OPTIMAL PLACEMENT OF DISTRIBUTED GENERATION IN DISTRIBUTION NETWORKS

Ph. D. THESIS

by

SATISH KUMAR

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247667 (INDIA)

SEPTEMBER, 2013

OPTIMAL PLACEMENT OF DISTRIBUTED GENERATION IN DISTRIBUTION NETWORKS

A THESIS

Submitted in partial fulfilment of the

requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

ELECTRICAL ENGINEERING

by

SATISH KUMAR

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247 667 (INDIA)

SEPTEMBER, 2013

©INDIAN INSTITUTE OF TECHNOLOGY ROORKEE, ROORKEE-2013
ALL RIGHTS RESERVED

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **OPTIMAL PLACEMENT OF DISTRIBUTED GENERATION IN DISTRIBUTION NETWORKS** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Electrical Engineering of the Indian Institute of Technology Roorkee is an authentic record of my own work carried out during a period from December, 2009 to September, 2013 under the supervision of Dr. Barjeev Tyagi, Associate Professor, and Dr. Vishal Kumar, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(Satish Kumar)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

Date: ______________	(Vishal Kumar)	(Barjeev Tyagi)
	Supervisor	Supervisor

The Ph.D. Viva-Voce Examination of **Mr. SATISH KUMAR**, Research Scholar, has been held on……………………………………………………

Signature of Supervisor(s) **Chairman, SRC** **Signature of External Examiner**

Head of the Deptt./ Chairman, ODC

ABSTRACT

Objective of power system operation is to meet the demand at all the locations within power network economically and reliably. The traditional electric power generation systems utilize the conventional energy resources, such as fossil fuels, hydro, nuclear etc. for electricity generation. The operation of such traditional generation systems is based on centralized control utility generators. These generators deliver power to the widely dispersed users through an extensive transmission and distribution network. In the present environment, the justification for the large central-station plants is weakening, due to depleting conventional resources, increased transmission and distribution costs, deregulation trends, heightened environmental concerns, and technological advancements. Distributed Generations (DGs), a term commonly used for small-scale generations, offer solution to many of these new challenges. DGs are also referred to as ‘Embedded Generations’ or ‘Disperse Generations’. CIGRE define DG as the generating plant with a maximum capacity of less than 100MW, which is usually connected to the distribution networks and that are neither centrally planned nor dispatched. There are many definitions of DG in the literature as it depends upon the many technologies and many applications in different environment. Presently, numbers of DG technologies are available in the market and few are still in the research and development stage. Some currently available technologies are reciprocating engines, micro turbines, combustion gas turbines, fuel cells, photovoltaic, and wind turbines. During the last few years, the penetration of DG in the power distribution systems has been increasing rapidly in many parts of the world. As the penetration of distributed generation is increasing in the distribution network, it is no more passive in nature and its characteristics is becoming similar to an active transmission network. Therefore, it is in the best interest of all the players involved to allocate them in an optimal way such that it could increase reliability, reduce system losses and hence improve the voltage profile while serving the primary goal of power injection. It is evident that any loss reduction is beneficial to distribution utilities, which is generally the entity responsibility to keep the losses at low level. Loss reduction is therefore most important factor to be considered in planning and operation of DG.

In this work, different types of DGs based on their capability of injecting real and/or reactive power have been proposed to be placed in a planned manner into the distribution systems. The developed methodologies will be helpful to the developing countries like India, for integrating DG into the electrical systems for improvement in the system performance and for

mitigation of the power deficiency. The availability of quality supply of electricity is very crucial for the sustained growth of a country. Presently, India is in power deficient state, the average power deficiency is nearly 12.2% of peak demand. In the developing countries like India, DGs may widely be used to supply electric loads in integration with the grid. Some of the factors that must be taken into account in the planning process of expanding distribution system with DG are: the capacity of DG unit, best location and technology, the network connection, capacity of existing system, protection schemes, among others. Different methodologies and tools have been developed to identify optimal places to install DG capacity and its size. These methodologies are based on: knowledge-based approaches, optimization programs or heuristic techniques. The computer aided techniques have been employed for the purpose of mathematical modeling and implementation of the various approaches for the optimal placement of DGs in order to reduce losses and the improvement in voltage profiles. References reveal that many heuristic techniques like genetic algorithm (GA), tabu search algorithm, ant colony search algorithm and fuzzy logic have been used for optimal placement of DG, which requires extended computational time, and large memory size. Naturally, a more efficient approach is the need of the hour. Therefore, an analytical method and the application of particle swarm optimization (PSO) technique have been proposed in the present work for optimal placement of DGs to minimize the system losses, improvement in voltage profile and maximization of benefits. The PSO technique is computationally efficient and is a metaheuristic as it makes few or no assumptions about the problem being optimized and can search very large spaces of candidate solutions. It does not require that the optimization problem be differentiable as is required by classical optimization methods. Considerable amount of work on the sizing and siting of DGs have been reported in the literature, however some of the research gaps need attention of the researchers. Analytical methodology, PSO based algorithm and hybrid approaches have been applied to different configurations of DGs in different distribution systems. The results obtained have been compared for the validation of the proposed approaches.

Optimal placement of DG units in the distribution systems reduces the energy losses, improves the voltage profile, releases the transmission capacity, decreases equipment stress, and defers transmission and distribution upgrades. For even a small distribution network, the selection of the best DG allocation plan among the different possibilities needs computationally arduous efforts. Least loss method is one of the criteria to select the appropriate bus for DG placement, consequently, to reduce the search space and thus, to save the computational time to attain an optimal solution. To cater this requirement, an analytical approach has been developed for calculating the optimal size and location of type-I DGs in radial distribution system. The developed algorithm has been successfully applied to a 33-bus and 69-bus distribution test systems. The obtained results have been compared with the results obtained using PSO technique and loss sensitivity approach.

The proper allocation of DG units in distribution system plays a important role in achieving economical, technical, and qualitative benefits. Depending on their location, DG units may improve or worsen the system performance. The reduction of real power losses, improvement in voltage profile, diminution of harmonic pollution, enhancement in reliability, and deferral of network upgrade have been reported as the primary aims for DG placement in the literature. Most of these DG allocation techniques are well suited to allocate DGs injecting real power output. Since these existing techniques, do not incorporate the integration of type-I DG in reactive power compensated network. In this work optimal placement of type-I DG is integrated in reactive power compensated network in distribution systems. The reactive power of the network is compensated by the optimal placement of Capacitor. An analytical approach has been developed in this work to determine the optimal size, location and optimal power factor to achieve the objective by compensating the active and reactive powers. The objective function, considering the real power system loss has been minimized. The constraints on power flow equations, on bus voltages, on line loadings, and on sizes of DG and Capacitor have been considered. As distributed generation is defined as the generation of electricity by facilities that are sufficiently smaller than the central generating plants so to allow interconnection at nearly any point in a power system. The maximum DG installed capacity limits have been considered as 30%. The proposed approach has been applied to a 33-bus distribution test system, and also to a 69-bus distribution test system. In the proposed work, optimal power factor of DG has also been evaluated, and the effect of variation of power factor on the system losses has been analyzed. The results of the analytical approach have been compared with the results obtained based on other approaches like PSO and GA. As the capital cost of Capacitor is too less as compared to capital cost of DG. The integration of type-I DG in reactive power compensated network provides more economy to the system.

The existing literature reveals that, the optimal placement of the DG in the distribution systems is for reduction of power losses, Improvement in system voltage profile, maximization of DG capacity, minimization of investment and diminution of harmonic pollution. The optimal placement of different types of DGs i.e., type-I DG, type-II DG, type-III DG and type-IV DG in the distribution system have not been given due consideration in the techniques reported. Hence, a realistic mathematical approach considering different types of DGs has been proposed here.

Therefore, in this work suitable mathematical formulations have been developed for the optimal placement of different types of DG sources with various system constraints to minimize the system losses. The PSO based algorithm has been developed for the proposed approach and the obtained results are also verified with analytical approach results.

Most of the optimal placement techniques to allocate multiple DGs use heuristic approach only, and do not take the advantage of analytical approach. The analytical techniques may not be appropriate for optimal placements of multiple DGs alone. To fill this void, a hybrid approach has been developed in this work for optimal placement of multiple DGs of multiple types. In this approach the sizes of multiple DGs are evaluated at each bus and the optimal locations and power factor are determined by PSO technique. The objective function has been minimized under operating constraints. The proposed hybrid approach is tested on 33-bus and 69-bus test systems and the obtained results are compared with the results obtained using PSO.

The distribution system planners effort to supply economical and reliable electric power to the customer. It is important to design, operate and maintain the power system with lowest cost and highest benefit. Loss reduction and improvement in voltage profile are two important goals for electrical distribution companies. These companies work on various technologies and optimization programs to achieve economic benefits. They provide electricity with high quality and also prevent interruptions in distribution systems. The impact of DG on system operation depends highly on its location in the distribution system. Installation of DGs at improper locations would lead to increase in energy loss and loading of distribution feeders. For this reason, an optimization method must be used to find optimal DG location and size considering the costs and benefits to the customer and the utility. Optimal DG placement is a multivariable optimization problem with different operating constraints on DG in distribution system. Therefore, mathematical formulations for optimal sizing and siting of DGs and Capacitors in the distribution systems have also been developed in this work. The cost of electricity sold to the electricity market, loss reduction revenue, operating costs of DGs, constraints on number of DGs and Capacitors, maintenance costs and the payback period have been considered in this optimization. The developed formulation is a mixed-integer non-linear optimization problem and their solution has been obtained by a hybrid technique based on PSO approach.

The various contributions made through this work are summarized as follows:

- An analytical approach has been developed for optimal placement of type-I DG in the distribution system and the obtained results are compared with PSO technique and loss sensitivity approach results to validate the developed algorithm,
- An analytical approach has been presented for optimal placement of type-I DG in reactive power compensated networks in a distribution system. The optimal power factor has also been considered in this work,
- A PSO based algorithm has been proposed for optimal placement of different types of DGs sources i.e., type-I DG, type-II DG, type-III DG and type-IV DG in the distribution system and the results are validated with analytical approach,
- An hybrid approach consisting of analytical method and PSO technique has been developed for optimal allocation of the multiple DG units in the distribution networks, comparison has been made with the developed PSO algorithm,
- An objective function has been developed for the cost benefit analysis for DG placement in distribution network. This objective function has been maximized using PSO technique for the profit, taking the initial costs, operating costs, maintenance costs of DGs and Capacitors, cost of grid power, cost of DG power, present worth factor and payback period into consideration.

ACKNOWLEDGEMENTS

My foremost and profound gratitude goes to my guides **Dr. Barjeev Tyagi**, Associate Professor and **Dr. Vishal Kumar**, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, India, for their proficient and enthusiastic guidance, useful criticism, moral support, continuous encouragement, and immense help throughout the research and believing in me all the time. With their wide experience, sharp and incisive intellect, maestro ability combined with astute research methodology, and deep insight of the subject have unerringly steered the work on smooth and steady course. I sincerely appreciate their pronounced individualities, humanistic and warm personal approach, which have given me the strength and will to carry this research work. I humbly acknowledge a lifetime gratitude to my mentors.

I express my deep sense of gratitude to the Dr. Parmod Aggarwal, Professor and Head, Department of Electrical Engineering, for providing the necessary facilities and healthy environment to carry out the research work. I extend my thanks to all members of the Department of the Electrical Engineering, with its diverse nature of the faculty that has constituted the strength of the department.

I express my sincere thanks to Prof. S. P. Srivastva, Chairman D.R.C. and Prof. B. Das, Chairman S.R.C. and being member of my research committee, Department of Electrical Engineering and Dr. D. Das, Professor, Department of Water Resources Development and Management for sparing their valuable time in reviewing and critically examining the work.

My heartfelt thanks are due to the families of Dr. Barjeev Tyagi and Dr. Vishal Kumar for providing the moral support and co-operations, which made my stay at Roorkee, comfortable and memorable.

I wish to thank my M. Tech. friend Mr. Bhaskara Rama Sai for giving me support and energy in realizing my thoughts as successful research work.

I am indebted to my father Sh. Mange Ram Kansal and my mother Late Smt. Kaushalya Devi for their eternal support and everlasting blessings. I gratefully acknowledge the inspiration and unflagging support of my parents and parents-in-law. I wish to express my deepest gratitude to my brothers, Mr. Pawan Kansal, Mr. Ahsok Kansal and their families. I wish to express my wholeheartedly thanks to my brother-in-law, Dr. Prem Pal Bansal and their families.

I express my sincere appreciation and gratitude to my wife Gagan and my daughters Tanvi, Khanak and my lovely son Divesh, for bearing joyfully all the sorts of inconvenience and hard ship during my involvement in this work. I thank my wife for her patience, encouragement and close cooperation during the tenure of this work.

I would like to dedicate this research work to my family.

My special thanks are due to all my senior, fellow and junior research scholars Derminder Singh, Charu Sharma, K.S. Sajan, Himanshu Chaudhary at IIT Roorkee, for their cooperation and moral support from time to time. I am thankful to non-teaching staff of the Department of Electrical Engineering for their help and support.

I acknowledge my sincere gratitude to the Director, Baba Hira Singh Bhattal Institute of Engineering and Technology, Lehragaga, District Sangrur, Punjab (my parent institute), for granting me study leave to accomplish the Ph.D. work. I am thankful to my colleagues for sharing my work load at the institute in my absence.

Lastly, I owe a deep sense of gratitude to the All-Pervading, All-Sustaining Spirit whose divine light and warmth provided me the perseverance, guidance, inspiration, faith and strength to carry on even when the going got tough.

(Satish Kumar)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

The list of principle symbols used in the text and their abbreviations are given below. For the sake of clarity and similarity of symbols used in the text, some symbols are redundantly abbreviated.

Symbol	Stands for
Z_{ij}	Impendence of the line between bus i and bus j.
r_{ij}	Resistance of the line between bus i and bus j.
x_{ij}	Reactance of the line between bus i and bus j.
V_i	Voltage magnitude at bus i.
V_{min}	Minimum voltage magnitude of system buses.
V_{max}	Maximum voltage magnitude of system buses.
V_j	Voltage magnitude at bus j.
δ_i	Voltage angle at bus i.
δ_j	Voltage angle at bus j.
P_i	Active power injections at bus i.
Q_i	Reactive power injections at bus i.
P_j	Active power injections at bus j.
Q_j	Reactive power injections at bus j.
G_{ij}	Conductance of the line between bus i and bus j.
B_{ij}	Susceptance of the line between bus i and bus j.
P_{Gi}	Active power generation of generator at bus i.

Q_{Gi}	Reactive power generation of generator at bus i.
P_{Di}	Active power demand at bus i.
Q_{Di}	Reactive power demand at bus i.
P_{DGi}	Real power injection from DG placed at node i.
Q_{DGi}	Reactive power injection from DG placed at node i.
I_i	Current magnitude at bus i.
$I_i^{\boldsymbol{Rated}}$	Rated current permissible for branch i.
N	Number of buses.
X_m	Position of mth particle.
V_m	Velocity of mth particle.
v^k	Current velocity.
v^{k+1}	Modified velocity.
S^k	Current searching point.
S^{k+1}	Modified searching point.
$\mathrm{v}_{\mathrm{pbest}}$	Velocity based on pbest.
$\mathrm{v}_{\mathrm{gbest}}$	Velocity based on gbest.
n	Number of particles in a group.
m	Number of members in a particle.
pbest_i	pbest of agent i.
gbest_i	gbest of the group.
ω_i	Weight function for velocity of agent i.

c_i	Weight coefficients for each term i.
ω_{min}	Minimum weights.
ω_{max}	Maximum weights.
k	Current iteration.
k_{max}	Maximum iteration.
p.u.	Per unit.
%	Percentage
P_L	Real power loss
Q_L	Reactive power loss
IC_i	initial cost of i^{th} DG
IC_j	initial cost of j^{th} Capacitor
n	total number of years
ΔT	total number of working hours
MC_{DG}	Maintenance cost of DG
MC_{Cap}	Maintenance cost of Capacitor
IR	interest rate
S_T	rated capacity of the substation
S_{DG}	Capacity of DG
S_{Cap}	Capacity of Capacitor
n	total number of years
NDG	Number of DG

$NCap$	Number of Capacitor
K_{DGi}	capacity of i^{th} DG
K_{Capj}	capacity of j^{th} Capacitor
EP_G	electricity price of grid power
EP_{DG}	electricity price of DG power
OC_i	operating cost of i^{th} DG
OC_J	operating cost of j^{th} Capacitor
$\Delta Loss_{ij}$	reduction in real power loss due to DG and Capacitor
c_1 *and* c_2	PSO parameters
α, β	Parameters of Beta distribution function
S_i^{Max}	Loading limit for i^{th} branch
S_i	Apparent power flow in i^{th} branch
MW	Mega watt
MVAr	Mega volt ampere reactive
MWh	Megawatt hour
kWh	Kilowatt hour
MVArh	Mega volt ampere reactive hour
₹	Indian Rupee
LLR	Loss reduction revenue
$S_{T_{Real}}$	Rated capacity of real power of the transformer
$S_{T_{React.}}$	Rated capacity of reactive power of the transformer

PSO	Particle swarm optimization
GA	Genetic algorithm
S/S	Substation
Ω	Ohm
O & M	Operation and maintenance
β^t	Present Worth factor
IF	Inflation rate

LIST OF ABBREVIATIONS

The abbreviations used in the text have been defined at appropriate places, however, for easy reference, the list of abbreviations are being given below.

Abbreviation	**Stands for**
AC	Alternating Current
DC	Direct Current
DG	Distributed Generation
eq.	Equation
et al.	and others
etc.	et cetera
Fig.	Figure
GA	Genetic Algorithm
h	hour
i.e.	that is to say
IEEE	Institute of Electrical and Electronics Engineers
kV	kilo Volt
kW	kilo Watt
MVA	Mega Volt Ampere
MVAR	Megavolt ampere reactive
MW	Mega Watt
NR	Newton-Raphson
PSO	Particle swarm optimization
pu	per unit
PV	Photovoltaic

sec	second
Wp	peak-watt
wrt	with respect to
IR	Interest rate
IF	Inflation rate
NDG	Number of DG
NCap	Number of Capacitor
S/S	Substation
LLR	Loss reduction revenue
O & M	Operation and maintenance
ABC	Ant bee colony
ACO	Ant colony algorithm
EPRI	Electric power Research Institute
CIGRE	International Council on Large Electric Systems
OPF	Optimal power flow
p.f.	Power Factor
ANSI	American National Standards Institute

CHAPTER – 1

INTRODUCTION

1.1 OVERVIEW

The objective of power system operation is to meet the demand at all the locations within power network as economically and reliably as possible. The traditional electric power generation systems utilize the conventional energy resources, such as fossil fuels, hydro, nuclear etc. for electricity generation. The operation of such traditional generation systems is based on centralized control utility generators. These generators deliver power to widely dispersed users through an extensive transmission and distribution network. In the present environment, the justification for large central-station plants is weakening due to depleting conventional resources, increased transmission and distribution costs, deregulation trends, heightened environmental concerns, and technological advancements. Distributed Generation (DG), a term commonly used for small-scale generations, offer solution to many of these new challenges. Recent developments in small renewable/clean generation technologies such as wind turbines, photovoltaic, fuel cells, micro turbines and so on has drawn distribution utilities' attention to possible changes in the distribution system infrastructure and policy by deploying DG in distribution systems.

DG includes small generators, ranging from few kilowatts to megawatts, scattered throughout the power system, to provide the electric power to the consumer. The DGs are located either at utility's site or customer's site, or at on isolated site that is not connected to the network. CIGRE define DG as the generating plant with a maximum capacity of less than 100MW, which is usually connected to the distribution networks and that are neither centrally planned nor dispatched [28]. Other organization like, EPRI has defined the range as few kilowatts up to 50MW. Ackermann et al. [150] have given the definition of DG as: "DG is an electric power generation source connected directly to the distribution network or on the customer side of the meter." Considering the different definitions, it is evident that the meaning of DG is small-scale electricity generation.

The share of DG in power systems has been increasing in the last few years and it would further increase in near future because of the reasons stated earlier. Moreover, the policy initiatives taken to promote the DG throughout the world also indicate that the percentage of share will grow rapidly. There are number of DG technologies available and few of them are still in research and development stage. Currently some available technologies are reciprocating engines, combustion gas turbines, fuel cells, photovoltaic, and wind turbines. Each one of these technologies has its own benefits and limitations. Among all the DGs, gas turbines and diesel engines make up most of the capacity installed. Simultaneously, the new DG technology like micro turbine is being introduced and an older one like reciprocating engines is being improved [166]. Fuel cells have also attracted the attention of researchers.

1.2 MOTIVATION FOR THE PRESENT WORK

India is one of the fastest growing economics and has out of the highest development rate in the world. The availability of quality supply of electricity is very crucial for the sustained growth of the country. Electricity demand in India has been increasing rapidly, and generating capacity has grown manifold from 1,712 MW in 1950 to more than 211,766.22 MW today, though still representing only 860.72 kWh per capita per year. This per capita figure is expected to almost triple by 2020, with 6.3% annual growth. Presently, the country is in power deficient state, the average power deficiency is nearly 12.2% of peak demand. All the provinces are facing the power deficiency, in provinces like UP, MP, Maharashtra, Bihar, and Punjab; it is more than 20 percent. The power deficient situation of the country results in power cuts, blackouts, etc. Further, due to the changing weather conditions throughout the year, the amount of electric heating and cooling load is very high, which causes the high demand of electricity during these seasons. The establishment of large sized central power plants require huge amount of investment and long term planning. The environmental issues associated with nuclear and thermal power plants have made the conditions further challenging. The above-mentioned causes make the distribution generation from fuel cells, wind turbines, photovoltaic, and small/ micro hydro plants and gas/diesel generators compulsory for the continuous growth of the country under prevailing conditions.

1.3 CENTRAL VERSUS DISTRIBUTED GENERATION

The bulk of electric power used worldwide is produced at central station power plants, most of them utilizing large, fossil-fuel combustion or nuclear boilers to produce steam that derives steam turbine generators. The maximum power output of the majority of these central station generators is between 150 MW and 1200 MW. This makes them relatively large, in term the physical size and the facilities requirements, and often making site selection and procurement a real challenge. To keep pace with the growing power demand, low cost and quick solution is required. DG fulfills both the aspects and is being utilized extensively in today's power system.

1.4 ADVANTAGES OF DG INTIGERATION INTO POWER SYSTEMS

DG has several other advantages that make them attractive in some or all circumstances. Again, the value of these advantages varies from one situation to another, and given as follows:

1.4.1 Economical Benefits of DGs Integration

The economic benefits of DG integration can be summarized in following points as:

1. Installation of DG units near the load centers defers the necessity for:
    - Construction of new substations or expansion of existing ones,
    - Extension of new transmission lines to energize new substations,
2. Integration of DGs improves the system efficiency by:
    - Reducing the feeder power loss and minimizing the cost of losses,
    - Enhancing the system voltage profile and minimizing the number of required voltage regulators and capacitors,
    - Decreasing the loading on existing electric equipments, minimizing their maintenance costs, and increasing their service lives.
3. The planning of DG is considered as a short-term investment approach from the point of view of capital investment due to:
    - Low capital cost,
    - Paying the revenue and benefits back in a short period of time,
    - Requiring less time for installation (varying between a month and few years depending on the technology and size of DG).
4. Integration of DGs in distribution system minimizes the investment risk due to reduced capital costs and less installation time.

1.4.2 Operational Benefits of DGs Integration

Various operational benefits of DG integration are as follows:

1. DGs deliver safe, clean, reliable, and efficient electrical energy with no or low emissions,
2. DGs integration in the distribution system reduces the number of electric elements (substations, transformers, feeders, capacitors, regulators, protective

devices, and control circuits) in the network, which in turn, leads to minimization of number of possibilities as well as randomness of faults and outage occurrences,

3. DGs directly provide power in the vicinity of the loads and help in reducing the loadings on feeders,
4. DGs with their modern power electronic interface devices can be interconnected to the grid to meet power quality, reliability, and voltage profile requirements,
5. DG units can be operated for:
   - Peak load shaving to minimizing the required centralized reserve power,
   - Stand-by generation in case of electric utility failure,
6. Customer- owned DGs can help customer by providing some portion of their demands during peak load periods and by feeding the excess power to the grid during the light load periods. This way, they can get some revenue back from the electric utility.

1.5 DISADVANTAGES OF DG INTEGRATION

Inspite of several significant advantages of DG integration, the following may be the negative impacts on the system:

1. DGs may adversely affect the system stability,
2. Integration of DG may disturb the co-ordination and rating of existing devices,
3. DG units may increase the fault current levels of the system depending on their locations,
4. Use of invertors with asynchronous DG sources for interconnection, may inject harmonics into the system,
5. The capital cost per KW-installed power of DG is higher as compared to large central plants,

1.6 RENEWABLE ENERGY AS DG

The integration of DGs in power networks in India have been improved significantly in past few years. However, this requires more concern for the growth of the country. India is blessed with abundant solar energy equivalent to 5000 trillion kWh/yr besides several indirect forms of solar energy manifesting as hydro power, ocean energy, wind energy, bio-energy etc. Table 1.1 gives renewable energy potential in India [111, 110, and 42] and actual progress achieved up to the year 2012.

Table 1.1 Renewable Energy Potential in India

Energy source	Estimated Potential	Cumulative Installed capacity/ number
Wind power	45,000 MW	18321.10 MW
Small Hydro (upto 25 MW)	15,000 MW	3464.59 MW
Biomass Power	16,000 MW	1242.60 MW
Bagasse Cogeneration	3,500 MW	2199.33 MW
Waste to energy	2,700 MW	93.68 MW
Solar Power (SPV)	-----	1047.16 MW
Family size Biogas Plants	12 million	45.45 Lakh
Solar street lighting system	-----	1,19,634 nos.
Home lighting system	-----	6,03,307 nos.
Solar Lanterns	-----	7, 97,344 nos.
Solar photovoltaic power plants	2.92 MWp	
Solar water heating systems	140 million m^2 of collector area	5.63 Million m^2 of collector area
Solar photovoltaic pumps	-----	7334 nos.
Biomass gasifiers	-----	153.04 MW

Though the figures seem to be impressive, the contribution of renewable energy has not been significant. One of the constraints is low budgetary allocations (less than 1% of energy sector). Renewable energy programs are specially designed to meet the growing energy needs in rural areas for promoting decentralized and hybrid development so as to stem growing migration of rural population to urban areas in search of better living condition. Renewable sources already contribute to about 5% of the total power generating capacity in the country. Prospects for renewable are steadily improving in India (% of total installed capacity is expected to be 10% by 2020).

1.7 LITERATURE REVIEW

The area of optimal DGs placement is quite vast and consequently, the available references in this area are also extensive. The aim of this thesis is to perform comprehensive study of some of the problems related to the optimal sizing and siting of DGs in the distribution system to reduce the real power loss, improve the voltage profile and maximize the benefits. Available literature on various aspects of optimal placement and sizing of different types of DGs in the distribution system has been discussed as follows:

In the past decade, much effort has been contributed to solve the optimal capacitor placement problem by utilizing different algorithms and considering different objectives. The capacitors have been widely used in power system to reduce the power losses, improve the voltage sag, and increase the distribution feeder capacity. Capacitors provide reactive power required to low power factor loads, thereby decreasing the line current that reduces the active power loss (I^2R) of the line and therefore considered as a type of DG that generate reactive power. The capacitor placement problem could naturally be formulated as a mixed integer optimization problem. Various algorithms are used to solve the problem. For example, heuristic constructive algorithm has been presented in [66], in which the integer variables are represented by sigmoid function. Another heuristic method has been adopted to obtain a near optimal solution for realistic sized systems, with an objective of minimizing harmonic levels, losses and capacitor costs [20]. This method has been extended to take unbalanced load into consideration in [51]. Ant colony search algorithm has been used in [23] to study the optimal placement of capacitor as well as the optimal feeder reconfiguration problem in the distribution system. Various objectives have been proposed for the optimal placement of capacitor. The objective function of minimizing the economic cost subject to voltage limits, sizes of installed capacitors at each bus, and power quality limits of harmonics has been considered in [90]. The impacts of capacitor placement on distribution system reliability have been considered in [4] by defining two objective functions. The first one is the sum of reliability cost and investment cost, and the second one is the sum of reliability cost, cost of losses and investment cost. Mixed integer non-linear programming has been suggested by D. O. Leonardo et al. [33] for capacitor placement as well as for reconfiguration in order to achieve the objective of minimum energy loss operation of a radial distribution network. M.A.S. Masoum et al. [99] applied GA to minimize the cost of power loss and capacitor bank. The solution has been achieved considering various constraints like voltage limit, number and size of capacitors. J.V. Schmill [73] presented the well-known 2/3 rule for the placement of capacitor assuming a uniform load on a uniform distribution feeder. Neagle et al. [117] presented loss reduction achieved by one capacitor bank placed along the feeder considering uniformly distributed loads, uniformly decreasing loads and equally peak distributed loaded feeders. R.F. Cork [131] studied the effect of fixed capacitors in a radial distribution network with distributed loads for the reduction in energy loss. H. Dura [59] considered the capacitor sizes as discrete variables and employed dynamic programming, whereas Grainger et al. [71] developed a nonlinear programming based method in which capacitor location and capacity were expressed as continuous variables and they also formulated the capacitor placement and voltage regulation problem by proposed decoupled solution methodology for general distribution system [75]. Baran and Wu [84, 85] presented a method using mixed integer programming for the optimal placement of capacitor. Sundharajan and Pahwa [149] proposed the genetic algorithm approach to determine the optimal placement of capacitors, based on the mechanism of natural selection. Various other artificial intelligence techniques such as fuzzy logic, PSO and ant colony optimizations have also been used as tools for solving optimal capacitor allocation [34, 146, 148 and 163] to minimize the system loss, improvement in voltage profiles and other economic benefits. Recently, S.P. Singh et al. [148] employed the optimal placement of capacitors both switched and variable in the distribution system to minimize the real power loss and maximize the saving using PSO technique.

The available reference on various aspects of optimal placement and sizing of DGs in the distribution system reveal the use of various algorithms to solve the problem. An analytical method has been proposed in [112], to calculate the optimum size of DG at each bus in a primary distribution system, and to identify the best location corresponding to the optimum size of DG for the reduction in real power losses of the network. The real power loss formula has been used to find the optimal size of DG. The authors also determined the loss sensitivity factor to determine the best location for the placement of DG. However, optimal placement of the DG by this approach violates the standard minimum service voltage limit and the DG injects only the real power. An analytical expression has been developed in [25] that determine the optimal location of DG in a radial network for minimizing power distribution loss. Uniformly, centrally, and increasingly distributed load profiles with time invariant and time varying loads have been considered to solve the problem. T. Gozel et al. [152] also used the analytical approach to determine the optimal size and location by loss sensitivity factor, based on equivalent current injection technique without the use of admittance matrix for different types of loads i.e. constant power, constant current and constant impedance loads. Gandomkar et al. [87] minimized the network power losses by locating the DG units at selected nodes in the distribution or sub-transmission systems. Bhowmik et al. [1] developed an analytical method to predict allowable distribution resources in a radial feeder in order to limit the voltage harmonics. Griffin et al. [153]

presented an iterative algorithm to determine the near optimal placement of DGs in a power grid. An analytical method has been proposed for the allocation of DG units in the distribution systems. Kashem et al. [96] presented an analytical approach to minimize power loss in the distribution system by optimizing the size, location and operating point of DGs. They have considered two load characteristics: constant impedance load and constant current load. D. Thukaram et al. [37] presented the optimal placement of DG using relative electrical distance between the DG and the load point to minimize the power loss. A. Kazemi et al. [6] also determined the best size and location of DG in the distribution networks to reduce the real power losses by using analytical approach similar as used in [112]. G. Tuba et al. [55] found the optimal size and location of DG to minimize the system losses by using analytical expressions for uniform, centrally and increasing load models for the placement of single DG. Popovic et al. [40] and Greatbanks et al. [74] presented an iterative methodology using loss sensitivity and voltage sensitivity analysis of power flow equations to identify the best locations for placing DGs in the distribution network. Seon-Ju Ahn et al. [145] presented the placement of multiple DGs in a microgrid by the control of active power and frequency of the generated power. The authors proposed the various control modes and configurations of DGs and resulted that feeder flow control mode is more efficient with proper modification as compared to unit output-power control for proper sharing of power within the permissible frequency range of the system. D. Q. Hung et al. [45] determined the optimal size and optimal location of different types of DGs i.e. DGs capable of injecting real power, reactive power and both real power and reactive powers by analytical approach to minimize the losses and improve the voltage profile. The work has been extended in [44] to determine the optimal placement of different types of multiple DGs by improved analytical (IA) method which minimizes the power distribution loss and improves the voltage profile. The authors also determined the optimal power factor at which the power is generated by the DG. P. Mahat et al. [119] have presented simulation study for the optimal location and size of wind turbine DG in the primary distribution network.

In some of the approaches reported in litrature, Genetic algorithm (GA) has been applied to determine the optimal size and site of DGs to improve the power system performance. G.P. Harrison et al. [57] presented a hybrid method to find the best combination of sites for connecting a predefined number of DGs within the distribution network. The GA has been applied to search a large range of combinations of locations, employing optimal power flow to define available capacity for each combination. Using GA based technique; Kuri et al. [21] proposed a multi-objective formulation for optimal sizing and positioning of DGs in the distribution system. R.K. Singh et al. [132] also have determined the optimal size and location of

DG, based on nodal pricing benefit, loss reduction, and voltage improvement. The voltage rise issues have taken into consideration and it has been observed that a small capacity DG which is optimally placed gives more benefits as compared to a large capacity DG which is not optimally placed. The authors in [133], determined the optimal size and location of multiple DGs for increasing, centrally and uniform distributed loads for radial and networked systems. V. Kumar et al. [159] applied GA for the optimal placement of DG in the compensated distribution network for the complete restoration the system under cold load pick up (CLPU) condition. The operation of DGs conserves load diversity during outage period. The placement of DG during CLPU reduces the total demand of the system significantly, also improves the voltage profile and reliability of the network. Caire et al. [126] determined the system voltage drop and number of DGs in the distribution system along with voltage sensitivity indices. Refs [26, 157] presented the GA based methodologies to determine the optimal placement of DGs to minimize the real power loss and maximizing the benefits in terms of energy savings by reduction in active power loss. C. Tautiva et al. [24] determined the optimal placement and size of DG by taking the energy losses, voltage profile, reliability and initial investment, operating cost, price of electricity, cost of losses and energy not supplied into consideration and observed that reduction in loss is maximum, when the DG is installed at remote bus bars for maximum benefits. D. Singh et al. [35] presented the penetration of DG in the distribution company for maximization of profit and minimization of energy system losses with time varying loads and taking various constraints of the system into consideration. The authors in [36] placed the optimal size of DG at optimal location in the distribution system based on real and reactive power indices with different load models and MVA capacity. They used the voltage profile indices for the improvement of MVA capacity and voltage profile of the system, and observed the effects of load models on the optimal size and location of DG. For minimizing the system losses, Mardaneh et al. [92] developed GA based algorithm to optimize the location and the size of DGs for a distribution network in order to minimize the cost associated with the active and reactive generations of the DGs. Celli et al. [52] applied GA for the optimal sizing and siting of DGs in the distribution networks, considering technical constraints like feeder capacity limits, feeder voltage profile, and short circuit current in the network. Decision theory based heuristic optimization algorithm has been used to handle the uncertainties associated with the DG penetration. Celli et al. [53] developed the multi-objective formulation to achieve the best balance among cost of network upgrading, cost of purchased energy, cost of energy losses, and cost of energy not supplied. M. Mohammadi et al. [94] developed the optimal deign of microgrid consisting of PV, fuel cell, battery banks and DGs under hybrid electricity market to maximize the net present worth and observed that the net present worth decreases in hybrid electricity market compared to electricity pool market.

The particle swarm optimization (PSO) has also been exploited as a search tool to minimize the system losses as reported many authors. El-Zonkoly et al. [14] determined the optimal placement of multiple DGs using PSO technique as a multiobjective function taking the various indices like real and reactive power loss indices, voltage profile, MVA capacity and short-circuit level indices into consideration to achieve the desired objective. W. Krueasuk et al. [168] determined the optimal size and location of different types of DGs i.e. DG producing real power, producing reactive power and the DG producing real power and in turn absorbing reactive power in the distribution system for the reduction in real power losses. M.P. Lalitha et al. [106] and M. F. AlHajri et al. [102] determined the optimal size of DG at optimal location for the minimization of network power losses and improvement in the voltage profile taking the constraints of the system into account. P. Phonrattanasak [120] applied PSO technique to determine the optimal size and location of DG to minimize the economic cost and emission pollutants and it is observed that the economic cost and emission cost decreases when the number of DG increases. Carpinelli et al. [50] solved a multi-objective problem to minimize the cost of energy losses, the voltage profile indices, and the total harmonic distortion indices at all the system buses. El-Zonkoly et al. [13] also formulated the multiobjective function taking the various indices like real and reactive power loss indices, voltage profile, MVA capacity and short-circuit level indices to achieve the desired objective by the optimal placement of multiple DGs using PSO based technique.

In some other references, heuristic approaches like fuzzy-logic, ant colony algorithm, hybrid approaches have also been reported. EI-Khattam et al. [167] proposed a heuristic approach for DG capacity investment under competitive electricity market auction as well as fixed bilateral contact scenario. The optimal sizing and siting decisions for DG capacity has been obtained through a cost-benefit analysis approach from the perspective of a distribution company. R.A. Jabr and B.C. Pal [129] proposed the ordinal optimisation method for the placement of multiple DGs to minimize the loss and maximize the DGs capacities. S. Ghosh et al. [138] determined the optimum size and location of DG by using simple approach; the authors take the weights of energy loss and cost of DG. The weights have been changed to achieve the objective. M.R. Haghifam et al. [108] used fuzzy variables in the minimization of the cost taking the initial cost, operating cost, maintenance cost and cost of losses into consideration. The various technical constraints like risk of voltage violation, loading constraints and economic constraints due to uncertainty in electricity market price, have been taken into account. H.

Falaghi et al. [60] developed an ant colony optimization (ACO) based algorithm to minimize the cost taking the initial investment on DGs, operating cost, maintenance cost, electricity price of market, inflation rate, interest rate, present worth factor over the described planning period. Authors in [48] have utilized the ABC algorithm to determine the optimal size and sites of DG's and capacitor combinations. Their work included the two load scenarios at predetermined power factor. M.F. Akorede et al. [100] determined the optimal location and size of DG to maximize the system loading and profit for the distribution company using GA with fuzzy controller. They also observed the viability of DG when the upgradation of the substation and feeders is required due to the increase in load. M.H. Moradi et al. [104] determined the optimal location of DG by the application of GA and optimal size of DG with PSO technique to minimize the real power loss and improve the voltage profile of the system. M. M. Elnashar et al. [91] determined the optimum sitting and sizing of a large DG in mesh connected distribution system. They have given the different importance to voltage profile and power loss by giving them different weights. A.K. Singh et al. [12] presented the integration of various types of renewable DGs in the distribution system to minimize the cost of each source and combination of different types of DGs. The authors have determined the optimal locations for different types of DGs sources using mixed integer non-linear programming to minimize the objective function. A. Keane et al. [7] employed linear programming technique to optimize the location of DGs in the distribution networks. They maximized the total DG capacity considering the technical constraints applied on voltage profile, line loadings, equipment ratings, and faults levels. Y.M. Atwa et al. [171] presented the optimal placement of wind DGs in the distribution system to minimize the annual energy losses using generation-load model. The optimization problem has been solved by using mixed integer non-linear programming in GAMS software considering various system constraints. N. Khalesi et al. [116] presented the optimal placement of DGs for the improvement in system reliability by using dynamic programming with the consideration of different load models. Rahman et al. [155] presented an evolutionary programming based technique. The sensitivities of voltage stability with respect to change in injected active and reactive power at load buses have been consider to identifying the suitable location for DG placement. M. Ahmadigorji et al. [83, 82] presented the optimal placement of DG in the system using forward dynamic programming to maximize the benefit to the consumers and electric utility by taking various operational constraints. D. Gautum et al. [29, 30] used OPF based on locational marginal price and consumer payment, taking the marginal loss component and a congestion component into account for social welfare and net profit maximization. It was observed that the high penetration of DG leads to less benefit for DG owner.

Some other approaches have also been used for DG placement. An iteration algorithm has been used by H. Hedayati et al. [61], in which power flow is adopted to decide the most sensitive bus to voltage collapse with maximum loading for DG installation. The Objective functions are constituted for the reduction in the power loss, increase in power transfer capacity and the maximization of loading, and increase in voltage stability margins. M.F. Akorede et al. [100] installed the optimal size of DG in the existing system to maximize the system loading and profit to the distribution company for a particular period. It was observed that penetration of DG is more cost effective than the expansion of substation and feeder facilities to meet the increasing demand of the consumers. B. Tyagi et al. [22] determined the optimal placement of reactive power sources based on technical and economic criteria. The authors determined the optimal location based on loss sensitivity index and taking few top ranked load bus for economic analysis to minimize the objective function.

1.8 OBJECTIVES AND AUTHOR'S CONTRIBUTION

Many researches have investigated and analyzed the impacts of DG placement in the distribution system on various measures of system performance, such as voltage profile, regulation, power losses, system stability and cost benefits. The optimal placement of DG in distribution systems offers several technical and economic benefits to utilities and customers, such as reduced line and transformer losses, improved system voltage profile, reduced central generating station reserve requirements, relieved transmission and distribution congestion, improved system reliability, enhanced power quality, deferred transformer and transmission line upgrades, extended equipment maintenance intervals, reduced environmental impacts and an overall improvement of system efficiency. At the same time, however, placement of DGs does not always guarantee an enhanced system performance. Depending on the size, location and penetration level, DG may have negative impacts on energy losses, voltage regulation, system reliability, power quality, and system stability. On the basis of generated power DG's can be characterized into different types as [45]:

Type I: DG capable of injecting real power only, like photovoltaic, fuel cells etc. are the good examples of Type-I DG,

Type II: DG capable of injecting reactive power only to improve the voltage profile fall in Type-II DG, e.g. kvar compensator, synchronous compensator, capacitors etc.

Type III: DG capable of injecting both real and reactive power, e.g. synchronous generators, Type IV: DG capable of injecting real but consuming reactive power, e.g. induction generators used with turbines.

Most of the approaches presented so far to formulate the optimal placement problem of DG are considering only the type-I DGs. In the present work all the four types of DGs are considered for their optimal placement. Different methodologies and approaches have been developed to identify optimal location to install DG with optimal size. These methodologies are based on: mathematical analysis and search techniques. The computer aided formulations have been made for the purpose of mathematical modeling and implementation of the various approaches for the optimal placement of DGs in order to reduce losses and the improvement in voltage profiles.

References reveal that many heuristic techniques like genetic algorithm (GA), tabu search algorithm, ant colony search algorithm and fuzzy algorithm have been used for optimal placement of DG. Therefore the application of efficient search approach is the need for the solution of such optimization problems. Therefore, particle swarm optimization (PSO) based technique have been applied in this thesis for the optimal placement of DGs to minimize the losses and improvement in voltage profile and system performance. The PSO technique is computationally efficient and is a metaheuristic as it makes few or no assumptions about the problem being optimized and can search very large space of candidate solutions. The comparisons of obtained results with those obtained by analytical method validate the use of PSO based algorithm for the optimal placement of DGs in the distribution system. A PSO based technique has been proposed for determining the optimal size and location of DGs in radial distribution system. The developed algorithm has been applied, to 33-bus and 69-bus distribution test systems. The obtained results have been compared with the analytical approach results in terms of optimal size, location and reduction in line losses.

As reported in the literature, most of these DG integration techniques are well suited to allocate DGs with real power output i.e., Type-I DGs. The references focusing on the integration of type-I DG along with reactive compensating devices like capacitors are few [48, 89, 95, 137, and159]. Hence, the problem, regarding the optimal allocation of type-I DG in reactive power compensated distribution systems, still requires adequate attention. Mostly, the reactive power of the network is compensated by the optimal placement of type-II DG (capacitor). In this work the simultaneously placement of type-I and type-II DGs in distribution systems is addressed. PSO based algorithm has been developed to find the optimal size and locations of type-I and type-II DGs to minimize the real power loss with the consideration of the various system constraints. An analytical approach has also been proposed in this work to determine the optimal size and location, and optimal power factor to achieve the objective. The objective function for finding the real power loss has been minimized. The constraints on power flow equations, on bus voltages, on line loadings, and on sizes of type-I and type-II DGs have also been taken into account. As distributed generation is defined as the generation of electricity by facilities that are sufficiently smaller than the central generating plants so to allow interconnection at nearly any point in a power system. Hence, in the present work the total installed capacity of type-I and type-II DGs in the network have been limited to less than 30% of substation rated capacity to maintain the concept of DG against centralized generation and the sizes of type-I and type-II DGs are taken as per standard rating available in the market. The optimal power factor of DG has also been evaluated, and the effect of variation of power factor on the system losses has also been analyzed. The proposed approach has been illustrated on 33-bus and 69-bus power distribution systems. The results obtained have been compared with the existing approach in terms of optimal size, location and reduction in line losses.

On the basis of availability of natural energy sources like wind energy, hydro energy, solar energy etc., the different type of electric power generator are installed. These different types of generators involve different costs and benefits. The proposed work exploits the diversity of generation by the optimal placement of type-IV DG used in wind turbines. It is evident from literature that, in the problem of DG placement the optimization has been performed for reduction in power losses, Improvement in system voltage profile, maximization of benefits, minimization of investment cost. However, the optimal placement of type-IV DGs in the distribution system has not been given due consideration in the reported work. Some of the references have addressed the placement of different types of DGs [12, 44, 45, 113 and 119]. Therefore, in this thesis suitable mathematical formulations have been developed for the optimal placement of type-IV DG sources to minimize the system losses with various system constraints. The PSO based algorithm has been developed for the proposed approach and the results obtained are also verified with the results of analytical approach.

The analytical approaches [26, 44, 129, 133, and 157] reported in literature have some limitations. These approaches are not suitable for large sizes power networks because of their mathematical complexity. The multiple DGs are placed in iterations, placing one DG in each iteration, which may not lead to an optimal solution. The heuristic based approaches are more suitable to determine the optimal size and location of multiple DGs in a larger system. A hybrid approach has been proposed in this thesis for optimal placement of multiple DGs which exploits the advantages of both analytical and heuristic approaches. In this approach the sizes of multiple DGs are evaluate at each bus by analytical method while the optimal locations and power factor are determined by application of PSO technique. The various operating constraints e.g. power flow equations, voltage limits, line current carrying capacities are taken into account. The proposed hybrid approach is tested on 33-bus and 69-bus test systems and the results obtained are compared with the results obtained with other approaches.

Distribution system planners effort to supply economical and reliable electric supply to customers [24, 35, 50, 53, 82, 83, 92, 94, 100, 101, 113, 116, 120, 132, 138, 148, 167]. It is important to design, operate and maintain reliable power systems with lowest cost and highest benefit. Loss reduction and improvement in voltage profile are two important goals for electrical distribution companies. The companies need various technologies and optimization programs to bring these economic benefits. The electricity is supplied with high quality and reliability and also prevents interruptions in the power supply. On the other hand, the cost involved in DG placement and operation is also reduced by proper reactive power compensation. For this reason, an optimization method has been presented to find the optimal location and size of DG considering the costs and benefits to the customers and the utility. Optimal placement of DG is a multivariable optimization problem with different operating constraints. Therefore, mathematical formulations for optimal sizing and siting of DGs and capacitors in the distribution systems have also been developed in this thesis. The cost of electricity sold to the electricity market, loss reduction revenue, operating costs and maintenance costs of DGs and capacitors, constraints on number of DGs and capacitors and their sizes to maintain the concept of distributed generation, and the time period in which the total cost occurred can be recovered have been taken as constraints. The developed formulation is a mixed-integer non-linear optimization problem and their solution has been obtained by PSO based technique.

1.9 ORGANIZATION OF THE THESIS

The present thesis has been organized into seven chapters and the work included in each chapter has been presented in the following sequence:

Chapter-1 the current chapter, gives an overview of distributed generation, presents detailed literature review on the problems towards the problem area and the objective taken in this work, and finally, outlines the organization of the present thesis.

Chapter-2 deals with the development of analytical approach for the optimal placement of type-I DG in the distribution system taking the system constraints into account and the results obtained are validated with a proposed PSO algorithm results.

Chapter-3 describes a mathematical formulation developed for optimal placement of type-I DG and type-II DG in power network. The reactive power of the network is compensated by the optimal placement of type-II DG. The sizes of DGs are evaluated with and without size limit. The optimal power factor has also been evaluated.

Chapter-4 presents the optimal placement of type-III DG. A hybrid approach has been proposed that utilizes the feature of both, the analytical and the PSO approach. The optimal power factors are also evaluated. The optimal placement of DGs are determined with and without size limit.

Chapter-5 proposes the placement of type-IV DG for the integration of non-conventional energy sources like wind turbine. Both the developed approaches, analytical and PSO are applied for determining the optimal size and sites.

Chapter-6 describes the mathematical formulations for the optimal placement of real power and reactive power sources in distribution networks for maximization of benefits. The initial installation cost, operating and maintenance costs of DGs and capacitors, cost of grid power have been taken into account. The involved costs have been evaluated considering interest rate paid, inflation rate for the described planning period.

Chapter-7 concludes the work contained in the main body of the thesis and presents the suggestions for the future work.

CHAPTER – 2

OPTIMAL PLACEMENT OF TYPE-I DGs

2.1 INTRODUCTION

During the last few years the penetration of DG in the power distribution systems has been increasing rapidly in many parts of the world. As the penetration of distributed generation is increasing in the distribution network, it is no more passive in nature and its characteristics is becoming similar to an active transmission network. Therefore, it is in the best interest of all the players involved to allocate them in an optimal way such that it will reduce power distribution loss, improve the voltage profile and hence increase system reliability, while serving the primary goal of power injection.

There are many approaches for deciding the optimum sizing and siting of DG units in distribution systems. Some of the factors that must be taken into account in the planning process of expanding distribution system with DG are: the capacity of DG unit, best location and technology, the network connection, capacity of existing system, protection schemes, among others. Different methodologies and tools have been developed to identify optimal places to install DG and its size. These methodologies are based on analytical tools, optimization programs or heuristic techniques. Much effort has been contributed to solve the optimal DG placement problem, utilizing different algorithms and considering different objectives.

In the past decade, much effort has been contributed to solve the optimal DG placement problem, utilizing different algorithms and considering different objectives. The DG placement problem could naturally be formulated as a mixed integer nonlinear optimization problem. Various algorithms have been used to solve the optimal problem considering real power loss as the objective function. An analytical method has been proposed in [1, 6, 25, 44, 45, 49, 55, 96, 112, 152] to decide the optimal allocation of DG, in radial as well as in mashed systems, to minimize real power losses. Genetic algorithms (GA) [26, 35, 52, 92, 100, 126, 132, 133, 157, 159, 160], PSO techniques [9, 13, 14, 102, 104, 106, 113, 115, 120, 148, 168], and other heuristic approaches [7, 37, 40, 48, 60, 68, 74, 78, 83, 108, 116, 128, 129, 155, 167, 171] have also been applied to determine the optimal size of DG to minimize the system losses. All the approaches differ from each other by way of their problem formulation and/or the problem solution methods employed. An analytical approach [112] has been proposed to calculate the optimum size of DG at each bus of the primary distribution system and to identify the best location corresponding to the optimum size of DG for reduction in real power loss of the network. However, the optimal placement of DG by this approach violates the voltage constraints of the system. D.Q. Hung et al. [45] determined the optimal size and optimal location of different types of DGs by analytical approach. In this work, the authors have exploited the DG, capable of injecting real and reactive power. Authors in [44] have also determined the optimal placement of different types of multiple DGs by improved analytical method to minimize the power distribution loss and improvement in voltage profile.

PSO based techniques have also been applied to minimize the system losses as reported in the literature. W. Krueasuk et al. [168] determined the optimal size and location of different types of DGs in the distribution system for the reduction in real power loss using PSO technique. M. F. AlHajri et al. [102] determined the optimal size of DG at optimal location by using PSO technique for minimization of network power loss and improvement in the voltage profile taking the constraints of the system into account. Recently, S.P. Singh et al. [148] employed the optimal placement of DGs in the distribution system to minimize the real power loss and maximize the saving using PSO technique.

In the present work, analytical approach, and PSO based technique have been applied for the optimal placement of type-I DG units in the distribution systems. DGs supplying only real power have been considered for the placement. Two power distribution networks, 33-bus and 69-bus, have been used for the illustration purpose. The results obtained from analytical and PSO approaches have been compared. A significant reduction in losses and improvement in voltage profile have been observed.

2.2 LOCATION AND SIZING ISSUES

The placement of DG plays an important role in minimizing the losses. Fig. 2.1 shows a three dimension plot of typical power loss versus size of DG at each bus in the 69-bus distribution test system for the given loading conditions [84]. From the figure, it is clear that at a particular bus, as the size of DG increases the loss also decreases and at a particular value of size, the loss reaches to its minimum. If the size of DG is further increased, the losses starts to increase and it may overshoot the losses of the base case. It is also observed from the figure that the location of DG plays an important role in minimizing the losses. Therefore, it can be concluded that for a given characteristics of the distribution system, it is not advisable to install the DG of any size in the network. The size of DG at most should be such that it does not increase the line losses and also does not violate other required operating constraints. Any attempt to install high capacity DG with the purpose of exporting power beyond the substation (reverse flow of power though distribution substation), may lead to very high losses and failure of protection schemes designed for radial networks [112]. Thus without reinforcement of the system, the use of

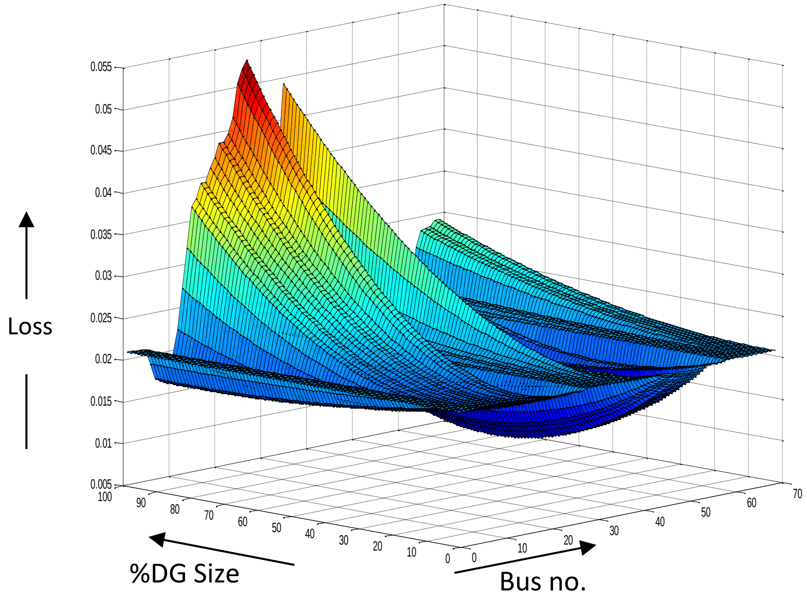


Figure 2.1: Effect of size and location of DG on system loss

high capacity DG may lead to excessive power flow through small-sized conductors and hence results in higher losses and may causes protection collapse. In the following section, determination of the optimal location and size of type-I DG has been explained.

2.3 PROBLEM FORMULATION

This section deals with the problem formulation for finding the optimal size and location of type-I DG and defines various constraints associated with different standard operational limits.

2.3.1 Objective Function

The objective of the current DG placement problem is to minimize the power distribution losses in the network. In this chapter, the Exact Loss formula [47] as given by (2.1) has been used to evaluate the real power losses of the system. The objective function is given by,

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \tag{2.1}$$

2.3.2 Constraints

There are certain standard limits for the parameters defined for the proper operation of the power system. These limits/constraints are required to be satisfied.

(a) Constraint on power flow equations

The power flow equations of the network should be satisfied, which can be written as:

$$P_{Gi} - P_{Di} = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \cos\left(\delta_i - \delta_j\right) + B_{ij} \sin\left(\delta_i - \delta_j\right) \right] \qquad \forall i = 1,2,3, \ldots \ldots N \qquad (2.2)$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \sin\left(\delta_i - \delta_j\right) - B_{ij} \cos\left(\delta_i - \delta_j\right) \right] \qquad \forall i = 1,2,3, \ldots \ldots N \qquad (2.3)$$

(b) Constraint on bus voltage magnitude

The inclusion of DG may cause either over-voltage or under-voltage in the distribution system, which is undesirable. Hence, the voltage magnitude at each bus of the system is restricted by lower and upper limits. This constraint can be given as:

$$V_{min} \le V_i \le V_{max} \qquad (2.4)$$

Where,

V_i = Voltage magnitude at i^{th} bus, $\forall i \in N$
N = Number of buses in the system,
V_{min} = Minimum voltage limit,
V_{max} = Maximum voltage limit.

The American National Standards Institute (ANSI) standard C84.1-1989 has stipulated that voltage variations in a distribution system should be controlled within the range of -13% to 7% [18]. In this work, the allowable voltage limits are considered as ± 5%.

(c) Constraints on line current

In transmission and distribution systems, each line or branch is designed to carry a certain amount of maximum current, which is termed as ‘Thermal Limit’. Loading a line beyond its thermal limit can cause severe damage to the line. Hence, the planner must make sure that the line loading limits are not violated due to integration of DGs. The constraints on line loadings can be given as:

$$I_i \le I_i^{Rated} \qquad \forall i \in N_{Br} \qquad (2.5)$$

Where,

I_i = Current flow in i^{th} branch,

N_{Br} = Number of branches in the system,

I_i^{Rated} = Current permissible for i^{th} branch.

2.3.3 Assumptions

The following assumptions have been made in the solution of current problem of placement of type-I DG in distribution systems:

I. The bus loading given in the data are considered as peak load,

II. Type-I DG can deliver only active power.

2.4 PROPOSED APPROACHES

The optimal placement of type-I DG is proposed in two ways, first by the application of the analytical approach and then using the PSO based approach. Although, the analytical approach gives exact optimal solution, but in a large system it takes more computational time since it calculates the size of DG at each bus. It is not suitable for placement of multiple DGs as the size of next DG may not be optimal for loss minimization. Hence, in a larger system, heuristic approaches are more suitable for finding the location and size of DG. PSO is a metaheuristic as it makes few or no assumptions about the problem being optimized and can search very large spaces of candidate solutions.

2.4.1 Analytical Approach

Consider a N bus distribution system. The total real power loss in the system is given by (2.1).

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

Where,

$$\alpha_{ij} = \frac{R_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right) \tag{2.6}$$

$$\beta_{ij} = \frac{R_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right) \tag{2.7}$$

and

$Z_{ij} = r_{ij} + jx_{ij},$ Z_{ij} is i^{th} row and J^{th} column element of $[Z_{bus}]$ matrix (2.8)

Z_{ij}- Impendence of the line between bus *i* and bus *j*,

r_{ij}- Resistance of the line between bus *i* and bus *j*,

x_{ij}- Reactance of the line between bus *i* and bus *j*,

V_i- Voltage magnitude at bus *i*,

V_j- Voltage magnitude at bus *j*,

δ_i-Voltage angle at bus *i*,

δ_j-Voltage angle at bus *j*,

P_i & Q_i are active and reactive power injections at bus *i*,

P_j & Q_j are active and reactive power injections at bus *j*.

The total power loss against real power injection is a parabolic function and at the point of minimum loss, the rate of change of loss with respect to injected power becomes zero.

$$\frac{\partial P_L}{\partial P_i} = 2\alpha_{ii}P_i + 2\sum_{\substack{j=1\\ j\neq i}}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right) = 0 \tag{2.9}$$

It follows that

$$P_i = -\frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\ j\neq i}}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right)\right] \tag{2.10}$$

This is given as

$$P_i = P_{Gi} - P_{Di} \tag{2.11}$$

Where,

P_{Gi}- Power generated at bus *i*,

P_{Di}- Power delivered at bus *i*.

If P_{DGi} is the real power generation from type-I DG placed at bus *i*, then

$$P_i = P_{DGi} - P_{Di} \tag{2.12}$$

and

$$P_{DGi} = P_{Di} - \frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\ j\neq i}}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right)\right] \tag{2.13}$$

Equation (2.13) gives the amount of active power that is to be supplied by type-I DG at bus *i*, for the loss to be minimum. Any size of type-I DG other than P_{DGi} placed at bus *i*, will lead to higher loss. The optimal size of type-I DG can be determined by satisfying the system constraints for each bus. The bus with the DG of determined size and satisfying all the constraints is the optimal location for the placement of DG.

2.4.1.1 Computational Procedure

Following is the computational flow involved in determining the optimal size and optimal location of type-I DG by analytical approach in a distribution system.

Step 1: Calculate the base case loss using distribution load flow based on backward sweep-forward sweep method as given in the Appendix-B.

Step 2: Find the base case loss using (2.1).

Step 3: Find the size of type-I DG at each bus except the reference bus using (2.13) for minimum distribution loss.

Step 4: Check constraint violation after the placement of DG, determined in step 3, at each bus.

Step 5: Select the bus for minimum loss while satisfying all the constraints for the placement of DG, i.e. the optimal location.

Step 6: Run the load flow with the type-I DG of optimal size placed at the optimal location.

Step 7: Calculate the reduction in real power loss after placement of the type-I DG.

The analytical approach provides exact optimal solution however, requires the evaluation of each bus for the placement and may be suitable for a smaller network. The heuristic based approaches are more suitable to determine the optimal size and location of DGs in a larger system. Therefore a search is required for dealing with large networks. In this thesis PSO has been used for searching the optimal solution.

2.5 PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a population-based optimization method first proposed by Kennedy and Eberhart in 1995, inspired by social behavior of bird flocking or fish schooling [72]. The PSO as an optimization tool provides a population-based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience (This value is called Pbest), and according to the experience of a neighboring particle (This value is called Gbest), made use of the best position encountered by itself and its neighbor as shown in Fig. 2.2. This modification can be represented by the concept of velocity. In PSO algorithm, particle swarm consists of *n* particles, and the position of each particle stands for the potential solution in *d*-dimensional space. The particles change its condition according to the following three principles:

(i) Inertia,
(ii) Change the condition according to its most optimist particle,
(iii) Change the condition according to the swarm's most optimist particle.

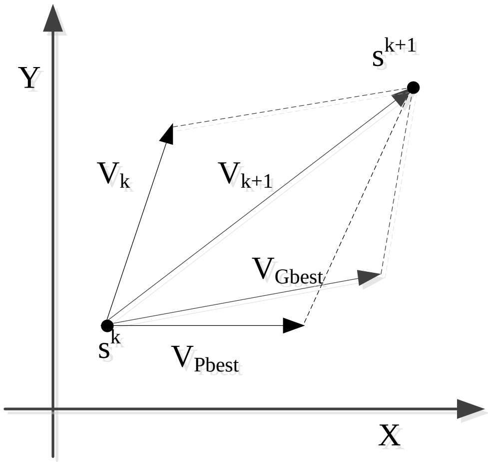


Figure 2.2 Concept of a searching point by PSO

The velocity of each particle can be modified by the following equation:

$$v_{id}^{k+1} = \omega v_{id}^{k} + c_1 rand \times \left(pbest_{id} - s_{id}^{k}\right) + c_2 rand \times \left(gbest_{id} - s_{id}^{k}\right) \qquad (2.14)$$

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$S_{id}^{k+1} = S_{id}^{k} + v_{id}^{k+1}, \qquad i = 1,2,\dots,n, \quad d = 1,2,\dots,m \qquad (2.15)$$

Where,

S^k is current searching point,
S^{k+1} is modified searching point,
v^k is current velocity,

v^{k+1}	is modified velocity of agent *i,*
v_{pbest}	is velocity based on pbest, ,
v_{gbest}	is velocity based on gbest,
n	is number of particles in a group,
m	is number of members in a particle,
$pbest_i$	is pbest of agent *i,*
$gbest_i$	is gbest of the group,
ω_i	is weight function for velocity of agent *i,*
c_i	is weight coefficients for each term.

An Inertia weight ω is a proportional agent that is related with the speed of last time. The influence that the last speed has on the current speed can be controlled by inertia weights. The bigger ω is, the bigger the PSO's searching ability for the whole is, and the smaller ω is, the bigger the PSO's searching ability for the partial. Generally, ω is equal to 1, so at the later period of the several generations, there is a lack of the searching ability for the partial. Experimental results show that PSO has the biggest speed of convergence when ω is between 0.8 and 1.2. While experimenting, ω is confined from 0.9 to 0.4 according to the linear decrease, which makes PSO search for the bigger space at the beginning and locate the position quickly where there is the most optimist solution. As ω is decreasing, the speed of the particle will also slow down to search for the delicate partial. The method quickens the speed of the convergence, and the function of the PSO is improved. When the problem that is to be solved is very complex, this method makes PSO's searching ability for the whole at the later period after several generation is not adequate, the most optimist solution cannot be found, so the inertia weights can be used to work out the problem. The following weight function is used:

$$\omega_i = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{k_{max}}.k \tag{2.16}$$

Where,

ω_{min} and ω_{max} are the minimum and maximum weights respectively and k and k_{max} are the current and maximum iteration. Appropriate value ranges for C_1 and C_2 are 1 to 2, but 2 is the most appropriate in many cases. Appropriate values for ω_{min} and ω_{max} are 0.4 and 0.9 [130] respectively.

2.5.1 Stopping Criteria

There can be many kinds of stopping criteria. Four of those ways to determine stopping criteria are given below.

1. Set a maximum number of iterations after which it has to stop which depends upon the number of variables the problem, complexity of the objective function and number of particles of the PSO being implemented.
2. Stop when change in *pbest* from the previous iteration to the current iteration is below a certain value ε or taken as zero.
3. Stop when change in *particle* from the previous iteration to the current iteration is below a certain value ε.
4. Stop if Gbest is not changing for a particular number of iterations.

2.5.2 General PSO Algorithm

The PSO-based approach for minimizing the fitness takes the following steps:

Step 1: Randomly generate an initial population (array) of particles (particle consist of all the variable parameters that are needed to be varied) with random positions and velocities on dimensions in the solution space. Set the iteration counter k = 1.

Step 2: Calculate fitness of each particle using objective function.

Step 3: For each particle, compare its objective value with the individual best. If the objective value is lower than Pbest, set this value as the current Pbest, and record the corresponding particle position.

Step 4: Choose the particle associated with the minimum individual best Pbest of all particles, and set the value of this Pbest as the current overall best Gbest.

Step 5: Update the weight, velocity and position of particle using equation (2.16), (2.14) and (2.15) respectively.

Step 6: If the iteration number reaches the maximum limit, go to Step 7. Otherwise, set iteration index k = k + 1, and go back to Step 2.

Step 7: Print out the optimal solution to the target problem.

2.5.3 Advantages of Particle Swarm Optimization

The followings are the advantages of particle swarm optimization:

- PSO algorithm is based on the swarm intelligence. It can be used for both research and engineering use,

- There is no overlapping and mutation calculation in PSO algorithm. The search can be carried out by the speed of the particle. For the development of several generations, only the most optimist particle can transmit information onto the other particles, and the researching speed is very fast,
- The calculations in PSO algorithm are very simple as compared with the others, it has the larger optimization ability and can be completed easily,
- PSO adopts the real number code, and it is decided directly by the solution. The number of the dimension is equal to the constant of the solution.

2.5.4 Disadvantages of Particle Swarm Optimization

The disadvantages of particle swarm optimization are:

- The PSO algorithm suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction,
- It cannot solve the scattered problems,
- The algorithm cannot solve the problems of non-coordinate system, such as solution to the energy field and the moving rules of the particles in the energy field.

2.6 PSO BASED APPROACH FOR TYPE-I DG PLACEMENT

Consider the i^{th} particle in an *n*-dimensional vector is represented as:

$$X_i = \left(x_{i,1}, x_{i,2}, x_{i,3}, \dots\dots\dots\dots x_{i,n}\right) \tag{2.17}$$

Where $x_{i,n}$ is the variable of the objective function to be optimized. In the present work the numbers of particles are taken as 10 and the dimension of search space is 2 (DG location and DG size).

2.6.1 Proposed PSO Algorithm

The PSO based approach for solving the problem of optimal placement of type-I DG to minimize the loss takes the following steps:

Step 1: Input the line and bus data, and the bus voltage limits.

Step 2: Calculate the loss using distribution load flow.

Step 3: Generates randomly an initial population (array) of particles with random positions and velocities on dimensions (size of DG and location of DG) in the solution space. Set the iteration counter *k* = 0.

Step 4: For each particle if the bus voltage is within the limits as given above, evaluate the total loss in equation (2.1). Otherwise, that particle is infeasible.

Step 5: For each particle, compare its objective value with the individual best. If the objective value is lower than *Pbest*, set this value as the current *Pbest*, and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best *Pbest* of all particles, and set the value of this *Pbest* as the current overall best *Gbest*.

Step7: Update the weights, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Else, update iteration index $k = k + 1$, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal location and size of type-I DG and the corresponding fitness value representing the minimum total real power loss.

2.7 RESULTS AND DISCUSSION

Both the approaches, analytical and PSO have been applied on two different power distribution test systems. A computer software program has been developed for the proposed analytical approach, and PSO based technique in MATLAB environment.

12.66 kV, 33-Bus Distribution System

The first system is 33-bus radial distribution systems with total load of 3.72 MW and 2.3 MVAr [97] with Beaver conductors. The schematic diagram for 12.66 kV, 33-bus distribution system is depicted in Fig. A.1, while the relevant data are presented in Table A.1 of APPENDIX-A. This system is fed by a sub-station at bus number 1 (Fig. A.1).

Based on the analytical expressions (2.13), the size of type-I DG is calculated at each bus of the test system as shown in Fig. 2.3. By placing the size of DG at the respective bus as obtained from (2.13), the total power losses of the system are calculated and results are shown in Fig. 2.4.

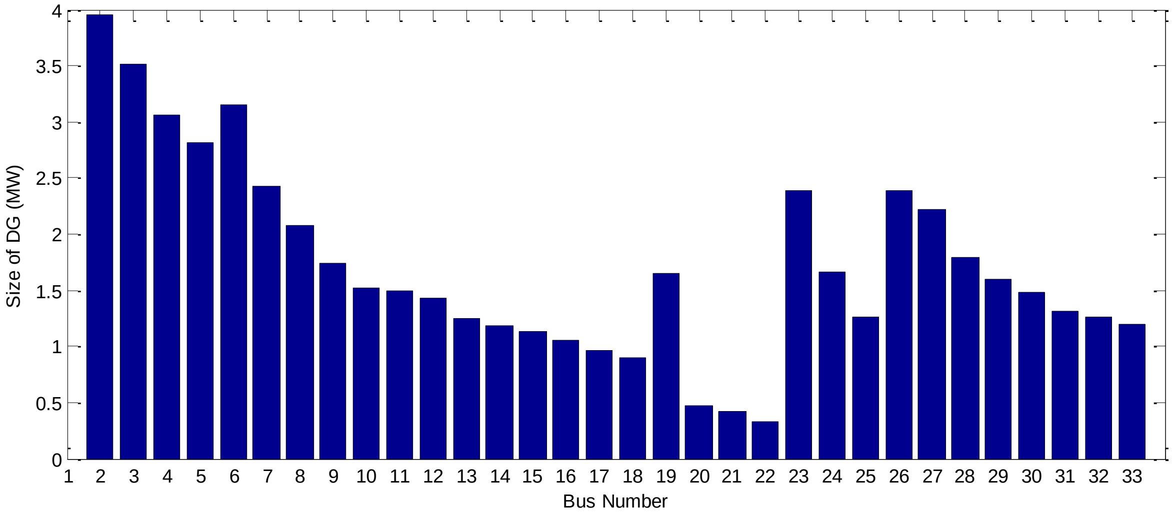


Figure 2.3: Optimum size of type-I DG at each bus for 33 bus system

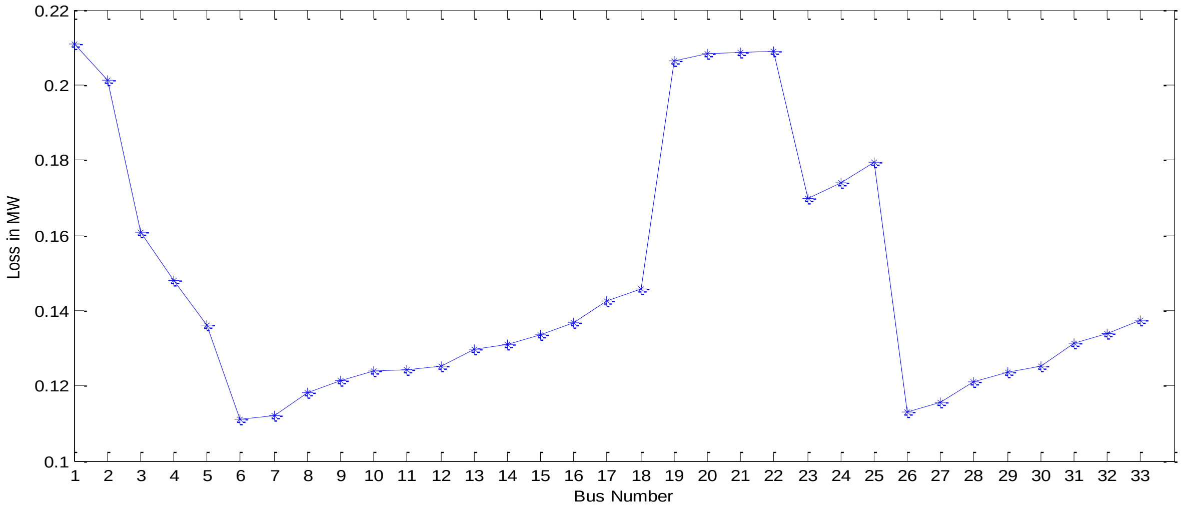


Figure 2.4: Total Power Loss with appropriate size of type-I DG at respective bus for 33 bus system

The bus having the least power loss is the optimal location for the placement of DG. From the Fig. 2.4, it is observed that bus no. 6 having the minimum total power loss after the placement of type-I DG. Hence, bus number 6 is the optimal location. The optimal size of DG is determined by taking the system constraints into consideration. The reduction in line losses are 45.4% with the placement of 3.15 MW DG at bus number 6, as shown in Table 2.1.

The reduction in line losses by the proposed PSO technique is also 45.4% with the placement of 3.15 MW DG size at bus 6 as shown in Table 2.1. It is observed that the reduction in line loss, optimal size and location obtained by the PSO approach are same, as verified by the analytical approach.

Table 2.1: Power loss with and without DG for 33-bus system

Method	Optimum location	Optimum DG size (MW)	Power loss (KW)	
			Without DG	With DG
Analytical approach	Bus 6	3.15	210.97	115.2
PSO technique	Bus 6	3.15	210.97	115.1

The voltage at the buses 6-18, and 26-33 violates the minimum allowable voltage limit before the installation of DG. The voltage profile of the system improves after the optimal placement of type-I DG as shown in Table 2.2.

Table 2.2: Bus voltage before and after the placement of type-I DG of 33-bus system

Bus Number	Bus Voltage p.u.		Bus Number	Bus Voltage p.u.	
	Before DG	After DG		Before DG	After DG
1	1.0000	1.0000	18	0.9038	0.9501
2	0.9970	0.9989	19	0.9965	0.9984
3	0.9829	0.9948	20	0.9929	0.9984
4	0.9754	0.9948	21	0.9922	0.9941
5	0.9679	0.9951	22	0.9916	0.9935
6	0.9495	0.9933	23	0.9793	0.9913
7	0.9459	0.9901	24	0.9726	0.9847
8	0.9323	0.9771	25	0.9693	0.9814
9	0.9259	0.9711	26	0.9475	0.9914
10	0.9201	0.9655	27	0.9449	0.9840
11	0.9192	0.9647	28	0.9335	0.9780
12	0.9177	0.9633	29	0.9253	0.9702
13	0.9115	0.9579	30	0.9218	0.9667
14	0.9092	0.9553	31	0.9176	0.9628
15	0.9078	0.9539	32	0.9167	0.9620
16	0.9064	0.9526	33	0.9164	0.9617
17	0.9044	0.9507			

12.66 kV, 69-Bus Distribution System

The second test system is a 69-bus radial distribution system having total load of 3.80 MW and 2.69 MVAr [84] with Beaver conductors. The single line diagram for 12.66 kV, 69-bus distribution system is depicted in Fig. A.2, while the relevant data is presented in Table A.2 of APPENDIX-A. This system is supplied by a sub-station connected at bus number 1 (Fig. A.2).

Based on the analytical expression, the size of type-I DG is calculated at each bus of 69-bus system for the loss to be minimum and Fig. 2.5 shows the size of DG at each bus. The total power loss of the system is determined after the placement of type-I DG for each bus. The bus having the least power loss is the optimal location for the placement of DG.

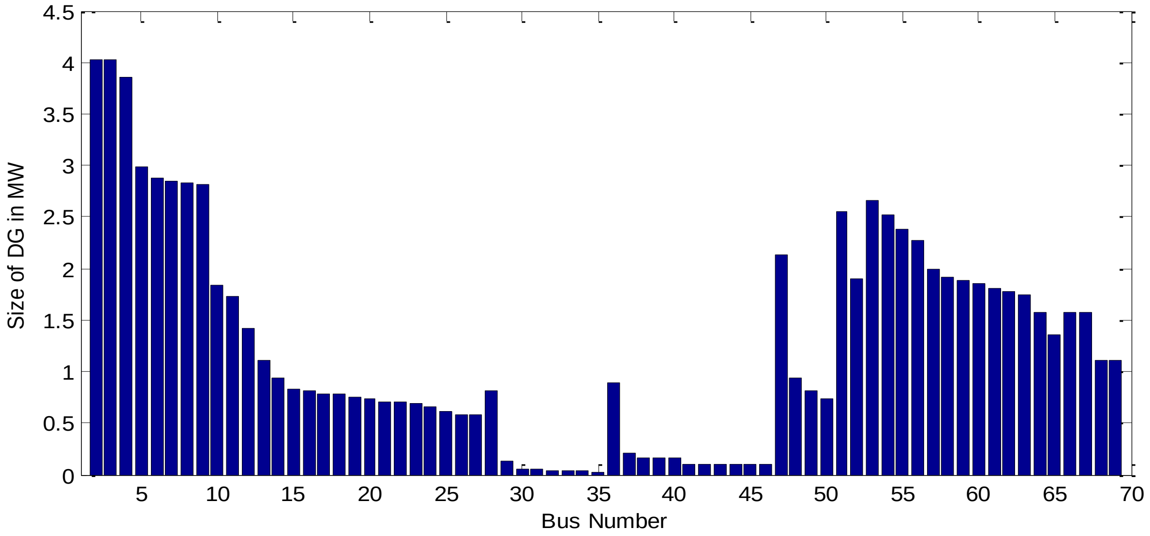


Figure 2.5: Optimum size of type-I DG at each bus for 69-bus system

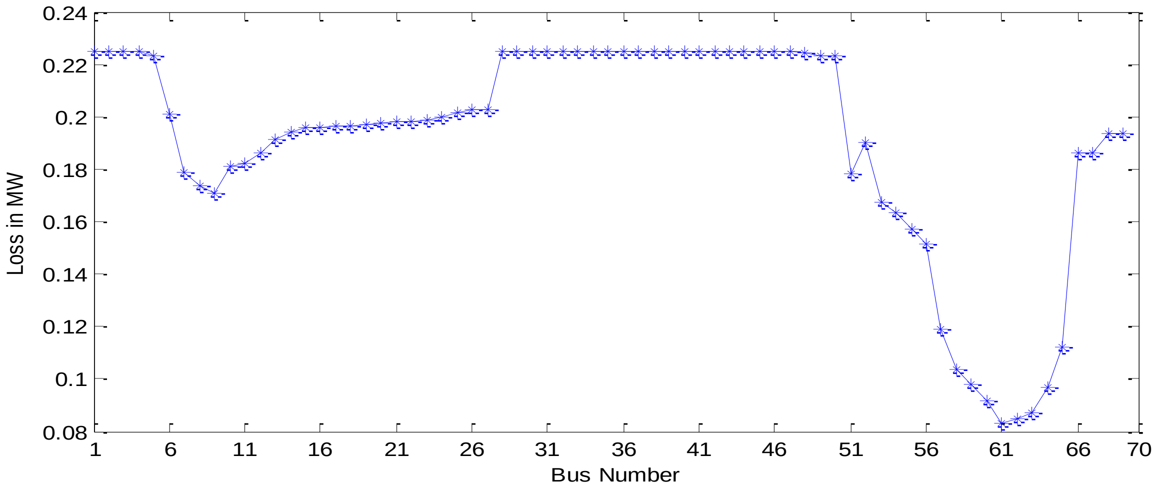


Figure 2.6: Total Power Loss with appropriate size of type-I DG at respective bus for 69 bus system

From the Fig. 2.6, it is observed that bus number 61 having the minimum power loss. Hence, bus 61 is the optimal location for the placement of DG. The reduction in power loss by both the analytical approach and PSO technique are 62.9%. i.e., both the approaches results exactly same reduction in line loss by the placement of same size of DG at same location as shown in Table 2.3.

Table 2.3: Power loss with and without DG for 69-bus system

Method	**Optimum location**	**Optimum DG size (MW)**	**Power loss (KW)**	
			Without DG	**With DG**
Analytical approach	Bus 61	1.81	225	83.4
PSO technique	Bus 61	1.81	225	83.4

Table 2.4 shows the voltage at each bus of the network before and after the installation of DG. It is observed that the voltage profile improves at these buses after the optimal placement of type-I DG.

Table 2.4: Bus voltage before and after the placement of type-I DG of 69-bus system

Bus Number	Bus Voltage p.u.		Bus Number	Bus Voltage p.u.	
	Before DG	After DG		Before DG	After DG
1	1.0000	1.0000	36	0.9999	0.9999
2	1.0000	1.0000	37	0.9997	0.9998
3	0.9999	0.9999	38	0.9996	0.9996
4	0.9998	0.9999	39	0.9995	0.9996
5	0.9990	0.9994	40	0.9995	0.9996
6	0.9901	0.9950	41	0.9988	0.9989
7	0.9808	0.9904	42	0.9986	0.9986
8	0.9786	0.9893	43	0.9985	0.9985
9	0.9774	0.9888	44	0.9985	0.9985
10	0.9724	0.9838	45	0.9984	0.9984
11	0.9713	0.9827	46	0.9984	0.9984
12	0.9682	0.9796	47	0.9998	0.9998
13	0.9652	0.9767	48	0.9985	0.9986
14	0.9623	0.9738	49	0.9947	0.9947
15	0.9595	0.9710	50	0.9941	0.9942
16	0.9589	0.9705	51	0.9785	0.9893
17	0.9580	0.9696	52	0.9785	0.9893
18	0.9580	0.9696	53	0.9747	0.9881
19	0.9576	0.9691	54	0.9714	0.9874
20	0.9573	0.9688	55	0.9669	0.9864
21	0.9568	0.9683	56	0.9626	0.9855
22	0.9568	0.9683	57	0.9400	0.9824

23	0.9567	0.9683	58	0.9289	0.9809
24	0.9565	0.9681	59	0.9246	0.9803
25	0.9564	0.9679	60	0.9196	0.9799
26	0.9563	0.9679	61	0.9122	0.9787
27	0.9563	0.9678	62	0.9119	0.9784
28	0.9999	0.9999	63	0.9115	0.9781
29	0.9999	0.9999	64	0.9096	0.9763
30	0.9997	0.9997	65	0.9090	0.9758
31	0.9997	0.9997	66	0.9713	0.9827
32	0.9996	0.9996	67	0.9713	0.9827
33	0.9993	0.9994	68	0.9678	0.9773
34	0.9990	0.9990	69	0.9678	0.9773
35	0.9989	0.9990			

2.8 CONCLUSION

Optimal placement of type-I DG plays an important role for maximizing the total real power loss reduction and improvement in the voltage profile of the systems. The analytical approach provides exact optimal solution however, these approaches are not suitable for large sizes power networks because of their mathematical complexity. Therefore, the heuristic based approaches are more suitable to determine the optimal size and location of DGs in a larger system.

CHAPTER – 3

OPTIMAL PLACEMENT OF TYPE-I AND TYPE-II DG IN DISTRIBUTION NETWORK

3.1 INTRODUCTION

In the previous chapter an algorithm for optimal placement of type-I DG injecting real power by different approaches has been studied to minimize the real power loss and enhancement in voltage profile of the radial distribution system. This chapter deals with a methodology, for optimal placement of type-I DG and type-II DG in the network. Capacitor is considered as type-II DG. The reactive power is compensated by the optimal placement of type-II DG in order to enhance the system performance. As the placement of type-I and type-II DGs not only minimize the active power loss and enhancement of the voltage profile of the distribution system to the great extent but also minimize the size of type-I DG, which provides more economical solution for loss reduction.

The proper allocation of DG units in distribution system plays a decisive role in achieving economical, technical, and qualitative benefits. Depending on their location, DG units may improve or worsen the system performance. The reduction of real power losses, improvement in voltage profile, diminution of harmonic pollution, enhancement in reliability, and deferral of network upgrade have been reported as the primary aims for DG placement in the literature. These DG allocation techniques are well suited to allocate type-I DGs injecting real power output and however do not have explored the advantage of type-II DG for reactive power compensation in power distribution network. In this chapter, optimal placement of type-I DG and type-II DGs are integrated together in distribution systems. The type-II DG placed provides reactive power compensation. The analytical approach and PSO based algorithm have been proposed in this thesis to determine the optimal size, location and optimal power factor to achieve the objective by compensating the active and reactive powers. The objective function, considering the real power system loss has been minimized. The constraints on power flow equations, bus voltages, line loadings, and on sizes of type-I DG and type-II DGs have also been considered. As distributed generation is defined as the generation of electricity by facilities that are sufficiently smaller than the central generating plants, so to allow interconnection at any point in a power system. There is no defined limit on the amount of generation through DG. The maximum DG installed capacity limits have been considered as 30% and 50% in [165] and [158] respectively. Hence, In this work the total installed capacity of DGs in the network has been limited to less than 30% of substation rated capacity [165] to maintain the concept of DG against centralized generation and the sizes of DGs are such that which are easily available in the market.

Besides, several optimization tools, including artificial intelligence techniques are proposed for achieving the optimal placement of DG in the power distribution systems for loss reduction can be listed as, analytical approaches [1, 6, 44, 45, 49, 55, 96, 112, 151,152], fuzzy-GA method [79, 16], genetic algorithm and Hereford Ranch algorithm [76, 87], the genetic algorithm [10, 21, 24, 26, 57, 94, 126, 132, 157, 159, 160], improved tabu search [38, 93, 124], ant colony search algorithm [27, 67], and PSO techniques [5, 14, 15, 104, 107, 109, 113, 115, 120, 140-142, 148, 164, 161]. Optimal placement of type-II DG for loss reduction, a well-known 2/3 rule has been presented in [73] for uniformly distributed loads. Many researchers have applied other techniques such as fuzzy expert system [65], and dynamic programming [154] for finding the best locations for the placement of type-II DG to reduce losses. Most of the approaches presented so far model the optimal placement of type-I and type-II DG independently. In this chapter, optimal placement of type-I and type-II DG is integrated into distribution systems.

3.2 PROBLEM FORMULATION

The problem of placement of type-I and type-II DG is to determine the optimal size and locations of type-I and type-II DGs to minimize the desired objective function as given in (2.1), while meeting the system constraints. The type-II DG integration provides reactive power compensation. In this case all constraints described in section 2.3.2 in chapter-2 are considered.

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

3.2.1 Assumptions

The following assumptions have been made in solving the current optimization problem.

i. Type-I DG can inject only active power,

ii. Type-II DG can inject only reactive power,

iii. The sizing and locations for DGs placement are determined at constant load condition in the network.

3.3 PROPOSED APPROACHES

The problem formulated above for the placement of type-I and type-II DG have been solved by the following two approaches, proposed in this work.

(i) Analytical approach

(ii) PSO based approach

The analytical approach provides exact optimal solution however, requires the evaluation of each bus for the placement and may be suitable for a smaller network. Therefore, PSO based approach has also been used which can be applied even for large networks.

3.3.1 Analytical Approach

The total power loss in power system is represented by "Exact Loss" formula as given by (2.1) in chapter-2. For minimum losses, the rate of change of real power losses with respect to injected real power becomes zero, which provides the size of type-I DG at each bus for the loss to be minimum and is given by (2.13). Similarly for reactive power injection, for minimum losses, the rate of change of losses with respect to injected reactive power becomes zero.

Therefore,

$$\frac{\partial P_L}{\partial Q_i} = 2\alpha_{ii}Q_i + 2\sum_{\substack{j=1 \\ j\neq i}}^{N}\left(\alpha_{ij}Q_j + \beta_{ij}P_j\right) = 0 \tag{3.1}$$

It follows that

$$Q_i = -\frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1 \\ j\neq i}}^{N}\left(\alpha_{ij}Q_j + \beta_{ij}P_j\right)\right] \tag{3.2}$$

If $Q_i = Q_{Gi} - Q_{Di}$ (3.3)

Where,

Q_{Gi}- reactive power generations of generators at bus *i*,

Q_{Di}- reactive load demand at bus *i*.

If Q_{DGi} is the reactive power generation from type-II DG placed at bus *i*, then

$$Q_i = \; Q_{DGi} - Q_{Di} \tag{3.4}$$

and
$$Q_{DGi} = Q_{Di} - \frac{1}{\alpha_{ii}}\left[\sum_{\substack{j=1\\ j\neq i}}^{N}\left(\alpha_{ij}Q_j + \beta_{ij}P_j\right)\right] \tag{3.5}$$

Equations (2.13) and (3.5) give the amount of active and reactive powers to be supplied by type-I DG and type-II DG at bus *i*, for the loss to be minimum. The optimal sizes of type-I and type-II DGs can be determined by satisfying the considered system constraints. The bus, at which the total power loss comes to be minimum after the placement of type-I and type-II DGs while satisfying the constraints, will be the optimal location for type-I and type-II DG placement. Optimal locations for type-I and type-II DGs may be same or different. If the optimal locations for both the sources are same, then the power factor of power injection may be considered as optimal power factor [45] and is given as:

$$OPF = \frac{P_{DG_i}}{\sqrt{{P_{DG_i}}^2 + {Q_{DG_i}}^2}} \tag{3.6}$$

The following is the computational flow involved to determine the optimal size and location of type-I and type-II DGs.

Step 1: Run load flow for base case.

Step 2: Find the base case loss using (2.1).

Step 3: Find the size of type-I and type-II DGs at each bus except the reference bus, using (2.13) and (3.5) for the minimum distribution loss.

Step 4: Check constraint violation after the placement of type-I and type-II DGs determined in step 3.

Step 5: Select the bus for minimum loss while satisfying all the constraints.

Step 6: Calculate optimal power factor using (3.6), if type-I and type-II DGs are placed at same bus.

Step 7: Evaluate the reduction in real power loss after the placement of optimal sizes of type-I and type-II DGs at optimal locations.

3.3.2 Proposed PSO Based Approach

PSO algorithm discussed in section 2.5 has been modified in this work to include the type-II DG as reactive power source. The dimension of search space is taken as 4 (locations of type-I and type-II DG and sizes of type-I and type-II DG). Fitness function for PSO algorithm is taken, as given by (2.1) and the constraints are taken as explained in sections 2.3.2. The flow chart of the modified PSO algorithm is given in Fig. 3.1.

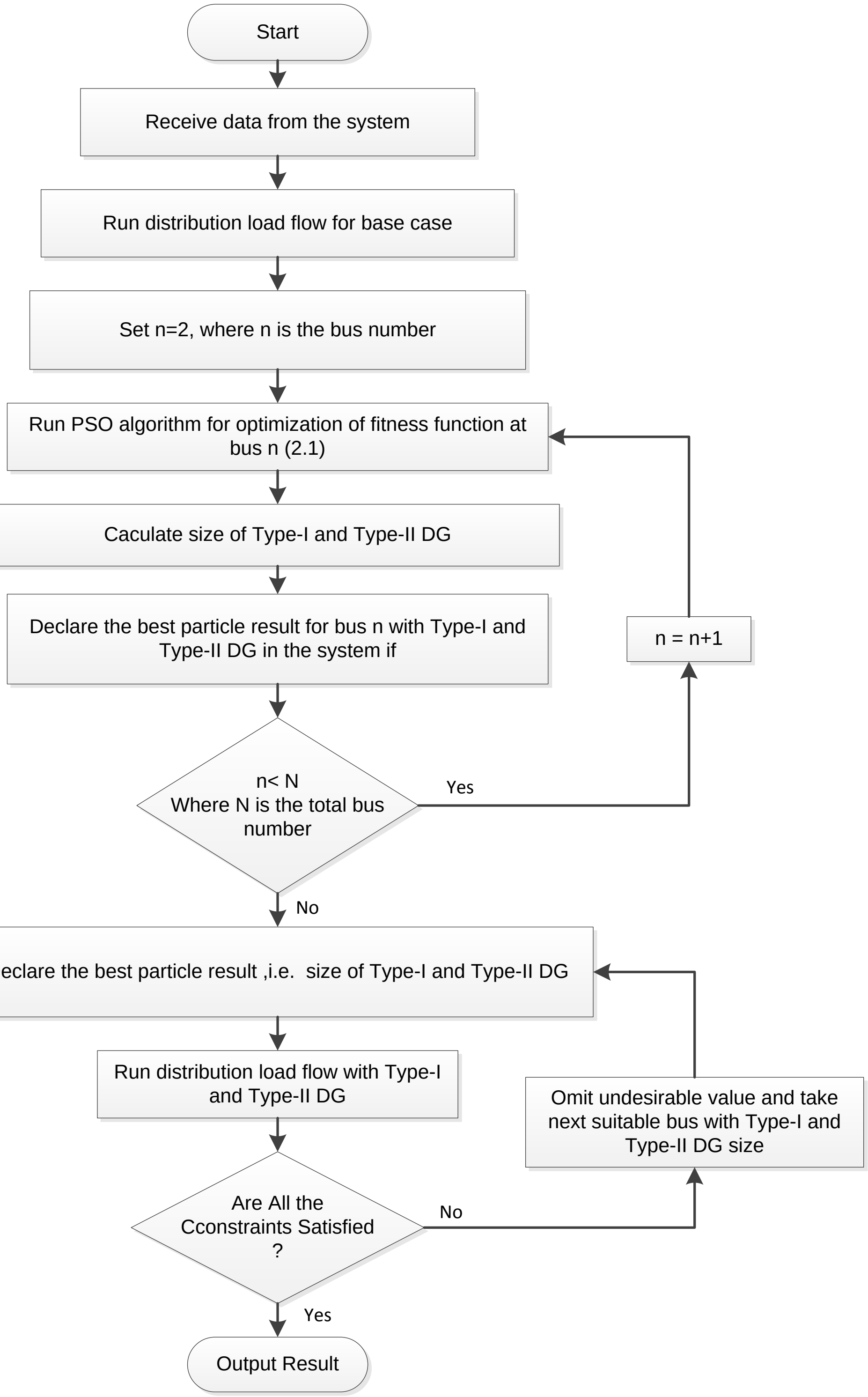


Figure 3.1 Optimal placement of type-I DG and type-II DG using PSO

3.3.3 Results and Discussion

The proposed methodology as described in section 3.3 has been tested on 33-bus, and 69-bus systems. The relevant data is presented in Table A.1 and Table A.2 of APPENDIX-A. The base voltage for both the test systems is 12.66 kV. The summary of base case load flow results for both the test systems is given in Table 3.1.

Table 3.1: Summary of the 33-bus and 69-bus base case

Test System	33-Bus	69-Bus
Σ kW loss	211	225
Σ kVAr loss	143	102.2
$\|V_{min}\|$,p.u.	0.9038	0.9092
$\|V_{max}\|$,p.u	1.0000	1.0000

For optimal placement of type-I and type-II DG, two cases are considered in this work. In the first case, both the sources can be placed anywhere in the network and those locations where the active power distribution loss is minimum are the optimal locations. In second case, both the sources are placed at the same bus and the bus where the loss is minimum has been considered as the optimal location. Results of both the cases are given in the following sections.

Case-I: Type-I and Type-II DG placed at different location

In this case, type-I and type-II DG can be placed at any location in the network. The significant reduction in real power distribution loss has been observed. Analytical approach and PSO based technique described in section 3.3 have been used to determine the optimal locations and sizes for type-I and type-II DG. In 33-bus system optimal location for type-I DG by both the approaches is bus number 6 while for type-II DG, optimal location is 30. The reduction in real power loss by PSO approach are slightly higher than the analytical approach with slight change in the sizes of DGs as given in Table 3.2 for the 33-bus test system. The reduction in real power losses are 72.72% and 72.29% by analytical approach and PSO approach respectively. The slight change in the sizes of DGs and reduction in real power losses are due to heuristic nature of PSO.

In 69-bus system optimal location for both the type-I and type-II DG is same, bus number 61. The reduction in real power loss and the sizes of type-I and type-II DG obtained by PSO approach are exactly same as compared to analytical approach results as shown in Table 3.2.

Table 3.2: Type-I and Type-II DG at different locations by analytical and PSO approach

System	Approach	DG Type	Location	Installed DG size		Power loss (kW)
				(MW)	(MVAr)	
33-bus system	Without DG					211
	Analytical	Type-I & II DGs	6	2.483		58.51
			30		1.223	
	PSO	Type-I & II DGs	6	2.532		58.45
			30		1.256	
69-bus system	Without DG					225
	Analytical	Type-I & II DGs	61	1.808	1.292	23.19
	PSO	Type-I & II DGs	61	1.808	1.292	24.19

The improvement in minimum voltage for both the system has been observed as 0.049 p.u. and 0.063 p.u. by the placement of type-I and type-II DGs for 33-bus and 69-bus test system respectively and is shown in Fig 3.2 and Fig. 3.3 respectively.

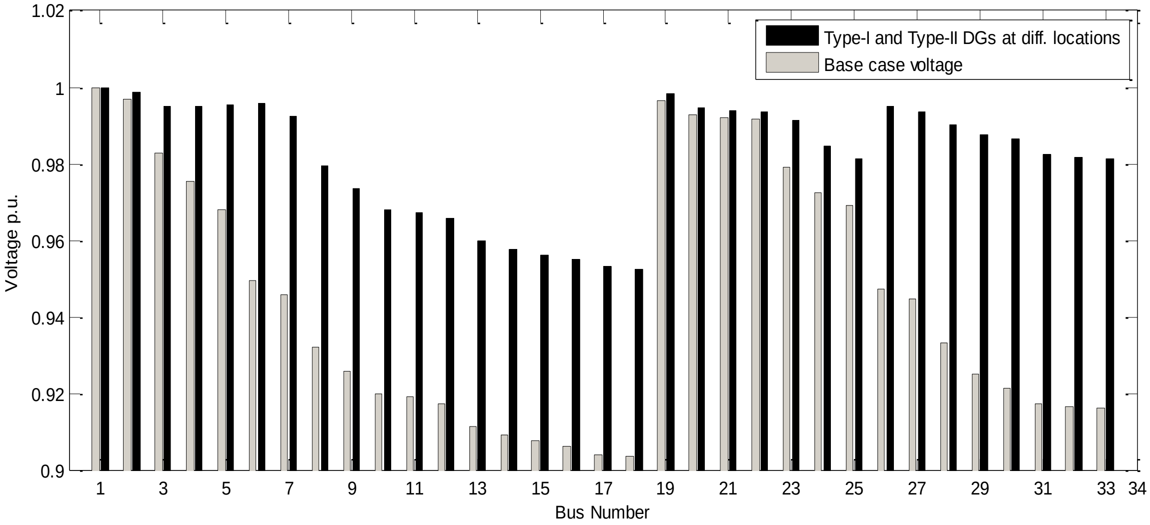


Figure 3.2 Voltage profile before and after placement of Type-I and Type-II DGs of 33- bus system

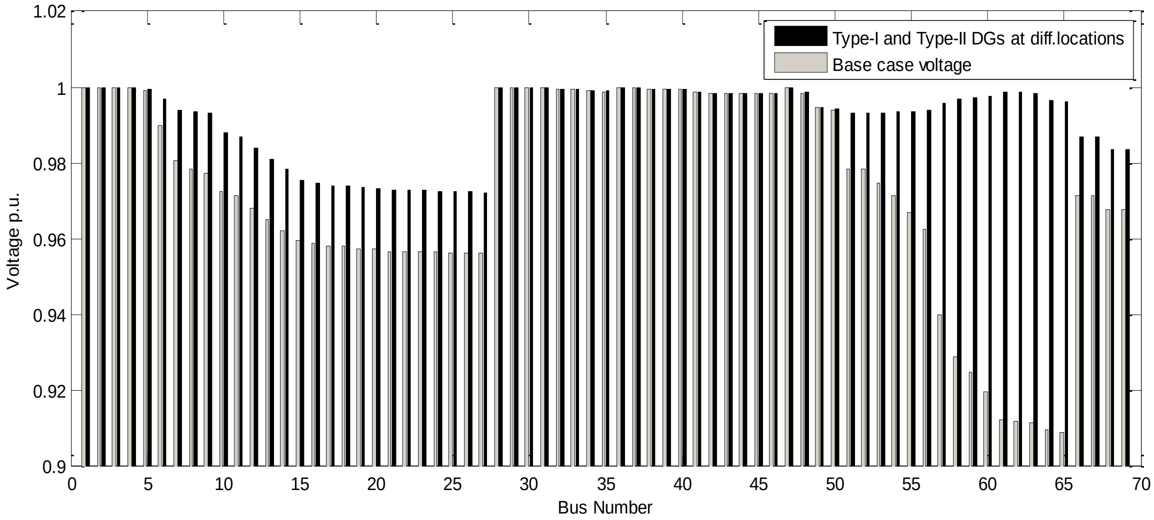


Figure 3.3 Voltage profile before and after placement of Type-I and Type-II DGs of 69-bus system

Case-II: Type-I and Type-II DG placed at same location

In this case active power and reactive power generations from type-I and type-II DGs are placed at the same bus. Table 3.3 shows the real power loss reduction for both the test systems are 67.82% and 89.7%, respectively, by both the analytical and PSO approaches. The negligible change in the reduction of line losses is observed with the small changes in the sizes of DGs due to heuristic nature of PSO algorithm. The improvement in $|V_{min}|$ has been observed as 0.053 p.u. and 0.063 p.u. for 33-bus and 69-bus test systems respectively.

Table 3.3: Type-I and Type-II DG at same locations by analytical and PSO approach

System	Approach	DG Type	Location	Installed DG size		Power loss (kW)
				(MW)	(MVAr)	
33-bus system	Without DG					211
	Analytical	Type-I & II DGs	6	2.49	1.72	67.95
	PSO	Type-I & II DGs	6	2.53	1.26	67.95
69-bus system	Without DG					225
	Analytical	Type-I & II DGs	61	1.81	1.29	23.19
	PSO	Type-I & II DGs	61	1.83	1.30	24.17

If the locations of type-I and type-II DGs are same then either the two DGs (one of type-I and other of type-II) or single type-III DG (Satisfying the active and reactive power requirement) can be placed at this location. If the reactive power is more than the reactive rating of type-III DG, then an additional type-II DG with type-III DG can be used.

3.4 TYPE-I AND TYPE-II DG WITH SIZE CONSTRAINT

As seen from the results, the sizes of type-I and type-II DGs are so large as compared to the system load. Therefore to maintain the concept of distribution generation the sizes of type-I and type-II DGs are restricted to some limit. Hence, in this work, the total installed capacity of type-I and type-II DGs in the network has been limited to less than 30% of substation rated capacity [165] to maintain the concept of DG against centralized generation. For optimal placement of type-I and type-II DG, again two cases are considered in this work. In the first case, both the sources can be placed anywhere in the network. In second case, both the sources are placed at the same bus. At this location power factor will also be optimal. The sizes of type-I DG in kW and type-II DG in kVAr are considered in the steps of 100, which are easily available in the market. The placement of type-I and type-II DG considering the size constraint has been solved by the analytical approach and PSO based approach.

3.4.1 Analytical Approach

The analytical approach as described in section 3.3.1 has been used along with an additional size constraint as described below.

- The total installed capacity of type-I DG and type-II DG in the network has been limited to less than 30% of substation rated capacity to maintain the concept of DG against centralized generation [165].

$$S_{\text{Type I DG}} \leq 0.30 S_{T_{Real}} \tag{3.7}$$

$$S_{\text{Type II DG}} \leq 0.30 S_{T_{React.}} \tag{3. 8}$$

Where, $S_{\text{Type I DG}}$ and $S_{\text{Type II DG}}$ are the capacities of type-I and type-II DGs and S_T is the rated capacity of the substation.

Case-I Type-I DG and Type-II DG placed at different location

In this case, type-I DG and type-II DG can be placed at any location in the network. Analytical approach described in section 3.3.1 has been used to determine the optimal location and size for type-I DG and type-II DGs. In 33-bus system optimal location for type-I DG is bus number 8 while for type-II DG, optimal location is 30. In 69-bus system optimal location for both the type-I and type-II DG is same, bus number 61. The results for both the test systems are given in Table 3.4. The reduction in real power losses are 66.74% and 87.91% for the 33-bus and the 69-bus test systems respectively.

Table 3.4: Type-I DG and Type-II DG at different locations by analytical approach

Test System	33-Bus	69-Bus
Type-I DG Type-II DG	1500 kW, placed at **bus 8** 900 kVAr, placed at **bus 30**	1500 kW, placed at **bus 61** 1200 kVAr, placed **at bus 61**
Σ kW loss	70.17	27.2
Σ kVAr loss	49.1	17.4
$\|V_{min}\|$,p.u.	0.9547	0.9702
$\|V_{max}\|$,p.u	1.0000	1.0000

The improvement in minimum voltage for both the system has been observed as 0.051 p.u. and 0.061 p.u. respectively. The voltage profile improvement of 33-bus system and 69-bus test system are shown in Fig 3.4 and Fig. 3.5 respectively.

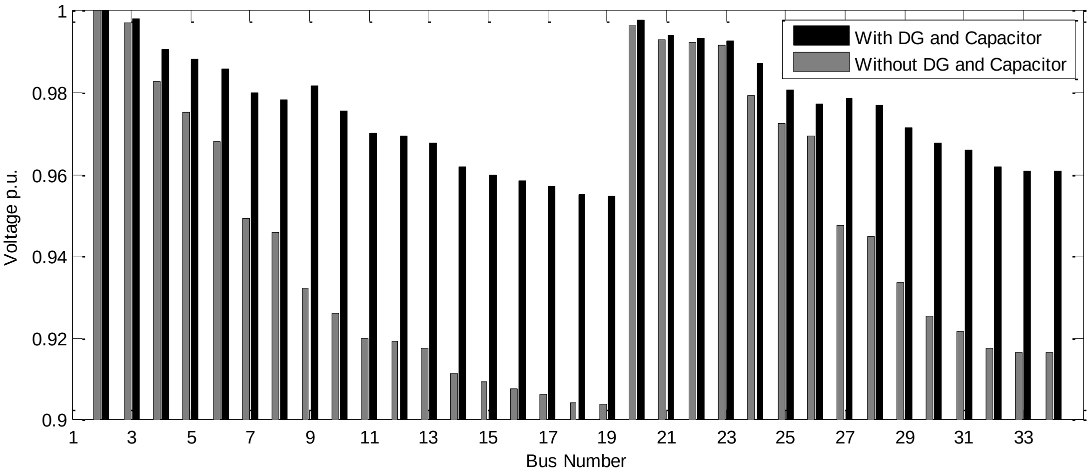


Figure 3.4 Voltage profile with type-I and type-II DG placed at different locations for 33-bus system

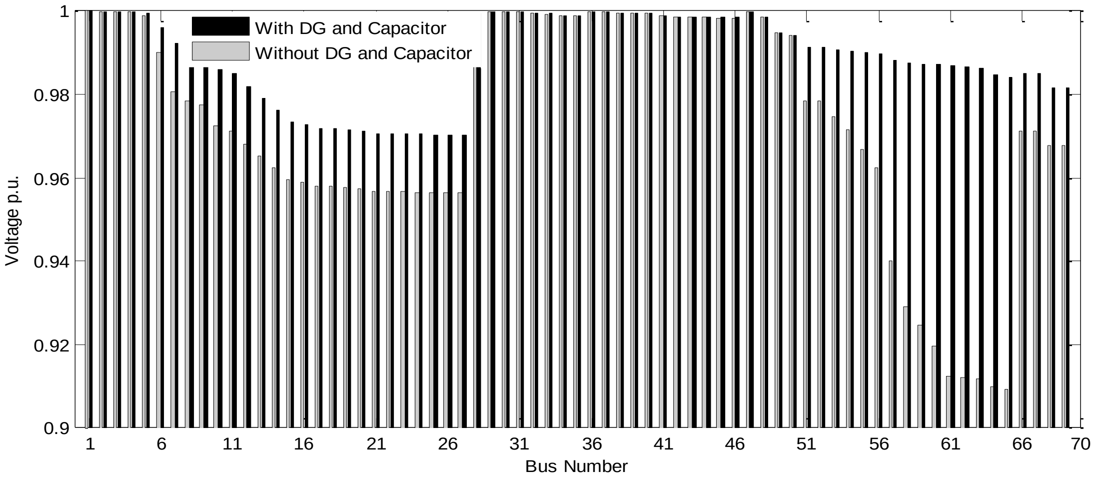


Figure 3.5 Voltage profile with type-I and type-II DG placed at different locations for 69-bus system

Case-II Type-I DG and Type-II DG placed at same location

In this case active power and reactive power generations from type-I DG and type-II DG may be coupled. Table 3.5 shows the real power loss reduction for both the test systems are 64.15% and 87.91%, respectively. The improvement in $|V_{min}|$ has been observed as 0.0362 p.u. and 0.061 p.u. for 33-bus and 69-bus test systems respectively. For both the cases, the placement of type-I DG and type-II DG in 69-bus test system is same, so the loss reduction and voltage profile improvement remains unaffected.

Table 3.5: Type-I DG and Type-II DG placed at same locations by analytical approach

Test System	33-Bus	69-Bus
Type-I DG Type-II DG	1500 kW, placed at **bus 30** 900 kVAr, placed at **bus 30**	1500 kW, placed at **bus 61** 1200 kVAr, placed at **bus 61**
Σ kW loss	75.65	27.2
Σ kVAr loss	56.13	17.4
Optimal *P.f.* (Leading)	0.86	0.78
$\|V_{min}\|$,p.u.	0.9400	0.9702
$\|V_{max}\|$,p.u	1.0000	1.0000

The voltage profile improvement of 33-bus system is shown in Fig 3.6 and for 69-bus system the voltage profile remains same as shown in Fig. 3.5.

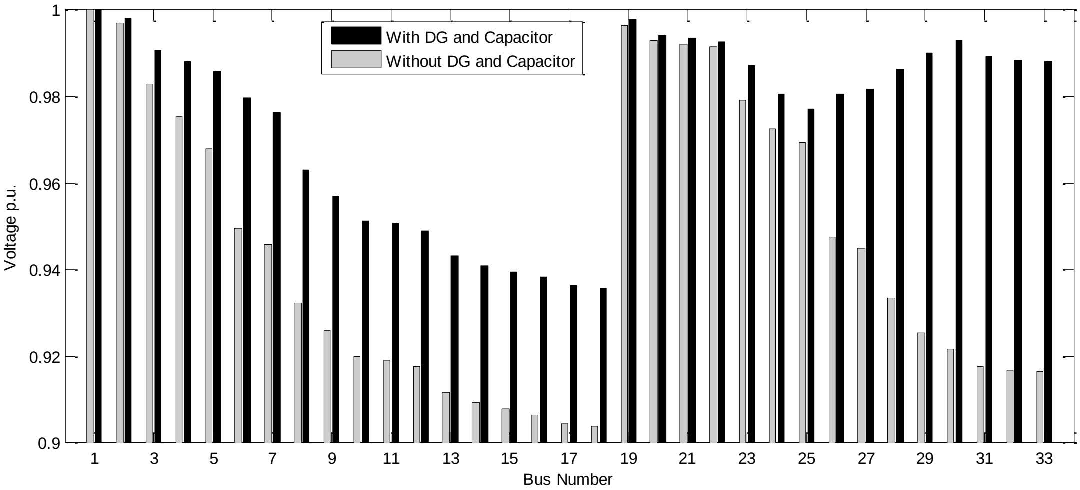


Figure 3.6 Voltage profile with type-I and type-II DGs placed at same location for 33-bus system

For this case, the generated active and reactive powers can be used for the calculation of optimal power factor (p.f.). The calculated optimal power factors for 33 and 69-bus systems are 0.86 leading and 0.78 leading respectively as shown in Table 3.5. The change in total real power loss with respect to variation in p.f. is shown in Fig.3.7 for 33-bus system. If active and reactive power generations from type-I DG and type-II DG are kept constant, then the total power losses are minimum at 0.86 leading power factor of the combination, which is considered optimal power factor. Fig.3.8 also shows the similar variation in real power loss with the variation in p.f. for 69-bus test system.

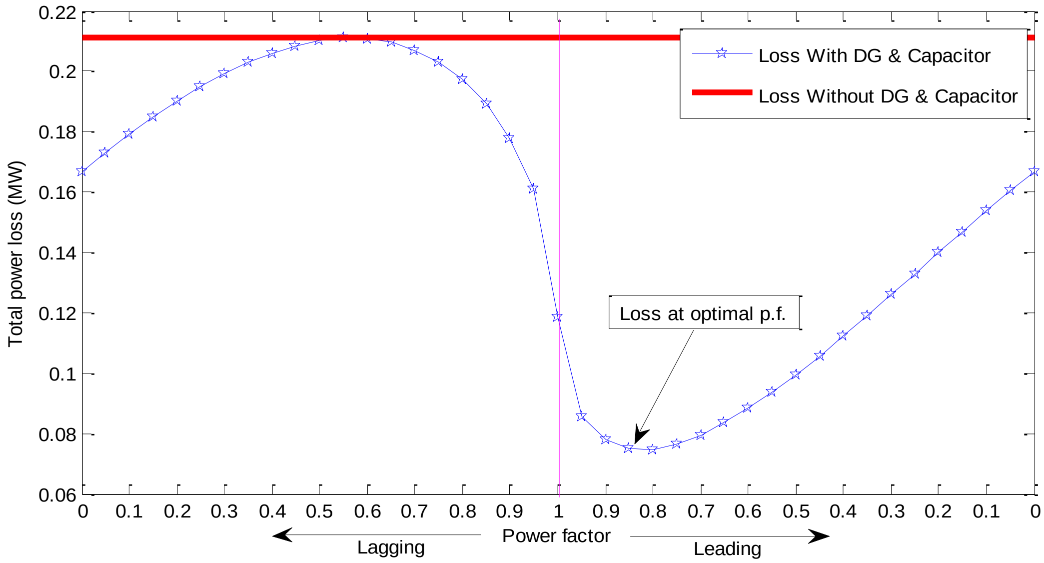


Figure 3.7 Change in total real power loss with the variation in p.f. for 33-bus system

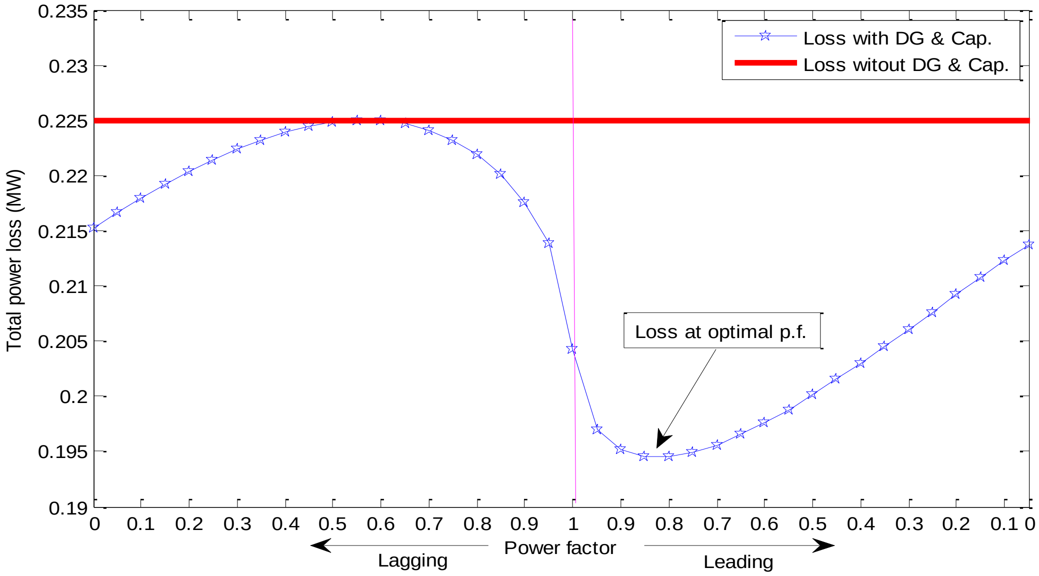


Figure 3.8 Change in total real power loss with the variation in p.f. for 69-bus system

3.4.2 PSO Based Approach

The proposed PSO based approach has been applied on the same test systems as described in section 3.3.1.1 to illustrate the optimal placement of type-I and type-II DGs considering the size constraints to minimize the power distribution loss. Similar to analytical approach, both the cases when type-I DG and type-II DG are placed on same bus and on different buses have been considered. The total active power losses without any type-I DG and type-II DG are 211 kW and 225 kW in 33-bus and 69-bus test systems respectively.

Case-I Type-I DG and Type-II DG placed at different location

In this case, type-I DG and type-II DG are placed at different locations. The significant reduction in real power distribution loss has been observed. The results for both the test systems are given in Table 3.6. The reduction in real power losses are 66.74% and 87.91% for the 33-bus and the 69-bus test systems respectively, which verify the results obtained by analytical approach as given in Table 3.4. The improvement in voltage profiles for both test systems is also same as in the case of analytical approach and is shown in Fig.3.4 and Fig.3.5.

Table 3.6: Type-I DG and Type-II DG at different locations by PSO approach

Test System	33-Bus	69-Bus
Type-I DG Type-II DG	1500 kW, placed at **bus 8** 900 kVAr, placed at **bus 30**	1500 kW, placed at **bus 61** 1200 kVAr, placed **at bus 61**
Σ kW loss	70.17	27.2
Σ kVAr loss	49.1	17.4
$\lvert V_{min} \rvert$,p.u.	0.9547	0.9702
$\lvert V_{max} \rvert$,p.u	1.0000	1.0000

Case-II Type-I DG and Type-II DG placed at same location

In this case type-I DG and type-II DG are placed at same location. Table 3.7 shows the real power loss reduction for both the test systems. The power factor calculated using the optimal sizes of type-I and type-II DG placed on the same bus, has been considered as optimal power factor. The improvement in $|V_{min}|$ has been observed as 0.036 p.u. and 0.061 p.u. for 33-bus and 69-bus test systems respectively. The voltage profile improvement of 33-bus system is shown in Fig 3.6 and for 69-bus system is shown in Fig. 3.5, which are same as in case of analytical approach. The improvement in results in terms of loss reduction by PSO based and analytical approach are also same.

Table 3.7: Type-I DG and Type-II DG placed at same locations by PSO approach

Test System	33-Bus	69-Bus
Type-I DG Type-II DG	1500 kW, placed at **bus 30** 900 kVAr, placed at **bus 30**	1500 kW, placed at **bus 61** 1200 kVAr, placed at **bus 61**
Σ kW loss	75.65	27.2
Σ kVAr loss	56.13	17.4
Optimal *P.f.* (Leading)	0.86	0.78
$\|V_{min}\|$,p.u.	0.9400	0.9702
$\|V_{max}\|$,p.u	1.0000	1.0000

It is concluded from the above discussion that integration of type-I and type-II DG not only compensate active and reactive power of the network but also reduces the size of DG to a great extent. In chapter-2, the size of type-I DG comes to be very large (3.15 MW), whereas in this work the size of type-I DG is only 1.5 MW under the same voltage and line constraints for 33-bus system to minimize the real power distribution loss.

3.5 CONCLUSION

In this chapter, the application of analytical and PSO based approach have been proposed for finding the optimal location and size of type-I and type-II DG in power network. The objective function has been minimized with the consideration of various operational constraints. The two cases, when the type-I and type-II DG are placed on the same bus and on different buses have been studied. The placement of type-I and type-II DG considering the size constraint has also been considered in this work to maintain the concept of distributed generation. The sizes of type-I DG in kW and type-II DG in kVAr are considered in the steps of 100, which are easily available in the market. Optimal placement of type-I and type-II DG improves the voltage profile of the system. Placement of type-I and type-II DG at different optimal locations further minimize the losses. The placement of type-I and type-II DG reduces the required size of type-I DG to a great extent. The cost of type-II DG is much less than the cost of type-I DG, which provides more economy to the solution for loss reduction.

CHAPTER – 4

OPTIMAL PLACEMENT OF MULTIPLE DGs OF TYPE-I, TYPE-II AND TYPE-III

4.1 INTRODUCTION

In the previous chapter, analytical and PSO based approaches have been applied for the optimal placement of type-I DG and type-II DG sources. However, only one unit of DG of each was considered for the placement. In this chapter, a hybrid approach has been proposed for the placement of more than one unit of type-III DGs.

The distributed or decentralized generation units connected to local distribution systems are not dispatchable by central operator, but they can have a significant impact on the power flow, stability, voltage profile, reliability, short circuit level and quality of power supply for customers and electricity suppliers. Optimization techniques have been employed for generation allocation in power network, allowing for the best allocation of the DG. There are many approaches for deciding the optimal sizing and siting of DG units in distribution systems. Some of the factors that must be taken into account in the planning process of expanding distribution system with DG are: the number and capacity of DG units, best location and technology, the network connection, capacity of existing system, protection schemes, among others. Different methodologies and approaches have been developed to identify optimal places to install DG capacity on case to case basis. These methodologies are based on analytical tools, optimization programs or heuristic techniques. Most of them find the optimal allocation and size of single DG in order to reduce losses and improve voltage profiles [1, 6, 11, 37, 45, 49, 54, 55, 70, 74, 92, 96, 105, 119, 121, 122, 126, 142, 148, 156, 160, 162, and 164]. Others include the placement of multiple DGs with artificial intelligence-based optimization methods [58, 101, 139, 165, and 172] and a few go with analytical approach [26, 44, 133, 129, and 157].

Most of the optimal placement techniques to allocate multiple DGs use heuristic approach only, and do not take the advantage of analytical approach. The analytical approaches may not be appropriate for optimal placements of multiple DGs alone. A hybrid approach has been proposed in the present work for optimal placement of multiple DGs of type-III. In this chapter, hybridization of analytical method and heuristic search for the optimal placement of multiple type-III DGs in power distribution network for reduction of power loss has been proposed. In this approach, the sizes of DGs are evaluated at each bus by analytical method while the locations are determined by PSO based technique. The objective function has been minimized under operating constraints. The improvements in bus voltage profile and optimal power factor of the DGs have also been observed. The present work develops the comprehensive formula by extending the analytical expression presented in [112, 44], and a PSO based hybrid technique has been proposed to identify best locations to achieve the desired objective. In addition to the hybrid approach nested PSO formulation for determining sizes and locations of DGs has been developed. Both the approaches are tested on 33-bus test system and the obtained results are compared.

4.2 PROBLEM FORMULATION

In section 3.3.1 of chapter-3, an analytical method was described to determine the size of a type-I and type-II DGs which can work at a certain power factor. The same concept has been improvised in [45] to formulate a method for placing multiple numbers of DGs of similar characteristics. This is a mathematical based method which is applied for DGs that can generate power at a power factor (p.f.) other than unity power factor. In this method a mathematical approach is given to find the sizes of DGs but optimal locations and optimal p.f.s are found using PSO. This method can be used for DGs which can run at variable p.f. or a particular fixed p.f.

4.2.1 Sizing at Various Locations

Assuming $a_{k_i} = (sign)\tan\left(\cos^{-1}\left[PF_{DG_{k_i}}\right]\right)$, the reactive power output of DG, where k_i is the bus number of i^{th} DG. i=1, 2, 3,........n, where n is the number of DGs to be placed. Therefore,

$$Q_{DG\,k_i} = a_{k_i} P_{DG\,k_i} \qquad (4.1)$$

In which

$$sign = \begin{cases} +1: DG\ injecting\ Reactive\ Power \\ -1: DG\ consuming\ Reactive\ power \end{cases}$$

$PF_{DG_{k_i}}$ is the power factor of DG at k_i^{th} bus of i^{th} DG. The active and reactive power injected at bus k_i, where DG is located, are given by (4.2) and (4.3), respectively,

$$P_{k_i} = P_{DG\,k_i} - P_{D\,k_i} \qquad \dots (4.2)$$

$$Q_{k_i} = Q_{DG_{k_i}} - Q_{D_{k_i}} = a_{ki}P_{DG_{k_i}} - Q_{D_{k_i}} \qquad \ldots(4.3)$$

Substituting (4.2) and (4.3) into (2.1), the power loss equation is written as

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\begin{matrix}\alpha_{ij}\left(\left(P_{DG_{k_i}} - P_{D_{k_i}}\right)P_j + \left(a_{k_i}P_{DG_{k_i}} - Q_{D_{k_i}}\right)Q_j\right)\\ +\beta_{ij}\left(\left(a_{k_i}P_{DG_{k_i}} - Q_{D_{k_i}}\right)P_j - \left(P_{DG_{k_i}} - P_{D_{k_i}}\right)Q_j\right)\end{matrix}\right] \qquad \ldots(4.4)$$

Differentiating P_L w.r.t. $P_{DG_{k_1}}$

$$A_{k_1k_1}P_{DG_{k_1}} + A_{k_2k_1}P_{DG_{k_2}} + \cdots + A_{k_ik_1}P_{DG_{k_i}} + \cdots + A_{k_nk_1}P_{DG_{k_n}} = B_{k_1}$$

Differentiating P_L w.r.t. $P_{DG_{k_2}}$

$$A_{k_1k_2}P_{DG_{k_1}} + A_{k_2k_2}P_{DG_{k_2}} + \cdots + A_{k_ik_2}P_{DG_{k_i}} + \cdots + A_{k_nk_2}P_{DG_{k_n}} = B_{k_2}$$

Similarly Differentiating P_L w.r.t. $P_{DG_{k_i}}$

$$A_{k_1k_i}P_{DG_{k_1}} + A_{k_2k_i}P_{DG_{k_2}} + \cdots + A_{k_ik_i}P_{DG_{k_i}} + \cdots + A_{k_nk_i}P_{DG_{k_n}} = B_{k_i}$$

There will be n equations with n variables. These equations can be written as

$$[P_{DG}]_{n\times 1} = [A]_{n\times n}^{-1} \times [B]_{n\times 1} \qquad \ldots(4.5)$$

Where,

$$[P_{DG}]_{n\times 1} = \left[P_{DG_{k_1}} \quad \cdots \quad P_{DG_{k_i}} \quad \ldots \quad P_{DG_{k_n}}\right]^T$$

$$A_{k_ik_j} = \begin{cases}\alpha_{k_ik_i}\left(1 + a_{k_i}^2\right) & if\ \ k_i = k_j\\ \alpha_{k_ik_j}\left(1 + a_{k_i}a_{k_j}\right) + \beta_{k_ik_j}\left(a_{k_i} - a_{k_j}\right) & if\ \ k_i \neq k_j\end{cases}$$

$$B_{k_i} = \left(\begin{matrix}\alpha_{k_ik_i}\left(P_{D_{k_i}} + a_{k_i}Q_{D_{k_i}}\right)\\ +\displaystyle\sum_{\substack{j=1\\ j\neq i\ (in\ \ k_i)}}^{n}\left(\begin{matrix}\alpha_{k_ik_j}\left(P_{D_{k_j}} + a_{k_i}Q_{D_{k_j}}\right)\\ -\beta_{k_ik_j}\left(Q_{D_{k_j}} - a_{k_i}P_{D_{k_j}}\right)\end{matrix}\right)\\ +\displaystyle\sum_{\substack{j=1\\ j\neq k_1,k_2,\ldots,k_n}}^{N}\left(\begin{matrix}\alpha_{k_ik_j}\left(P_{D_{k_j}} + a_{k_i}Q_{D_{k_j}}\right)\\ -\beta_{k_ik_j}\left(Q_{D_{k_j}} - a_{k_i}P_{D_{k_j}}\right)\end{matrix}\right)\end{matrix}\right)$$

The proposed method for calculating optimum sizes is Multivariable Optimization technique [143]. From (4.5) the optimal sizes of multiple DGs at each bus can be calculated for the losses to be minimum.

4.2.2 Selecting Optimal Locations and Power Factor

For single DG placement, the number of combinations of buses possible is the total number of buses in the system. So it was simple to calculate DG size and to evaluate the loss at every bus. But when it comes to determine combination of N buses in the same network for nDGs the number of combinations possible are $^{N}C_{n}$ where, n is number of DGs and N is number of buses in the network. So a search technique or a heuristic method needs to be implemented to find optimal location. The optimal location for the placement of multiple DGs is determined by using PSO technique taking the location as the variable and optimal power factor of each optimal DG is also calculated by PSO technique taking the p.f. as the another variable.

4.2.3 Proposed Algorithm

The proposed approach has been developed to determine the optimal sizes and locations of multiple type-III DGs, and is given step by step in the following.

Step 1: Input line and bus data, and bus voltage limits.

Step 2: Calculate the loss using distribution load flow.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Location of DGs and p.f of DGs) in the solution space. Set the iteration counter k = 0.

Step 4: For each particle, calculate the sizes of DGs using (4.5).

Step 5: If the bus voltage is within the limits as given, evaluate the total loss using (2.1). Otherwise, that particle is infeasible.

Step 5: For each particle, compare its objective value with the individual best. If the objective value is lower than Pbest, set this value as the current Pbest, and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best Pbest of all particles, and set the value of this Pbest as the current overall best Gbest.

Step 7: Update the weight, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Otherwise, set iteration index k = k + 1, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal locations and size of DG and the corresponding fitness value representing the minimum total real power loss.

4.2.4 Results

Table 4.1 shows the optimal placement of multiple type-III DGs with optimal power factors at optimal locations to minimize the power losses by proposed approach for a 33-bus network. The sizes of type-III DGs are determined by analytical approach and optimal locations and p.f. by the application of PSO approach. The reduction in real power losses are 67.82% for the placement of single type-III DG. For two DG and three DGs placements, the reductions in losses are 86.44%, and 94.45%. As the number of DG units is increased, the loss reduction becomes more effective.

Table 4.1: Multiple Type-III DGs with optimal power p.f. for 33 bus distribution system

Case	Bus number	DG Capacity (MW)	Power factor (p.f.)	Power loss (kW)
Without DG				211
1 DG	6	2.4999	0.8236	67.9
2 DG	13 30	0.9445 1.0917	0.9083 0.7241	28.6
3 DG	13 24 30	0.7884 1.0666 1.0267	0.9028 0.8991 0.7136	11.7

4.3 Hybrid Approach for Multiple Type-III DGs

This section proposes a better way to find optimal power factor for type-III DGs. This method can be implemented to find any combination of different types of DGs. Both the cases were formulated and simulated in this section. The derivation for the sizes of type-I DGs and type-II DGs is described below. Consider the exact loss formula given by (2.1) and reproduced below.

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

Let *n* be the total number of DGs of (Type-I) and *k₁, k₂,……..kₙ* be their locations and $P_{DG_{k_1}}, P_{DG_{k_2}}, \dots\dots\dots.. P_{DG_{k_n}}$ be their respective size that are to be placed in a network containing N buses.

Let *m* be the total number of DGs (Type-II) and l_1, $l_2, \dots\dots.. l_m$ be their locations and $Q_{DG_{l_1}}, Q_{DG_{l_2}}, \dots\dots\dots.. Q_{DG_{l_m}}$ be their respective size that are to be placed in a network containing N number of buses.

If $P_{DG_{k_1}}, P_{DG_{k_2}}, \dots\dots\dots.. P_{DG_{k_n}}$ are the real power generation from the DG placed at buses $k_1, k_2, \dots\dots.. k_n$, then injected real powers are

$$\left[P_{k_1} = P_{DG_{k_1}} - P_{D_{k_1}}\right], \dots\dots\dots\dots\dots\dots\dots\dots \left[P_{k_n} = P_{DG_{k_n}} - P_{D_{k_n}}\right] \tag{4.6}$$

Similarly, injected reactive powers are

$$\left[Q_{l_1} = Q_{DG_{l_1}} - Q_{D_{l_1}}\right], \dots\dots\dots\dots\dots\dots\dots\dots.. \left[Q_{l_m} = Q_{DG_{l_m}} - Q_{D_{l_m}}\right] \tag{4.7}$$

Differentiating P_L w.r.t P_{k_1}

$$\frac{\partial P_L}{\partial P_{k_1}} = 2\alpha_{k_1k_1}P_{k_1} + 2\sum_{\substack{j=1\\ j\neq k_1}}^{N}\left(\alpha_{k_1j}P_j - \beta_{k_1j}Q_j\right) = 0 \tag{4.8}$$

or

$$\alpha_{k_1k_1}P_{k_1} + \alpha_{k_1k_2}P_{k_2} \dots + \alpha_{k_1k_n}P_{k_n} - \beta_{k_1l_1}Q_{l_1} - \beta_{k_1l_2}Q_{l_2} \dots - \beta_{k_1l_m}Q_{l_m}$$
$$= -\sum_{\substack{j=1\\ j\neq k_1,k_2,\dots k_n\\ j\neq l_1,l_2,\dots l_m}}^{N}\left(\alpha_{k_1j}P_j - \beta_{k_1j}Q_j\right) \tag{4.9}$$

Similarly, differentiating P_L w.r.t P_{k_n}

$$\frac{\partial P_L}{\partial P_{k_n}} = 2\alpha_{k_nk_n}P_{k_n} + 2\sum_{\substack{j=1\\ j\neq k_n}}^{N}\left(\alpha_{k_nj}P_j - \beta_{k_nj}Q_j\right) = 0 \tag{4.10}$$

or

$$\alpha_{k_n k_1} P_{k_1} + \alpha_{k_n k_2} P_{k_2} \ldots + \alpha_{k_n k_n} P_{k_n} - \beta_{k_n l_1} Q_{l_1} - \beta_{k_n l_2} Q_{l_2} \ldots - \beta_{k_n l_m} Q_{l_m} = -\sum_{\substack{j=1 \\ j\neq k_1,k_2,\ldots k_n \\ j\neq l_1,l_2,\ldots l_m}}^{N} \left(\alpha_{k_n j} P_j - \beta_{k_n j} Q_j\right) \qquad (4.11)$$

Differentiating P_L w.r.t Q_{l_1}

$$\frac{\partial P_L}{\partial Q_{l_1}} = 2\alpha_{l_1 l_1} Q_{l_1} + 2\sum_{\substack{j=1 \\ j\neq l_1}}^{N} \left(\alpha_{l_1 j} P_j + \beta_{l_1 j} Q_j\right) = 0 \qquad (4.12)$$

or

$$\beta_{l_1 k_1} P_{k_1} + \beta_{l_1 k_2} P_{k_2} \ldots + \beta_{l_1 k_n} P_{k_n} + \alpha_{l_1 l_1} Q_{l_1} + \alpha_{l_1 l_2} Q_{l_2} \ldots + \alpha_{l_1 l_m} Q_{l_m} = -\sum_{\substack{j=1 \\ j\neq k_1,k_2,\ldots k_n \\ j\neq l_1,l_2,\ldots l_m}}^{N} \left(\alpha_{l_1 j} P_j + \beta_{l_1 j} Q_j\right) \qquad (4.13)$$

Similarly, differentiating P_Lw.r.t Q_{l_m}

$$\frac{\partial P_L}{\partial Q_{l_m}} = 2\alpha_{l_m l_m} Q_{l_m} + 2\sum_{\substack{j=1 \\ j\neq l_m}}^{N} \left(\alpha_{l_m j} P_j + \beta_{l_m j} Q_j\right) = 0 \qquad (4.14)$$

or

$$\beta_{l_m k_1} P_{k_1} + \beta_{l_m k_2} P_{k_2} \ldots + \beta_{l_m k_n} P_{k_n} + \alpha_{l_m l_1} Q_{l_1} + \alpha_{l_m l_2} Q_{l_2} \ldots + \alpha_{l_m l_m} Q_{l_m} = -\sum_{\substack{j=1 \\ j\neq k_1,k_2,\ldots k_n \\ j\neq l_1,l_2,\ldots l_m}}^{N} \left(\alpha_{l_m j} P_j + \beta_{l_m j} Q_j\right) \qquad (4.15)$$

The above equations can be rearranged as:

$$\begin{bmatrix} \alpha_{k_1k_1} & \alpha_{k_1k_2} & \cdots & \alpha_{k_1k_n} & -\beta_{k_1l_1} & -\beta_{k_1l_2} & \cdots & -\beta_{k_1l_m} \\ \alpha_{k_2k_1} & \alpha_{k_2k_2} & \cdots & \alpha_{k_2k_n} & -\beta_{k_2l_1} & -\beta_{k_2l_2} & \cdots & -\beta_{k_2l_m} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \alpha_{k_nk_1} & \alpha_{k_nk_2} & \cdots & \alpha_{k_nk_n} & -\beta_{k_nl_1} & -\beta_{k_nl_2} & \cdots & -\beta_{k_nl_m} \\ \beta_{l_1k_1} & \beta_{l_1k_2} & \cdots & \beta_{l_1k_n} & \alpha_{l_1l_1} & \alpha_{l_1l_2} & \cdots & \alpha_{l_1l_m} \\ \beta_{l_2k_1} & \beta_{l_2k_2} & \cdots & \beta_{l_2k_n} & \alpha_{l_2l_1} & \alpha_{l_2l_2} & \cdots & \alpha_{l_2l_m} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \beta_{l_mk_1} & \beta_{l_mk_2} & \cdots & \beta_{l_mk_n} & \alpha_{l_ml_1} & \alpha_{l_ml_2} & \cdots & \alpha_{l_ml_m} \end{bmatrix} \begin{bmatrix} P_{k_1} \\ P_{k_2} \\ \vdots \\ P_{k_n} \\ Q_{l_1} \\ Q_{l_2} \\ \vdots \\ Q_{l_m} \end{bmatrix} = - \begin{bmatrix} B_{k_1} \\ B_{k_2} \\ \vdots \\ B_{k_n} \\ C_{l_1} \\ C_{l_2} \\ \vdots \\ C_{l_m} \end{bmatrix} \qquad (4.16)$$

Where

$$B_{k_i} = \sum_{\substack{j=1 \\ j\neq k_1,k_2,\ldots k_n \\ j\neq l_1,l_2,\ldots l_m}}^{N} \left(\alpha_{k_ij}P_j - \beta_{k_ij}Q_j\right); \qquad i = 1,2,\ldots\ldots n \qquad (4.17)$$

and

$$C_{l_i} = \sum_{\substack{j=1 \\ j\neq k_1,k_2,\ldots k_n \\ j\neq l_1,l_2,\ldots l_m}}^{N} \left(\alpha_{l_ij}P_j + \beta_{l_ij}Q_j\right); \qquad i = 1,2,\ldots\ldots m \qquad (4.18)$$

Let

$$\begin{bmatrix} [A_{11}]_{n\times n} & [A_{12}]_{n\times m} \\ [A_{21}]_{m\times n} & [A_{22}]_{m\times m} \end{bmatrix} = \begin{bmatrix} \alpha_{k_1k_1} & \alpha_{k_1k_2} & \cdots & \alpha_{k_1k_n} & -\beta_{k_1l_1} & -\beta_{k_1l_2} & \cdots & -\beta_{k_1l_m} \\ \alpha_{k_2k_1} & \alpha_{k_2k_2} & \cdots & \alpha_{k_2k_n} & -\beta_{k_2l_1} & -\beta_{k_2l_2} & \cdots & -\beta_{k_2l_m} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \alpha_{k_nk_1} & \alpha_{k_nk_2} & \cdots & \alpha_{k_nk_n} & -\beta_{k_nl_1} & -\beta_{k_nl_2} & \cdots & -\beta_{k_nl_m} \\ \beta_{l_1k_1} & \beta_{l_1k_2} & \cdots & \beta_{l_1k_n} & \alpha_{l_1l_1} & \alpha_{l_1l_2} & \cdots & \alpha_{l_1l_m} \\ \beta_{l_2k_1} & \beta_{l_2k_2} & \cdots & \beta_{l_2k_n} & \alpha_{l_2l_1} & \alpha_{l_2l_2} & \cdots & \alpha_{l_2l_m} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \beta_{l_mk_1} & \beta_{l_mk_2} & \cdots & \beta_{l_mk_n} & \alpha_{l_ml_1} & \alpha_{l_ml_2} & \cdots & \alpha_{l_ml_m} \end{bmatrix} \qquad (4.19)$$

Therefore, equation (4.16) can be written as

$$\begin{bmatrix} [A_{11}]_{n\times n} & [A_{12}]_{n\times m} \\ [A_{21}]_{m\times n} & [A_{22}]_{m\times m} \end{bmatrix} \begin{bmatrix} \left[P_{k_i}\right]_{n\times 1} \\ \left[Q_{l_i}\right]_{m\times 1} \end{bmatrix} = \begin{bmatrix} \left[B_{k_i}\right]_{n\times 1} \\ \left[C_{l_i}\right]_{m\times 1} \end{bmatrix} \qquad (4.20)$$

or

$$\begin{bmatrix} \left[P_{k_i}\right]_{n\times 1} \\ \left[Q_{l_i}\right]_{m\times 1} \end{bmatrix} = \begin{bmatrix} [A_{11}]_{n\times n} & [A_{12}]_{n\times m} \\ [A_{21}]_{m\times n} & [A_{22}]_{m\times m} \end{bmatrix}^{-1} \begin{bmatrix} \left[B_{k_i}\right]_{n\times 1} \\ \left[C_{l_i}\right]_{m\times 1} \end{bmatrix} \qquad (4.21)$$

Let

$$\begin{bmatrix} [A_{11}]_{n\times n} & [A_{12}]_{n\times m} \\ [A_{21}]_{m\times n} & [A_{22}]_{m\times m} \end{bmatrix}^{-1} = \begin{bmatrix} [A'_{11}] & [A'_{12}] \\ [A'_{21}] & [A'_{22}] \end{bmatrix} \qquad (4.22)$$

Therefore

$$[P_{k_i}]_{n\times 1} = [A'_{11}]_{n\times n}\,[B_{k_i}]_{n\times 1} + [A'_{12}]_{n\times m}\,[C_{l_i}]_{m\times 1} \tag{4.23}$$

and

$$[Q_{l_i}]_{m\times 1} = [A'_{21}]_{m\times n}\,[B_{k_i}]_{n\times 1} + [A'_{22}]_{m\times m}\,[C_{l_i}]_{m\times 1} \tag{4.24}$$

Hence, the active power injected at bus k_i, can be evaluated as given below

$$[P_{DG\,k_i}]_{n\times 1} = [P_{k_i}]_{n\times 1} + [P_{D_i}] \tag{4.25}$$

Where P_{D_i} is the active power demand at bus k_i, and

$$[Q_{DG\,l_i}]_{m\times 1} = [Q_{l_i}]_{m\times 1} + [Q_{D_i}] \tag{4.26}$$

Where Q_{D_i} is the reactive power demand at bus l_i.

Equation (4.25) gives the size of Type-I DG at ${k_i}^{th}$ bus and (4.26) gives the size of Type-II DG at ${l_i}^{th}$ bus for the loss to be minimum.

4.3.1 Optimal Locations

As discussed earlier, the number of combinations is too large for evaluating all the combinations. So a search technique is used for determining optimal location. The optimal location for the placement of multiple DGs is determined by using PSO technique taking the location as the variable.

Note: For type-1 DG, $k_i \neq l_j\ \forall\, j$; For type-2 DG (i.e. capacitor), $l_i \neq k_j\ \forall\ j$;

For type-3 DG, $k_i = l_j$

4.3.2 Optimal Power Factor

Optimal power factor is determined using (4.25) and (4.26) in case of $k_i = l_j$. Therefore optimal power factor can be evaluated as

$$PF_{DG\,i} = \frac{P_{DG\,i}}{\sqrt{{P_{DG\,i}}^2 + {Q_{DG\,i}}^2}} \tag{4.27}$$

4.3.3 Computational Procedure

The PSO-based hybrid approach for solving the optimal placement of multiple DGs problem to minimize the loss takes the following steps:

Step 1: Input line and bus data, and bus voltage limits.

Step 2: Calculate the loss using distribution load flow based on backward sweep-forward sweep method.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Locations of type-I DGs & Locations of type-II DGs) in the solution space. Set the iteration counter k = 0.

Step 4: For each particle, calculate the sizes of P_{DG_i} and Q_{DG_i} using (4.25) and (4.26).

Step 5: If the bus voltage is within the limits as given, evaluate the total loss using (2.1). Otherwise, that particle is infeasible.

Step 6: For each particle, apply compare its objective value with the individual best. If the objective value is lower than Pbest, set this value as the current Pbest, and record the corresponding particle position.

Step 7: Choose the particle associated with the minimum individual best Pbest of all particles, and set the value of this Pbest as the current overall best Gbest.

Step 8: Update the weight, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 9: If the iteration number reaches the maximum limit, go to Step 10. Otherwise, set iteration index k = k + 1, and go back to Step 3.

Step 10: Print out the optimal solution to the target problem. The best position includes the optimal locations and sizes of DG and the corresponding fitness value representing the minimum total real power loss.

4.3.4 Results

Based on the proposed approach, optimum sizes of type-I DGs and type-II DGs are calculated at various locations for the test system. Table 4.2 shows the optimal placement of multiple DGs with optimal power factors at optimal locations to minimize the power losses by hybrid approach in a 33-bus system. The results are obtained by the proposed approach and are given in Table 4.2. Table 4.2 shows better results than by using the proposed approach discussed in section 4.2.

Table 4.2 Multiple Type-III DG placement by Hybrid approach for 33-bus system

Number of DGs	Location	Installed DG size		Optimal p.f.	Power loss (kW)
		(MW)	(MVAr)		
1 DG	6	2.4908	1.7213	0.8227	67.951
2 DGs	13	0.8286	0.3869	0.9061	28.559
	30	1.1141	1.0558	0.7258	
3 DGs	13	0.7822	0.3649	0.9062	11.763
	24	1.0696	0.5164	0.9005	
	30	1.0162	1.0074	0.7102	

Table 4.3 shows the locations, sizes of the Type-I (DG) and Type-II (capacitor) DGs and respective loss in the network when the given combination of DGs is applied simultaneously considering $\mathrm{P}_{\mathrm{DG}_\mathrm{i}}$ *and* $\mathrm{Q}_{\mathrm{DG}_\mathrm{i}}$ to be independent of each other.

Table 4.3 Multiple Type-I and Type-II DGs placement for 33 Bus System

	No DG			1 DG			2 DGs			3 DGs		
	loc	size	loss	loc	size	loss	loc	size	loss	loc	size	loss
No Capacitors				6	2.49	111.2	13	0.83	87.3	13	0.79	72.9
							30	1.1		24	1.07	
										30	1.01	
One Capacitor	30	1.23	151.4	6	2.49	58.5	13	0.83	36.1	14	0.75	22.3
				30	1.22		30	1.11		24	1.07	
							30	1.22		30	1.02	
										30	1.22	
Two Capacitors	12	0.43	141.9	6	2.49	50.4	13	0.83	28.5	14	0.75	14.9
	30	1.04		12	0.44		30	1.11		24	1.07	
				30	1.03		12	0.44		30	1.03	
							30	1.04		12	0.44	
										30	1.04	
Three Capacitors	13	0.36	138.4	6	2.49	47.2	13	0.83	25.3	14	0.75	11.8
	24	0.51		13	0.37		30	1.11		24	1.07	
	30	1.02		24	0.52		13	0.36		30	1.03	
				30	1.01		24	0.52		13	0.36	
							30	1.01		24	0.52	
										30	1.01	

4.4 PSO APPROACH

In general certain limits cannot be applied while evaluating the loss using analytical methods. This methodology was proposed to show that a heuristic method like PSO which can optimize a problem of any order and with any kind of characteristics including constraints. To compare the results from Table 4.3 an algorithm was proposed ignoring size limits. The algorithm was proposed to find the results by considering all the limits. The objective is same as in all the above cases i.e. to minimize power distribution loss.

4.4.1 Proposed PSO Algorithm

The PSO-based approach for solving the optimal placement of DG problem to minimize the loss takes the following steps:

Step 1: Input line and bus data, and bus voltage limits.

Step 2: Calculate the loss using distribution load flow based on backward sweep-forward sweep method.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Locations of type-I and type-II DGs & Sizes of type-I and type-II DGs) in the solution space. Set the iteration counter k = 0.

Step 4: For each particle, find voltage profile after placing the combination. If the bus voltage is within the limits as given, evaluate the total loss using equation 2.1. Otherwise, that particle is infeasible so set it to base case.

Step 5: For each particle, compare its objective value with the individual best. If the objective value is lower than Pbest, set this value as the current Pbest, and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best Pbest of all particles, and set the value of this Pbest as the current overall best Gbest.

Step 7: Update the weight, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Otherwise, set iteration index k = k + 1, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal locations and sizes of DG and the corresponding fitness value representing the minimum total real power loss.

4.4.2 PSO Algorithm Considering Size Constraints

In the proposed PSO algorithm, size constraints are considered to maintain the concept of DG against the centralized generation as explained in section 3.4 of chapter-3, for solving the optimal placement of DG problem to minimize the loss takes the following steps:

Step 1: Input line and bus data, and bus voltage limits.

Step 2: Calculate the loss using distribution load flow based on backward sweep- forward sweep method.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Locations of type-I and type-II DGs & Sizes of type-I and type-II DGs) in the solution space. Set the iteration counter k = 0.

Step 4: For each particle, scale the size variables in the particles to the size limits of the network. Find voltage profile after placing the combination. If the bus voltage is within the limits as given, evaluate the total loss using equation 2.1. Otherwise, that particle is infeasible so set it to base case.

Step 5: For each particle, compare its objective value with the individual best. If the objective value is lower than Pbest, set this value as the current Pbest, and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best Pbest of all particles, and set the value of this Pbest as the current overall best Gbest.

Step 7: Update the weight, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Otherwise, set iteration index k = k + 1, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal locations and sizes of DG and the corresponding fitness value representing the minimum total real power loss.

4.4.3 Results

Table 4.4 shows the comparison of multiple placement of DGs by hybrid approach with PSO based approach and it is seen that placement of DGs by hybrid approach at particular bus gives the same reduction in losses as given by PSO based approach. It can be observed that the results obtained by hybrid approach are comparable with PSO approach results.

Table 4.5 shows the results for different combinations of DGs which is very useful for taking a wise decision to place DGs. It is observed from Table 4.5, that it would be wise to place 2 DGs and by considering the cost either 1 or 2 capacitors can be placed.

Table 4.4 Comparison of Multiple DGs and Capacitors by Hybrid and PSO approach

Hybrid approach					PSO approach			
Cases	Bus No.	Capacity		Loss in (kW)	Bus No.	Capacity		Loss in (kW)
		P (MW)	Q (MVAR)			P (MW)	Q (MVAR)	
case-1 1DG	6	2.4908		111.2	6	2.5902		111.02
case-2 1DG,1Cap	6	2.4829		58.5	6	2.5317		58.45
	30		1.2232		30		1.2558	
case-3 2DG, 2Cap	12		0.4357	28.5	12		0.4491	28.493
	13	0.8281			13	0.8462		
	30	1.1143	1.0358		30	1.1375	1.0437	
case-4 5DG, 5Cap	6	0.7438		5.2	6	0.7264	0	5.597
	8		0.1874		7		0.3607	
	10	0.3837			10	0.3701		
	14		0.2485		14		0.298	
	16	0.3796			16	0.399		
	24	0.9536	0.4662		25	0.7312	0.3777	
	26		0.2198		30		0.9057	
	30		0.8803		31	0.7028		
	31	0.6756						

Table 4.5 Multiple DGs placement with size constraints for 33 Bus System

	1 DG			2 DGs			3 DGs		
	Loc.	Size	Loss (in kW)	Loc.	Size	Loss (in kW)	Loc.	Size	Loss (in kW)
No Capacitors				14	0.71	93.8	10	0.42	91.9
				31	0.79		16	0.38	
							31	0.7	
One Capacitor	8	1.5	70.2	14	0.71	45.4	10	0.42	43.6
	30	0.9		31	0.79		16	0.38	
				30	0.9		31	0.7	
							30	0.9	
Two Capacitors	8	1.5	67.1	14	0.71	42.3	10	0.41	40.6
	14	0.21		31	0.79		16	0.38	
	30	0.69		14	0.21		31	0.71	
				30	0.69		14	0.21	
							30	0.69	
Three Capacitors	8	1.5	66.8	14	0.71	42	10	0.41	40.3
	14	0.21		31	0.79		16	0.38	
	30	0.49		14	0.21		31	0.71	
	32	0.2		30	0.49		14	0.21	
				32	0.2		30	0.49	
							32	0.2	

4.5 PSO with Size Limit and Ceiling Effect

Practical systems have DGs of certain size which are fixed. Till this point all the methods show continuous values of DG sizes. Ceiling effect is not included in any of the methods. This method specifically is developed to determine the ceiled sizes of generators for which minimum losses occur. Sizes of both DG and capacitor are ceiled to upper 100kW of the generation size. The algorithm for this method is described in the following section.

4.5.1 Proposed Algorithm

Step 1: Input line and bus data, and bus voltage limits.

Step 2: Calculate the loss using distribution load flow based on backward sweep-forward sweep method.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Locations of DGs & Capacitors and Sizes of DGs & Capacitors) in the solution space. Set the iteration counter k = 0.

Step 4: For each particle, scale the size variables in the particles to the size limits of the network. Ciel the sizes of DG and Capacitor to upper100kW and find Voltage profile after placing the combination. If the bus voltage is within the limits as given, evaluate the total loss using equation 2.1. Otherwise, that particle is infeasible so set it to base case loss.

Step 5: For each particle, compare its objective value with the individual best. If the objective value is lower than Pbest, set this value as the current Pbest, and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best Pbest of all particles, and set the value of this Pbest as the current overall best Gbest.

Step 7: Update the weight, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Otherwise, set iteration index k = k + 1, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal locations and sizes of DG and the corresponding fitness value representing the minimum total real power loss.

4.5.2 Results

Table 4.6 shows the result of the PSO approach with ceiling on the sizes of DGs and capacitors in 33 bus network. The sizes of DGs and capacitors obtained are such that which are standard rating and are easily available in the market. It is observe that there are large combinations of DGs and capacitors to compensate the active and reactive power of the network to minimize the power distribution loss. Table-4.6 can be used as a guidance table for distribution utility.

Table 4.6 Multiple DGs and Capacitors placement for 33 Bus System

	1 DG			2 DGs			3 DGs		
	loc	size	loss	loc	size	loss	loc	size	loss
No Capacitors				14	0.7	93.8	10	0.5	92.1
				31	0.8		16	0.3	
							31	0.7	
One Capacitor	8	1.5	70.2	14	0.7	45.4	10	0.5	43.8
	30	0.9		31	0.8		16	0.3	
				30	0.9		31	0.7	
							30	0.9	
Two Capacitors	8	1.5	67.1	14	0.7	42.3	10	0.4	41
	14	0.2		31	0.8		16	0.4	
	31	0.7		14	0.2		31	0.7	
				31	0.7		14	0.2	
							31	0.7	
Three Capacitors	8	1.5	66.8	14	0.7	42	10	0.4	40.3
	14	0.2		31	0.8		16	0.4	
	30	0.6		14	0.2		31	0.7	
	32	0.1		30	0.6		14	0.2	
				32	0.1		30	0.6	
							32	0.1	

4.6 Conclusion

In this work multiple type-III DGs are placed based on two different approaches to minimize the power distribution loss. In the first case, sizes of type-III DGs are evaluated by optimizing the active power generation and power factor or reactive power generation and the results obtained are compared. The sizes of DGs are evaluated by analytical approach and the locations and p.f.s are determined by the application of PSO approach. In the second case, different types of DGs (Type-I and Type-II) are coupled at the same location to determine their respective power factors. The sizes of type-I and type-II DGs are evaluated by analytical approach and the locations are determined by the applications by PSO approach. In this work, different types of DGs, type-I DG (DG) and type-II DG (capacitors) are combined together with different combinations by different approach to minimize the power distribution loss.

CHAPTER – 5

OPTIMAL PLACEMENT OF TYPE IV DG

5.1 INTRODUCTION

In the previous chapters an algorithm for optimal placement of DGs injecting real, injecting reactive power and injecting both real and reactive power has been proposed by different approaches to minimize the real power loss. In this chapter, analytical approach has been applied for the placement of type-IV DG for the integration of non-conventional energy sources like wind turbine. Type-IV DG has different characteristics as compared to other types of DGs. The type-IV DG supplies real power and in turn absorbs the reactive power. The results obtained are compared with PSO based approach.

As reported in the literature, various techniques/approaches have been applied for the optimal allocation of DGs injecting real power [1, 3, 6, 25, 7, 44, 40, 45, 55, 87, 100, 112, 116, 152, 160,], injecting reactive power [2, 4, 20, 23, 34, 51, 71, 73, 85, 86, 90, 99, 117, 146, 149, 163], and injecting both real and reactive powers [45, 119, 147, 169-170]. The approaches applied for the placement of DGs injecting real power and consuming reactive power are few. Therefore, it is evident that, the optimal placement of DG injecting real power and consuming reactive power i.e. type-IV DG in the distribution system needs more attention. Hence, a suitable methodology is required for optimal placement of type-IV DG in the system.

5.2 SIZE & SITE ALLOCATION OF TYPE IV DG

Type-IV DG has different characteristics as compared to other three types of DGs. The type-IV DG supplies real power and in turn absorbs the reactive power. This work proposes the application of analytical approach to find the optimal placement of type-IV DG in the primary distribution system to reduce the real power loss and improvement in voltage profile. The results are verified with PSO based approach which uses analytical expressions of induction generator characteristics for proper deployment of the DG unit and the effects on system performance are also investigated.

5.2.1 Problem Formulation

In this section problem is formulated for finding the optimal size and location of type-IV DG (e.g. Induction generator) using its characteristic expressions. The induction generator supplies the real power and in turn absorbs the reactive power [46]. Most of the type-IV DG have the similar active and reactive power generation characteristics and can be expressed as (5.1). The solution of the network has been obtained by forward-backward load flow method. The objective of placement of type-IV DG is to minimize the real power loss and is given by (2.1).

$$Minimize\ P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[A_{ij}\left(P_iP_j + Q_iQ_j\right) + B_{ij}\left(Q_iP_j - P_iQ_j\right)\right]$$

The analytical approach and PSO based algorithm have been proposed for determining the optimal size and location of type-IV DG, and are explained in the following subsections.

5.2.1.1 Analytical Approach

The type-IV DG produces real power and in turn absorbs reactive power. The reactive power consumed by the DG is a function of active power generated and may be represented by [110].

$$Q_{DG} = -(0.5 + P_{DG}^2) \tag{5.1}$$

Substituting (5.1) into (2.1), the power loss equation is written as

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[A_{ij}\begin{bmatrix}(P_{DGi} - P_{Di})P_j + \\ \left(-1 - 0.04P_{DGi}^2 - Q_{Di}\right)Q_j\end{bmatrix} + B_{ij}\begin{bmatrix}\left(-1 - 0.04P_{DGi}^2 - Q_{Di}\right)P_j \\ -(P_{DGi} - P_{Di})Q_j\end{bmatrix}\right] \tag{5.2}$$

The total power loss against the injected power is a parabolic function and, at the minimum losses, the rate of change of losses with respect to injected power becomes zero [112].

$$\frac{\partial P_L}{\partial P_{DGi}} = 2A_{ii}\left(P_i - 0.08P_{DGi}Q_j\right) + 2\sum_{\substack{j=1\\ j\neq i}}^{N} B_{ij}\left(-0.08P_{DGi}P_j - Q_j\right) = 0 \tag{5.3}$$

or

$$\begin{bmatrix}A_{ii}\left[P_{DGi} - P_{Di} + 0.08P_{DGi}\left(0.05 + 0.04P_{DGi}^2 + Q_{Di}\right)\right] \\ +\sum_{\substack{j=1\\ j\neq i}}^{N}\left(A_{ij}P_j - B_{ij}Q_j\right) - 0.08P_{DGi}\sum_{\substack{j=1\\ j\neq i}}^{N}\left(A_{ij}Q_j + B_{ij}P_j\right)\end{bmatrix} = 0 \tag{5.4}$$

$$Let \quad X_i = \sum_{\substack{J=1 \\ J \neq i}}^{n} \left(A_{ij} P_j - B_{ij} Q_j \right); \qquad and \qquad Y_i = \sum_{\substack{J=1 \\ J \neq i}}^{n} \left(A_{ii} Q_j + B_{ij} P_j \right) \tag{5.5}$$

Therefore, interms of X_i and Y_i (5.4) can be written as

$$\begin{bmatrix} 0.0032 A_{ii} P_{DGi}^3 + (X_i - A_{ii} P_{Di}) + \\ P_{DGi} [1.004 A_{ii} + 0.08 A_{ii} Q_{Di} - 0.08 Y_i] \end{bmatrix} = 0 \tag{5.6}$$

The above equation is a polynomial of P_{DGi} and can be solved to find the size of type-IV DG (P_{DGi}) at each location *i* for the minimum real power loss in the network. The optimal location can be found by the placement of DG of size as obtained from (5.6), at the considered bus, the bus at which the total power loss is minimum after the placement of DG and all the constraints are satisfied will be the optimal location.

5.2.1.1.1 Computational Procedure

Step 1: Run the base case load flow.

Step 2: Find the optimum size of DG for each bus by solving (5.6) and calculate the reactive power drawn by DG for each bus using (5.1).

Step 3: Compute approximate loss using (2.1) for each bus by placing DG of optimum size and reactive power drawn by it which is obtained in step 2 for that bus. Inject the power from DG for that bus and use base case values for state variables.

Step 4: Locate the bus at which the loss is minimum after DG placement. This is the optimum location for DG.

Step 5: Run load flow with type-IV DG to get the optimal size and location.

5.2.1.2 PSO Based Approach

In the above approach it is required to solve a cubic equation every time which gives real and complex roots, and also it is difficult to solve this equation. So a PSO approach was proposed for a faster and more optimized solution. The main objective is to minimize the total power loss as given in (2.1) while meeting the network constraints.

5.2.1.2.1 PSO Algorithm

The PSO-based approach for solving the optimal placement of type-IV DG problem to minimize the loss takes the following steps [15]:

Step 1: Input line and bus data.

Step 2: Calculate the loss using distribution load flow based on backward sweep-forward sweep method.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Size of DG and Location of DG) in the solution space. Set the iteration counter k = 0.

Step 4: For each particle, calculate the Q_{DGi} using (5.1) and if the bus voltage is within the limits, evaluate the total loss in (2.1). Otherwise, that particle is infeasible so set it to base case.

Step 5: Compare particles objective value with the individual best. If the objective value is lower than Pbest, set this value as the current Pbest, and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best Pbest of all particles, and set the value of this Pbest as the current overall best Gbest.

Step 7: Update the weight, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Otherwise, set iteration index k = k + 1, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal locations and sizes of type-IV DG and the corresponding fitness value representing the minimum total real power loss.

5.2.2 Results and Discussion

As explained in section 3.3.3, 33-bus and 69-bus distribution systems have been used for the illustration of the proposed algorithm. The optimum size of type-IV DG determined using analytical approach at each bus of 33-bus test system and crossponding power loss are shown in Figs. 5.1 and 5.2 respectively.

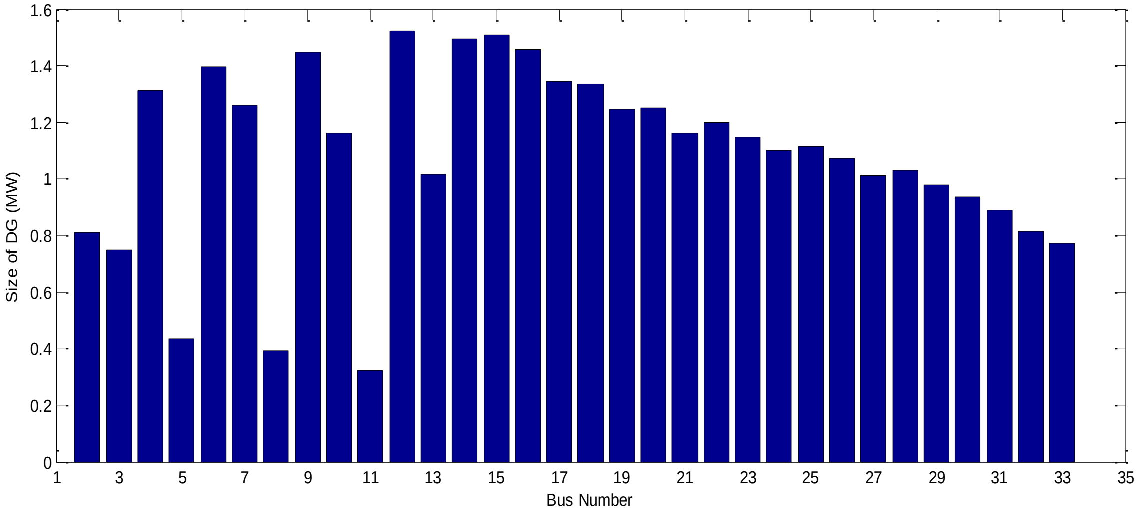


Figure 5.1 Optimum size of DG at various locations for minimum power loss of 33-bus distribution system

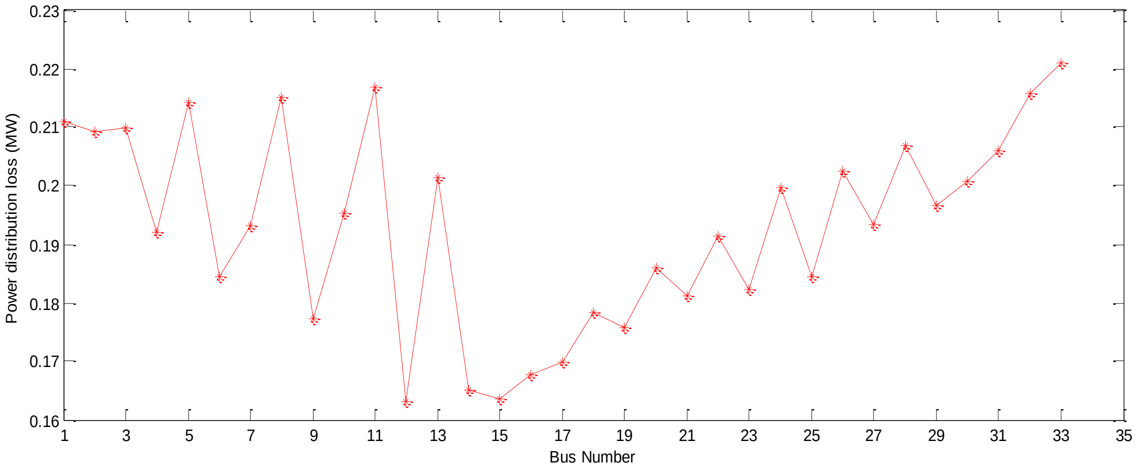


Figure 5.2 Power distribution loss w.r.t. power injected at each bus of 33 bus system

The bus where the total loss comes to be minimum after the placement of DG will be optimal location for the placement of type-IV DG. From the Fig. 3.16, it is observed that the optimal location is bus number 12 with a real power loss of 163.3 kW by analytical approach.

Similarly, Figs. 5.3 and 5.4, show the optimum sizes of type-IV DG w.r.t. power injected at each bus for the loss to be minimum and power distribution loss crossponding to the optimal size of DG at that bus for 69-bus system respectively. It is observed that, a type-IV DG producing 1.43 MW and consuming 0.581 MVAr, when installed at bus No. 56 minimizes the power distribution loss as shown in Table 5.1. The reductions in real power losses achieved by both the approaches are nearly same.

Table 5.1 Type-IV DG placement for 33 bus and 69 bus systems by analytical and PSO approach

Case	Test system	Optimum location	Optimum DG size		Real Power loss (KW)		% reduction in real power loss
			(MW)	(MVAr)	Without DG	With DG	
Analytical	33 bus	Bus 12	1.52	0.592	211	163.3	22.61%
PSO			**1.52**	**0.593**	**211**	**163.3**	**22.61%**
Analytical	69 bus	Bus 56	1.43	0.581	225	160.6	28.62%
PSO			**1.44**	**0.578**	**225**	**160.8**	**28.53%**

The optimal sized type-IV DG, injecting real power of 1.52 MW and consuming reactive power of 0.592 MVAr, is placed at bus number 12, minimizes the real power loss by 22.61%. The reduction in real power loss are 28.62% by the analytical approach, when the optimal size of type-IV DG is placed at bus 56 in a 69-bus test system as shown in Table 5.1. The reductions in real power loss achieved by the application of PSO approach are nearly same as compared to analytical approach with slight changes in size of DG. This change is due to heuristic nature of PSO algorithm.

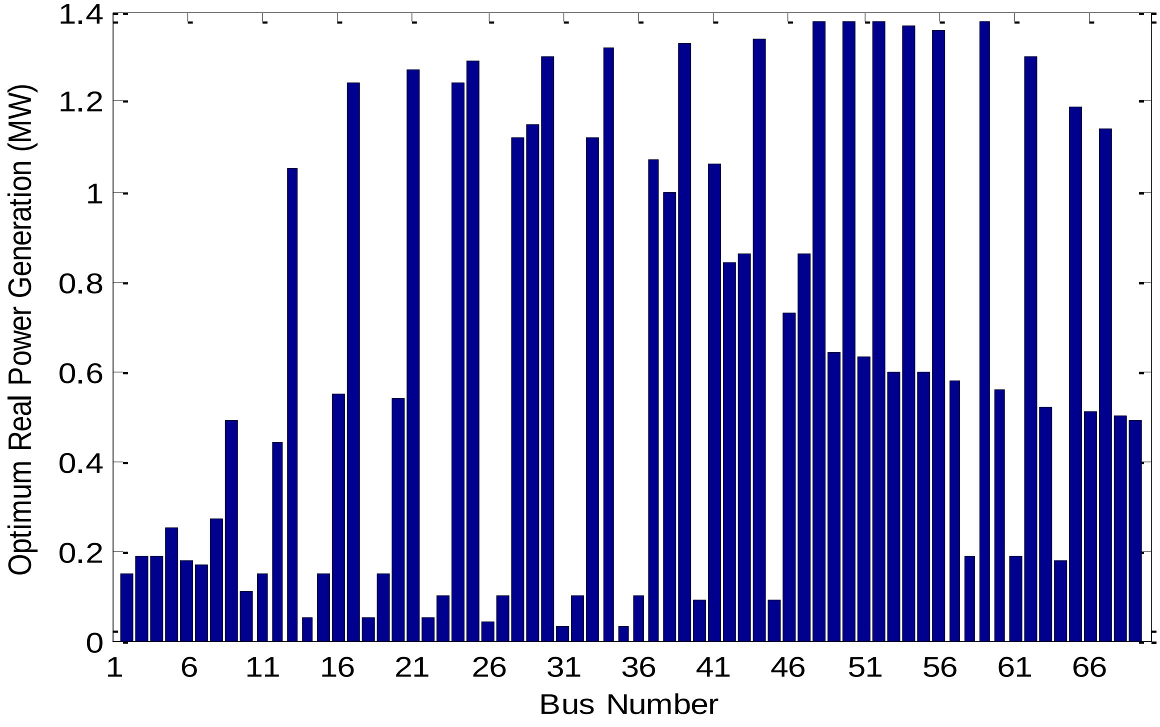


Figure 5.3 Optimum size of DG at various locations minimum power loss for 69-bus system

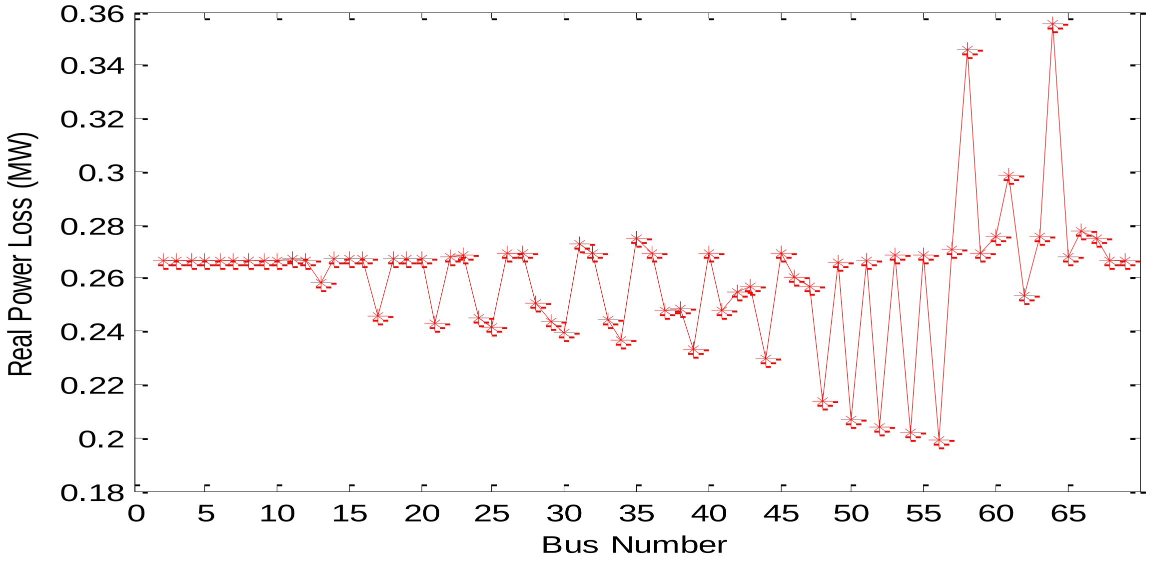


Figure 5.4 Power distribution loss w.r.t. power injected at each bus of 69-bus system

From the Figs. 5.5 and 5.6 it is seen that the significant improvement in the bus voltages by the placement of type-IV DG in 33-bus and 69-bus test distribution systems respectively by both the analytical and PSO based approach.

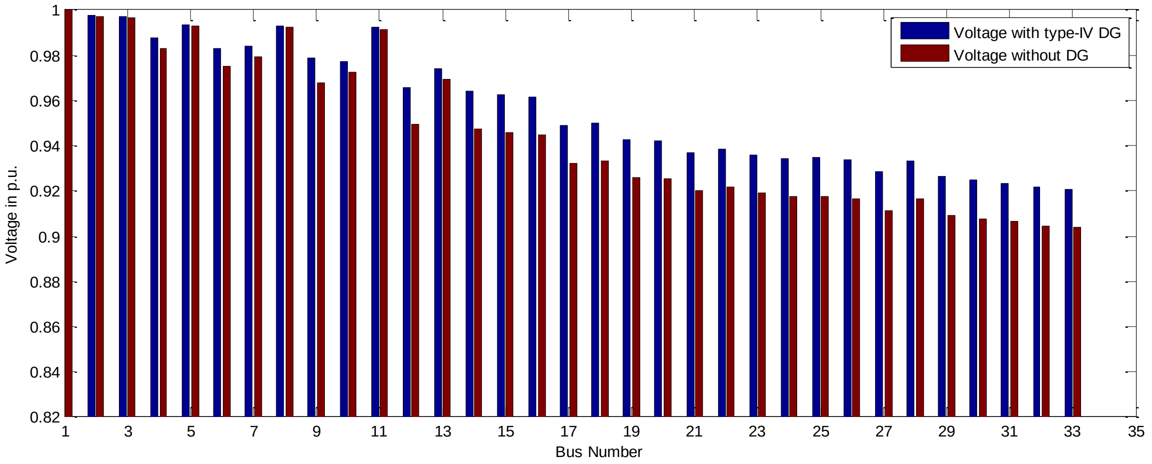


Figure 5.5 Voltage profile with type-IV DG of 33-bus system by analytical approach

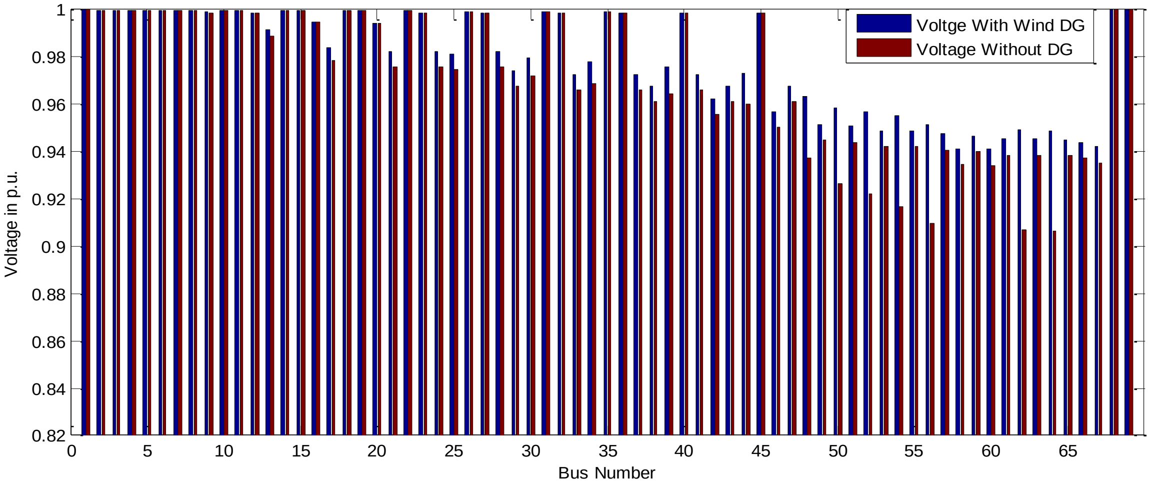


Figure 5.6 Improvement of voltage profile with type-IV DG of 69-bus system by analytical approach

5.3 CONCLUSIONS

In this work, type IV DG is considered for optimal placement. Optimal placement problem has been solved using the analytical approach and the application of PSO based algorithm. The objective function has been minimized to place type-IV DG with various operational constraints. The type IV DG, requires special attention due to its special characteristics, as it generates real power and consumes reactive power. The placement and analysis of type-IV DGs give guidance for integration of non-conventional energy sources like wind turbine.

CHAPTER – 6

COST & BENEFIT BASED DG PLACEMENT

6.1 INTRODUCTION

In the previous chapters, various issues related to optimal placement of DG have been addressed. In all the cases, the main objective is to minimize the power distribution loss taking place in distribution system. In this chapter, study has been performed for optimal sizing and siting of real and reactive power sources in the distribution systems taking various technical and economic factors in order to maximize the profit for the distribution company.

Generally, distribution system planners make an effort to supply economical and reliable electric power to the customer. Thus it is important to design, operate and maintain the power system with lowest cost and highest benefit. Loss reduction and improvement in voltage profile become two important goals for electrical distribution companies. To achieve this, these companies work on various technologies and optimization programs to improve the economic benefits. With advances in technology and restructuring of electric power systems, DGs are predicted to play an important role in the future. DG sources can be placed in distribution networks to provide grid reinforcement, reduction in power losses and on-peak operating costs, improved voltage profiles and load factors and deferring or eliminating system upgrades. The impact of DG on system operation depends highly on its location in the distribution system. Installation of DGs at improper locations would lead to an increase in energy loss and loading of distribution feeders. For these reasons, an optimization method must be used to work out the optimal DG location and size, keeping in consideration the costs and benefits for both the customer as well as the utility. Optimal DG placement is a multivariable optimization problem with different operating constraints on DG in distribution system.

Most of the approaches presented so far that make use of artificial intelligence algorithms, analytical approaches or load flow approaches to optimize DG placement [1, 8, 19, 25, 44, 45, 50, 52, 62, 77, 81, 88, 96, 112, 118, 121, 122, 134-136, 138, 151] are based on minimizing power loss. Authors in [1, 6, 25, 44, 45, 55, 64, 87, 96, 112, 119, 151, 152] solve the problem by analytical approach, employing a combination of genetic algorithm and simulated annealing [52, 50], genetic algorithm [26, 52, 77, 92, 100, 107, 126, 132, 133, 157, 159], tabu search method [38, 172, 19], fuzzy approach [16, 79, 90, 118, and 138], load flow approaches [8, 44, 45, and 112], sequential optimization and [7, 15, 32, 37, 40, 48, 56, 60, 62, 74, 83, 108, 116, 129, 155, 167, 171] other heuristic approaches. Optimal placement of capacitor for real power loss reduction, has been presented in [2, 4, 20, 23, 33, 34, 51, 59, 65, 66, 71, 73, 85, 86, 90, 99, 117, 124, 127, 131, 144, 146, 149, 154, 163], for uniformly distributed loads. Distribution system planners effort to supply economical and reliable electric supply to customers [24, 35, 50, 53, 82, 83, 92, 94, 100, 101, 113, 116, 120, 132, 138, 148, 167]. It is important to design, operate and maintain reliable power systems with lowest cost and highest benefit. Loss reduction and improvement in voltage profile are two important goals for electrical distribution companies. The companies need various technologies and optimization programs to bring these economic benefits.

Most of the research work presented so far modeling the optimal placement of DG or multiple DGs or Capacitors for minimization of the real power loss. A mathematical formulation for optimal sizing and siting of DGs and Capacitors in the distribution systems has been developed in this chapter for maximizing the profit. The various technical and economic factors such as the cost of electricity sold in the electricity market, loss reduction revenue, operating costs of DGs, constraints on the number of DGs and Capacitors, maintenance costs and the payback period have been considered for this optimization. It has been assumed that DGs generates real power. The developed formulation is a mixed-integer, non-linear optimization problem and its solution has been obtained by a PSO based approach.

6.2 PROBLEM FORMULATION

In this section, economical benefits and DG and Capacitor costs are submitted and modeled. It is considered that the companies are responsible for fulfilling the customer demand, and operation and management of DG installations. All of these responsibilities are focused on cost reduction and improvement in quality and reliability of customer service. Therefore costs and benefits of DGs and Capacitors allocation in network can be expressed as follows.

6.2.1 DGs and Capacitors Investments evaluation

Following are the DG and the Capacitor costs used for modeling of a system which maximizes the benefits of the distribution company.

6.2.1.1 Installation costs

The cost of DG and Capacitor units, investigation fee, site preparation, construction, monitoring equipment, etc. are included in installation costs. These costs can be formulated as following equation. All the costs are taken in Indian rupee (₹).

$$C_1 = \sum_{i=1}^{NDG} K_{DGi} * IC_i + \sum_{j=1}^{NCap} K_{Capj} * IC_j \quad (6.1)$$

Where, $i = 1, 2, 3 \ldots\ldots\ldots\ldots NDG,$ number of DGs and $j = 1, 2, 3 \ldots\ldots\ldots\ldots\ldots NCap,$ number of Capacitors to be placed. K_{DGi} is the capacity of i^{th} DG in MW and K_{Capj} is the capacity of j^{th} Capacitor in MVAR. IC_i is the initial cost of i^{th} DG in ₹/MW and IC_j is the initial cost of j^{th} Capacitor in ₹/MVAR.

6.2.1.2 Operating Costs

The operating costs of DG and Capacitor include the costs incurred while producing electricity for consumers. The operating costs of Capacitors are assumed to be zero. Operating costs become,

$$C_2 = \sum_{i=1}^{NDG} [K_{DGi} * OC_i] * \Delta T \quad (6.2)$$

Where, OC_i is the operating cost of i^{th} DG in ₹/MWh and ΔT is the total number of operating hours in a year.

If IR is the interest rate and IF the inflation rate, then the present worth factor can be represented as:

$$Present\ Worth\ Factor, \beta^t = \sum_{t=1}^{n} \left(\frac{1 + IF}{1 + IR}\right)^t \quad (6.3)$$

Where, n is the total number of year of planning period. The present worth value of operating cost in a given planning year can be calculated as:

$$PWV\ (C_2) = \sum_{i=1}^{NDG} [K_{DGi} * OC_i] * \Delta T * \beta^t \quad (6.4)$$

6.2.1.3 Maintenance Cost

Another yearly cost of DGs and Capacitors relates to maintenance cost. Maintenance costs include the annual mechanical and electrical inquiry and renovation cost. This cost is independent of placement of DG or Capacitor in the network.

$$C_3 = \left[\sum_{i=1}^{NDG} (K_{DGi} * IC_i) * MC_{DGi} + \sum_{j=1}^{NCap} \left(K_{Capj} * IC_j\right) * MC_{Capj} \right] \qquad (6.5)$$

Where, MC_{DGi} and MC_{Capj} are the maintenance costs of i^{th} DG and *jth* Capacitor in ₹. The present worth value of this annual cost for the planning period is calculated as:

$$PWV(C_3) = \left[\sum_{i=1}^{NDG} (K_{DGi} * IC_i) * MC_{DGi} + \sum_{j=1}^{NCap} \left(K_{Capj} * IC_j\right) * MC_{Capj} \right] * \beta^t \qquad (6.6)$$

6.2.2 DGs and Capacitors benefits evaluation

Distribution companies have huge incentive for placing these DGs and Capacitors optimally in the network. Some of them are summarized in the following section.

6.2.2.1 Active power demand reduction from transmission line

In restructured power system, Distribution Company purchases its power from transmission grid in order to meet the power demand of the customer. The DGs installed by distribution utility, are utilized in fulfilling the power demand of its customer and can also be used to sell the generated power during low demand period. There are certain costs and benefits associated with DG placement in the network.

Energy sold to the electricity market (Grid) during ΔT time segment,

$$C_4 = \sum_{i=1}^{NDG} K_{DGi}.\ \Delta T * EP_G \qquad (6.7)$$

Where, EP_G is the electricity price of grid power in ₹/kWh. The present worth value of electricity generated from DG by the distributed company can be calculated as:

$$PWV(C_4) = \sum_{i=1}^{NDG} K_{DGi}.\ \Delta T * EP_G * \beta^t \qquad (6.8)$$

6.2.2.2 Loss reduction revenue

Optimal placement of DGs and Capacitors in the distribution system minimizes the real power loss. This loss reduction is the primary area of concern for Distribution Company aiming to maximize the profit. The loss reduction revenue in the presence of DGs and Capacitors can be evaluate as:

$$C_5 = \sum_{i=1}^{NDG} \sum_{j=1}^{NCap} \Delta Loss_{ij}.\Delta T * EP_G \tag{6.9}$$

Where, $\Delta Loss_{ij}$ is the reduction in real power losses when number of DGs and Capacitors are placed in the system in kW and EP_G is the electricity price of grid in ₹/kWh. The present worth value of loss reduction revenue in a planning horizon can be calculated as:

$$PWV(C_5) = \sum_{i=1}^{NDG} \sum_{j=1}^{NCap} \Delta Loss_{ij}.\Delta T * EP_G * \beta^t \tag{6.10}$$

6.3 OBJECTIVE FUNCTION

In conclusion, cost and benefit view points which have been described in previous sections are considered in one unique objective function that is formulated below. In this section, an objective function has been presented for maximization of the profit for distribution company,

$$Max\ Z = \ Benefits - Investments \tag{6.11}$$

$$\begin{aligned} Max\ Z = & \sum_{i=1}^{NDG} \left[K_{DGi}.EP_G + \sum_{j=1}^{NCap} \Delta Loss_{ij}.EP_G - K_{DGi}.OC_i \right] \Delta T.\beta^t \\ & - \sum_{i=1}^{NDG} [K_{DGi}.IC_i\{1 + MC_{DGi}.\beta^t\}] \\ & - \sum_{j=1}^{NCap} \left[K_{Capj}.IC_j\{1 + MC_{Capj}.\beta^t\}\right] \end{aligned} \tag{6.12}$$

Subjected to the same constraints as given in (2.2) to (2.5) and (3.7), (3.8) which are reproduce below.

(i) Power flow equations corresponding to both active and reactive power balance for all the buses, are same as (2.2) and (2.3).

$$P_i = \sum_{j=1}^{N} V_i V_j \left[G_{ij}\cos\left(\delta_i - \delta_j\right) + B_{ij}\sin\left(\delta_i - \delta_j\right)\right] \qquad \forall i = 1,2,3,\ldots\ldots N$$

$$Q_i = \sum_{j=1}^{N} V_i V_j \left[G_{ij}\sin\left(\delta_i - \delta_j\right) - B_{ij}\cos\left(\delta_i - \delta_j\right)\right] \qquad \forall i = 1,2,3,\ldots\ldots N$$

(ii) Voltage limits:

The voltage must be kept within standard limits at each bus. Here the voltage limits are taken as ±5% of rated voltage.

$$|V|_i^{min} \leq |V|_i \leq V_i^{max} \qquad i \in buses\ of\ the\ network$$

(iii) Current limits:

In transmission and distribution systems, each line or branch is designed to carry a certain amount of maximum current. Loading a line beyond its current limit can cause severe damage to the line. Hence, the planner must make sure that the line loading limits are not violated due to integration of DGs. The constraints on line loadings can be given as:

$$I_i \leq I_i^{Rated} \qquad \forall i \in N_{Br}$$

Where,

I_i = Current flow in i^{th} branch,

N_{Br} = Number of branches in the system,

I_i^{Rated} = Current permissible for i^{th} branch.

(iv) DG constraints:

The total installed capacity of DGs and Capacitors in the network has been limited to equal to or less than 30% of substation rated capacity to maintain the concept of DG against centralized generation.

$$S_{DG} \leq 0.30 S_{T_{Real}}$$

$$S_{Cap.} \leq 0.30 S_{T_{React.}}$$

Where S_T is the rated capacity of the substation.

6.4 COMPUTATIONAL PROCEDURE

A PSO based algorithm as discussed in chapter-2 has been proposed and applied to maximize the profit to the Distribution Company through the optimal allocation DG and Capacitor in the distribution system. The brief description of proposed PSO based algorithm is given in the following section.

6.4.1 PSO based technique

The maximization of profit of Distribution Company, given by (6.12) has been taken as fitness function in PSO algorithm. The velocity and position of the particles are updated after each iteration. The sizes of DGs and Capacitors are varied between 0 to 30% of substation rated capacity of the network. In PSO algorithm the population size of swarms and the number of iterations are fixed. Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Sizes of DGs and Capacitors, Locations of DGs and Capacitors) in the solution space. Evaluate the fitness function maximizing the profit with optimal sizes of DGs and Capacitors at optimal locations. PSO is a metaheuristic as it makes few or no assumptions about the problem being optimized and can search very large spaces of candidate solutions.

6.4.2 Proposed Optimization algorithm

The PSO based algorithm for the allocation of number of DGs and Capacitors in the distribution system, taking the constraints into consideration to maximizing the profit to Distribution Company is described in following steps,

Step 1: Input line data, bus data.

Step 2: Calculate the loss using exact loss formula (2.1) for base case.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions (Location of DGs and Capacitors and sizes of DGs and Capacitors) in the solution space. Set the iteration counter k = 0. For each particle check all the constraints, if the constraints are satisfied, evaluate the total loss using (2.1). Otherwise, that particle is infeasible so set it to base case loss.

Step 4: Input DG and Capacitor cost data, number and years of planning.

Step 5: For each particle, compare its objective value (6.12) with the individual best. If the objective value is higher than P*best*, set this value as the current P*best*, and record the corresponding particle position. Choose the particle associated with the maximum individual best P*best* of all particles, and set the value of this P*best* as the current overall best G*best*.

Step 6: Update the weight, velocity and position of particle using (2.16), (2.14) and (2.15) respectively.

Step 7: If the iteration number reaches the maximum limit, go to next step. Otherwise, set iteration index k = k + 1, and repeat the process.

Step 8: Print out the optimal solution to the target problem. The best position includes the optimal sizes of DGs and Capacitors at optimal locations and the corresponding fitness value representing the maximum profit in a specified time period.

6.5 CASE STUDY

The proposed PSO based algorithm as described in section 6.4.1 has been applied on the 33 and 69 bus systems as described in APPENDIX-A of Table A.1 and A.2 respectively. The line diagram of 33-bus, and 69-bus, 12.66 kV distribution network are shown in Fig. A.1 and Fig. A.2 respectively. The backward-forward sweep load flow method has been used for network solution in each of the cases.

In the present case study, the available operating hours of DGs operation are considered as given in [62]. Total number of expected hours available for operation = (1 - .01) x 8760 = 7884 hours. i.e. DG will be available for 7884 hours during the year. The DG unit has been assumed out of service 10% of the operation time, due to both predicted and unpredicted (O & M) reasons. Where, 8760 hours are the total number of hours in a year.

In addition, commercial information regarding DGs and Capacitors has been taken from [25, 100, 138, 159 and 160], and is given below. The electricity price of Grid is considered as ₹5 per kWh [125]. All the costs are taken in Indian Rupee (₹).

DG installation cost, IC_i = 25 x 10^6 ₹/MW

Capacitor installation cost, IC_j = 100 x 10^3 ₹/MVAr

DG operational cost, OC_i = 2.5 x 10^3 ₹/MWh

Capacitor operational cost, OC_j = 0 ₹/MVArh

DG maintenance cost, MC_{DG} = ₹ (10000+20% of DG installation cost)/ Year

Capacitor maintenance cost, MC_{Cap}= ₹ (5000+20% of Capacitor installation cost)/ Year

Interest rate, IR = 12.5%

Inflation rate, IF = 9%

Planning Period, n = 10 Years

6.5.1 RESULTS ANALYSIS AND DISCUSSION

The planning of DG and Capacitor placement has been carried out for a planning period of 10 years. Table-6.1 has been resulted from simulation shows the effect of DG and in a 33-bus test system. The cost incurred in operation and maintenance is given in the table and acquired profit during planning period.

Table 6.1: Cost Benefits and Profit in DG and Capacitor placement for 33-bus system

Costs/Benefits			Costs (₹)
Installation cost of DG (₹)			375×10^5
Installation cost of Capacitor (₹)			9×10^4
Benefits of loss reduction (₹)			4.35×10^7
Benefits of reduction in purchased energy (₹)			4.99×10^8
Operational costs of DG (₹)			2.49×10^8
Maintenance cost of DG (₹)			6.34×10^7
Maintenance cost of Capacitor (₹)			1.94×10^5
Total profit (₹)			1937.94×10^5
Size DG and Capacitor	1.5 (MW)	0.9 (MVAr)	
Location DG and Capacitor	8	30	
Planning period			10 year

Based on the simulation results, Table-6.1 presents the cost benefits and profits in DG and Capacitor placement by proposed PSO based algorithm. The results obtained shows that the optimal size of DG and Capacitor comes out to be 1.5 MW and 0.9 MVAr at optimal locations 8 and 30 respectively in 33-bus test system. With total investment of 375.9 lacks, in the planning period of 10 years, the total profit comes out to be ₹1937.94 lacks to the distribution company. The profit earned by the distribution company is due to the low installation cost and negligible operational cost of Capacitor. The placement of DG with capacitor minimizes the power distribution loss to the great extent, which can be seen in the form of loss reduction benefit of ₹435 lacks for the considered planning period. The time to execute the optimization problem comes out to be 30.81 second.

It is also observed form the results that the profit to the distribution company comes out to be ₹315.23 lacks, if alone DG of 1.5 MW is operated for a period of 3 years. The profit to the distribution utility increases so high, if a capacitor of 0.9 MVAr is operated with DG for the same time period, i.e. ₹396.62 lacks. Hence, it is concluded that by the small investment of ₹0.9 lacks on Capacitor, the profit to the distribution increases to ₹81.39 lacks in a considered time period. It is also studied that, if both DG and capacitor are operated for two years, the profit to the distributed utility decreases i.e., ₹143.14 lacks. Hence, it is concluded that a total initial investment of ₹ 375.9 lacks is recovered within time period of three years.

In order to maximize the objective function, the optimal locations and sizes determined as 1.5 MW of DG and 1.2 MVAr of Capacitor, placed at same 61 bus. The 10 years of planning period is considered, in case of 69-bus test system. From the simulated results, it is observed that with the initial investments of ₹376.2 lacks on DG and Capacitor provides a maximum profit of ₹2137.19 lacks to the distribution company in a planning period of 10 years. The installation cost of Capacitor is very small as compared to DG cost. The capacitor placement with DG has large impact in minimizing the power distribution loss as shown in Table 6.2. The operational costs of Capacitor are negligible as compared to operational costs of DG, whereas, the maintenance costs of capacitor are also very less as compared to DG. The proposed optimization problem has been executed in a time period of 51.76 seconds.

Table 6.2: Cost Benefits and Profit in DG and Capacitor placement for 69-bus system

Costs/Benefits			Costs (₹)
Initial investment on DG (₹)			375×10^5
Initial Investment on Capacitor (₹)			1.2×10^5
Benefits of loss reduction (₹)			6.52×10^7
Benefits of reduction in purchased energy (₹)			4.99×10^8
Operational costs of DG (₹)			2.49×10^8
Maintenance cost of DG (₹)			6.34×10^7
Maintenance cost of Capacitor (₹)			2.45×10^5
Total profit (₹)			2137.19×10^5
Size DG and Capacitor	1.5 (MW)	1.2 (MVAr)	
Location DG and Capacitor	61	61	
Planning period			10 year

When both DG and a Capacitor of 1.5 MW and 1.2 MVAr are placed at bus 61 provides a benefit of ₹462.83 lacks to the distribution utility, if operated for 3 years. If operated for two years, the profit reduces to ₹191.95 lacks. Hence a total initial investment of ₹376.2 lacks can be recovered also less than 3 years. It is observed from simulated a result that, with the installation of Capacitor with DG at optimal location increases the profit to the distribution company tremendously, i.e. with the small investment on Capacitor installation maximizes the benefit to the distribution company. As the operational costs of Capacitor are nil and the maintenance costs of Capacitor are also too low as compared to DG as shown in Table 6.1 and Table 6.3.

6.6 VOLTAGE PROFILE

The optimal placement of 1.5 MW DG and 0.9 MVAr Capacitor at bus number 8 and 30 respectively improves the bus voltage of 33-bus test system as shown in Fig. 6.1. From the fig.6.1, it is observed that voltage profile of each bus improves with the optimal placement of DG and Capacitor as compared to the base case.

In case of 69-bus test system, the base case voltage of each bus improves with the placement of 1.5 MW DG and 1.2 MVAr Capacitor at bus number 61 as shown in Fig. 6.2. This is another advantage of capacitor placement in addition to maximize the profit to distribution owner.

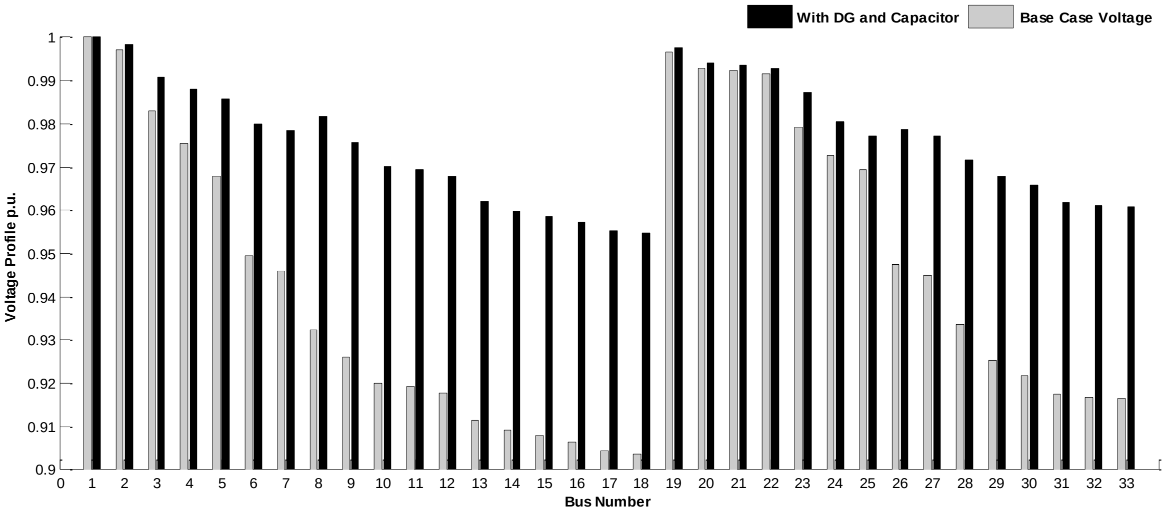


Figure 6.1 Voltage profile of the 33-bus system

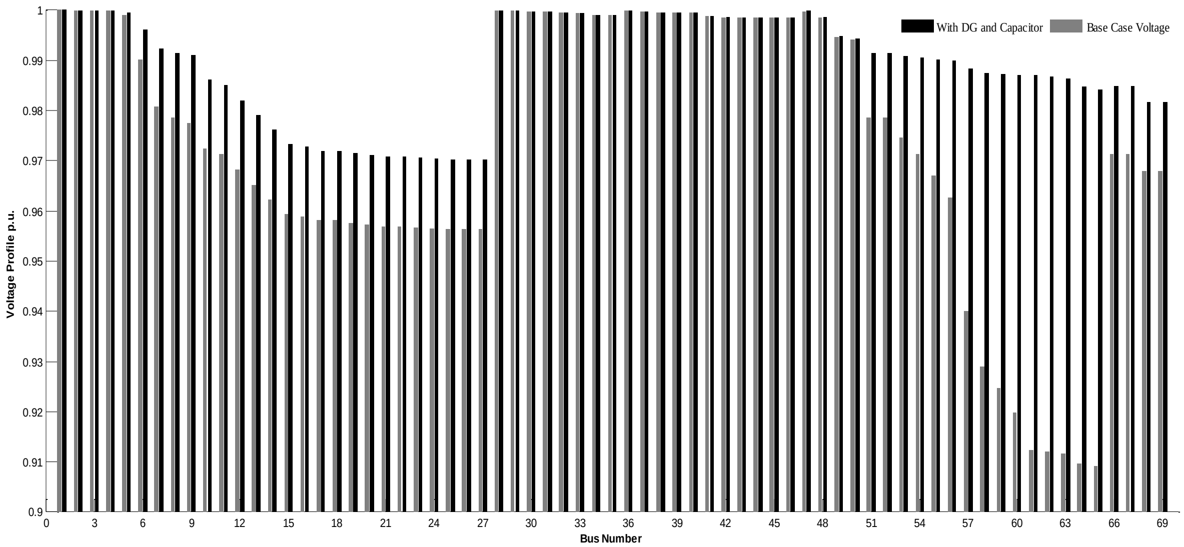


Figure 6.2 Voltage profile of the 69-bus system

6.7 CONCLUSION

In this Chapter, PSO based optimization technique has been proposed to determine the best locations for DG and capacitor in the distribution network with various technical and economic factors, which results maximizing profit. The problem has been optimized considering different planning periods. Results show that the installation of capacitor with DG reduces the loss of the network drastically, that maximize the profit to the distribution company and the initial investments can be recovered in shorter time period. As the installation and maintenance costs of capacitor are significantly less as compared to DG costs and operational cost is negligible, therefore, the installation of DG and capacitor provides more economy to solution.

In addition to the above benefits, the DG along with capacitor placement also provides improvement in voltage profile of the network buses in allowable limits and decreases the stress on the line conductors causing increase their life span.

CHAPTER – 7

CONCLUSION AND FUTURE SCOPE

7.1 GENERAL

The diminishing fossil fuels, increased transmission and distribution costs, deregulation trends, global environmental concerns, and technological advancements have led to an upsurge in awareness for the development and utilization of DGs worldwide. Therefore, the aim of this thesis has been to study the various issues of optimal placement of DG in detail and develop the schemes for the solution of the problems associated with optimal placement of DGs. The developed methodologies will be useful for integrating the DG into the distribution systems. The proper allocation of DG units in distribution system plays a decisive role in achieving economical, technical, and qualitative benefits. Depending on their location, DG units may improve or worsen the system performance. The main conclusions of the present investigation are summarized below.

In this chapter, the important findings of the work comprising this thesis have been highlighted and the suggestions for future work in the area of optimal DG placement have been presented.

7.2 SUMMARY OF SIGNIFICANT FINDINGS

The important contributions of the presented work in the area of **optimal placement of distributed generation in distribution networks** can be summarized as follows:

During the last few years, the penetration of DG in the power distribution systems has been increasing rapidly in many parts of the world. As the penetration of DG is increasing in the distribution network, it is no more passive in nature and its characteristics is becoming similar to an active transmission network. Therefore, it is in the best interest of all the players involved to allocate them in an optimal way such that it could increase reliability, reduce system losses and hence improve the voltage profile while serving the primary goal of power injection. It is evident that any loss reduction is beneficial to distribution utilities, which is generally the entity responsibility to keep the losses at low level. Loss reduction is therefore most important factor to be considered in planning and operation of the DG.

In this thesis, different types of DGs based on their capability of injecting real and/or reactive power have been proposed to be placed in a planned manner into the distribution systems. The developed methodologies will be helpful to the developing countries like India, for integrating DG into the electrical systems for improvement in the system performance and for mitigation of the power deficiency. The availability of quality supply of electricity is very crucial for the sustained growth of a country. Presently, India is in power deficient state, the average power deficiency is nearly 12.2% of peak demand. The power deficient situation of the country results in power cuts, blackouts, etc. In the developing countries like India, DGs may widely be used to supply electric loads in integration with the grid.

Optimal placement of DG units in the distribution systems reduces the energy losses, improves the voltage profile, releases the transmission capacity, decreases equipment stress, and defers transmission and distribution upgrades. For even a small distribution network, the selection of the best DG allocation plan among the different possibilities needs computationally arduous efforts. Least loss method is one of the criteria to select the appropriate bus for DG placement, consequently, to reduce the search space and thus, to save the computational time to attain an optimal solution. To cater this requirement, the analytical approach has been utilized for determining the optimal size and location of type-I DGs in radial distribution system.

The proposed analytical approach has been tested on a 33-bus and 69-bus distribution test systems taking the various operating constraints into consideration. Comparing the obtained results with those obtained by the application of PSO based approach; the following conclusions have been drawn:

- Optimal placement of type-I DG injecting real power maximizes the reduction in power distribution losses of the distribution system.
- Optimal allocation of DG also improves the voltage profiles of the system.
- PSO based approach is also useful for the optimal placement of DGs and shows utility for large networks.

The reduction of real power losses, improvement in voltage profile, and deferral of network upgrade have been reported as the primary aims for DG placement. Most of these DG allocation techniques are well suited to allocate DGs injecting real power output. Since these existing techniques, do not exploit the advantage of reactive power compensated in the network. In this thesis, optimal placement of type-I DG and type-II DG has been performed. The reactive power of the network is compensated by the optimal placement of type-II DG. An analytical approach has been proposed in this work to determine the optimal size, location and optimal power factor to achieve the objective of reduction in power distribution losses by compensating the active and reactive powers with the incorporation of various operating constraints. The maximum DG installed capacity limit has been considered as 30% of the total capacity of the substation to maintain the concept of distributed generation against centralized generation. The optimal power factor of DG has also been evaluated, and the effect of variation of power factor on the system losses has been analyzed.

To validate the proposed algorithm, the obtained results have been compared with the results obtained by the PSO and based approach. By comparison, the following conclusions have been made:

- ➢ Placement of type-I DG and type-II DG compensate the reactive power that reduces the size of required DG and losses more significantly,
- ➢ Placement of type-I DG and type-II DG improves the bus voltage and avoid the violation of the limit,
- ➢ Provides more economy solution for loss reduction, since cost of capacitor is too less as compared to DG cost.

A suitable mathematical formulation has been developed for the optimal placement of multiple DG of type-III. To explore the advantages of both analytical method and searches, a hybrid approach has been proposed for the optimal placement of multiple DGs of multiple types. In this approach, the sizes of multiple DGs are evaluated using the analytical method and the optimal locations are determined by PSO based technique. The objective function has been minimized under operating constraints. The proposed hybrid approach is tested on 33-bus and 69-bus test systems and the results obtained are compared. The proposed approach has following outcomes:

- Allocation of multiple DGs of multiple types reduces the distribution loss significantly,
- Operation of placed type-III DG at optimal power factor further reduces the losses,
- Optimal placement of multiple DGs not only reduces the line losses but also minimize the required size of DGs.

An analytical approach has been applied for the placement of type-IV DG for the integration of non-conventional energy sources like wind turbine. The type IV DG requires special attention due to its special characteristics, as it generates real power and consumes reactive power. The placement and analysis of type-IV DGs give guidance for integration of non-conventional energy sources like wind turbine.

- Integration of type-IV DGs give guidance for non-conventional energy sources like wind turbine.

The distribution system planners effort to supply economical and reliable electric power to the customer. It is important to design, operate and maintain the power system with lowest cost and highest benefit. These companies work on various technologies and optimization programs to achieve economic benefits as well as to provide high quality uninterrupted supply. Therefore, the profit optimization has been carried out The inflation has been taken into account by incorporating present worth factor. Following conclusions have been derived from the obtained results,:

- Placement of DG and capacitor produce benefits to the utility in the considered planning period,
- Initial investments can be recovered in a short time period,
- The initial investments and maintenance costs of capacitor are too less as compared to DG costs, hence capacitor placement provide major contribution to economy,
- Installation of DG and capacitor provides more saving to the distribution utility by producing both the real and reactive power,
- DG and capacitor integration reducing of power flow in conductors, hence decreases stress on the conductors which increases their life time.

7.3 SCOPE FOR FUTURE RESEARCH

Research and development is a continuous process. Each end of a research work opens many more avenues for future research. As a consequence of the investigations carried out in this thesis in the area of optimal placement of distributed generation in distribution systems, followings are the research ideas that need to be explored further as the future scope of the presented work:

- The developed analytical approach for the optimal placement of DG can be extended for congestion management on a real system.

- The optimal placement problem can be extended to renewable energy sources for sensitivity and reliability improvements.

- Optimal DG placement problem considers only radial distribution systems and constant power load model. This technique can be extended further to incorporate voltage dependent load models and meshed structure of distribution systems.

- Economic dispatch problem of smart grid by the integration of distributed generation may be explored.

- Distributed generation allocation problem may be extended for service restoration during power cuts and peak hours.
- DG allocation problem may be extended to see the impact on transient stability of power system.
- Optimal DG allocation problem may be extended to other FACTS components.
- The considerations on the reliability and power quality of the system have not been incorporated in placement problems. These shortcomings can be removed in the further extension of this work.

The subject matter addressed in this thesis is relevant in the energy deficient countries such as India, and will continue to attract attention.

BIBLIOGRAPHY

[1] A. Bhowmik, A. Maitra, S.M. Halpin, and J.E. Schatz, "Determination of allowable penetration levels of distributed generation resources based on harmonic limit considerations*," IEEE Trans. Power Del.*, vol. 18, no. 2, pp. 619-624, April 2003.

[2] A. Chandramouli, P.K. Kalra, et al, Discussion on "Optimal Selection of Capacitor for Radial Distribution System Using Genetic Algorithm," by Sundhararajan, S and Pahwa, Anil, *IEEE Trans. Power Syst.*, vol. 9, no.3, pp.1499-1507, August 1994.

[3] A. Goel, S. Mishra, and A.N. Jha, "Power Flow Control of a Solid Oxide Fuel-Cell for Grid Connected Operation," *International Conference on Power Electronics, Drives and Energy Systems*, (PEDES), New Delhi, pp.1-6, December 2006.

[4] A.H. Etemadi and M. Fotuhi-Firuzabad, "Distribution system reliability enhancement using optimal capacitor placement," *IET Gener. Transm. Distrib.*, vol. 2, pp. 621-631, 2008.

[5] A.K. Sinha and P. Bajpai, "Swarm Intelligence Based Optimal Sizing of Solar PV, Fuel Cell and Battery Hybrid System," *International Conference on Power and Energy Systems*, IIT Kharagpur, Kharagpur, 2012.

[6] A. Kazemi and M. Sadeghi, "Sitting and sizing of distributed generation for loss reduction," *Power and Energy Conference*, APPEEC, Asia-Pacific, Wuhan, pp.1-4, March 2009.

[7] A. Keane and M. O'Malley, "Optimal allocation of embedded generation on distribution networks," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1640-1646, August 2005.

[8] A. Kumar, W. Gao, "Optimal distributed generation location using mixed integer non-linear programming in hybrid electricity markets," *IET Gener. Transm. Distrib.*, vol. 4, no. 2, pp. 281–98, 2010.

[9] A. Nasri, M.E.H. Golshan and S.M.S. Nejad, "Optimal planning of dispatchable and non-dispatchable distributed generation units for minimizing distribution system's energy loss using particle swarm optimization," *Int. Trans. Electr. Energ. Syst.*, December 2012.

[10] A.A.A. El-Ela, S.M. Allam, M.M. Shatla, "Maximal optimal benefits of distributed generation using genetic algorithms," *Elect. Power Syst. Res.*, vol.80, pp.869-877, January 2010.

[11] A.C. Rueda-Medina, J. F. Franco, M. J. Rider, A. Padilha-Feltrin, R. Romero, "A mixed-integer linear programming approach for optimal type, size and allocation of distributed

generation in radial distribution systems," *Elect. Power Syst. Res*., vol. 97, pp. 133–143, 2013.

[12] A.K. Singh and S.K. Parida, "Combined Optimal Placement of Solar, Wind and Fuel cell Based DGs Using AHP," *World Renewable Energy Congress*, Sweden, pp. 3113-3120, May 2011.

[13] A.M. El-Zonkoly, "Optimal placement of multi DG units including different load models using PSO," *Smart Grid and Renewable Energy*, vol. 1, no.1, pp. 160–171, December 2010.

[14] A.M. El-Zonkoly, "Optimal placement of multi-distributed generation units including different load models using particle swarm optimization," *IET Gener. Transm. Distrib.*, vol. 5, no. 7, pp. 760–771, July 2011.

[15] A.M. El-Zonkoly, "Optimal placement of multi-distributed generation units including different load models using particle swarm optimization," *Swarm and Evol. Comp.*, vol.1, pp. 50-59, 2011.

[16] A.R. Phadke, M. Fozdar, and K.R. Niazi, "Multi-objective fuzzy-GA formulation for optimal placement and sizing of shunt FACTS controller," *International conference on Power Systems*, Jaipur, India, pp.1-6, December 2009.

[17] A.S. Pabla, "Electric Power Distribution," Tata McGraw-Hill, New Delhi, 4th Edition, Appendix II, pp. 3143-3151, June 1981.

[18] American National Standards Institute, "American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hertz)," National Electrical Manufacturers Association, 2006.

[19] B. Cano Edwin, "Utilizing fuzzy optimization for distributed generation allocation," *IEEE Conference region 10, TENCON*, October 2007.

[20] B. Gou and A. Abur, "Optimal capacitor placement for improving power quality," *Proceedings of IEEE/PES Summer Meeting*, vol.1, pp. 488-492, July 1999.

[21] B. Kuri, M.A. Redfem, and F. Li, "Optimization of rating and positioning of dispersed generation with minimum network disruption," *Proceedings of IEEE/PES General Meeting*, vol. 2, pp. 2074-2078, June 2004.

[22] B. Tyagi and S. C. Srivastava, "A Method for Optimal Placement of Reactive Sources & Reactive Power Procurement in Competitive Electricity Markets," *IEEE Conference Power India*, Kanpur, pp. 1-6, 2006.

[23] C. Chung-Fu, “Reconfiguration and Capacitor Placement for Loss Reduction of Distribution Systems by Ant Colony Search Algorithm,” *IEEE Trans. Power Syst.,* vol. 23, pp. 1747-1755, 2008.

[24] C. Tautiva and A. Cadena, “Optimal Placement of Distributed Generation on Distribution Networks,” *IEEE/PES Transmission and Distribution Conference and Exposition*, Bogota, pp. 1-5, August 2008.

[25] C. Wang and M.H. Nehrir, “Analytical approaches for optimal placement of distributed generation sources in power systems,” *IEEE Trans. Power Syst*., vol. 19, no.4, pp. 2068-2076, November 2004.

[26] C.L.T. Borges, and D.M. Falcao, “Optimal distributed generation allocation for reliability, losses and voltage improvement,” *Elect. Power and Energy Syst*., vol. 28, no. 6, pp. 413-420, July 2006.

[27] C.T. Su, C.F. Chang, and J.P. Chiou, “Distribution network reconfigu-ration for loss reduction by ant colony search algorithm,” *Electr. Power Syst. Res*. 75, no. 2-3, pp.190-199, 2005.

[28] CIGRE: ‘Impact of increasing contribution of dispersed generation on the power system’, Working Group 37.23, 1999.

[29] D. Gautam and N. Mithulananthan, “Locating Distributed Generator in the LMP-based Electricity Market for Social Welfare Maximization” *Elect. Power Comp. Syst*., vol. 35, pp.489-503, 2007.

[30] D. Gautam and N. Mithulananthan, “Optimal DG placement in deregulated electricity market,” *Electr. Power Syst. Res*., vol.77, no.12, pp.1627-1636, October 2007.

[31] D. K. Kathod, “Optimal Planning of Distributed Generation Systems,” Ph.D. Thesis, Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, July 2007.

[32] D. K. Khatod, V. Pant, and J. Sharma, “Evolutionary Programming Based Optimal Placement of Renewable Distributed Generators,” *IEEE Trans. Power Syst*., vol. 28, no. 2, pp. 683-695, May 2013.

[33] D. O. Leonardo W, C. Sandoval Jr, D. O. Edimar J, Pereira JLR, Silva Jr Ivo C, and C. Jeferson, “Optimal reconfiguration and capacitor allocation in radial distribution systems for energy losses minimization,” *Elect. Power and Energy Syst*., vol. 32, no.8, pp. 840–848, 2010.

[34] D. Sattianadan, M. Sudhkaran, K.V. kumar, and S. Vidyasagar, “Optimal Placement of Capacitor in Radial Distribution System Using PSO,” *International Conference on Sustainable Energy and Intelligent System*, Chennai, pp.326-331, July 2011.

[35] D. Singh, D. Singh, and K. S. Verma, “Multiobjective Optimization for DG Planning With Load Models,” *IEEE Trans. Power Syst*., vol.24, no.1, pp. 427-436, February 2009.

[36] D. Singh, D. Singh, and K.S. Verma, “Comparative Analysis for Penetration of Distributed Generation in Power Systems,” *IEEE International Conference on Sustainable Energy Technologies,* (ICSET), pp. 1271-1276, November 2008.

[37] D. Thukaram, C. Vyjayanthi, and S. Surendra, “Optimal Placement of Distributed Generation for a Projected Load Increase Using Relative Electrical Distance Approach,” *3rd International Conference on Power Systems*, IIT Kharagpur, December 2009.

[38] D. Zhang, Z. Fu, and L. Zhang, “An improved TS algorithm for loss minimum reconfiguration in large-scale distribution systems,” *Electr. Power Syst. Res*. 77, no. 5-6, pp.685-694, 2007.

[39] D. Zhu, R.P. Broadwater, T. Kwa-Sur, R. Seguin, and H. Asgeirsson, “Impact of DG placement on reliability and efficiency with time-varying loads,” *IEEE Trans. Power Syst*., vol. 21, pp. 419-427, 2006.

[40] D.H. Popovic, J.A. Greatbanks, M. Begovic, and A. Pregelj, “Placement of distributed generators and reclosers for distribution network security and reliability,” *Elect. Power and Energy Syst.*, vol. 27, no. 5-6, pp. 398-408, June-July 2005.

[41] D.P. Kothari and I.J. Nagrath, Modern Power System Analysis, Third Edition, 2003 (20th reprint 2010), Tata McGraw Hill, New Delhi.

[42] D.P. Kothari, “Renewable Energy Scenario in India” *IEEE PES Winter Meeting*, vol.1, pp. 643-636, August 2002.

[43] D.P. Kothari, J.S. Dhillon, “Power System Optimization,” New Delhi: Prentice-Hall of India Pvt. Ltd. 2006.

[44] D.Q. Hung and N. Mithulananthan, “Multiple distributed generators placement in Primary Distribution Networks for loss reduction,” *IEEE Trans. Industr. Electr*., vol.60, no.4, pp.1700-1708, April 2013.

[45] D.Q. Hung, N. Mithulananthan, and R.C. Bansal, “Analytical Expressions for DG Allocation in Primary Distribution Networks,” *IEEE Trans. Energy Conv*., vol.25, no.3, pp. 814-820, September 2010.

[46] DTI, “Network Performance Benefits of Energy Storage for a Large Wind Farm,” Retrieved February 7, 2005, http://www.dti.gov.uk/renewables/publications/pdfs/ke1002460000.pdf/2004.

[47] Elgerd IO, Electric energy system theory: an introduction, McGraw- Hill; 1971.

[48] F.S. Abu-Mouti and M.E. El-Hawary, “Optimal Distributed Generation Allocation and Sizing in Distribution Systems via Artificial Bee Colony Algorithm”, *IEEE Trans. Power Del.*, vol.26, no.4, pp. 2090-2101, 2011.

[49] F.S. Abu-Mouti, M.E. El-Hawary, “Heuristic curve-fitted technique for distributed generation optimization in radial distribution feeder systems,” *IET Gener. Transm. Distrib.*, vol. 5, no. 2, pp. 172-180, 2011.

[50] G. Carpinelli, G. Celli, S. Mocci, F. Pilo, and A. Russo, “Optimization of embedded generation sizing and siting by using a double trade-off method,” *IEE Proc. Gener., Transm. Distrib.*, vol. 152, no. 4, pp. 503-513, July 2005.

[51] G. Carpinelli, P. Varilone, V. Di Vito, and A. Abur, “Capacitor placement in three-phase distribution systems with nonlinear and unbalanced loads,” *IEE Proc. Gener. Transm. Distrib.,* vol. 152, pp. 47-52, 2005.

[52] G. Celli, and F. Pilo, “Optimal distributed generation allocation in MV distribution networks,” *IEEE/PES International Conference on Power Industry Computer Applications,* (PICA), Sydney, Australia, May 2001.

[53] G. Celli, E. Ghiani, S. Mocci, and F. Pilo, “A multiobjective evolutionary algorithm for the sizing and siting of distributed generation,” *IEEE Trans. Power Syst*., vol. 20, no. 2, pp.750-757, May 2005.

[54] G. Mallesham, S. Mishra, and A. N. Jha, “Automatic Generation Control of Microgrid using Artificial Intelligence Techniques,” *IEEE/PES General Meeting*, San Diego, CA, pp.1-8, July 2012.

[55] G. Tuba, M. H. Hocaoglu, U. Eminoglu, and A. Balikci, “Optimal Placement and Sizing of Distributed Generation on Radial Feeder with Different Static Load Models”, *IEEE International Conference on Future Power Systems*, Amsterdam, pp. 2-6, November 2005.

[56] G.N. Koutroumpezis, A.S. Safigianni, “Optimum allocation of the maximum possible distributed generation penetration in a distribution network,” *Elect. Power Syst. Res*., vol. 80, pp. 1421-1427, 2010.

[57] G.P. Harrison, A. Piccolo, P. Siano, and A.R. Wallace, “Hybrid GA and OPF evaluation of network capacity for distributed generation connections,” *Elect. Power Syst. Res*., vol. 78, no. 3, pp. 392-398, March 2008.

[58] H. Doagou-Mojarrad, G.B. Gharehpetian, H. Rastegar, J. Olamaei, “Optimal placement and sizing of DG (distributed generation) units in distribution networks by novel hybrid evolutionary algorithm,” *Energy*, vol. 54, pp. 129–138, 2013

[59] H. Dura, “Optimum Number Size of Shunt Capacitors in Radial Distribution Feeders: A Dynamic Programming Approach,” *IEEE Trans. Power App. and Syst*., vol. 87, pp. 1769-1774, September 1968.

[60] H. Falaghi and M. R. Haghifam, “ACO Based Algorithm for Distributed Generation Sources Allocation and Sizing in Distribution Systems,” *IEEE Conference Power Tech-2007*, Switzerland, July 2007.

[61] H. Hedayati, S. A. Nabaviniaki, and A. Akbarimajd, “A Method for Placement of DG Units in Distribution Networks,” *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1620-1628, July 2008.

[62] H. L. Willis and W. G. Scott, Distributed Power Generation Planning and Evaluation. New York: Marcel Dekker, 2000.

[63] H. L. Wills, Power Distribution Planning Reference Book. New York: Marcel Dekker, 2004.

[64] H. Zechun and L. Furong, “Cost-Benefit Analyses of Active Distribution Network management, Part I: Annual Benefit Analysis,” *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1067-1074, 2012.

[65] H.N. Ng, M.M.A. Salama, and A.Y. Chikhani, “Capacitor allocation by approximate reasoning: fuzzy capacitor placement,” *IEEE Trans. Power Del.,* vol.15, no.1, pp. 393-398, Jan. 2000.

[66] C. da Silva, S. Carneiro, E. J. de Oliveira, J. de Souza Costa, J. L. Rezende Pereira, and P. A. N. Garcia, “A Heuristic Constructive Algorithm for Capacitor Placement on Distribution Systems,” *IEEE Trans. Power Syst*., vol. 23, no.4, pp. 1619-1626, November 2008.

[67] Hussain and A.K. Roy, “Optimal distributed generation allocation in distribution systems employing modified artificial bee colony algorithm to reduce losses and improve voltage profile,” *International conference on Advances in Engineering, Science and Management,* Guwahati, India, pp. 565-570, March 2012.

[68] J. A. M. García, A. J. G. Mena, “Optimal distributed generation location and size using a modified teaching–learning based optimization algorithm,” *Elect. Power and Energy Syst*., vol. 50, pp. 65–75, September 2013.

[69] J. Hazra and A. K. Sinha, “A multi-objective optimal power flow using particle swarm optimization,” *Euro, Trans. Electr. Power*, vol. 21, pp.1028–1045, 2011.

[70] J. Hazra and A. K. Sinha, “A Study on Real and Reactive Power Optimization using Particle Swarm Optimization,” *2nd International Conference on Industrial and Information Systems,* (ICIIS) , Sri Lanka, August 2007.

[71] J. J. Grainger and S. H. Lee, “Optimum Size and Location of Shunt Capacitors for Reduction of Losses on Distribution Feeders,” *IEEE Trans. Power App. and Syst*., vol. 100, no. 3, pp. 1105-1118, March 1981.

[72] J. Kennedy and R. Eberhart, “Particle Swarm Optimizer,” *IEEE International Conference on Neural Networks*, Australia, pp.1942-1948, 1995.

[73] J. V. Schmill, "Optimum Size and Location of Shunt Capacitors on Distribution Feeders," *IEEE Trans. Power App. and Syst*., vol. 84, pp. 825-832, September 1965.

[74] J.A. Greatbanks, D.H. Popovic, M. Begovic, A. Pregelj, and T.C. Green, “On optimization for security and reliability of power systems with distributed generation,” *IEEE Bologna Power Tech Conference*, Bologna, Italy, June 2003

[75] J.J. Grainger and S. Civanlar, “Volt/Var Control on Distribution Systems with Lateral Branches Using Shunt Capacitors and Voltage Regulators Part III: The Numerical Results,” *IEEE Trans. Power App. and Syst*., vol. 104, no. 11, pp. 3291-3297, November 1985.

[76] J.O. Kim, S.W. Nam, S.K. Park, and C. Singh, “Dispersed generation planning using improved Hereford Ranch algorithm,” *Electr. Power Syst. Res*., vol.47, no.1, pp.47-55, October 1998.

[77] K. Nara, Y. Hayashi, K. Ikeda, and T. Ashizawa, “Application of tabu search to optimal placement of distributed generators,” *IEEE/PES winter meeting*, pp. 918–923, 2001.

[78] K. Nekooei, M. M. Farsangi, H. Nezamabadi-Pour, and K. Y. Lee, “An Improved Multi-Objective Harmony Search for Optimal Placement of DGs in Distribution Systems,” *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 557-567, March 2013

[79] K.H. Kim, Y.J. Lee, S.B. Rhee, S.K. Lee, and S.K. You, “Dispersed generator placement using fussy-GA in distribution systems,” *IEEE/PES Summer Meeting*, USA, vol.3, pp.1148-1153, July 2002.

[80] L.D. Arya, L.S. Titare and D.P. Kothari, “Improved Particle Swarm Optimization (PSO) Applied to Reactive Power Reserve Maximization” *Elect. Power and Energy Syst*., vol. 32, no. 6, pp. 368-374, June 2010.

[81] Le DT, M.A. Kashem, M. Negnevitsky, and G. Ledwich, “Optimal distributed generation parameters for reducing losses with economic consideration,” *IEEE/PES General Meeting*, pp. 1–8, June 2007.

[82] M. Ahmadigorji, A. Abbaspour, A. R. Ghahnavieh, and M. F. Firuzabad, “Optimal DG placement in distribution systems using cost/worth analysis,” *World Academy of Science, Engineering and Technology 25*, pp. 746-753, 2009.

[83] M. Wang, and J. Zhong, “A Novel Method for Distributed Generation and Capacitor Optimal Placement considering Voltage Profiles,” *IEEE/PES General Meeting*, San Diego, CA, pp.1-6, July 2011.

[84] M. E. Baran and F. F. Wu, “Optimal capacitor placement on radial distribution systems,” *IEEE Trans. Power Del*., vol. 4, no.1, pp. 725-734, January 1989.

[85] M. E. Baran and F. F. Wu, “Optimal Sizing of Capacitors Placed on a Radial Distribution System,” *IEEE Trans. Power Del*., vol. 4, no.1, pp. 1105-1117, January 1989.

[86] M. E. Baran and F. F. Wu, “Network Reconfiguration In Distribution Systems For Loss Reduction And Load Balancing,” *IEEE Trans. Power Del*., vol. 4, no.2, pp. 1401-1407, April 1989.

[87] M. Gandomkar, M. Vakilian, and M. Ehsan, “Optimal distributed generation allocation in distribution network using Hereford Ranch algorithm,” *Proceedings of 8th International Conference on Electrical Machines and Systems,* (ICEMS), vol. 2, pp. 916-918, September 2005.

[88] M. Gandomkar, M. Vakilian, and M. Ehsan, “A combination of genetic algorithm and simulated annealing for optimal DG allocation in distribution networks,” *Canadian conference on electrical and computer engineering*, pp. 645–648, May 2005.

[89] M. Kalantari and A. Kazemi, “Placement of Distributed Generation unit and Capacitor Allocation in Distribution Systems using Genetic Algorithm,” *10th International Conference on Environment and Electrical Engineering,* (EEEIC), Tehran, Iran, pp. 1-5, 2011.

[90] M. Ladjavardi and M.A.S. Masoum, “Genetically Optimized Fuzzy Placement and Sizing of Capacitor Banks in Distorted Distribution Networks,” *IEEE Trans. Power Del.,* vol. 23, pp. 449-456, 2008.

[91] M. M. Elnashar, R. El. Shatshat, and M.M.A. Salama, “Optimum siting and sizing of a large distributed generator in a mesh connected system,” *Elect. Power Syst. Res.,* vol.80, no.6, pp. 690-697, June 2010.

[92] M. Mardaneh and G.B. Gharehpetian, “Siting and sizing of DG units using GA and OPF based technique,” *Proceedings of IEEE Region 10 Conference-TENCON*, vol. C, pp. 331-334, November 2004.

[93] M. Mohammadi, M. Nafar, “Optimal placement of multitypes DG as independent private sector under pool/hybrid power market using GA-based Tabu Search method,” *Elect. Power and Energy Syst.*, vol. 51, pp. 43–53, October 2013

[94] M. Mohammadi, S.H. Hosseinian, and G.B. Gharehpetian, “GA-based optimal sizing of microgrid and DG units under pool and hybrid electricity markets,” *Elect. Power and Energy Syst.,* vol. 35, no.1, pp. 83-92, February 2012.

[95] M. Wang and J. Zhong, “A Novel Method for Distributed Generation and Capacitor Optimal Placement considering Voltage Profiles,” *IEEE/PES General Meeting*, Hong Kong, China, pp.1-6, 2011.

[96] M.A. Kashem, A.D.T. Le, M. Negnevitsky, and G. Ledwich, “Distributed generation for minimization of power losses in distribution systems,” *Proceeding of IEEE/PES General Meeting,* Montreal, June 2006.

[97] M.A. Kashem, V. Ganapathy, G.B. Jasmon, and M.I. Buhari, “A novel method for loss minimization in distribution networks,” *Proceeding of International Conference Electric Utility Deregulation and Restructuring and Power Technology*, London, April 2000.

[98] M.A. Pai, Computer techniques in power system analysis, 2nd Edition, New Delhi, India: Tata McGraw-Hill, 2005.

[99] M.A.S. Masoum, M. Ladjevardi, A. Jafarian, and E.F. Fuchs, “Optimal placement, replacement and sizing of capacitor banks in distorted distribution networks by genetic algorithms,” *IEEE Trans. Power Del*., vol.19, no.4, pp. 1794-1801, October 2004.

[100] M.F. Akorede, H. Hizam, I. Aris, and M.Z.A. Ab Kadir, “Effective method for optimal allocation of distributed generation units in meshed electric power systems” *IET Gener. Transm. Distrib.,* vol. 5, no. 2, pp. 276–287, February 2011.

[101] M. Aman, G.B. Jasmon, H. Mokhlis, A.H.A. Bakar, “Optimal placement and sizing of a DG based on a new power stability index and line losses,” *Elect. Power and Energy Syst.*, vol. 43, no.1, pp. 1296–1304, December 2012.

[102] M.F. AlHajri, M.R. AlRashidi, and M.E. El-Hawary, “Hybrid Particle Swarm Optimization Approach for Optimal Distribution Generation Sizing and Allocation in Distribution

Systems," *Canadian Conference on Electrical and Computer Engineering Canadian Conference,* (CCECE) Vancouver, pp.1290-1293, April 2007.

[103] M.H. Haque, "Efficient load flow method for distribution systems with radial or mesh configuration," *IEE Proc. Gener. Transm. Distrib*., vol. 143, no.1, January 1996.

[104] M.H. Moradi and M. Abedini, "A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems," *Elect. Power and Energy Syst.,* vol. 34, no.1, pp. 66-74, January 2012.

[105] M.M. Aman, G.B. Jasmon, A.H.A. Bakar, H. Mokhlis, "A new approach for optimum DG placement and sizing based on voltage stability maximization and minimization of power losses," *Energy Conv. and Mange*., vol. 70, pp. 202–210, 2013.

[106] M.P. Latitha, V.C.V. Reddy, and V. Usha, "Optimal DG placement for minimum real power loss in radial distribution systems using PSO," *Journal of Theoretical and Applied Information Technology*, pp.107-115, 2010.

[107] M.R. AlRashidi, M.F. AlHajri, "Optimal planning of multiple distributed generation sources in distribution networks: A new approach," *Energy Conv. and Mange*., vol. 52, pp. 3301–3308, 2011.

[108] M.R. Haghifam, H. Falaghi, and O.P. Malik, "Risk-based distributed generation placement," *IET Gener. Transm. & Distrib*., vol. 2, no. 2, pp. 252-260, 2008.

[109] M.Z.C. Wanik, I. Erlich, and A. Mohamed, "Intelligent Management of Distributed Generators Reactive Power for Loss Minimization and Voltage Control," *15th IEEE Mediterranean Electrotechnical Conference,* (MELECON), Valletta, pp. 685-690, April 2010.

[110] MNRE, "Centre for Wind Energy Technology (C-WET) Chennai". http://www.mnre.gov.in/booklets/Book10-e.pdf.

[111] MNRE, "New and renewable energy", Cumulative achievements as on 30.06.2012", http://www.mnre.gov.in.

[112] N. Acharya, P. Mahat, and N. Mithulananthan, "An analytical approach for DG allocation in primary distribution network", *Elect. Power and Energy Syst*., vol. 28, no. 10, pp. 669-678, December 2006.

[113] N. Jain, S. N. Singh, and S. C. Srivastava, "A Generalized Approach for DG Planning and Viability Analysis under Market Scenario," *IEEE Trans. Industrial Electr*., vol. 60, issue 11, November 2013.

[114] N. Jain, S. N. Singh, and S. C. Srivastava, “Meta-Heuristic Approach for Distributed Generation Planning in Electricity Market Paradigm,” *IEEE/PES General Meeting*, 2012.

[115] N. Jain, S. N. Singh, and S. C. Srivastava, “Particle Swarm Optimization Based Method for Optimal Siting and Sizing of Multiple Distributed Generators,” *16th National Power System Conference*, Hyderabad, December 2010.

[116] N. Khalesi, N. Rezaei, and M.R. Haghifam, “DG allocation with application of dynamic programming for loss reduction and reliability improvement,” *Elect. Power and Energy Syst*., vol. 33, no. 2, pp. 288-295, February 2011.

[117] N. M. Neagle and D.R. Samson, “Loss Reduction from Capacitors installed on Primary Feeders,” *AIEE Transactions*, vol. 75, no. 3, pp. 950-959, January 1956.

[118] N.S. Rau and Y-H Wan, “Optimum location of resources in distributed planning,” *IEEE Trans. Power Syst*., vol.4, pp. 2014–2020, 1994.

[119] P. Mahat, W. Ongsakul, and N. Mithulananthan, “Optimal placement of wind turbine DG in primary distribution systems for real loss reduction,” *Proceedings of Energy for sustainable development: Prospects and Issues for Asia*, Thailand, March 2006.

[120] P. Phonrattanasak, “Optimal Placement of DG Using Multiobjective Particle Swarm Optimization,” *IEEE 2nd International Conference on Mechanical and Electrical Technology,* (ICMET), pp.342-346, September 2010.

[121] P. S. Georgilakis, and N. D. Hatziargyriou, “Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research,” *IEEE Trans. Power Syst.*, pp.1-9, to be published.

[122] P. Paliwal, N.P. Patidar and R.K. Nema, “A Comprehensive Survey of Optimization Techniques used for Distributed Generator Siting and Sizing,” *Proceedings of IEEE Southeastcon,* Orlando, FL, pp. 1-7, March 2012.

[123] Q. Bai, “Analysis of Particle Swarm Optimization Algorithm,” *Computer and Information Science,* vol. 3, no.1, pp.180-184, 2010.

[124] R. A. Gallego, A.J. Monticelli, and R. Romero, “Optimal capacitor placement in radial distribution networks,” *IEEE Trans. Power Del*., vol.16, no.4, pp. 630-637, Nov. 2001.

[125] R. Banerjee, “Comparison of options for distributed generation in India,” *Energy Policy*, vol. 34, pp.101–111, 2006.

[126] R. Caire, N. Retiere, E. Morin, M. Fontela, and N. Hadjsaid, “Voltage management of distributed generation in distribution networks,” *Proceedings of IEEE/PES General Meeting,* vol. 1, pp. 282-287, July 2003.

[127] R. Hosseinzadehdehkordi, M.E. Nasab, H. Shayeghi, M. Karimi and P. Farhadi, “Optimal sizing and siting of shunt capacitor banks by a new improved differential evolutionary algorithm,” *Int. Trans. Electr. Energ. Syst*., January 2013.

[128] R. Kollu, S.R. Rayapudi and V.L.N. Sadhu, “A novel method for optimal placement of distributed generation in distribution systems using HSDO,” *Int. Trans. Electr. Energ. Syst.*, December 2012.

[129] R.A. Jabr and B.C. Pal, “Ordinal optimisation approach for locating and sizing of distributed generation” *IET Gener. Transm. Distrib*., vol. 3, no. 8, pp. 713–723, August 2009.

[130] R.C. Eberhart and Y. Shi, “Comparing inertial weights and constriction factor in particle swarm optimization,” *Proceedings of the 2000 International congress on Evaluating computation,* California, pp. 84-88, 2000.

[131] R.F. Cook, “Analysis of Capacitor Application by Load Cycle,” *AIEE Transactions*, vol. 78, no. 3, pp. 950-957, May 1959.

[132] R.K. Singh and S.K. Goswami, “Optimal allocation of distributed generations based on nodal pricing for profit, loss reduction and voltage improvement including voltage rise issue,” *Elect. Power and Energy syst*., vol. 32, no.6, pp. 637-644, July 2010.

[133] R.K. Singh and S.K. Goswami, “Optimum Siting and Sizing of Distributed Generations in Radial and Networked Systems,” *Elect. Power Comp. and Syst*., vol.37, no. 2, pp.127-145, January 2009.

[134] R.M. Kamel and B. Kermanshahi, “Optimal Size and Location of Distributed Generations for Minimizing Power Losses in a Primary Distribution Network,” *Comp. Sci. & Eng. and Elect. Eng.*, vol. 16, no. 2, pp. 137-144, 2009.

[135] R.S. Al Abri, E.F. El-Saadany, and Y. M. Atwa, “Optimal Placement and Sizing Method to Improve the Voltage Stability Margin in a Distribution System Using Distributed Generation,” *IEEE Trans. Power Syst*., vol. 28, no. 1, February 2013.

[136] R.S. Rao, K. Ravindra, K. Satish, and S. V. L. Narasimham, “Power Loss Minimization in Distribution System Using Network Reconfiguration in the Presence of Distributed Generation,” *IEEE Trans. Power Syst*., vol. 28, no. 1, pp. 317-325, February 2013.

[137] S. A. Taher, M. Hasani, and A. Karimian, “A novel method for optimal capacitor placement and sizing in distribution systems with nonlinear loads and DG using GA,” *Commun. Nonlinear Sci. Numer. Simulat*., vol. 16, pp. 851-862, 2011.

[138] S. Ghosh, S.P. Ghoshal, and S. Ghosh, “Optimal sizing and placement of distributed generation in a network system,” *Elect. Power and Energy Syst*., vol. 32, pp. 849-856, January 2010.

[139] S. K. Injeti, N. P. Kumar, “A novel approach to identify optimal access point and capacity of multiple DGs in a small, medium and large scale radial distribution systems,” *Elect. Power and Energy Syst*., vol. 45, no.1, pp. 142–151, February 2013.

[140] S. Kansal, B.B.R. Sai, B. Taygi, and V. Kumar, “Optimal placement of Distributed Generation in distribution networks,” *International Journal of Engineering, Science and Technology*, vol. 3, no. 3, pp. 47-55, April 2011.

[141] S. Kansal, B.B.R. Sai, B. Taygi, and V. Kumar, “Optimal placement of Wind Based Generation in distribution networks,” *IET Renewable Power Generation Conference*, Edinburgh, (UK), pp. 1-6, 2011.

[142] S. Kansal, V. Kumar, B. Taygi, “Composite Active and Reactive Power Compensation of distribution networks” *Proceedings of 7th IEEE International conference on Industrial and Information Systems*, (ICIIS-2012), IIT Madras, Chennai, 6 - 9 August 2012.

[143] S. S. Rao, Engineering optimization: theory and practice, McGraw-Hill.

[144] S. Sundhararajan and A. Pahwa, “Optimal Selection of Capacitor for Radial Distribution System Using Genetic Algorithm,” *IEEE Trans. Power Syst*., vol. 9, no.3, pp.1499-1507, August 1994.

[145] S.J. Ahn, J.W. Park, Y. Chung, S. Moon, S.H. Kang, and S.R. Nam, “Power-Sharing Method of Multiple Distributed Generators Considering Control Modes and Configurations of a Microgrid,” *IEEE Trans. Power Del*., vol. 25,no.3, pp. 2007-2016, July 2010.

[146] S.M. Kannan, A.R.G. Monica, and S.M.R. Slochanal, “Fuzzy Logic Based Optimal Capacitor Placement on Radial Distribution Feeders,” *IEEE Trans. Power Syst*., vol.3, no. 2, October 2008.

[147] S.M. Sajjadi, M-R Haghifam, J. Salehi, “Simultaneous placement of distributed generation and capacitors in distribution networks considering voltage stability index,” *Elect. Power and Energy Syst*., vol. 46, pp. 366–375, March 2013.

[148] S.P. Singh and A.R. Rao, “Optimal allocation of capacitors in distribution systems using particle swarm optimization,” *Elect. Power Syst. Res*., vol. 43, pp.1267–1275, 2012.

[149] Sundharajan and A. Pahwa, “Optimal selection of capacitors for radial distribution systems using genetic algorithm,” *IEEE Trans. Power Syst*., vol. 9, no.3, pp.1499-1507, August 1994.

[150] T. Ackermann, G. Andersson, and L. Soder, "Distributed generation: a definition", *Elect. Power Syst. Res.*, vol. 57, no. 3, pp. 195-204, April 2001.

[151] T. Gozel and M. H. Hocaoglu, "An analytical method for the sizing and sitting of distributed generators in radial systems," *Electr. Power Syst. Res.*, vol.79, pp. 912-918, 2009.

[152] T. Gozel, M.H. Hocaoglu, U. Eminoglu, and A. Balikci, "Optimal placement and sizing of distributed generation on radial feeder with different static load models," *International Conference on Future Power Systems*, pp. 2-6, November 2005.

[153] T. Griffin, K. Tomsovic, D. Secrest, and A. Law, "Placement of dispersed generations system for reduced Losses," *Proceeding of 33rd Hawaii International Conference on System Science*, Maui, HI, January 2000.

[154] T.H. Fawzi, S.M. El-Sobki, and M.A. Abdel-Halim, "A new approach for the application of shunt capacitors to the primary distribution feeders," *IEEE Trans. Power App. Syst.*, vol. PAS-102, no.1, pp. 10-13, Jan.. 1983.

[155] T.K.A. Rahman, S.R.A. Rahim and I. Musirin, "Optimal allocation and sizing of embedded generators," *Proceedings of National Power and Energy Conference* (PECON), Kuala Lumpur, Malaysia, pp. 288-294, November 2004.

[156] T.N. Shukla, S.P. Singh and K.B. Naik, "Allocation of Optimal distributed generation using GA for minimum system losses in radial distribution networks", *Int. J. of Engineering, Science and Technology,* Vol. 2, No. 3, pp. 94-106, 2010.

[157] T.N. Shukla, S.P. Singh, V. Srinivasarao and K.B. Naik, "Optimal Sizing of Distributed Generation Placed on Radial Distribution Systems", *Elect. Power Comp. and Syst.*, vol.38, no.3, pp. 260-274, January 2010.

[158] V. H. Mendez, J. Rivier, and T. Gomez, "Assesment of energy distribution losses for increasing penetration of distributed generation," *IEEE Trans.Power Syst.*, vol. 21, no. 2, pp. 533–540, May 2006.

[159] V. Kumar, Rohit Kumar, I. Gupta, and H.O. Gupta, "DG integrated approach for service restoration under cold load pickup," *IEEE Trans. Power Del.*, vol. 25, no.1, pp. 398-406, January 2010.

[160] V. Kumar, "Power Distribution System Under Cold Load Pickup," Ph.D. Thesis, Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, 2006.

[161] V.S. Pappala and I. Erlich, “Power System Optimization under Uncertainties: A PSO Approach,” *IEEE Swarm Intelligence Symposium*, St. Louis, MO, pp.1-8, September 2008.

[162] V.S. Pappala, and I. Erlich, “A New Approach for Solving the Unit Commitment Problem by Adaptive Particle Swarm Optimization,” *IEEE/PES General Meeting*, Pittsburgh, PA, pp.1-6, July 2008.

[163] V.V.K. Reddy and M. Sydulu, “Index and GA based Optimal Location and Sizing of Distribution System Capacitors,” *IEEE/PES General Meeting*, Tampa, FL, pp.1-4, June 2007.

[164] V.V.S.N. Murthy, A. Kumar, “Comparison of optimal DG allocation methods in radial distribution systems based on sensitivity approaches,” *Elect. Power and Energy Syst*., vol. 53, pp. 450–467, December 2013.

[165] W. El-Khattam, Y.G. Hegazy, and M.M.A. Salama, “An integrated distributed generation optimization model for distribution system planning,” *IEEE Trans. Power Syst*., vol. 20, no. 2, pp. 1158–1165, May 2005.

[166] W. El-Khattam and M.M.A. Salama, “Distributed system planning using distributed generation,” *Proceedings of IEEE Canadian Conference on Electrical and Computer Engineering*, Canada, vol. 1, pp. 579-582, May 2003.

[167] W. El-Khattam, K. Bhattacharya, Y. Hegazy, and M.M.A. Salama, “Optimal investment planning for distributed generation in a competitive electricity market,” *IEEE Trans. Power Syst*., vol. 19, no. 3, pp. 1674-1684, August 2004.

[168] W. Krueasuk and O. Weerakorn, “Optimal Placement of Distributed Generation Using Particle Swarm Optimization,” *Proceedings of the Australasian Universities Power Engineering Conference* (AUPEC), Melbourne, Australia, December 2006.

[169] W. Prommee and W. Ongsakul, “Optimal multi-distributed generation placement by adaptive weight particle swarm optimization,” *International Conference on Control, Automation and Systems,* (ICCAS), pp. 1663-1668, 2008.

[170] W. Prommee and W. Ongsakul, “Optimal multiple distributed generation placement in microgrid system by improved reinitialized social structures particle swarm optimization,” *Euro, Trans. Electr. Power*, vol. 21, no.1, pp. 489-504, 2011.

[171] Y.M. Atwa and E.F. El-Saadany, “Probabilistic approach for optimal allocation of wind-based distributed generation in distribution systems,” *IET Ren. Power Gener*., vol. 5, no. 1, pp. 79–88, November 2010.

[172] Y.M. Atwa, E.F. El-Saadany, M.M.A. Salama, and R. Seethapathy, “Optimal renewable resources mix for distribution system energy loss minimization,” *IEEE Trans. Power Syst.*, vol. 25 , no. 1, pp. 360-370, 2010.

[173] Z. Yiqin, “Optimal Reactive Power Planning Based on Improved Tabu Search Algorithm,” *International Conference on Electrical and Control Engineering*, Changzhou, China, pp.3945-3948, 2010.

[174] Z. Jianchao, J. Jing, C. Zhihua, Particle swam optimization Algorithm [M].Science Publishing Company of Beijing, 2004.

LIST OF PUBLICATIONS FROM THE WORK

On the basis of research work carried out, following papers have been published/under review in international journals and published in proceedings of international/ National conferences.

INTERNATIONAL JOURNALS:

[1] Satish Kansal, B.B.R.Sai, Barjeev Tyagi, Vishal Kumar "Optimal placement of Distributed Generation in distribution networks" *International Journal of Engineering, Science and Technology,* vol. 3, no. 3, pp. 47-55, April 2011.

[2] Satish Kansal, Vishal Kumar, Barjeev Tyagi, "Optimal Placement of Different type of DG Sources in Distribution Networks" *International Journal of Electrical Power and Energy Systems,* vol. 53, pp. 752-760 December 2013.

[3] Satish Kansal, Vishal Kumar, Barjeev Tyagi, "Optimal Placement of Distributed Generator and Capacitor for Power Compensation in Distribution Network" *Electric Power Systems and Components (Under- review)*

[4] Satish Kansal, Vishal Kumar, Barjeev Tyagi, "Hybrid Approach for Placement of Multiple DGs of Multiple Type in Primary Distribution Networks" *Electrical Power Systems Research (Under-review).*

[5] Satish Kansal, Vishal Kumar, Barjeev Tyagi, "DG and Capacitor Integration in Power Distribution Systems*" IET Generation, Transmission & Distribution* (Under-review).

INTERNATIONAL/NATIONAL CONFERENCES:

[1] Satish Kansal, Vishal Kumar, Barjeev Taygi, "Multiple Distributed Generators Placement in Compensated Primary Distribution Networks" Asia Smart Grid and Electromobility Conference (ASGE-2013), 29-30th October, 2013, Singapore (Under-review).

[2] Satish Kansal**,** Vishal Kumar, Barjeev Taygi, "Hybrid Approach for Placement of Multiple Distributed Generators in Distribution Network" Proceedings of *17th* National Power Systems Conference, (NPSC-2012)*,* Department of Electrical Engineering, IIT-BHU Varanasi, 12 - 14 December, 2012.

[3] Satish Kansal**,** Vishal Kumar, Barjeev Taygi, "Composite Active and Reactive Power Compensation of distribution networks" Proceedings of 7th IEEE International conference on Industrial and Information Systems,(ICIIS-2012)*,* Department of Electrical Engineering, IIT Madras, 6 - 9 August 2012.

[4] Satish Kansal, B.B.R.Sai, Barjeev Taygi, Vishal Kumar "Optimal placement of Wind-Based Generation in distribution networks" Proceedings of International conference IET Renewable Power Generation (RPG-2011), Edinburgh, United Kingdom, 6 - 8 September 2011.

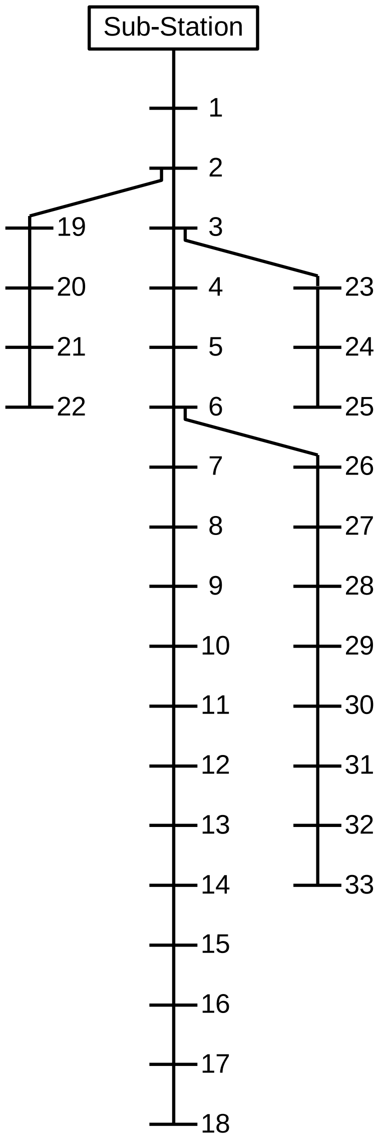
[5] †Satish Kansal, B.B.R.Sai, Barjeev Taygi, Vishal Kumar "Optimal placement of Distributed Generation in distribution networks" Proceedings of National conference on Recent Advantages in Electrical Power and Energy System Management, RAEPSM-2011, at M.M.M. Engineering College Gorakhpur (U.P.) on 25-26 March 2011.

†**Best Paper Award** the paper presented at National Conference RAEPSEM-2011 at MMMEC Gorakhpur (UP) on **"Optimal Placement of Distributed Generation in Distribution Networks"** held on 25-26 March 2011.

APPENDIX-A

12.66 kV, 33-Bus Distribution System

The schematic diagram of a 12.66 kV, 33-bus distribution test system is illustrated in Fig. A.1. The relevant data for this test system have been acquired from reference [20] and are given in Table A.1.



Type of Conductor: Beaver

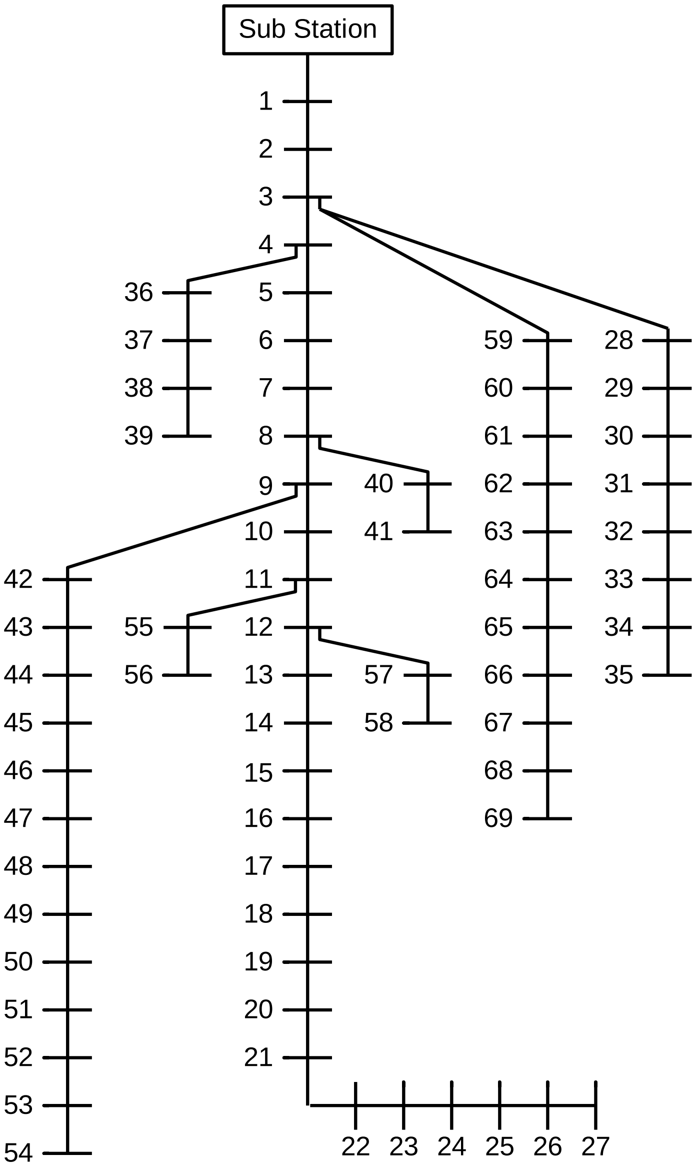
Figure A.1: Single line representation of 12.66 kV, 33-bus distribution system

Table A.1: Branch data and bus data for 12.66 kV, 33-bus distribution system

Branch Number	Bus Number		Branch Parameters		Load at Receiving End Bus	
	Sending End	Receiving End	Resistance (ohm)	Reactance (ohm)	Real (kW)	Reactive (kVAR)
1	1	2	0.0922	0.0470	0.0	0.0
2	2	3	0.4930	0.2511	100.0	60.0
3	3	4	0.3660	0.1864	90.0	40.0
4	4	5	0.3811	0.1941	120.0	80.0
5	5	6	0.8190	0.7070	60.0	30.0
6	6	7	0.1872	0.6188	0.0	20.0
7	7	8	0.7114	0.2351	200.0	100.0
8	8	9	1.0300	0.7400	200.0	100.0
9	9	10	1.0400	0.7400	60.0	20.0
10	10	11	0.1960	0.0650	60.0	20.0
11	11	12	0.3744	0.1238	45.0	30.0
12	12	13	1.4680	1.1550	60.0	35.0
13	13	14	0.5416	0.7129	60.0	35.0
14	14	15	0.5910	0.5260	120.0	80.0
15	15	16	0.7463	0.5450	60.0	10.0
16	16	17	1.2890	1.7210	60.0	20.0
17	17	18	0.7320	0.5740	160.0	20.0
18	2	19	0.1640	0.1565	90.0	40.0
19	19	20	1.5042	1.3554	90.0	40.0
20	20	21	0.4095	0.4784	90.0	40.0
21	21	22	0.7089	0.9373	90.0	40.0
22	3	23	0.4512	0.3083	90.0	40.0
23	23	24	0.8980	0.7091	90.0	50.0
24	24	25	0.8960	0.7011	420.0	200.0
25	6	26	0.2030	0.1034	420.0	200.0
26	26	27	0.2842	0.1447	60.0	25.0
27	27	28	1.0590	0.9337	60.0	25.0
28	28	29	0.8042	0.7006	60.0	20.0
29	29	30	0.5075	0.2585	120.0	70.0
30	30	31	0.9744	0.9630	200.0	600.0
31	31	32	0.3105	0.3619	150.0	70.0
32	32	33	0.3410	0.5302	210.0	100.0

12.66 kV, 69-Bus Distribution System

The single line diagram of a 12.66 kV, 69-bus distribution test system is shown in Fig. A.2. The necessary data for 12.66 kV, 69-bus distribution test system have been obtained from reference [21] and are presented in Table A.2.



Type of Conductor: Beaver

Figure A.2: Single line representation of 12.66 kV, 69-bus distribution system

Table A.2: Branch data and bus data for 12.66 kV, 69-bus distribution system

Branch Number	Bus Number		Branch Parameters		Load at Receiving End Bus	
	Sending End	Receiving End	Resistance (ohm)	Reactance (ohm)	Real (kW)	Reactive (kVAR)
1	1	2	0.0005	0.0012	0.0000	0.0000
2	2	3	0.0005	0.0012	0.0000	0.0000
3	3	4	0.0015	0.0036	0.0000	0.0000
4	4	5	0.0251	0.0294	0.0000	0.0000
5	5	6	0.3660	0.1864	0.8780	0.7200
6	6	7	0.3811	0.1941	13.4550	9.9820
7	7	8	0.0922	0.0470	24.8870	17.8100
8	8	9	0.0493	0.0251	10.0000	7.2080
9	9	10	0.8190	0.2707	9.3330	6.6660
10	10	11	0.1872	0.0619	48.5000	34.6090
11	11	12	0.7114	0.2351	48.5000	34.6090
12	12	13	1.0300	0.3400	2.7100	1.8210
13	13	14	1.0440	0.3450	2.7100	1.8210
14	14	15	1.0580	0.3496	0.0000	0.0000
15	15	16	0.1966	0.0650	15.1760	10.1980
16	16	17	0.3744	0.1238	16.5000	11.7750
17	17	18	0.0047	0.0016	16.5000	11.7750
18	18	19	0.3276	0.1083	0.0000	0.0000
19	19	20	0.2106	0.0696	0.3160	0.2120
20	20	21	0.3416	0.1129	37.9830	27.1000
21	21	22	0.0140	0.0046	1.7620	1.1840
22	22	23	0.1591	0.0526	0.0000	0.0000
23	23	24	0.3463	0.1145	9.3900	6.6700
24	24	25	0.7488	0.2475	0.0000	0.0000
25	25	26	0.3089	0.1021	4.6670	3.3300
26	26	27	0.1732	0.0572	4.6670	3.3300
27	3	28	0.0044	0.0108	8.6670	6.1850
28	28	29	0.0640	0.1565	8.6670	6.1850
29	29	30	0.3978	0.1315	0.0000	0.0000
30	30	31	0.0702	0.0232	0.0000	0.0000
31	31	32	0.3510	0.1160	0.0000	0.0000
32	32	33	0.8390	0.2816	4.5820	3.2600
33	33	34	1.7080	0.5646	6.5010	4.5490

34	34	35	1.4740	0.4873	1.9200	1.2900
35	4	36	0.0034	0.0084	0.0000	0.0000
37	37	38	0.2898	0.7091	28.2260	91.4620

Table A.2: *(Continued)* Branch data and bus data for 12.66 kV, 69-bus system

38	38	39	0.0822	0.2011	128.2260	91.4620
39	8	40	0.0928	0.0473	13.5120	9.4420
40	40	41	0.3319	0.1114	1.2020	0.8940
41	9	42	0.1740	0.0886	1.4490	1.1620
42	42	43	0.2030	0.1034	8.7870	6.3220
43	43	44	0.2842	0.1447	8.0000	5.7080
44	44	45	0.2813	0.1433	0.0000	0.0000
45	45	46	1.5900	0.5337	0.0000	0.0000
46	46	47	0.7837	0.2630	0.0000	0.0000
47	47	48	0.3042	0.1006	0.6670	24.0250
48	48	49	0.3861	0.1172	0.0000	0.0000
49	49	50	0.5075	0.2585	414.6670	295.9100
50	50	51	0.0974	0.0496	10.6670	7.6120
51	51	52	0.1450	0.0738	0.0000	0.0000
52	52	53	0.7105	0.3619	75.6700	53.8730
53	53	54	1.0410	0.5302	19.6700	13.9120
54	11	55	0.2012	0.0611	6.0000	4.2820
55	55	56	0.0047	0.0014	6.0000	4.2820
56	12	57	0.7394	0.2444	9.3330	6.6600
57	57	58	0.0047	0.0016	9.3330	6.6600
58	3	59	0.0044	0.0108	8.6670	6.1850
59	59	60	0.0640	0.1565	8.6670	6.1850
60	60	61	0.1053	0.1230	0.0000	0.0000
61	61	62	0.0304	0.0355	8.0000	5.7090
62	62	63	0.0018	0.0021	8.0000	5.7090
63	63	64	0.7283	0.8509	0.3920	0.3250
64	64	65	0.3100	0.3623	0.0000	0.0000
65	65	66	0.0410	0.0478	2.0000	1.4270
66	66	67	0.0092	0.0116	0.0000	0.0000
67	67	68	0.1089	0.1373	3.0760	8.7870
68	68	69	0.0009	0.0012	3.0760	8.7870

APPENDIX-B

BACKWARD–FORWARD SWEEP LOAD FLOW METHOD:

Power flow method for solving radial distribution networks, using a multi-port compensation technique and basic formulations of Kirchhoff's laws. This method has excellent convergence characteristics and is very robust. A computer program implementing this power flow solution scheme was developed and successfully applied to several practical distribution networks with radial structure. This program was successfully used for solving radial distribution networks. The method can be applied to the solution of both the three-phase (unbalanced) and single-phase (balanced) representation of the network. In this thesis, however, only the single phase representation is used.

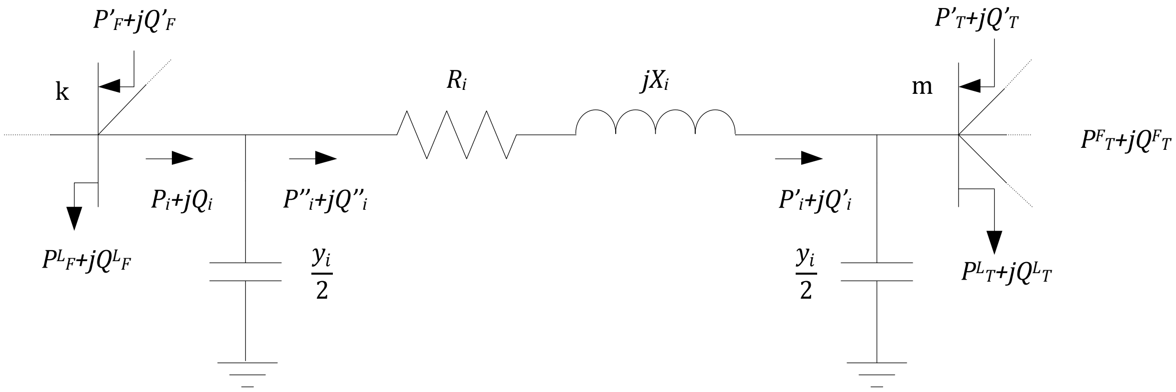


Figure B1: π circuit model of the branch

B.1 Load Flow Equations:

The load flow problem of a single source network can be solved iteratively from two sets of recursive equations. The recursive equations in backward and forward directions are derived as follows.

Consider that the branch ***i*** in a tree is connected between buses *F* and *T.* Bus *F* is closer to the root bus. The series impedance and shunt admittance of the branch are (R_i+jX_i) and y_i respectively. The $\boldsymbol{\pi}$ circuit model of the branch is shown in Fig. B.1.

The active (P_i'') and reactive (Q_i'') power flow through the series impedance of the branch as shown in Fig. B.1, can be written as:

$$P_i'' = P_T^F + P_T^L - P_T^I \qquad \dots(B.1)$$

$$Q_i'' = Q_T^F + Q_T^L - Q_T^I - \frac{{V_T}^2\, y_i}{2} \qquad \ldots (B.2)$$

Here, the superscripts *L, F* and ***I*** in *P* and *Q* represent the load, flow and injection, respectively. The flow P_T^F (Q_T^F) is the sum of the active (reactive) power flow through all the downstream branches that are connected to bus *T.* The procedure of finding the power injections (P_T^I and Q_T^I) at the LBPs is described in the next Section. The active (P_i) and reactive (Q_i) power flow through branch i near bus ***F*** can be written as:

$$P_i' = P_i'' + \frac{{P_i''}^2 + {Q_i''}^2}{{V_T}^2} \,.R_i \qquad (B.3)$$

$$Q_i' = Q_i'' + \frac{{P_i''}^2 + {Q_i''}^2}{{V_T}^2} \,.X_i \qquad (B.4)$$

Equations (B.3) and (B.4) can be used recursively in a backward direction to find the power flow through each branch in the tree. The backward direction means the equations are first applied to the last branch of the tree and proceed in reverse direction until the first branch is reached. By knowing the power flow through each branch, the voltage magnitude and angle at each bus can be obtained from another set of recursive equations in a forward direction.

Consider that the angle of voltage at bus ***F*** is zero. The complex voltage at bus *T,* in Fig. B 1, can be written as.

where

$$P_i = P_i' \qquad (B.5)$$

$$Q_i = Q_i' - \frac{{V_T}^2\, y_{c_i}}{2} \qquad (B.6)$$

and I_i is the current through the series impedance (R_i+jX_i). The voltage magnitude and angle at bus ***T*** can be written as:

$$V_T(i) = \sqrt{V_F(i)^2 - 2\left(P_i' R_i + Q_i' X_i\right) + \frac{{P_i''}^2 + {Q_i''}^2}{V_T(i)^2}\left({R_i}^2 + {X_i}^2\right)} \qquad (B.7)$$

$$\delta_T(i) = \delta_F(i) - tan^{-1}\left(\frac{P_i' R_i + Q_i' X_i}{V_F(i)^2 - \left(P_i' R_i + Q_i' X_i\right)}\right) \qquad (B.8)$$

Equations (B.7) and (B.8) can be used recursively in a forward direction to find the voltage and angle, respectively, of all buses in the tree.

Layers Creation or Branch numbering:

The Layers creation process of a network requires the construction of a tree of the network. The tree is constructed in several layers and it starts at the root bus where the source is connected [84]. The root bus is the swing or slack bus of the network. The first layer consists of all branches that are connected to the root bus. The next (second) layer consists of all branches that are connected to the receiving end bus of the branches in the previous (first) layer and so on. All branches of the network should be considered in the tree and they should appear only once. The branch numbering process starts at the first layer. The numbering of branches in any layer starts only after numbering all the branches in the previous layer. An example for 33 bus network is shown in the Figure B.2.

B.2 Layers Creation or Branch numbering

The Layers creation process of a network requires the construction of a tree of the network. The tree is constructed in several layers and it starts at the root bus where the source is connected [84]. The root bus is the swing or slack bus of the network. The first layer consists of all branches that are connected to the root bus. The next (second) layer consists of all branches that are connected to the receiving end bus of the branches in the previous (first) layer and so on. All branches of the network should be considered in the tree and they should appear only once. The branch numbering process starts at the first layer. The numbering of branches in any layer starts only after numbering all the branches in the previous layer. An example for 33 bus network is shown in the Figure B.2.

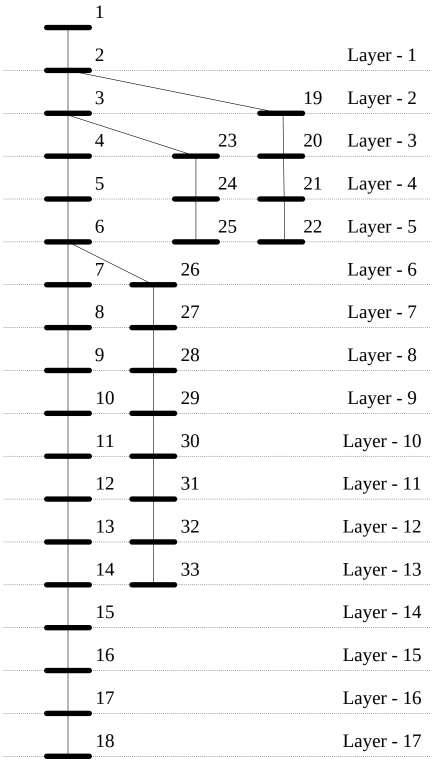


Figure B.2 Layers creation for 33

Load flow Algorithm (Backward – Forward sweep method):

The iterative sequence of steps followed by the Backward – Forward sweep method is as following:

Step 1: Divide the Distribution Network into layers as explained in section B.1.

Step 2: Assume Flat Voltage Profile and set iteration count k = 1.

Step 3: Backward Sweep: Calculate Line flows using equations (B.1) to (B.8) from last layer to first for all the branches of layers.

Step 4: Forward Sweep: Compute $V_T(i)$ and $\delta_T(i)$ using equations B.7 and B.9.

Step 5: Stopping Criteria: if $\Delta P_i \leq \varepsilon_P \, and \, \Delta Q_i \leq \varepsilon_Q$ then Stop iterations otherwise increment iteration i.e. k = k+1 and continue Steps 2-4.

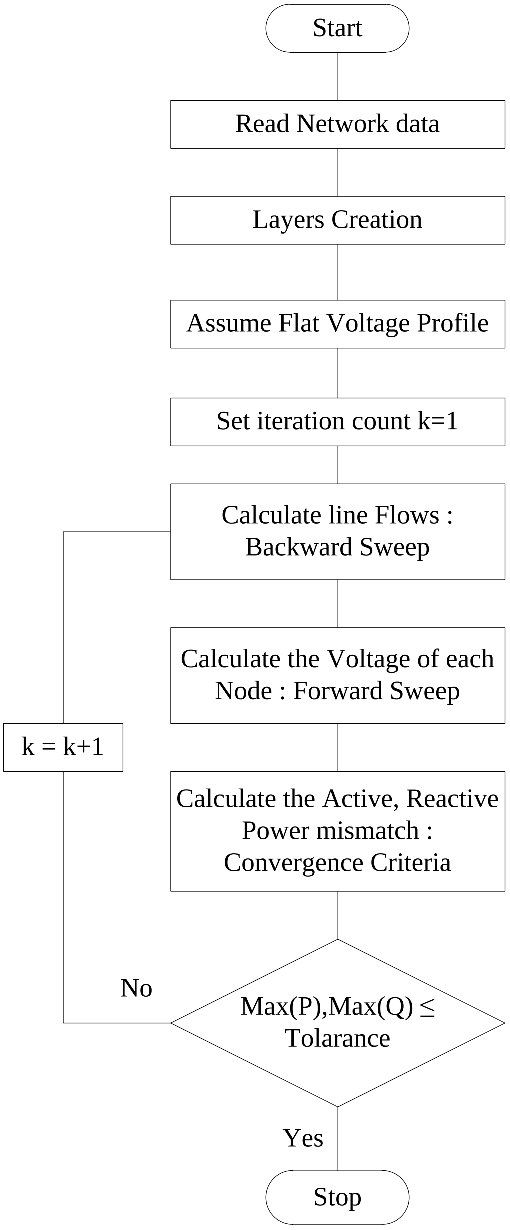


Figure B.3 Flowchart for Backward forward sweep method