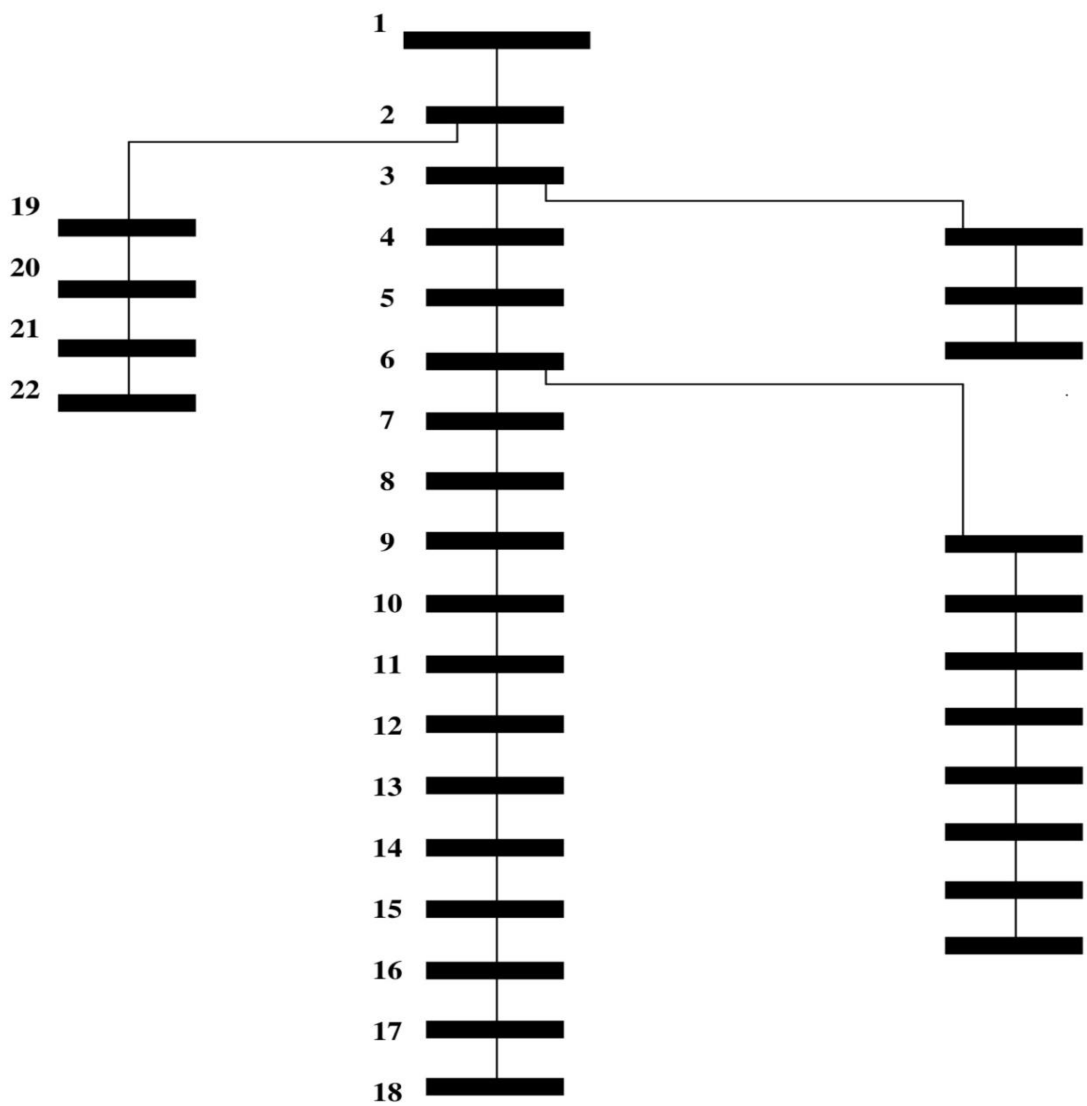


Figure 3.8 33-node radial distribution system.

CHAPTER-4
RESULTS AND DISCUSSIONS

4.1 RESULTS BEFORE DG ALLOCATION

Before installing a DG unit of optimal size and power factor the network real power loss is calculated by using backward/ forward sweep load flow method. The real power loss for the IEEE 33-node radial distribution test system is 201.7543 kW. The voltage profile of the system is tabulated in Table 4.1.

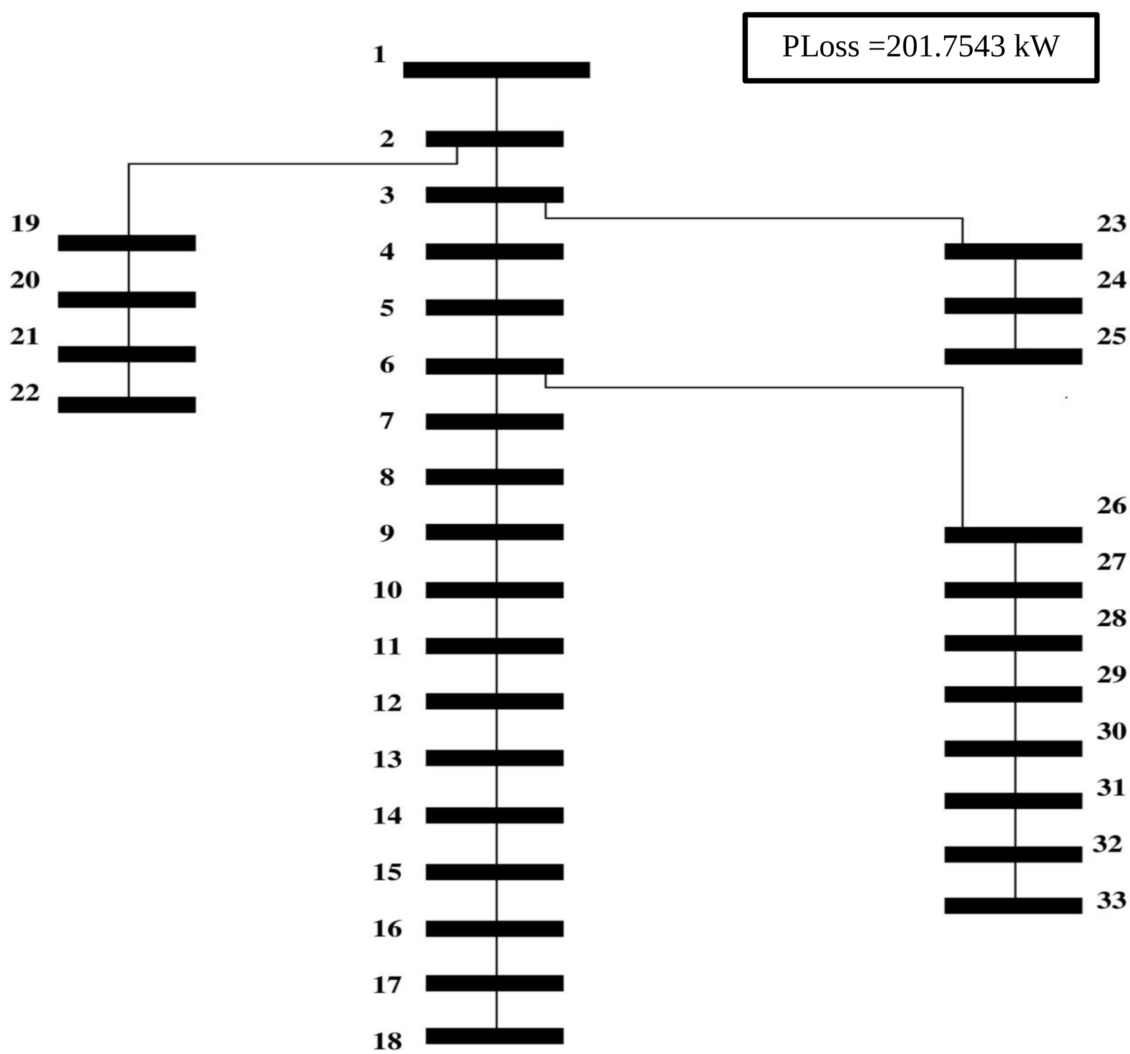


Figure 4.1 33-node radial distribution system base case power losses.

4.2 RESULTS AFTER TYPE 1 DG ALLOCATION

After getting the base case load flow for the given IEEE 33-node radial distribution test system a fuzzy expert system is implemented in fuzzy toolbox. The optimal node for DG allocation is found from the fuzzy expert system i.e. node number 6. Optimal size of Type 1 DG unit is found by using an analytical method discussed in the previous chapter. The optimal Type 1 DG size is 2.59 MVA with unity power factor. The total real power loss of the network after the Type 1 DG placement at node 6 is 102.7790 kW. The percentage of loss reduction after installation of Type 1 DG is 49.05%.

$$\%\ \boldsymbol{loss\ reduction} = \frac{\boldsymbol{Power\ loss\ without\ DG - Power\ loss\ with\ DG}}{\boldsymbol{Power\ loss\ without\ DG}} \times \mathbf{100}$$

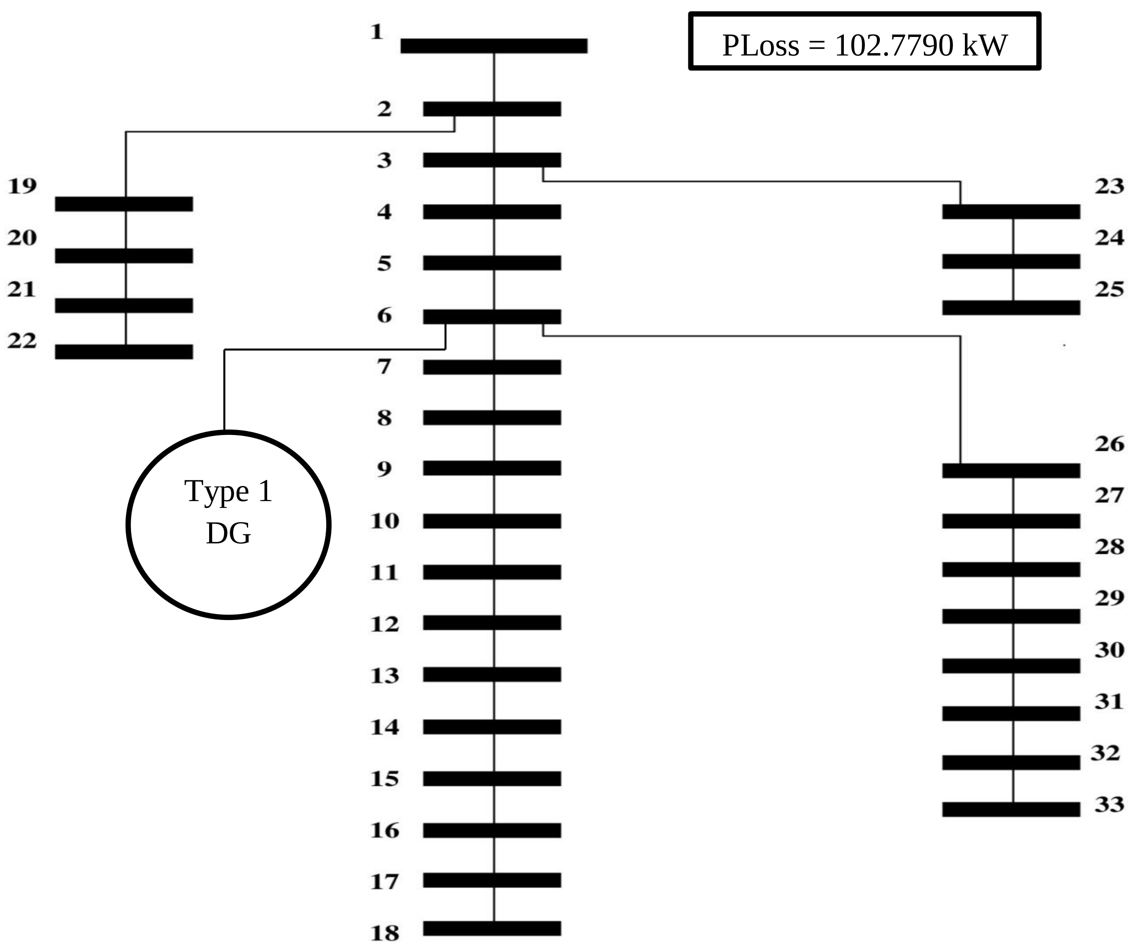


Figure 4.2 Power losses with Type 1 DG unit.

4.3 RESULTS AFTER TYPE 2 DG ALLOCATION

The optimal size of Type 2 DG to be placed in the radial distribution system is found 3.1 MVA with 0.85 lag power factor. The total real power loss after Type 2 DG unit allocation is 61.6505 kW. The percentage of loss reduction after Type 2 DG allocation is 69.44%.

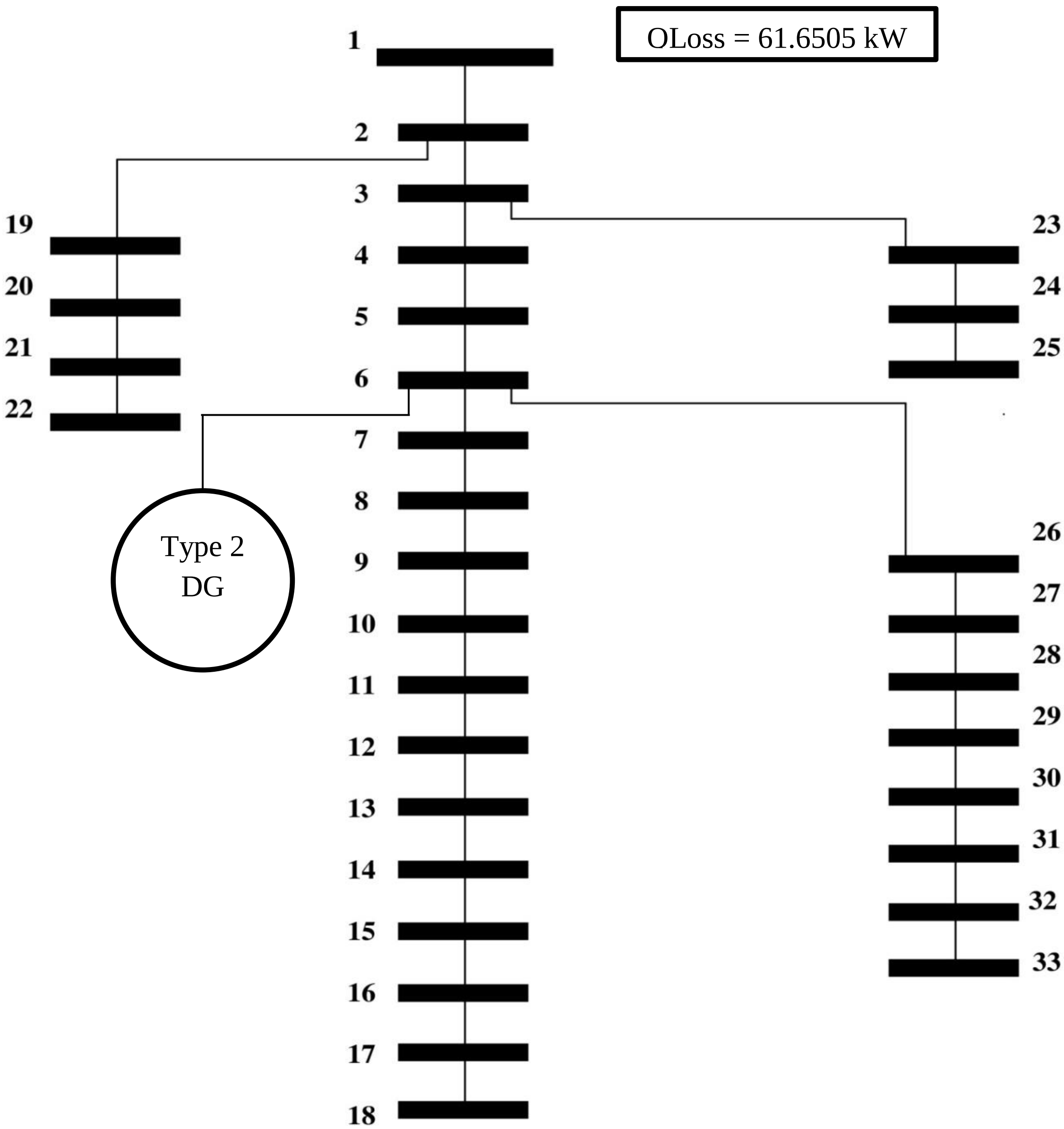


Figure 4.3 Power losses with Type 2 DG unit.

Table 4.1 Bus voltages with/ without DG unit

Node number	Node voltage without DG	Node voltage with Type 1 DG	Node voltage with Type 2 DG
1	1.000000000	1.000000000	1.000000000
2	0.997039361	0.998654349	0.999131941
3	0.982982915	0.993247363	0.996257585
4	0.975529053	0.992202789	0.997063298
5	0.968160451	0.991517465	0.998285682
6	0.949813660	0.987770407	1.001485037
7	0.946361134	0.984283150	0.998207992
8	0.941515601	0.979660855	0.993624526
9	0.935265575	0.973609229	0.987710219
10	0.929468555	0.968000431	0.982225353
11	0.928608019	0.967180532	0.981412025
12	0.927107591	0.965750144	0.979993996
13	0.921021555	0.959842463	0.974236052
14	0.918775865	0.957627812	0.972109060
15	0.917374388	0.956254483	0.970782383
16	0.916013920	0.954931635	0.969495316
17	0.914010371	0.952949948	0.967597348
18	**0.913406606**	**0.952363422**	**0.967026217**
19	0.996511413	0.998126964	0.998605169
20	0.992937295	0.994556829	0.995038978
21	0.992233905	0.993854055	0.994337184
22	0.991597779	0.993218410	0.993702520
23	0.979398339	0.989695290	0.992722822
24	0.972730390	0.983082611	0.986148815
25	0.969407570	0.979787464	0.982872917
26	0.947897949	0.985964576	0.999673351
27	0.945353259	0.983568876	0.997267145

28	0.933954444	0.972714394	0.986487659
29	0.925770144	0.964934940	0.978748585
30	0.922247158	0.961638965	0.975417874
31	0.918068967	0.957577271	0.971467673
32	0.917148828	0.956679505	0.970597711
33	0.916863664	0.956400843	0.970328094

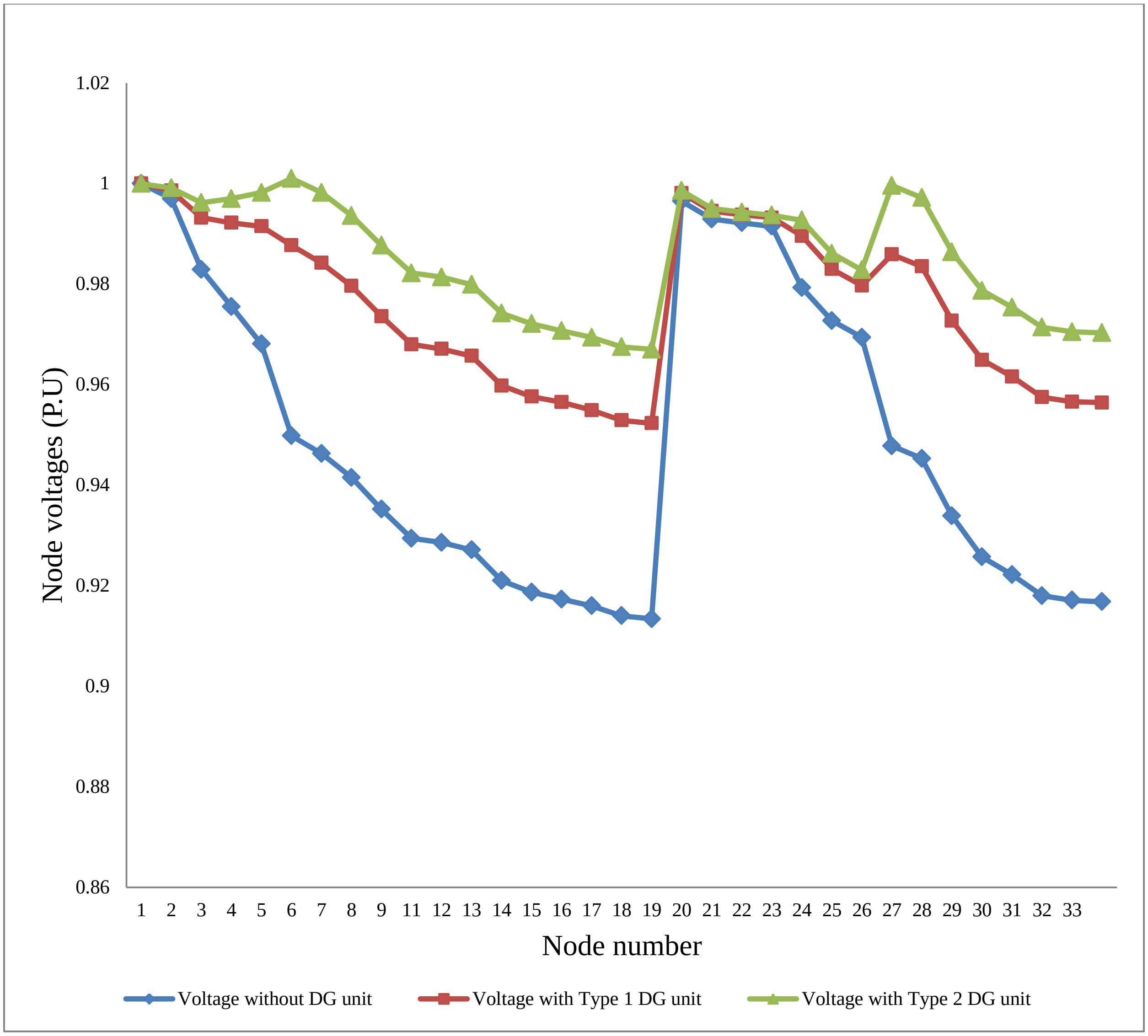


Figure 4.4 Voltage profile with/ without DG unit

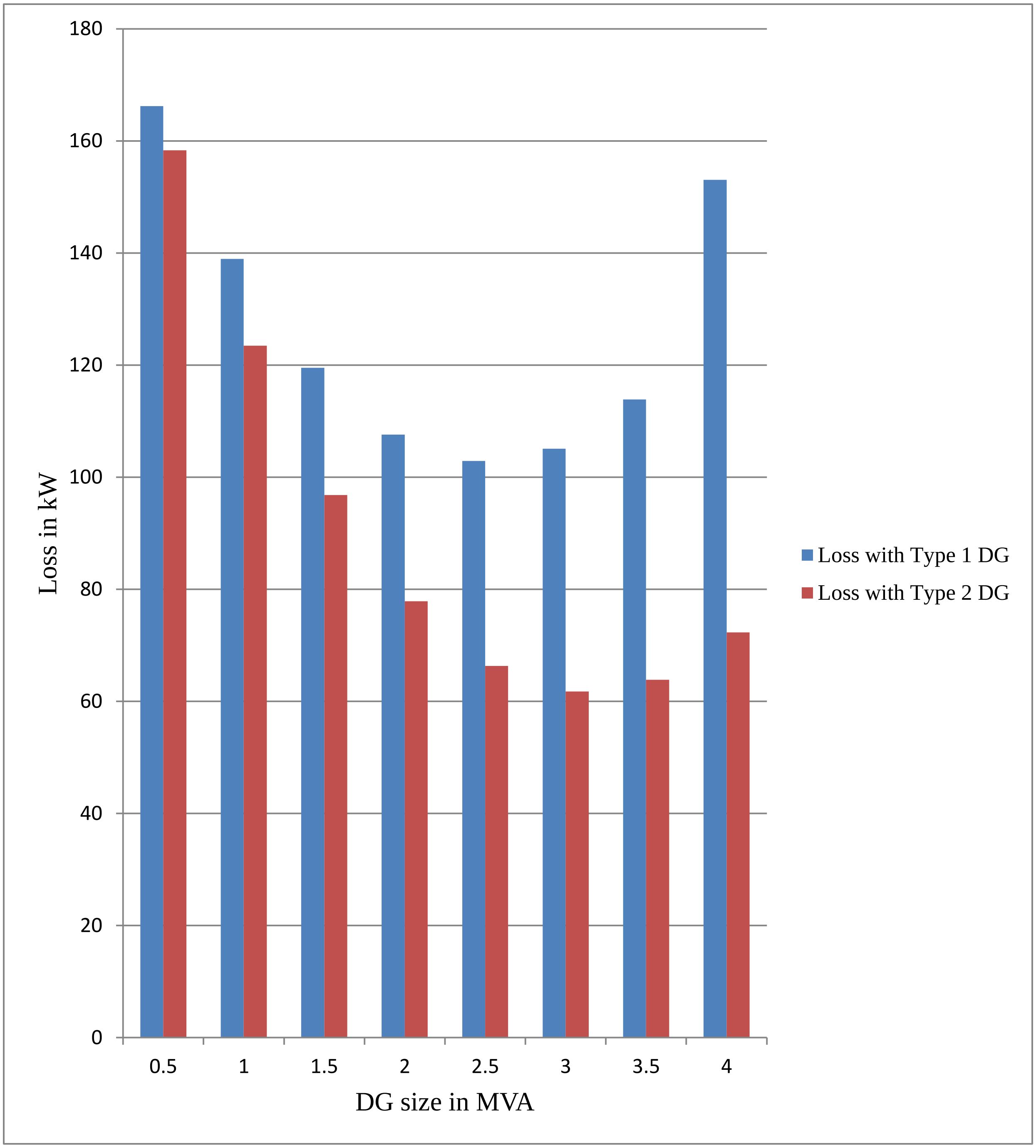


Figure 4.5 Loss reductions with Type 1 and Type 2 DG unit.

4.4 COMPARISON WITH PREVIOUS WORKS

In this section the results obtained have been compared with previous results on 33-node radial distribution system to show the feasibility of the proposed method.

Table 4.2 Comparisons of the optimal results of different approaches (DGs Type 1)

Method	Bus number for DG placement	Size of the DG unit (MVA)	Percentage of loss reduction
Loss sensitivity factor (LSF) [11]	10	1.400	41.55%
Artificial Bee Colony (ABC) [28]	6	3.380	44.83%
Particle swarm optimization (PSO) [36]	6	2.5792	47.37%
Proposed method	6	2.590	49.05%

Table 4.3 Comparison of the optimal result with other approach (DGs Type 2)

Method	Bus number for DG placement	Size of the DG unit (MVA)	Percentage of loss reduction
Particle swarm optimization (PSO) [36]	6	3.1207	67.83%
Proposed method	6	3.1000	69.44%

CHAPTER-5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

This thesis shows loss reduction by DG allocation of a radial distribution network. A 33-node test system is used for this purpose. The following conclusions can be drawn from the work

1) A backward/forward sweep method of load flow has been used for the load flow solution. It gives fast convergence to the load flow problem and it takes smaller number of iteration as compared to other methods.

2) Fuzzy expert system which has been used in this method is found efficient considering losses and voltage values of each node to find out the optimal node where the DG should be placed.

3) An analytical method has been used to find the optimal size of DG unit. It is also found that voltage profile improvement is more in the radial distribution system by installing Type 2 DG unit rather than Type 1 DG unit.

5.2 FUTURE SCOPE

After all the above discussion it is very clear that there is a scope of future work in this thesis. It can be discussed by the following points

1) Assessment of power loss reduction in a radial distribution system by installing other types of DG unit with considering their optimal power factor and size.

2) The above proposed method can be utilized in larger test system for its validity and effectiveness.

3) Obvious there are some other techniques for loss reduction which can be utilized.

LIST OF PUBLICATIONS

1. Avik Metia and Smarajit Ghosh, “A literature survey on different loss minimization techniques used in distribution network,” International Journal of Scientific Research and Education, Vol. 3, No. 6, pp. 3861-3877, 2015. [**Published**]
2. Avik Metia and Smarajit Ghosh, “Fuzzy based DG allocation for loss minimization in a radial distribution system” communicated in Balkan Journal of Electrical and Computer Engineering. [**Communicated**]

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Appendix-A

Table A.1 Line data of 33-node radial distribution network

Branch Number	Sending-end	Receiving-end	Resistance (Ω)	Reactance (Ω)
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2511
3	3	4	0.3660	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	0.7144	0.2351
8	8	9	1.0300	0.7400
9	9	10	1.0440	0.7400
10	10	11	0.1966	0.0650
11	11	12	0.3744	0.1238
12	12	13	1.4680	1.1550
13	13	14	0.5416	0.7129
14	14	15	0.5910	0.5260
15	15	16	0.7463	0.5450
16	16	17	1.2890	1.7210
17	17	18	0.7320	0.5740
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.8980	0.7091
24	24	25	0.8960	0.7011
25	6	26	0.2030	0.1034

26	26	27	0.2842	0.1447
27	27	28	1.0590	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.9630
31	31	32	0.3105	0.3619
32	32	33	0.3410	0.5302

Table A.2 Load data of 33-node radial distribution system

Node Number	PL(kW)	QL (kVAr)
1	0	0
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40

20	90	40
21	90	40
22	90	40
23	90	50
24	420	200
25	420	200
26	60	25
27	60	25
28	60	20
29	120	70
30	200	600
31	150	70
32	210	100
33	60	40

Base kV= 12.66 and Base MVA= 100