



# UNIVERSITY OF NAIROBI

Department of Electrical and Electronic Engineering

## MSC (ELECTRICAL AND ELECTRONIC ENGINEERING)

SYSTEM LOSS REDUCTION AND VOLTAGE PROFILE IMPROVEMENT  
BY OPTIMAL PLACEMENT AND SIZING OF DISTRIBUTED GENERATION  
(DG) USING A HYBRID OF GENETIC ALGORITHM (GA) AND IMPROVED  
PARTICLE SWARM OPTIMIZATION (IPSO)

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*A thesis submitted in partial fulfillment of the degree of Master of Science in  
Electrical and Electronic Engineering of the University of Nairobi.*

**DECLARATION**

This MSC research work is my original work and has not been presented for a degree award in this or any other university.

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This MSC research work has been submitted to the School of Engineering, Department of Electrical and Information Engineering, The University of Nairobi with my approval as supervisor

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## **DEDICATION**

I dedicate this thesis work to my son Charles Junior and My loving wife Martha, dad Charles, mother Jane and grandmother Margaret for continually inspiring me to work hard in my academics, my brothers Dr. Mulwa, Nicodemus and Robert and my sisters Margaret, Mwikali, Tabitha, Syombua and Elizabeth for their prayers and encouragement, not forgetting the occasional much needed distractions they provided. I love you all so much and thank God everyday for blessing me with you.

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## **ABBREVIATIONS**

ABC-Artificial Bee Colony algorithm  
AC-Alternating Current  
ACO-Anti-Colony Optimization  
BCO-Bee Colony Optimization  
CSF-Combined Sensitivity Factors  
DE-Differential Evolutionary  
DG-Distributed Generator  
DGs-Distributed Generators  
DISCO-Distribution Company  
DPSO-Discrete Particle Swarm Optimization  
DSO-Distribution System Operators  
EPRI-Electric Power Research Institute  
EPSO-Evolutionary Particle Swarm Optimization  
FACTS-Flexible Alternating Current Transmission Systems  
GA-Genetic Algorithm  
HCBMOP-Hybrid and Constraint Based Multi Objective Programming  
HPF-Harmonic Power Flow  
HPSO-Hybrid Particle Swarm Optimization  
HSA-Harmony Search Algorithm  
IPSO-Improved Particle Swarm Optimization  
LLRI-Line Loss Reduction Index  
LSF-Loss Sensitivity Factor method  
MAMD-Multiple Attribute Making Decision  
MPSO-Modified Particle Swarm Optimization  
ORPF-Optimal Reactive Power Flow  
PDIP-Primal-Dual Interior-Point  
PLI-Power Loss Index  
PLRI-Real Power Loss Reduction Index  
PSO-Particle Swarm Optimization

QLRI-Reactive Power Loss Reduction Index  
RCGA-Real-Coded Genetic Algorithm  
SFLA-Shuffled Frog Leaping Algorithm  
SGA-Simple Genetic Algorithm  
SQP-Sequential Quadratic Programming  
STATCOM-Static Compensators  
T&D-Transmission and Distribution  
THD-Total Harmonic Distortion  
VPII-Voltage Profile Improvement Index  
VPI-Voltage Profile Index

## ABSTRACT

Though several algorithms for optimizing DG location and size in a power system network with the aim of reducing system power losses and improving voltage profile have already been proposed, they still suffer from several drawbacks. As a result much can be done in coming up with new algorithms or improving the already existing ones so as to address this important issue more efficiently and effectively. Majority of the proposed algorithms have emphasized on real power losses only in their formulations. They have ignored the reactive power losses which are key in the operation of power systems. In modern practical power systems reactive power injection plays a critical role in voltage stability control, thus the reactive power losses need to be incorporated in optimizing DG allocation for voltage profile improvement. The results of the few works which have considered reactive power losses in their optimization can be improved by using more recent and accurate algorithms. This research work aimed at solving this problem by proposing a hybrid of GA and IPSO to optimize DG location and size while considering both real and reactive power losses. Both real and reactive power flow and power loss sensitivity factors were utilized in identifying the candidate buses for DG allocation. This reduced the search space for the algorithm and thus increased its rate of convergence. The suggested method was programmed under MATLAB 2011 software and tested using IEEE 30-bus test system, IEEE 33-bus test system and IEEE 57-bus test system by considering three types of DGs. The results obtained were compared to those obtained by other researchers. It was observed that GA-IPSO method performed better in terms of reducing both real and reactive power losses as compared to Heuristic, GA, PSO and IPSO methods. For the IEEE 30-bus test system, the percentage reduction in real power loss was 35.46%, 35.82% and 35.21% while the percentage reduction in reactive power loss was 36.01%, 35.95% and 35.88% for type 1, type 2 and type 3 DGs respectively. The voltage profile of the networks after optimizing DG locations and sizes using GA-IPSO method were also found to be much improved with the lowest bus voltage improved to 1.01pu and 0.959pu for the IEEE 30-bus and 33-bus test systems respectively. The effects of DG penetration on system power losses and voltage profiles were studied. The system power losses reduced with the introduction of DGs in the network up to an optimal number where any further DG inclusion resulted to an increase in system power losses and deviation of bus voltages outside acceptable limits.

## **CHAPTER 1: INTRODUCTION**

### **1.1 Distribution Systems**

The objective of power system operation is to meet the demand at all the locations within the 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, delivering power through an extensive transmission and distribution system, to meet the given demands of widely dispersed users. Nowadays, 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.

Distribution system provides a final link between the high voltage transmission system and the consumers. A radial distribution system has main feeders and lateral distributors. The main feeder originates from substation and passes through different consumer loads. Laterals are connected to individual loads [1]. Generally radial distribution systems are used because of their simplicity. Power loss in a distribution system is high because of low voltage and hence high current.

Electricity networks are in the era of major transition from stable passive distribution networks with unidirectional electricity transportation to active distribution networks with bidirectional electricity transportation. Radial distribution networks without any DG units are considered passive since the electrical power is supplied by the national grid system to the customers embedded in the distribution networks. They become active when DG units are added to the distribution system leading to bidirectional power flows in the networks [2].

In an active distribution network the amount of energy lost in transmitting electricity is less as compared to the passive distribution network, because the electricity is generated very near to the load center. Active Distribution Network has several advantages like reduced line losses, voltage profile improvement, reduced emission of pollutants, increased overall efficiency, improved power quality and relieved T&D congestion. Hence, utilities and distribution companies need

tools for proper planning and operation of Active Distribution Networks. The most important benefits are reduction of line losses and voltage stability improvement. These are crucially important in determining the size and location of DG unit to be placed in the distribution networks. Studies indicate that poor selection of location and size of a DG in a distribution system would lead to higher losses than the losses without DG [3a, 3b].

## **1.2 Distribution Systems Power Loss Minimization**

As previously stated, among the many benefits of distributed generation, reduction in system line losses is one of them. Normally, the real power loss draws more attention for the utilities, as it reduces the efficiency of transmitting energy to customers. Nevertheless, reactive power loss is obviously not less important. This is due to the fact that reactive power flow in the system needs to be maintained at a certain amount for sufficient voltage level. Consequently, reactive power makes it possible to transfer real power through transmission and distribution lines to customers. System loss reduction by strategically placed DG along the network feeder can be very useful if the decision maker is committed to reduce losses and to improve network performance (e.g. on the level of losses and/or reliability) maintaining investments to a reasonable low level [4]. This feature may be very useful in case of revenue recovered by distribution company (DISCO) which is not only based on the asset value but also on network performance.

## **1.3 Distribution Systems Voltage Profile Improvement**

In a power system, the system operator is obligated to maintain voltage level of each customer bus within the required limit. To ensure voltage profiles are satisfactory in distribution systems, different standards have been established to provide stipulations or recommendations. For example, the American National Standards Institute (ANSI) standard C84.1 has stipulated that voltage variations in a distribution system should be controlled within the range of -13% to 7% [5]. Actually in practice, many electricity companies try to control voltage variations within the range of  $\pm 6\%$ . One of the upcoming widely adopted methods for improving voltage profiles of distribution systems is introducing distributed generation (DG) in distribution systems. The DG units improve voltage profiles by changing power flow patterns. The locations and size of DGs would have a significant impact on the effect of voltage profile enhancement.

## **1.4 Distributed Generation**

Distributed generation (DG) is small-scale power generation that is usually connected to distribution system. The Electric Power Research Institute (EPRI) defines DG as generation from a few kilowatts up to 50MW [6]. CIGRE define DG as the generation, which has the characteristics (CIGRE, 1999): it is not centrally planned; it is not centrally dispatched at present; it is usually connected to the distribution networks; it is smaller than 50-100MW. Ackermann *et al.* have given the most recent 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.” [7].

In most power systems, a large portion of electricity demand is supplied by large-scale generators. This is because of economic advantages of these units over small ones. However, in the last decade, technological innovations and a changing economic and regulatory environment have resulted in a renewed interest for DG units. A study by the Electric Power Research Institute (EPRI) indicated that by 2010, 25% of the new generation was to be distributed. Natural Gas foundation concluded that this figure could be as high as 30% [8]. Different technologies are used for DG sources such as photo voltaic cells, wind generation, combustion engines, fuel cells and other types of generation from the resources that are available in the geographical area [9].

### **1.4.1 Importance of DG**

The main motive behind applying DGs in the power distribution are energy efficiency or rational use of energy, deregulation or competition policy, diversification of energy sources, availability of modular generating plant, ease of finding locations for smaller generators, shorter construction time and lower capital costs for smaller plants, and proximity of the generation plant to heavy loads, which can reduce the transmission costs. The DG when connected to network can provide a number of benefits. Some of the benefits are power losses reduction, energy undelivered costs reduction, preventing or delaying network expansion [10, 11]. Other benefits are peak load operating costs reduction, improved voltage profile and improved load factor [12]. In addition to providing benefits, DG can also have negative impacts on network. These impacts include frequency deviation, voltage deviation and harmonics on network [13]. The increase of power

losses is another effect that may occur [10, 14]. Thus careful considerations need to be taken when sizing and locating DGs in distribution systems.

#### **1.4.2 DG placement and Sizing**

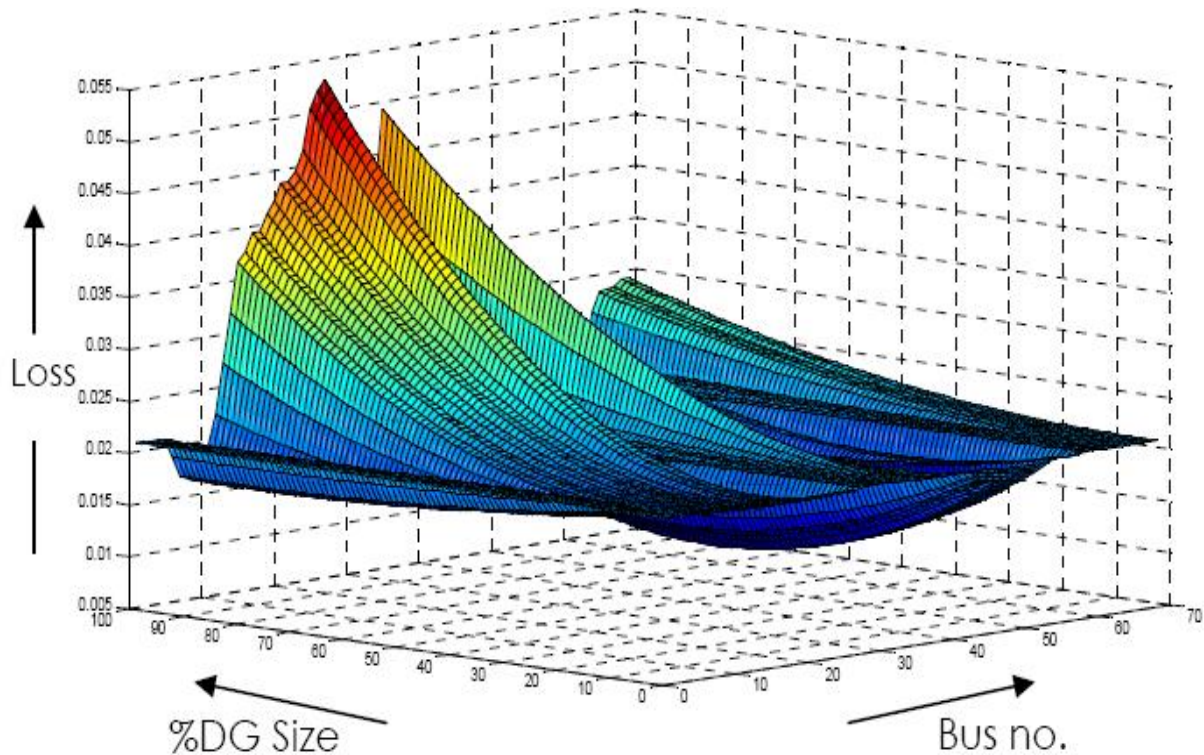
Traditionally load growth is forecasted by distribution companies until a predetermined amount is reached, whereby a new capacity must be added to the network. This new capacity is usually the addition of new substations or expanding existing substations capacities and their associated new feeders or both. However, the flexibility, technologies, technical & monetary benefits and concepts of DG planning is challenging this state of matters and gaining credibility as a solution to the distribution planning problems with the prohibitively high cost of power curtailment in the changing regulatory and economic scenarios. This enhances DG as an attractive distribution planning option that avoids causing degradation of power quality, reliability and control of the utility systems [3, 15, 16]. Quinta et al. (1993) and Khator and Leung (1997) reported that the distribution system planning problem is to identify a combination of expansion projects for the least cost network investment that satisfies load growth requirements without violating any system and operational constraints [17, 18].

Usually, DGs are integrated with the existing distribution system and lots of studies are done to find out the best location and size of DGs to produce utmost benefits. The main characteristics that are considered for the identification of an optimal DG location and size are the minimization of transmission loss, maximization of supply reliability and maximization of profit of the distribution companies (DISCOs). Due to extensive costs, the DGs should be allocated properly with optimal size to enhance the system performance in order to minimize the system loss as well as to get some improvements in the voltage profile while maintaining the stability of the system. The effect of placing a DG on network parameters usually differs on the basis of its type, location and load at the connection point [9]. Thus interconnection planning of DG to electrical network must consider a number of factors. The factors include DG technology; capacity of DG unit; location of DG connected and network connection type [10, 14].

Figure 1.1 shows a 3D plot of typical power loss versus size of DG at each bus in a certain distribution test system. From the figure, it is obvious that for a particular bus, as the size of DG is increased, the losses are reduced to a minimum value and increased beyond a size of DG (that



is, the optimal DG size) at that location. If the size of DG is further increased, the losses starts to increase and it is likely that it may overshoot the losses of the base case. Also notice that location of DG plays an important role in minimizing the losses.



**Figure 1.1** Effect of size and location of DG on system loss [7]

The important conclusion that can be drawn from figure 1.1 is that, given the characteristics of the distribution system, it is not advisable to construct too high DG in the network. The size at most should be such that it is consumable within the distribution substation boundary. Any attempt to install high capacity DG with the purpose of exporting power beyond the substation (reverse flow of power though distribution substation), will lead to very high losses. Thus, the size of distribution system in terms of load (MW) will play an important role in selecting the size of DG. The reason for higher losses at high capacity of DG can be explained by the fact that the distribution system was initially designed such that power flows from the sending end (source substation) to the load and conductor sizes are gradually decreased from the substation to consumer point. Thus without reinforcement of the system, the use of high capacity DG will lead to excessive power flow through small-sized conductors and hence results in higher losses.

## 1.5 Survey of Earlier Work

Different researchers have proposed different ways for solving the problem of voltage improvement and loss minimization in distribution systems. Recently researchers are moving away from the usual use of capacitors to the introduction of DGs in the systems. In the recent past, much effort has been contributed to solving the optimal DG placement problem, utilizing different algorithms and considering different objectives. The DG placement problem could be formulated as an optimization problem. Various algorithms are used to solve the problem. The methods used to solve this problem can be divided into three categories;

1. Analytical Methods
2. Computational Methods
3. Artificial Intelligence Methods

### 1.5.1 Analytical Methods

Though the analytical methods suffer from many draw backs they are still used in optimizing the location and size of DGs in distribution systems. This is because they are easy to work with and their logical analysis can easily be followed.

**Graham *et al.* (2000) [19]** applied Loss Sensitivity Factor method (LSF) based on the principle of linearization of the original nonlinear equation (loss equation) around the initial operating point, which helps to reduce the amount of solution space. Optimal placement of DG units is determined exclusively for the various distributed load profiles to minimize the total losses. They iteratively increased the size of DG unit at all buses and then calculated the losses; based on loss calculation they ranked the nodes. Top ranked nodes are selected for DG unit placement.

**In EI-hattam and Salma (2004) [20]**, an analytical approach has been presented to identify appropriate location to place single DG in radial as well as loop systems to minimize losses. But, in this approach, optimal sizing is not considered.

**H. Iyer, S. Ray, and R. Ramakumar (2005) [21]** proposed a new approach involving two new quadratic voltage profile improvement indices ( $VPII1$  and  $VPII2$ ) for voltage profile improvement using DGs. The Primal-Dual Interior-Point (PDIP) method was employed to identify the optimal location and real and reactive power generation on the basis of the newly

proposed indices. The models treated the voltage profile in a quadratic form in order for it to be employed in an optimization procedure.

**D. Issicaba *et al.* (2006) [22]** presented a new approach for optimization and automatic control of reactive power in distribution feeders and substations. The proposed methodology was based on modeling an agent objecting to learn and discover the optimal location, placement policy, and control scheme of capacitor banks, by means of trial-and-error interactions in an environment so as to improve voltage regulation and reduce power losses. Sensitivity-based analysis could improve the proposed methodology.

**C. L. Su (2009) [23]** presented a comparative analysis of voltage control strategies in distribution networks with DGs. He proposed several voltage control strategies that incorporated existing voltage control devices and reactive power compensators with various degrees of integration. His results showed that the coordinated control strategy integrating distribution and generation plants was the most effective among the proposed control strategies and can provide an effective way to manage network voltage against DG penetration.

**W. Huang *et al.* (2010) [24]** proposed two optimization-based models for computing the allowable penetration level of multiple DGs, taking into account voltage regulation constraints. In the suggested models, on-load tap changing transformer was modeled in detail with a switch function, and the impact of distributed generator outages was included. Their challenge was to develop efficient algorithms for dealing with problems with a large number of DGs to be sited.

**Minnan Wang and Jin Zhong (2011) [5]** suggested two optimization models to obtain the optimal placements of DGs and capacitor banks to maintain better voltage profiles in distribution systems. First, the optimal DG placement problem was formulated as a modified optimal power flow problem, with an innovative mathematical representation of voltage profile optimization. Then the capacitor optimal placement problem was modeled and solved. Both models were tested on the IEEE 41 bus distribution system, which is a radial system. From their research they concluded that the strategic placement of DG units would have a strong influence on the voltage profile improvement of the distribution system and capacitor banks could be assigned optimally to procure a better voltage profile.

**Gopiya Naik, D. K. Khatod and M. P. Sharma (2012) [25]** presented a simple method for real power loss reduction, voltage profile improvement and substation capacity release. The proposed method was based on voltage sensitivity index analysis and power flow analysis which was done using the forward-backward sweep method. The forward-backward sweep based algorithm had the advantage of low memory requirements, computational efficiency and robust convergence characteristic.

**T. S. Sirish *et al.* (2013) [26]** implemented a KVS- Direct Search Algorithm to determine the optimal sizes of Static Capacitors and Type-3 Distributed Generators (DGs) together with their optimal locations in 69 Bus Radial Distribution Systems so that maximum possible reduction in real power loss is obtained. The algorithm searches for all possible locations in the system for a particular size of capacitor or DG and places them at the bus which gives maximum reduction in active power loss. The optimal sizes of capacitors and DGs are chosen to be standard sizes that are available in the market that is, discrete sizes of capacitors and DGs are considered.

**Mamta Karayat *et al.* (2013) [27]** proposed the use of Modified KVS – Direct Search Algorithm to determine the optimal sizes of Static Capacitors and Type-2 Distributed Generators (DGs) together with their optimal locations in radial distribution systems so that maximum possible reduction in real power loss is obtained. The algorithm searches for all possible locations in the system for a particular size of capacitor or DG and places them at the bus which gives maximum reduction in active power loss.

**Ramachandra Murthy *et al.* (2013) [28]** proposed a new Direct Search Algorithm to determine the optimal sizes of Static Capacitors and Type -3 Distributed Generators (DGs) together with their optimal locations in radial distribution systems so as to obtain maximum possible reduction in real power loss. The algorithm searched for all possible locations in the system for a particular size of capacitor or DG and placed them at the bus which gave maximum reduction in active power loss. The optimal sizes of capacitors and DGs were chosen to be standard sizes that were available. Discrete sizes of capacitors and DGs were considered. The algorithm was tested on standard 33 bus systems.

**M. A. Mahmud *et al.* [29]** presented a way to control voltage of distribution networks with DG using reactive power compensation approach. In their paper, the voltage control approach was shown based on the worst case scenario of the network. To keep the voltage profile within the specified limits, it was essential to regulate the reactive power of the compensators. Simulation results clearly showed that specified voltage could be obtained by using reactive power compensation.

**Ashwani Kumar and Wenzhong Gao [30]** presented a multi-objective optimization approach for determining optimal location of DGs in deregulated electricity markets with an aim of improving the voltage profile and reducing the line losses. This approach combined the use of power flow and power loss sensitivity factors in identifying the most suitable zone and then optimized the solution by maximizing the voltage improvement and minimizing the line losses in the network. This work did not consider reactive power loss in optimization.

**An D.T Le *et al.* [31]** developed a technique based on voltage sensitivity of lines to optimize voltage improvement by effectively injecting active and reactive power of DGs. An index derived from the thevenin equivalent of a network and voltage condition of the system was developed to obtain optimal or near optimal placement of DG for maximum voltage improvement in a distribution feeder.

**Rau and Wan [32]** have used gradient and second order method to minimize loss, line loading and reactive power requirements in the Distribution network. They later investigated loss minimization using analytical based 2/3 rule, assuming a constant power source and a uniformly distributed load.

### **1.5.2 Computational Methods**

Another class of techniques used for optimizing the location and size of DGs in a power system is the computational methods. Though these methods are fast compared to the other classes of techniques their drawback is that they are complex and reproduction of their results may be difficult or sometimes impossible.

**An D.T. Le, M.A. Kashem *et al.* (2007) [33]** addressed the issue of optimizing DG planning in terms of DG size and location to reduce the amount of line losses in the distribution networks.

Their optimization methodology, which was based on the Sequential Quadratic Programming (SQP) algorithm, assessed the compatibility of different generation schemes upon the level of power loss reduction and DG cost.

**Andrija Volkanovski *et al.* (2009) [34]** presented an approach for optimal reactive-power compensation in distribution networks based on simulated annealing method and deterministic initialization. Their results confirmed the need for application and optimization of the reactive power compensation in the distribution networks. The bus voltages were improved, losses were decreased and the available transfer capacities of the interconnections were increased. The decrease in energy losses and peak load in the distribution network resulted in substantial yearly savings.

**Andrew Keane *et al.* (2011) [35]** proposed a passive solution to reduce the impact of DG reactive power demand on the transmission system voltages and overcome the distribution voltage rise barrier such that more DG could be connected. The fixed power factors of the generators and the tap setting of the transmission transformer were determined by a linear programming formulation.

**El-khattam *et al.* [36]** used a Heuristic Iterative Search method to minimize the cost of investment and operation of DGs, loss and energy required by customers; which **Satish Kansal, Sai, Barjeev Tyagi and Vishal Kumar [8]** later applied to minimize DG investment, operation losses and energy purchased from the main grid.

### **1.5.3 Artificial Intelligence Methods**

The analytical and the computational optimization methods are being phased out by the most promising artificial intelligence methods. This is because among other benefits the artificial intelligence techniques are not gradient based and thus are not prone to being trapped in local minimum. The results from the artificial intelligence optimization algorithms are also easily reproducible. Some of the artificial intelligence methods include;

### 1.5.3.1 Genetic Algorithm (GA) Based Optimization Techniques

Genetic Algorithm (GA) being one of the most common artificial intelligence optimization techniques has been used in several literatures. GA has been used by several authors to optimize the location and size of DGs in power systems.

**Ault and McDonald (2000)** and **Caisheng and Nehrir (2004)** [37, 38] used Genetic Algorithm (GA) based method to determine size and location of DG units. They have addressed the problem in terms of cost, considering cost function may lead to deviation of exact size of the DG unit at suitable location. It always gives a near optimal solution, but it is computationally demanding and slow in convergence.

**R. Hooshmand and M. Ataei (2007)** [39] solved the problem of optimal placement of capacitor banks for unbalanced distribution systems with meshed/radial configurations using Real-Coded Genetic Algorithm (RCGA). Fixed and switched capacitors were optimally utilized in loss reduction and controlling the voltages of distribution systems.

**Rahmat-Allah Hooshmand (2007)** [40] presented a technique for finding the optimal values of the fixed and switched capacitors in the distribution networks based on the real coded genetic algorithm (RCGA). The modeling of the loads at different load levels was simulated with low voltage and medium voltage capacitors that are available on the market. In addition to the various parameters in the optimization problem, RCGA was used to find the best and real optimal network with the best rate for the capacitors.

**S. Jalilzadeh et al. (2007)** [41] did a research on voltage profile and its importance in distribution systems using Genetic algorithm. Reactive power injection especially in end busses that are far from slack buss was used in order to facilitate the improvement of voltage profile. Genetic algorithm was selected as the search method to determine optimum value of injected reactive power. Results showed that voltage profile was improved and amount of losses was decreased by this method.

**T. N. Shukla, S.P. Singh and K. B Naik (2010)** [4] used GA to optimally locate DG for minimum system losses in radial distribution networks. The problem is formulated as an optimization problem with minimization of real power loss subject to equality and inequality

constraints and solution is obtained using GA. The appropriate location is decided on the basis of active power loss sensitivity to real power injection through DG. They demonstrated that the benefit increases with increased number of locations within certain locations beyond which it is uneconomical. This formulation considered active power losses only.

**Saeed Boyerahmadi and Mehrdad Movahed Poor (2013) [42]** investigated the effects of shunt capacitors placement and distributed generation power plants on power loss reduction and voltage profile improvement in radial distribution systems using Genetic Algorithms. From their results, they concluded that locating capacitors and distributed generation plants in the most suitable places leads to loss reduction and voltage profile improvement. The best place for distributed generation plants and shunt capacitors placement is near the load.

**Carpinelli *et al.* [43]** employed GA with decision making approach to minimize the cost of power losses and network upgrading for a wind generator with a peak load and constant load growth.

#### **1.5.3.2 Particle Swarm Optimization (PSO) Based Techniques**

Particle Swarm Optimization (PSO) techniques have also been used in several open literatures by different authors in the optimization of DG location and size in a power system with the aim of reducing system power losses and improving voltage profile.

**Amin Hajizadeh and Ehsan Hajizadeh (2008) [44a, 44b]** suggested a PSO-based planning of distribution systems with distributed generations. They presented a multi-objective formulation for optimal siting and sizing of DG resources in distribution systems in order to minimize the cost of power losses and energy not supplied. The implemented technique was based on PSO and weight method that was employed to obtain the best compromise between these costs

**Kai Zou *et al.* (2009) [45]** proposed a method for voltage support in distribution systems by employing DG units and shunt capacitors. The target voltage support zones were identified using a numerical/analytical method thus reducing the large search space. The strategic placement of DG units and shunt capacitors is proposed for overall voltage support and power loss reduction by minimizing the investment cost for DG units and shunt capacitors using PSO.



**I. Ziari and G. Platt (2010) [46]** employed a Hybrid PSO (HPSO) to minimize the reliability and line loss costs along with the investment cost of electricity networks through optimal planning of DG and capacitor banks. The PSO is modified by mutation and crossover operators to decrease the risk of catching in the local minima. They only considered real power losses in their research.

**Naveen Jain, S.N. Singh and S.C. Srivastava (2010) [47]** presented a method for optimal siting and sizing of multiple DGs using PSO by minimizing power loss while maintaining the voltage profile and stability margin. Their results showed that the method performed better or at least similar in comparison to other classical and analytical methods for the single DG placement problem. However, in the placement of the third DG it violated some of the constraints.

**I. Ziari *et al.* (2010) [48]** proposed methodology for optimal allocation and sizing of capacitors to minimize the transmission line loss and to improve the voltage profile. They presented a modified discrete PSO to find the optimal placement and size of capacitors in a distribution system. The results showed that the proposed methodology was more accurate and robust compared to pure DPSO, genetic algorithm, and nonlinear programming.

**A. Khanjanzadeh *et al.* (2011) [49]** examined the effects of location and capacity of a DG on increasing steady state voltage stability in radial distributed systems through PSO and finally compared the results to GA algorithm on the terms of speed, accuracy and convergence. The conclusion was that the response of the PSO method was more accurate than GA method and speed of convergence for PSO was superior too.

**K. Varesi (2011) [50]** proposed a PSO based technique for the optimal allocation of DG units in the power system to help in power loss reduction and voltage profile improvement. Load flow algorithm was combined appropriately with PSO to determine the optimal number, type, size and location of DG units. He only considered two types of DG units in his work.

**Mohammad M. and M. A. Nasab (2011) [51]** suggested a PSO based multi-objective approach for optimal sizing and placement of DG. A hybrid objective function was used which had two parts, in the first part the Power Loss Reduction Index was considered while in the second part Reliability Improvement Index was considered. The research considered active power losses only.

**P. Umapathi Reddy *et al.* (2011) [52]** presented a PSO based approach for loss reduction in unbalanced radial distribution system. They proposed an efficient algorithm for determining the location, type and size of capacitor bank to be installed in unbalanced radial distribution system. The power loss indices (PLI) analysis was used for capacitor placement problem and also presented a candidate bus identification method to determine the best locations for optimal capacitor placement. The PSO based approach was used to find the optimal sizing of the capacitor bank in unbalanced radial distribution systems.

**J. J. Jamian *et al.* (2012) [53]** implemented an Evolutionary PSO for sizing DGs to achieve power loss reduction. They argued that though EPSO and PSO give same performance in finding the optimal size of DG, EPSO can give superior results by having less iteration and shorter computation time. Besides that, EPSO avoids the problem of being trapped in a local minimum by selecting the survival particles to remain in the next iteration.

**Yustra, Mochamad Ashari and Adi Soeprijanto (2012) [54]** proposed a method based on Improved PSO (IPSO) for optimal DG allocation with the aim of reducing system losses. IPSO generated more optimal solution than PSO and SGA methods using active power losses reduction parameter. However, IPSO method needed more iterations to converge compared to the other two methods.

**M. Vatankhah and S.M. Hosseini (2012) [55]** proposed the use of new coding in PSO which included both active and reactive powers of DGs to achieve better profile improvement by optimizing the size and location of the DGs. In their proposed method, four set of weighing factors are chosen based on the importance and criticality of the different loads. Their results showed that the weighting factor had a considerable effect on voltage profile improvement.

**Arash Afraz *et al.* (2012) [56]** also proposed a PSO based approach to optimize the sizing and sitting of DGs in radial distribution systems with an objective of reducing line losses and improving voltage profile. The proposed objective function was a multi-objective one considering active and reactive power losses of the system and the voltage profile. In their research they considered a DG generating active power only.

**N. Mancor, B. Mahdad and K. Srairi (2012) [57]** proposed an efficient variant of PSO to solve the multi-objective optimal reactive power flow (ORPF) based flexible AC transmission system

(FACTS) using multi STATCOM controllers by adjusting dynamically their parameters setting. The two objectives function considered were power loss and voltage deviation.

**Mehdi Nafar (2012) [58]** proposed a PSO-based optimal placement of DGs in distribution systems considering voltage stability and short circuit level improvement. They investigated the voltage stability assessment with the consideration of uneven regional load growth pattern and economic dispatch of the online generation units, aiming at assessing the voltage stability margin of a power system for a given operating condition and network topology in more realistic manner.

**Somayeh Hajforoosh *et al.* (2012) [59]** implemented an aggregation-based PSO algorithm for optimal placement and sizing of static synchronous series compensator (SSSC) device to maximize social welfare. The proposed approach relied on particle swarm optimization to capture the near-optimal solutions, as well as the location and rating of SSSC while the Newton based load flow solution minimizes the mismatch equations. Simulation results of the proposed CAPSO algorithm were compared to solutions obtained by sequential quadratic programming (SQP) and Fuzzy based genetic algorithm (Fuzzy-GA).

**M. M. Aman *et al.* (2013) [60]** used Particle Swarm Optimization (PSO) algorithm for simultaneous finding of optimum DG and shunt capacitor bank location and size in power systems. The proposed algorithm was tested on 12-bus, 30-bus, 33-bus and 69-bus radial distribution networks. The result showed that the proposed methods had significantly reduced the power system losses as well as improving the overall loading factor.

**Nasim Ali Khan *et al.* (2013) [61]** presented a Novel Binary Particle Swarm Optimization (NBPSO) technique for improvement of total voltage profile and line loss minimization in power distribution system by incorporating optimal placement of shunt capacitors with constraints which include limits on voltage and sizes of installed capacitors. NBPSO acted as near global optimizer for determining the optimal sizing and siting of capacitors. Incorporating shunt capacitors in the distribution system reduced the total line power losses the total voltage deviation.

**M. Heydari *et al.* (2013) [62]** used discrete particle swarm optimization (DPSO) approach for the optimal placement and sizing of distributed generations and capacitors in distribution systems for simultaneous voltage profile improvement, loss and total harmonic distortion (THD) reduction. Their objective function had a term which prevented harmonic resonance between capacitor reactance and system reactance. Constraints included voltage limit, voltage THD, number/ size of capacitors and generators. The IEEE 33-bus test system was modified and employed in testing the proposed algorithm.

**Soroudi and Ehsan [9]** used Particle Swarm Optimization on a multi- load level to minimize the cost of active losses, investment and operation cost of DG and emission cost. SGA and PSO method was identified had a weakness. Both of methods had a great possibility to get stuck in local optimum solutions. This means that the solution resulting from the methods is not necessarily the most optimal one. The application of more advanced artificial intelligence method was proposed as a solution to overcome the problem.

### **2.1.3.3 Other Artificial Intelligence Based Optimization Techniques**

Other than GA and PSO, there are other artificial intelligence optimization techniques which have being utilized in optimizing the placement and sizing of DGs and capacitors in distribution networks. Some of these techniques include;

**M. Padma, N. Sinarami and V.C Veera (2010) [63]** presented a new methodology using Artificial Bee Colony algorithm (ABC) for the placement of DG in the radial distribution systems to reduce the real power losses and to improve the voltage profile. The results proved that the ABC algorithm is simple in nature than GA and PSO so it takes less computation time.

**M.A.Taghikhani (2012) [64]** proposed an approach for DG allocation and sizing in distribution network using modified Shuffled Frog Leaping Algorithm(SFLA) so as to maximize the system voltage profile and reduces line losses. Benefits of employing DG were analyzed using Voltage Profile Improvement Index (VPPI) and Line Loss Reduction Index (LLRI).

**Mohammad Karimi *et al.* (2012) [65]** suggested a methodology for solving optimal capacitor allocation problem using DE algorithm in practical distribution networks. Differential

Evolutionary (DE) algorithm was proposed to determine optimal location, size, and number of capacitor banks in the radial distribution networks.

**Mohammad Falahi Sohi and Morteza Shirdel (2012) [66]** optimized the problem of DG placement and sizing for loss reduction and line capacity improvement using the novel and heuristic BCO algorithm. This was incorporated with the forward-backward sweep power flow.

**Reza Khorram-Nia *et al.* (2013) [67]** proposed a new stochastic framework based on the probabilistic load flow to consider the uncertainty effects in the Distribution Static Compensator (DSTATCOM) allocation and sizing problem. The proposed method was based on the point estimate method (PEM) to capture the uncertainty associated with the forecast error of the loads. In order to explore the search space globally, a new optimization algorithm based on Bat Algorithm (BA) was proposed too.

**K. Valipour *et al.* (2013) [68]** presented a new approach based on Biogeography Based Optimization (BBO) algorithm for the simultaneous power quality improvement and optimal placement and sizing of capacitor banks and distributed generation (DGs) in the presence of voltage harmonic in radial distribution networks. The optimization aimed at minimizing the power losses and voltage profiles and THD improvement. Biogeography Based Optimization is a novel evolutionary algorithm that is based on the mathematics of biogeography.

**M. Abbagana, G. A. Bakare, and I. Mustapha [69]** also proposed a technique for optimal placement and sizing of a DG in a power distribution system using Differential Evolution (DE). In the optimization problem the DG sources were added to the network to mainly reduce the power losses and improve the voltage profile by supplying a net amount of power.

#### **2.1.3.4 Comparisons and Hybrid Based Optimization Techniques**

Researchers have come up with several hybrids incorporating different optimization techniques. The most common hybrids are those combining an artificial intelligence method to another artificial intelligence technique or to either an analytical or computational method. From the literature given here it is clear that most of the hybridization result to better solutions than either of the methods if considered separately.

**L. Grant, G. K. Venayagamoorthy and G. Krost (2008) [70]** presented a comparison of swarm intelligence and evolutionary techniques based approaches for minimization of system losses and improvement of voltage profile in a power system. They showed that by averaging the results over a multitude of trial runs, PSO indeed outperforms the DE (Differential Evolution) approach on the problem when comparing power loss reduction and number of iterations required. Their results also showed that MPSO allowed for further reduction of the real power losses while maintaining a satisfactory voltage profile.

**R. Srinivasa Rao (2010) [71]** proposed an hybrid approach which combined network configuration and capacitor placement using Harmony Search Algorithm (HSA) to minimize power loss and improve voltage profile. Their results were observed to be superior to those for network configuration or capacitor control. The use of capacitor control is not effective for heavy active loads while the network reconfiguration cannot effectively reduce the power losses caused by reactive power flow.

**K.V.S. Ramachandra Murthy *et al.* (2010) [72]** did a comparison between Conventional methods, GA and PSO with respect to optimal capacitor placement in agricultural distribution system for loss reduction and voltage profile improvement. PSO method gave better results than GA whose results were better compared to results obtained using convectional techniques.

**P. Subbaraj and P. N. Rajnarayanan (2010) [73]** proposed a two-phase hybrid particle swarm optimization (PSO) based approach to solve optimal reactive power dispatch (ORPD) problem. In their hybrid approach, PSO was used to explore the optimal region and direct search was used as local optimization technique for finer convergence. The performance of the proposed hybrid approach was demonstrated with the IEEE 30-bus and IEEE 57-bus systems. The test results showed that, the proposed approach not only improved the solution quality but reduced the computation time also.

**O. Amanifar and M.E Hamedani Golshan (2011) [74]**, used Particle Swarm Optimization Method and sensitivity analysis to optimally place and size DG for loss and THD reduction and voltage profile improvement. First, a radial distribution power flow algorithm is executed to find the global optimal solution. Then, with respect to voltage profile, THD and loss reduction and by using the sensitivity analysis, PSO was used to calculate the objective function and to verify bus

voltage limits. To include the presence of harmonics, PSO was integrated with harmonic power flow (HPF). The research considered a DG generating real power only.

**S. Chandrashekhara Reddy *et al.* (2012) [10]**, proposed a hybrid technique which includes genetic algorithm (GA) and neural network (NN) for identification of possible locations for fixing DGs and the amount of power to be generated by the DG to achieve power quality improvement. They argued that by fixing DGs at suitable locations and evaluating generating power based on the load conditions, the power quality of a system can be improved. In this work only real power loss was considered.

**M. Abedini and H. Saremi (2012) [75]** presented a combination of GA and PSO for optimal DG location and sizing in distribution systems with load uncertainty. The combined method was implemented for the 52 bus system to minimize real power losses and increase voltage stability. The proposed method was found to produce better results compared to either of the two methods. They only considered active power losses. They also optimized the location and size of a DG generating active power only.

**Hamed Piarehzadeh, Amir Khanjanzadeh and Reza Pejmanfer (2012) [76]** presented a comparison of harmony search algorithm and PSO for DG allocation to improve steady state voltage stability of distribution networks. By comparing the results to PSO results (Khanjanzadeh *et al.*, 2011) it was concluded that using Harmony Search Algorithm was more acceptable.

**H. Musa and S.S. Adamu (2013) [77]** presented a new application of hybridized PSO for optimal allocation of single and multiple Distributed Generation (DG) units in distribution network. The proposed algorithm called Ranked Evolutionary Particle swarm optimization (REPSO) combines PSO with Evolutionary programming Optimization methods to simultaneously place and size DG units in radial distribution network. The performance of the proposed method showed significant reduction in power losses, improved voltage profile of the network and effectiveness in the search for optimal solutions.

**B. Bhattacharyya, S.K. Goswami and R.C. Bansal [78]** presented a new approach for optimizing reactive power planning based on fuzzy logic and particle swarm optimization (PSO). The objectives were to minimize real power loss and to improve the voltage profile of a given

interconnected power system.. The proposed hybrid fuzzy PSO technique was observed to be more superior compared to simple DE, GA and PSO techniques.

**Celli *et al.* [79a]** proposed the use of Hybrid and Constraint Based Multi Objective Programming (HCBMOP) and GA method to minimize the cost of network upgrading, power losses and energy required by customer. He later used the method to minimize the cost of network upgrading, cost of energy losses and DG network acceptability index with the DG fully considered as a valid planning alternative.

**Celli *et al.* [79b]** later used the method proposed in [79a] for a peak load with constant growth rate and a constant power source to minimize the cost of losses and to improve voltage quality and harmonic distortions.

**Kamalnia *et al.* [80]** used GA and MAMD approach on a PQ model DG to investigate its technical attributes such as reactive power flows, voltage variation and active loss as well as the economic attributes which include line congestion, capital cost and emission.

## **1.6 Statement of the Problem**

As mentioned earlier, the major factors behind the increasing trend in DG utilization include: electricity market liberalization, development in DG technology, constraints on the construction of new transmission lines, reliability enhancement and concerns about environmental aspects. In liberalized electricity markets, there is an incentive for distribution companies (DISCOs) to reduce the loss of distribution systems. This is because only a fixed percent of their losses are compensated so loss reduction increases their profit. Some restrictions on environmental pollutions may force the DISCOs to use green power or less pollutant technologies.

The optimal allocation of Distributed Generation (DG) with loss minimization and voltage profile improvement as the key objectives has been an important aspect of DGs connected to electrical networks. As can be seen from the literature review the traditional analytical methods for optimizing DG allocation are being phased out by the upcoming artificial intelligence methods. This is because the analytical methods are majorly gradient based and have a disadvantage of being trapped in a local minimum.



In this research, two artificial intelligence optimization techniques, that is, GA and PSO algorithms are combined so as to come up with a more superior algorithm for this purpose. The hybrid technique aims at inheriting the good traits from the two techniques while avoiding the undesirable ones. Inertia weight ( $w$ ) which is added to the normal PSO algorithm as a way of overcoming the weakness of being trapped in local optimum solutions is also studied in detail. Some GA operators, that is, crossover and mutation are incorporated in the PSO algorithm so as to help in coming up with more superior particles as well as discarding the inferior ones.

Both real and reactive power flow and power loss sensitivity factors are used in identifying the candidate buses for DG allocation. This helps in reducing the search space for the algorithm thus reducing the iteration time.

In modern practical power systems reactive power injection plays a critical role in voltage stability control, thus the reactive power losses need to be incorporated in optimizing DG allocation for voltage profile improvement. As a result this research considers both real and reactive power losses in solving the problem at hand.

In addition, the research considers the optimization of location and size of a multi-type DG. The multi-type DG is assumed to be operating in any of the following three conditions:

1. DG injecting only active power. In this research, the DG is referred to as Type 1 DG.
2. DG injecting both active and reactive power. In this research, the DG is referred to as Type 2 DG.
3. DG injecting active power and absorbing reactive power. In this research, the DG is referred to as Type 3 DG.

To the best of my knowledge, no evidence exists in open literature on combined sensitivity factor based GA-IPSO hybridization technique which considers both active and reactive power losses when locating and sizing DGs. It is this gap that this research work aims to fill. The problem, as treated in this study, may be subdivided into, four main parts:

- (i) Formulation of combined sensitivity factors - This involves the combination of both power flow and power loss sensitivity factors so as to utilize them in choosing the candidate DG locations.

- (ii) Study of both GA and PSO techniques and their respective parameters – Here the study of crossover and mutation for GA and weight factor for PSO is done in detail giving their most suitable values.
- (iii) Hybridization of GA and PSO for DG placement and sizing – In this section a hybrid technique is developed incorporating both GA and PSO techniques so as to solve the problem at hand.
- (iv) Testing and analysis of the hybrid algorithm – Three test bus systems are employed (30 bus, 33 bus and 57 bus systems). The results obtained are analyzed and compared to results obtained by other researchers.

## **1.7 Objectives**

So as to achieve the objective of reducing system losses and improving voltage profile by optimal placement and sizing of distributed generation (DG), the following problems were addressed;

1. To utilize both real and reactive power flow and power loss sensitivity factors in reducing the algorithms search space.
2. To formulate a multi-objective function taking into consideration real power loss reduction index (PLRI), reactive power loss reduction index (QLRI) and voltage profile improvement index (VPII).
3. To design a hybrid approach for optimizing DG location and size in a distribution system. The hybrid algorithm will combine both GA and PSO optimization technique features.
4. To test the hybrid algorithm considering the three types of DGs mentioned above and compare the results with those obtained by other researchers using different optimization methods.
5. To investigate the effect of DG penetration on system power losses and voltage profiles using the three types of DGs.

## **1.8 Organization of the Thesis**

This thesis research work is organized into six chapters. Chapter one is on introduction. Here the distribution systems are introduced in general. The system power loss reduction phenomenon and the voltage profile improvement aspect are discussed in this chapter. Distributed Generation

and its effects are also explained satisfactorily here. This chapter also covers the previous works done by researchers and its gaps/deficiencies. Then the problem to be solved by this research work is stated clearly here.

Chapter two covers mainly the implementation of different formulations to help in solving the problem stated. Here the combined sensitivity factors are described and formulated. The multi-objective function and the operational constraints are also formulated in this chapter. In Chapter three the details on the choice of optimization techniques and the reasons behind their selection is analyzed. Each of the chosen optimization techniques is then studied in detail giving its parameters, implementation steps and flow charts.

Chapter four deal with the hybridization of the already chosen optimization techniques. The adopted selection, crossover and mutation methods for this research are described. The steps of the proposed algorithm and its flowchart are detailed in this chapter. In chapter five the results obtained are presented and analyzed in terms of tables and graphs. A detailed discussion about the obtained results is also given on this chapter.

Chapter six covers the conclusions made from the results obtained, the beneficiaries of this research work and the recommendations made for furthering this research work. After chapter six a list of the research papers published in international journals from this work is also given.

## CHAPTER 2: SENSITIVITY FACTORS AND MULTI-OBJECTIVE FUNCTION

### 2.1 Introduction

This chapter deals with the formulations of the system sensitivity factors and the multi-objective function. The constraints to which the multi-objective function is subjected to are also defined here. Generally, both real and reactive power flow and power loss sensitivity factors are formulated using the full Newton-Raphson load flow Jacobian matrix while the multi-objective function is formulated taking into consideration the three key factors, that is, real power loss reduction, reactive power loss reduction and voltage profile improvement. Both equality and inequality constraints are defined.

### 2.2 System Power Flow Sensitivity Factors

System power flow sensitivity is the change in power flow in a transmission or distribution line connected between two buses say bus  $i$  and bus  $j$  due to unit change in the power injected at any bus in the system.

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

$$S_i = P_i + jQ_i = V_i J_i^* ; i = 1, 2, \dots, n \quad (2.1)$$

Where;

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

$J_i$  is the source current injected into the bus

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

$$S_i^* = P_i - jQ_i = V_i^* J_i ; i = 1, 2, \dots, n \quad (2.2)$$

The source current is given by;

$$J_i = \sum_{j=1}^n Y_{ij} V_j ; i = 1, 2, \dots, n \quad (2.3)$$

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

$$P_i - jQ_i = V_i^* \sum_{j=1}^n Y_{ij} V_j ; i = 1, 2, \dots, n \quad (2.4)$$

Equating real and imaginary parts of the above equation we get:

$$P_i = Re\{V_i^* \sum_{j=1}^n Y_{ij} V_j\} \quad (2.5a)$$

$$Q_i = -Im\{V_i^* \sum_{j=1}^n Y_{ij} V_j\} \quad (2.5b)$$

In polar form  $V_i$  and  $Y_{ij}$  can be expressed as:

$$V_i = |V_i| e^{j\delta_i} \quad (2.6)$$

$$Y_{ij} = |Y_{ij}| e^{j\theta_{ij}} \quad (2.7)$$

From the polar representations given above the real and reactive powers can be expressed in general as shown;

$$P_i = |V_i| \sum_{j=1}^n |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_{ij}); i = 1, 2, \dots, n \quad (2.8a)$$

$$Q_i = -|V_i| \sum_{j=1}^n |V_j| |Y_{ij}| \sin(\theta_{ij} + \delta_{ij}); i = 1, 2, \dots, n \quad (2.8b)$$

### 2.2.1 Change in Real Power Flow Analysis.

The real power flow in a line  $k$  connecting two buses, bus  $i$  and bus  $j$  can be expressed as:

$$P_{ij} = V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_{ij}) - V_i^2 Y_{ij} \cos\theta_{ij} \quad (2.9)$$

Where;

$V_i$  and  $V_j$  are the voltage magnitudes at buses  $i$  and  $j$  respectively

$\delta_i$  and  $\delta_j$  are the voltage angles at buses  $i$  and  $j$  respectively

$Y_{ij}$  is magnitude of the  $ij^{th}$  element of the  $Y_{BUS}$  matrix

$\theta_{ij}$  is the angle of the  $ij^{th}$  element of the  $Y_{BUS}$  matrix

Mathematically, the real power flow sensitivity can be written as:

$$\begin{bmatrix} \Delta P_{ij} \\ \Delta P_n \\ \Delta Q_{ij} \\ \Delta Q_n \end{bmatrix} \quad (2.10)$$

Using Taylor series approximation while ignoring second and higher order terms the change in real line flow can be expressed as:

$$\Delta P_{ij} = \frac{\partial P_{ij}}{\partial \delta_i} \Delta \delta_i + \frac{\partial P_{ij}}{\partial \delta_j} \Delta \delta_j + \frac{\partial P_{ij}}{\partial V_i} \Delta V_i + \frac{\partial P_{ij}}{\partial V_j} \Delta V_j \quad (2.11)$$

The coefficients appearing in the above equation can be obtained using the partial derivatives of real power flow with respect to variables  $\delta$  and  $V$  as shown below:

$$\frac{\partial P_{ij}}{\partial \delta_i} = V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_{ij}) \quad (2.12a)$$

$$\frac{\partial P_{ij}}{\partial \delta_j} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_{ij}) \quad (2.12b)$$

$$\frac{\partial P_{ij}}{\partial V_i} = V_j Y_{ij} \cos(\theta_{ij} + \delta_{ij}) - 2V_i Y_{ij} \cos \theta_{ij} \quad (2.12c)$$

$$\frac{\partial P_{ij}}{\partial V_j} = V_i Y_{ij} \cos(\theta_{ij} + \delta_{ij}) \quad (2.12d)$$

### 2.2.2 Change in Reactive Power Flow Analysis.

The reactive power flow in a line  $k$  connecting two buses, bus  $i$  and bus  $j$  can be expressed as:

$$Q_{ij} = -V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_{ij}) + V_i^2 Y_{ij} \sin \theta_{ij} - \frac{V_i^2 Y_{sh}}{2} \quad (2.13)$$

Where;

$V_i$  and  $V_j$  are the voltage magnitudes at buses  $i$  and  $j$  respectively

$\delta_i$  and  $\delta_j$  are the voltage angles at buses  $i$  and  $j$  respectively

$Y_{ij}$  is magnitude of the  $ij^{th}$  element of the  $Y_{Bus}$  matrix

$\theta_{ij}$  is the angle of the  $ij^{th}$  element of the  $Y_{Bus}$  matrix

$Y_{sh}$  is the shunt charging admittance of line  $k$ .

Mathematically, the reactive power flow sensitivity can be written as:

$$\begin{bmatrix} \Delta Q_{ij} \\ \Delta P_n \\ \Delta Q_{ij} \\ \Delta Q_n \end{bmatrix} \quad (2.14)$$

Using Taylor series approximation while ignoring second and higher order terms the change in reactive line flow can be expressed as:

$$\Delta Q_{ij} = \frac{\partial Q_{ij}}{\partial \delta_i} \Delta \delta_i + \frac{\partial Q_{ij}}{\partial \delta_j} \Delta \delta_j + \frac{\partial Q_{ij}}{\partial V_i} \Delta V_i + \frac{\partial Q_{ij}}{\partial V_j} \Delta V_j \quad (2.15)$$

The coefficients appearing in the above equation can be obtained using the partial derivatives of reactive power flow with respect to variables  $\delta$  and  $V$  as shown;

$$\frac{\partial Q_{ij}}{\partial \delta_i} = V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_{ij}) \quad (2.16a)$$

$$\frac{\partial Q_{ij}}{\partial \delta_j} = -V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_{ij}) \quad (2.16b)$$

$$\frac{\partial Q_{ij}}{\partial V_i} = -V_j Y_{ij} \sin(\theta_{ij} + \delta_{ij}) + 2V_i Y_{ij} \cos\theta_{ij} - V_i Y_{sh} \quad (2.16c)$$

$$\frac{\partial Q_{ij}}{\partial V_j} = -V_i Y_{ij} \sin(\theta_{ij} + \delta_{ij}) \quad (2.16d)$$

### 2.2.3 Formulating the Power Flow Sensitivity Factors

The real power flow sensitivity factors represent the change in the real power flow over a transmission or distribution line connected between bus- $i$  and bus- $j$  due to the change in active power injected at any other bus- $n$  while the reactive power flow sensitivity factors represent the change in the reactive power flow over a transmission or distribution line connected between bus- $i$  and bus- $j$  due to the change in reactive power injected at any other bus- $n$ . The equations for the changes in the line flows can be arranged in matrix form and expressed as;

$$\begin{bmatrix} \Delta P_{ij} \\ \Delta Q_{ij} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} & \frac{\partial P_{ij}}{\partial V} \\ \frac{\partial Q_{ij}}{\partial \delta} & \frac{\partial Q_{ij}}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (2.17)$$

The variables  $\Delta \delta$  and  $\Delta V$  can be obtained from load flow solution using Newton Raphson technique as follows;

The full N-R load flow Jacobian matrix is expressed as;

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (2.18)$$

Thus from this equation the variables  $\Delta \delta$  and  $\Delta V$  can be obtained:

$$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (2.19)$$

Now substituting the obtained equation for  $\Delta \delta$  and  $\Delta V$  in the equation for the change in line flows we have:

$$\begin{bmatrix} \Delta P_{ij} \\ \Delta Q_{ij} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} & \frac{\partial P_{ij}}{\partial V} \\ \frac{\partial Q_{ij}}{\partial \delta} & \frac{\partial Q_{ij}}{\partial V} \end{bmatrix} [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (2.20)$$

The above equation gives the change in both real and reactive power flow and thus using this equation the real and reactive power flow sensitivity factors can be determined as given in Appendix A.

The real power flow sensitivity factors are represented as;

$$\begin{bmatrix} \frac{\partial P_{ij}}{\partial P_n} \\ \frac{\partial P_{ij}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} F_{P-P} \\ F_{P-Q} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} \\ \frac{\partial P_{ij}}{\partial V} \end{bmatrix} \quad (2.21a)$$

The reactive power flow sensitivity factors are represented as;

$$\begin{bmatrix} \frac{\partial Q_{ij}}{\partial P_n} \\ \frac{\partial Q_{ij}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} F_{Q-P} \\ F_{Q-Q} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial Q_{ij}}{\partial \delta} \\ \frac{\partial Q_{ij}}{\partial V} \end{bmatrix} \quad (2.21b)$$

Where;

$F_{P-P}$  is the real power flow sensitivity related to the real power injection.

$F_{P-Q}$  is the active flow sensitivity related to the reactive power injection.

$F_{Q-P}$  is the reactive power flow sensitivity related to the active power injection.

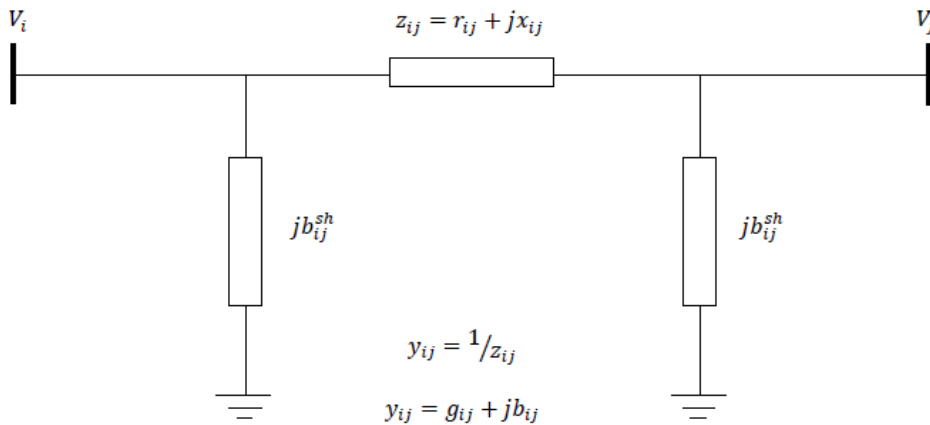
$F_{Q-Q}$  is the reactive power flow sensitivity related to the reactive power injection.

$J$  is the Jacobian matrix of power flow, and the superscript  $T$  indicates the transpose.

Here the four sensitivities are column vectors with dimension of number of the system busses.

### 2.3 System Power Loss Sensitivity Factors

From the circuit diagram shown below both real and reactive power loss sensitivity factors can be calculated.



**Figure 2.1:** Circuit diagram of a line lumped model



### 2.3.1 Change in Real Power Loss Analysis.

The active power loss of the line lumped model shown in the line-(*pie*) circuit is given by;

$$P_{L(ij)} = g_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}) \quad (2.22)$$

Thus the total active power loss in the circuit can be expressed as;

$$P_{L(total)} = \sum_{l=1}^{nL} [g_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij})] \quad (2.23)$$

Where;

$nL$  is the number of lines of the network;

$g_{ij}$  is the conductance of the line i-j

$V_i$  is the nodal voltage of bus i

$V_j$  is the nodal voltage of bus j

$\delta_{ij}$  is the phase angle difference between the busses i and j.

Mathematically, the real power loss sensitivity can be written as:

$$\begin{bmatrix} \frac{\Delta P_{L(ij)}}{\Delta P_n} \\ \frac{\Delta P_{L(ij)}}{\Delta Q_n} \end{bmatrix} \quad (2.24)$$

Using Taylor series approximation while ignoring second and higher order terms the change in real power loss can be expressed as:

$$\Delta P_{L(ij)} = \frac{\partial P_{L(ij)}}{\partial \delta_i} \Delta \delta_i + \frac{\partial P_{L(ij)}}{\partial \delta_j} \Delta \delta_j + \frac{\partial P_{L(ij)}}{\partial V_i} \Delta V_i + \frac{\partial P_{L(ij)}}{\partial V_j} \Delta V_j \quad (2.25)$$

The coefficients appearing in the above equation can be obtained using the partial derivatives of real power loss with respect to variables  $\delta$  and  $V$  as shown below:

$$\frac{\partial P_{L(ij)}}{\partial \delta_i} = 2g_{ij}V_iV_j\sin \delta_{ij} \quad (2.26a)$$

$$\frac{\partial P_{L(ij)}}{\partial \delta_j} = -2g_{ij}V_iV_j\sin \delta_{ij} \quad (2.26b)$$

$$\begin{aligned} \frac{\partial P_{L(ij)}}{\partial V_i} &= g_{ij}(2V_i - 2V_j\cos \delta_{ij}) \\ &= 2g_{ij}(V_i - V_j\cos \delta_{ij}) \end{aligned} \quad (2.26c)$$

$$\begin{aligned} \frac{\partial P_{L(ij)}}{\partial V_j} &= g_{ij}(2V_j - 2V_i\cos \delta_{ij}) \\ &= 2g_{ij}(V_j - V_i\cos \delta_{ij}) \end{aligned} \quad (2.26d)$$

### 2.3.2 Change in Reactive Power Loss Analysis.

The reactive power loss in a line  $l$  connecting two buses, bus  $i$  and bus  $j$  can be expressed as:

$$Q_{L(total)} = \sum_{l=1}^{nL} [-b_{ij}^{sh}(V_i^2 + V_j^2) - b_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij})] \quad (2.27)$$

Where;

$nL$  is the number of lines of the network;

$b_{ij}^{sh}$  is the shunt susceptance of the line  $i-j$

$b_{ij}$  is the susceptance of the line  $i-j$

$V_i$  is the nodal voltage of bus  $i$

$V_j$  is the nodal voltage of bus  $j$

$\delta_{ij}$  is the phase angle difference between the busses  $i$  and  $j$ .

Mathematically, the reactive power loss sensitivity can be written as:

$$\begin{bmatrix} \frac{\Delta Q_{L(ij)}}{\Delta P_n} \\ \frac{\Delta Q_{L(ij)}}{\Delta Q_n} \end{bmatrix} \quad (2.28)$$

Using Taylor series approximation while ignoring second and higher order terms the change in reactive power loss can be expressed as:

$$\Delta Q_{L(ij)} = \frac{\partial Q_{L(ij)}}{\partial \delta_i} \Delta \delta_i + \frac{\partial Q_{L(ij)}}{\partial \delta_j} \Delta \delta_j + \frac{\partial Q_{L(ij)}}{\partial v_i} \Delta V_i + \frac{\partial Q_{L(ij)}}{\partial v_j} \Delta V_j \quad (2.29)$$

The coefficients appearing in the above equation can be obtained using the partial derivatives of reactive power loss with respect to variables  $\delta$  and  $V$  as shown below

$$\frac{\partial Q_{L(ij)}}{\partial \delta_i} = -2b_{ij}V_iV_j\sin \delta_{ij} \quad (2.30a)$$

$$\frac{\partial Q_{L(ij)}}{\partial \delta_j} = 2b_{ij}V_iV_j\sin \delta_{ij} \quad (2.30b)$$

$$\begin{aligned} \frac{\partial Q_{L(ij)}}{\partial v_i} &= -2b_{ij}^{sh}V_i - b_{ij}(2V_i - 2V_j\cos \delta_{ij}) \\ &= -2[b_{ij}^{sh}V_i + b_{ij}(V_i - V_j\cos \delta_{ij})] \end{aligned} \quad (2.30c)$$

$$\begin{aligned} \frac{\partial Q_{L(ij)}}{\partial v_j} &= -2b_{ij}^{sh}V_j - b_{ij}(2V_j - 2V_i\cos \delta_{ij}) \\ &= -2[b_{ij}^{sh}V_j + b_{ij}(V_j - V_i\cos \delta_{ij})] \end{aligned} \quad (2.30d)$$

### 2.3.3 Formulating the Power Loss Sensitivity Factors

The real power loss sensitivity factors represent the change in the real power loss over a transmission or distribution line connected between bus- $i$  and bus- $j$  due to the change in active power or reactive power injected at any other bus- $n$  while the reactive power loss sensitivity factors represent the change in the reactive power loss over a transmission or distribution line connected between bus- $i$  and bus- $j$  due to the change in reactive power or real power injected at any other bus- $n$ . The equations for the changes in the line flows can be arranged in matrix form and expressed as;

$$\begin{bmatrix} \Delta P_{L(ij)} \\ \Delta Q_{L(ij)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} & \frac{\partial P_{L(ij)}}{\partial V} \\ \frac{\partial Q_{L(ij)}}{\partial \delta} & \frac{\partial Q_{L(ij)}}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (2.31)$$

The variables  $\Delta \delta$  and  $\Delta V$  can be obtained from load flow solution using Newton Raphson technique as follows; from the full N-R load flow Jacobian matrix:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (2.32)$$

We can have;

$$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (2.33)$$

Now substituting the obtained equation for  $\Delta \delta$  and  $\Delta V$  in the equation for the change power losses we have:

$$\begin{bmatrix} \Delta P_{L(ij)} \\ \Delta Q_{L(ij)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} & \frac{\partial P_{L(ij)}}{\partial V} \\ \frac{\partial Q_{L(ij)}}{\partial \delta} & \frac{\partial Q_{L(ij)}}{\partial V} \end{bmatrix} [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (2.34)$$

From this equation the real and reactive power loss sensitivity factors are obtained as shown in Appendix B.

Now the real power loss sensitivity factors are represented by;

$$\begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial P_n} \\ \frac{\partial P_{L(ij)}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} S_{P-P} \\ S_{P-Q} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} \\ \frac{\partial P_{L(ij)}}{\partial V} \end{bmatrix} \quad (2.35a)$$

The reactive power loss sensitivity factors are expressed as;

$$\begin{bmatrix} \frac{\partial Q_L(ij)}{\partial P_n} \\ \frac{\partial Q_L(ij)}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} S_{Q-P} \\ S_{Q-Q} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial Q_L(ij)}{\partial \delta} \\ \frac{\partial Q_L(ij)}{\partial V} \end{bmatrix} \quad (2.35b)$$

Where;

$S_{P-P}$  is the real power loss sensitivity related to the real power injection.

$S_{P-Q}$  is the active loss sensitivity related to the reactive power injection.

$S_{Q-P}$  is the reactive power loss sensitivity related to the active power injection.

$S_{Q-Q}$  is the reactive power loss sensitivity related to the reactive power injection.

$J$  is the Jacobian matrix of power flow, and the superscript  $T$  indicates the transpose.

Here the four sensitivities are column vectors with dimension of number of the system busses.

## 2.4 Objective Function Parameters

The multi-objective index for the performance calculation of distribution systems for DG size and location planning with load models considers the below mentioned indices by giving a weight to each index.

### 2.4.1 Real Power Loss Reduction Index

A common strategy for sizing and placement of DG is to minimize system power loss of the power system. Real Power Loss Reduction Factor Index per node is defined as the ratio of percentage reduction in real power loss from base case when a DG is installed at bus  $i$ . Real Power Loss Reduction Index (PLRI) is expressed as:

$$PLRI = \frac{P_{L(base)} - P_{L(DGi)}}{P_{L(base)}} \quad (2.36)$$

Where,

$P_{L(base)}$  is the active power loss before DG installation

$P_{L(DGi)}$  is the real power loss in study system after installation of DG

### 2.4.2 Reactive Power Loss Reduction Index

In order to determine the effect of DG in reactive power losses, Reactive Power Loss Reduction Factor Index is incorporated in the objective function. This refers to the ratio of percentage

reduction in reactive power loss from base case when a DG is installed at bus i. Reactive Power Loss Reduction Index (QLRI) is expressed as;

$$QLRI = \frac{Q_{L(base)} - Q_{L(DGi)}}{Q_{L(base)}} \quad (2.37)$$

Where,

$Q_{L(base)}$  is the reactive power loss before DG installation

$Q_{L(DGi)}$  is the reactive power loss in study system after installation of DG

### 2.4.3 Voltage Profile Improvement Index

In a power system the voltage at each bus should be within the acceptable range and the line flows within the limits. These limits are important so that integration of DG into the system does not increase the cost for voltage control or replacement of existing lines. The Voltage Profile Improvement Index penalizes the size-location pair which gives higher voltage deviations from the base voltage. The Voltage Profile Improvement Index (VPII) is defined as;

$$VPII = \frac{1}{\lambda + \max_{i=2}^n (|1 - V_{(DGi)}|)} \quad (2.38)$$

Where,

$V_{(DGi)}$  is the voltage value after DG installation.

$\lambda$  is a scalar value.

### 2.4.4 Multi-objective Function Formulation

In order to achieve the performance calculation of distributed systems for DG size and location the Multi-Objective Function (MOF) is given by;

$$MOF = w_1 PLRI + w_2 QLRI + w_3 VPII \quad (2.39)$$

Where;

$w_1$ ,  $w_2$  and  $w_3$  are the respective weights assigned to each factor.

The sum of the absolute values of the weights assigned to all the impacts should add up to one.

That is;

$$|w_1| + |w_2| + |w_3| = 1 \quad (2.40)$$

These weights are indicated to give the corresponding importance to each impact indices for penetration of DG with load models and depend on the required analysis. The weights vary

according to engineer's concerns. The index whose impact outperforms the others in terms of importance and benefits is given a larger weight and vice versa.

## 2.5 Operational Constraints Formulation

The above formulated multi-objective function is minimized subject to various operational constraints so as satisfy the electrical requirements for the distribution network.

### 2.5.1 Load balance constraint

For each bus, the following load regulations should be satisfied;

$$P_{gni} - P_{dni} - V_{ni} \sum_{j=1}^N V_{nj} Y_{nj} \cos(\delta_{ni} - \delta_{nj} - \theta_{nj}) = 0 \quad (2.41a)$$

$$Q_{gni} - Q_{dni} - V_{ni} \sum_{j=1}^N V_{nj} Y_{nj} \sin(\delta_{ni} - \delta_{nj} - \theta_{nj}) = 0 \quad (2.41b)$$

Where;

$$n_i = 1, 2, \dots, n_n$$

### 2.5.2 Power Generation Limit

This includes the upper and lower real and reactive power generation limit of generators and other reactive sources at bus-i.

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}, i = 1, 2, \dots, N_g \quad (2.42a)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}, i = 1, 2, \dots, N_g \quad (2.42b)$$

Where;

$P_{gi}^{min}$  and  $P_{gi}^{max}$  are the minimum and maximum real power generation limits

$Q_{gi}^{min}$  and  $Q_{gi}^{max}$  are the minimum and maximum reactive power generation limits.

### 2.5.3 Voltage Limit

This includes the upper and lower voltage magnitude limit,  $V_i^{min}$  and  $V_i^{max}$  at bus-i. Practically, the generator voltage will be the load/bus voltage plus some values related to impedance of the

line and the power flows along the line. The voltage must be kept within standard limits at each bus.

$$V_i^{min} \leq V_i \leq V_i^{max}, i = 1, 2, \dots N_b \quad (2.43)$$

Where;

$V_i^{min}$  and  $V_i^{max}$  are the minimum and maximum voltage limits.

#### 2.5.4 DG Power Generation Limit

This includes the upper and lower real and reactive power generation limits of distributed generators (DGs) connected at bus-i.

$$P_{DGi}^{min} \leq P_{DGi} \leq P_{DGi}^{max}, i = 1, 2, \dots N_{DG} \quad (2.44a)$$

$$Q_{DGi}^{min} \leq Q_{DGi} \leq Q_{DGi}^{max}, i = 1, 2, \dots N_{DG} \quad (2.44b)$$

Where;

$P_{DGi}^{min}$  and  $P_{DGi}^{max}$  are the minimum and maximum real power generation limit of distributed generators.

$Q_{DGi}^{min}$  and  $Q_{DGi}^{max}$  are the minimum and maximum reactive power generation limits of distributed generators.

## 2.6 Summary

In this chapter both system power flow sensitivity factors and system power loss sensitivity factors have been formulated to be used in getting the combined sensitivity factors. The combined sensitivity factors will be used to get the candidate busses for DG allocation. The multi-objective function to be used in calculating fitness for solutions during optimization has also been formulated in this chapter. The chapter ends by defining the systems operational constraints.

## CHAPTER 3: THEORY OF GA AND PSO TECHNIQUES

### 3.1 Choice of Optimization Techniques

There are different optimization techniques which can be used in optimizing the location and size of DG(s) in a distribution power system so as to ensure reduced system power losses and improved voltage profile. With this in mind there is need to come up with the most effective optimization techniques so that reliable results are obtained. In this research the work of Shulka *et al.* (2010) [4] was a key one in selecting Genetic algorithm as one of these techniques. This work presents GA as a technique which has the ability to search a vast area and come up with reliable results. This is because as stated bad solutions do not affect GA's end solution negatively since they are discarded as the iterations progress. On the other hand the work by Yustra *et al.* (2012) [54] formed a key basis in choosing PSO as the other optimization technique. In this work the strengths of PSO as an optimization technique and its flexibility to absorb other parameters for improvement are clearly presented. Thus as a result GA was selected to be used in the initial stages for exploration purposes and then a PSO improved by incorporating crossover and mutation parameters was selected to be used later for exploitation purposes. Given these strengths for the two optimization techniques the hybridization was deemed to give excellent results.

### 3.2 Genetic Algorithm

Genetic Algorithm simulates the biological processes that allows the consecutive generations in a population to adapt to their environment. Genetic Algorithms are unconstrained optimization methods, which model the evolutionary adaptation in nature. The Genetic Algorithm initiates the mechanism of the natural selection and evolution and aims to solve an optimization problem with objective function  $f(x)$ .

Where;

$x = x_1, x_2, \dots, x_N$  is the N-dimensional vector of optimization parameters.

Genes and chromosomes are the basic building blocks of the GA. The conventional standard GA (SGA) encodes the optimization parameters into binary code string. A gene in SGA is a binary code. A chromosome is a concatenation of genes that takes the form;



$$\text{Chromosome} = [g_1^1 g_2^1 \dots g_{L_1}^1, g_1^2 g_2^2 \dots g_{L_2}^2, \dots, g_1^N g_2^N \dots g_{L_N}^N] = [x_1 x_2 \dots x_N]$$

Where;

$g_j^i$  is a gene.

$L_i$  is the length of the code string of the  $i^{\text{th}}$  optimization parameter

$$x_k = [g_1^k g_2^k \dots g_{L_k}^k]$$

In depth description of the method is not provided here as GA has been applied in several problems and excellent texts [4, 10, 37-42, 81, 82]. GA is one of the effective parameter search techniques which are considered when conventional techniques have not achieved the desired speed, accuracy or efficiency. GA is different from conventional optimization and search procedures in the following ways.

1. GA usually works with coding of parameters rather than the parameters themselves.
2. This technique searches from a population of points rather than a single point.
3. It uses only objective functions rather than additional information such as their derivatives.
4. GA use probabilistic transition rules, and not deterministic rules.

The following are some of the advantages of GA.

1. They require no knowledge of gradient information about the response surface.
2. They are resistant to becoming trapped in local optima therefore can be employed for a wide variety of optimization problems.
3. It can quickly scan a vast solution set.
4. Bad proposals do not affect the end solution negatively as they are simply discarded.
5. It doesn't have to know any rules of the problem - it works by its own internal rules.

For the advantages of parallel searching, robust searching, and searching mechanism based on the principle of natural evolution, genetic algorithm has found applications in many areas and has become one of the most successful optimization algorithms. Figure 3.1 gives the flowchart representation for a basic GA algorithm.

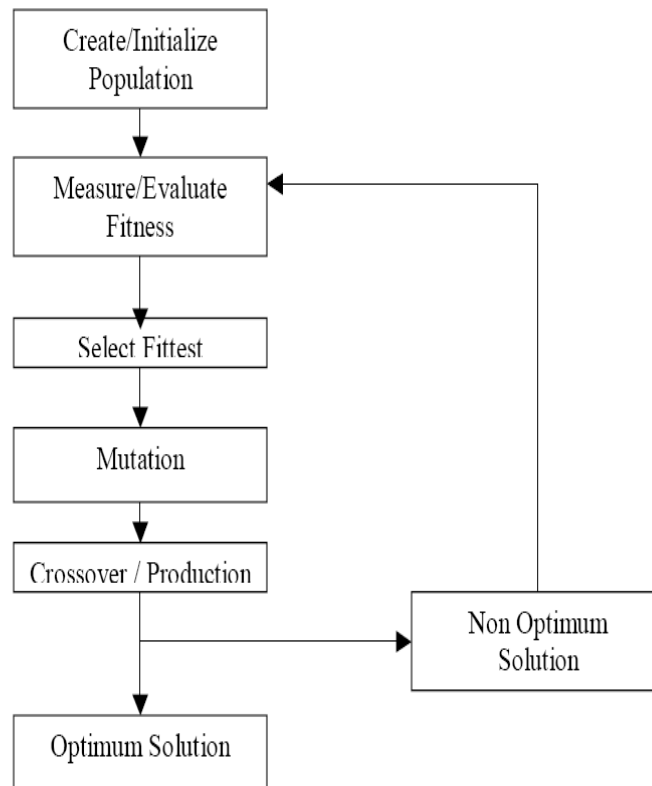


Figure 3.1: Flowchart for basic GA Algorithm

### 3.2.1 Choice of GA Parameters

Selection of appropriate GA parameters is crucial for its faster convergence. In absence of any guideline to choose these parameters, some mechanism has to be devised. The GA parameters include:

#### 3.2.1.1 Initial population

The normal GA operates on a population of  $N$  chromosomes simultaneously. The initial population of these numbered vectors is created randomly. Each of these vectors represents one possible solution to the search problem. The population size ( $N$ ) generally varies from 2 to 2.5 times the number of genes.

### **3.2.1.2 Scaling**

In some occasions a scaling operator (a preprocessor) is usually used to scale the object function into an appropriate Fitness Function. It aims to prevent premature convergence in the early stages of the evolution process and to speed up the convergence in the more advanced stages of the process.

### **3.2.1.3 Termination criterion**

After the fitness has been calculated, it has to be determined if the termination criterion has been met. This can be done in several ways. The common termination criteria are;

1. When certain accuracy has been met.
2. When a finite predefined generation number has been reached. In this case the best fit among the population is declared the winner and solution to the problem.

### **3.2.1.4 Selection**

This operator selects good chromosomes on the basis of their fitness values and produces a temporary population, namely, the mating pool. This can be achieved by many different schemes, but the most common method is Roulette Wheel Selection. The roulette wheel is biased with the fitness of each of solution candidates. The wheel is spun  $M$ -times where  $M$  is the number of strings in the population. This operation generates a measure that reflects the fitness of the previous generation's candidates.

### **3.2.1.5 Crossover and Mutation**

Typically, the types of crossover (e.g. one-point, two-point and  $N$ -point, and random multipoint crossover) and mutation are based on user choice. The crossover operator is the main search tool. It mates chromosomes in the mating pool by pairs and generates candidate offspring by crossing over the mated pairs with probability  $P_{cross}$ . Typically the probability of parent-chromosome crossover is assumed to be between 0.6 and 1.0. After crossover, some of the genes in the candidate offspring are inverted with the probability  $P_{mut}$ . This is the mutation operation for the GA. The mutation operator is included to prevent premature convergence by ensuring the population diversity. A new population is therefore generated. Typically, the probability of mutation ( $P_{mut}$ ) is assumed to be between 0.01 and 0.1.

### 3.2.1.6 Elitism

The worst chromosome in the newly generated population is replaced by the best chromosome in the old population if the best number in the newly generated population is worse than that in the old population. This is adopted to ensure the algorithm's convergence. This method of preserving the elite parent is called elitism.

### 3.2.2 GA Implementation Steps

In GA algorithm, the population has  $n$  chromosomes that represent candidate solution; each chromosome is an  $m$  dimensional real value vector where  $m$  is the number of optimized parameters. GA methodology discussed above is implemented using the following steps.

**Step 1: (initialization):** Set the iteration counter  $k = 1$  and generates randomly  $n$  chromosomes.

**Step 2: (fitness):** Evaluate each chromosome in the initial population using the objective function,  $F$ .

**Step 3: (Selection):** Depending on individual chromosome fitness and using a given selection scheme (for example, roulette wheel method) select two parent chromosomes from the population for mating.

**Step 4: (Crossover and Mutation):** With a crossover probability, cross over the selected parents to form a new child. With a selected mutation probability and method mutate the genes in the new child at each chromosome.

**Step 5: (new population):** Create a new population by repeating steps 3 and 4 while accepting the new formed child until the new population is completed:

**Step 6: (Elitism):** Replace the worst chromosome in the newly generated population by the best chromosome in the old population if the best one in the newly generated population is worse than that in the old population. This is adopted to ensure the algorithm's convergence.

**Step 7: (replacement):** Replace old population with new generated population for a further run of algorithm.

**Step 8: (Iteration updating):** Update the iterations counter  $k = k+1$

**Step 9:** If stopping criteria is satisfied go to step 10 else go to step 2.

**Step 10:** Stop, the optimized solution is the chromosome with the best fitness in the present population.

### 3.2.3 Customized GA flow-chart

Figure 3.2 gives a flow chart of a customized Genetic Algorithm which can be used in solving engineering problems. The flowchart has been constructed using the above mentioned steps for GA implementation.

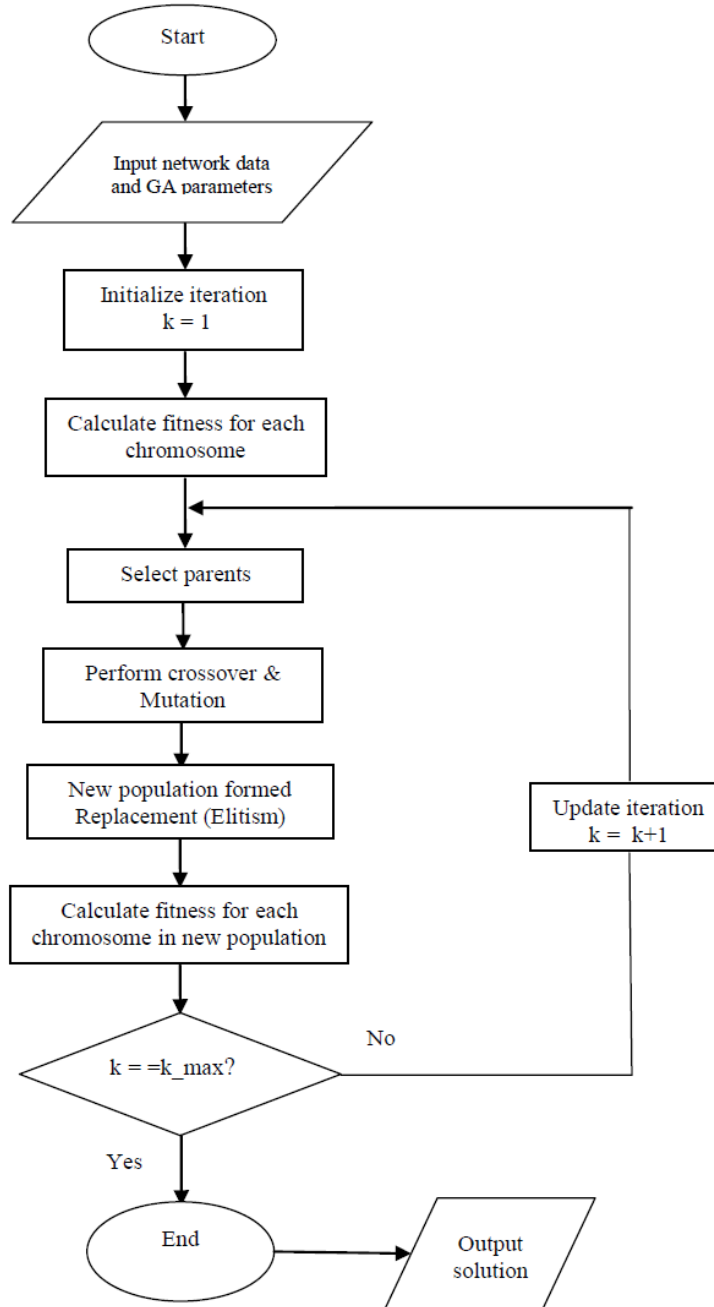


Figure 3.2: A flow chart of a customized Genetic Algorithm

### 3.3 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 [7]. The PSO algorithm starts with a population of particles with random positions in the search space. Each particle is a solution of the problem and has a fitness value. The fitness is evaluated and is to be optimized. A velocity is defined which directs each particle's position and gets updated in each iteration. Particles gradually move toward the optima due to their best position they have ever experienced and the best solution which group has experienced [8]. The velocity of a particle is updated due to three factors: the past velocity of the particle, the best position particle has experienced so far and the best position the entire swarm has experienced so far as shown in figures 3.3 and 3.4.

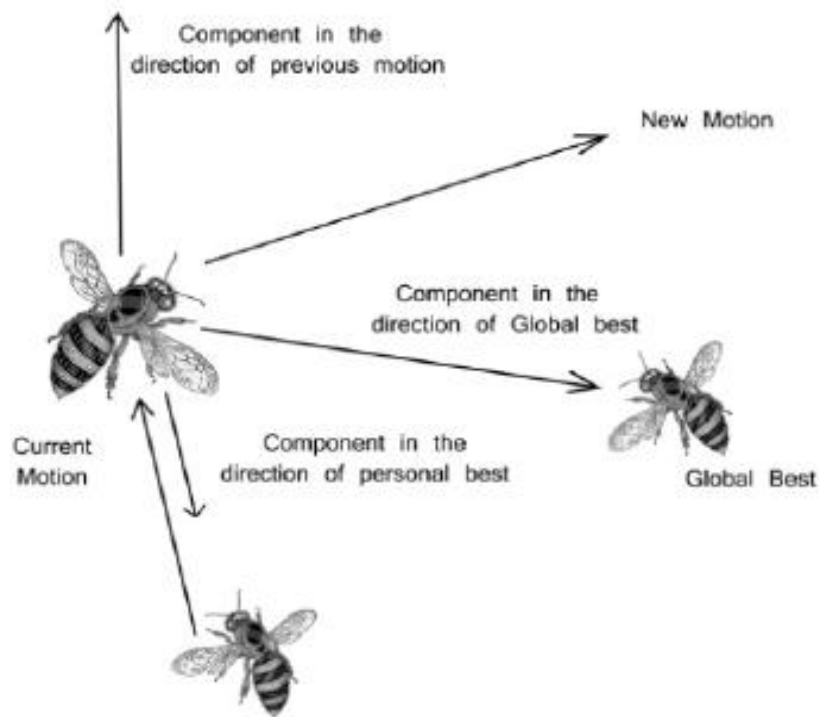


Figure 3.3: Concept of a searching point by PSO

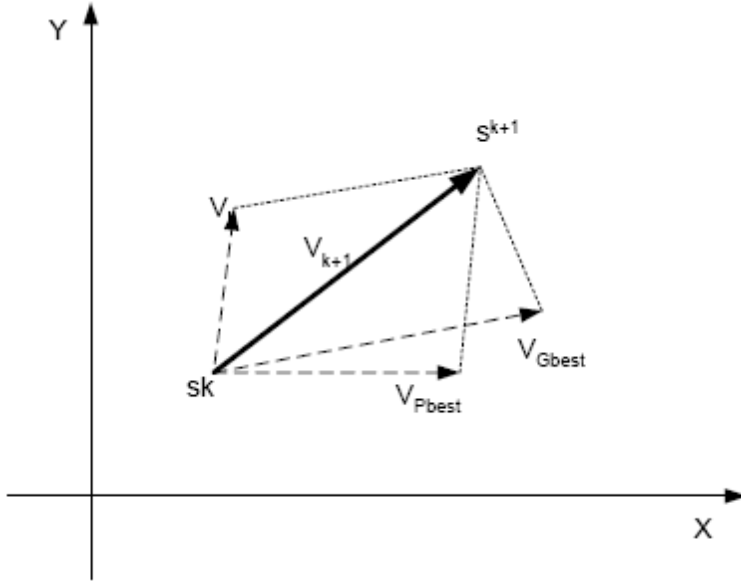


Figure 3.4: Velocity updating in PSO

Mathematically the modification process may be expressed as follows:

$$V_{id}^{k+1} = wV_{id}^k + c_1r(P_{best_{id}} - S_{id}^k) + c_2r(G_{best_{id}} - S_{id}^k) \quad (3.1)$$

$$S_{id}^{k+1} = S_{id}^k + V_{id}^{k+1} ; i=1, 2, \dots, n \ \& \ d=1, 2, \dots, m \quad (3.2)$$

Where,

$V_{id}^{k+1}$  is modified velocity of agent  $i$

$w$  is weight function for velocity of agent

$V_{id}^k$  is current velocity

$c_1$  and  $c_2$  are weight coefficients for each term respectively

$r$  is a random number.

$P_{best_{id}}$  is the particles best position

$S_{id}^k$  is current searching point

$S_{id}^{k+1}$  is the modified searching point

$G_{best_{id}}$  is the groups best position

$n$  is number of particles in a group

$m$  is number of members in a particle

The following weight function is used:

$$w_k = w_{max} - \frac{(w_{max} - w_{min})}{k_{max}} \cdot k \quad (3.3)$$

Where,

$w_{min}$  and  $w_{max}$  are the minimum and maximum weights respectively.

$k$  and  $k_{max}$  are the current and maximum iteration.

PSO has many advantages which include.

1. PSO is based on the swarm intelligence. It can be applied into both scientific research and engineering use.
2. PSO has an advantage of a fast convergence rate in comparison to most optimization techniques including Genetic Algorithm.
3. PSO have no overlapping and mutation calculation. The search can be carried out by the speed of the particle, for example in comparison with GA.
4. During the development of several generations, only the most optimist particle can transmit information onto the other particles, and the speed of the researching is very fast.
5. Calculation in PSO is very simple. Compared with the other developing calculations, it occupies the bigger optimization ability.
6. 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.

The only major disadvantages of PSO are;

1. The method easily suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction.
2. The method may not work out properly the problems of non-coordinate system, such as the solution to the energy field and the moving rules of the particles in the energy field.



Figure 3.5 gives the flow chart of a basic Particle Swarm Optimization algorithm.

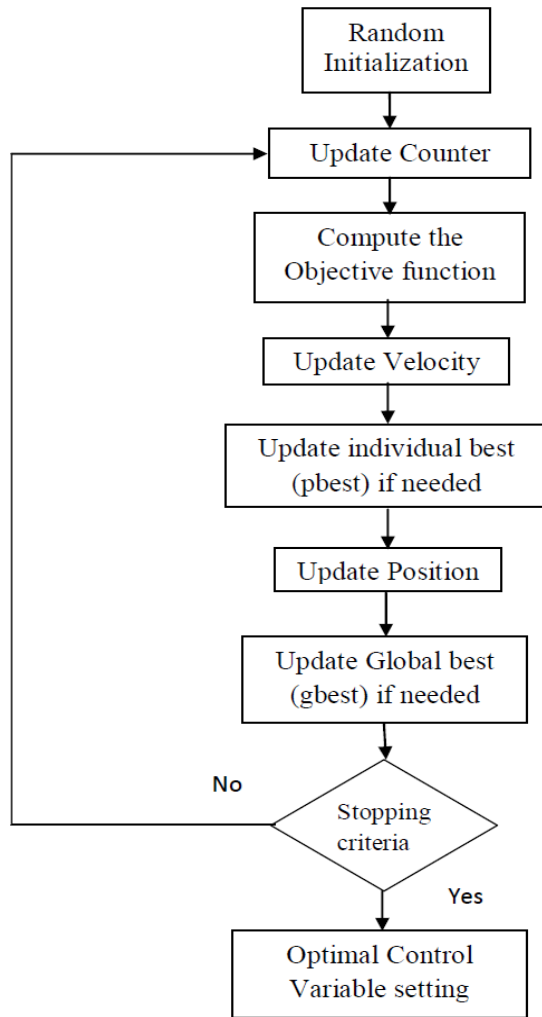


Figure 3.5: A flowchart for basic PSO Algorithm

### 3.3.1 Choice of PSO Parameters

The most important parameters in PSO algorithm include:

#### 3.3.1.1 Particle Velocity

The current velocity  $V_{id}^k$  is constrained in the limits  $V_{id}^{min} \leq V_{id}^k \leq V_{id}^{max}$ . The parameter  $V^{max}$  determines the resolution, or fitness, showing which regions are to be searched between the present position and the target position. If  $V^{max}$  is very high, particles might fly past good solutions. This is because the particles move in larger steps and the solution reached may not

optimal. Similarly if  $V^{max}$  is too small, particles take longer time to reach desired solutions. They may even not explore sufficiently hence being captured in local minimum solutions. In many experiences with PSO,  $V^{max}$  is often set at 12–25% of the dynamic range of the variable on each dimension [1].

### **3.3.1.2 Random Numbers**

The uniform random values are in the range [0, 1]. They help in achieving the stochastic behavior of PSO.

### **3.3.1.3 Weighting Coefficients**

The parameters  $c_1$  and  $c_2$  represent the weighting of the stochastic acceleration terms. High values result in abrupt movement toward, or past, target regions. On the other hand, low values allow particles to roam far from the target regions before being tugged back. The parameters  $c_1$  and  $c_2$  may be adopted in the range [1, 2] as the number of iterations increases, but in many applications  $c_1$  and  $c_2$  are often constants.  $c_1$  and  $c_2$  control the rate of relative influence of the memory of other particles and their typical values are  $c_1 = c_2 = 2$ .

### **3.3.1.4 Inertia Weight**

Suitable choice of the inertia weight  $w$  can supply a balance between global and local explorations. That is a balancing factor between exploration and exploitation. For faster convergence, inertia weight is usually selected to be high at the beginning and is decreased in course of optimization. In general, the inertia weight  $w$  is adjusted according to equation (3.3) above. Appropriate values for  $w_{min}$  and  $w_{max}$  are 0.4 and 0.9 respectively.

### **3.3.1.5 Termination criterion**

After the initial phase, several iterations of update and evaluation steps are performed until a stopping condition is met. Generally, the stopping condition is the attainment of a predefined maximum numbers of iterations or the attainment of certain accuracy in the solution.

### 3.3.2 PSO Implementation Steps

In PSO algorithm, the population has  $n$  particles that represent candidate solutions. Each particle is an  $m$  dimensional real valued vector where  $m$  is the number of optimized parameters. Therefore each optimized parameter represents a dimension of the problem space. The PSO technique can be described in the following steps.

**Step 1: Initialization:** Set the iteration counter  $k = 1$ . Randomly generates an initial population (array) of  $n$  particles. Initial velocity of each particle is randomly generated for evaluation of the objective function.  $k_{max}$ ,  $w_{min}$ ,  $w_{max}$ ,  $c_1$  and  $c_2$  are assigned. In this step, the lower and higher bound of regional constraints is specified too.

**Step 2: Objective function calculation:** Calculate the objective function and fitness value of each particle. The fitness value of each particle during the first iteration becomes its  $p_{best}$ . The best fitness value among all the  $p_{best}$  is denoted as  $q_{best}$ .

**Step 3: Velocity modification:** Modify the velocity of each particle using the below equation;

$$V_{id}^{k+1} = wV_{id}^k + c_1r(P_{best_{id}} - S_{id}^k) + c_2r(G_{best_{id}} - S_{id}^k) \quad (3.4)$$

Then generate the new particles based on the following equation:

$$S_{id}^{k+1} = S_{id}^k + V_{id}^{k+1} ; i=1, 2, \dots, n \ \& \ d=1, 2, \dots, m \quad (3.5)$$

**Step 4: Upgrading of  $p_{best}$ ,  $q_{best}$ :** Compute the fitness value of each new. Compare the calculated fitness value of each new particle with its  $p_{best}$ . If the fitness value of a particle is better than the previous  $p_{best}$  then  $p_{best}$  is updated with the current value. If the best  $p_{best}$  is better than  $q_{best}$ , then  $q_{best}$  is substituted with the best  $p_{best}$ .

**Step 5: Iteration updating:** Update the iteration counter,  $k = k+1$ .

**Step 6:** If stopping criteria is satisfied go to step 7 else go to step 3.

**Step 7:** Stop. The particle that generates the latest  $q_{best}$  is the optimal solution of PSO.

### 3.3.3 Customized PSO flow-chart

For each type of optimization problem to be solved by PSO, the PSO algorithm has to be adapted to this kind of problem. Figure 3.6 gives a flowchart of a customized PSO algorithm customized to solve engineering optimization problems.

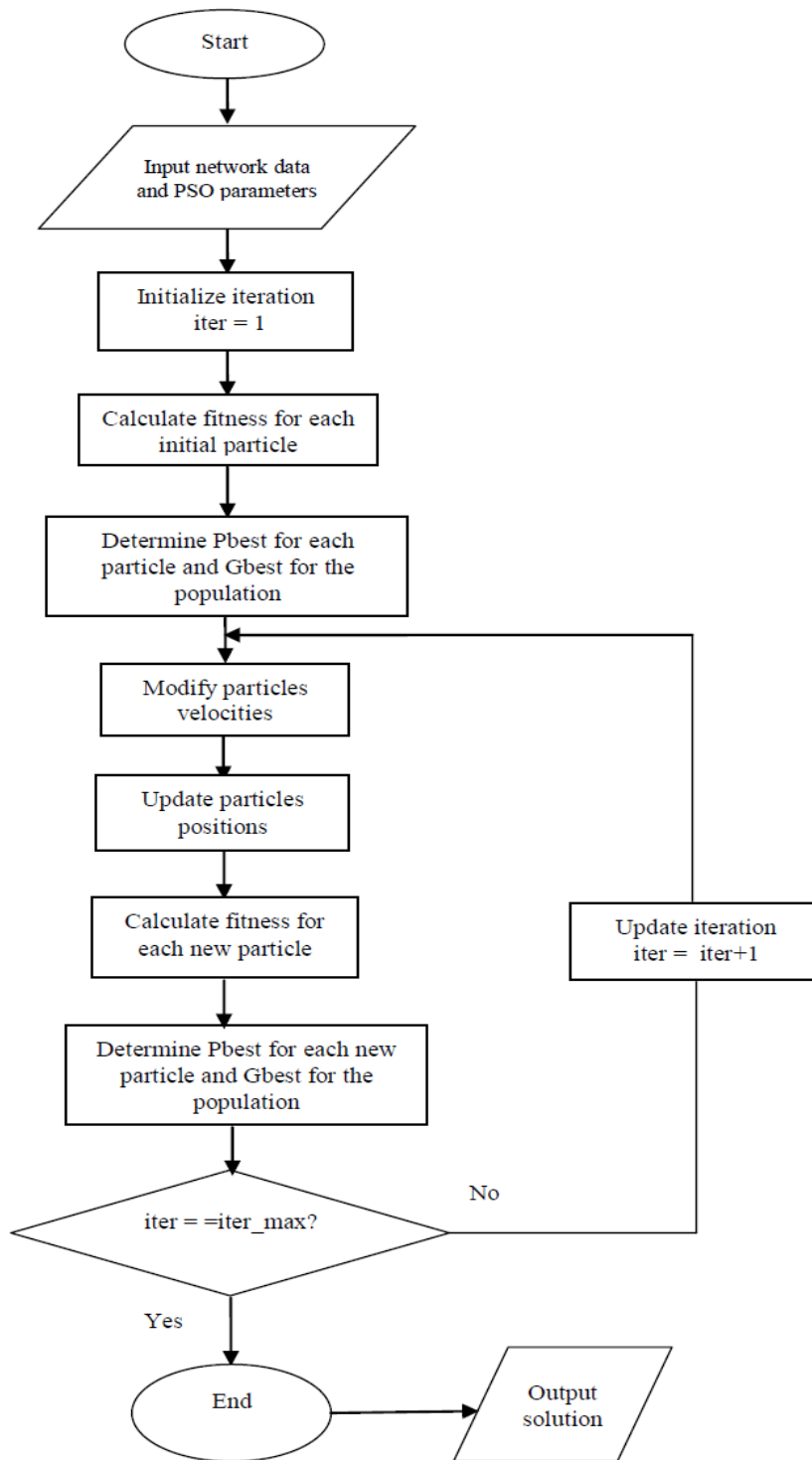


Figure 3.6: A flow chart of a customized PSO Algorithm

## CHAPTER 4: HYBRIDIZATION OF GA AND IPSO FOR OPTIMAL DG ALLOCATION

### 4.1 Introduction

This chapter covers the hybridization tools used in this research and the proposed methodology for hybridization. There are different ways in which these two optimization techniques can be hybridized so as to come up with a better method to solve the problem at hand. In this research work several ways were investigated before settling on the methodology detailed in this chapter. The steps of the proposed algorithm are also detailed in this chapter. Before going into details of the proposed methodology it is important that a review of some of the important tools used is done. These tools as discussed in this chapter include the selection methods employed and the type of crossover and mutation used.

### 4.2 Roulette Wheel and Greedy Selection Methods

#### 4.2.1 Roulette Wheel Selection Method

Roulette wheel selection, also known as Fitness proportionate selection, is a genetic operator used in genetic algorithms for selecting potentially useful solutions for recombination. The idea behind the roulette wheel selection technique is that each individual is given a chance to become a parent in proportion to its fitness. Thus, this fitness level is used to associate a probability of selection with each individual chromosome. If  $f_i$  is the fitness of individual  $i$  in the population, its probability of being selected is given by;

$$p_i = \frac{f_i}{\sum_{j=1}^N f_j} \quad (4.1)$$

Where,  $N$  is the number of individuals in the population.

It is called roulette wheel selection as the chances of selecting a parent can be seen as spinning a roulette wheel in a casino with the size of the slot for each parent being proportional to its fitness. Obviously those with the largest fitness (slot sizes) have more chance of being chosen. Although candidate solutions with a higher fitness will be less likely to be eliminated, there is still a chance that they may be. Therefore contrast to a less sophisticated selection algorithm, such as truncation selection, which will eliminate a fixed percentage of the weakest candidates; with roulette wheel selection there is a chance some weaker solutions may survive the selection

process. This is an advantage, as though a solution may be weak, it may include some component which could prove useful following the recombination process. In the same case, it is possible for one member to dominate all the others and get selected a high proportion of the time.

In this research work roulette wheel selection method was employed in Genetic Algorithm part. This is because as evident later in the steps of proposed methodology, the algorithm first used Genetic Algorithm to do exploration thus making this selection method the most favorable one.

#### **4.2.2 Greedy selection Method**

A greedy selection algorithm always makes the choice that looks best at the moment. The hope is that a locally optimal choice will lead to a globally optimal solution. This technique might also be called a "single-minded" technique or a technique that gobbles up all of its favorites first. The idea behind a greedy algorithm is to perform a single procedure in the recipe over and over again until it can't be done any more and see what kind of results it will produce. It may not produce the very best solution, but it *is* one way of approaching the problem and sometimes yields very good (or even the best possible) results.

The choice made by a greedy algorithm may depend on choices made so far but not on future choices. It iteratively makes one greedy choice after another, reducing each given problem into a smaller one. In other words, a greedy algorithm never reconsiders its choices in iteration. This is the main difference from roulette wheel selection method which is exhaustive and is guaranteed to find the solution in most cases. After every stage, roulette wheel selection method makes decisions based on all the choices available including choices involved in the previous stage, and may reconsider the previous stage's algorithmic path to solution.

Greedy selection is one of the most straightforward design techniques. Most problems have  $n$  inputs and solution to these problems contains a subset of inputs that satisfies a given constraint. A feasible solution is therefore any subset that satisfies the constraint; that is a solution that maximizes or minimizes a given objective function. Greedy selection is used to determine a feasible solution that may or may not be optimal. At every point, a decision is made that is locally optimal; and hope that it leads to a globally optimal solution. This leads to a powerful method for getting a solution that works well for a wide range of applications.

After exploration is done in the GA section of the algorithm there is need for exploitation of the already partially optimized solutions so as to come up with the most optimal solution(s). This exploitation section was done in the IPSO section and thus greedy selection method was used to facilitate this due to its nature.

### 4.3 Arithmetic Crossover and Mutation

In this research work crossover and mutation has been applied to both GA and PSO sections in the hybridized algorithm. These operators help in avoiding pre-mature convergence/partial optimism and thus improving the performance of algorithms. In Michalewicz, 1994 and Gen & Cheng, 1997 *arithmetic crossover* is defined as the combination of two parent chromosomes  $X_{p1}$  and  $X_{p2}$  to give two children chromosomes  $X_{c1}$  and  $X_{c2}$  to as follows [83]:

$$X_{c1} = \lambda X_{p1} + (1 - \lambda) X_{p2} \quad (4.2a)$$

$$X_{c2} = \lambda X_{p2} + (1 - \lambda) X_{p1} \quad (4.2b)$$

$\lambda \in (0,1)$  is generated randomly between 0 and 1 and used to compute the children as shown

For a given child;

$$X_{cl}^k = X_{l1}^k, \dots, X_{lj}^k, \dots, X_{lm}^k \quad (4.3)$$

Where,

$$l = 1, 2, \dots, N; j = 1, 2, \dots, m$$

If the element  $X_{lj}^k$  is selected for mutation, the resulting offspring is given by;

$$X_{cl}^k = X_{l1}^k, \dots, X_{lj}^{k*}, \dots, X_{lm}^k$$

Where,

$$X_{lj}^{k*} = X_{lj}^k + \Delta X_{lj}^k \quad (4.4)$$

$\Delta X_{lj}^k$  is randomly selected from the two possible choices:

$$\Delta X_{lj}^k = r(X_{lj}^{max} - X_{lj}^k) \left(1 - \frac{k}{k_{max}}\right) \quad (4.5a)$$

$$\text{or } \Delta X_{lj}^k = r(X_{lj}^{min} - X_{lj}^k) \left(1 - \frac{k}{k_{max}}\right) \quad (4.5b)$$

$r$  is a random number In between 0 and 1

Arithmetic crossover and mutation was employed because it enabled the use of real coded chromosomes in the algorithm. Thus the encoding of chromosomes from real values to binary numbers and decoding them back was avoided making the algorithm not only less complex but also reducing its computation time.

Shukla et al. (2011) [4] did a great work in investigating the effects of the variations of crossover and mutation probabilities on a objective function. This work proposes a crossover probability of 0.85 and a mutation probability of 0.01 as the best figures to work with during optimization. Thus the same figures have being used in this research work.

#### **4.4 Proposed Methodology**

This research work proposes the use of a hybrid of Genetic Algorithm (GA) and Improved Particle Swarm Optimization (IPSO) for optimal allocation of DG. The DG is considered to be located in the distribution system with the aim of reducing system losses and improving voltage profile.

System power flow and power loss sensitivity factors have been used in order to come up with the candidate buses for DG location. This helps in reducing the search space for the algorithm and thus making it to converge faster. The results of these sensitivity factors are then passed to GA which gives possible DG sizes for each location. This is done by randomly initializing the DG sizes for each location and then optimizing these values using a predefined multi-objective function. In general GA performs exploration and comes up with promising solutions which are passed to IPSO for fine tuning.

The GA output which is handed to IPSO comprise of some sets of solutions each having a DG location and the associated DG size. IPSO then uses these GA optimized results as its set of initial particles. This assists to achieve faster convergence. IPSO fine tunes solutions from Genetic Algorithm so as to come up with an optimal solution.



The block diagram in figure 4.1 shows the general procedure of the proposed methodology;

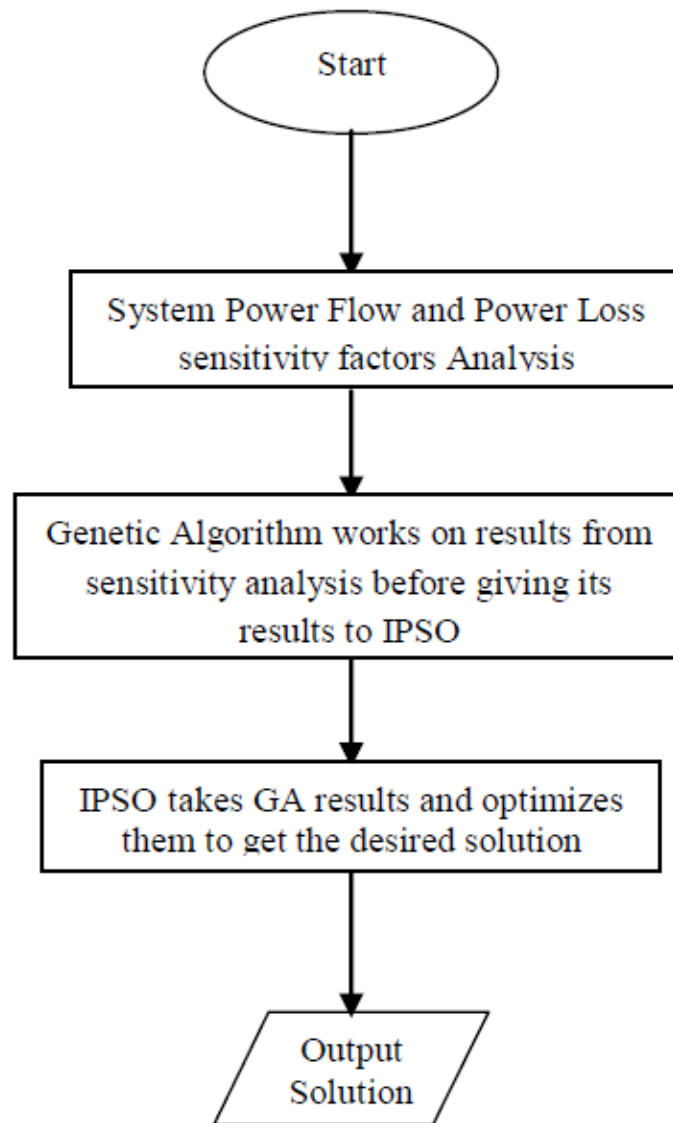


Figure 4.1: A block diagram showing general procedure of the proposed methodology

#### 4.4.1 Steps of the Proposed Algorithm

The proposed GA-IPSO based approach for optimal allocation of DG units in the distribution systems is as detailed in the following implementation steps;

1. Get system data by reading the power system parameters.

2. Employ Newton-Raphson method for load flow studies to calculate system base case power loss.
3. Compute CSF for each bus and arrange buses in order of sensitivity.

$$CSF_i = (F_{P-Pi} \times F_{Q-Pi}) + (F_{P-Qi} \times F_{Q-Qi}) + (S_{P-Pi} \times S_{Q-Pi}) + (S_{P-Qi} \times S_{Q-Qi}) \quad (4.6)$$

4. Buses with high sensitivities are chosen as candidate buses.
5. Input both GA and IPSO control parameters.
6. Set candidate bus count  $i = 1$
7. While  $i \leq 1$

- (i) Initialize N chromosomes with random values to represent possible DG sizes.

$$P_{DG}^{min} \leq P_{DGj} \leq P_{DG}^{max} \text{ and } Q_{DG}^{min} \leq Q_{DGj} \leq Q_{DG}^{max}, j = 1, 2, \dots, N \quad (4.7)$$

- (ii) Set iteration count (for GA)  $k = 1$

- (iii) While  $k \leq k_{max}$

- a) Evaluate each chromosomes fitness using the multi-objective.
- b) Using roulette wheel selection method select two chromosomes ( $X_{p1}$  and  $X_{p2}$ ).
- c) Perform crossover and mutation based on the probabilities  $P_{cross}$  and  $P_{mut}$
- d) Create a new population by repeating steps (b) and (c) while accepting the newly formed children until the new population is complete.
- e) Replace old population with new population.
- f) Update the iterations counter  $k = k + 1$

- (iv) Stop and pass current chromosomes (partially optimized) to IPSO.

- (v) Use GA optimized chromosomes as initial IPSO particles.

- (vi) Calculate the fitness value for each particle using the multi-objective function. The value of each particle becomes its  $p_{best}$ . The particle value with the best fitness among all the  $p_{best}$  is denoted as  $q_{best}$

- (vii) Set iteration count (for IPSO)  $iter = 1$

- (viii) While  $iter \leq iter_{max}$

- a) Modify the velocity of each particle element as shown.

$$V_{id}^{k+1} = wV_{id}^k + c_1r(P_{best_{id}} - S_{id}^k) + c_2r(G_{best_{id}} - S_{id}^k) \quad (4.8)$$

Where;

$$w_{iter} = w_{max} - \frac{(w_{max}-w_{min}) \cdot iter}{iter_{max}} \quad (4.9)$$

- b) Then generate the new position for each particle element.

$$S_{id}^{iter+1} = S_{id}^{iter} + V_{id}^{iter+1} \quad (4.10)$$

- c) Using greedy selection method select two chromosomes ( $S_{p1}$  and  $S_{p2}$ ).
- d) Perform crossover and mutation based on the probabilities  $P_{cross}$  and  $P_{mut}$
- e) Create a new population by repeating steps (c) and (d) while accepting the newly formed children until the new population is complete.
- f) Compute the fitness value of each new particle and update  $p_{best}$  and  $q_{best}$  as shown;

$$p_{best(j)}^{iter+1} = \begin{cases} S_{(j)}^{iter+1} & \text{if } MOF_j^{iter+1} < MOF_j^{iter} \\ p_{best(j)}^{iter} & \text{if } MOF_j^{iter+1} \geq MOF_j^{iter} \end{cases} \quad (4.11a)$$

$$q_{best}^{iter+1} = \begin{cases} p_{best(j)}^{iter+1} & \text{if } MOF^{iter+1} < MOF^{iter} \\ q_{best}^{iter} & \text{if } MOF^{iter+1} \geq MOF^{iter} \end{cases} \quad (4.11b)$$

- g) Update the iteration counter,  $iter = iter + 1$

(ix) Stop. The particle that generates the latest  $q_{best}$  is the optimal solution.

(x) With the latest  $q_{best}$  in the network calculate system power loss and bus voltages ( $P_{L(DGi)}, Q_{L(DGi)}$  and  $V_{(DGi)}$ ).

(xi) Update the candidate bus  $i = i + 1$

8. Compare the fitness of candidate buses  $q_{best}$  and get the most minimized one(s).
9. The results give the optimal locations and their respective optimal DG sizes.

### 4.4.2 Flow Chart for Proposed Algorithm

Below is the flowchart for the above explained steps of the proposed algorithm;

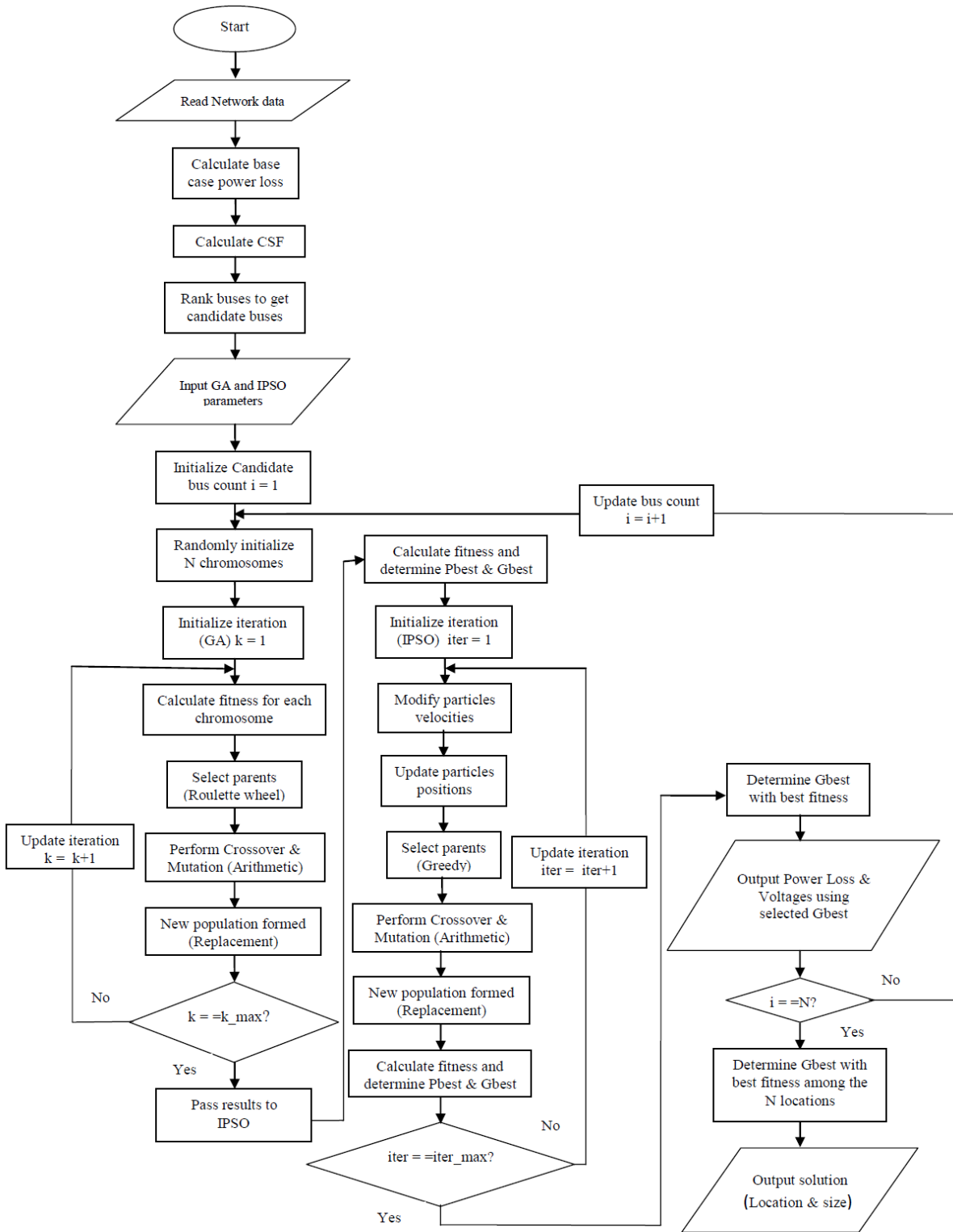


Figure 4.2: A flow chart of the proposed algorithm

## CHAPTER 5: RESULTS AND DISCUSSIONS

### 5.1 Introduction

In this chapter the results obtained using GA-IPSO method have been presented. The algorithm outlined in the previous chapter was implemented and programmed in Matlab 2011. The main codes programmed according to the implementation steps of the proposed algorithm are given in Appendix K. The results are subdivided into different sections depending on the test bus system under consideration and the type of DG being optimally place and sized. Different comparisons have also been done so as to show the reliability of this algorithm in reducing real and reactive network losses and improving voltage profile in relation to other algorithms in open literature.

### 5.2 Choice of Weights values for Multi-objective Function

As mentioned earlier, the allocation of the various weights in a given multi-objective function vary according to the engineer's concern. In this research work, more emphasizes is given to real power loss reduction since this results to a considerable decrease in total cost of operation. Though, this is not to mean that the other two factors are not important. Thus taking this into consideration a study of the effect of the weights on the fitness was done so as to determine the best weights combination to adopt in coming up with the multi-objective function. During this study the values of the weights were assumed positive and restricted as follows;

- $w_1$  was restricted between 0.5 and 0.8
- $w_2$  and  $w_3$  were restricted between 0.1 and 0.4

This was done so as to ensure that much emphasizes is given to the real power loss reduction index as earlier stated while at the same time ensuring that all the three indices are taken into consideration while formulating the multi-objective function.

It is also important to note that the condition  $|w_1| + |w_2| + |w_3| = 1$  has to be satisfied in each case. Table 5.1 gives the results obtained in this study.

Table 5.1: Effects of Weights on Fitness

<b>w1</b>	<b>w2</b>	<b>w3</b>	<b>Best Fitness</b>
0.5	0.1	0.4	0.9094
0.5	0.2	0.3	0.9102
0.5	0.3	0.2	0.9099
0.5	0.4	0.1	0.9103
0.6	0.1	0.3	0.9107
<b>0.6</b>	<b>0.2</b>	<b>0.2</b>	<b>0.9091</b>
0.6	0.3	0.1	0.9096
0.7	0.1	0.2	0.91
0.7	0.2	0.1	0.9102
0.8	0.1	0.1	0.9092

From the results presented in the above table the combination of weights chosen is the one which gave the minimum best fitness. Thus the weights chosen were;  $w_1 = 0.6$ ,  $w_2 = 0.2$ ,  $w_3 = 0.2$  and the MOF was given by;

$$MOF = 0.6PLRI + 0.2QLRI + 0.2VPPII \quad (5.1)$$

The algorithm was test run at different values of iterations and it was observed that the Genetic Algorithm part needed at least five iterations while the IPSO part needed at least 20 iterations to achieve consistent convergence for all the cases considered. The algorithm also required a minimum of 20 chromosomes/particles so as to produce reliable results.

### 5.3 Results Using a 30 Bus Test System

In this case the DG(s) was assumed to be located in an IEEE 30-bus test system. The diagram of this network is given in Appendix C while its line and bus data are as shown in Appendices D and E respectively. For comparison purposes the base case real power losses of this test system were taken as 17.9773MW as given by Yustra *et al.* in their which they proposed an algorithm to optimize the location and size of a multi-type DG [54]. Since the main objective of Yustra *et al.* work was to minimize real power losses they did not take into account the reactive power losses. Thus the base case reactive power losses were obtained using Newton Raphson method to be

68.8881MVAR. To ensure fair comparison the number of DGs to be optimally located and sized was maintained same with that of the work under comparison; that is four DGs. The DG limits were taken to be as follows so as to ensure the same values during validation;

- 0MW -12MW for real power limit (Type 1, 2 and 3 DGs)
- 0MVar – 3MVar for reactive power limit (Type 2 DG)
- -3MVar – 0MVar for reactive power limit (Type 3 DG)

### 5.3.1 Results for all Candidate Buses

The combined sensitivity factors were analyzed for all the buses and the buses which gave a combined sensitivity factor of more than 0.8 were taken to be the candidate buses. So as to be able to choose the optimal location(s) of the DG(s) and their respective optimal sizes, results were obtained taking into consideration all the candidate buses. This was done for each of the three types of DG and the obtained results tabulated as shown in table 5.2;

Table 5.2: Results for CSF, Fitness and optimal DG sizes for candidate buses

Candidate Bus	Combined Sensitivity Factor (CSF)	Type 1 DG		Type 2 DG		Type 3 DG	
		Fitness	DG Size (MW)	Fitness	DG Size (MW+jMVar)	Fitness	DG Size (MW+jMVar)
10	0.8789	0.9176	11.987	0.9178	12+j2.6903	0.9176	11.9826-j0
11	0.9236	0.9198	11.9813	0.9198	11.8514+j2.9983	0.9198	11.8403-j2.1163
15	0.8352	0.9165	11.5058	0.9157	12+j2.5159	0.9169	12-j1.4395
17	0.8733	0.9173	11.9985	0.9167	12+j2.4561	0.9173	11.6399-j0.0601
18	1.022	0.9134	11.9548	0.9125	11.9865+j3	0.9149	11.9873-j2.9989
19	1.0957	0.9118	11.7099	0.9109	11.7872+j2.9609	0.9118	12-j0.4882
20	1.0637	0.9133	11.5875	0.9125	11.7311+j2.8894	0.9133	11.6636-j0.3807
21	0.9973	0.9128	11.9937	0.9119	12+j2.5813	0.9128	11.947-j0.5042
22	1.0558	0.9169	11.9876	0.9163	12+j2.7596	0.9169	11.9909-j0
23	0.9909	0.9129	11.7103	0.9118	11.7548+j3	0.9129	12-j0.0886
24	1.0349	0.9123	11.996	0.9112	12+j1.3702	0.9123	11.9179-j0.0692
25	0.8743	0.9175	11.5228	0.9154	11.9782+j3	0.9165	10.6418-j0.57
26	1.0064	0.9221	11.824	0.9198	11.9763+j1.5112	0.9216	11.8898-j0
30	0.811	0.9091	11.7061	0.9083	11.8308+j1.5817	0.9191	11.3651-j0.5807

### 5.3.2 Results Considering Type 1 DG

The choice of the four optimal locations for the DGs of type 1 and their respective optimal sizes was done using table 5.2 above. In table 5.2 the two columns for fitness and DG size under type 1 DG were used to facilitate this. This was done by selecting those locations which had the minimum fitness values and their respective DG sizes. The four selected optimal locations and their respective optimal DG sizes were as follows in order of effectiveness;

1. Bus number 30 with a DG size of 11.7061MW
2. Bus number 19 with a DG size of 11.7099MW
3. Bus number 24 with a DG size of 11.9960MW
4. Bus number 21 with a DG size of 11.9937MW

With the chosen four DG sizes and locations a load flow study was done using Newton Raphson method so as to determine the associated power losses and voltage levels. The results obtained for the power losses were compared to results from other methods. The comparison is given in the table below.

Table 5.3: A comparison of Results obtained using Type 1 DG

Methodology	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
		MW	MW	Mvar	MW	Mvar	%MW	%Mvar
SGA[54]	10	11.472	12.3919	-	5.5853	-	31.07	-
	10	11.904						
	19	11.052						
	24	11.772						
PSO[54]	10	11.694	12.2622	-	5.7151	-	31.79	-
	15	11.394						
	20	11.378						
	30	10.577						
IPSO[54]	10	11.625	12.1851	-	5.7922	-	32.22	-
	10	11.956						
	22	11.995						
	30	11.986						
GA-IPSO (This Method)	19	11.7099	11.602	44.084	6.3753	24.8041	35.46	36.01
	21	11.9937						
	24	11.996						
	30	11.7061						



The above results for type 1 DG clearly show that the GA-IPSO method gave the greatest reduction in real power loss compared to all the other methodologies. The percentage real power loss reduction from this method was 35.46% compared to 32.22% for IPSO, 31.79% for PSO and 31.07% for SGA. Though the work used for comparison only considered real power losses, the reduction in reactive power losses given by GA-IPSO method using this type of DG is considerably great. The reactive power losses were reduced by a percentage of 36.01%. It is also important to note that the sizes of DG obtained compare well to the sizes from the other methods. Therefore the GA-IPSO method is seen to be superior to the other three methods in terms of optimizing the location and size of a type 1 DG with the objective of reducing system power losses.

### 5.3.2.1 Bus Voltage Profile using Type 1 DG

It is important to note that the inclusion of DG(s) in a power system network can result to unacceptable voltage levels in certain buses in the system. With that in mind it was important to check the voltage profile of the IEEE 30 bus system after the inclusion of the DGs for voltage deviation outside the limits and also compare it with voltage profiles obtained by other researchers. Table 5.4 below gives the voltage comparison for the case without a DG in the system and then with DGs optimally located and sized using SGA, PSO, IPSO and GA-IPSO. Figure 5.1 also gives a graph for this comparison.

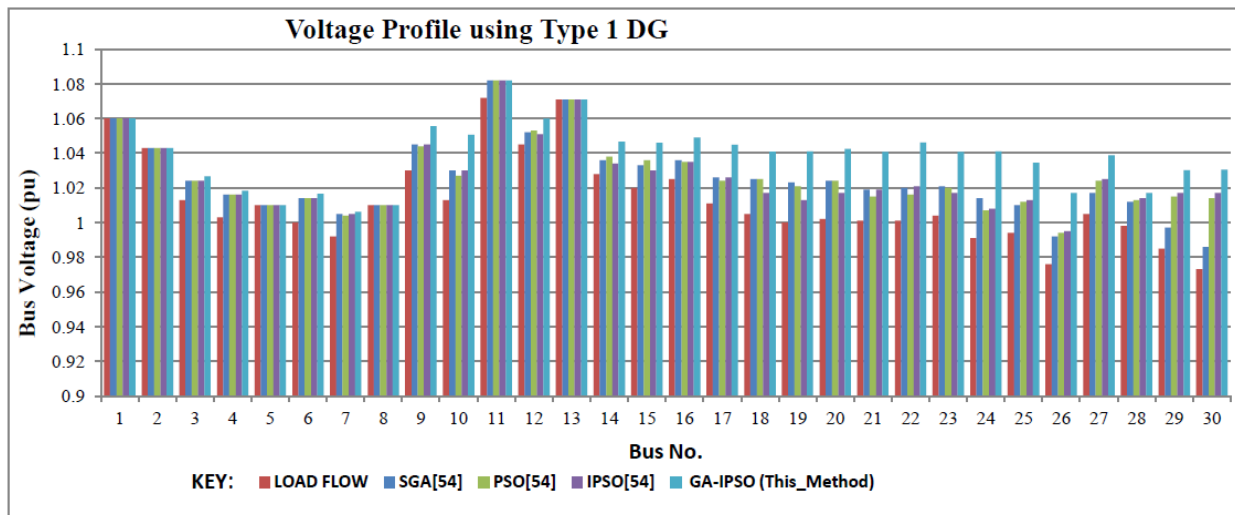


Figure 5.1: A figure showing bus voltage profile comparison using Type 1 DG

Table 5.4: A Comparison of Bus Voltages using Type 1 DG

	VOLTAGE WITHOUT DG (pu)	VOLTAGE WITH TYPE 1 DG (pu)					VOLTAGE WITHOUT DG (pu)	VOLTAGE WITH TYPE 1 DG (pu)			
Bus No.	LOAD FLOW	SGA[54]	PSO[54]	IPSO[54]	GA-IPSO (This_Method)	Bus No.	LOAD FLOW	SGA[54]	PSO[54]	IPSO[54]	GA-IPSO (This_Method)
1	1.06	1.06	1.06	1.06	1.06	16	1.025	1.036	1.035	1.035	1.049
2	1.043	1.043	1.043	1.043	1.043	17	1.011	1.026	1.024	1.026	1.0449
3	1.013	1.024	1.024	1.024	1.0266	18	1.005	1.025	1.025	1.017	1.0409
4	1.003	1.016	1.016	1.016	1.0184	19	1	1.023	1.021	1.013	1.041
5	1.01	1.01	1.01	1.01	1.01	20	1.002	1.024	1.024	1.017	1.0425
6	1	1.014	1.014	1.014	1.0166	21	1.001	1.019	1.015	1.019	1.0406
7	0.992	1.005	1.004	1.005	1.0062	22	1.001	1.02	1.016	1.021	1.0462
8	1.01	1.01	1.01	1.01	1.01	23	1.004	1.021	1.02	1.017	1.0406
9	1.03	1.045	1.044	1.045	1.0557	24	0.991	1.014	1.007	1.008	1.041
10	1.013	1.03	1.027	1.03	1.0506	25	0.994	1.01	1.012	1.013	1.0344
11	1.072	1.082	1.082	1.082	1.082	26	0.976	0.992	0.994	0.995	1.017
12	1.045	1.052	1.053	1.051	1.0599	27	1.005	1.017	1.024	1.025	1.0388
13	1.071	1.071	1.071	1.071	1.071	28	0.998	1.012	1.013	1.014	1.017
14	1.028	1.036	1.038	1.034	1.0467	29	0.985	0.997	1.015	1.017	1.0303
15	1.02	1.033	1.036	1.03	1.046	30	0.973	0.986	1.014	1.017	1.0306

Although the voltages of an ideal IEEE 30 bus system are within the acceptable ranges that is 0.95pu to 1.1pu, the inclusion of a DG can affect this voltage stability. From Table 5.4 and Figure 5.1 it can be seen that the inclusion of the DGs does not result to deviation of voltage levels outside the acceptable limits. As it is evident all the bus voltages were in the range of 1.0pu to 1.1pu. Thus the GA-IPSO method improved the voltage levels of those buses which had voltages of less than 1.0pu to at least 1.01pu while ensuring that no voltage level rises above the acceptable limit.

### 5.3.3 Results Considering Type 2 DG

Similarly the four optimal locations for the DGs of type 2 and their respective optimal sizes were chosen using the respective columns for fitness and DG size in table 5.2. The locations which gave the minimum fitness values and their respective DG sizes were selected. The four selected optimal locations and their respective optimal DG sizes were as follows in order of effectiveness;

1. Bus number 30 with a DG generating 11.8308MW and 1.5817MVar
2. Bus number 19 with a DG generating 11.7872MW and 2.9609MVar

3. Bus number 24 with a DG generating 12MW and 1.3702MVar
4. Bus number 23 with a DG generating 11.7548MW and 3MVar

The chosen four DG sizes were assumed to be in their respective locations and a load flow study was done using Newton Raphson method so as to determine the associated power losses and voltage levels. The comparison of the results obtained for the power losses is given in the table below.

Table 5.5: A comparison of results obtained using Type 2 DG

Methodology	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
			MW	Mvar	MW	Mvar	%MW	%Mvar
SGA[54]	10	11.364+j1.219	12.2258	-	5.7515	-	31.99	-
	23	11.472+j1.168						
	24	11.916+j2.037						
	30	9.816+j1.468						
PSO[54]	10	11.474+j2.159	12.1056	-	5.8717	-	32.66	-
	17	11.981+j0.919						
	20	11.67+j2.309						
	30	11.349+j3						
IPSO[54]	10	11.83+j0.001	11.945	-	6.0323	-	33.56	-
	21	11.433+j3						
	24	11.739+j3						
	30	11.995+j0.001						
GA-IPSO (This Method)	19	11.7872+j2.9609	11.538	44.126	6.4393	24.7621	35.82	35.95
	23	11.7548+j3						
	24	12+j1.3702						
	30	11.8308+j1.5817						

Type 2 DG being one of the most commonly used DGs, its results are quite important and of much interest. From the table above, the percentage reduction in real power losses obtained when optimizing the location and size of this type of DG using GA-IPSO method is 35.82%. This percentage is the highest when compared to the other three methodologies; IPSO gave a reduction of 33.56%, PSO gave a reduction of 32.66% while SGA resulted to a real power reduction percentage of 31.99%. The reduction in reactive power losses was 24.7621Mvar which is about 35.95% of the total reactive power losses in the system before DG installation. The sizes of the DGs chosen are also comparable to the sizes obtained using the other techniques.

### 5.3.3.1 Bus Voltage Profile using Type 2 DG

The voltage profile of the IEEE 30 bus system was also examined after the inclusion of the optimally placed and sized type 2 DGs. The results of the bus voltage levels under this condition were tabulated as shown in Table 5.6 below. This table also gives a comparison of these results to the case without DG inclusion and with DGs placed and sized with other methods. A bar graph was also plotted to facilitate this comparison purpose as shown in figure 5.2.

Table 5.6: A Comparison of Bus Voltages using Type 2 DG

VOLTAGE WITHOUT DG (pu)		VOLTAGE WITH TYPE 2 DG (pu)				VOLTAGE WITHOUT DG (pu)		VOLTAGE WITH TYPE 2 DG (pu)			
Bus No.	LOAD FLOW	SGA[54]	PSO[54]	IPSO[54]	GA-IPSO (This Method)	Bus No.	LOAD FLOW	SGA[54]	PSO[54]	IPSO[54]	GA-IPSO (This Method)
1	1.06	1.06	1.06	1.06	1.06	16	1.025	1.038	1.041	1.038	1.0536
2	1.043	1.043	1.043	1.043	1.043	17	1.011	1.028	1.035	1.03	1.0507
3	1.013	1.025	1.025	1.025	1.0273	18	1.005	1.023	1.029	1.022	1.0499
4	1.003	1.016	1.017	1.016	1.0193	19	1	1.018	1.028	1.018	1.0517
5	1.01	1.01	1.01	1.01	1.01	20	1.002	1.02	1.033	1.021	1.0521
6	1	1.014	1.015	1.015	1.0175	21	1.001	1.021	1.023	1.027	1.048
7	0.992	1.005	1.005	1.005	1.0067	22	1.001	1.023	1.024	1.028	1.0539
8	1.01	1.01	1.01	1.01	1.01	23	1.004	1.037	1.022	1.027	1.0497
9	1.03	1.046	1.048	1.047	1.0589	24	0.991	1.026	1.013	1.025	1.0506
10	1.013	1.031	1.035	1.034	1.0569	25	0.994	1.026	1.022	1.024	1.0435
11	1.072	1.082	1.082	1.082	1.082	26	0.976	1.008	1.004	1.006	1.0263
12	1.045	1.055	1.054	1.054	1.0633	27	1.005	1.034	1.035	1.031	1.0474
13	1.071	1.071	1.071	1.071	1.071	28	0.998	1.015	1.015	1.015	1.0186
14	1.028	1.04	1.039	1.038	1.0516	29	0.985	1.026	1.032	1.023	1.0417
15	1.02	1.038	1.036	1.035	1.0522	30	0.973	1.027	1.037	1.024	1.045

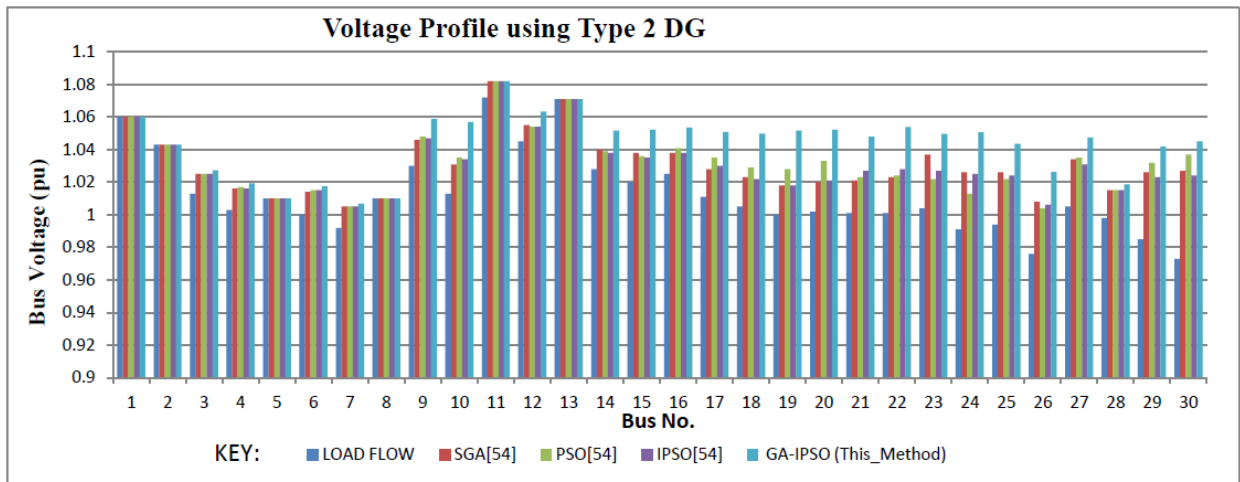


Figure 5.2: A figure showing bus voltage profile comparison using Type 2 DG

Since the multi-objective function used in the location and sizing of the DGs included a voltage profile factor, it can be seen from table 5.6 and figure 5.2 that this helped in achieving a better voltage profile even after inclusion of DGs. The lowest bus voltage was improved from 0.973pu for the case without DGs to a lowest bus voltage of 1.01pu for the case of DGs optimally placed and sized using GA-IPSO method while ensuring that the highest bus voltage level is within the acceptable limit.

### **5.3.4 Results Considering Type 3 DG**

Just like in the previous two cases, table 5.2 was used in obtaining the four optimal locations for the DGs of type 3 and their respective optimal sizes. The locations which gave the minimum fitness values and their respective DG sizes under this DG type were selected. The four selected optimal locations and their respective optimal DG sizes were as follows in order of effectiveness;

1. Bus number 30 with a DG generating 11.3651MW and absorbing 0.5807MVar
2. Bus number 19 with a DG generating 12MW and absorbing 0.4882MVar
3. Bus number 24 with a DG generating 11.9179MW and absorbing 0.0692MVar
4. Bus number 21 with a DG generating 11.9470MW and absorbing 0.5042MVar

Similarly the chosen four DG sizes were assumed to be in their respective locations and a load flow study was done using Newton Raphson method so as to determine the associated power losses and bus voltage levels. The comparison of the results obtained for the power losses is given in the table 5.7. From these results it is vividly clear that GA/IPSO method gave the greatest real power loss reduction margin as compared to the other three methodologies when dealing with type 3 DG. With a real power reduction percentage of 35.21% compared to IPSO's 32.08%, 31.56% from PSO and 30.32% from SGA it is with no doubt that GA-IPSO method performs best among the optimization techniques being compared. Though the reference work under comparison (Yustra et al.) considered only real power losses the results of GA/IPSO showed considerable reduction of reactive power losses in the system. For this type of DG the method gave a percentage reduction in reactive power losses of 35.88%. The sizes of DG obtained using GA-IPSO method also compare well to those obtained using the other methods.

Table 5.7: A comparison of results obtained using Type 3 DG

Methodology	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
		MW-jMVar	MW	Mvar	MW	Mvar	%MW	%Mvar
SGA[54]	10	9.384-j0.088	12.5265	-	5.4509	-	30.32	-
	18	11.112-j0.715						
	22	11.748-j0.589						
	30	10.008-j0.487						
PSO[54]	10	11.885-j0.797	12.1056	-	5.6729	-	31.56	-
	18	10.881-j3						
	20	11.563-j0.899						
	30	11.35-j0.383						
IPSO[54]	10	12-j0.526	12.2099	-	5.7674	-	32.08	-
	19	10.861-j3						
	22	11.917-j2.837						
	30	11.956-j0.526						
GA-IPSO (This Method)	19	12-j0.4882	11.647	44.169	6.3303	24.7191	35.21	35.88
	21	11.947-j0.5042						
	24	11.9179-j0.0692						
	30	11.3651-j0.5807						

### 5.3.4.1 Bus Voltage Profile using Type 3 DG

The bus voltage levels of the IEEE 30 bus system after the inclusion of type 3 DGs was as tabulated in table 5.8 which gives the comparison of the results obtained from this method and those from other techniques. Figure 5.3 also helps in bringing out this comparison more clearly.

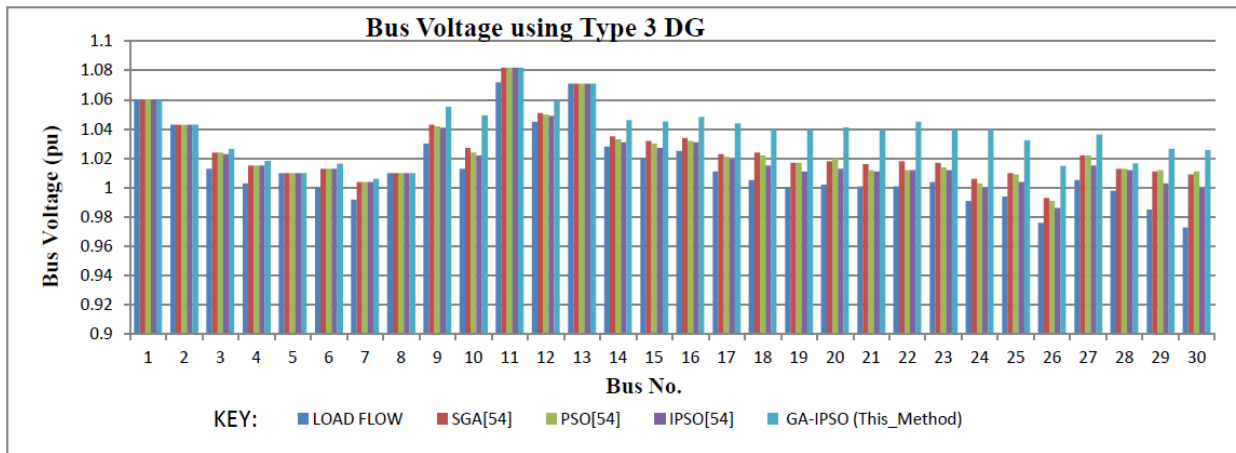


Figure 5.3: A figure showing bus voltage profile comparison using Type 3 DG

Table 5.8: A Comparison of Bus Voltages using Type 3 DG

VOLTAGE WITHOUT DG (pu)		VOLTAGE WITH TYPE 3 DG (pu)				VOLTAGE WITHOUT DG (pu)		VOLTAGE WITH TYPE 3 DG (pu)			
Bus No.	LOAD FLOW	SGA[54]	PSO[54]	IPSO[54]	GA-IPSO (This Method)	Bus No.	LOAD FLOW	SGA[54]	PSO[54]	IPSO[54]	GA-IPSO (This Method)
1	1.06	1.06	1.06	1.06	1.06	16	1.025	1.034	1.032	1.031	1.0483
2	1.043	1.043	1.043	1.043	1.043	17	1.011	1.023	1.021	1.019	1.0439
3	1.013	1.024	1.024	1.023	1.0264	18	1.005	1.024	1.022	1.015	1.0396
4	1.003	1.015	1.015	1.015	1.0182	19	1	1.017	1.017	1.011	1.0394
5	1.01	1.01	1.01	1.01	1.01	20	1.002	1.018	1.02	1.013	1.0411
6	1	1.013	1.013	1.013	1.0164	21	1.001	1.016	1.012	1.011	1.0392
7	0.992	1.004	1.004	1.004	1.006	22	1.001	1.018	1.012	1.012	1.0449
8	1.01	1.01	1.01	1.01	1.01	23	1.004	1.017	1.014	1.012	1.0392
9	1.03	1.043	1.042	1.041	1.0551	24	0.991	1.006	1.003	1	1.0394
10	1.013	1.027	1.024	1.022	1.0495	25	0.994	1.01	1.009	1.004	1.0323
11	1.072	1.082	1.082	1.082	1.082	26	0.976	0.993	0.991	0.986	1.0148
12	1.045	1.051	1.05	1.049	1.0594	27	1.005	1.022	1.022	1.015	1.0363
13	1.071	1.071	1.071	1.071	1.071	28	0.998	1.013	1.013	1.012	1.0166
14	1.028	1.035	1.033	1.031	1.046	29	0.985	1.011	1.012	1.003	1.0265
15	1.02	1.032	1.03	1.027	1.0451	30	0.973	1.009	1.011	1	1.0255

The results given in table 5.8 clearly show that the inclusion of the DGs by optimally placing and sizing them using the GA-IPSO method result to the improvement of the lowest bus voltage level. By using this method to optimize the location and size of type 3 DG the lowest bus voltage level was improved from 0.973pu for the base case scenario without DG inclusion to 1.01pu. At the same time the highest value was maintained at 1.082pu. Thus with this and the affirmation of the bar graph in figure 5.3 the improvement in bus voltage profile can be ascertained.

#### 5.4 Results Using a 33 Bus Test System

The distribution test system used here is the radial IEEE 33-bus test system. The diagram of this test system is shown in Appendix F while its line and bus data are given in Appendix G. The system has 32 sectionalizing branches, 5 tie switches, nominal voltage of 12.66KV and a total system load of 3.72 MW and 2.3 MVAR. Shulka *et al.* (2010) [4] reported the base case system loss of 216.00KW. This value was obtained using backward sweep power flow method. Shulka *et al.* work was only concerned with active power and thus gave only real power losses. It was important to consider other works which gives both active and reactive power losses and thus K. Varesi (2011) [50] work was chosen in this case. This work gives a base case real power loss of 211KW and reactive power loss of 143KVAR on the 33-bus test system using distribution load

flow method. Thus for comparison purposes the real and reactive power losses of the 33-bus test system before DG installation were taken to be 216KW and 143KVAR respectively.

#### 5.4.1 Results for Real and Reactive Power losses

For validation purposes it was important to compare the results obtained when using the GA-IPSO method with those obtained by other researchers. Thus the research works by Shulka *et al.* [4] and K. Varesi [50] were chosen for this purpose. Shulka *et al.* work considered a DG generating real power only and it also emphasized on the reduction of real power losses only. On the other hand K. Varesi not only considered a similar DG but also included the case of a DG generating both real and reactive power losses. He even included both real and reactive power loss reduction with voltage profile improvement to his research objective. This made this work a better reference point for comparison. Thus the GA-IPSO method was used to optimize the size and location of a type 2 DG (DG generating both real and reactive power) in an IEEE 33 bus system. The results obtained were compared to those obtained by the other researchers as shown in the below table.

Table 5.9: Optimal DG location and size with Real and Reactive Power losses comparison

METHODOLOGY	OPTIMAL LOCATION	DG SIZE		POWER LOSS		LOSS REDUCTION		%LOSS REDUCTION	
		KW	Kvar	KW	Kvar	KW	Kvar	$\Delta$ PL	$\Delta$ QL
Backward Sweep Power Flow [4]	(No DG)	(No DG)	(No DG)	216	–	–	–	–	–
Distribution Load flow [50]	(No DG)	(No DG)	(No DG)	211	143	–	–	–	–
Heuristic [4]	Bus 6	2490	–	132.83	–	83.17	–	38.5	–
GA [4]	Bus 6	2380	–	132.64	–	83.36	–	38.59	–
PSO 1 [50]	Bus 6	2591	–	112	83	104	60	48.15	41.96
PSO 2 [50]	Bus 6	2551	1755	68	55	148	88	68.52	61.54
GA-IPSO (This Method)	Bus 6	2563.4	1739.6	66.23	55.42	149.77	87.58	69.34	61.24

As it can be seen from the above table all the methods used for comparison gave bus number 6 as the most optimal location for the DG. The proposed methodology also chooses this same node as is most preferred DG location. It is also noted that the size of DG chosen by the proposed GA/IPSO algorithm lies within range when compared to sizes from other methods in



comparison. Key interest is taken to PSO 2 which considers a DG generating both active and reactive power just like in the proposed methodology and gives a DG size of 2551KW for active power and 1755KVAR for reactive power. The proposed method gives a slightly higher value for the real part of 2563.4KW and a slightly lower value for the reactive power which is 1739.6KVAR. In terms of loss reduction the proposed method gives the highest real power loss reduction of 149.77KW which is around 69.34% of the total real power loss before DG installation. The reactive power loss comparison can be greatly compared to that of the PSO 2 method (the better method) with a reduction of 87.58KVAR which is about 61.24% of the total reactive power loss before DG installation.

#### 5.4.2 Bus Voltages Comparisons

As stated earlier the work by K. Varesi [50] included voltage profile improvement in its objective and thus made a better comparison reference. Table 5.10 below gives a comparison between the bus voltages obtained after optimizing the type 2 DG using the GA-IPSO method and those obtained by K. Varesi (2011) [50]. Table 5.11 gives a comparison on the percentage improvement on lowest bus voltages.

Table 5.10: A Comparison of Bus Voltages in per unit

Bus No.	Load flow	PSO [50]	GA-IPSO (This-Method)	Bus No.	Load flow	PSO [50]	GA-IPSO (This-Method)	Bus No.	Load flow	PSO [50]	GA-IPSO (This-Method)
1	1	1	1	12	0.918	0.961	0.971	23	0.98	0.99	0.992
2	0.998	0.998	0.998	13	0.911	0.954	0.966	24	0.975	0.984	0.986
3	0.982	0.995	0.997	14	0.914	0.953	0.964	25	0.97	0.981	0.982
4	0.979	0.995	0.997	15	0.908	0.951	0.962	26	0.948	0.989	0.998
5	0.965	0.994	0.998	16	0.907	0.95	0.961	27	0.945	0.987	0.998
6	0.945	0.99	1	17	0.905	0.948	0.96	28	0.934	0.978	0.986
7	0.942	0.988	0.998	18	0.904	0.947	0.959	29	0.926	0.968	0.979
8	0.931	0.975	0.985	19	0.998	0.998	0.998	30	0.921	0.965	0.977
9	0.925	0.969	0.98	20	0.996	0.996	0.996	31	0.919	0.961	0.972
10	0.921	0.963	0.972	21	0.995	0.995	0.995	32	0.918	0.96	0.971
11	0.92	0.962	0.972	22	0.994	0.994	0.994	33	0.917	0.96	0.971

Table 5.11: Percentage Improvement on the Lowest Bus Voltage.

METHODOLOGY	LOWEST BUS VOLTAGE (pu)	% VOLTAGE IMPROVEMENT
Load Flow	0.904	–
PSO[50]	0.947	4.757
GA-IPSO (This Method)	0.959	6.084

### 5.4.3 Bus Voltage Profile Improvement

The effect of sizing and locating DG using the proposed method on voltage profile improvement can be clearly seen in Figure 5.4.

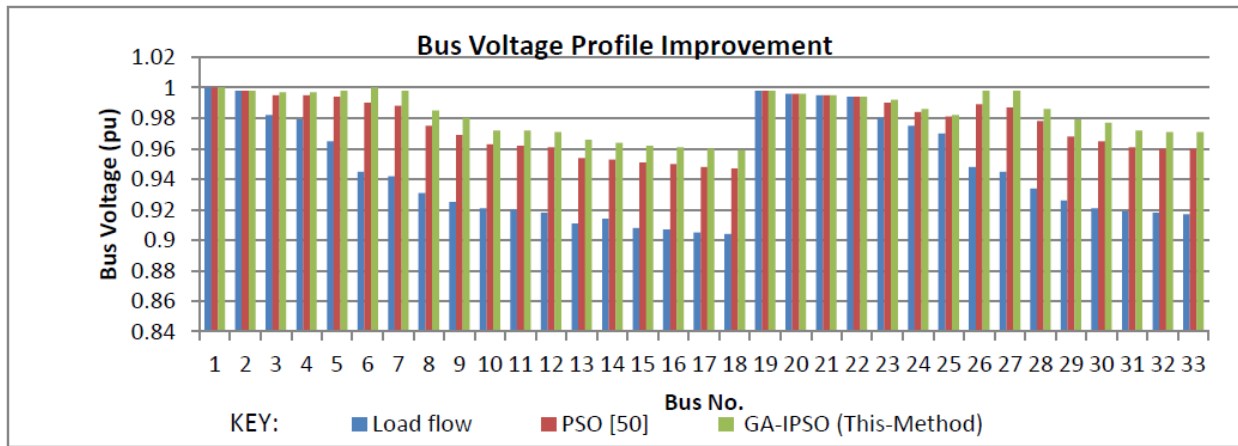


Figure 5.4: A figure showing bus voltage profile improvement

From the results in Table 5.10 and Figure 5.4 it is vividly clear that the proposed methodology results to a better voltage profile improvement in the system. This is because the DG allocation by this methodology results to an improvement in the voltage of nearly all the buses in the system. Table 5.11 shows that the proposed methodology results to a 6.084% increase in the lowest bus voltage by increase it from 0.904pu to 0.959pu as compared to 4.757% given by the PSO method.

### 5.5 Results Using a 57 Bus Test System

The number of DGs to be included in a power network can be limited by several factors. The two main factors are the undesirable effects on power system parameters and the economical factors. This research was mainly concerned with the system power losses and the voltage profile of the

network and thus the effects of DG penetration on these system parameters have been investigated. Having considered both an interconnected and radial distribution networks and verified the robustness of the method, an IEEE 57-bus test system was chosen for this study. The chosen network is as shown in Appendix H. The line data for this network is given in Appendix I while its bus data is given in Appendix J. The DG limits were taken to be as follows so as to have consistency;

- 0MW - 48MW for real power limit (Type 1, 2 and 3 DGs)
- 0Mvar – 12Mvar for reactive power limit (Type 2 DG)
- -12Mvar – 0Mvar for reactive power limit (Type 3 DG)

### 5.5.1 Results for all candidate buses

First the candidate buses were determined by calculating the combined sensitivity factors.

Table 5.12: Results for CSF, Fitness and optimal DG sizes for Multi-type DGs

Candidate Bus	Combined Sensitivity Factor (CSF)	Type 1 DG		Type 2 DG		Type 3 DG	
		Best Fitness	Optimal DG Size (MW)	Best Fitness	Optimal DG Size (MW+jMVar)	Best Fitness	Optimal DG Size (MW-jMVar)
20	2.1061	0.9353	33.2021	0.926	37.6749+j11.9859	0.9353	32.7253-j0.001
21	2.8008	0.9004	46.5596	0.8836	48.0000+j10.4589	0.9013	48.0000-j1.5419
22	2.8791	0.8746	46.8139	0.8611	47.9106+j6.3397	0.8777	48.0000-j6.1658
23	2.9762	0.8766	47.3897	0.866	45.8303+j4.6948	0.8831	46.0081-j7.5359
24	3.2714	0.8922	47.4899	0.8909	45.2434+j9.8077	0.897	47.9426-j6.2209
25	5.4205	0.9045	42.6524	0.894	39.1268+j11.7171	0.9057	35.988-j0.0013
26	3.1434	0.8924	47.0261	0.8878	47.9842+j11.4922	0.8924	47.9842-j0.5083
30	6.3047	0.9117	34.919	0.8988	41.4083+j11.9527	0.9127	30.4329-j0.001
31	7.8862	0.9158	28.9128	0.911	28.6948+j3.3142	0.9251	21.8681-j3.1198
32	8.4795	0.9101	33.9803	0.892	40.9075+j10.5395	0.9109	32.1819-j0.2996
33	8.608	0.9164	30.8295	0.8982	35.4590+j12.0000	0.9164	31.3338-j0.001
34	5.4583	0.8809	42.2194	0.8659	48.0000+j10.2438	0.8809	47.3603-j0.8602
35	5.0239	<b>0.87</b>	47.9067	0.8666	48.0000+j3.5331	0.8864	47.9929-j8.4063
36	4.5135	<b>0.8647</b>	47.2636	<b>0.8518</b>	47.6629+j11.9389	<b>0.8647</b>	47.6629-j0.0618
37	4.0675	<b>0.8703</b>	43.7156	0.8665	43.7301+j6.0236	0.8806	43.7301-j5.9769
38	2.533	0.8725	46.9809	<b>0.8596</b>	48.0000+j5.4762	<b>0.8755</b>	48.0000-j6.8463
39	4.1402	<b>0.8713</b>	47.1203	<b>0.8605</b>	47.9977+j7.6497	0.8837	48.0000-j7.2272
40	4.4436	0.8729	47.9143	<b>0.8589</b>	47.9997+j11.7857	<b>0.8729</b>	47.6203-j1.1514
42	2.2378	0.9017	43.569	0.898	38.8838+j12.0000	0.9037	38.8838-j0.001
48	2.0026	0.881	47.1642	0.8678	48.0000+j11.2684	0.881	48.0000-j0.7325
56	2.8485	0.8758	47.7474	0.8714	46.7052+j11.9966	<b>0.8758</b>	46.7052-j0.0044
57	3.3324	0.9003	43.0099	0.8879	46.8758+j11.8312	0.9003	42.9512-j1.3107

The buses were then arranged in order of sensitivity and those with a combined sensitivity factor of more than 2.0 were selected as the candidate buses. For each candidate bus the optimal DG size was determined together with its associated best fitness for the three types of DGs. The results are as shown in table 5.12 below.

### **5.5.2 Effects of DG penetration on power system losses**

Here a study is done to show the effects of DG penetration on power system losses. Both real and reactive power losses are considered in this case and each type analyzed. The number of DGs was assumed to increase from one, two, three and then four. This was done sequentially ensuring that the candidate bus with the most optimal size was chosen first followed with the others in the same order. Thus the most optimal DG location and size was included in the four cases.

#### **5.5.2.1 Results Considering Type 1 DG**

For this type of DG the four candidate locations chosen in order of priority and their optimal sizes are given as;

1. Bus number 36 with a DG generating 47.2636MW
2. Bus number 35 with a DG generating 47.9067MW
3. Bus number 37 with a DG generating 43.7156MW
4. Bus number 39 with a DG generating 47.1203MW

Table 5.13 gives the results obtained for power losses in the system as the number of DGs in the network is increased from one DG to four DGs.

As it can be seen from table 5.13 the introduction of only one type 1 DG on bus 36 reduced the real power losses from the base case scenario of 28.043MW to 22.583MW and the reactive losses from 153.731Mvar to 131.751Mvar. The inclusion of the second DG in the system further reduced both real and reactive power losses to 22.178MW and 120.69Mvar. The introduction of the third DG reduces only the reactive power losses to 116.903Mvar while on the other hand results to an increase in the real power losses to 23.818MW though this value is still less than the base case real power loss value.

Table 5.13: Effects of type 1 DG penetration on system power losses

Number of DGs	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
			MW	Mvar	MW	Mvar	%MW	%Mvar
<b>One</b>	36	47.2636	22.583	131.751	5.46	21.98	19.47	14.3
<b>Two</b>	36	47.2636	22.178	120.69	5.865	33.041	20.91	21.49
	35	47.9067						
<b>Three</b>	36	47.2636	23.818	116.903	4.225	36.828	15.07	23.96
	35	47.9067						
	37	43.7156						
<b>Four</b>	36	47.2636	28.846	120.153	-0.803	33.578	-2.86	21.84
	35	47.9067						
	37	43.7156						
	39	47.1203						

It is also of interest to note that the inclusion of the fourth DG in the system results to increase in both real and reactive power losses. As a matter of fact the real power losses are increased to a value greater than the case without DG in the network. Thus when considering this type of DG the optimal number of DGs to be placed in this case is two when considering real power losses reduction and three when considering reactive power losses only. This is because the introduction of an additional DG results to an increase in the power losses from the previous case.

### 5.5.2.2 Results Considering Type 2 DG

When a type 2 DG was considered the four candidate locations and their respective optimal DG sizes chosen in order of priority were;

1. Bus number 36 with a DG generating 47.6629MW and 11.9389Mvar
2. Bus number 40 with a DG generating 47.9997MW and 11.7857Mvar
3. Bus number 38 with a DG generating 48MW and 5.4762Mvar
4. Bus number 39 with a DG generating 47.9977MW and 7.6497Mvar

The results obtained in this case were tabulated in table 5.14 as shown;

Table 5.14: Effects of type 2 DG penetration on system power losses

Number of DGs	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
		MW+jMVar	MW	Mvar	MW	Mvar	%MW	%Mvar
One	36	47.6629+j11.9389	21.764	131.309	6.279	22.422	22.39	14.59
Two	36	47.6629+j11.9389	21.216	122.358	6.827	31.373	24.34	20.41
	40	47.9997+j11.7857						
Three	36	47.6629+j11.9389	19.137	112.787	8.906	40.944	31.76	26.63
	40	47.9997+j11.7857						
	38	48+j5.4762						
Four	36	47.6629+j11.9389	22.023	113.789	6.02	39.942	21.47	25.98
	40	47.9997+j11.7857						
	38	48+j5.4762						
	39	47.9977+j7.6497						

From the results tabulated above, the introduction of the first optimally placed and sized type 2 DG in the network reduced the real power losses from the base case value of 28.043MW to 21.764MW and the reactive power losses from 153.731Mvar to 131.309Mvar. The inclusion of the second and third DG in the network further reduces the real power losses to 21.216MW and 19.137MW and the reactive power losses to 122.358Mvar and 112.787Mvar respectively. It is evident that the introduction of the fourth DG in the network increases both real and reactive power losses in the system from the previous case. Thus the optimal number of DGs for real reactive power loss reduction when considering this type of DG was determined to be three.

### 5.5.2.3 Results Considering Type 3 DG

The four candidate locations chosen and their optimal DG sizes in order of priority for investigating the effects of type 3 DG penetration on system power losses were;

1. Bus number 36 with a DG generating 47.6629MW and absorbing 0.0618Mvar
2. Bus number 40 with a DG generating 47.6203MW and absorbing 1.1514Mvar
3. Bus number 38 with a DG generating 48MW and absorbing 6.8463Mvar
4. Bus number 56 with a DG generating 46.7052MW and absorbing 0.0044Mvar

Table 5.15 gives the results of the power losses obtained when the above chosen DGs are placed in their respective locations starting with one DG the two, three and finally four DGs.

Table 5.15: Effects of type 3 DG penetration on system power losses

Number of DGs	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
		MW-jMVar	MW	Mvar	MW	Mvar	%MW	%Mvar
<b>One</b>	36	47.6629-j0.0618	22.566	131.621	5.477	22.11	19.53	14.38
<b>Two</b>	36	47.6629-j0.0618	22.345	121.093	5.698	32.638	20.32	21.23
	40	47.6203-j1.1514						
<b>Three</b>	36	47.6629-j0.0618	20.104	111.248	7.939	42.483	28.31	27.63
	40	47.6203-j1.1514						
	38	48-j6.8463						
<b>Four</b>	36	47.6629-j0.0618	22.656	107.823	5.387	45.908	19.21	29.86
	40	47.6203-j1.1514						
	38	48-j6.8463						
	56	46.7052-j0.0044						

The optimal placement and sizing of the first DG in the network results to a decrease in real power losses of the system from a base case loss of 28.043MW to 22.566MW and reactive power losses from 153.731Mvar to 131.621Mvar. The introduction of the second and third DGs in the network further reduces the real power losses to 22.345MW and 20.104MW and reactive power losses to 121.093Mvar and 111.248Mvar respectively. It is important to note that though the inclusion of the fourth DG in the network results to a further reduction in reactive power losses to 107.823Mvar, it results to an increase of real power losses from the previous 20.104MW to 22.656MW though this value is still less than the base case real power loss value. Thus the optimal number of DGs in the system is three when considering real power losses but the four DGs can be included in the network if the objective is to reduce reactive power losses.

### 5.5.3 Effect of DG penetration on Bus Voltage Profile

Other than system power losses, bus voltage profile was another key power system parameter of interest in this research work. Thus the effects of DG penetration on voltage profile were investigated for the three types of DGs. Table 5.16 shows a comparison of lower bus voltages for the case without DG and with different DG types and penetration in the network. Figure 5.5 also gives this comparison in terms of a bar graph.

Table 5.16: Lowest Bus Voltages for different DG types and DG numbers

Number of DGs	Lowest Bus Voltage (pu)			
	Without DG	Type 1 DG	Type 2 DG	Type 3 DG
One	0.9353	0.9459	0.9578	0.9459
Two		0.9586	0.9663	0.9578
Three		0.962	0.9754	0.9676
Four		0.9635	0.9807	0.9707

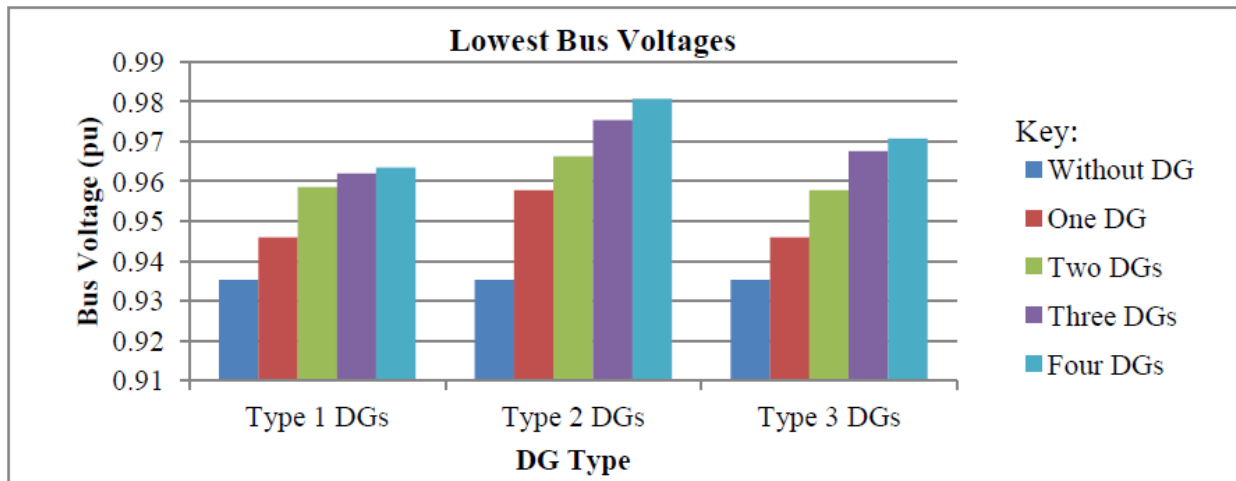


Figure 5.5: A graph of the lowest bus voltages for different DG types and DG numbers

From both table 5.16 and figure 5.5 above it can be seen that all the three cases resulted to an increase in the lowest bus voltage level. It also important to note that there was an increase for each additional DG added in the network up to the fourth DG. Since the most ideal case was to have this voltage as close to 1pu as possible it can be concluded that type 2 DG performed better in this case compared to the other two types. This is because its lowest bus voltage level with four DGs in the system was 0.9807pu, though this might compromise the highest bus voltage value as evident in table 5.17. Table 5.17 gives the comparison in the highest bus voltages for different DG types and penetration which is further represented in the graph of figure 5.6.



Table 5.17: Highest Bus Voltages for different DG types and DG numbers

Number of DGs	Highest Bus Voltage (pu)			
	Without DG	Type 1 DG	Type 2 DG	Type 3 DG
One	1.059	1.0664	1.0747	1.0663
Two		1.0709	1.1153	1.0701
Three		1.0899	1.129	1.0799
Four		1.1049	1.1589	1.1059

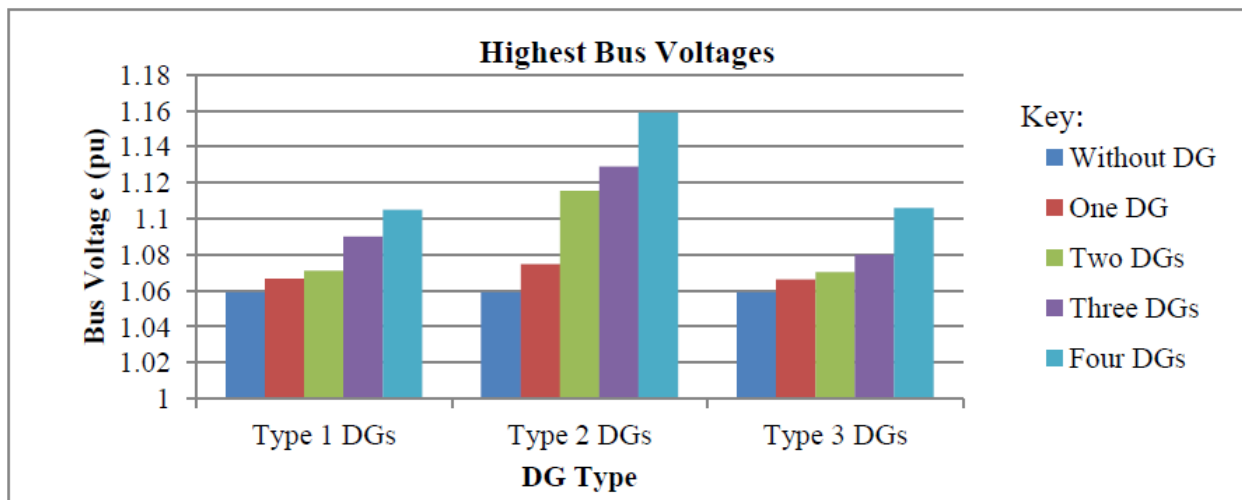


Figure 5.6: A graph of the highest bus voltages for different DG types and DG numbers

With the effects of the different DG types and numbers on lowest bus voltage in mind it can be seen that the same effects are shown for the highest bus voltages. That is all the three types of DGs results to an increase in the highest bus voltage level with an increase in number of DGs in the network. This increase might limit the number of DGs to be included in a system depending on the voltage limit specifications given by the particular country's regulation authorities.

## CHAPTER 6: CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

### 6.1 Conclusion

In conclusion, this research work showed the formulation and implementation of a hybridized GA-IPSO algorithm to help in reducing system power losses and improving voltage profile by optimizing the location and size of multi-type DG(s). The combined sensitivity factors were formulated and used effectively in reducing the search space for algorithm. For the IEEE 30-bus test system 14 candidate buses were chosen and for IEEE 57-bus system 22 candidate buses were chosen as possible DG locations. As seen from the results the GA-IPSO method gave the greatest loss reduction when compared to SGA, PSO and IPSO methods in all the three types of DGs considered using the IEEE 30-bus system. The percentage reduction in real power loss was 35.46%, 35.82% and 35.21% while the percentage reactive power loss reduction was 36.01%, 35.95% and 35.88% for type 1, type 2 and type 3 DGs respectively. The voltage profile was generally improved with lowest bus voltages of 1.01pu in all the three cases.

The GA-IPSO method also performed well in reducing the losses and improving the voltage profile of the IEEE 33-bus test system. The algorithm chose bus number 6 as the optimal DG location and reduced the real and reactive power losses by 149.77MW and 87.58Mvar respectively. The method also improved the lowest bus voltage from a value of 0.904pu to 0.959pu. Thus the GA-IPSO method proved more suited for this optimization as compared to Heuristic, GA, IPSO 1 and IPSO two methods. After using the GA-IPSO method to study the effects of DG penetration on power losses and voltage profile it was clearly shown that the system power losses reduced with the introduction on DGs in to the network up to an optimal number where any further DG inclusion resulted to an increase in system power losses. The voltage profile also behaved in a similar manner where further DG introduction from the optimal number resulted to deviation of bus voltages outside the acceptable limits.

Thus the objectives of the research work were achieved successfully and the implemented GA-IPSO method was proved to be a better method for optimizing the location and size of multi-type DGs in different power networks with the aim of reducing both real and reactive power losses and improving network voltage profiles.

## **6.2 Beneficiaries of this work**

This research work is beneficial to different parties both directly and indirectly. The direct beneficiaries of this research work are the distribution companies. Some of the direct benefits from this work to the DISCOs include;

- This research work will help the distribution companies in reducing both real and reactive power losses in their networks. This reduction in losses will enable them avoid some of the penalties and compensations they incur and hence result to an improvement in their profit margins.
- The research work will also ensure that they improve the voltage levels at the consumers to the required limits. This will enable the DISCOs to avoid the costs incurred during compensation of spoilt customer equipment due to voltage deviations outside the acceptable limits. As a result this makes the companies more economical and reliable in operation.
- The work will help the power companies incorporate small-sized green energy sources to their networks easily and more reliably. This is of much importance due to the changing attention in power production with the shifting in green energy.

Other parties will also benefit substantially from this research work. An example of this is the end customers who will feel secure knowing that they are operating their machines with stable voltage profiles. All these benefits relate back to the country's economy as a whole and thus the whole community.

## **6.3 Recommendations for Future Work**

1. After programming the code in Matlab 2011, long iteration time was noted and thus more work can be done in trying to reduce this time.
2. The Multi-objective function can be improved by taking into consideration other power system parameters like stability issues.

## RESEARCH PAPERS OUT OF THIS PRESENT WORK PUBLISHED IN INTERNATIONAL JOURNALS

- Julius Kilonzi Charles and Dr. Nicodemus Abungu Odero, “*A GA/PSO based approach for system loss reduction and voltage profile improvement employing arithmetic crossover and mutation*”, International Journal of Engineering Science and Technology (IJEST) ISSN : 0975-5462 , Vol. 5 No.07, July 2013 pp 1501-1510
- Julius Kilonzi Charles and Dr. Nicodemus Abungu Odero, “*Effects of Distributed Generation penetration on system power losses and voltage profiles*”, International Journal of Scientific and Research Publications (IJSRP), ISSN: 2250-3153, Volume 3, Issue 12, December 2013 Edition.
- Julius Kilonzi Charles and Dr. Nicodemus Abungu Odero, “*A combined sensitivity factor based GA-IPSO approach for system loss reduction and voltage profile enhancement*”, International Journal of Innovative Research in Engineering and Science (IJRES) ISSN: 2319-5665, December 2013, issue 2, volume 12.

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## APPENDICES:

### Appendix A: Power Flow Sensitivity Factor Formulation

The equation below gives the change in real and reactive power flow.

$$\begin{bmatrix} \Delta P_{ij} \\ \Delta Q_{ij} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} & \frac{\partial P_{ij}}{\partial v} \\ \frac{\partial Q_{ij}}{\partial \delta} & \frac{\partial Q_{ij}}{\partial v} \end{bmatrix} [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (\text{A.1})$$

Using this equation the real and reactive power flow sensitivity factors can be determined.

$$\begin{bmatrix} \Delta P_{ij} \\ \Delta Q_{ij} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} & \frac{\partial P_{ij}}{\partial v} \\ \frac{\partial Q_{ij}}{\partial \delta} & \frac{\partial Q_{ij}}{\partial v} \end{bmatrix} \begin{bmatrix} J_{11}^* & J_{12}^* \\ J_{21}^* & J_{22}^* \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (\text{A.2})$$

$$= \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} & \frac{\partial P_{ij}}{\partial v} \\ \frac{\partial Q_{ij}}{\partial \delta} & \frac{\partial Q_{ij}}{\partial v} \end{bmatrix} \begin{bmatrix} J_{11}^* \Delta P_n + J_{12}^* \Delta Q_n \\ J_{21}^* \Delta P_n + J_{22}^* \Delta Q_n \end{bmatrix} \quad (\text{A.3})$$

$$= \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} (J_{11}^* \Delta P_n + J_{12}^* \Delta Q_n) + \frac{\partial P_{ij}}{\partial v} (J_{21}^* \Delta P_n + J_{22}^* \Delta Q_n) \\ \frac{\partial Q_{ij}}{\partial \delta} (J_{11}^* \Delta P_n + J_{12}^* \Delta Q_n) + \frac{\partial Q_{ij}}{\partial v} (J_{21}^* \Delta P_n + J_{22}^* \Delta Q_n) \end{bmatrix} \quad (\text{A.4})$$

From the above matrix the changes in real and reactive power losses can now be expressed as;

$$\Delta P_{ij} = J_{11}^* \Delta P_n \frac{\partial P_{ij}}{\partial \delta} + J_{12}^* \Delta Q_n \frac{\partial P_{ij}}{\partial \delta} + J_{21}^* \Delta P_n \frac{\partial P_{ij}}{\partial v} + J_{22}^* \Delta Q_n \frac{\partial P_{ij}}{\partial v} \quad (\text{A.5})$$

$$\Delta Q_{ij} = J_{11}^* \Delta P_n \frac{\partial Q_{ij}}{\partial \delta} + J_{12}^* \Delta Q_n \frac{\partial Q_{ij}}{\partial \delta} + J_{21}^* \Delta P_n \frac{\partial Q_{ij}}{\partial v} + J_{22}^* \Delta Q_n \frac{\partial Q_{ij}}{\partial v} \quad (\text{A.6})$$

From the above two equations we deduce that;

$$\frac{\Delta P_{ij}}{\Delta P_n} \cong \frac{\partial P_{ij}}{\partial P_n} = J_{11}^* \frac{\partial P_{ij}}{\partial \delta} + J_{21}^* \frac{\partial P_{ij}}{\partial v} \quad (\text{A.7})$$

$$\frac{\Delta P_{ij}}{\Delta Q_n} \cong \frac{\partial P_{ij}}{\partial Q_n} = J_{12}^* \frac{\partial P_{ij}}{\partial \delta} + J_{22}^* \frac{\partial P_{ij}}{\partial v} \quad (\text{A.8})$$

$$\frac{\Delta Q_{ij}}{\Delta Q_n} \cong \frac{\partial Q_{ij}}{\partial Q_n} = J_{12}^* \frac{\partial Q_{ij}}{\partial \delta} + J_{22}^* \frac{\partial Q_{ij}}{\partial v} \quad (\text{A.9})$$

$$\frac{\Delta Q_{ij}}{\Delta P_n} \cong \frac{\partial Q_{ij}}{\partial P_n} = J_{11}^* \frac{\partial Q_{ij}}{\partial \delta} + J_{21}^* \frac{\partial Q_{ij}}{\partial v} \quad (\text{A.10})$$

These equations can be re-arranged as shown below;

$$\begin{bmatrix} \frac{\partial P_{ij}}{\partial P_n} \\ \frac{\partial P_{ij}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} F_{P-P} \\ F_{P-Q} \end{bmatrix} = \begin{bmatrix} J_{11}^* & J_{21}^* \\ J_{12}^* & J_{22}^* \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} \\ \frac{\partial P_{ij}}{\partial v} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial P_{ij}}{\partial \delta} \\ \frac{\partial P_{ij}}{\partial v} \end{bmatrix} \quad (\text{A.11})$$

$$\begin{bmatrix} \frac{\partial Q_{ij}}{\partial P_n} \\ \frac{\partial Q_{ij}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} F_{Q-P} \\ F_{Q-Q} \end{bmatrix} = \begin{bmatrix} J_{11}^* & J_{21}^* \\ J_{12}^* & J_{22}^* \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial Q_{ij}}{\partial \delta} \\ \frac{\partial Q_{ij}}{\partial V} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial Q_{ij}}{\partial \delta} \\ \frac{\partial Q_{ij}}{\partial V} \end{bmatrix} \quad (\text{A.12})$$

Where;

$F_{P-P}$  is the real power flow sensitivity related to the real power injection.

$F_{P-Q}$  is the active flow sensitivity related to the reactive power injection.

$F_{Q-P}$  is the reactive power flow sensitivity related to the active power injection.

$F_{Q-Q}$  is the reactive power flow sensitivity related to the reactive power injection.

$J$  is the Jacobian matrix of power flow, and the superscript  $T$  indicates the transpose.

## Appendix B: Power Flow Sensitivity Factor Formulation

The equation below gives the change in real and reactive power losses.

$$\begin{bmatrix} \Delta P_{L(ij)} \\ \Delta Q_{L(ij)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} & \frac{\partial P_{L(ij)}}{\partial V} \\ \frac{\partial Q_{L(ij)}}{\partial \delta} & \frac{\partial Q_{L(ij)}}{\partial V} \end{bmatrix} [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (\text{B.1})$$

Using this equation the real and reactive power loss sensitivity factors can be determined. We have;

$$\begin{bmatrix} \Delta P_{L(ij)} \\ \Delta Q_{L(ij)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} & \frac{\partial P_{L(ij)}}{\partial V} \\ \frac{\partial Q_{L(ij)}}{\partial \delta} & \frac{\partial Q_{L(ij)}}{\partial V} \end{bmatrix} \begin{bmatrix} J_{11}^* & J_{12}^* \\ J_{21}^* & J_{22}^* \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (\text{B.2})$$

$$= \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} & \frac{\partial P_{L(ij)}}{\partial V} \\ \frac{\partial Q_{L(ij)}}{\partial \delta} & \frac{\partial Q_{L(ij)}}{\partial V} \end{bmatrix} \begin{bmatrix} J_{11}^* \Delta P_n + J_{12}^* \Delta Q_n \\ J_{21}^* \Delta P_n + J_{22}^* \Delta Q_n \end{bmatrix} \quad (\text{B.3})$$

$$= \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} (J_{11}^* \Delta P_n + J_{12}^* \Delta Q_n) + \frac{\partial P_{L(ij)}}{\partial V} (J_{21}^* \Delta P_n + J_{22}^* \Delta Q_n) \\ \frac{\partial Q_{L(ij)}}{\partial \delta} (J_{11}^* \Delta P_n + J_{12}^* \Delta Q_n) + \frac{\partial Q_{L(ij)}}{\partial V} (J_{21}^* \Delta P_n + J_{22}^* \Delta Q_n) \end{bmatrix} \quad (\text{B.4})$$

From the above matrix the changes in real and reactive power losses can now be expressed as;

$$\Delta P_{L(ij)} = J_{11}^* \Delta P_n \frac{\partial P_{L(ij)}}{\partial \delta} + J_{12}^* \Delta Q_n \frac{\partial P_{L(ij)}}{\partial \delta} + J_{21}^* \Delta P_n \frac{\partial P_{L(ij)}}{\partial V} + J_{22}^* \Delta Q_n \frac{\partial P_{L(ij)}}{\partial V} \quad (\text{B.5})$$

$$\Delta Q_{L(ij)} = J_{11}^* \Delta P_n \frac{\partial Q_{L(ij)}}{\partial \delta} + J_{12}^* \Delta Q_n \frac{\partial Q_{L(ij)}}{\partial \delta} + J_{21}^* \Delta P_n \frac{\partial Q_{L(ij)}}{\partial V} + J_{22}^* \Delta Q_n \frac{\partial Q_{L(ij)}}{\partial V} \quad (\text{B.6})$$

From the above two equations we deduce that;

$$\frac{\Delta P_{L(ij)}}{\Delta P_n} \cong \frac{\partial P_{L(ij)}}{\partial P_n} = J_{11}^* \frac{\partial P_{L(ij)}}{\partial \delta} + J_{21}^* \frac{\partial P_{L(ij)}}{\partial V} \quad (\text{B.7})$$

$$\frac{\Delta P_{L(ij)}}{\Delta Q_n} \cong \frac{\partial P_{L(ij)}}{\partial Q_n} = J_{12}^* \frac{\partial P_{L(ij)}}{\partial \delta} + J_{22}^* \frac{\partial P_{L(ij)}}{\partial V} \quad (\text{B.8})$$

$$\frac{\Delta Q_{L(ij)}}{\Delta Q_n} \cong \frac{\partial Q_{L(ij)}}{\partial Q_n} = J_{12}^* \frac{\partial Q_{L(ij)}}{\partial \delta} + J_{22}^* \frac{\partial Q_{L(ij)}}{\partial V} \quad (\text{B.9})$$

$$\frac{\Delta Q_{L(ij)}}{\Delta P_n} \cong \frac{\partial Q_{L(ij)}}{\partial P_n} = J_{11}^* \frac{\partial Q_{L(ij)}}{\partial \delta} + J_{21}^* \frac{\partial Q_{L(ij)}}{\partial V} \quad (\text{B.10})$$

These equations can be re-arranged as shown below;

$$\begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial P_n} \\ \frac{\partial P_{L(ij)}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} S_{P-P} \\ S_{P-Q} \end{bmatrix} = \begin{bmatrix} J_{11}^* & J_{21}^* \\ J_{12}^* & J_{22}^* \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} \\ \frac{\partial P_{L(ij)}}{\partial V} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta} \\ \frac{\partial P_{L(ij)}}{\partial V} \end{bmatrix} \quad (\text{B.11})$$

$$\begin{bmatrix} \frac{\partial Q_{L(ij)}}{\partial P_n} \\ \frac{\partial Q_{L(ij)}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} S_{Q-P} \\ S_{Q-Q} \end{bmatrix} = \begin{bmatrix} J_{11}^* & J_{21}^* \\ J_{12}^* & J_{22}^* \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial Q_{L(ij)}}{\partial \delta} \\ \frac{\partial Q_{L(ij)}}{\partial V} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial Q_{L(ij)}}{\partial \delta} \\ \frac{\partial Q_{L(ij)}}{\partial V} \end{bmatrix} \quad (\text{B.12})$$

Where;

$S_{P-P}$  is the real power loss sensitivity related to the real power injection.

$S_{P-Q}$  is the active loss sensitivity related to the reactive power injection.

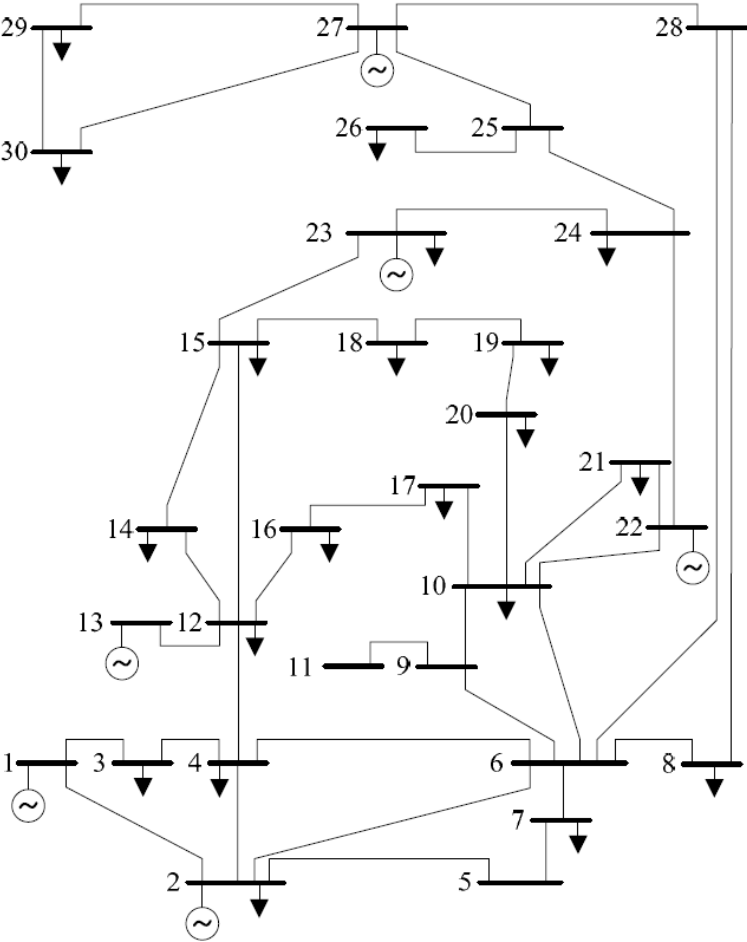
$S_{Q-P}$  is the reactive power loss sensitivity related to the active power injection.

$S_{Q-Q}$  is the reactive power loss sensitivity related to the reactive power injection.

$J$  is the Jacobian matrix of power flow, and the superscript  $T$  indicates the transpose.



**Appendix C: IEEE 30-bus test system**



Appendix D: Line data for 30-bus test system

Line No.	From Bus	To Bus	Line Impedance		Half Line Charging Susceptance (p.u.)	MVA Rating
			Resistance (p.u.)	Reactance (p.u.)		
1	1	2	0.0192	0.0575	0.0264	130
2	1	3	0.0452	0.1652	0.0204	130
3	2	4	0.0570	0.1737	0.0184	65
4	3	4	0.0132	0.0379	0.0042	130
5	2	5	0.0472	0.1983	0.0209	130
6	2	6	0.0581	0.1763	0.0187	65
7	4	6	0.0119	0.0414	0.0045	90
8	5	7	0.0460	0.1160	0.0102	70
9	6	7	0.0267	0.0820	0.0085	130
10	6	8	0.0120	0.0420	0.0045	32
11	6	9	0	0.2080	0	65
12	6	10	0	0.5560	0	32
13	9	11	0	0.2080	0	65
14	9	10	0	0.1100	0	65
15	4	12	0	0.2560	0	65
16	12	13	0	0.1400	0	65
17	12	14	0.1231	0.2559	0	32
18	12	15	0.0662	0.1304	0	32
19	12	16	0.0945	0.1987	0	16
20	14	15	0.2210	0.1997	0	16
21	16	17	0.0524	0.1923	0	16
22	15	18	0.1073	0.2185	0	16
23	18	19	0.0639	0.1292	0	16
24	19	20	0.0340	0.0680	0	16
25	10	20	0.0936	0.2090	0	32

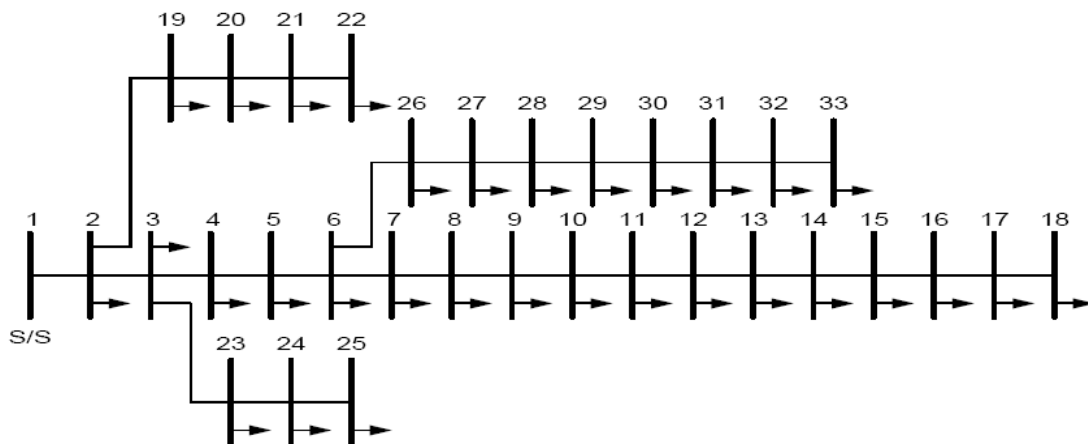
26	10	17	0.0324	0.0845	0	32
27	10	21	0.0348	0.0749	0	32
28	10	22	0.0727	0.1499	0	32
29	21	22	0.0116	0.0236	0	32
30	15	23	0.1000	0.2020	0	16
31	22	24	0.1150	0.1790	0	16
32	23	24	0.1320	0.2700	0	16
33	24	25	0.1885	0.3292	0	16
34	25	26	0.2544	0.3800	0	16
35	25	27	0.1093	0.2087	0	16
36	28	27	0	0.3960	0	65
37	27	29	0.2198	0.4153	0	16
38	27	30	0.3202	0.6027	0	16
39	29	30	0.2399	0.4533	0	26
40	8	28	0.0636	0.2000	0.0214	32
41	6	28	0.0169	0.0599	0.0065	32

### Appendix E: Bus data and load flow results for 30-bus test system

Bus No.	Bus Voltage		Generation		Load		Reactive Power Limits	
	Magnitude (p.u.)	Phase Angle (degrees)	Real Power (p.u.)	Reactive Power (p.u.)	Real Power (p.u.)	Reactive Power (p.u.)	$Q_{min}$ (p.u.)	$Q_{max}$ (p.u.)
1	1.06	0.000	1.3848	-0.0279	0.000	0.000	-	-
2	1.045	0.000	0.4	0.5	0.217	0.127	-0.2	0.6
3	1.000	0.000	0.000	0.000	0.024	0.012	-	-
4	1.060	0.000	0.000	0.000	0.076	0.016	-	-
5	1.010	0.000	0.000	0.37	0.942	0.19	-0.15	0.625
6	1.000	0.000	0.000	0.000	0.000	0.000	-	-
7	1.000	0.000	0.000	0.000	0.228	0.109	-	-
8	1.010	0.000	0.000	0.373	0.3	0.3	-0.15	0.50
9	1.000	0.000	0.000	0.000	0.000	0.000	-	-
10	1.000	0.000	0.000	0.000	0.058	0.02	-	-
11	1.082	0.000	0.000	0.162	0.000	0.000	-0.10	0.40
12	1.000	0.000	0.000	0.000	0.112	0.075	-	-
13	1.071	0.000	0.000	0.106	0.000	0.000	-0.15	0.45
14	1.000	0.000	0.000	0.000	0.062	0.016	-	-
15	1.000	0.000	0.000	0.000	0.082	0.025	-	-
16	1.000	0.000	0.000	0.000	0.035	0.018	-	-
17	1.000	0.000	0.000	0.000	0.09	0.058	-	-
18	1.000	0.000	0.000	0.000	0.032	0.009	-	-
19	1.000	0.000	0.000	0.000	0.095	0.034	-	-

20	1.000	0.000	0.000	0.000	0.022	0.007	-	-
21	1.000	0.000	0.000	0.000	0.175	0.112	-	-
22	1.000	0.000	0.000	0.000	0.000	0.000	-	-
23	1.000	0.000	0.000	0.000	0.032	0.016	-	-
24	1.000	0.000	0.000	0.000	0.087	0.067	-	-
25	1.000	0.000	0.000	0.000	0.000	0.000	-	-
26	1.000	0.000	0.000	0.000	0.035	0.023	-	-
27	1.000	0.000	0.000	0.000	0.000	0.000	-	-
28	1.000	0.000	0.000	0.000	0.000	0.000	-	-
29	1.000	0.000	0.000	0.000	0.024	0.009	-	-
30	1.000	0.000	0.000	0.000	0.106	0.019	-	-

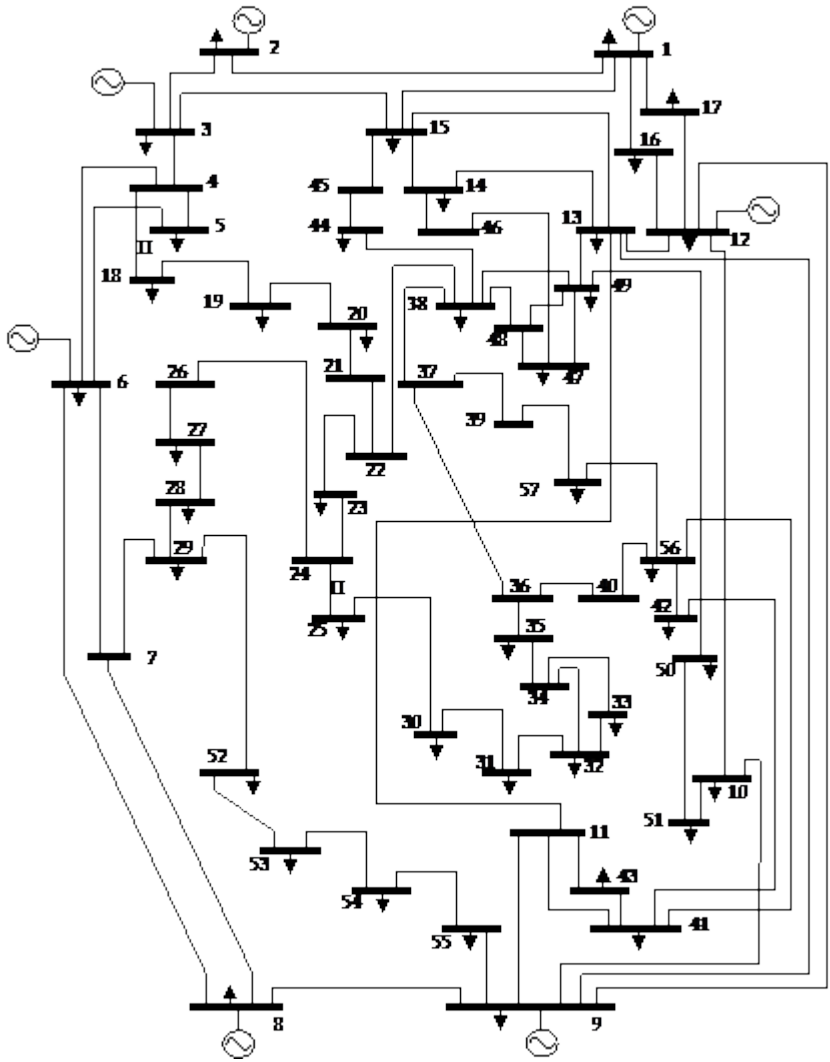
## Appendix F: IEEE 33-bus test system



### Appendix G: Line and Bus data for IEEE 33-bus test system

Sending Bus	Receiving Bus	R ( $\Omega$ )	X ( $\Omega$ )	Load at Receiving Bus	
				P (kW)	Q (kVAr)
1	2	0.0922	0.0477	100	60
2	3	0.4930	0.2511	90	40
3	4	0.3660	0.1864	120	80
4	5	0.3811	0.1941	60	30
5	6	0.8190	0.7070	60	20
6	7	0.1872	0.6188	200	100
7	8	1.7114	1.2351	200	100
8	9	1.0300	0.7400	60	20
9	10	1.0400	0.7400	60	20
10	11	0.1966	0.0650	45	30
11	12	0.3744	0.1238	60	35
12	13	1.4680	1.1550	60	35
13	14	0.5416	0.7129	120	80
14	15	0.5910	0.5260	60	10
15	16	0.7463	0.5450	60	20
16	17	1.2890	1.7210	60	20
17	18	0.7320	0.5740	90	40
2	19	0.1640	0.1565	90	40
19	20	1.5042	1.3554	90	40
20	21	0.4095	0.4784	90	40
21	22	0.7089	0.9373	90	40
3	23	0.4512	0.3083	90	50
23	24	0.8980	0.7091	520	200
24	25	0.6960	0.7011	320	200
6	26	0.2030	0.1034	60	25
26	27	0.2842	0.1447	60	25
27	28	1.0590	0.9337	60	20
28	29	0.8042	0.7006	120	70
29	30	0.5075	0.2585	200	600
30	31	0.9744	0.9630	250	70
31	32	0.3105	0.3619	210	100
32	33	0.3410	0.5302	60	40

Appendix H: IEEE 57-bus test system



**Appendix I: Line data for IEEE 57-bus test system**

Line No.	From Bus	To Bus	Line Impedance		Half Line Charging Susceptance (p.u)
			Resistance (p.u)	Reactance (p.u)	
1	1	2	0.0083	0.028	0.0645
2	2	3	0.0298	0.085	0.0409
3	3	4	0.0112	0.0366	0.0190
4	4	5	0.0625	0.132	0.0129
5	4	6	0.043	0.148	0.0174
6	6	7	0.02	0.102	0.0138
7	6	8	0.0339	0.173	0.0235
8	8	9	0.0099	0.0505	0.0274
9	9	10	0.0369	0.1679	0.0220
10	9	11	0.0258	0.0848	0.0109
11	9	12	0.0648	0.295	0.0386
12	9	13	0.0481	0.158	0.0203
13	13	14	0.0132	0.0434	0.0055
14	13	15	0.0269	0.0869	0.0115
15	1	15	0.0178	0.091	0.0494
16	1	16	0.0454	0.206	0.0273
17	1	17	0.0238	0.108	0.0143
18	3	15	0.0162	0.053	0.0272



19	4	18	0	0.555	0
20	4	18	0	0.43	0
21	5	6	0.0302	0.0641	0.0062
22	7	8	0.0139	0.0712	0.0097
23	10	12	0.0277	0.1262	0.0164
24	11	13	0.0223	0.0732	0.0094
25	12	13	0.0178	0.058	0.0302
26	12	16	0.018	0.0813	0.0108
27	12	17	0.0397	0.179	0.0238
28	14	15	0.0171	0.0547	0.0074
29	18	19	0.461	0.685	0
30	19	20	0.283	0.434	0
31	21	20	0	0.7767	0
32	21	22	0.0736	0.117	0
33	22	23	0.0099	0.0152	0
34	23	24	0.166	0.256	0.0042
35	24	25	0	1.182	0
36	24	25	0	1.23	0
37	24	26	0	0.0473	0
38	26	27	0.165	0.254	0
39	27	28	0.0618	0.0954	0
40	28	29	0.0418	0.0587	0
41	7	29	0	0.0648	0
42	25	30	0.135	0.202	0
43	30	31	0.326	0.497	0
44	31	32	0.507	0.755	0
45	32	33	0.0392	0.036	0
46	34	32	0	0.953	0
47	34	35	0.052	0.078	0.0016

48	35	36	0.043	0.0537	0.0008
49	36	37	0.029	0.0366	0
50	37	38	0.0651	0.1009	0.0010
51	37	39	0.0239	0.0379	0
52	36	40	0.03	0.0466	0
53	22	38	0.0192	0.0295	0
54	11	41	0	0.749	0
55	41	42	0.207	0.352	0
56	41	43	0	0.412	0
57	38	44	0.0289	0.0585	0.0010
58	15	45	0	0.1042	0
59	14	46	0	0.0735	0
60	46	47	0.023	0.068	0.0016
61	47	48	0.0182	0.0233	0
62	48	49	0.0834	0.129	0.0024
63	49	50	0.0801	0.128	0
64	50	51	0.1386	0.22	0
65	10	51	0	0.0712	0
66	13	49	0	0.191	0
67	29	52	0.1442	0.187	0
68	52	53	0.0762	0.0984	0
69	53	54	0.1878	0.232	0
70	54	55	0.1732	0.2265	0
71	11	43	0	0.153	0
72	44	45	0.0624	0.1242	0.0020
73	40	56	0	1.195	0
74	56	41	0.553	0.549	0
75	56	42	0.2125	0.354	0
76	39	57	0	1.355	0

77	57	56	0.174	0.26	0
78	38	49	0.115	0.177	0.0030
79	38	48	0.0312	0.0482	0
80	9	55	0	0.1205	0

**Appendix J: Bus data and load flow results for IEEE 57-bus test system**

Bus No.	Bus Voltage		Generation		Load		Reactive Power Limits	
	Magnitude (p.u)	Phase Angle (degrees)	Real Power (p.u)	Reactive Power (p.u)	Real Power (p.u)	Reactive Power (p.u)	$Q_{min}$ (p.u)	$Q_{max}$ (p.u)
1	1.040	0.000	4.78	1.289	0.55	0.17	-	-
2	1.010	0.000	0.000	-0.008	0.03	0.88	-0.17	0.50
3	0.985	0.000	0.4	-0.01	0.41	0.21	-0.10	0.60
4	1.000	0.000	0.000	0.000	0.000	0.000	--	-
5	1.000	0.000	0.000	0.000	0.13	0.04	-	-
6	0.98	0.000	0.000	0.008	0.75	0.02	-0.08	0.25
7	1.000	0.000	0.000	0.000	0.000	0.000	-	-
8	1.005	0.000	4.50	0.621	1.50	0.22	-1.40	2
9	0.98	0.000	0.000	0.022	1.21	0.26	-0.03	0.09
10	1.000	0.000	0.000	0.000	0.05	0.02	-	-
11	1.000	0.000	0.000	0.000	0.000	0.000	-	-
12	1.015	0.000	3.10	1.285	3.77	0.24	-0.5	1.55
13	1.000	0.000	0.000	0.000	0.18	0.023	-	-
14	1.000	0.000	0.000	0.000	0.105	0.053	-	-

15	1.000	0.000	0.000	0.000	0.22	0.05	-	-
16	1.000	0.000	0.000	0.000	0.43	0.03	-	-
17	1.000	0.000	0.000	0.000	0.42	0.08	-	-
18	1.000	0.000	0.000	0.000	0.272	0.098	-	-
19	1.000	0.000	0.000	0.000	0.033	0.06	-	-
20	1.000	0.000	0.000	0.000	0.023	0.01	-	-
21	1.000	0.000	0.000	0.000	0.000	0.000	-	-
22	1.000	0.000	0.000	0.000	0.000	0.000	-	-
23	1.000	0.000	0.000	0.000	0.063	0.021	-	-
24	1.000	0.000	0.000	0.000	0.000	0.000	-	-
25	1.000	0.000	0.000	0.000	0.063	0.032	-	-
26	1.000	0.000	0.000	0.000	0.000	0.000	-	-
27	1.000	0.000	0.000	0.000	0.093	0.005	-	-
28	1.000	0.000	0.000	0.000	0.046	0.023	-	-
29	1.000	0.000	0.000	0.000	0.17	0.026	-	-
30	1.000	0.000	0.000	0.000	0.036	0.018	-	-
31	1.000	0.000	0.000	0.000	0.058	0.029	-	-
32	1.000	0.000	0.000	0.000	0.016	0.008	-	-
33	1.000	0.000	0.000	0.000	0.038	0.019	-	-
34	1.000	0.000	0.000	0.000	0.000	0.000	-	-
35	1.000	0.000	0.000	0.000	0.06	0.03	-	-
36	1.000	0.000	0.000	0.000	0.000	0.000	-	-
37	1.000	0.000	0.000	0.000	0.000	0.000	-	-

38	1.000	0.000	0.000	0.000	0.14	0.07	-	-
39	1.000	0.000	0.000	0.000	0.000	0.000	-	-
40	1.000	0.000	0.000	0.000	0.000	0.000	-	-
41	1.000	0.000	0.000	0.000	0.063	0.03	-	-
42	1.000	0.000	0.000	0.000	0.071	0.044	-	-
43	1.000	0.000	0.000	0.000	0.02	0.01	-	-
44	1.000	0.000	0.000	0.000	0.12	0.018	-	-
45	1.000	0.000	0.000	0.000	0.000	0.000	-	-
46	1.000	0.000	0.000	0.000	0.000	0.000	-	-
47	1.000	0.000	0.000	0.000	0.297	0.116	-	-
48	1.000	0.000	0.000	0.000	0.000	0.000	-	-
49	1.000	0.000	0.000	0.000	0.18	0.085	-	-
50	1.000	0.000	0.000	0.000	0.21	0.105	-	-
51	1.000	0.000	0.000	0.000	0.18	0.053	-	-
52	1.000	0.000	0.000	0.000	0.049	0.022	-	-
53	1.000	0.000	0.000	0.000	0.20	0.10	-	-
54	1.000	0.000	0.000	0.000	0.041	0.014	-	-
55	1.000	0.000	0.000	0.000	0.068	0.034	-	-
56	1.000	0.000	0.000	0.000	0.076	0.022	-	-
57	1.000	0.000	0.000	0.000	0.067	0.02	-	-

## Appendix K: The MATLAB codes for the research work.

### *The main Matlab program calling the sub-programs*

```
% This function performs GA-IPSO Optimization

GAIPSO(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V)
Np=20;
Nd=2;
Nt=10;
num = 30;
PDG_min = 0;
PDG_max = 12;
QDG_min = 0;
QDG_max = 0;
busd = busdatas(num);
V = busd(:,3);
CandidateBus = [10; 11; 15; 17; 18; 19; 20; 21; 22; 23; 24; 25; 26; 30];
for z=14
    Bus = CandidateBus(z)
    xMin=[PDG_min, QDG_min];
xMax=[PDG_max, QDG_max];
vMin=-0.5;
vMax=1.5;
w_max=0.9;
w_min=0.4;
    C1 = 2.00;    % Constant 1
    C2 = 2.00;    % Constant 2
    R = zeros(Np, Nd);
    Vel = zeros (Np, Nd);
    p=1:Np;
    k=1:Nt;
bestFitnessHistory = [];
    R = GA4pso(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
    M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
    R;
    for p =1:Np
        pBestValue(p) = M(p);
            for i =1:Nd
                pBestPosition(p,i)= R(p,i);
            end
        end
        gBestValue = min(M);
        index=find(M==min(M));
        gBestPosition = R(index,:);

        pBestPosition;
        gBestPosition;
        pBestValue;
        gBestValue;
    for k=1:Nt % For each iteration
        R = UpdatedR(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
        Pnew = [];
        for u=1:Np/2
            X= CrossMut2(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
            Pnew = [Pnew; X];
        end
        Pnew;
        R=Pnew;
```

```

for p=1:Np
    for i=1:Nd
        % Correct any errors
        if R(p,i) > xMax(1,i)
            R(p,i) = xMax(1,i);
        elseif R(p,i) < xMin(1,i)
            R(p,i) = xMin(1,i);
        end
    end
end
% Evaluate Fitness
M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
R;
for p=1:Np
    %Check if it is a personal best
    %If it is, record the value and the position
    if M(p) < pBestValue(p)
        pBestValue(p) = M(p);
        for i=1:Nd
            pBestPosition(p,i) = R(p,i);
        end
    end
    % Check if it is a global best
    % If it is, record the value and the position
    if M(p) < gBestValue
        gBestValue = M(p);
        for i=1:Nd
            gBestPosition(i) = R(p,i);
        end
    end
end
bestFitnessHistory(k) = gBestValue;
% Calculate Velocity
w = w_max - ((w_max - w_min) / Nt) * k; % evaluate w
for p=1:Np
    for i=1:Nd
        Vel(p,i) = w * Vel(p,i) + rand * C1 * (pBestPosition(p,i) - R(p,i)) + rand *
        C2 * (gBestPosition(i) - R(p,i));
        if Vel(p,i) > vMax
            Vel(p,i) = vMax;
        elseif Vel(p,i) < vMin
            Vel(p,i) = vMin;
        end
    end
end
Vel;
gBestPosition=gBestPosition(1,:);
gBestValue;
k=k+1;
end
pBestPosition;
gBestPosition
pBestValue;
gBestValue
z=z+1;
end
end

```

## The sub-program for calculating Combined Sensitivity Factors

```

%This code calculates combined sensitivity factors
function F = sensst(nb, num, V, del, BMva)
nbus = 57;
num = nbus;
nb = nbus;
Y = ybusppg(nbus);
g = real(Y);
b = imag(Y);
[V del JJ] = NewtonRaphson1();
busd = busdatas(nbus); % Calling busdatas..
linedt = linedatas(num);
Bsh = (linedt(:,5)*2);
fb = linedt(:,1); % From bus number...
tb = linedt(:,2); % To bus number...
nl = length(fb); % No. of Branches..
BMva = 100; % Base MVA..
bus = busd(:,1); % Bus Number..
type = busd(:,2); % Type of Bus 1-Slack, 2-PV, 3-PQ..
pv = find(type == 2 | type == 1); % PV Buses..
pq = find(type == 3); % PQ Buses..
npv = length(pv); % No. of PV buses..
npq = length(pq); % No. of PQ buses..
%Line Power loss
for m = 1:nl
    i = fb(m); j = tb(m);
    %Real Line Losses
    PL(m) = (-g(i,j) * ((V(i))^2 + (V(j))^2 - 2 * V(i) * V(j) * cos (del(i)-del(j))));
    %Reactive Line Losses
    QL(m) = b(i,j) * ((V(i))^2 + (V(j))^2 - 2 * V(i) * V(j) * cos (del(i)-del(j)));
end
    PLoss= sum(PL)*BMva
    QLoss= sum(QL)*BMva
% Real Power Loss Derivatives
DPLdel = zeros (nb-1,1);
DQLdel = zeros (nb-1,1);
for m = 1:nl
    i = fb(m); j = tb(m);
    for n = 1:nb-1
        if i == n
            DPLdel(n) = DPLdel(n) + (-2 * g(i,j) * V(i) * V(j) * sin (del(i)-del(j)));
            DQLdel(n) = DQLdel(n) + (2 * b(i,j) * V(i) * V(j) * sin (del(i)-del(j)));
        end
    end
end
DPLV = zeros(npq,1);
DQLV = zeros(npq,1);
for m = 1:nl
    i = fb(m); j = tb(m);
    for n = 1:npq
        if i == pq(n)
            DPLV(n) = DPLV(n) + (-2 * g(i,j) * (V(i) - V(j) * cos(del(i)-del(j))));
            DQLV(n) = DQLV(n) + (2 * (b(i,j) * (V(i) - V(j) * cos(del(i)-del(j))));
        end
    end
end
%Line Power Flows
for m = 1:nl
    i = fb(m); j = tb(m);
    %Real Line Flows
    P(i,j) = g(i,j) * V(i) * (V(j) * cos(del(i)-del(j))-V(i)) - b(i,j) * V(i) * V(j) * sin
    (del(i)-del(j));
    %Reactive Line Flows Q(i,j) = -V(i) * V(j) * (b(i,j) * cos(del(i)-del(j)) -
    g(i,j) * sin(del(i)-del(j))) + (V(i))^2 * (b(i,j));

```



```

end
% Power Flow Derivatives
DPdel = zeros (nb-1,1);
DQdel = zeros (nb-1,1);
for m = 1:nl
    i = fb(m); j = tb(m);
    for n = 1:nb-1
        if i == n
DPdel(n) = DPdel(n) + (V(i) * V(j) * (g(i,j) * sin (del(i)-del(j)) + b(i,j) * cos(del(i)-
del(j))));
DQdel(n) = DQdel(n) + (-V(i) * V(j) * (g(i,j) * cos (del(i)-del(j)) - b(i,j) *
sin(del(i)-del(j))));
            end
        end
    end
end
DPV = zeros(npq,1);
DQV = zeros(npq,1);
for m = 1:nl
    i = fb(m); j = tb(m);
    for n = 1:npq
        if i == pq(n)
DPV(n) = DPV(n) + (V(i) * (g(i,j) * cos (del(i)-del(j)) - b(i,j) * sin(del(i)-del(j))) -
2 * V(i) * g(i,j));
DQV(n) = DQV(n) + (-V(j) * (b(i,j) * cos (del(i)-del(j)) + g(i,j) * sin(del(i)-del(j))) +
2 * V(i) * (b(i,j)));
            end
        end
    end
end
M1 = [DPLdel; DPLV];
M2 = [DQLdel; DQLV];
M3 = [DPdel; DPV];
M4 = [DQdel; DQV];
S_P = JJ * M1;
S_Q = JJ * M2;
F_P = JJ * M3;
F_Q = JJ * M4;
for k = 1: nb-1
    Sp_p(k) = S_P(k);
    Sq_p(k) = S_Q(k);
    Fp_p(k) = F_P(k);
    Fq_p(k) = F_Q(k);
end
for k = 1:npq
    Sp_q(k) = S_P((nb-1)+k);
    Sq_q(k) = S_Q((nb-1)+k);
    Fp_q(k) = F_P((nb-1)+k);
    Fq_q(k) = F_Q((nb-1)+k);
end
CSF = zeros (nb-1,1);
for m = 2:nb
    for n = 1:npq
        if m == pq(n)
CSF(m) = (Sp_p(m-1)*Sq_p(m-1))+(Sp_q(n)*Sq_q(n))+(Fp_p(m-1)*Fq_p(m-1))+(Fp_q(n)*Fq_q(n));
            end
        end
    for n = 2:npv
        if m == pv(n)
            CSF(m) = (Sp_p(m-1)*Sq_p(m-1))+(Fp_p(m-1)*Fq_p(m-1));
            end
        end
    end
end
end

```

### *The sub-program for the GA section*

```
% This function performs Genetic Algorithm Optimization.
function R = GA4pso(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V)
Nt = 5;
PBestV = [];
PBestP = [];
    R = zeros(Np, Nd); % Position
    for p=1:Np % For each Particle
        for i =1:Nd % For each dimension
            R(p,i) = xMin(1,i) + (xMax(1,i)-xMin(1,i)) * rand;
        end
    end
Vel = zeros (Np, Nd);
p=1:Np;
k=0;
M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
R;
for p =1:Np
    pBestValue(p) = M(p);
    for i =1:Nd
        pBestPosition(p,i)= R(p,i);
    end
end
for k=1:Nt % For each time step
    Pnew = [];
    for u=1:Np/2
        X = CrossMut(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
        Pnew = [Pnew; X];
    end
    R=Pnew;
    % Update Position
    for p=1:Np
        for i=1:Nd
            % Correct any errors
            if R(p,i) > xMax(1,i)
                R(p,i) = xMax(1,i);
            elseif R(p,i) < xMin(1,i)
                R(p,i) = xMin(1,i);
            end
        end
    end
    % Evaluate Fitness
    M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
    for p=1:Np
        %Check if it is a personal best, If it is, record the value and the position
        if M(p) < pBestValue(p)
            pBestValue(p) = M(p);
            for i=1:Nd
                pBestPosition(p,i) = R(p,i);
            end
        end
    end
    k=k+1;
end
PBestV = [PBestV; pBestValue];
PBestP = [PBestP; pBestPosition];
R = PBestP;
end
```

### *The sub-program for the determining the fitness*

```
% This function calculate the fitness of each population member.

function M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p,
V)

    % Initialize Fitness Values
M = zeros(Np,1);

for p=1:Np

    PLbase=17.528;

    QLbase=68.888;
    R;
    [SL V] = NewtonRaphson(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p,
V);
    PL = SL(1,1);
    QL = SL(1,2);
    V;

    for n=1:30
        VPII(n) = (1-V(n));
    end
    VPI(p) = 1/(10 + max(abs(VPII)));
    PLRI(p) = ((PLbase-PL) ./ PLbase);
    QLRI(p) = ((QLbase-QL) ./ QLbase);

    %define weights for MOF. These weights must sum up to unity
    w1=0.6;
    w2=0.2;
    w3=0.2;

    M(p) = 1/(1+(w1*PLRI(p)) + (w2*QLRI(p)) + (w3*VPI(p)));
    %M(p) = 1/(1+(PLRI(p)));

    p=p+1;
end
M;

end
```

### *The sub-program for updating the PSO particles*

```
function Ubusdt = UpdatedBusdatas(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k,
Vel, Bus, p, V)
num = 30;

busdt = busdatas(num);
Pg = busdt(:,5);      % PGi..
Qg = busdt(:,6);

R = UpdatedR(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);

j = Bus;

PgBus = busdt(j,5);
QgBus = busdt(j,6);

busdt(j,5)=PgBus+R(p,1);
busdt(j,6)=QgBus+R(p,2);

Ubusdt=busdt;

end

function R = UpdatedR(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p,
V)

% Update Position

for p=1:Np
    for i=1:Nd
        R(p,i) = R(p,i) + Vel(p,i);

        % Correct any errors
        if R(p,i) > xMax(1,i)
            R(p,i) = xMax(1,i);
        elseif R(p,i) < xMin(1,i)
            R(p,i) = xMin(1,i);
        end
    end
end
R;
```

## *The sub-programs for performing Roulette Wheel and Greedy selections*

```
% This function performs roulette wheel selection method.
function Rp = Selection(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V)
for h=1:2
M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
for p=1:Np;
    fitC(p)=M(p); %generates the fitness from Fitness values using Objective function.
end
s=0;
for p=1:Np;
    s=s+fitC(p);
end
t=0;
for p=1:Np;
    f(p)=fitC(p)/s; %probability of the ith value
    t=t+f(p); %to calculate the cummulative probability
    cp(p)=t; %cumulative probability stored.
    ec(p)=f(p)*Np; %Expected Count is generated
end
rn=rand(Np); %generating a n X n array of random numbers.
for p=1:Np;
    g(p)=rn(1,p);
end
for p=1:Np;
    ex(p)=round(ec(p));
end
for p=1:Np;
    for i=1:Np;
        if (cp(i)>=g(p));
            sl(p)=i;
            break;
        end
    end
end
for p=1:Np
    d(p)=0;
end
for p=1:Np
    d(sl(p))=d(sl(p))+1;
end
index=find(d==max(d));
p_selected=R(index,1);
q_selected=R(index,2);
X=[p_selected q_selected];
Rp(h,:)=X(1,:);
end
Rp;
end

% This function performs greedy selection method.
function Rp = Selection2(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V)
M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
for p=1:Np;
    fitC(p)=M(p); %generates the fitness from Fitness values using Fitness function.
end
index=find(M==min(M));
indext=index(1,:);
M(index)=1;
A=M;
ind=find(A==min(A));
indt=ind(1,:);
Rp = [R(indext,:); R(indt,:)];
end
```

### *The sub-program for performing Arithmetic crossover and mutation*

```
% This function implements crossover and mutation
function X = CrossMut(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V

for j=1:Nd/2
Rp = Selection(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);

Xp1=Rp(1,:);
Xp2=Rp(2,:);
PDG_max = 12;
QDG_max = 20;
Xcmax=[PDG_max QDG_max];
P_cross = 0.85;
P_mut = 0.01;

    z=rand(1);
    if z<P_cross
    u=rand(1);
    Xc1=(u*Xp1)+((1-u)*Xp2);
    Xc2=(u*Xp2)+((1-u)*Xp1);
    else
        Xc1=Xp1;
        Xc2=Xp2;
    end
    Xc1;
    Xc2;
    if z<P_mut
        r=rand(1);
        DXc1=r*(Xcmax-Xc1)*(1-k./Nt);
        DXc2=r*(Xcmax-Xc2)*(1-k./Nt);
        X1=Xc1+DXc1;
        X2=Xc2+DXc2;
    else
        X1=Xc1;
        X2=Xc2;
    end

X=[X1;X2];
end

end
```

## The sub-program for performing Newton Raphson Load flow

```

% Program for Newton-Raphson Load Flow Analysis..
function [SL V] = NewtonRaphson(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V)
nbus = 30;
Y = ybusppg(nbus);
busd = busdatas(nbus);
BMva = 100;
bus = busd(:,1);           % Bus Number..
type = busd(:,2);         % Type of Bus 1-Slack, 2-PV, 3-PQ..
V = busd(:,3);           % Specified Voltage..
del = busd(:,4);         % Voltage Angle..
Ubusdt = UpdatedBusdatas(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
Pg = Ubusdt(:,5)/BMva;    % PGi..
Qg = Ubusdt(:,6)/BMva;    % QGi..
Pl = busd(:,7)/BMva;     % PLi..
Ql = busd(:,8)/BMva;     % QLi..
Qmin = busd(:,9)/BMva;   % Minimum Reactive Power Limit..
Qmax = busd(:,10)/BMva;  % Maximum Reactive Power Limit..
P = Pg - Pl;             % Pi = PGi - PLi..
Q = Qg - Ql;            % Qi = QGi - QLi..
Psp = P;                 % P Specified..
Qsp = Q;                 % Q Specified..
G = real(Y);             % Conductance matrix..
B = imag(Y);             % Susceptance matrix..
pv = find(type == 2 | type == 1); % PV Buses..
pq = find(type == 3);    % PQ Buses..
npv = length(pv);       % No. of PV buses..
npq = length(pq);       % No. of PQ buses..
Tol = 1;
Iter = 1;
while (Tol > 1e-5)      % Iteration starting..
    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) + B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) - B(i,k)*cos(del(i)-del(k)));
        end
    end
    % Checking Q-limit violations..
    for n = 2:nbus
        if type(n) == 2
            QG = Q(n)+Ql(n);
            if QG < Qmin(n)
                V(n) = V(n) + 0.01;
            elseif QG > Qmax(n)
                V(n) = V(n) - 0.01;
            end
        end
    end
    % Calculate change from specified value
    dPa = Psp-P;
    dQa = Qsp-Q;
    k = 1;
    dQ = zeros(npq,1);
    for i = 1:nbus
        if type(i) == 3
            dQ(k,1) = dQa(i);
            k = k+1;
        end
    end
    dP = dPa(2:nbus);
    M = [dP; dQ];        % Mismatch Vector
end

```

```

% Jacobian
% J1 - Derivative of Real Power Injections with Angles..
J1 = zeros(nbus-1,nbus-1);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
J1(i,k) = J1(i,k) + V(m)* V(n)*(-G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
            end
        J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
        else
J1(i,k) = V(m)* V(n)*(G(m,n)*sin(del(m)-del(n)) - B(m,n)*cos(del(m)-del(n)));
        end
    end
end
% J2 - Derivative of Real Power Injections with V..
J2 = zeros(nbus-1,npq);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
J2(i,k) = J2(i,k) + V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
        J2(i,k) = J2(i,k) + V(m)*G(m,m);
        else
J2(i,k) = V(m)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
        end
    end
end
% J3 - Derivative of Reactive Power Injections with Angles..
J3 = zeros(npq,nbus-1);
for i = 1:npq
    m = pq(i);
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
J3(i,k) = J3(i,k) + V(m)* V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
        J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
        else
J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) - B(m,n)*sin(del(m)-del(n)));
        end
    end
end
% J4 - Derivative of Reactive Power Injections with V..
J4 = zeros(npq,npq);
for i = 1:npq
    m = pq(i);
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-del(n)) - B(m,n)*cos(del(m)-del(n)));
            end
        J4(i,k) = J4(i,k) - V(m)*B(m,m);
        else
J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) - B(m,n)*cos(del(m)-del(n)));
        end
    end
end

```



```

        end
    end
end
J = [J1 J2; J3 J4]; % Jacobian Matrix..
X = inv(J)*M; % Correction Vector
dTh = X(1:nbus-1); % Change in Voltage Angle..
dV = X(nbus:end); % Change in Voltage Magnitude..
% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus); % Voltage Angle..
k = 1;
for i = 2:nbus
    if type(i) == 3
        V(i) = dV(k) + V(i); % Voltage Magnitude..
        k = k+1;
    end
end
Iter = Iter + 1;
Tol = max(abs(M)); % Tolerance..
end
PLQL = loadflow(nbus,V,del,BMva); % Calling Loadflow.m..
V;
SL = PLQL;
end

```

```

% Program to for Admittance And Impedance Bus Formation....
function Y = ybusppg(num) % Returns Y
linedata = linedatas(num); % Calling Linedatas...
fb = linedata(:,1); % From bus number...
tb = linedata(:,2); % To bus number...
r = linedata(:,3); % Resistance, R...
x = linedata(:,4); % Reactance, X...
b = linedata(:,5); % Ground Admittance, B/2...
a = linedata(:,6); % Tap setting value..
z = r + i*x; % z matrix...
y = 1./z; % To get inverse of each element...
b = i*b; % Make B imaginary...
nb = max(max(fb),max(tb)); % No. of buses...
nl = length(fb); % No. of branches...
Y = zeros(nb,nb); % Initialise YBus...
% Formation of the Off Diagonal Elements...
for k = 1:nl
    Y(fb(k),tb(k)) = Y(fb(k),tb(k)) - y(k)/a(k);
    Y(tb(k),fb(k)) = Y(fb(k),tb(k));
end
% Formation of Diagonal Elements...
for m = 1:nb
    for n = 1:nl
        if fb(n) == m
            Y(m,m) = Y(m,m) + y(n)/(a(n)^2) + b(n);
        elseif tb(n) == m
            Y(m,m) = Y(m,m) + y(n) + b(n);
        end
    end
end
end
end

```

**The sub-program for returning initial bus data of the IEEE test systems**

```

% This code Returns Initial Bus datas of the system...
function busdt = busdatas(num)
% Type....
% 1 - Slack Bus..
% 2 - PV Bus..
% 3 - PQ Bus..
%
% |Bus | Type | Vsp | theta | PGi | QGi | PLi | QLi | Qmin | Qmax |
busdat30 = [1  1  1.06  0  0  0  0  0  0  0;
2  2  1.043  0  40  50  21.7  12.7  -40  50;
3  3  1.0  0  0  0  2.4  1.2  0  0;
4  3  1.06  0  0  0  7.6  1.6  0  0;
5  2  1.01  0  0  37  94.2  19.0  -40  40;
6  3  1.0  0  0  0  0.0  0.0  0  0;
7  3  1.0  0  0  0  22.8  10.9  0  0;
8  2  1.01  0  0  37.3  30.0  30.0  -10  40;
9  3  1.0  0  0  0  0.0  0.0  0  0;
10 3  1.0  0  0  19  5.8  2.0  0  0;
11 2  1.082  0  0  16.2  0.0  0.0  -6  24;
12 3  1.0  0  0  0  11.2  7.5  0  0;
13 2  1.071  0  0  10.6  0.0  0.0  -6  24;
14 3  1.0  0  0  0  6.2  1.6  0  0;
15 3  1.0  0  0  0  8.2  2.5  0  0;
16 3  1.0  0  0  0  3.5  1.8  0  0;
17 3  1.0  0  0  0  9.0  5.8  0  0;
18 3  1.0  0  0  0  3.2  0.9  0  0;
19 3  1.0  0  0  0  9.5  3.4  0  0;
20 3  1.0  0  0  0  2.2  0.7  0  0;
21 3  1.0  0  0  0  17.5  11.2  0  0;
22 3  1.0  0  0  0  0.0  0.0  0  0;
23 3  1.0  0  0  0  3.2  1.6  0  0;
24 3  1.0  0  0  4.3  8.7  6.7  0  0;
25 3  1.0  0  0  0  0.0  0.0  0  0;
26 3  1.0  0  0  0  3.5  2.3  0  0;
27 3  1.0  0  0  0  0.0  0.0  0  0;
28 3  1.0  0  0  0  0.0  0.0  0  0;
29 3  1.0  0  0  0  2.4  0.9  0  0;
30 3  1.0  0  0  0  10.6  1.9  0  0 ];

%
% |Bus | Type | Vsp | theta | PGi | QGi | PLi | QLi | Qmin | Qmax |
busdat33 = [1  1  1.000  0  0.0  0.0  0.0  0.0  0.0  0.0;
2  3  1.000  0  0.0  0.0  0.1  0.06  0.0  0.0;
3  3  1.000  0  0.0  0.0  0.09  0.04  0.0  0.0;
4  3  1.000  0  0.0  0.0  0.12  0.08  0.0  0.0;
5  3  1.000  0  0.0  0.0  0.06  0.03  0.0  0.0;
6  3  1.000  0  0.0  0.0  0.06  0.02  0.0  0.0;
7  3  1.000  0  0.0  0.0  0.2  0.1  0.0  0.0;
8  3  1.000  0  0.0  0.0  0.2  0.1  0.0  0.0;
9  3  1.000  0  0.0  0.0  0.06  0.02  0.0  0.0;
10 3  1.000  0  0.0  0.0  0.06  0.02  0.0  0.0;
11 3  1.000  0  0.0  0.0  0.045  0.03  0.0  0.0;
12 3  1.000  0  0.0  0.0  0.06  0.035  0.0  0.0;
13 3  1.000  0  0.0  0.0  0.06  0.035  0.0  0.0;
14 3  1.000  0  0.0  0.0  0.12  0.08  0.0  0.0;
15 3  1.000  0  0.0  0.0  0.06  0.01  0.0  0.0;
16 3  1.000  0  0.0  0.0  0.06  0.02  0.0  0.0;
17 3  1.000  0  0.0  0.0  0.06  0.02  0.0  0.0;
18 3  1.000  0  0.0  0.0  0.09  0.04  0.0  0.0;
19 3  1.000  0  0.0  0.0  0.09  0.04  0.0  0.0;
20 3  1.000  0  0.0  0.0  0.09  0.04  0.0  0.0;
21 3  1.000  0  0.0  0.0  0.09  0.04  0.0  0.0;
22 3  1.000  0  0.0  0.0  0.09  0.04  0.0  0.0;
23 3  1.000  0  0.0  0.0  0.09  0.05  0.0  0.0;
24 3  1.000  0  0.0  0.0  0.42  0.2  0.0  0.0;
25 3  1.000  0  0.0  0.0  0.42  0.2  0.0  0.0;
26 3  1.000  0  0.0  0.0  0.06  0.025  0.0  0.0;
27 3  1.000  0  0.0  0.0  0.06  0.025  0.0  0.0;
28 3  1.000  0  0.0  0.0  0.06  0.02  0.0  0.0;
29 3  1.000  0  0.0  0.0  0.12  0.07  0.0  0.0;
30 3  1.000  0  0.0  0.0  0.2  0.6  0.0  0.0;
31 3  1.000  0  0.0  0.0  0.15  0.07  0.0  0.0;

```

```

32 3 1.000 0 0.0 0.0 0.21 0.1 0.0 0.0;
33 3 1.000 0 0.0 0.0 0.06 0.04 0.0 0.0];

%
busdat57 = [Bus | Type | Vsp | theta | PGi | QGi | PLi | QLi | Qmin | Qmax |
1 1 1.040 0 0.0 0.0 0.0 0.0 0.0 0.0;
2 2 1.010 0 3.0 88.0 0.0 -0.8 50.0 -17.0;
3 2 0.985 0 41.0 21.0 40.0 -1.0 60.0 -10.0;
4 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
5 3 1.000 0 13.0 4.0 0.0 0.0 0.0 0.0;
6 2 0.980 0 75.0 2.0 0.0 0.8 25.0 -8.0;
7 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
8 2 1.005 0 150.0 22.0 450.0 62.1 200.0 -140.0;
9 2 0.980 0 121.0 26.0 0.0 2.2 9.0 -3.0;
10 3 1.000 0 5.0 2.0 0.0 0.0 0.0 0.0;
11 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
12 2 1.015 0 377.0 24.0 310.0 128.5 155.0 -150.0;
13 3 1.000 0 18.0 2.3 0.0 0.0 0.0 0.0;
14 3 1.000 0 10.5 5.3 0.0 0.0 0.0 0.0;
15 3 1.000 0 22.0 5.0 0.0 0.0 0.0 0.0;
16 3 1.000 0 43.0 3.0 0.0 0.0 0.0 0.0;
17 3 1.000 0 42.0 8.0 0.0 0.0 0.0 0.0;
18 3 1.000 0 27.2 9.8 0.0 0.0 0.0 0.0;
19 3 1.000 0 3.3 0.6 0.0 0.0 0.0 0.0;
20 3 1.000 0 2.3 1.0 0.0 0.0 0.0 0.0;
21 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
22 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
23 3 1.000 0 6.3 2.1 0.0 0.0 0.0 0.0;
24 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
25 3 1.000 0 6.3 3.2 0.0 0.0 0.0 0.0;
26 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
27 3 1.000 0 9.3 0.5 0.0 0.0 0.0 0.0;
28 3 1.000 0 4.6 2.3 0.0 0.0 0.0 0.0;
29 3 1.000 0 17.0 2.6 0.0 0.0 0.0 0.0;
30 3 1.000 0 3.6 1.8 0.0 0.0 0.0 0.0;
31 3 1.000 0 5.8 2.9 0.0 0.0 0.0 0.0;
32 3 1.000 0 1.6 0.8 0.0 0.0 0.0 0.0;
33 3 1.000 0 3.8 1.9 0.0 0.0 0.0 0.0;
34 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
35 3 1.000 0 6.0 3.0 0.0 0.0 0.0 0.0;
36 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
37 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
38 3 1.000 0 14.0 7.0 0.0 0.0 0.0 0.0;
39 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
40 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
41 3 1.000 0 6.3 3.0 0.0 0.0 0.0 0.0;
42 3 1.000 0 7.1 4.4 0.0 0.0 0.0 0.0;
43 3 1.000 0 2.0 1.0 0.0 0.0 0.0 0.0;
44 3 1.000 0 12.0 1.8 0.0 0.0 0.0 0.0;
45 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
46 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
47 3 1.000 0 29.7 11.6 0.0 0.0 0.0 0.0;
48 3 1.000 0 0.0 0.0 0.0 0.0 0.0 0.0;
49 3 1.000 0 18.0 8.5 0.0 0.0 0.0 0.0;
50 3 1.000 0 21.0 10.5 0.0 0.0 0.0 0.0;
51 3 1.000 0 18.0 5.3 0.0 0.0 0.0 0.0;
52 3 1.000 0 4.9 2.2 0.0 0.0 0.0 0.0;
53 3 1.000 0 20.0 10.0 0.0 0.0 0.0 0.0;
54 3 1.000 0 4.1 1.4 0.0 0.0 0.0 0.0;
55 3 1.000 0 6.8 3.4 0.0 0.0 0.0 0.0;
56 3 1.000 0 7.6 2.2 0.0 0.0 0.0 0.0;
57 3 1.000 0 6.7 2.0 0.0 0.0 0.0 0.0];

switch num
case 30
busdt = busdat30;
case 33
busdt = busdat33;
case 57
busdt = busdat57;
end

```

**The sub-program for returning initial line data of the IEEE test systems**

```

% This code returns Line data of the system...
function linedt = linedatas(num)
%      | From | To | R | X | B/2 | X'mer |
%      | Bus  | Bus | pu | pu | pu  | TAP (a) |
linedat30 = [ 1      2      0.0192  0.0575  0.0264  1
              1      3      0.0452  0.1652  0.0204  1
              2      4      0.0570  0.1737  0.0184  1
              3      4      0.0132  0.0379  0.0042  1
              2      5      0.0472  0.1983  0.0209  1
              2      6      0.0581  0.1763  0.0187  1
              4      6      0.0119  0.0414  0.0045  1
              5      7      0.0460  0.1160  0.0102  1
              6      7      0.0267  0.0820  0.0085  1
              6      8      0.0120  0.0420  0.0045  1
              6      9      0.0      0.2080  0.0      0.978
              6     10      0.0      0.5560  0.0      0.969
              9     11      0.0      0.2080  0.0      1
              9     10      0.0      0.1100  0.0      1
              4     12      0.0      0.2560  0.0      0.932
             12     13      0.0      0.1400  0.0      1
             12     14      0.1231  0.2559  0.0      1
             12     15      0.0662  0.1304  0.0      1
             12     16      0.0945  0.1987  0.0      1
             14     15      0.2210  0.1997  0.0      1
             16     17      0.0824  0.1923  0.0      1
             15     18      0.1073  0.2185  0.0      1
             18     19      0.0639  0.1292  0.0      1
             19     20      0.0340  0.0680  0.0      1
             10     20      0.0936  0.2090  0.0      1
             10     17      0.0324  0.0845  0.0      1
             10     21      0.0348  0.0749  0.0      1
             10     22      0.0727  0.1499  0.0      1
             21     23      0.0116  0.0236  0.0      1
             15     23      0.1000  0.2020  0.0      1
             22     24      0.1150  0.1790  0.0      1
             23     24      0.1320  0.2700  0.0      1
             24     25      0.1885  0.3292  0.0      1
             25     26      0.2544  0.3800  0.0      1
             25     27      0.1093  0.2087  0.0      1
             28     27      0.0      0.3960  0.0      0.968
             27     29      0.2198  0.4153  0.0      1
             27     30      0.3202  0.6027  0.0      1
             29     30      0.2399  0.4533  0.0      1
              8     28      0.0636  0.2000  0.0214  1
              6     28      0.0169  0.0599  0.065  1 ];

%      | From | To | R | X | B/2 | X'mer |
%      | Bus  | Bus | pu | pu | pu  | TAP (a) |
linedat33 = [  2      3  0.03076  0.01567  0      1
              3      4  0.02284  0.01163  0      1
              4      5  0.02378  0.01211  0      1
              5      6  0.0511   0.04411  0      1
              6      7  0.01168  0.03861  0      1
              7      8  0.04439  0.01467  0      1
              8      9  0.06426  0.04617  0      1
              9     10  0.06514  0.04617  0      1
             10     11  0.01227  0.00406  0      1

```

```

11 12 0.02336 0.00772 0 1
12 13 0.09159 0.07206 0 1
13 14 0.03379 0.04448 0 1
14 15 0.03687 0.03282 0 1
15 16 0.04656 0.034 0 1
16 17 0.08042 0.10738 0 1
17 18 0.04567 0.03581 0 1
2 19 0.01023 0.00976 0 1
19 20 0.09385 0.08457 0 1
20 21 0.02555 0.02985 0 1
21 22 0.04423 0.05848 0 1
3 23 0.02815 0.01924 0 1
23 24 0.05603 0.04424 0 1
24 25 0.0559 0.04374 0 1
6 26 0.01267 0.00645 0 1
26 27 0.01773 0.00903 0 1
27 28 0.06607 0.05826 0 1
28 29 0.05018 0.04371 0 1
29 30 0.03166 0.01613 0 1
30 31 0.0608 0.06008 0 1
31 32 0.01937 0.02258 0 1
32 33 0.02128 0.03319 0 1
1 2 0.00575 0.00293 0 1];

```

```

%      | From | To | R | X | B/2 | X'mer |
%      | Bus  | Bus | pu | pu | pu   | TAP (a) |
linedat57 = [ 1 2 0.0083 0.0280 0.0645 1
2 3 0.0298 0.0850 0.0409 1
3 4 0.0112 0.0366 0.0190 1
4 5 0.0625 0.1320 0.0129 1
4 6 0.0430 0.1480 0.0174 1
6 7 0.0200 0.1020 0.0138 1
6 8 0.0339 0.1730 0.0235 1
8 9 0.0099 0.0505 0.0274 1
9 10 0.0369 0.1679 0.0220 1
9 11 0.0258 0.0848 0.0109 1
9 12 0.0648 0.2950 0.0386 1
9 13 0.0481 0.1580 0.0203 1
13 14 0.0132 0.0434 0.0055 1
13 15 0.0269 0.0869 0.0115 1
1 15 0.0178 0.0910 0.0494 1
1 16 0.0454 0.2060 0.0273 1
1 17 0.0238 0.1080 0.0143 1
3 15 0.0162 0.0530 0.0272 1
4 18 0.0 0.5550 0.0 0.970
4 18 0.0 0.4300 0.0 0.978
5 6 0.0302 0.0641 0.0062 1
7 8 0.0139 0.0712 0.0097 1
10 12 0.0277 0.1262 0.0164 1
11 13 0.0223 0.0732 0.0094 1
12 13 0.0178 0.0580 0.0302 1
12 16 0.0180 0.0813 0.0108 1
12 17 0.0397 0.1790 0.0238 1
14 15 0.0171 0.0547 0.0074 1
18 19 0.4610 0.6850 0.0 1
19 20 0.2830 0.4340 0.0 1
21 20 0.0 0.7767 0.0 1.043

```

21	22	0.0736	0.1170	0.0	1
22	23	0.0099	0.0152	0.0	1
23	24	0.1660	0.2560	0.0042	1
24	25	0.0	1.1820	0.0	1
24	25	0.0	1.2300	0.0	1
24	26	0.0	0.0473	0.0	1.043
26	27	0.1650	0.2540	0.0	1
27	28	0.0618	0.0954	0.0	1
28	29	0.0418	0.0587	0.0	1
7	29	0.0	0.0648	0.0	0.967
25	30	0.1350	0.2020	0.0	1
30	31	0.3260	0.4970	0.0	1
31	32	0.5070	0.7550	0.0	1
32	33	0.0392	0.0360	0.0	1
34	32	0.0	0.9530	0.0	0.975
34	35	0.0520	0.0780	0.0016	1
35	36	0.0430	0.0537	0.0008	1
36	37	0.0290	0.0366	0.0	1
37	38	0.0651	0.1009	0.0010	1
37	39	0.0239	0.0379	0.0	1
36	40	0.0300	0.0466	0.0	1
22	38	0.0192	0.0295	0.0	1
11	41	0.0	0.7490	0.0	0.955
41	42	0.2070	0.3520	0.0	1
41	43	0.0	0.4120	0.0	1
38	44	0.0289	0.0585	0.0010	1
15	45	0.0	0.1042	0.0	0.955
14	46	0.0	0.0735	0.0	0.900
46	47	0.0230	0.0680	0.0016	1
47	48	0.0182	0.0233	0.0	1
48	49	0.0834	0.1290	0.0024	1
49	50	0.0801	0.1280	0.0	1
50	51	0.1386	0.2200	0.0	1
10	51	0.0	0.0712	0.0	0.930
13	49	0.0	0.1910	0.0	0.895
29	52	0.1442	0.1870	0.0	1
52	53	0.0762	0.0984	0.0	1
53	54	0.1878	0.2320	0.0	1
54	55	0.1732	0.2265	0.0	1
11	43	0.0	0.1530	0.0	0.958
44	45	0.0624	0.1242	0.0020	1
40	56	0.0	1.1950	0.0	0.958
56	41	0.5530	0.5490	0.0	1
56	42	0.2125	0.3540	0.0	1
39	57	0.0	1.3550	0.0	0.980
57	56	0.1740	0.2600	0.0	1
38	49	0.1150	0.1770	0.0015	1
38	48	0.0312	0.0482	0.0	1
9	55	0.0	0.1205	0.0	0.940];

```

switch num
  case 30
    linedt = linedat30;
  case 33
    linedt = linedat33;
  case 57
    linedt = linedat57;
end

```