OPTIMAL CAPACITOR PLACEMENT IN RADIAL DISTRIBUTION SYSTEM USING GENETIC ALGORITHM

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **"Optimal Capacitor Placement in Radial Distribution System using Genetic Algorithm"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in ***Power Systems & Electric Drives*** submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Sanjay K. Jain, Assistant Professor, EIED.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university

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ABSTRACT

A distribution system is an interface between the bulk power system and the consumers. Among these systems, radial distribution systems are popular because of low cost and simple design. In distribution systems, the voltages at buses reduces when moved away from the substation, also the losses are high. The reason for decrease in voltage and high losses is the insufficient amount of reactive power, which can be provided by the shunt capacitors.

The work reported in this thesis is carried out with the objective of identifying the optimal locations and sizes (kVAr ratings) of shunt capacitors to be placed in radial distribution system to have overall economy considering the saving due to energy loss minimization and cost of capacitors. For the purpose two stage methodology is used. In first stage, the load flow of pre-compensated distribution system is carried out. On the basis of load flow solutions, loss sensitivity factors (LSF) indicating the potential locations for compensation are computed. From LSF, the candidate number of buses is identified. In the second stage, genetic algorithm is used to identify the sizes of the capacitor for minimizing the energy loss cost and capacitor cost. A coding scheme is implemented where the identification of location and size of capacitor is represented by one dimensional array. The developed algorithm is tested for 33-bus and 69-bus radial distribution systems while taking the different step sizes for capacitors.

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CHAPTER-1

INTRODUCTION

1.1 OVERVIEW

The analysis of a distribution system is an important area of activity, as distribution systems provide the vital link between the bulk power system and the consumers. A distribution circuit normally uses primary or main feeders and lateral distributors. A main feeder originates from the substation and passes through the major load centers. Lateral distributors connect the individual transformers at their ends. Many distribution systems used in practice have a single circuit main feeder and are defined as radial distribution systems. Radial distribution systems are popular because of their simple design and generally low cost.

The modern power distribution network is constantly being faced with an ever-growing load demand, this increasing load is resulting into increased burden and reduced voltage. The distribution network also has a typical feature that the voltages at buses (nodes) reduces if moved away from substation. This decrease in voltage is mainly due to insufficient amount of reactive power. Even in certain industrial areas under critical loading, it may lead to voltage collapse. Thus to improve the voltage profile and to avoid voltage collapse reactive compensation is required.

It is well known that losses in a distribution system are significantly high compared to that in a transmission system. The need of improving the overall efficiency of power delivery has forced the power utilities to reduce the losses at distribution level. Many arrangements can be worked out to reduce these losses like network reconfiguration, shunt capacitor placements etc. The shunt capacitors supply part of the reactive power demand, thereby reducing the current and MVA in lines. Installation of shunt capacitors on distribution network will help in reducing energy losses, peak demand losses and improvement in the system voltage profile, system stability and power factor of the system. However to achieve these objectives, keeping in mind the overall economy, the size and location of capacitors should be decided.

1.2 LITERATURE REVIEW

The literature on distribution system is very much diversified, the brief review is presented on the subject of capacitor placement in distribution systems.

For the capacitor placement problem in distribution system repeated load flow solution is required. There are a number of load flow solution techniques are available in the text books such as Gauss-Seidel, Newton-Raphson and Fast Decoupled Load Flow method, but most of the methods have been grown up around transmission systems [1-2]. The distribution system has high R/X ratio and the conventional load flow method may not be suitable.

A number of methods have been proposed in the literature [3-9] for the distribution networks. Shirmohammadi *et al.* [3] has proposed a load flow method for distribution networks using a multi-port compensation technique and basic formulations of Kirchhoff's Laws. Rajicic and Tamura [5] has modified the fast decoupled load flow method to suit high R/X ratio nature of distribution system. Various methods [6-9] have been reported for the load flow of radial distribution system. Ghosh and Das [6] have proposed a method for the load flow of radial distribution network using the evaluation based on algebraic expression of receiving end voltage. Teng [8, 9] has proposed the load flow of radial distribution system employing bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices.

Capacitor placement problem is well researched topic. Neagle and Samson [10] considered loss reduction by one capacitor bank placed along the feeder by considering uniformly distributed loads, uniformly decreasing loads and equally distributed loads along the feeder. A general application curves for selecting location and size of single capacitors to minimize loss has been presented.

Cook [11] considered the effects of fixed capacitors on radial distribution network with distributed loads and considered the reduction in energy loss. A methodology has been used to determine the ratings and location of fixed capacitors on the radial feeder for periodic load cycle. Cook [12] considered fixed and switched capacitors and discussed the methodology to decide the timing for the operation of switched capacitors.

Maxwell [13] suggested there are several benefits of capacitor placement which include: (i) reduced kVA input to feeder (ii) reduced I^2R loss and energy losses (iii) reduced I^2X losses (iv) reduced regulation cost (v) increased revenue as a result of increased voltage levels. Major benefits are due to the reduction in kVA input, kW demand and energy loss.

Schmill [14] considered feeders with uniformly distributed and randomly distributed loads. A simplified method for capacitor application has been developed. Bae [15] presented an analytical method for capacitor allocation, under the assumptions (i) capacitor banks optimally located for specific load levels (ii) voltage regulation is not considered (iii) loads are assumed to be uniformly distributed along the feeder with the size of capacitor banks assumed equivalent (iv) only losses due to reactive current component are considered. The equations to determine the best capacitor locations and the loss reduction under varying load conditions has also presented.

Brown [16] discussed the performance of variable reactive power source applied to distribution primary feeders and the approach is limited to a single source of reactive power. While, Desai and Brown [17] include multiple variable sources. Comparison has been made with corresponding conditions resulting from the application of fixed capacitors.

Duran [18] considered the problem as dynamic programming problem and utilized a multistage maximizing process. While, Baran and Wu [19] proposed a mixed integer programming technique, in which the problem is decomposed into two levels. The problem at the top level is called the master problem which is an integer programming problem and is used to place the capacitor (i.e. to determine the number and the location of the capacitors). The problem at the bottom level is called the slave problem and is used by the master problem to determine the types and the settings of capacitors placed. The sizing problem and the associated solution algorithm has been presented in [20].

Grainger and Lee [21] considered the problem as non-linear programming problem, the capacitor sizes have been considered as continuous variables and iterative solution scheme has been proposed. Lee and Grainger [22] later introduced switched type capacitors with simultaneous switching and a voltage dependent model for loss reduction has been proposed in [23]. Grainger *et al.* [24] proposed a solution method to determine the optimal design and real time control scheme for switched capacitors with nonsimultaneous switching under certain asssumptions. Wang *et al.* [25, 26] have used quadratic integer programming to determine the number, locations and sizes of capacitors to be placed.

Kaplan [27] solved the capacitor placement problem by computerized trial and error heuristic method. Ponnavaikko and Rao [28] used a local optimization technique called the method of local variations by considering voltage raise at light load condition. Haque [29] developed a method for minimizing the loss associated with the reactive component of branch currents by placing capacitor at proper locations.

El-Kib *et al.* [30] developed a model considered asymmetrical, multi-grounded feeders and unbalanced loads. To determine the optimal size, locations and switching intervals of fixed and switched capacitors have been determined. Huang *et al.* [31] introduced a Tabu Search-based method to solve the capacitor placement problem. A comparison has been made with simulated annealing method.

Chiang *et al.* [32, 33] have used the method of simulated annealing to obtain the optimum values of shunt capacitors for radial distribution networks. Sundhararajan and Pahwa [34] have solved the general capacitor placement problem in a distribution system using a genetic algorithm. Sensitivity analysis has been used to select the candidate locations of capacitors. Milosevic and Begovic [35], Das [36] also proposed shunt capacitor problem using Genetic Algorithm. Das [37] presented the problem by using Fuzzy-GA method, in that sensitivity analysis has been used to identify the candidate buses for shunt capacitor placement.

1.3 OBJECTIVE OF THE WORK

The objective of the present work is to identify the location and sizes of capacitors to be placed in radial distribution system have the overall economy using genetic algorithm.

A recent load flow technique for a radial distribution using BIBC and BCBV has been used. The candidate buses for shunt capacitor placement have been identified using Loss Sensitivity Factors. The sizes of the capacitors have been found using Genetic Algorithm, while optimizing the overall economy calculated considering the energy loss cost and capacitor cost.

1.4 ORGANIZATION OF THE THESIS

The work carried out in this Thesis has been summarized in five chapters. The Chapter 1 highlights the brief introduction, summary of work carried out by various researchers, and the outline of the thesis is also given in this chapter. The Chapter 2 explains the Load Flow technique of distribution system using BIBC and BCBV matrix. The Chapter 3 briefly describes Loss Sensitivity Factor to identify the candidate buses for shunt capacitor placement, objective function for overall economy and steps for Capacitor Allocation using Genetic Algorithm. The Chapter 4 details the results and discussion pertaining to various test cases. The conclusions and the scope of further work are detailed in Chapter 5.

CHAPTER-2

DISTRIBUTION SYSTEM LOAD FLOW

2.1 INTRODUCTION

The load flow of a power network provides the steady state solution through which various parameters of interest like currents, voltages, losses etc can be calculated. The load flow is important for the analysis of distribution system, to investigate the issues related to planning, design and the operation and control. Some applications like optimal capacitor placement in distribution system and distribution automation system, requires repeated load flow solution. Many methods such as Gauss-Seidel, Newton-Raphson are well reported to carry out the load flow of transmission system. The use of these methods for distribution system may not be advantageous because they are mostly based on the general meshed topology of a typical transmission system where as most distribution systems have a radial or tree structure. Further distribution system posses high R/X ratio, which cause the distribution systems to be ill conditioned for conventional load flow methods.

Some other inherent characteristics of electric distribution systems are (i) Radial or weakly meshed structure (ii) unbalanced operation and unbalanced distributed loads (iii) large number of buses and branches (iv) It has wide range of resistance and reactance values (v) Distribution system has multiphase operation.

The efficiency of the optimization problem of distribution system depends on the load flow algorithm because load flow solution has to run for many times. Therefore, the load flow solution of distribution system should have robust and time efficient characteristics. A method which can find the load flow solution of radial distribution system directly by using topological characteristic of distribution network [8, 9] is used. In this method, the formulation of time consuming Jacobian matrix or admittance matrix, which are required in the conventional methods, is avoided. This method is explained in brief.

2.2 LOAD FLOW OF RADIAL DISTRIBUTION SYSTEM [8,9]

The method to carry out the load flow for distribution system under balanced operating condition employing constant power load model can be under stood through the following points:

- Equivalent current injection.
- Formulation of BIBC matrix.
- Formulation of BCBV matrix.

2.2.1 EQUIVALENT CURRENT INJECTION

The method is based on the equivalent current injection. At bus i, the complex power S_i is specified and the corresponding equivalent current injection at the *k*-th iteration of the solution is computed as

$$S_i = (P_i + jQ_i) \qquad i = 1, 2, \ldots, N, \tag{2.1}$$

$$I_i^k = I_i^r(V_i^k) + jI_i^k(V_i^k) = \left(\frac{P_{i+J}Q_i}{V_i^k}\right)^* \tag{2.2}$$

where,

S_i is the complex power at the i-th bus.

P_i is the real power at the i-th bus.

Q_i is the reactive power at the i-th bus.

V_i^k is the bus voltage at the *k*-th iteration for i-th bus.

I_i^k is the equivalent current injection at the *k*-th iteration for i-th bus.

I_i^r and I_i^i are the real and imaginary parts of the equivalent current injection at the *k*-th iteration for i-th bus.

2.2.2 FORMATION OF BIBC MATRIX

The formulation of Bus-injection to Branch-current (BIBC) matrix is explained with the help of simple distribution system shown in Fig. 2.1.

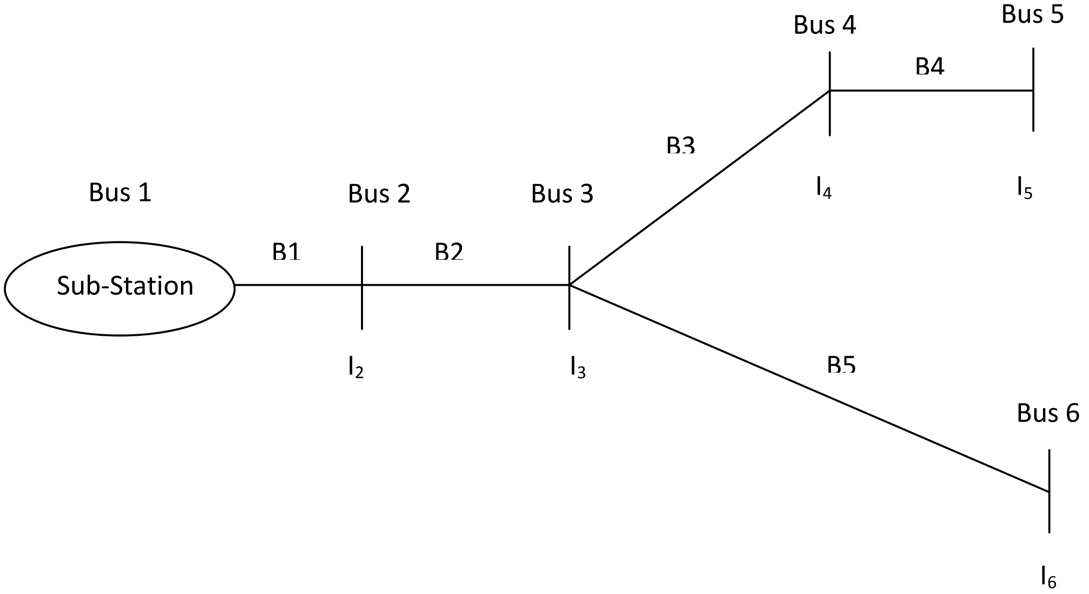

Figure 2.1: A typical distribution system

The power injections at each bus can be converted into the equivalent current injections using eq. (2.2) and a set of equations can be written by applying Kirchhoff's Current Law (KCL) at each bus. Then, the branch currents can be formed as a function of the equivalent current injections. As shown in Fig. 2.1, the branch currents B_5, B_4, B_3, B_2 and B_1 can be expressed as:

$$B_5 = I_6, \tag{2.3}$$

$$B_4 = I_5, \tag{2.4}$$

$$B_3 = I_4 + I_5, \tag{2.5}$$

$$B_2 = I_3 + I_4 + I_5 + I_6, \tag{2.6}$$

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6, \tag{2.7}$$

From the above equations the BIBC matrix can be obtained as:

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \qquad (2.8)$$

The general form as of eq. (2.8) can be expressed as:

$$[B] = [BIBC]\,[I] \qquad (2.9)$$

The formulation of BIBC matrix for distribution system shown in Fig. 2.1 is given in eq. (2.8) and eq. (2.9). For general network, the BIBC matrix can be formed through the following steps:

Step 1: For a system with m branch sections and an n-bus, the dimension of the BIBC matrix is m × (n– 1).

Step 2: If a line section (B_k) is located between Bus i and Bus j, copy the column of the i-th bus of BIBC matrix to the column of the j-th bus and fill a + 1 in the position of the k-th row and the j-th bus column. This is explained in Fig. 2.2.

Step 3: Repeat step (2) until all the line sections are included in the BIBC matrix.

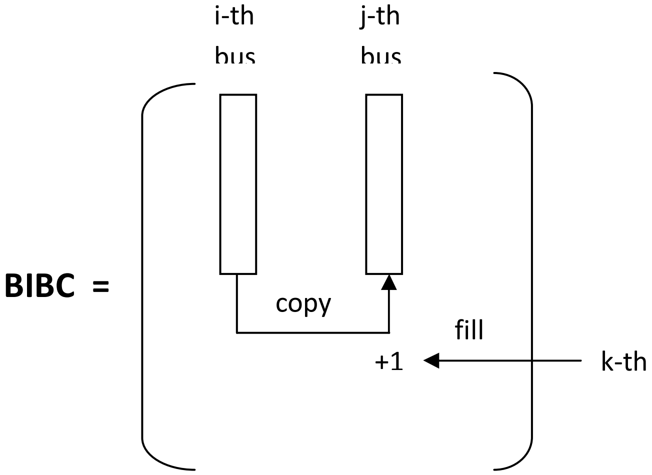

Figure 2.2: The formation of step (2) for BIBC matrix

2.2.3 FORMATION OF BCBV MATRIX

The Branch-Current to Bus voltage (BCBV) matrix summarizes the relation between branch current and bus voltages. The relations between the branch currents and bus voltages can be obtained easily. As shown in Fig. 2.1, the voltages of Bus 2, 3, and 4 are expressed as:

$$V_2 = V_1 - B_1 Z_{12}, \tag{2.10}$$

$$V_3 = V_2 - B_2 Z_{23}, \tag{2.11}$$

$$V_4 = V_3 - B_3 Z_{34}, \tag{2.12}$$

Substituting eqs. (2.10) and (2.11) into eq. (2.12), the voltage of Bus 4 can be rewritten as:

$$V_4 = V_1 - B_1 Z_{12} - B_2 Z_{23} - B_3 Z_{34} \tag{2.13}$$

From eq. (2.13), it can be seen that the bus voltage can be expressed as a function of the branch currents, line parameters and substation voltage. Similar procedures can be utilized for other buses, and the Branch-Current to Bus-Voltage (BCBV) matrix can be derived as:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \tag{2.14}$$

The general form of eq. (2.14) can be expressed as:

$$[\Delta V] = [BCBV]\ [B] \tag{2.15}$$

The formulation of BCBV matrix for distribution system shown in Fig. 2.1 is given in eq. (2.14) and eq. (2.15). For general network, the BCBV matrix can be formed through the following steps:

Step 1: For a system with m branch sections and an n-bus, the dimension of the BCBV matrix is (n – 1) × m.

Step 2: If a line section (B_k) is located between Bus i and Bus j, copy the row of the i-th bus of the BCBV matrix to the row of the j-th bus, and fill the line impedance (Z_{ij}) in the position of the j-th bus row and the k-th column. This is explained in Fig. 2.3.

Step 3: Repeat Step (2) until all the line sections are included in the BCBV matrix.

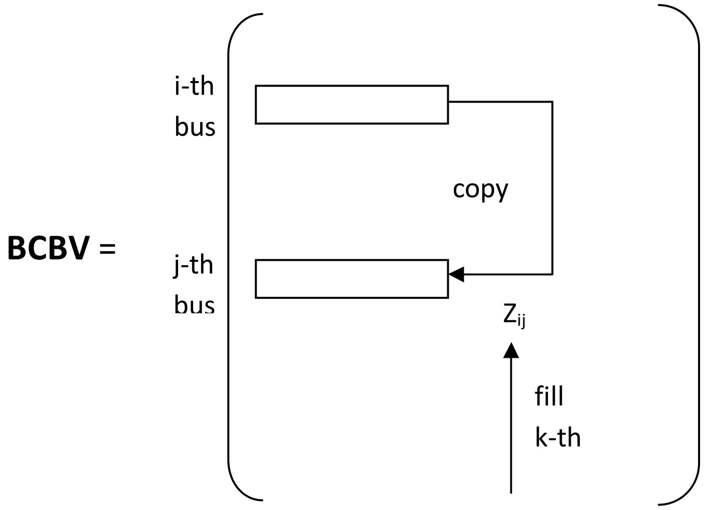

Figure 2.3: The formation of step (2) for BCBV matrix

From Fig. (2.2) and Fig. (2.3), it can be seen that the algorithms for the BIBC and BCBV matrices are almost similar. The only difference in the formation of BIBC matrix and BCBV matrix is that, in BIBC matrix i-th bus column is copied to the column of the j-th bus and fill with +1 in the k-th row and the j-th bus column, while in BCBV matrix row of the i-th bus is copied to the row of the j-th bus and fill the line impedance (Z_{ij}) in the position of the j-th bus row and the k-th column.

2.2.4 SOLUTION METHODOLOGY

The formation of BIBC and BCBV matrices is explained in section 2.2.2 and 2.2.3. These matrices explore the topological structure of distribution systems. The BIBC matrix is responsible for the relations between the bus current injections and branch currents. The corresponding variation of the branch currents, which is generated by the variation at the current injection buses, can be found directly by using the BIBC matrix. The BCBV matrix is responsible for the relations between the branch currents and bus voltages. The corresponding variation of the bus voltages, which is generated by the variation of the branch currents, can be found directly by using the BCBV matrix. Combining eqs. (2.9) and (2.15), the relations between the bus current injections and bus voltages can be expressed as:

$$[\Delta V] = [BCBV][BIBC][I] \tag{2.16}$$

$$[DLF] = [BCBV][BIBC] \tag{2.17}$$

Therefore

$$[\Delta V] = [DLF][I] \tag{2.18}$$

The solution for the load flow can be obtained by solving eqs. (2.19) and (2.20) iteratively which are given below:

$$I_i^K = I_i^r(V_i^K) + jI_i^i(V_i^K) = \left(\frac{P_i + jQ_i}{V_i^K}\right)^* \tag{2.19}$$

$$[\Delta V^{k+1}] = [DLF][I^k] \tag{2.20}$$

$$[V^{k+1}] = [V^0] + [\Delta V^{k+1}] \tag{2.21}$$

The new formulation as explained uses only the DLF matrix to solve load flow problem. Therefore this method is very time efficient, which is suitable for on-line operation and optimization problem of distribution system.

2.3 ALGORITHM FOR DISTRIBUTION SYSTEM LOAD FLOW

The algorithm steps for load flow solution of distribution system is given below:

Step1: Read the distribution system line data and load data.

Step 2: Form the BIBC matrix by using steps given in section 2.2.2. The relationship can be expressed as –

$[B] = [BIBC]\ [I]$

Step 3: Form the BCBV matrix by using steps given in section 2.2.3. The relationship therefore can be expressed as –

$[\Delta V] = [BCBV]\ [B]$

Step 4: Form the DLF matrix by using the eq. (2.17). The relationship will be –

$[DLF] = [BCBV][BIBC]$

$[\Delta V] = [DLF][I]$

Step 5: Set Iteration k = 0.

Step 6: Iteration k = k + 1.

Step 7: Update voltages by using eqs. (2.19), (2.20), (2.21), as -

$$I_i^K = I_i^r(V_i^K) + jI_i^i(V_i^K) = \left(\frac{P_i + jQ_i}{V_i^K}\right)^*$$

$[\Delta V^{k+1}] = [DLF][I^k]$

$[V^{k+1}] = [V^0] + [\Delta V^{k+1}]$

Step 8: If max $((|I_i^{K+1}|-|I_i^K|) > \text{tolerance})$ goto step 6.

Step 9: Calculate line flows, and losses from final bus voltages.

Step 10: Print bus voltages, line flows and losses.

Step 11: Stop

The above algorithm steps are shown in Flowchart given as Fig. 2.4.

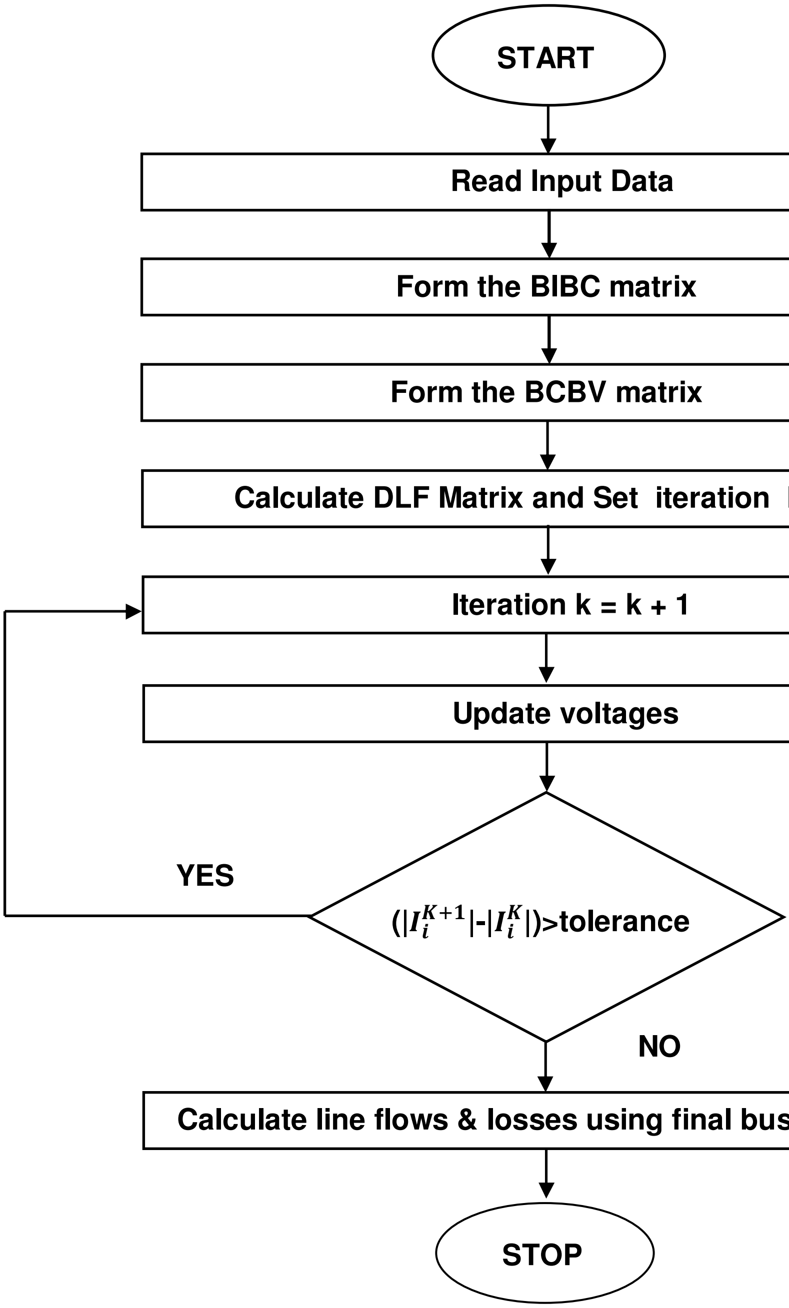

Figure 2.4: Flowchart for load flow solution for radial distribution system

2.4 CONCLUSION

In this chapter, a direct approach algorithm for distribution load flow has been formulated. The Bus Injection to Branch Current (BIBC) matrix is responsible for the variation between the bus current injection and branch current, and the Branch Current to Bus voltage (BCBV) matrix is responsible for the variation between the branch current and bus voltage. The load flow is based on these two matrices and their matrix multiplication. With the formulation of this load flow of radial distribution system, the much needed background has been prepared to work in the area of capacitor placement problem in radial distribution system.

CHAPTER-3

CAPACITOR PLACEMENT IN DISTRIBUTION SYSTEM USING GENETIC ALGORITHM

3.1 INTRODUCTION

Loss Minimization in power system has assumed greater significance, because substantial amount of generated power is being wasted as losses. Studies have shown that 70% of the total system losses are occurring in the distribution system, while transmission lines account for only 30% of the total losses. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at the distribution level. The following methods are adopted for reduction of distribution system losses.

- Reinforcement of the feeders.
- Reactive power compensation.
- High voltage distribution system.
- Grading of conductor.
- Feeder reconfiguration.

Among the above listed methods, the reactive power compensation is most commonly used method for loss reduction in distribution system. The distribution network is usually compensated by either series or shunt capacitors. Series capacitors increase the maximum power limit while shunt capacitors have several benefits [38]. Some of the benefits are: (i) reduce real and reactive power loss in the system (ii) increase voltage level at the load and power factor of source (iii) improve voltage regulation (iv) improve stability (v) improve power factor of the system (vi) decrease kVA loading on source generators etc. However to achieve these objective(s), the optimal locations of capacitors and sizes should be find out. Certainly, the locations and sizes of the capacitors will be influenced by the objective under consideration.

3.2 THE OBJECTIVE FUNCTION

The aim of the present work is to find out the location and sizes of the shunt capacitor so as to maximize the net saving by minimizing the energy loss cost for a given period of time and considering cost of shunt capacitors. Therefore, the objective function consists of two main terms: energy loss cost and capacitors cost. Mathematical formulation of the terms used in objective function is given below:

Term 1: Energy loss Cost (ELS):

If I_i is the current of section-i in time duration T, then energy loss in section-i is given by:

$$EL_{i,} = I_i^2 \times R_i \times T \tag{3.1}$$

The Energy loss (EL) in time T of a feeder with n sections can be calculated as:

$$EL = \sum_{i=1}^{n} EL_i \tag{3.2}$$

The Energy loss cost (ELC) can be calculated by multiplying eq. (3.2) with the energy rate (C_e)

$$ELC = C_e \times EL \tag{3.3}$$

where

$EL_{i,}$ is energy loss (kW) in section–i in time duration T.

I_i is the current of the section-i

R_i is the resistance of section-i.

T is the time duration.

C_e is the energy rate.

ELC is the energy loss cost.

Term 2: Capacitor Cost (CC):

Capacitor cost is divided into two terms: constant installation cost and variable cost which is proportional to the rating of capacitors. Therefore capacitor cost is expressed as:

$$\mathrm{CC} = \mathrm{C_{ci}} + (\,\mathrm{C_{cv}} \times \mathrm{Q_{ck}}\,) \tag{3.4}$$

where,

C_{ci} is the constant installation cost of capacitor.

C_{cv} is the rate of capacitor per kVAr.

Q_{ck} is the rating of capacitor on bus-k in kVAr.

The cost function is obtained by combining eqs. (3.3) and (3.4) [36]. This cost function is considered as the objective function to be minimized in the present work. The cost function 'S' is therefore expressed as:

Minimize

$$\mathrm{S} = \mathrm{C_e} \times \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{EL_i} + \sum_{\mathrm{k=1}}^{\mathrm{ncap}} \mathrm{C_{ci}} + (\,\mathrm{C_{cv}} \times \mathrm{Q_{ck}}) \tag{3.5}$$

where

S is the cost function for minimization.

By minimizing the cost function, the net saving due to the reduction of energy losses for a given period of time including the cost of capacitors is given below:

$$\text{Net Saving} = \mathrm{BEL} - \mathrm{CC} \tag{3.6}$$

where

$\mathrm{BEL} = \mathrm{ELC}_{(\text{without capacitor})} - \mathrm{ELC}_{(\text{with capacitor})}$

BEL is benefit due to energy loss reduction.

$\mathrm{ELC}_{(\text{without capacitor})}$ is energy loss cost without capacitor.

$\mathrm{ELC}_{(\text{with capacitor})}$ is energy loss cost with capacitor.

CC is the total capacitors cost as expressed by eq. (3.4).

3.3 LOSS SENSITIVITY FACTOR AND CANDIDATE BUS SELECTION

The loss sensitivity factor and the criterion to select the candidate buses for compensation are summarized in this section.

3.3.1 LOSS SENSITIVITY FACTOR

To identify the location for capacitor placement in distribution system Loss Sensitivity Factors have been used [39]. The loss sensitivity factor is able to predict which bus will have the biggest loss reduction when a capacitor is placed. Therefore, these sensitive buses can serve as candidate buses for the capacitor placement. The estimation of these candidate buses basically helps in reduction of the search space for the optimization problem. As only few buses can be candidate buses for compensation, the installation cost on capacitors can also be reduced. Consider a distribution line with an impedance R + jX and a load of $P_{eff} + jQ_{eff}$ connected between 'i' and 'j' buses as given below in Fig. 3.1.

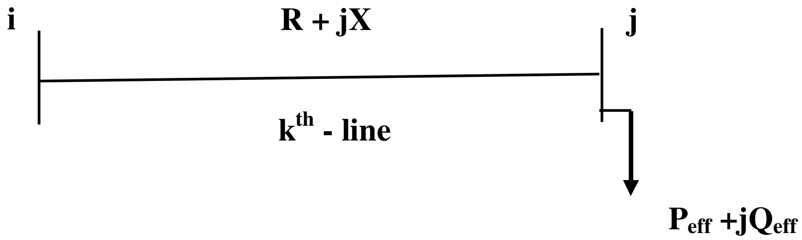

Figure 3.1: A distribution line with an impedance and a load

Real power loss in the line of the above Fig. 3.1 is given by $[I_k^2]$ * $[R_k]$, which can also be expressed as,

$$P_{lineloss}[j] = \frac{\left(P_{eff}^2\,[j] \;+\; Q_{eff}^2[j]\right) \;*\; R[k]}{(V[j])^2} \tag{3.7}$$

Similarly the reactive power loss in the kth line is given by

$$Q_{\text{lineloss}}[j] = \frac{\left(P_{\text{eff}}^2\,[j] \ + \ Q_{\text{eff}}^2[j]\right) \ * \ X[k]}{(V[j])^2} \tag{3.8}$$

where

$P_{\text{eff}}\,[j]$ = Total effective active power supplied beyond the bus ‘j’

$Q_{\text{eff}}\,[j]$ = Total effective reactive power supplied beyond the bus ‘j’

Now, the Loss Sensitivity Factors can be calculated as:

$$\frac{\partial P_{\text{lineloss}}\,[j]}{\partial Q_{\text{eff}}[j]} = \frac{(2 * Q_{\text{eff}}[j]) \ * \ R[k]}{(V[j])^2} \tag{3.9}$$

$$\frac{\partial Q_{\text{lineloss}}[j]}{\partial Q_{\text{eff}}[j]} = \frac{(2 * Q_{\text{eff}}[j]) \ * \ X[k]}{(V[j])^2} \tag{3.10}$$

3.3.2 CANDIDATE BUS SELECTION USING LOSS SENSITIVITY FACTOR

The Loss Sensitivity Factor $(\partial P_{loss}/\partial Q_{eff})$ as given in eq. (3.9) has been calculated from the base case load flows. The values of loss sensitivity factors have been arranged in descending order and correspondingly the bus numbers are stored in bus position ‘bpos [i]’ vector. The descending order of $(\partial P_{loss}/\partial Q_{eff})$ elements of ‘bpos [i]’ vector will decide the sequence in which the buses are to considered for compensation. At these buses of ‘bpos [i]’ vector, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given as below:

$$\text{norm}[i] = |V[i]|/0.95 \tag{3.11}$$

The ‘norm[i]’ decides whether the buses need reactive compensation or not. The buses whose norm[i] value is less than 1.01 can be selected as the candidate buses for capacitor placement. The following are the steps to be performed to find out the potential buses for capacitor placement:

Step 1: Calculate the Loss Sensitivity Factor at the buses of distribution system using Eq. (3.9).

Step 2: Arrange the value of Loss Sensitivity Factor in descending order. Also store the respective buses into bus position vector bpos[i].

Step 3: Calculate the normalized voltage magnitude norm[i] of the buses of bpos[i] using Eq. (3.11).

Step 4: The buses whose norm[i] is less than 1.01 are selected as candidate buses for capacitor placement.

3.4 CAPACITOR ALLOCATION USING GA

The developed algorithm for identifying the sizing and location is based on Genetic Algorithm (GA). The development of algorithm is explained with a review on GA.

A GA is an iterative procedure which begins with a randomly generated set of solutions referred as initial population. For each solution in the set, objective function and fitness are calculated. On the basis of these fitness functions, pool of selected population is formed by selection operators, the solution in this pool has better average fitness then that of initial population. The crossover and mutation operator are used to generate new solutions with the help of solution in the pool. The process is repeated iteratively while maintain fixed number of solutions in pool of selected population, as the iteration progress, the solution improves and optimal solution is obtained.

During the selection process of the GA, good solutions are selected from the initial generated population for producing offspring. Good solutions are selected randomly from the initial generated population using a mechanism which favours the more fit individuals. Good individuals will probably be selected several times in a generation but poor solutions may not be selected at all.

The second GA operator is crossover. In the crossover two parents are selected randomly from the pool of selected/obtained population by the selection process. Crossover produces two offsprings which has some basic properties of the parents. The mutation operator generates an offspring using a random solution from pool.

Each new solution is evaluated i.e. objective function and fitness values are calculated. These newly created offsprings and the populations are combined. The combined population is put for selection by selection operator. With the above description, a simple Genetic Algorithm is given as follow:

Step 1: Randomly generate initial population strings.

Step 2: Calculate the fitness value for each string in the population.

Step 3: Create the pool after selection.

Step 3: Create offsprings through crossover and mutation operation.

Step 4:` Evaluate the offsprings and calculate the fitness value for each solution.

Step 5: If the search goal is achieved, or an allowable generation is attained, return the best chromosome as the solution; otherwise go to step 3.

The standard procedure of GA is depicted in Flowchart as shown in Fig. 3.2.

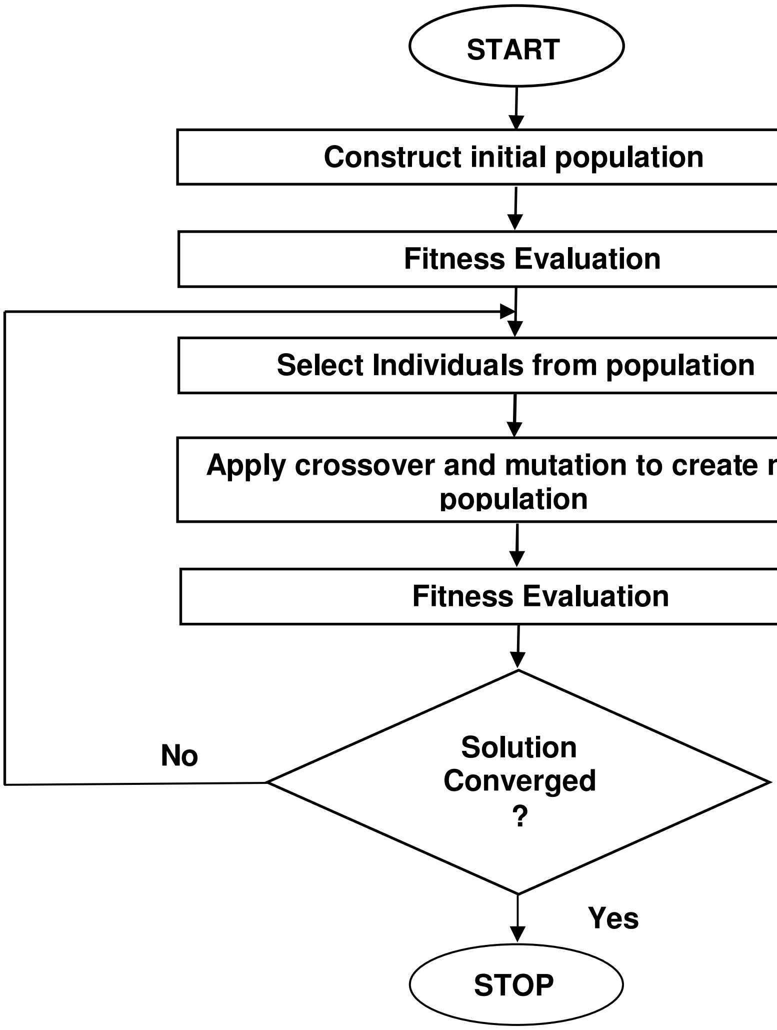

Figure 3.2: Genetic Algorithm Flowchart

3.4.1 CODING SCHEME

The success of the GA structure will lies on the coding scheme, the coding scheme and the brief discussion of various operators with reference to the problem of interest is summarized as:

Here the coding scheme for 33-bus radial distribution system has been discussed. First step is to obtain the base case load flow solution for distribution system using the algorithm discussed in Chapter 2. Then identify the potential buses for capacitor placement by using loss sensitivity factor as discussed in section (3.3.2). Using the loss sensitivity factor, the potential buses for shunt capacitor placement are obtained and these potential buses should be preserved.

Let the number of Potential Buses = [29 7 30 28 12]

Having identified the potential buses, the sizing is attempted using GA. Let the capacitor allowable range is from 100 kVAr to 1100 kVAr in step size of 50 kVAr. The sizes of capacitor to be install at those potential buses are given below:

Capacitor sizes for respective potential buses = [300 150 750 250 350]

From the above it is clear that 300 kVAr capacitor is install at bus number 29, 150 kVAr capacitor at bus number 7 and so on….

3.4.2 INITIALIZATION AND FITNESS FUNCTION

Initialization is the generation of initial population. Here, the initial population is generated randomly which is the capacitors of different sizes (kVAr ratings) to be install at the potential buses. The population size effects the efficiency and performance of the algorithm. It can be stated that string length is equal to the number of buses selected for the shunt capacitor placement problem.

After generating population of required size the corresponding load flow solution has to run to evaluate the objective function ‘S’ as stated in eq. 3.5 and the fitness function f(x) calculated as given below:

$$S = C_e \times \sum_{i=1}^{n} EL_i + \sum_{k=1}^{ncap} C_{ci} + (C_{cv} \times Q_{ck})$$

$$f(x) = \frac{1}{1+S} \qquad 3.12$$

The load flow solution, evaluation of objective function and fitness function is repeated for all the strings in the population. The procedure to determine the fitness function ‘f(x)’ is very much application oriented. It is directly associated with the objective function value in the optimization problem. In the capacitor placement problem, the objective function is the minimization of cost function.

3.4.3 REPRODUCTION

The first genetic algorithm operator is reproduction. This determines which strings in the current population will be used to create the next population or be part of pool of selected population. So, sometime this operator is also named as the selection operator. This is done by using a biased random - selection methodology. That is parents are randomly selected from the current population in such a way that the ‘best’ strings in the population have more chance of being selected. There are many ways to do this, such as by Roulette Wheel selection, Boltzman selection, tournament selection, rank selection etc. In the present work Roulette Wheel selection has been used.

Reproduction is simply an operator where by an old solution is copied into a mating pool. The solution with a higher fitness value have higher probability of being selected into mating pool and contributing one or more offspring in the next generation. The following are the steps carried out for the roulette wheel selection process [36]:

Step 1: Sum the fitness of all the population members. Call it as total fitness.

Step 2: Generate a random number (r) between zero and the total fitness.

Step 3: Select a population member whose cumulative fitness obtained from adding its fitness to the fitness of the proceeding population members is greater than or equal to random number (r).

3.4.4 CROSSOVER

Here the two selected parents is utilized in certain fashion to generate two children who bear some of the useful characteristics of parents and expected to be more fit than parents. The random selection technique is used to pick up two parents randomly from the existing population. After selecting the parents, crossover can be carried out using methods like Single Point Crossover, Multi-point Crossover or Uniform Crossover arrangements.

In the present work single point crossover has been used. This is illustrated in the following example. Let Parent1 and Parent2 be the two parents selected randomly for crossover. Assume the strings parent1 and parent2 as given below and, a crossover site is selected randomly as an integer between 1 and string length.

Parent1 = { 100 400 200 500 100 }
Parent2 = {300 500 100 600 700}

For illustration the string length is taken as 5, but in the thesis work string length depends upon the number of candidate buses for compensation. Let the crossover site is 3rd position. Then children Child1 and Child2 are generated as below.

Child1 = { **100 400 200** 600 700 }
Child2 = { 300 500 100 **500 100** }

It is seen that each crossover resulted in two children. In order to control crossover also there is a parameter called "Crossover Probability (P_e)". This probability is used as a decision variable before performing the crossover. This probability is known as the crossover rate. Crossover probability lies in the range of 0.7-1 [40]. The following steps are carried out to perform crossover.

Step 1: Select two parents by randomly selection method from the population.
Step 2: Generate random number between 0 and 1.
Step 3: Set a crossover probability 'Pc'.

Step 4: If the randomly generated number is greater than crossover probability ‘Pc’ Child1 and Child2 are directly selected as Parent1 and Parent2. This Step is equivalent to the case of crossover where crossover site is equal to the string length.

Step 5: If the randomly generated number is less than crossover probability ‘Pc’ than crossover takes place.

3.4.5 MUTATION

This operator is capable of creation new genetic material in the population to maintain the population diversity. It is nothing but random alteration of capacitor size. The following example illustrates the mutation operation.

Let Mutation site is at 4th position of the string.

Original String = { 400 100 500 200 800 }
String after mutation = { 400 100 500 **950** 800 }

In the above illustration after getting the mutation site, a random value is generated from 100 to 1100 is placed at the mutation site. Mutation is the process of random modification of the value of a string position with a small probability. The mutation probability ‘P_m’ lies in the range of 0.0001 to 0.01 [40].The following steps to be carried out to perform the mutation:

Step 1: Generate random number between 0 and 1.

Step 2: Set a crossover probability ‘Pc’.

Step 3: If the randomly generated number is less than mutation probability ‘P_m’ than mutation is performed on the off-springs generated by the crossover.

3.5 ALGORITHM FOR CAPACITOR ALLOCATION

The general outline of the Loss Sensitivity Factor and the Genetic algorithm for capacitor placement problem is discussed in the previous sections. The set of steps have been shown below to solve the capacitor placement problem:

Step 1: Read the distribution system branch impedance values and the bus real and reactive Power data.

Step 2: Run the Load Flow of Distribution System by using steps given in section 2.3, to find out voltage magnitudes at the buses and total power loss.

Step 3: Select the candidate buses by using steps given in section 3.3.2.

Step 4: Set GEN = 0

Step 5: Form initial population of real numbers, which is randomly selected value of capacitors to be installed at the candidate buses for compensation.

Step 6: Update the reactive power at candidate buses.

Step 7: Run the Load Flow of Distribution System by using steps given in section 2.3, with updated reactive power at the candidate buses for each population. Also calculate total power loss for each population.

Step 8: Calculate the total Energy Loss Cost (ELC) and Capacitor Cost (CC) for each population by using Eqs. (3.3) and (3.4)

Step 9: For each population, evaluate the objective function and the fitness value. The objective function for each population is the total energy loss cost and the cost of capacitors given in Eq. (3.5)

Step 10: GEN = GEN + 1

Step 11: Select the solutions in pool from initial population by using Roulette Wheel Selection procedure given in section 3.4.3.

Step 12: Perform Crossover on the solutions selected randomly from the pool using procedure given in section 3.4.4 and generate two offsprings.

Step 13: Perform Mutation on the offspring generated by the crossover operation using the procedure given in section 3.4.5 and generate the offspring.

Step 14: Calculate Energy Loss Cost (ELC) and capacitors cost (CC) Also evaluate Objective function and Fitness Function of each offsprings.

Step 15: Combine the solutions of the pool and the offsprings and refer them as new population.

Step 16: Replace new population with initial population for next generation.

Step 17: Go to step 10, till the solution converges.

Step 18: STOP

The above set of steps for the Capacitor Placement in radial distribution system is depicted in Flowchart as shown in Fig. 3.3.

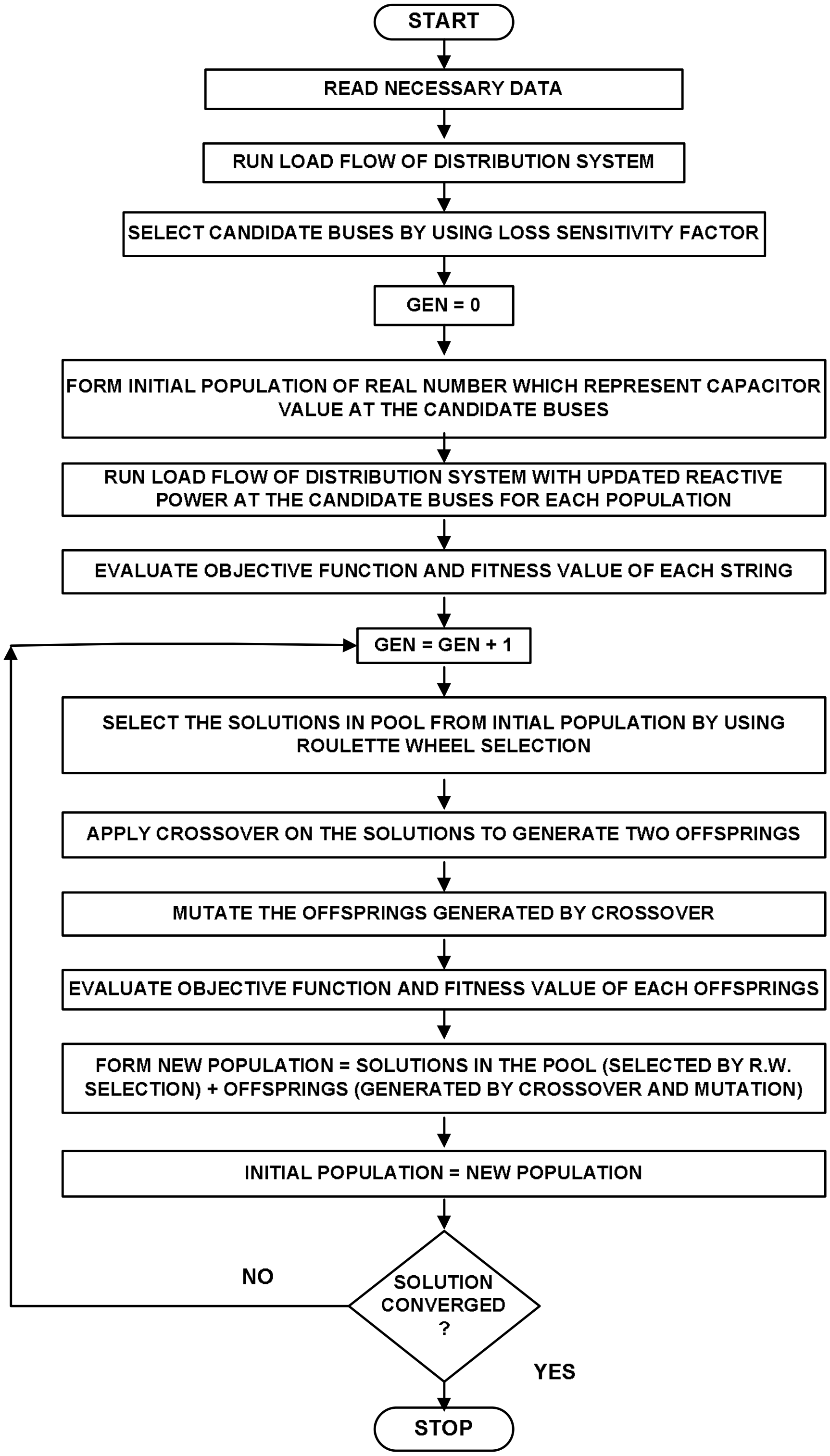

Figure 3.3: Flowchart for capacitor placement in distribution system

3.6 CONCLUSION

In this chapter loss sensitivity factors and genetic algorithm for capacitor placement in the distribution system have been discussed. The loss sensitivity factors are used to determine the candidate buses for compensation and genetic algorithm is used to find the sizes of shunt capacitors to be installed at candidate buses.

CHAPTER-4

RESULTS AND DISCUSSION

In this chapter results have been presented after the implementation of the algorithm discussed in Chapter 3. The algorithm have been developed in MATLAB environment. The algorithm has been tested on 33-bus and 69-bus radial distribution system (RDS), correspondingly, bus data and line data for 33-bus and 69-bus radial distribution system are [7, 37] given in Appendix-A and Appendix-B respectively.

Loss Sensitivity Factor discussed in Chapter 3 has been used to find out the potential buses for capacitor placement. Among the total potential buses selected by loss sensitivity factor, different number of candidate buses are selected and the effectiveness of compensation is discussed for maximum annual saving after considering saving due to energy loss cost and capacitor cost. The effectiveness of the algorithm for above systems has been studied for two cases namely.

Case I: Capacitor step size as 50 kVAr.
Case II: Capacitor step size as 1 kVAr.

In all simulations, the following parameters have been used [36]:

1. population size = 100
3. maximum Generation = 100
4. crossover probability ‘P_c’ = 1
5. mutation probability ‘P_m’ = 0.006
6. energy rate = US $0.06/kWh.
7. capacitor installation cost ‘C_{ci}’ = US $1000.
8. capacitor rate ‘C_{cv}’ = US $3.0/kVAr.

4.1 Optimal Capacitor Placement on 33-Bus RDS

The 33-bus radial distribution system, as shown in Fig. (4.1), has following characteristics:

Number of buses = 33

Number of lines = 32

Slack Bus No =1

Base Voltage=12.66 KV

Base MVA=100 MVA

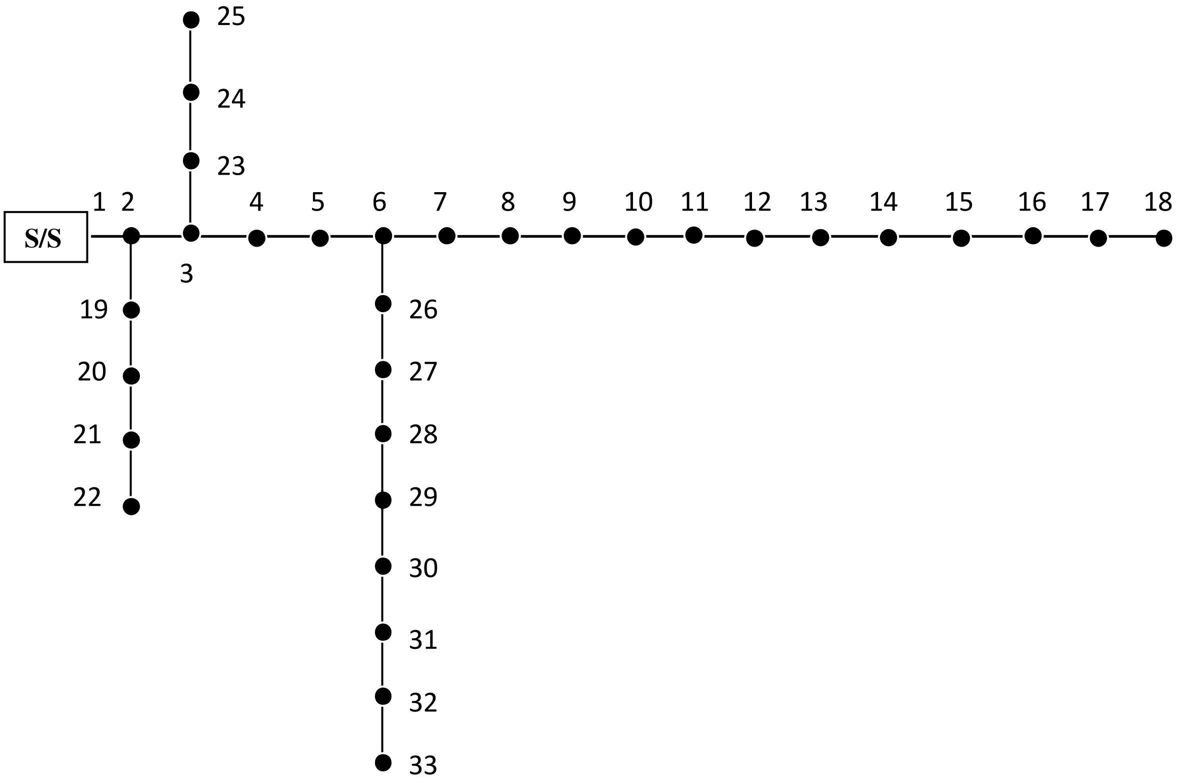

Figure (4.1): 33-Bus Radial Distribution System

The load flow of the distribution system is obtained using the algorithm discussed in Chapter 2. The load flow result of 33-bus RDS without shunt compensation are summarizes in Table 4.1.

Table (4.1): Base Case Load Flow Solution of 33-Bus RDS

Bus Number	Voltage Magnitude in p.u.	Angles in degrees
1	1.0000	0.0000
2	0.9970	0.0136
3	0.9829	0.0958
4	0.9754	0.1619
5	0.9680	0.2290
6	0.9495	0.1349
7	0.9460	-0.0967
8	0.9323	-0.2501
9	0.9260	-0.3246
10	0.9201	-0.3888
11	0.9193	-0.3814
12	0.9178	-0.3697
13	0.9116	-0.4628
14	0.9093	-0.5430
15	0.9079	-0.5815
16	0.9065	-0.6052
17	0.9044	-0.6840
18	0.9038	-0.6938
19	0.9965	0.0028
20	0.9929	-0.0642
21	0.9922	-0.0836
22	0.9916	-0.1039
23	0.9793	0.0648
24	0.9726	-0.0239
25	0.9693	-0.0676
26	0.9476	0.1744
27	0.9450	0.2305
28	0.9336	0.3135
29	0.9253	0.3914
30	0.9218	0.4967
31	0.9176	0.4123
32	0.9167	0.3892
33	0.9164	0.3815

Total Power Losses = 210.7921 (kW)

Annual Energy Loss Cost = \$ 1,10,792

Minimum system voltage $|V_{18}|$ = 0.9038 p.u. at bus 18

Loss Sensitivity Factor method as discussed in Chapter 3 has been used to identify the potential buses for shunt capacitor placement. The buses have been ordered according to the Loss Sensitivity Factor values ($\partial P_{loss}/\partial Q_{eff}$) and for 33-bus system (the potential buses are 29, 7, 30, 28, 12, 13, 31……).

Case I: Capacitor step size as 50 kVAr.

In this case capacitor value has been taken as a discrete variable. The capacitor allowable range is from 100 kVAr to 1100 kVAr with discrete step of 50 kVAr.

Case I (a): In this case first five buses, having highest loss sensitivity values are selected as candidate buses, these candidate buses are (i.e. buses 29, 7, 30, 28, 12) and the capacitor sizes have been determined by using GA. Table (4.2) shows the optimal location and capacitor sizes using five candidate buses for 33-bus RDS (capacitor step size as 50 kVAr).

Table (4.2): Optimal Location and Capacitor Sizes using five candidate buses for 33-Bus RDS (capacitor step size as 50 kVAr).

Bus Number	Capacitor Size (KVAr)
29	250
7	350
30	650
28	100
12	200

The Fig. 4.2 shows 33-bus radial distribution system with shunt capacitor location and capacitor sizes as summarized in Table 4.2. For optimal location and sizes of capacitor as indicated in Table 4.2, the load flow solutions are given in Table 4.3. The capacitor placement results in the improvement in bus voltages and reduced power losses.

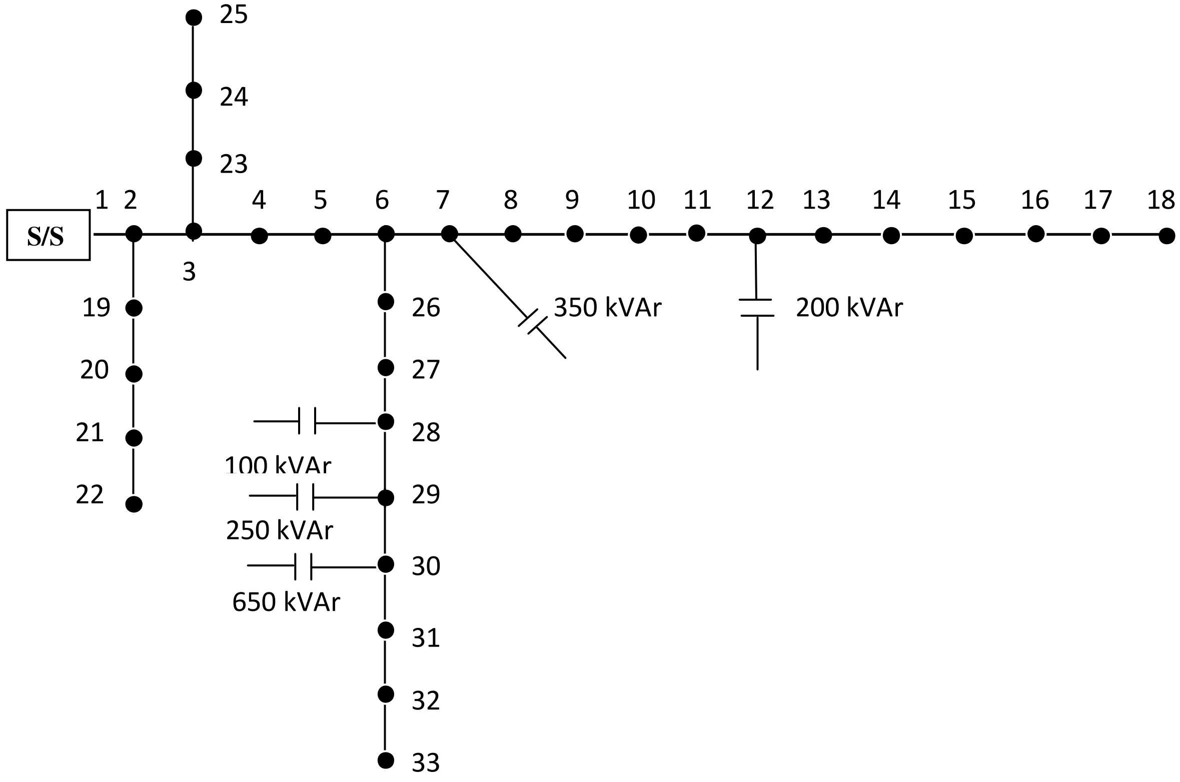

Figure 4.2: 33-Bus Radial Distribution System with Shunt Capacitor Location and Capacitor Sizes

Table (4.3): Load Flow Solutions of 33-Bus RDS
(with optimal capacitor placement at five candidate buses)

Bus Number	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value ‘Q’ in kVAr.
1	1.0000	0.0000	0
2	0.9975	-0.0378	0
3	0.9862	-0.2350	0
4	0.9807	-0.3802	0
5	0.9754	-0.5358	0
6	0.9645	-1.1077	0
7	**0.9632**	**-1.3695**	**350**
8	0.9516	-1.6492	0
9	0.9464	-1.8017	0
10	0.9417	-1.9458	0
11	0.9409	-1.9545	0
12	**0.9396**	**-1.9736**	**200**
13	0.9336	-2.0619	0
14	0.9314	-2.1380	0
15	0.9300	-2.1744	0
16	0.9287	-2.1969	0
17	0.9267	-2.2715	0
18	0.9261	-2.2808	0
19	0.9970	-0.0487	0
20	0.9934	-0.1156	0
21	0.9927	-0.1349	0
22	0.9921	-0.1552	0
23	0.9826	-0.2657	0
24	0.9759	-0.3537	0
25	0.9726	-0.3971	0
26	0.9633	-1.1478	0
27	0.9617	-1.2035	0
28	**0.9568**	**-1.5339**	**100**
29	**0.9529**	**-1.7429**	**250**
30	**0.9506**	**-1.7738**	**650**
31	0.9466	-1.8529	0
32	0.9457	-1.8745	0
33	0.9454	-1.8817	0

Total Power Losses ‘with capacitor’ = 140.5168 (kW)

Annual Energy Loss Cost = $ 73,855

Total capacitor costs = $9,650

Minimum system voltage $|V_{18}|$ = 0.9261 p.u. at bus 18.

Table 4.4 shown below gives the comparison of the results without and with capacitor placement. The total cost for the system without any compensation is found to be US $1,10,792. After compensation, the total cost which is sum of total energy loss cost and total capacitors cost is 83,505. From the results, it is seen that the annual saving is US $27,287 and minimum voltage level of the system has improved.

Table (4.4): Statistics of 33-Bus RDS without and with optimal placement of capacitors (5 candidate buses with capacitor step size 50 kVAr)

	Without capacitors	With capacitors
Minimum System Voltage (p.u.)	$V_{18} = 0.9038$	$V_{18} = 0.9261$
Power Loss (kW)	210.7921	140.5168
Buses and Capacitor size (kVAr)	-------	[(7, 350), (12, 200), (28, 100), (29, 250), (30, 650)]
Total Compensation	--------	1550 kVAr
Total Cost	$ 1,10,792	$ 83,505
Total Energy Loss Cost	$ 1,10,792	$ 73,855
Total capacitors cost	-------	$ 9,650
Total annual savings:		**$27,287**

Case I (b): In this case seven buses have been selected as candidate buses for shunt capacitor placement (i.e. buses 29, 7, 30, 28, 12, 13, 31) and the capacitor sizes have been determined by using GA. Table 4.5 gives the voltage profile of candidate buses for 33-Bus RDS without and with optimal placement of capacitors (7 candidate buses with capacitor step size 50 kVAr).

Table 4.6 compares the results without and with capacitor placement. The total cost for the system without any compensation is found to be US $1,10,792. After compensation, the total cost which is sum of total energy loss cost and total capacitors cost is 85,280. From the results, it is seen that the annual saving is US $25,512 and minimum voltage level of the system has improved. When comparing with the compensation at five buses with capacitor step size of 50 kVAr i.e. Table 4.4, the annual saving is less by $1775. This is mainly because of the increased installation cost at additional two buses.

Table (4.5): Voltage profile of candidate buses for 33-Bus RDS without and with optimal placement of capacitors (7 candidate buses, capacitor step size 50 kVAr)

	Without Capacitor		With Capacitor		
Bus No.	Voltage Magnitude in p.u.	Angles in degrees	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value 'Q' in kVAr.
7	0.9460	-0.0967	0.9629	-1.3708	150
12	0.9178	-0.3697	0.9421	-2.2347	100
13	0.9116	-0.4628	0.9380	-2.4713	250
28	0.9336	0.3135	0.9570	-1.5692	250
29	0.9253	0.3914	0.9527	-1.7473	150
30	0.9218	0.4967	0.9504	-1.7784	350
31	0.9176	0.4123	0.9483	-1.9736	300

Table (4.6): Statistics of 33-Bus RDS without and with optimal placement of capacitors (7 candidate buses with capacitor step size 50 kVAr)

	Without capacitors	With capacitors
Minimum System Voltage (p.u.)	$V_{18} = 0.9038$	$V_{18} = 0.9305$
Power Loss (kW)	210.7921	140.0888
Buses and Capacitor size (kVAr)	------	[(7, 150), (12, 100), (13, 250), (28, 250), (29, 150), (30, 350), (31, 300)]
Total Compensation (kVAr)	------	1550 kVAr
Total Cost	$ 1,10,792	$ 85,280
Total Energy Loss Cost	$ 1,10,792	$ 73,630
Total capacitors cost	------	$ 11,650
Total annual savings:		**$25,512**

Case II: In this case capacitor step size is considered as 1 kVAr and five candidate buses. The capacitor allowable range is from 1 kVAr to 1000 kVAr . The comparison of the load flow result at candidate buses and statistics of losses and saving for 33-Bus RDS are shown in Table 4.7. The comparison is made without and with capacitor placement while considering the capacitor step size as 50 kVAr and 1 kVAr. The annual saving is more with step size of 50 kVAr then with step size of 1 kVAr by US $ 96. This is due to reduced losses.

Table 4.7: Optimal Capacitor Placement at five candidate buses with capacitor size as 50 kVAr and 1 kVAr for 33-Bus RDS

	Without Capacitor		With Capacitor (Step size 50 kVAr)			With Capacitor (Step size 1 kVAr)		
Bus No.	Voltage Magnitude in p.u.	Angles in degrees	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value ‘Q’ in kVAr.	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value ‘Q’ in kVAr.
7	0.9460	-0.0967	0.9632	-1.3695	350	0.9631	-1.3747	165
12	0.9178	-0.3697	0.9396	-1.9736	200	0.9430	-2.3044	389
28	0.9336	0.3135	0.9568	-1.5339	100	0.9566	-1.5369	41
29	0.9253	0.3914	0.9529	-1.7429	250	0.9530	-1.7639	45
30	0.9218	0.4967	0.9506	-1.7738	650	0.9511	-1.8470	910
Power Loss (kW) = 210.7921			Power Loss (kW) = 140.5168			Power Loss (kW) = 140.7000		
Annual Energy Loss Cost $1,10,792			Annual Energy Loss Cost $73,855			Annual Energy Loss Cost $73,951		
Total Capcitors Cost $ 0.0			Total Capcitors Cost $ 9,650			Total Capcitors Cost $ 9650		
Total Cost = 1,10,792			Total Cost = 83,505			Total Cost = 83,601		
			Annual Saving $27,287			**Annual Saving $27,191**		

4.2 Optimal Capacitor Placement on 69-Bus RDS

The 69-bus radial distribution system, as shown in Fig. (4.3), has following characteristics:

Number of buses = 69
Number of lines = 68
Slack Bus No =1
Base Voltage=12.66 KV
Base MVA=100 MVA

The base case load flow solutions of 69-bus RDS without shunt compensation are summarizes in Table 4.8.

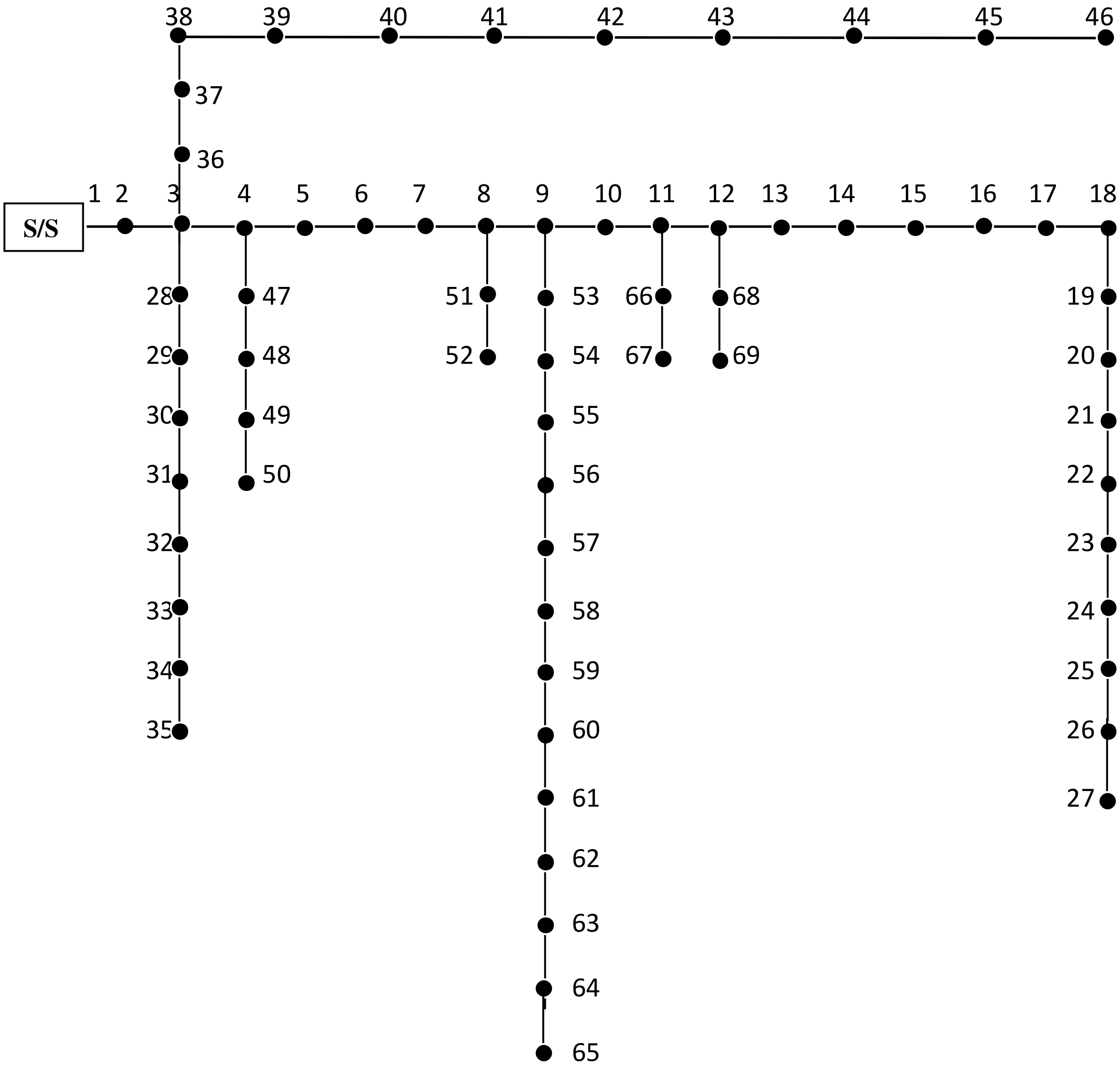

Figure (4.3): 69-Bus Radial Distribution System

Table (4.8): Base Case Load Flow Solution of 69-Bus RDS

Bus Number	Voltage Magnitude in p.u..	Angles in degrees	Bus Number	Voltage Magnitude in p.u..	Angles in degrees
1	1.0000	0.0000	36	0.9999	-0.0029
2	0.9999	-0.0012	37	0.9997	-0.0093
3	0.9999	-0.0025	38	0.9995	-0.0118
4	0.9998	-0.0059	39	0.9995	-0.0125
5	0.9990	-0.0185	40	0.9995	-0.0125
6	0.9900	0.0491	41	0.9988	-0.0235
7	0.9807	0.1206	42	0.9985	-0.0282
8	0.9785	0.1377	43	0.9985	-0.0288
9	0.9774	0.1465	44	0.9985	-0.0289
10	0.9724	0.2311	45	0.9984	-0.0307
11	0.9713	0.2499	46	0.9984	-0.0307
12	0.9681	0.3025	47	0.9997	-0.0077
13	0.9652	0.3487	48	0.9985	-0.0525
14	0.9623	0.3955	49	0.9947	-0.1916
15	0.9595	0.4415	50	0.9941	-0.2114
16	0.9589	0.4501	51	0.9785	0.1380
17	0.9581	0.4643	52	0.9785	0.1382
18	0.9581	0.4644	53	0.9746	0.1684
19	0.9576	0.4730	54	0.9714	0.1939
20	0.9573	0.4785	55	0.9669	0.2294
21	0.9568	0.4874	56	0.9625	0.2644
22	0.9568	0.4875	57	0.9400	0.6609
23	0.9567	0.4889	58	0.9290	0.8635
24	0.9566	0.4918	59	0.9247	0.9444
25	0.9564	0.4949	60	0.9197	1.0489
26	0.9563	0.4962	61	0.9123	1.1180
27	0.9563	0.4966	62	0.9120	1.1207
28	0.9999	-0.0027	63	0.9116	1.1243
29	0.9998	-0.0053	64	0.9097	1.1422
30	0.9997	-0.0032	65	0.9091	1.1476
31	0.9997	-0.0028	66	0.9712	0.2510
32	0.9996	-0.0009	67	0.9712	0.2510
33	0.9993	0.0035	68	0.9678	0.3086
34	0.9990	0.0093	69	0.9678	0.3086
35	0.9989	0.0104			

Total power losses ‘without capacitor’ = 224.9790 (kW)

Energy loss Cost for 1 year ‘without capacitor’ = $ 1,18,248

Minimum System voltage $|V_{65}|$ = 0.9091 p.u. at bus 65.

According to the Loss Sensitivity Factor values ($\partial P_{loss}/\partial Q_{eff}$), the potential buses for 69-bus system are 60, 63, 64, 20, 58, 16, 23, 25,…..

Case I: Capacitor step size as 50 kVAr.

In this case capacitor value has been taken as a discrete variable. The capacitor allowable range is from 100 kVAr to 1100 kVAr with discrete step of 50 kVAr.

Case I (a): In this case first five buses, having highest loss sensitivity values are selected as candidate buses, these buses are (i.e. buses 60, 63, 64, 20, 58) and then capacitor sizes have been determined by using GA. Table (4.9) shows the optimal location and capacitor sizes using five candidate buses for 69-bus RDS (capacitor step size 50 kVAr).

Table (4.9): Optimal Location and Capacitor Sizes using five candidate buses for 69-bus RDS (capacitor step size as 50 kVAr).

Bus Number	Capacitor Size (KVAr)
60	250
63	700
64	200
20	300
58	100

The Fig. 4.4 shows 69-bus radial distribution system with shunt capacitor location and capacitor sizes as summarized in Table 4.9. For optimal location and sizes of capacitor as indicated in Table 4.9, the load flow solutions are given in Table 4.10. The compensation results into reduced losses and improved voltage profile of buses.

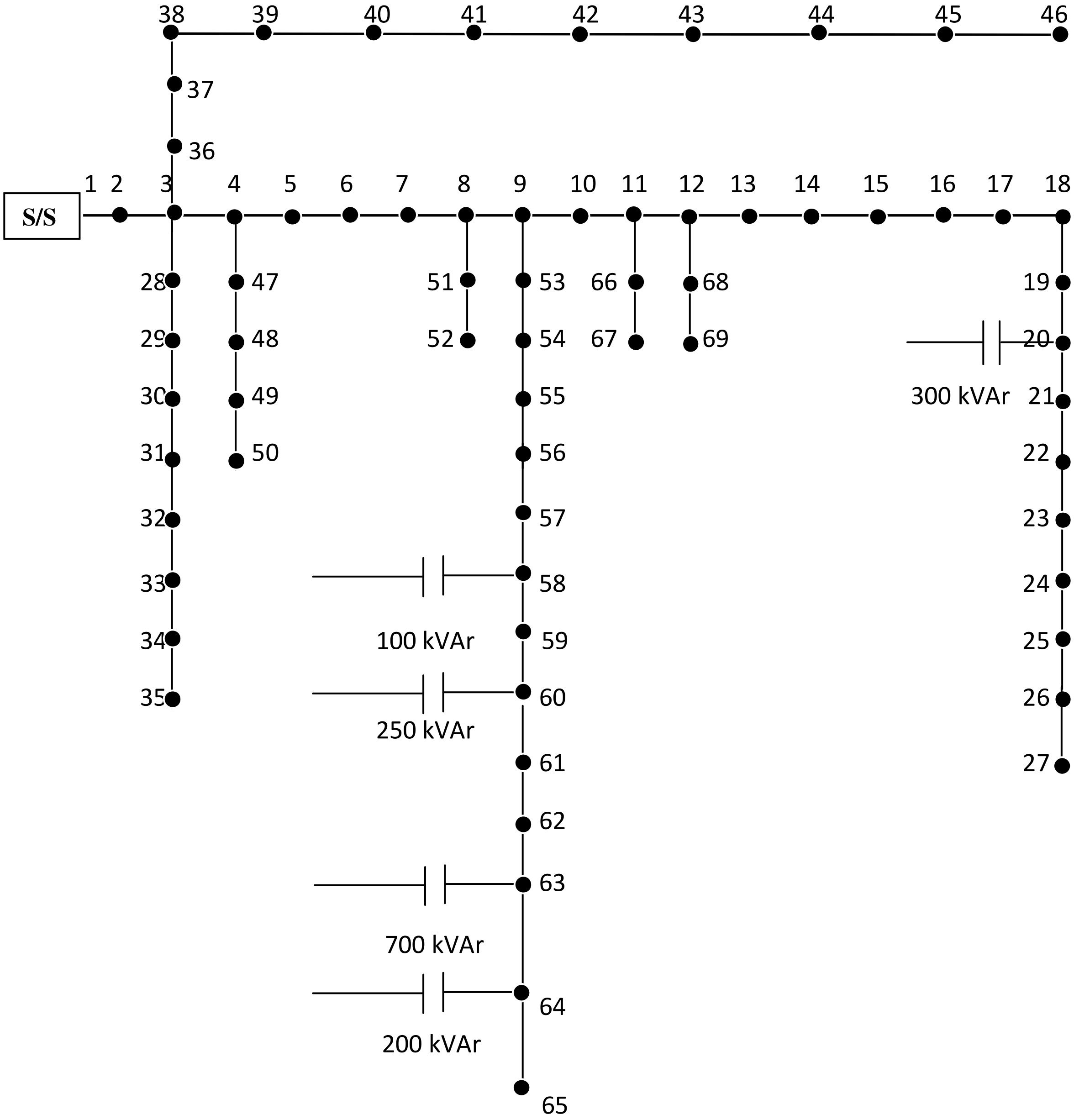

Figure 4.4: 69-Bus Radial Distribution System with Shunt Capacitor Location and Capacitor sizes

Table (4.10): Load Flow Solutions of 69-Bus RDS (with optimal capacitor placement at five candidate buses)

Bus Number	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value 'Q' in kVAr	Bus Number	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value 'Q' in kVAr
1	1.0000	0.0000	0	36	0.9999	-0.0034	0
2	0.9999	-0.0014	0	37	0.9997	-0.0098	0
3	0.9999	-0.0029	0	38	0.9996	-0.0122	0
4	0.9999	-0.0071	0	39	0.9995	-0.0129	0
5	0.9993	-0.0331	0	40	0.9995	-0.0130	0
6	0.9924	-0.1693	0	41	0.9988	-0.0240	0
7	0.9852	-0.3132	0	42	0.9985	-0.0286	0
8	0.9835	-0.3487	0	43	0.9985	-0.0292	0
9	0.9827	-0.3681	0	44	0.9985	-0.0294	0
10	0.9782	-0.3759	0	45	0.9984	-0.0312	0
11	0.9773	-0.3783	0	46	0.9984	-0.0312	0
12	0.9746	-0.4065	0	47	0.9998	-0.0089	0
13	0.9724	-0.4775	0	48	0.9986	-0.0537	0
14	0.9702	-0.5501	0	49	0.9947	-0.1928	0
15	0.9680	-0.6256	0	50	0.9942	-0.2126	0
16	0.9676	-0.6397	0	51	0.9835	-0.3484	0
17	0.9670	-0.6687	0	52	0.9835	-0.3482	0
18	0.9670	-0.6691	0	53	0.9807	-0.4268	0
19	0.9667	-0.6983	0	54	0.9783	-0.4957	0
20	**0.9665**	**-0.7170**	**300**	55	0.9752	-0.5932	0
21	0.9661	-0.7083	0	56	0.9721	-0.6908	0
22	0.9661	-0.7082	0	57	0.9545	-1.0701	0
23	0.9660	-0.7069	0	**58**	**0.9459**	**-1.2622**	**100**
24	0.9658	-0.7040	0	59	0.9425	-1.3246	0
25	0.9657	-0.7009	0	**60**	**0.9385**	**-1.4037**	**250**
26	0.9656	-0.6997	0	61	0.9328	-1.5240	0
27	0.9656	-0.6993	0	62	0.9328	-1.5574	0
28	0.9999	-0.0032	0	**63**	**0.9329**	**-1.6075**	**700**
29	0.9998	-0.0058	0	**64**	**0.9315**	**-1.6489**	**200**
30	0.9997	-0.0036	0	65	0.9310	-1.6438	0
31	0.9997	-0.0033	0	66	0.9772	-0.3772	0
32	0.9996	-0.0014	0	67	0.9772	-0.3772	0
33	0.9993	0.0029	0	68	0.9743	-0.4005	0
34	0.99903	0.0088	0	69	0.9743	-0.4005	0
35	0.9989	0.0099	0				

Total Power Losses 'with capacitor' = 147.3449 (KW)

Energy Loss Cost for 1 year 'with capacitor' = $ 77,444

Total capacitor costs = $9,650

Minimum System voltage at bus 65, $|V_{65}|$ = 0.9310 p.u.

Table 4.11 shown below gives the comparison of results without and with capacitor capacitor placement. The total cost for the system without any compensation is found to be US $1,18,248. After compensation, the total cost which is the sum of total energy loss cost and capacitors cost is US $ 87,094. From the results, it is seen that annual saving is US $31,154 and minimum voltage level of the system has improved.

Table (4.11): Statistics of 69-Bus RDS without and with optimal placement of capacitors (5 candidate buses with capacitor step size 50 kVAr)

	Without capacitors	With capacitors
Minimum System Voltage (p.u.)	V_{65} = 0.9091	V_{65} = 0.9310
Power Loss (kW)	224.9790	147.3449
Buses and Capacitor size (kVAr)	------	[(20, 300), (58, 100), (60, 250), (63, 700), (64, 200)]
Total Compensation (kVAr)	------	1550 kVAr
Total Cost	$ 1,18,248	$ 87,094
Total Energy Loss Cost	$ 1,18,248	$ 77,444
Total capacitors cost	0.0	$ 9,650
Total annual savings:		**$31,154**

Case I (b): In this case seven buses have been selected as candidate buses for shunt capacitor placement (i.e. buses 60, 63, 64, 20, 58, 16, 23) and the capacitor sizes have been determined by using GA. Table 4.12 gives the voltage profile of candidate buses for 69-Bus RDS without and with optimal placement of capacitors (7 candidate buses with capacitor step size 50 kVAr).

Table 4.13 compares the results without and with capacitor placement.The total cost for the system without any compensation is found to be US $1,18,248. After compensation, the total cost which is sum of total energy loss cost and total capacitors cost is 89,736. From the results, it is seen that the annual saving is US $28,511 and minimum voltage level of the system has improved. When comparing with the compensation at five buses with capacitor step size of 50 kVAr i.e. Table 4.12, the annual saving is less by $2643. This is mainly because of the increased installation cost at additional two buses.

Table (4.12): Voltage profile of candidate buses for 69-Bus RDS without and with optimal placement of capacitors (7 candidate buses, capacitor step size 50 kVAr)

	Without Capacitor		With Capacitor		
Bus No.	Voltage Magnitude in p.u.	Angles in degrees	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value 'Q' in kVAr.
16	0.9589	0.4501	0.9693	-0.9407	150
20	0.9573	0.4785	0.9683	-1.0177	200
23	0.9567	0.4889	0.9678	-1.0272	100
58	0.9290	0.8635	0.9452	-1.1518	250
60	0.9197	1.0489	0.9374	-1.2239	150
63	0.9116	1.1243	0.9314	-1.3822	550
64	0.9097	1.1422	0.9301	-1.4237	200

Table (4.13): Statistics of 69-Bus RDS without and with optimal placement of capacitors (7 candidate buses with capacitor step size 50 kVAr)

	Without capacitors	With capacitors
Minimum System Voltage (p.u.)	$V_{65} = 0.9091$	$V_{65} = 0.9295$
Power Loss (kW)	224.9790	148.2812
Buses and Capacitor size (kVAr)	------	[(16, 150), (20, 200), (23, 100), (58, 250), (60, 150), (63, 550), (64, 200)]
Total Compensation (kVAr)	------	1600 kVAr
Total Cost	\$ 1,18,248	\$ 89,736
Total Energy Loss Cost	\$ 1,18,248	\$ 77,936
Total capacitors cost	------	\$ 11,800
Total annual savings :		**\$28,511**

Case II: In this case capacitor step size is considered as 1 kVAr and five candidate buses. The capacitor allowable range is from 1 kVAr to 1000 kVAr . The comparison of the load flow result at candidate buses and statistics of losses and saving for 69-Bus RDS are shown in Table 4.14. The comparison is made without and with capacitor placement while considering the capacitor step size as 50 kVAr and 1 kVAr. The annual saving is more with step size of 50 kVAr then with step size of 1 kVAr by US \$30. This is due to lower losses.

Table (4.14): Optimal Capacitor Placement at five candidate buses with capacitor size as 50 kVAr and 1 kVAr for 69 bus RDS

	Without Capacitor		With Capacitor (Step size 50 kVAr)			With Capacitor (Step size 1 kVAr)		
Bus No.	Voltage Magnitude in p.u.	Angles in degrees	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value ‘Q’ in kVAr.	Voltage Magnitude in p.u.	Angles in degrees	Capcitor Value ‘Q’ in kVAr.
20	0.9573	0.4785	0.9665	-0.7170	300	0.9667	-0.7449	352
58	0.9290	0.8635	0.9459	-1.2622	100	0.9458	-1.2394	540
60	0.9197	1.0489	0.9385	-1.4037	250	0.9383	-1.3678	215
63	0.9116	1.1243	0.9329	-1.6075	700	0.9323	-1.5261	313
64	0.9097	1.1422	0.9315	-1.6489	200	0.9309	-1.5707	130
Power Loss (kW) = 224.9790			Power Loss (kW) = 147.3449			Power Loss (kW) = 147.4024		
Annual Energy Loss Cost $1,18,248			Annual Energy Loss Cost $77,444			Annual Energy Loss Cost $77,474		
Total Capcitors Cost $ 0.0			Total Capcitors Cost $ 9,650			Total Capcitors Cost $ 9650		
Total Cost = 1,18,248			Total Cost = 87,094			Total Cost = 87,124		
			Annual Saving $31,154			**Annual Saving $31,124**		

4.3 CONCLUSION

The optimal capacitor placement has been studied for 33-bus and 69-bus RDS, while considering different number of candidate buses for compensation, which are calculated with the help of precompensated load flow and loss sensitivity factor. The step size of 50 kVAr and 1 kVAr has been considered for the study. In both these system, the compensation at 5 buses with a step size of 50 kVAr is yielding better result than the compensated with 1 kVAr step size capacitor. When compared with compensation at more number of candidate buses the annual saving decreases. This is mainly due to increase in installation cost.

CHAPTER-5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 CONCLUSIONS

The work has been carried out to find the optimal locations and sizes (kVAr) of capacitors to be placed in radial distribution system to maximize the saving after considering the energy loss cost and capacitor cost. The above problem has been solved by two step methodology, the candidate locations for compensation are found using loss sensitivity factor calculated from base case load flow. The sizing has been attempted using Genetic Algorithm. In GA, coding scheme is developed to carry out the allocation problem, which is identification of location and size by one dimensional array. The study has been carried out on 33-bus and 69-bus radial distribution systems considering the capacitors step sizes of 50 kVAr and 1 kVAr. From the study the following conclusions are drawn.

- The compensation is yielding into increase in voltage profile, reduction in losses.
- The developed algorithm is effective in deciding the allocation of capacitors for different number of candidate buses and for different capacitor sizes.
- For the same number of buses, the annual saving due to capacitor step of 50 kVAr is more compared to the capacitor of step size 1 kVAr.
- For both 33-bus and 69-bus systems, the annual saving due to compensation at five candidate buses is higher than compensation at seven candidate buses.

5.2 SCOPE FOR FUTURE WORK

The completion of one research project opens the avenues for work in many other related areas. The following areas are identified for future work:

1. The study has been carried out on balanced distribution system. The capacitor allocation problem can be extended to unbalanced distribution system.
2. The allocation of DSTATCOM can be considered. This will also supportive during transients.

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APPENDIX-A

Table (A.1): Line Data for 33-Bus Radial Distribution System [7]

Branch Number	Sending-end Bus	Receiving-end Bus	Branch Resistance(Ω)	Branch Reactance (Ω)
1	1	2	0.0922	0.0477
2	2	3	0.4930	0.2511
3	3	4	0.3660	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	1.7114	1.2351
8	8	9	1.0300	0.7400
9	9	10	1.0040	0.7400
10	10	11	0.1966	0.0650
11	11	12	0.3744	0.1238
12	12	13	1.4680	1.1550
13	13	14	0.5416	0.7129
14	14	15	0.5910	0.5260
15	15	16	0.7463	0.5450
16	16	17	1.2890	1.7210
17	17	18	0.7320	0.5740
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.8980	0.7091
24	24	25	0.8960	0.7011
25	6	26	0.2030	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0590	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.9630
31	31	32	0.3105	0.3619
32	32	33	0.3410	0.5302

Table (A.2): Load Data for 33-Bus Radial Distribution System [7]

Bus Number	P(kW)	Q(kVAr)
1	0.0	0.0
2	100.0	60.0
3	90.0	40.0
4	120.0	80.0
5	60.0	30.0
6	60.0	20.0
7	200.0	100.0
8	200.0	100.0
9	60.0	20.0
10	60.0	20.0
11	45.0	30.0
12	60.0	35.0
13	60.0	35.0
14	120.0	80.0
15	60.0	10.0
16	60.0	20.0
17	60.0	20.0
18	90.0	40.0
19	90.0	40.0
20	90.0	40.0
21	90.0	40.0
22	90.0	40.0
23	90.0	50.0
24	420.0	200.0
25	420.0	200.0
26	60.0	25.0
27	60.0	25.0
28	60.0	20.0
29	120.0	70.0
30	200.0	600.0
31	150.0	70.0
32	210.0	100.0
33	60.0	40.0

(Base voltage = 12.66 kV, Base VA = 100MVA)

APPENDIX-B

Table (B.1): Line Data for 69-Bus Radial Distribution System [37]

Branch Number	Sending-end Bus	Receiving end Bus	Branch Resistance (Ω)	Branch Reactance (Ω)
1	1	2	0.0005	0.0012
2	2	3	0.0005	0.0012
3	3	4	0.0015	0.0036
4	4	5	0.0251	0.0294
5	5	6	0.3660	0.1864
6	6	7	0.3810	0.1941
7	7	8	0.0922	0.0470
8	8	9	0.0493	0.0251
9	9	10	0.8190	0.2707
10	10	11	0.1872	0.0619
11	11	12	0.7114	0.2351
12	12	13	1.0300	0.3400
13	13	14	1.0440	0.3400
14	14	15	1.0580	0.3496
15	15	16	0.1966	0.0650
16	16	17	0.3744	0.1238
17	17	18	0.0047	0.0016
18	18	19	0.3276	0.1083
19	19	20	0.2106	0.0690
20	20	21	0.3416	0.1129
21	21	22	0.0140	0.0046
22	22	23	0.1591	0.0526
23	23	24	0.3463	0.1145
24	24	25	0.7488	0.2475
25	25	26	0.3089	0.1021
26	26	27	0.1732	0.0572
27	3	28	0.0044	0.0108
28	28	29	0.0640	0.1565
29	29	30	0.3978	0.1315
30	30	31	0.0702	0.0232
31	31	32	0.3510	0.1160
32	32	33	0.8390	0.2816
33	33	34	1.7080	0.5646
34	34	35	1.4740	0.4873
35	3	36	0.0044	0.0108
36	36	37	0.0640	0.1565
37	37	38	0.1053	0.1230
38	38	39	0.0304	0.0355
39	39	40	0.0018	0.0021

40	40	41	0.7283	0.8509
41	41	42	0.3100	0.3623
42	42	43	0.0410	0.0478
43	43	44	0.0092	0.0116
44	44	45	0.1089	0.1373
45	45	46	0.0009	0.0012
46	4	47	0.0034	0.0084
47	47	48	0.0851	0.2083
48	48	49	0.2898	0.7091
49	49	50	0.0822	0.2011
50	8	51	0.0928	0.0473
51	51	52	0.3319	0.114
52	9	53	0.1740	0.0886
53	53	54	0.2030	0.1034
54	54	55	0.2842	0.1447
55	55	56	0.2813	0.1433
56	56	57	1.5900	0.5337
57	57	58	0.7837	0.2630
58	58	59	0.3042	0.1006
59	59	60	0.3861	0.1172
60	60	61	0.5075	0.2585
61	61	62	0.0974	0.0496
62	62	63	0.1450	0.0738
63	63	64	0.7105	0.3619
64	64	65	1.0410	0.5302
65	11	66	0.2012	0.0611
66	66	67	0.0047	0.0014
67	12	68	0.7394	0.2444
68	68	69	0.0047	0.0016

Table (B.2): Load Data for 69-Bus Radial Distribution Network [37]

Bus Number	P(kW)	Q(kVAr)	Bus Number	P(kW)	Q(kVAr)
1	0.0	0.0	36	26.0	18.55
2	0.0	0.0	37	26.0	18.55
3	0.0	0.0	38	0.0	0.0
4	0.0	0.0	39	24.0	17.0
5	0.0	0.0	40	24.0	17.0
6	2.6	2.2	41	1.20	1.0
7	40.40	30.0	42	0.0	0.0
8	75.0	54.0	43	6.0	4.30
9	30.0	22.0	44	0.0	0.0
10	28.0	19.0	45	39.22	26.30
11	145.0	104.0	46	39.22	26.30
12	145.0	104.0	47	0.0	0.0
13	8.0	5.0	48	79.0	56.40
14	8.0	5.0	49	384.70	274.50
15	0.0	0.0	50	384.70	274.50
16	45.0	30.0	51	40.50	28.30
17	60.0	35.0	52	3.60	2.70
18	60.0	35.0	53	4.35	3.50
19	0.0	0.0	54	26.40	19.0
20	1.0	0.60	55	24.0	17.20
21	114.0	81.0	56	0.0	0.0
22	5.0	3.50	57	0.0	0.0
23	0.0	0.0	58	0.0	0.0
24	28.0	20.0	59	100.0	72.0
25	0.0	0.0	60	0.0	0.0
26	14.0	10.0	61	1244.0	888.0
27	14.0	10.0	62	32.0	23.0
28	26.0	18.6	63	0.0	0.0
29	26.0	18.6	64	227.0	162.0
30	0.0	0.0	65	59.0	42.0
31	0.0	0.0	66	18.0	13.0
32	0.0	0.0	67	18.0	13.0
33	14.0	10.0	68	28.0	20.0
34	19.50	14.0	69	28.0	20.0
35	6.0	4.0			

(Base voltage = 12.66 kV, Base VA = 100MVA)