INTEGRATED DYNAMIC OPTIMAL POWER LOSS REDUCTION IN PRIMARY DISTRIBUTION SYSTEMS

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
of

MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power System Engineering)

By

PAWAR BANDOPANT BHIMRAO

M.G. CENTRAL LIBRARY
ACC No. G24693
Date 15/9/16
IIT ROORKEE

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

MAY 2015

CANDIDATE'S DECLARATION

I hereby declare that this thesis report entitled **INTEGRATED DYNAMIC OPTIMAL POWER LOSS REDUCTION IN PRIMARY DISTRIBUTION SYSTEMS**, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical Engineering with specialization in Power System Engineering is an authentic record of the work carried out by me during the period June 2014 through May 2015, under the supervision of **Dr. G.B.Kumbhar, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.** The matter presented in this thesis report has not been submitted by me for the award of any other degree of this institute or any other institutes.

Date: 23/05/2015

Place: Roorkee

Pawar Bandopant Bhimrao

CERTIFICATE

This is to certify that the above statement made by the candidate is true to the best of my knowledge and belief.

Dr. G.B.Kumbhar

Assistant Professor

Department of Electrical Engineering

Indian Institute of Technology Roorkee

ABSTRACT

An integrated power and energy loss optimization scheme consisting of Capacitor placement, Network Reconfiguration(NR) and Distributed Generation(DG) placement for the power and dynamic energy loss reduction and voltage profile improvement in primary radial distribution systems is proposed here. Individual power and energy loss reduction scheme i.e. Capacitor placement, NR and DG placement and combinations of these are tested on IEEE-33 and IEEE-69 bus systems and are analyzed comparatively. The different patterns of load types are taken into consideration to perform a practical study. The variable output of DG is considered by connecting the solar PV units into the distribution systems. Capacitors or the reactive power sources are considered if the DG units are unable to inject the reactive power. The developed backward/forward load flow method is used considering DGs as constant power sources. A meta heuristic Harmony Search Algorithm (HSA) is used for simultaneously determining the optimal reconfiguration and capacitor and DG sizes and locations. Different scenarios of Capacitor and DG placement and reconfiguration are considered to study the performance of the proposed method.

The objectives of this dissertation work are:

1. To propose an optimal dynamic power and energy loss optimization scheme.
2. Simulate the proposed scheme with IEEE-33 and IEEE-69 bus radial distribution systems.

Acknowledgements

I would like to express my deep sense of gratitude and sincere thanks to my beloved guide **Dr. G.B.Kumbhar**, Department of Electrical Engineering, Indian Institute of Technology Roorkee, for being helpful and a great source of inspiration. His keen interest and constant encouragement gave me the confidence to complete my work. I wish to extend my sincere thanks for his excellent guidance and suggestions for the successful completion of my work. Despite of his busy schedule, he used to review my dissertation progress, gave his valuable suggestions and made corrections. His dedication to work and self belief will always inspire me, and I hope to continue to work with his noble thoughts.

I would like to take this time to thank other faculty members of the department for their valuable suggestions and motivation.

I would like to extend my gratitude to my friends and classmates for their support throughout the past two years.I owe a lot to my family who unremittingly supported me during my years of study. I would like to pay high regards to my parents for being a true motivator throughout my life. Their relentless backing made this work possible and I would like to dedicate it to them.

Pawar Bandopant Bhimrao

Contents

List of Figures

List of Tables

Abbreviations

DG	Distributed Generation
ODGP	Optimal Distributed Generation Placement
NR	Network Reconfiguration
HSA	Harmony Search Algorithm
GA	Genetic Algorithm
DNO	Distribution Network Operator
DP	Dynamic Programming
MINLP	Mixed Integer Non Linear Programming
OPF	Optimal Power Flow
PSO	Particle Swarm Optimization
TS	Tabu Search
BIBC	Bus Injection to Branch Current
BCBV	Branch Current to Bus Voltage
KCL	Kirchoff's Current Law
HS	Harmony Search
HM	Harmony Memory
HMCR	Harmony Memory Considering Rate
PAR	Pitch Adjusting Rate
NI	Number of Improvisations
BW	Band Width
STATCOM	STATic COMpensator
PLR	Power Loss Reduction

To all the teachers in my life, past and present

भारतीय प्रौद्योगिकी संस्थान रुड़की
श्रमं विना न किमपि साध्यम
SHRAMAM VINA NA KIMAPI SADHYAM
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

Chapter 1

Introduction and Literature Review

1.1 Introduction

The power and energy loss reduction is one of the key planning issues in the distribution systems since the distribution system losses are much higher as compared to the transmission systems. In order to improve the overall efficiency, the power losses in the distribution systems should be reduced significantly. Most of the distribution systems are radial in nature for the effective coordination of the protective relays. The load demand on a distribution system increases continuously which results in increased burden on the feeders and the reduction in the bus voltages as we move away from the substation. This results in increased losses and increased peak demand. Increase in the power loss and the decrease in voltage profile are cumulative and it reduces the the distribution system stability and necessitates the expansion. Hence the power loss reduction is one of the crucial issue in the distribution system planning and operation.

There are various method of power loss reduction which automatically results in the voltage profile improvement such as capacitor placement, Network Reconfiguration(NR). The network reconfiguration changes the topology of the distribution system and the high demand loads are supplied via low impedance paths because of which the power losses get reduced. Capacitors inject the reactive power into the distribution systems which helps in improving the voltage profile and reducing the power loss. Nowadays the structure of the power system is changing due to integration Distributed Generation(DG) into the distribution networks for the improvement of the overall performance of the power system. Since the DG units inject the real and or reactive power into the distribution system, it reduces the load on the substation and if these are located properly then they also reduces the power losses in the distribution system and improves the voltage profile. Hence the NR, capacitor placement and DG integration are three methods of power loss reduction in the distribution systems.

Effective NR, DG and capacitor placement also results in reduction of the peak demand and peak operating cost, reduction in the burden on the substation transformers and feeders, diversification of energy resources, deferral of the transmission and distribution systems expansion, lowering of the transmission and distribution costs, improvement in the reliability and power quality.

The objective of the optimal capacitor and DG Placement(ODGP) is to find the best bus locations and sizes to optimize the distribution system planning and operation while satisfying the given constraints. As a planning issue the DG and capacitor locations and sizes can be considered as the decision variables but once the DG units and capacitors and integrated i.e. as an operational issue, the DG and capacitor sizes and tie switches are the decision variables for the optimal power loss reduction. Further the DG output may not be available continuously depending upon the source. In this case only NR and capacitor placement can be used to reduce the power loss. The network reconfiguration affects the topology and system operating conditions which also affect the ODGP and capacitor placement. Hence the NR, capacitor and DG placement should be manipulated simultaneously.

In this work, a meta-heuristic Harmony Search Algorithm(HSA) is implemented to optimize the power and energy loss subject to the operating constraints. Initially each of the power and energy loss reduction scheme i.e. NR, capacitor and DG placement is tested individually on IEEE-33 and IEEE-69 bus radial distribution systems. Then all the combinations of these schemes are implemented and the results are compared. This integrated scheme can be implemented to any type of the distribution system i.e. if the tie lines are not available then only capacitor and DG placement, if the DG units are not available then only NR and Capacitor placement, if both tie lines and DG units are not available then only capacitor placement method can be implemented. Again the loads at the buses does not remain constant. Also all the loads are not the constant power loads.

Hence for the practical study, the various types of loads i.e. Industrial, Commercial and Residential loads along with their load curves are taken into account. Solar PV are considered for varying DG output which is the common case in practice. Due to the high cost of commutation devices hourly reconfiguration is not possible. Hence the load curves are optimally divided into three intervals and also a single configuration which gives the optimal energy loss is found.

This dissertation report is divided into five chapters. The next section of this chapter presents a brief overview of different power and energy loss reduction techniques and methods used in the literature. Chapter 2 is dedicated to the load flow of the radial distribution systems. Chapter 3 explains the meta-heuristic HSA used for the optimization purpose. Chapter 4 explains all the three power loss reduction methods. Chapter 5 shows the results and the discussion on each of the power and energy loss reduction method. Final chapter aims at the conclusions drawn.

1.2 Literature Review

1.2.1 Capacitor Placement

To implement any power loss reduction method in the distribution systems, the repeated load flow is required. A direct approach for the distribution systems load flow is explained by Jen-Hao Teng in [1] which reduces the computation time required for the load flow calculations. Desai and Brown discussed the effect and performance of variable reactive power sources in primary distribution systems in [2]. Lee and Grainger [3] solved the optimal capacitor placement problem by non-linear programming with iterative method by taking capacitor sizes as continuous variables. In [4] Huang introduced a meta-heuristic Tabu Search method and compared the results with Simulated Annealing method. Sundhararajan and Pahwa [5] used the genetic algorithm for optimal capacitor placement. To select the candidate buses the sensitivity analysis is used. Milosevic, Begovic [6] proposed Genetic Algorithm for optimal shunt capacitor placement for conservative voltage reduction. Das [7] used Fuzzy-GA method for the optimal capacitor placement with sensitivity analysis for the candidate bus selection.

1.2.2 DG Placement

Various methods have been proposed to solve the ODGP problem with various objectives such as minimization of the power loss, energy loss, cost, voltage deviations and maximization of DG capacity, profit, voltage limit loadability. Again the ODGP problem considers single DG as well as multiple DGs case. The DG variables considered are number, bus location and size. Also the ODGP problem has been proposed with multiple constraints such as line capacity limits, voltage drop limits, short-circuit level limit, DG penetration limit, limit on the maximum number of DGs and reliability constraints. ODGP is solved by analytical, numerical as well as heuristic methods.

Analytical methods to find out the optimal bus location for a single DG having fixed size are described in [8]. An analytical method based on the loss sensitivity factor is used in [9] to the ODGP problem for a single DG. An analytical method explianed in [10] is used for the optimal sizing and siting of multiple DG units of different types.

Gradient search method for the ODGP problem in meshed networks with constraints on the fault level is described in [11]. ODGP is solved by using Linear Programming in [12] to achieve the maximum DG energy harvesting. The objective of the maximization of the profit of the distribution network operator (DNO) is considered using Dynamic Programming(DP) in [13]. Converter based DG units for the improvement of the the voltage stability margin are considered using MINLP in [14]. The ODGP in distribution systems is solved by the exhaustive search with variable demand in [15].

OPF and GA are combined in [16] for the optimal placement of DG units. ODGP is solved with the help of fuzzy GA for minimizing the power loss cost in [17]. A non-dominated sorting GA (NSGA) is implemented for maximization of the DG capacity in [18]. A hybrid GA along with immune algorithm is considered to solve the ODGP problem to maximize the profit [19]. A modified PSO is used for the ODGP of different DG types [20]. A hybrid PSO and GA is implemented in [21]. Discrete PSO is used for siting and OPF for sizing of the DG units [22]. HS algorithm along with loss sensitivity factors is used for ODGP in [33]. A stochastic model of the DG placement problem is implemented in [23] by a GA and by a combined scatter search and TS. The Heuristic ODGP method based upon the continuation of power flow is explained in [24]. The ODGP is evaluated by clustering techniques and exhaustive search method in two stages in [25].

1.2.3 Network Reconfiguration

A heuristic based on branch-and-bound-type optimization technique has been proposed by Shirmohammadi and Hong in [26]. Here initially all the switches are closed and then opened one by one to find out the the optimal power loss in the network. In [27] Huang and Chin have suggested a minimum loss configuration which is based on the artificial-intelligence. In [28] Das has proposed an algorithm which is based upon heuristic method and fuzzy approach to find the optimal reconfiguration of the distribution systems.

1.2.4 Combination of Network Reconfiguration and DG or Capacitor Placement

Most of the work has been done to reduce the power and energy losses by simultaneously considering two of the three power loss reduction methods i.e. NR, DG and capacitor placement. Till now all the three methods have not been considered simultaneously [29]. In [30] GA is used for minimization of power losses by simultaneous feeder reconfiguration and capacitor placement. Chang [31]has implemented ant colony search algorithm for reconguration and capacitor placement simultaneously to reduce the power loss. In [32] Discrete genetic algorithm (GA) has been used for feeder reconguration and capacitor placement simultaneously.

Various scenarios of DG placement and network reconfiguration are proposed and implemented by using HS algorithm in [33] and [34] with light, nominal and heavy loading conditions. But the capacitor placement is not considered here. Also the DG locations are fixed based on the loss sensitivity factors which may not be the optimal locations in actual practice. Again the constant power loads are considered here which is not the practical case. For the practical study various load types and load curves are considered in [35] for optimal NR and DG placement by optimally dividing the load curves and using combination of heuristic and meta-heuristic algorithms. But in this case the DG output during each interval is assumed to be constant which is not applicable for the cases where the output of DG units changes with time. In [36], solar PV buses are considered as PQ buses with negative generation when the distribution system is connected to the grid. A novel optimization technique which is called as Harmony Search Algorithm is used in [37] for solving complex, non-differentiable optimization problems without requiring any initial value settings. In this work HS algorithm is implemented for integrated power and energy loss reduction i.e. Capacitor placement, NR and DG placement are considered simultaneously. To make it dynamic the various load types and curves along with varying DG output are considered.

Chapter 2

Load Flow Analysis

2.1 Introduction

The steady state solution of the power system is obtained by using the load flow which gives the various parameters of interest such as the voltage magnitudes and phase angles, currents, power flows etc. The load flow solution is necessary for the planning, design, operation and control of the power system. Various methods such as Newton-Raphson, Gauss-Seidel, Decoupled method have been proposed for the load flow of the transmission systems. Most of the transmission systems have mesh topology while the distribution systems are radial in nature. Again R/X ratio is much higher in distribution systems due to which the conventional methods of load flow analysis may not converge for the distribution systems. Some of the characteristics of the distribution systems are as follows:

1. Radial or Weakly Meshed topology
2. Unbalanced loads and operation
3. Large number of lines and buses
4. High R/X ratio
5. Wide range of R and X

Based on the topological characteristic of the distribution systems, a method to find the load flow solution is modeled which is also known as Backward/Forward load flow method [1]. In this method it is not required to compute the Jacobian matrices in each iteration which reduces the computation time compared to conventional methods. This method is explained in the next sections.

2.2 Load Flow

The load flow of the radial distribution system considering the balanced operation and constant power loads consist of the following points:

1. Equivalent Current Injection
2. Formulation of Bus Injection to Branch Current(BIBC) Matrix
3. Formulation of Branch Current to Bus Voltage(BCBV) Matrix

2.2.1 Equivalent Current Injection

The equivalent current injection at a particular bus i with load S_i at the k-th iteration is given by the equation

$$S_i = P_i + jQ_i \qquad for \qquad i = 1, 2, 3....N \tag{2.1}$$

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{2.2}$$

where

S_i is the complex power at i-th bus

P_i is the real power at i-th bus

Q_i is the reactive power at i-th bus

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

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

2.2.2 Formulation Of BIBC Matrix

The formulation of BIBC matrix is illustrated with the help of a simple distribution system shown in the fig.(2.1).

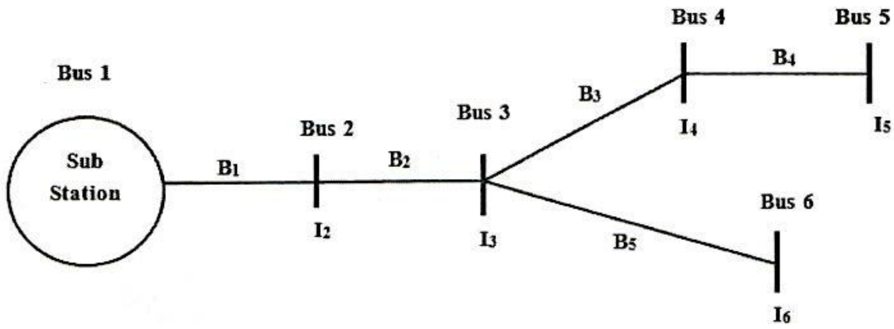

FIGURE 2.1: A Typical Distribution System

At each bus the power injections can be expressed in terms of equivalent current injection by using eq.(2.2) and a set of equations obtained by applying Kirchoff's Current Law(KCL) at each bus. Now branch currents can be expressed in terms of equivalent current injections. As shown in fig.(2.1), the branch currents B_1, B_2, B_3, B_4 and B_5 can be expressed as:

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

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

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

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

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

Using above equations the BIBC matrix can be formulated as:

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

The above expression can be written in general form as

$$[B] = [BIBC] * [I] \tag{2.8}$$

The general procedure to form the BIBC matrix using above equations which is shown with the illustrative fig.(2.2) is as follows:

1. For a distribution system with N buses and M branches the size of BIBC matrix is M*(N-1).

2. If a branch B_k lies in between bus i and bus j then copy the i-th bus column to j-th bus column of the BIBC matrix and add +1 at j-th bus column and k-th row as illustrated in fig.(2.2).

3. Repeat the above step until every branch is included in the BIBC matrix.

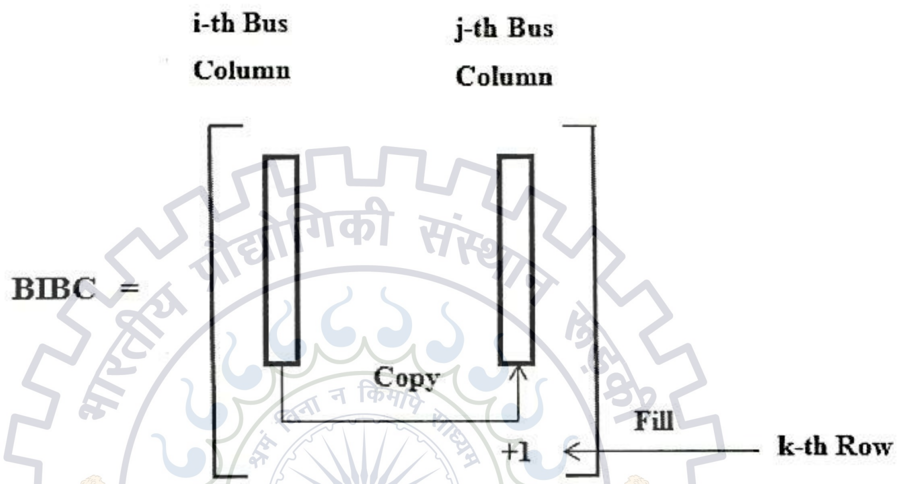

FIGURE 2.2: Formation of BIBC Matrix

2.2.3 Formulation Of BCBV Matrix

The Branch Current to Bus Voltage(BCBV) matrix relates the bus voltages to branch currents. From the fig. (2.1) the voltages at bus 2, 3 and 4 can be written in terms of branch currents as:

$$V_2 = V_1 - B_1 * Z_{12} \tag{2.9}$$

$$V_3 = V_2 - B_2 * Z_{23} \tag{2.10}$$

$$V_4 = V_3 - B_3 * Z_{34} \tag{2.11}$$

From the above equations the voltage at bus 4 can be written as:

$$V_4 = V_1 - B_1 * Z_{12} - B_2 * Z_{23} - B_3 * Z_{34} \tag{2.12}$$

From eq.(2.12) it is clear that the bus voltages can be expressed as function of substation voltage, branch currents and line impedance. The similar procedure is used to find out other bus voltages and the BCBV matrix is derived as:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 1 & 1 & 1 & 1 \\ Z_{12} & Z_{23} & 1 & 1 & 1 \\ Z_{12} & Z_{23} & Z_{34} & 1 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 1 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \times \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}$$

The above expression can be written in general form as:

$$\triangle V = BCBV * B \tag{2.13}$$

The general procedure to form the BCBV matrix using above equations which is shown with the illustrative fig.(2.3) is as follows:

1. For a distribution system with N buses and M branches the size of BCBV matrix is (N-1)* M.
2. If a branch B_k lies in between bus i and bus j then copy the i-th bus row to j-th bus row of the BCBV matrix and add Z_{ij} at j-th bus row and k-th column as illustrated in fig.(2.3).
3. Repeat the above step until every branches is included in the BCBV matrix.

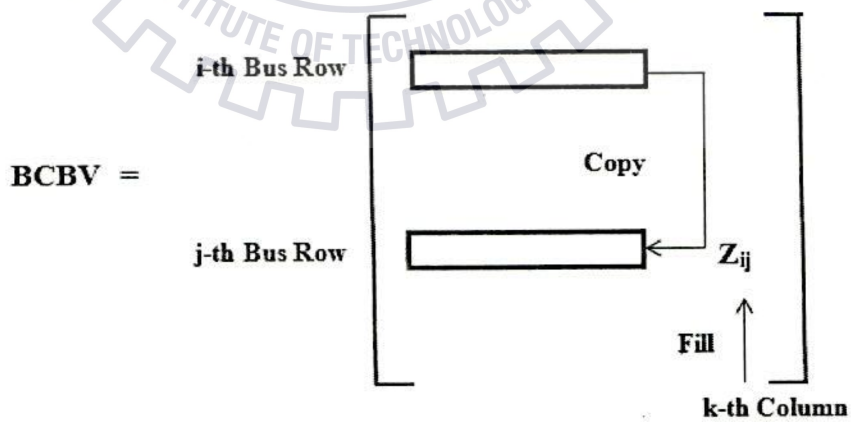

FIGURE 2.3: Formation of BCBV Matrix

From fig.(2.2) and fig.(2.3) it is clear that formulation of BIBC and BCBV matrices is much easier whatever may be the size of the distribution system. Again the procedure to form BIBC and BCBV matrices is almost similar only thing is that columns in BIBC are changed to rows in BCBV and +1 in BIBC to Z_{ij} in BCBV.

2.2.4 Solution Methodology

The procedure to form the BIBC and BCBV matrices is explained in the above sections. These matrices represent the topology of the distribution system. The BIBC matrix relates the bus current injections to the branch currents. Hence the variation in branch currents due to the variation in current injections can be directly calculated using BIBC matrix. The BCBV matrix relates the branch currents to the bus voltages. Hence the variation in bus voltages due to the variation in branch currents can be directly calculated using BCBV matrix. Combining eq.(2.8) and (2.13) the relationship between the bus voltages and the bus current injections can be written as:

$$[\triangle V] = [BCBV] * [BIBC] * [I] \tag{2.14}$$

Let

$$[DLF] = [BCBV] * [BIBC] \tag{2.15}$$

Therefore,

$$[\triangle V] = [DLF] * [I] \tag{2.16}$$

The load flow solution can be obtained by iteratively solving the following equations eq.(2.17), (2.18) and (2.19) which are given below:

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{2.17}$$

Let

$$[\triangle V_{k+1}] = [DLF] * [I_k] \tag{2.18}$$

Therefore,

$$[V_{k+1}] = [V_0] - [\triangle V_{k+1}] \tag{2.19}$$

As the DLF matrix does not changes as per iteration, this method is very time efficient and can be used for the optimization and on-line operation of the distribution systems.

2.3 Algorithm For Distribution System Load Flow

The steps involved in the load flow of the distribution system are as follows:

1. Start
2. Read the line and load data of the distribution system.
3. Form the BIBC matrix as illustrated in the subsection 2.2.2 where
   [B] = [BIBC] [I]
4. Form the BCBV matrix as illustrated in the subsection 2.2.3 where
   $[\triangle V]$ = [BCBV] [B]
5. Form the DLF matrix using the eq.(2.15), where
   [DLF] = [BCBV][BIBC]
   and $[\triangle V]$ = [DLF][I]
6. Set the iteration count k=0.
7. k=k+1
8. Update the voltages by using equations eq.(2.17), (2.18) and (2.19) as:
   $I_i^k = ((P_i + jQ_i)/V_i^k)^*$
   $[\triangle V_{k+1}] = [DLF] * [I_k]$
   $[V_{k+1}] = [V_0] - [\triangle V_{k+1}]$
9. If max $(|I_i^{k+1}| - |I_i^k|) > tolerance$ then go to the step 6.
10. From the final bus voltages calculate the line power flows and the losses.
11. Stop

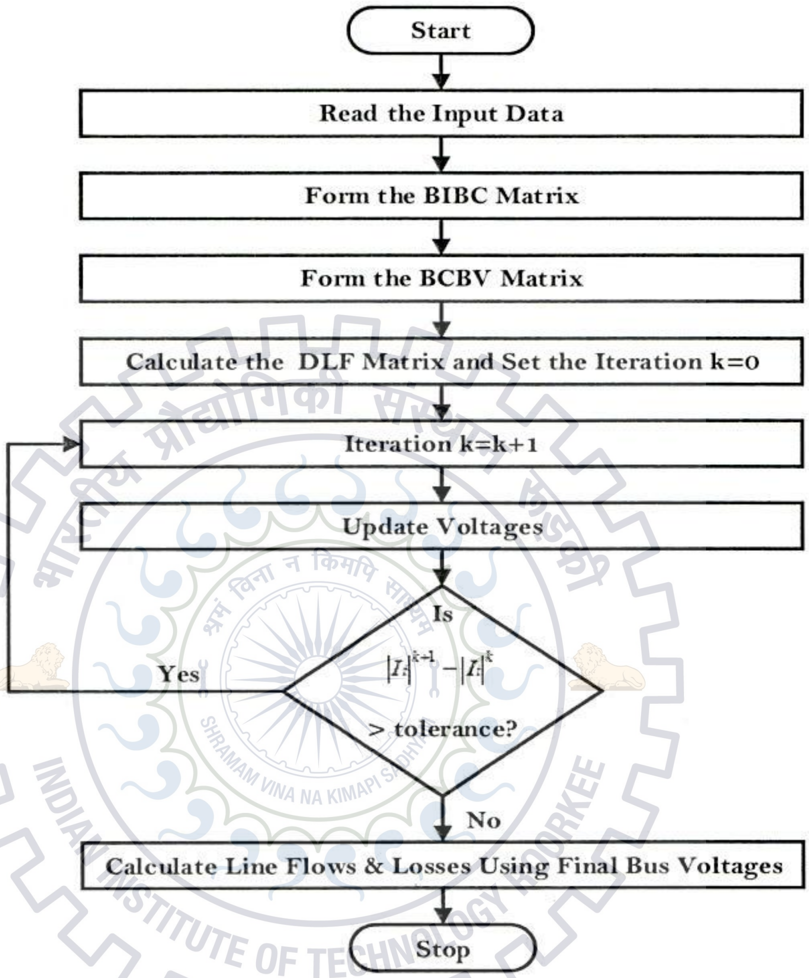

FIGURE 2.4: Flowchart for the Load Flow Solution of the Radial Distribution System

Chapter 3

Harmony Search Algorithm

3.1 Introduction

A meta-heuristic algorithm which mimics the process of improvisation of music players has been developed which is called as Harmony Search(HS) [37]. This harmony search in music is similar to find the optimal solution in an optimization problem. It is based on the concept that how the musicians play different notes of the different musical instruments for finding the best combination of frequencies which gives the best tune. Similarly in Harmony Search algorithm the best combination of available solutions is selected to find out the optimal solution of the objective function. Advantages of the HS algorithm are:

1. It is based on fewer mathematical requirements and does not need the initial value setting.
2. As it is based on the stochastic random searches, it can be applied to non-differential complex problems.
3. In this method a new solution vector is generated by considering all the existing solution vectors whereas in Genetic Algorithm(GA), only two parent vectors are taken into account.

3.2 Algorithm

The following steps are involved in the implementation of HSA:

1. Initialization of the optimization problem and algorithm parameters
2. Initialization of the harmony memory
3. Improvisation of a new harmony
4. Update of the harmony memory
5. Checking of the stopping criterion

3.2.1 Initialization of the Optimization Problem and HSA Parameters

The step 1 of the implementation of HSA is the initialization of optimization problem which is specified as follows:

Minimize $f(x)$ subject to $x_i \in X_i$ for all i=1, 2, 3.......N

and $x_i^L \leq X_i \leq x_i^U$

where,

$f(x)$ - the objective function to be minimized

x - the set of each decision variable x_i

X_i - the set of possible range of values for each decision variable x_i

N - the total number of decision variables

x_i^L and x_i^U - the lower and upper limit of each decision variable x_i

In this step, the HSA parameters are also specified which are as follows:

1. Harmony Memory Size(HMS)- which is the number of solution vectors in the Harmony Memory(HM) which is a memory location where all the solution vectors i.e. set of decision variables are stored.
2. Harmony memory Considering Rate(HMCR)
3. Pitch Adjusting Rate(PAR)
4. Bandwidth (BW)
5. Number of Improvisations(NI) or the stopping criterion

3.2.2 Initialization of the Harmony Memory(HM)

In this step, the HM matrix is filled with randomly generated solution vectors i.e. set of decision variables which are equal to HMS in number.

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & ... & x_N^1 \\ x_1^2 & x_2^2 & ... & x_N^2 \\ ... & ... & ... & ... \\ x_1^N & x_2^N & ... & x_N^N \end{bmatrix}$$

3.2.3 Improvisation of a New Harmony

Improvisation is the process of generating a new harmony. A new solution vector $x' = [x_1' \;\; x_2' \;\; x_3' \;\; ... \;\; x_N']$ is generated as per two rules:

1. Memory Consideration or Random Selection
2. Pitch Adjustment

3.2.3.1 Memory Consideration or Random Selection

Harmony memory considering Rate(HMCR) determines whether a new solution vector is to be selected from the existing Harmony Memory or it is to be generated randomly from the solution space i.e. the range of decision variables. The purpose of memory consideration is the wide search of the optimal solution in the search space. HMCR which lies in between 0 and 1 is the probability of selecting the new harmony vector from existing HM randomly and (1-HMCR) is the probability of generating it randomly from the solution space.

$x_i' \in [x_1^k \;\; x_2^k \;\; x_3^k \;\; ... \;\; x_N^k]$ with probability HMCR

and $x_i' \in X_i$ with probability (1-HMCR)

Since initially HM is filled with randomly generated solution vectors and then it is improvised, HMCR value greater than 0.5 gives the better results. Normally HMCR is set in between 0.7 and 0.95.

3.2.3.2 Pitch Adjustment

Every new harmony vector either generated by HM consideration or by random selection is examined for the pitch adjustment. This step of improvisation of harmony vector is mainly to search the solution in the narrow range around the solution vector generated by the previous step and the range of this search is set by the parameter bandwidth BW. Smaller the BW, smaller will be the search space. Pitch Adjusting Rate(PAR) sets the probability of the adjustment of the harmony vector while (1-PAR) is the probability of doing nothing.

Hence,

$x_i' = x_i' \pm rand() * BW$ with probability HMCR

and $x_i' = x_i'$ with probability (1-HMCR)

where, rand() is a random number between 0 and 1 and BW is the bandwidth of decision variables.

3.2.4 Update of the Harmony Memory

Once the harmony vector is improvised then the objective function is to be evaluated by considering the improvised harmony vector. If the new harmony is better than the worst harmony in the existing HM then The worst harmony in existing HM is replaced by the new harmony.

3.2.5 Checking of the Stopping Criterion

When the iteration number becomes equal to NI then computation is terminated. Now the best solution vector in the HM is the optimal solution of the given optimization problem.

The flowchart for the Harmony Search Algorithm is shown in the fig.(3.1).

भारतीय प्रौद्योगिकी संस्थान रुड़की INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

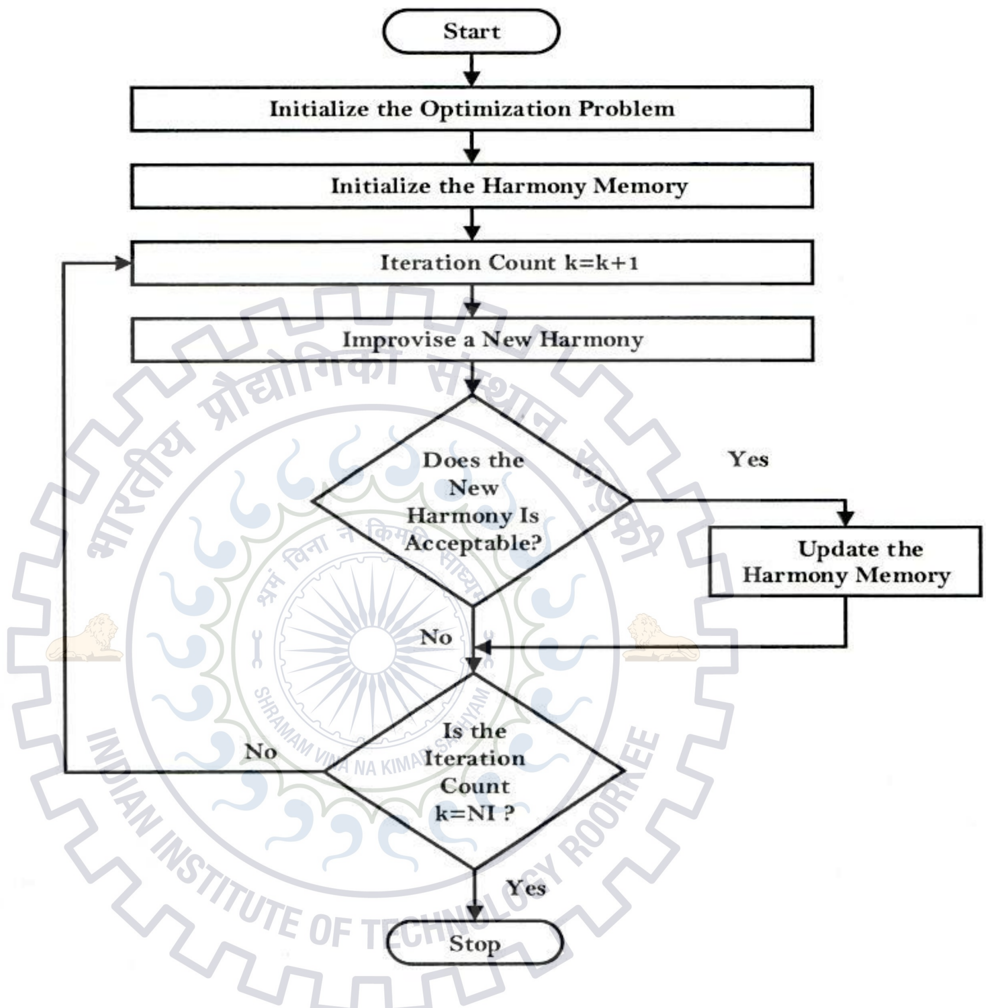

FIGURE 3.1: Flowchart for the Harmony Search Algorithm

Chapter 4

Power Loss Reduction Techniques and Application of HSA for Optimal Power Loss Reduction

4.1 Power Loss Reduction Techniques

4.1.1 Shunt Reactive Compensation

The shunt reactive compensation is generally used for the power loss reduction and voltage profile improvement in the distribution systems. To inject the reactive power into the distribution systems, capacitors placement is the most commonly used method. Capacitors may be uncontrolled or the step controlled. For the continuous control of the reactive power, synchronous compensators (overexcited synchronous machines operating on no load) are used. Nowadays for the continuous control of the reactive power to be injected into the system, a static converter based Distribution STATCOM is being used. Due to injection of the reactive power into the distribution feeders, the current drawn from the substation transformer is reduced and hence the total power loss. The followings are the advantages of shunt reactive compensation.

1. Decrease in the total power loss

2. Improvement in the voltage profile

3. Increase in the source power factor

4. Reduction in kVA loading on distribution transformer

5. Increase in the voltage regulation and stability of the distribution system

4.1.2 Network Reconfiguration

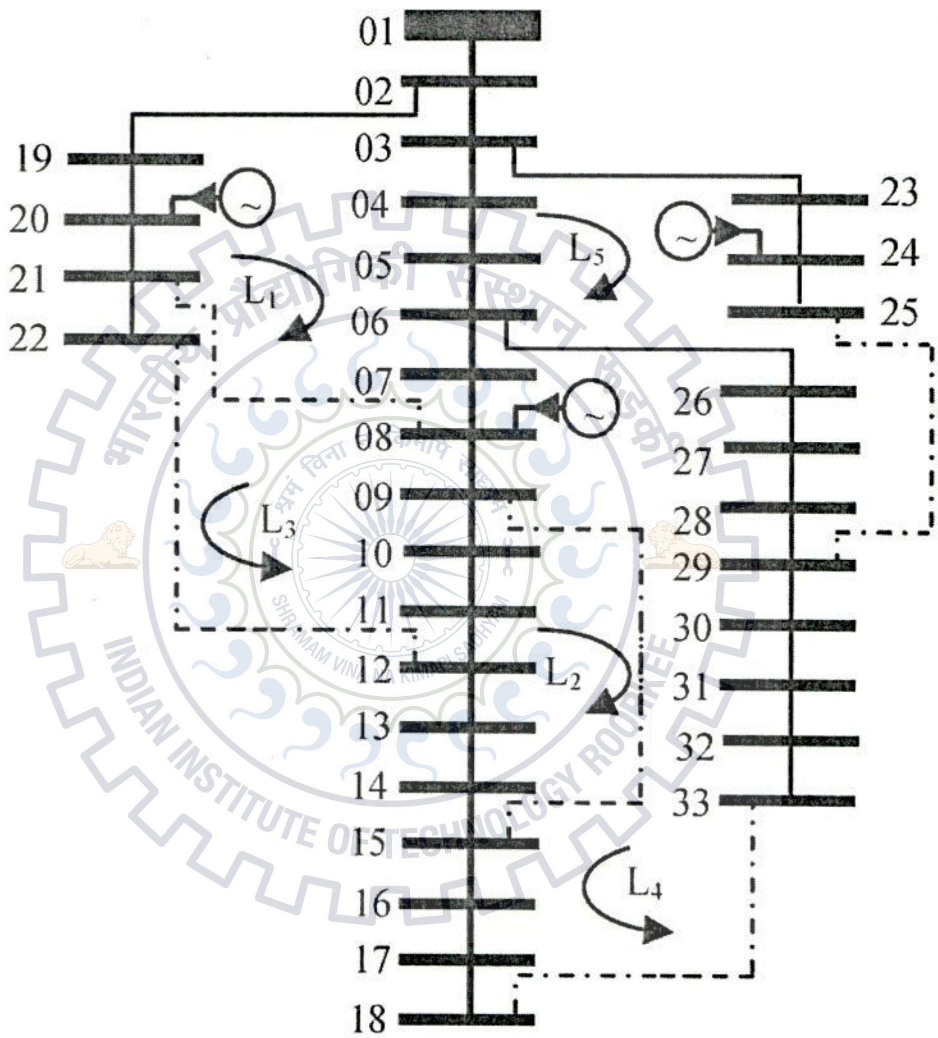

FIGURE 4.1: Base Topology of 33-bus Radial Distribution System in presence of DGs and Tie Lines [33]

Normally the topology of distribution systems is radial for the effective coordination of their protection systems. Distribution systems consists of two types of switches which serves both the purpose of protection and configuration control. These are sectionalizing (normally closed) and tie switches (normally open). By altering the status of the tie and sectionalizing switches, the topology of the distribution system is changed and the loads are transferred among the feeders while the radial nature of the system is still maintained.

This is called as feeder reconfiguration [33]. The following are the advantages of feeder reconfiguration:

1. Total power loss reduction in the distribution system
2. Balancing the system load
3. Voltage Profile Improvement
4. Increase in the system reliability and security
5. Improvement in the power quality

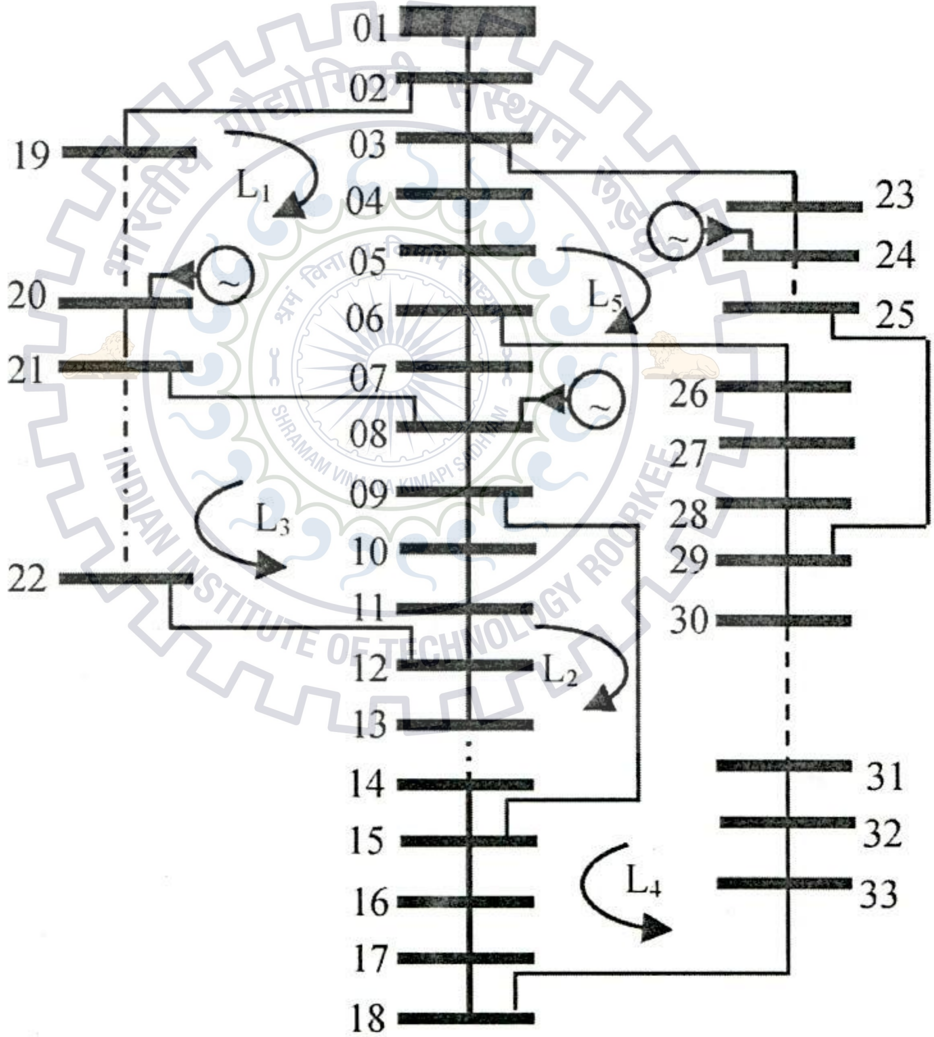

FIGURE 4.2: A Sample Reconfiguration of 33-Bus Radial Distribution System with DGs [33]

In the fig. (4.1) a 33-bus radial distribution system with tie lines is shown. The tie lines (shown by dotted lines) are connected between the buses 21 and 8, 22 and 12, 9 and 15, 25 and 29 and 18 and 33 with tie switches so as to control the operation of the line i.e.

either ON or OFF. Sectionalizing switches are present between any two buses which are connected by a dark line. By controlling the sectionalizing switch, the operation of the line can be controlled. Also three DGs are connected at the buses 8, 20 and 24.

With the addition of tie lines the loops L1, L2, L3, L4 and L5 are formed as shown in the fig. (4.1). Now switch positions in these loops are to be changed in such a way that only one switch is open in a loop so that all the buses are served and the radial structure of the network is still maintained. A sample reconfiguration of the 33 bus radial distribution system is shown in the fig. (4.2). Here all the tie switches shown in the fig. (4.1) are closed and the sectionalizing switches connecting buses 19 and 20, 21 and 22, 13 and 14, 24 and 25, 30 and 31 are opened. In this case the topology of the distribution system is changed but the radiality is still maintained.

4.1.3 DG Placement

4.1.3.1 Introduction

Distributed Generation (DG) refers to the small-scale generators (between 1kW 50MW) that generate the electricity near to the load centres and are directly connected to the electric distribution systems [29]. DG include various technologies which are enlisted in the next section. Distributed generation, which is also known as dispersed generation, decentralized generation or on-site generation, produces the electricity from many small scale energy sources. Conventional power generation consists of large centralized plants such such as fossil fuel plants(coal, gas fired), nuclear and large hydropower plants. These plants are having the excellent economies of scale, but the load centres are situated far away and the electricity is to be transmitted at long distances and also they affect the environment negatively. DG allows the collection of the energy from many sources with lower environmental impacts and high reliability of the supply.

4.1.3.2 Applications of DG Systems

The purposes behind the installation of the DG units are as follows:

1. To generate the entire electricity that a customer requires
2. To reduce the peak demand of a customer as well as the utility during the peak price periods

3. To provide the backup emergency supply of power
4. To integrate the renewable energy sources as green power sources
5. To defer the utility expansion
6. To provide the ancillary services such as power factor improvement, voltage regulation, frequency regulation etc.

4.1.3.3 DG Types

DG can be classified depending upon the injection of real(P) and reactive power(Q) as follows [10]:

1. Type 1: DG capable of injecting both P and Q
2. Type 2: DG capable of injecting P but consuming Q
3. Type 3: DG capable of injecting P only
4. Type 4: DG capable of injecting Q only

DG units using the synchronous machines (cogeneration plants, gas turbines etc.) fall in Type 1. Type-2 consists mainly induction generators used in the wind farms. Solar photovoltaics, micro-turbines and fuel cells which are connected to the grid by converters or inverters are examples of Type 3 DG. Synchronous Compensators such as gas turbines are the examples of Type-4 DG.

4.1.3.4 DG Technologies

DG technologies are broadly classified as the renewable or non-renewable technologies. Renewable technologies include solar (either concentrated or photovoltaic), wind turbines, geothermal. Normally the location and size of the wind turbines is suitable to connect it to the distribution system; Hence it is considered as DG. But the electricity generation from wind farms is owned by large companies; hence wind turbines are usually not includes in DG in the literature due to which these are not considered in this work. The IC engines , combined cycle plants, gas turbines, micro turbines and the fuel cells constitute the non-renewable DG. Among all the available technologies solar photovoltaics, IC engines, micro turbines and fuel cells play an important role in DG placement. Various DG technologies are enlisted below:

1. Internal Combustion Engines
2. Micro Turbine
3. Biomass
4. Fuel Cell
5. Small Hydro
6. Wind Turbine
7. Solar Photovoltaic
8. Concentrating Solar

4.1.3.5 Benefits of DG Systems

The advantages of integrating the DG units into the distribution systems are as follows:

1. It increases the power system reliability and improves the power quality.
2. DG provide ancillary services such as frequency regulation, voltage regulation.
3. It reduces the peak power demand.
4. It can also be used for the emergency supply of power.
5. It reduces the pressure on distribution and transmission lines.
6. It incorporates the use of renewable energy sources which is very helpful in reducing the carbon emissions.
7. It reduces the need for distribution and transmission system expansion.
8. Also it requires the lower capital cost as compared to the conventional power plants.

4.1.3.6 Challenges

However the DG integration into the distribution systems create the challenges which are given below.

1. The output of some of the renewable energy sources such as wind, PV and concentrated solar are variable in nature and are difficult to predict.

2. Connecting the DG to the distribution feeder introduces a source of energy at that point. This increases the fault level in the distribution system and complicates the protection schemes.

3. The key technical issues for the integration of DG to the grid are protection and islanding, reliability, metering, operational protocols for connection and disconnection, supply quality, and the management of reactive power.

4.2 Application of HSA for the Optimal Power Loss Reduction

4.2.1 For Fixed Load

Here the loads are considered as Constant Power loads and the power loss reduction method is evaluated for fixed loading condition. The DG units and shunt reactive compensators are assumed to be constant power sources. The DG units which are injecting only real power are considered along with shunt reactive compensators at the same buses. If the DG is capable of injecting both real and reactive power then it is not required to install the shunt reactive compensator at that bus.

In case of only DG, only capacitor or simultaneous DG and capacitor placement, the locations as well as sizes are the decision variables. Hence the nature of solution vector(harmony vector) is as follows:

$v = [Bus_1, Bus_2, Bus_3, P_1, P_2, P_3]$ - For DG Placement

$v = [Bus_1, Bus_2, Bus_3, Q_1, Q_2, Q_3]$ - For Capacitor Placement

$v = [Bus_1, Bus_2, P_1, Q_1, P_2, Q_2]$ - For simultaneous DG and Capacitor Placement

In case of the network reconfiguration, the tie switch positions are the decision variables. Hence the nature of solution vector is as follows:

$v = [SW_1, SW_2, SW_3, SW_4, SW_5]$ - With 5 tie lines

In case of the simultaneous NR and DG and/or capacitor placement the bus locations are taken from the best bus locations of the only DG placement case to reduce the complexity of the problem. Here the open switch positions and sizes of the DG units and or capacitors are the decision variables. Hence the nature of solution vector is as follows:

$v = [SW_1, SW_2, SW_3, SW_4, SW_5, P_1, P_2, P_3]$ - For NR and DG Placement

$v = [SW_1, SW_2, SW_3, SW_4, SW_5, Q_1, Q_2, Q_3]$ - For NR and Capacitor Placement

$v = [SW_1, SW_2, SW_3, SW_4, SW_5, P_1, Q_1, P_2, Q_2]$ - For NR, DG and Capacitor Placement

The test systems considered here are IEEE-33 bus and IEEE-69 bus radial distribution systems with 5 tie lines each. The substation voltage is 12.66 kV. The total load on 33 bus system is 3.715 $MW + 2.3$ $MVAR$ with toal power loss of 211 kW. The total load in case of 69 bus system is 3.802 $MW + 2.694$ $MVAR$ with toal power loss of 225 kW. The objective function to be minimized is the total power loss. The number of DG units and capacitors considered are 1, 2 and 3 resp. The parameters set in HSA are HMS=20, HMCR=0.9, PAR=0.4, NI=500. Minimum DG size considered is 250 kW and the maximum upto 100 % of the total load with bandwidth of 40 kW. The constraints considered are as follows:

1. Bus voltage constraints: $0.90 < V_{bus} < 1.05$
2. Line loading limits: in terms of maximum line currents
3. Maximum DG and Capacitor Penetration: upto 100 % of the load
4. Maximum number of DG or capacitors: 3

With these HSA is implemented and the results obtained are discussed in chapter 5.

4.2.2 For Varying Load

4.2.2.1 Load Curves

Actually the load on a distribution system does not remain constant and changes with time which is given by the daily load curve [38]. Again all the loads are not constant power loads but also consists constant current and constant impedance loads. Hence for the practical study residential, commercial and industrial loads are considered with load curves as shown in the fig.4.3.

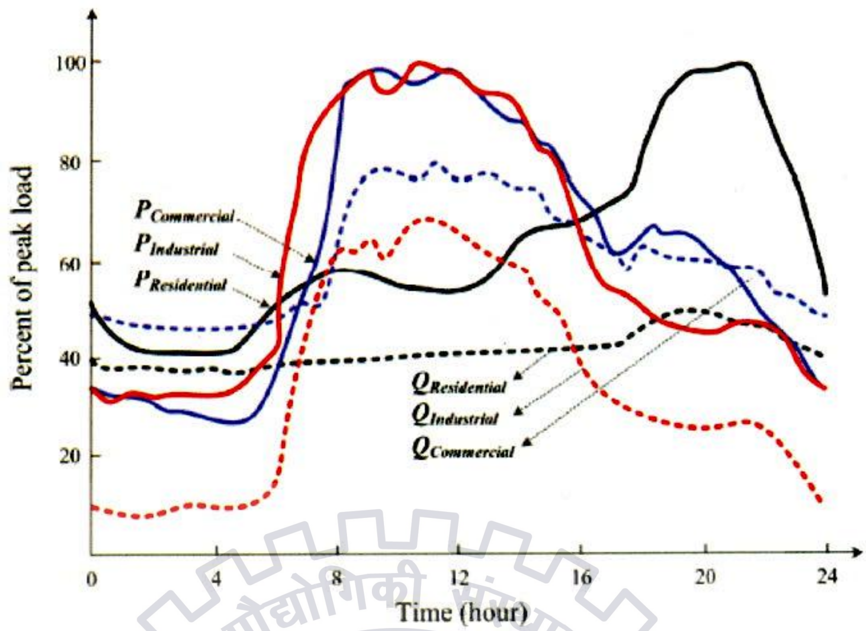

FIGURE 4.3: Typical Daily Load Curves [38]

4.2.2.2 Load Model

Here at each bus, the loads are modeled as voltage dependent polynomials which are given by eq.(4.1) and (4.2) [35].

$$P = P_0\left(A_p\left(\frac{V}{V_0}\right)^{\alpha_p} + B_p\left(\frac{V}{V_0}\right)^{\beta_p} + C_p\left(\frac{V}{V_0}\right)^{\gamma_p}\right) \tag{4.1}$$

$$Q = Q_0\left(A_q\left(\frac{V}{V_0}\right)^{\alpha_q} + B_q\left(\frac{V}{V_0}\right)^{\beta_q} + C_q\left(\frac{V}{V_0}\right)^{\gamma_q}\right) \tag{4.2}$$

where V_0, P_0 and Q_0 are the rated voltage, real and reactive power at rated voltage resp. A, B, C are the percentages of industrial, commercial and residential loads connected to each bus such that $A + B + C = 1$. The values of the exponents are given in the following table.

	$Industrial(\alpha)$	$Commercial(\beta)$	$Residential(\gamma)$
P	0.1	0.6	1.7
Q	0.6	2.5	2.6

TABLE 4.1: Table of Values of the Exponents in Polynomial Load Models

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

4.2.2.3 Load Interval

It is not possible to find out the optimal configuration and sizes of the DG units and capacitors at each instant as the load is changing. Hence the total load interval is optimally divided by using HSA with the following objective function:

$$F = Min. \quad \sum_{i=1}^{L}\sum_{k=1}^{Ti}\left((P_{avg_i} - P_{k_i})^2 + (Q_{avg_i} - Q_{k_i})^2)\right) \tag{4.3}$$

$$Subjected \quad to \qquad \sum_{i=1}^{L} Ti = 24 \tag{4.4}$$

where, P_{avg_i} and Q_{avg_i} are the average real and reactive demands at the load interval i. P_{k_i} and Q_{k_i} are the active and reactive power demands at $k-th$ hour of the load interval i. Ti is the total number of hours in the load interval i and L is the total number of load intervals. The procedure for the dynamic optimal power loss reduction is shown with the help of fig. 4.4

4.2.2.4 Multiple Solutions With a Single Configuration

Since the DLCs are considered and the load changes continuously, the main objective is to reduce the total energy loss over the entire day. Once the load curve has been optimally divided into three intervals, the optimal solution for the energy loss reduction by each method is to be found. Due to higher cost of the commutation devices, it is not possible to change the configuration of the distribution system in each interval. Hence the optimal configuration of the distribution system considering the energy loss for the entire day is found and kept constant throughout the day. Since this is an operational planning issue, the DG and/or capacitor bus locations are fixed. Here the capacitors or the reactive power sources are to be used if the DG can't supply reactive power and at the same buses. Here the best locations from the power loss optimization results are chosen. The sizes of DG units and or capacitors for each interval and the optimal configuration for the entire day is to be determined by using HSA. The loads considered in fixed load condition are taken as peak loads in this case. At each bus 40% residential, 35 % commercial and 25% industrial load is taken with polynomial load models. The results of each method for all the intervals implemented on IEEE-33 nad IEEE-69 bus distribution systems are discussed in chapter 5.

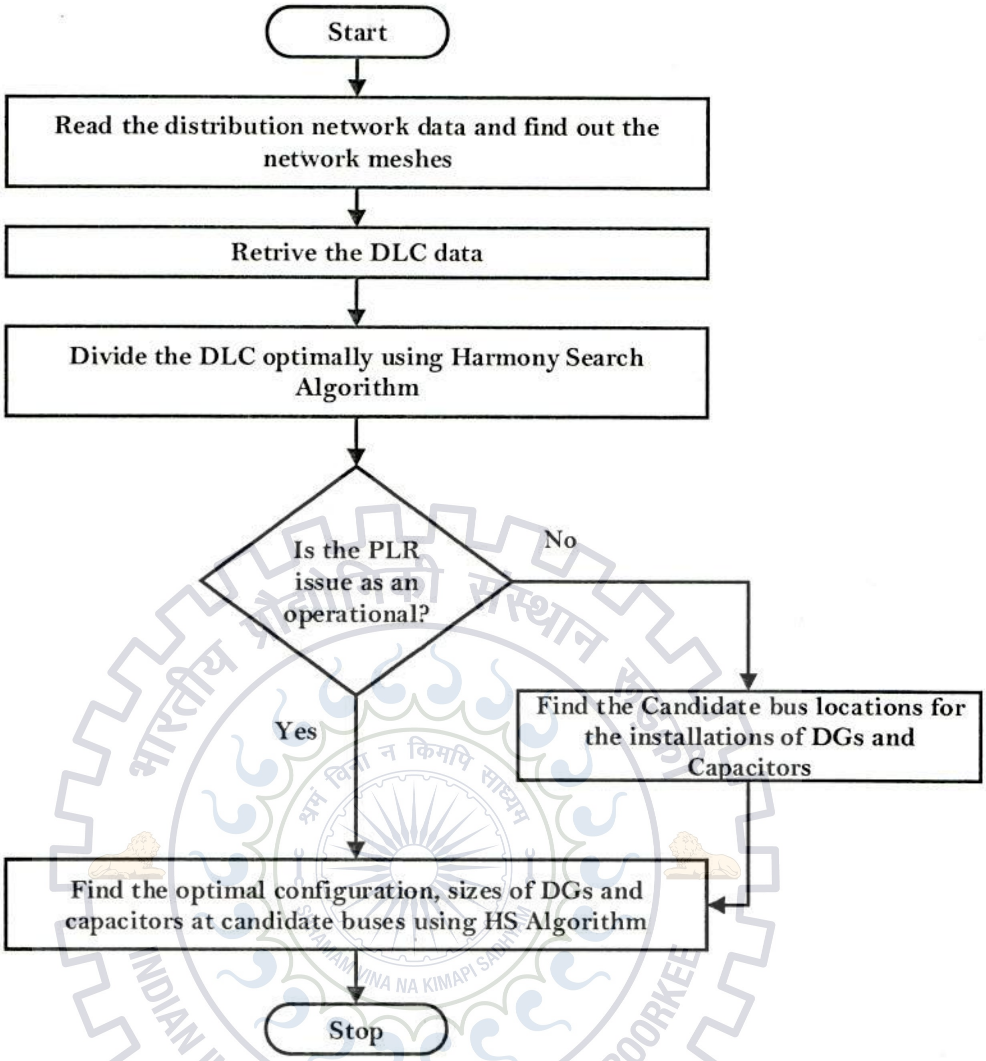

FIGURE 4.4: Flowchart for the Optimal Dynamic Power Loss Reduction in Distribution Systems

4.2.3 For Varying Load with Varying DG output

In case of the renewable energy sources such as solar PV, concentrated solar and wind turbines, the output is not fixed and changes as per the time of the day. Here though DGs are connected in the distribution system, they do not inject the power into the distribution feeders throughout the day. Hence the energy loss reduction and the voltage profile improvement in such cases is a complex issue. The fig. 4.5 shows the typical variation of the solar PV output throughout the day.

For this type of of condition the energy loss reduction techniques are capacitor placement, NR and simultaneous NR and capacitor placement since the DGs has been already

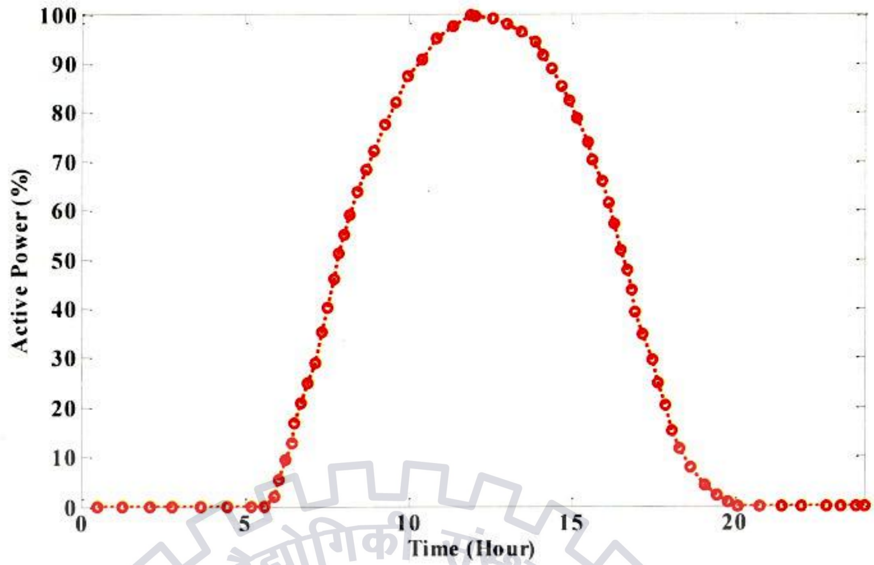

FIGURE 4.5: Generation Profile of A Typical Solar PV Unit [39]

connected in the distribution systems. Here three solar PV units of the optimal peak sizes 802 kW, 1075 kW and 1064 kW are considered in IEEE-33 bus system at the buses 13, 24 and 30 resp. In case of IEEE-69 bus system, three PV units of the optimal peak sizes 563 kW, 346 kW and 1716 kW are considered at the buses 11, 18 and 61 resp. In the load flow, the candidate buses are considered as PQ buses with negative generation [36]. Here the load curve is divided into three intervals depending upon the output of DG units. The loads considered in fixed load condition are taken as peak loads in this case. At each bus 40 % residential, 35 % commercial and 25 % industrial load is considered with polynomial load model. The bus locations for the capacitor placement are assumed to be the same as the DG locations. The results of the three methods are discussed in chapter 5.

Chapter 5

Results and Discussions

5.1 Fixed Load Condition

5.1.1 Only Capacitor Placement

The table 5.1 shows the reduction in power loss in IEEE-33 bus radial distribution system due to installation of 1, 2 and 3 capacitors resp. Here the capacitors literally does not mean only capacitor but the source of reactive power. The optimal location for installation of single capacitor is bus no. 30 and the size is 1258 kVAR. With this, the power loss reduces from 211 kW to 151.38 kW i.e. 28.26 %. With two capacitors at bus 12 and 30 of sizes 465 and 1063 kVAR, the power loss reduces upto 32.78%. The maximum power loss reduction is 34.47 % with three capacitors at buses 13, 24 and 30

TABLE 5.1: Results of Capacitor Placement in IEEE-33 Bus System

No. Of Capacitors	Bus Location	Size (kVAR)	Total Size (kVAR)	Total Power Loss (kW)	Reduction In Power Loss (%)
No Capacitor	-	-	-	211.00	-
1 Capacitor	30	1258	1258	151.38	28.26
2 Capacitors	30	1063	1528	141.84	32.78
	12	465			
3 Capacitors	30	1042	1933	138.27	34.47
	24	533			
	13	388			

TABLE 5.2: Results of Capacitor Placement in IEEE-69 Bus System

No. Of Capacitors	Bus Location	Size (kVAR)	Total Size (kVAR)	Total Power Loss (kW)	Reduction In Power Loss (%)
No Capacitor	-	-	-	224.96	-
1 Capacitor	61	1330	1330	152.00	32.44
2 Capacitors	12	568	1813	146.59	34.84
	61	1245			
3 Capacitors	18	305	1948	145.47	35.34
	61	1205			
	53	438			

of sizes 388, 533 and 1042 kVAR resp. Beyond this reduction in loss is less as compared to additional installed capacity.

The table 5.2 shows the reduction in power loss in IEEE-69 bus radial distribution system due to installation of 1, 2 and 3 capacitors resp. The optimal location for installation of single capacitor is bus no. 61 and the size is 1330 kVAR. With this, the power loss reduces from 225 kW to 152 kW i.e. 32.44 %. With two capacitors at bus 12 and 61 of sizes 568 and 1245 kVAR, the power loss reduces upto 34.84%. The maximum power loss reduction is 35.34 % with three capacitors at buses 18, 53 and 61 with sizes 305, 438 and 1205 kVAR resp. Here the total installed size is 1948 kVAR.

5.1.2 Only DG Placement

The table 5.3 shows the reduction in power loss in IEEE-33 bus radial distribution system due to installation of 1, 2 and 3 DG units resp. The optimal location for installation of single DG unit is bus no. 6 and the size is 2590 kW. With this, the power loss reduces from 211 kW to 111 kW i.e. 47.39 %. With two DG units at bus 12 and 30 of sizes 960 and 1109 kW, the power loss reduces upto 58.65%. The maximum power loss reduction is 65.50 % with three DG units at buses 13, 24 and 30 of sizes 802, 1075 and 1064 kW resp. Here the total installed DG size is 2941 kW which is 79.61 % of the total active power demand on the distribution system.

The table 5.4 shows the reduction in power loss in IEEE-69 bus radial distribution system due to installation of 1, 2 and 3 DG units resp. The optimal location for installation of single DG unit is bus no. 6 and the size is 1872 kW. With this, the power loss reduces from 225 kW to 83.19 kW i.e. 63.03 %. With two DG units at bus 12 and 61 of sizes 813 and 1735 kW, the power loss reduces upto 67.78%. The maximum power loss reduction

TABLE 5.3: Results of DG Placement in IEEE-33 Bus System

No. Of DG	Bus Location	Size(kW)	Total DG Size(kW)	Total Power Loss (kW)	% Loss Reduction
No DG	-	-		211 .00	-
1 DG	6	2590	2590	111.00	47.39
2 DG	30	1109	2069	87.25	58.65
	12	960			
3 DG	13	802	2941	72.79	65.50
	30	1064			
	24	1075			

is 69.14 % with three DG units at buses 11, 21 and 61 of sizes 563, 346 and 1716 kW resp. Here the total installed DG size is 2625 kW which is 69.04 % of the total active power demand on the distribution system.

5.1.3 Only Network Reconfiguration

The results of the network reconfiguration in IEEE-33 and IEEE-69 bus radial distribution systems are shown in the table 5.5. In case of 33 bus system there are 32 sectionalizing and 5 tie switches. In base case with all the tie lines open, the total power loss is 211 kW. By applying HSA, tie switch numbers in the optimal configuration are 7, 9, 14, 32, 28. The power loss get reduced from 211 kW to 139.98 kW which is 33.66 %.

In case of 69 bus system there are 68 sectionalizing and 5 tie switches. In base case with all the tie lines open, the total power loss is 225 kW. By applying HSA, tie switch numbers in the optimal configuration are 13, 18, 56, 61, 69. The power loss get reduced from 225 kW to 105.19 kW which is 53.25 %.

TABLE 5.4: Results of DG Placement in IEEE-69 Bus System

No. Of DG	Bus Location	Size(kW)	Total DG Size (kW)	Total Power Loss (kW)	% Loss Reduction
No DG	-	-		224.96	-
1 DG	61	1872	1872	83.19	63.03
2 DG	12	813	2548	72.50	67.78
	61	1735			
3 DG	21	346	2625	69.43	69.14
	61	1716			
	11	563			

TABLE 5.5: Results of Network Reconfiguration

System	Case	Tie Switch Numbers	Power Loss (kW)	% Reduction in Loss
33 Bus	Base	33,34,35,36,37	211.00	-
	Optimal Configuration	7,9,14,32,28	139.98	33.66
69 Bus	Base	69,70,71,72,73	294.96	-
	Optimal Configuration	13,18,56,61,69	105.19	53.25

5.1.4 Simultaneous Network Reconfiguration and Capacitor Placement

The results of simultaneous network reconfiguration and capacitor placement in IEEE-33 and IEEE-69 bus radial distribution systems are shown in the table 5.6. In case of 33 bus system, the tie switch numbers in the optimal configuration with a single capacitor are 7, 9, 14, 36, 37 and the capacitor size being 1071 kVAR at the bus 30. The power loss get reduced from 211 kW to 101 kW which is 52.13 % reduction. The tie switch numbers in the optimal configuration with two capacitors are 7, 9, 14, 36, 37 and the capacitor sizes being 1061 kVAR at the bus 30 and 390 kVAR at the bus 12. The power loss get reduced from 211 kW to 96.27 kW which is 54.37 % reduction. The tie switch numbers in the optimal configuration with a three capacitors are 7, 9, 14, 36, 37 and the capacitor sizes being 999 kVAR at the bus 30, 302 kVAR at the bus 13 and 494 kVAR at the bus 24. The power loss get reduced from 211 kW to 93.25 kW which is 55.81 % reduction.

In case of 69 bus system, the tie switch numbers in the optimal configuration with a single capacitor are 14, 42, 45, 55, 64 and the capacitor size being 894 kVAR at the bus 61. The power loss get reduced from 225 kW to 95.30 kW which is 57.64 % reduction. The tie switch numbers in the optimal configuration with two capacitors are 12, 18, 42, 53, 62 and the capacitor sizes being 991 kVAR at the bus 61 and 981 kVAR at the bus 17. The power loss get reduced from 225 kW to 92 kW which is 59.11 % reduction. The tie switch numbers in the optimal configuration with a three capacitors are 14, 16, 42, 52, 62 and the capacitor sizes being 916 kVAR at the bus 61, 402 kVAR at the bus 18 and 713 kVAR at the bus 1. The power loss get reduced from 211 kW to 83.54 kW which is 62.87 % reduction.

TABLE 5.6: Results of Simultaneous Network Reconfiguration and Capacitor Placement

System	Case	Capacitor Size (kVAR)	Tie Switch Numbers	Power Loss (kW)	% Reduction in Power Loss
33 Bus System	Base	-	33,34,35,36,37	211.00	-
	NR + 1 Capacitor	1071(30)	7,9,14,36,37	101.00	52.13
	NR + 2 Capacitors	390(12), 1061(30)	7,9,14,36,37	96.27	54.37
	NR + 3 Capacitors	494(24),302(13), 999(30)	7,9,14,36,37	93.25	55.81
69 Bus System	Base	-	69,70,71,72,73	294.96	-
	NR + 1 Capacitor	894(61)	14,42,45,55,64	95.30	57.64
	NR + 2 Capacitors	981(17),991(61)	12,18,42,53,62	92.00	59.11
	NR + 3 Capacitors	713(11),402(18), 916(61)	14,16,42,52,62	83.54	62.87

5.1.5 Simultaneous Network Reconfiguration and DG Placement

The results of simultaneous network reconfiguration and DG placement in IEEE-33 and IEEE-69 bus radial distribution systems are shown in the table 5.7. In case of 33 bus system, the tie switch numbers in the optimal configuration with a single DG are 10, 15, 28, 33, 34 and the DG size being 1621 kW at the bus 30. The power loss get reduced from 211 kW to 83.03 kW which is 60.65 % reduction. The tie switch numbers in the optimal configuration with two DGs are 7, 9, 26, 32, 34 and the DG sizes being 1021 kW at the bus 30 and 873 kW at the bus 12. The power loss get reduced from 211 kW to 69.59 kW which is 67.02 % reduction. The tie switch numbers in the optimal configuration with three DGs are 7, 9, 28, 34, 36 and the DG sizes being 1046 kW at the bus 30, 960 kW at the bus 13 and 621 kW at the bus 24. The power loss get reduced from 211 kW to 59.83 kW which is 71.64 % reduction.

In case of 69 bus system, the tie switch numbers in the optimal configuration with a single DG are 14,26,58,69,71 and the DG size being 1649 kW at the bus 61. The power loss get reduced from 225 kW to 56 kW which is 73.46% reduction. The tie switch numbers in the optimal configuration with two DGs are 13, 35, 44, 56, 64 and the DG sizes being 1381 kW at the bus 61 and 996 kW at the bus 17. The power loss get reduced from 225 kW to 49.01 kW which is 78.22 % reduction. The tie switch numbers in the optimal configuration with three DGs are 13, 35, 44, 56, 64 and the DG sizes being 1557

TABLE 5.7: Results of Simultaneous Network Reconfiguration and DG Placement

System	Case	DG Size (kW)	Tie Switch Numbers	Power Loss (kW)	% Reduction in Loss
33 Bus System	Base		33,34,35,36,37	211.00	-
	NR + 1 DG	1621(30)	10,15,28,33,34	83.03	60.65
	NR + 2 DG	873(12),1021(30	7,9,26,32,34	69.59	67.02
	NR + 3 DG	621(24),960(13), 1046(30)	7,9,28,34,36	59.83	71.64
69 Bus System	Base	-	69,70,71,72,73	224.96	-
	NR + 1 DG	1649(61)	14,26,58,69,71	56.00	73.46
	NR + 2 DG	996(17),1381(61	13,35,44,56,64	49.01	78.22
	NR + 3 DG	306(11),884(18), 1557(61)	13,35,44,56,64	48.84	78.29

kW at the bus 61, 884 kW at the bus 18 and 306 kW at the bus 11. The power loss get reduced from 225 kW to 47.84 kW which is 78.74 % reduction.

5.1.6 Simultaneous DG and Capacitor Placement

The table 5.8 shows the reduction in power loss in IEEE-33 bus radial distribution system due to simultaneous installation DG units and capacitors. Here the capacitor means the source of reactive power. For the DG capable of injecting both real and reactve power, capacitor placement is not required. In case DGs injecting only real power, the capacitors are installed at the same bus location. The optimal location for installation of single DG unit and capacitor is bus no. 6 and the sizes are 2526 kW and 1761 kVAR i.e. the p.f. of 0.8235. With this, the power loss reduces from 211 kW to 67.87 kW i.e. 67.83 %. With two DG units and two capacitors at bus 13 and 30 of sizes 841 kW and 412 kVAR, 1165 kW and 1042 kVAR resp. the power loss reduces upto 86.47%. The maximum power loss reduction is 94.27 % with three DG units and three capacitors at buses 13, 24 and 30 of sizes 772 kW and 401 kVAR, 976 kW and 589 kVAR and 1074 kW and 944 kVAR resp.

The table 5.9 shows the reduction in power loss in IEEE-69 bus radial distribution system due to installation of 1, 2 and 3 DG units resp. The optimal location for installation of single DG unit and capacitor is bus no. 61 and the sizes are 1833 kW and 1302 kVAR i.e. the p.f. of 0.8153. With this, the power loss reduces from 225 kW to 23.14 kW i.e. 89.72 %. With two DG units and two capacitors at bus 17 and 61 of sizes 512 kW and 355 kVAR, 1746 kW and 1224 kVAR resp. the power loss reduces upto 96.80%. The

TABLE 5.8: Results of Simultaneous DG and Capacitor Placement in IEEE-33 Bus Distribution System

Case	Bus Location	Size		p.f.	Total Loss (kW)	Reduction In loss (%)
		DG(kW)	Capacitor (kVAR)			
No DG	-	-			211 .00	-
1 DG+ 1C	6	2556	1761	0.8235	67.87	67.83
2 DG+ 2C	30	1165	1042	0.7453	28.54	86.47
	13	841	412	0.8980		
3 DG+ 3C	13	772	401	0.8874	12.07	94.27
	24	976	589	0.8561		
	30	1074	944	0.7511		

maximum power loss reduction is 98.08 % with three DG units and three capacitors at buses 11, 18 and 61 of sizes 538 kW and 293 kVAR, 377 kW and 261 kVAR and 1676 kW and 1206 kVAR resp.

5.1.7 Simultaneous NR, DG and Capacitor Placement

The results of integration of all the power loss reduction techniques i.e. simultaneous network reconfiguration, DG and capacitor placement are shown in the table 5.10. In case of IEEE-33 bus system, the tie switches in the optimal configuration are 7, 9, 17,

TABLE 5.9: Results of Simultaneous DG and Capacitor Placement in IEEE-69 Bus Distribution System

Case	Bus Location	Size		p.f.	Total Power Loss (kW)	Reduction In Loss (%)
		DG(kW)	Capacitor (kVAR)			
No DG	-	-			224.96	-
1 DG+ 1C	61	1833	1302	0.8153	23.14	89.72
2 DG+ 2C	61	1746	1224	0.8188	7.21	96.80
	17	512	355	0.8218		
3 DG+ 3C	18	377	261	0.8221	4.32	98.08
	11	538	293	0.8782		
	61	1676	1206	0.8117		

TABLE 5.10: Results of Simultaneous NR, DG and Capacitor Placement

System	Case	DG Size (kW)	Capacitor Size (kVAR)	Tie Switches	Total Power Loss(kW)	% Reduction in Power Loss
33 Bus System	Base	-	-	33,34,35,36,37	211.00	-
	NR+3DG+3C	948(24), 680(13), 1045(30)	524(24), 436(13), 880(30)	7,9,17,23,35	13.93	93.40
69 Bus System	Base	-	-	69,70,71,72,73	224.96	-
	NR+3DG+3C	450(11), 332(18), 1069(61)	360(11), 267(18), 826(61)	13,17,58,61,69	9.32	95.86

23, 35. The candidate buses are 13, 24 and 30. The DG sizes are 680, 948 and 1045 kW resp. The capacitor sizes are 436, 524 and 880 kVAR resp. The power loss get reduced from 211 kW to 13.93 kW i.e. 93.40 % reduction in power loss.

In case of IEEE-69 bus system, the tie switches in the optimal configuration are 13, 17, 58, 61, 69. The candidate buses are 11, 18 and 61. The DG sizes are 450, 332 and 1069 kW resp. The capacitor sizes are 360, 267 and 826 kVAR resp. The power loss get reduced from 225 kW to 9.32 kW i.e. 95.86 % reduction in power loss.

5.1.8 Comparison

The comparison of various power loss reduction techniques in terms of minimum bus voltage and % power loss reduction is shown in the table 5.11. In case IEEE-33 bus distribution system, the base case power loss is 211 kW with minimum bus voltage 0.9038. If only capacitor placement is employed then the total power loss can be reduced upto 34.47 % and the minimum bus voltage is 0.9317. If only network reconfiguration is implemented then the total power loss can be reduced upto 33.66 % and the minimum bus voltage is 0.9413. If only DG placement is implemented then the total power loss can be reduced upto 65.50 % and the minimum bus voltage is 0.9820. Simultaneous NR and capacitor placement results in power loss reduction upto 55.81 % and the minimum bus voltage 0.9593. Simultaneous NR and DG placement results in power loss reduction upto 71.64 % and the minimum bus voltage 0.9863. Simultaneous capacitor and DG placement results in power loss reduction upto 94.27 % and the minimum bus voltage

TABLE 5.11: Comparison of Various Power Loss Reduction Techniques

Case	33 Bus System			69 Bus System		
	Power Loss (kW)	% Reduction In Power Loss	Min. Bus Voltage (p.u.)	Power Loss (kW)	% Reduction In Power Loss	Min. Bus Voltage (p.u.)
Base	211.00	-	0.9038(18)	224.96	-	0.9092(65)
Only Capacitor Placement	138.27	34.47	0.9317(18)	145.47	35.34	0.9316(65)
Only NR	139.98	33.66	0.9413(32)	105.19	53.25	0.9495(61)
Only DG Placement	72.79	65.50	0.9820(18)	67.62	68.98	0.9789(65)
NR+ Capacitor	93.25	55.81	0.9593(33)	83.54	62.87	0.9623(62)
NR + DG	59.83	71.64	0.9863(33)	47.84	78.74	0.9725(64)
DG + Capacitor	12.07	94.27	0.9894(8)	4.32	98.00	0.9943(50)
NR+DG+ Capacitor	13.93	93.40	0.9863(18)	9.32	95.86	0.9845(62)

0.9894. Simultaneous implementation of all the three methods result in power loss reduction upto 93.40 % and the minimum bus voltage 0.9863.

In case IEEE-69 bus distribution system, the base case power loss is 225 kW with minimum bus voltage 0.9092. If only capacitor placement is employed then the total power loss can be reduced upto 35.34 % and the minimum bus voltage is 0.9316. If only network reconfiguration is implemented then the total power loss can be reduced upto 53.25 % and the minimum bus voltage is 0.9495. If only DG placement is implemented then the total power loss can be reduced upto 68.98 % and the minimum bus voltage is 0.9789. Simultaneous NR and capacitor placement results in power loss reduction upto 62.87 % and the minimum bus voltage 0.9593. Simultaneous NR and DG placement results in power loss reduction upto 78.74 % and the minimum bus voltage 0.9725. Simultaneous capacitor and DG placement results in power loss reduction upto 98.00 % and the minimum bus voltage 0.9943. Simultaneous implementation of all the three methods result in power loss reduction upto 95.86 % and the minimum bus voltage 0.9845.

The pivot charts of comparison of all the power loss reduction methods in terms of % power loss reduction and minimum bus voltage are shown in the fig. 5.1 and 5.2 resp.

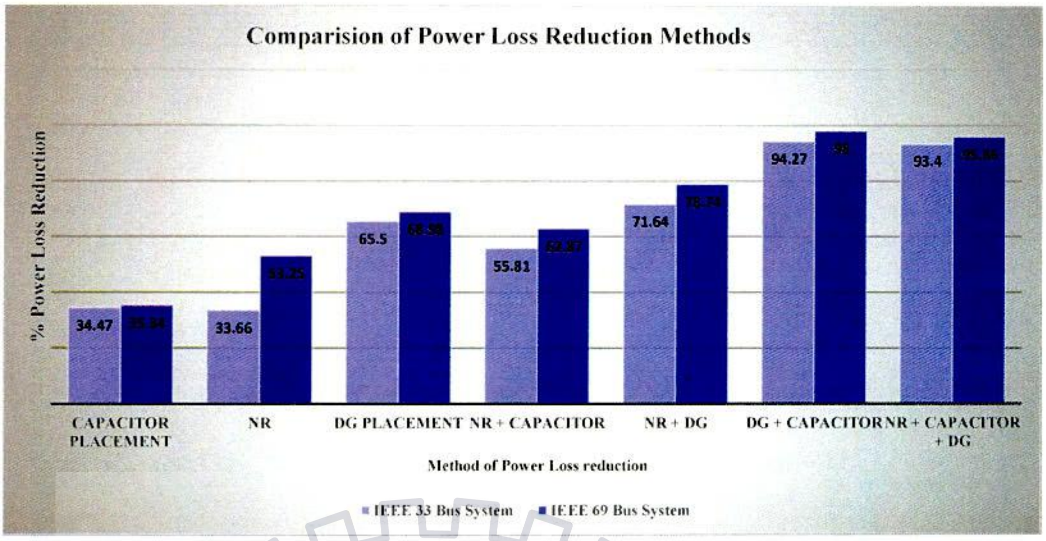

FIGURE 5.1: Comparison of Methods in terms of % Power Loss Reduction

5.1.9 Voltage Profile Improvement

The comparison of voltage profile improvement due to various power loss reduction methods is shown in the fig. 5.3 for IEEE-33 bus system and the fig. 5.4 for IEEE-69 bus radial distribution system.

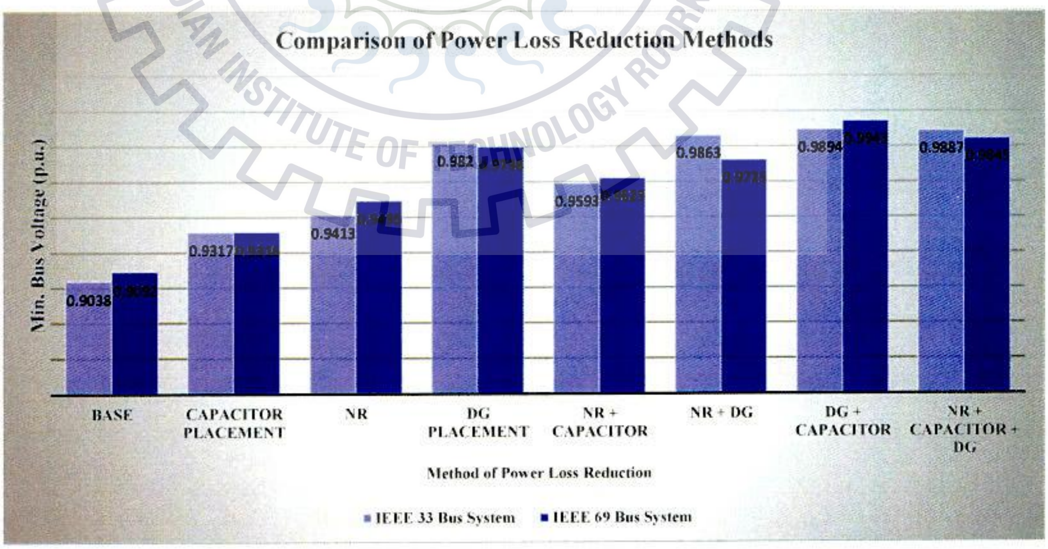

FIGURE 5.2: Comparison of Methods in terms of Minimum Bus Voltage

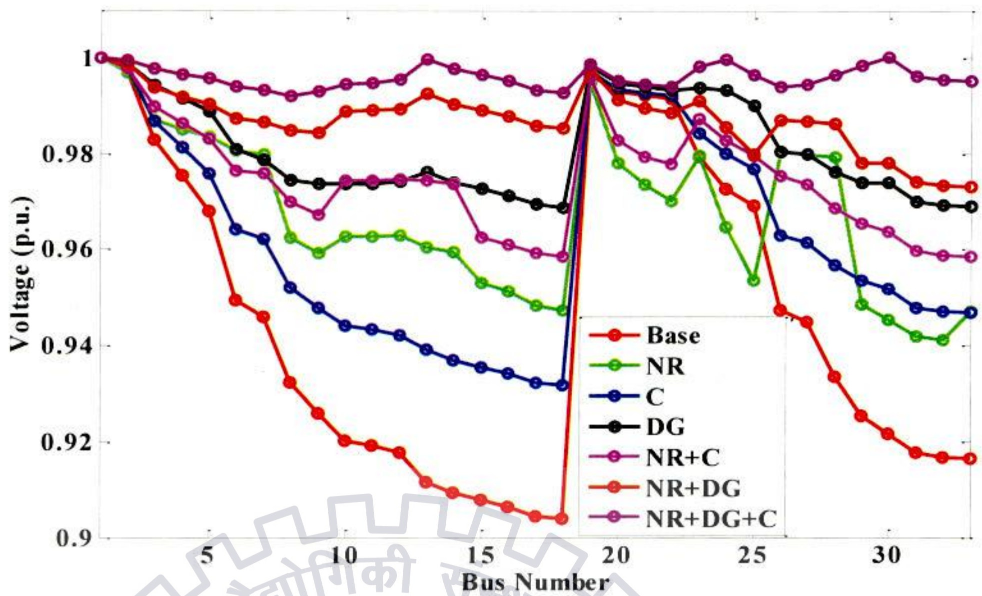

FIGURE 5.3: Voltage Profile Improvement in case of IEEE-33 Bus System

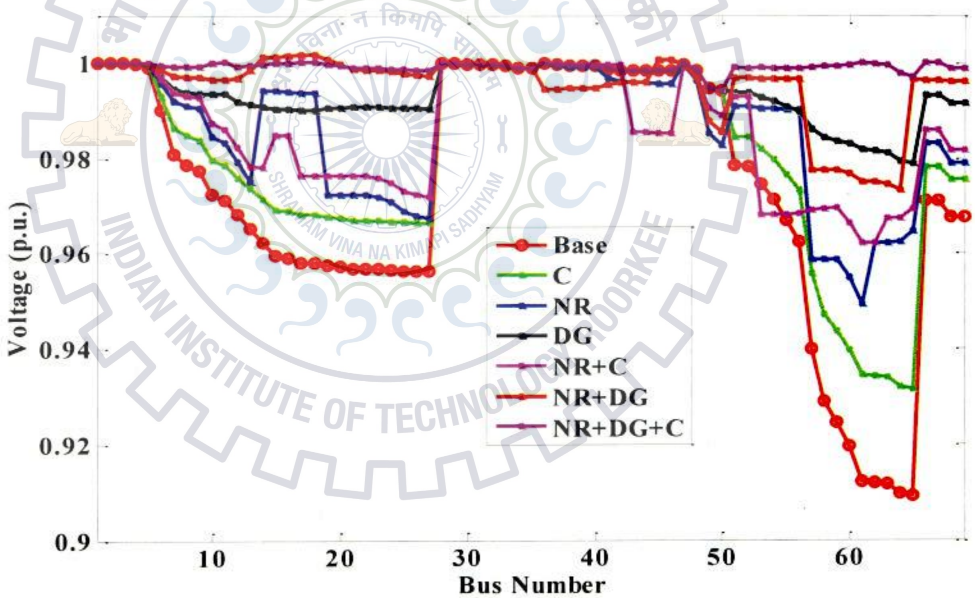

FIGURE 5.4: Voltage Profile Improvement in case of IEEE-69 Bus System

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

5.2 Varying Load Condition

Here the optimal division of the load curve is $[\,5 \quad 11 \quad 8\,]$ $Hrs.$ The average real and reactive power demand at each bus during the above three optimal intervals in per unit of peak load is $[\,0.3597 \quad 0.7207 \quad 0.6397\,]$ and $[\,0.3346 \quad 0.5274 \quad 0.4398\,]$ resp. The results of each method are discussed below.

TABLE 5.12: Base Case of Varying Load

System	Energy Loss (kWh)	Total Energy Loss (kWh)	Minimum Bus Voltage
33 Bus	144.90	1779.30	0.9625(18)
	1052.20		0.9315(18)
	582.20		0.9403(18)
69 Bus	148.46	1815.20	0.9685(65)
	1072.10		0.9407(65)
	594.6		0.9479(65)

5.2.1 Base Case

Table 5.12 shows the base case of the varying load condition when the load curve is divided into 5, 11 and 8 hrs. In case of 33 bus system, the total energy loss is 1779.3 kWh. The highest energy loss is in second interval and equal to 1052.20 kWh with lowest bus voltage of 0.9315 p.u. at bus 18. In case of 69 bus system, the total energy loss is 1815.20 kWh. The highest energy loss is in second interval and equal to 1072.10 kWh with lowest bus voltage of 0.9407 p.u. at bus 65.

5.2.2 Only Capacitor Placement

Table 5.13 shows the results of capacitor placement with the varying load condition. The amounts of reactive power to be injected at each candidate bus during each interval are shown in the table 5.13. In case of 33 bus system, the total optimal energy loss

TABLE 5.13: Results of Capacitor Placement with Varying Load

System	Base Case Energy Loss (kWh)	Capacitor Placement Case				% Energy Loss Reduction
		Size (kVAR)	Candidate Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	144.90	190.14, 392.29, 363.69	[13 24 30]	88.945	0.9732 (18)	26.55
	1052.2	324.23, 568.30, 445.27		777.86	0.9482 (18)	
	582.20	303.26, 461.65, 348.13		440.10	0.9553 (18)	
69 Bus	148.46	267.52, 179.13, 363.88	[11 18 61]	91.050	0.9745 (65)	26.57
	1072.1	387.83, 206.97, 590.49		786.66	0.9489 (65)	
	594.6	249.43, 185.33, 539.34		455.14	0.9549 (65)	

reduction is 26.55 % with improvement in minimum voltage from 0.9315 p.u. in base case to 0.9482 p.u. at bus 18. In case of 69 bus system, the total optimal energy loss reduction is 26.57 % with improvement in minimum voltage from 0.9407 p.u. in base case to 0.9489 p.u. at bus 65.

5.2.3 Only DG Placement

Table 5.14 shows the results of DG placement with the varying load condition. The amounts of real power to be injected at each candidate bus during each interval are shown in the table 5.14. In case of 33 bus system, the total optimal energy loss reduction is 58.64 % with improvement in minimum voltage from 0.9315 p.u. in base case to 0.9704 p.u. at bus 18. In case of 69 bus system, the total optimal energy loss reduction is 60.23 % with improvement in minimum voltage from 0.9407 p.u. in base case to 0.9788 p.u. at bus 65.

5.2.4 Only Network Reconfiguration

Table 5.15 shows the results of NR with the varying load condition. In case of 33 bus system, the tie switch numbers in the optimal configuration are 7,9,14,32,37 and the total optimal energy loss reduction is 31.10 % with improvement in minimum voltage from 0.9315 p.u. at bus 18 in base case to 0.9575 p.u. at bus 33. In case of 69 bus system, the tie switch numbers in the optimal configuration are 9,16,71,62,58 and the

TABLE 5.14: Results of DG Placement with Varying Load

System	Base Case Energy Loss (kWh)	DG Placement Case				% Energy Loss Reduction
		Size (kW)	Candidate Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	144.90	285.58, 282.63, 348.45	[13 24 30]	75.819	0.9829 (18)	58.64
	1052.20	519.21, 702.74, 682.62		435.78	0.9704 (18)	
	582.20	474.71, 677.06, 590.91		224.32	0.9754 (18)	
69 Bus	148.46	168.55, 105.19, 593.35	[11 18 61]	74.550	0.9904 (65)	60.23
	1072.10	637.06, 220.49, 950.92		431.39	0.9788 (65)	
	594.6	300.08, 300.60, 907.72		215.95	0.9828 (65)	

TABLE 5.15: Results of Network Reconfiguration with Varying Load

System	Base Case Energy Loss (kWh)	Network Reconfiguration Case			% Energy Loss Reduction
		Tie Switches In Optimal Configuration	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	144.90	7,9,14,32,37	99.875	0.9764(33)	31.10
	1052.2		725.60	0.9575(33)	
	582.20		400.49	0.9631(33)	
69 Bus	148.46	9,16,71,62,58	81.637	0.9804(62)	44.73
	1072.1		59.383	0.9645(62)	
	594.6		327.69	0.9692(62)	

total optimal energy loss reduction is 44.73 % with improvement in minimum voltage from 0.9315 p.u. at bus 65 in base case to 0.9645 p.u. at bus 62.

5.2.5 Simultaneous NR and Capacitor Placement

Table 5.16 shows the results of the simultaneous NR and capacitor placement with the varying load condition. The amounts of reactive power to be injected at each candidate bus during each interval are shown in the table 5.16. In case of 33 bus system, the tie switch numbers in the optimal configuration are 7,11, 28,34,36 and the total optimal energy loss reduction is 46.27 % with improvement in minimum voltage from 0.9315 p.u. at bus 18 in base case to 0.9700 p.u. at bus 33. In case of 69 bus system, the tie switch numbers in the optimal configuration are 16,38,43,58,61 and the total optimal energy loss reduction is 55.48 % with improvement in minimum voltage from 0.9315 p.u. at bus 65 in base case to 0.9732 p.u. at bus 62.

TABLE 5.16: Results of Simultaneous NR and Capacitor Placement with Varying Load

System	Base Case Energy Loss (kWh)	Simultaneous NR and Capacitor Placement Case					% Energy Loss Reduction
		Tie Switches In Optimal Configuration	Capacitor Size (kVAR)	Candidate Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	144.90	7,11, 28,34,36	224.49,462.83 188.42	[13 24 30]	66.507	0.9849 (33)	46.27
	1052.2		442.81,345.19 440.33		570.39	0.9700 (33)	
	582.20		277.04,317.62 413.98		319.06	0.9746 (33)	
69 Bus	148.46	16,38,43,58,61	338.53,178.48 372.38	[11 18 61]	55.441	0.9863 (62)	55.48
	1072.1		568.03,278.35 549.31		483.40	0.9732 (62)	
	594.6		288.67,251.95 553.74		269.29	0.9757 (62)	

TABLE 5.17: Results of Simultaneous NR and DG Placement with Varying Load

System	Base Case Energy Loss (kWh)	Simultaneous NR and DG Placement Case					% Energy Loss Reduction
		Tie Switches In Optimal Configuration	DG Size (kW)	Cand. Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	144.90	7,9,17,34,37	236.43,339.51 383.12	[13 24 30]	56.039	0.9884 (18)	68.44
	1052.2		471.37,559.36 694.23		334.63	0.9785 (18)	
	582.20		402.26,694.42 655.72		170.86	0.9836 (18)	
69 Bus	148.46	11,16,41,54,61	182.59,268.34 446.89	[11 18 61]	52.598	0.9893 (62)	71.22
	1072.1		598.02,358.03 826.04		313.25	0.9778 (62)	
	594.6		305.85,474.98 817.26		156.52	0.9840 (62)	

5.2.6 Simultaneous NR and DG Placement

Table 5.17 shows the results of the simultaneous NR and capacitor placement with the varying load condition. The amounts of real power to be injected at each candidate bus during each interval are shown in the table 5.17. In case of 33 bus system, the tie switch numbers in the optimal configuration are 7,9,17,34,37 and the total optimal energy loss reduction is 68.44 % with improvement in minimum voltage from 0.9315 p.u. in base case to 0.9785 p.u. at bus 18. In case of 69 bus system, the tie switch numbers in the optimal configuration are 11,16,41,54,61 and the total optimal energy loss reduction is 71.22 % with improvement in minimum voltage from 0.9315 p.u. at bus 65 in base case to 0.9778 p.u. at bus 62.

5.2.7 Simultaneous DG and Capacitor Placement

Table 5.18 shows the results of simultaneous DG and capacitor placement with the varying load condition. The amounts of real and reactive power to be injected at each candidate bus during each interval are shown in the table 5.19. In case of 33 bus system, the total optimal energy loss reduction is 92.04 % with improvement in minimum voltage from 0.9315 p.u. in base case to 0.9930 p.u. at bus 18. In case of 69 bus system, the total optimal energy loss reduction is 95.35 % with improvement in minimum voltage from 0.9407 p.u. in base case to 0.9934 p.u. at bus 65.

TABLE 5.18: Results of Simultaneous DG and Capacitor Placement with Varying Load

System	Base Case Energy Loss (kWh)	Simultaneous DG and Capacitor Placement Case					% Energy Loss Reduction
		DG Size (kW)	Capacitor Size (kVAR)	Candidate Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	144.90	286.25,382.37 380.86	253.77,253.8 369.07	[13 24 30]	12.157	0.9963 (18)	92.04
	1052.2	556.58,764.66 744.30	414.67,557.5 537.40		83.372	0.9930 (18)	
	582.20	487.43,663.98 679.14	349.16,479.6 454.26		46.058	0.9940 (18)	
69 Bus	148.46	412.5, 142.1, 514.6	17.6, 235.9, 343.8	[11 18 61]	16.853	0.9945 (65)	95.35
	1072.1	484.3, 362.5, 1089.1	232.4, 235.9, 724.2		43.625	0.9934 (65)	
	594.6	469.4, 240.9, 902.1	302.1, 181.5, 618.0		23.831	0.9923 (65)	

5.2.8 Simultaneous NR, DG and Capacitor Placement

Table 5.19 shows the results of the simultaneous NR, DG and capacitor placement with the varying load condition. The amounts of real and reactive power to be injected at each candidate bus during each interval are shown in the table 5.19. In case of 33 bus system, the tie switch numbers in the optimal configuration are 7,10,21,36,26 and the

TABLE 5.19: Results of Simultaneous NR, DG and Capacitor Placement with Varying Load

System	Base Case Energy Loss (kWh)	Simultaneous NR, DG and Capacitor Placement Case						% Energy Loss Reduction
		Tie Switches In Optimal Conf.	DG Size (kW)	Cap. Size (kVAR)	Cand. Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	144.90	7,10,21, 36,26	291.24 346.84 351.78	272.56 387.29 265.49	(13,24, 30)	12.244	0.9954 (18)	91.56
	1052.2		585.68 641.52 793.15	428.14 636.96 404.53		89.898	0.9918 (18)	
	582.20		525.49 643.10 630.29	351.40 394.68 458.13		48.009	0.9929 (18)	
69 Bus	148.46	11,16,35, 57,63	229.07 239.82 504.35	302.62 214.08 456.83	(11,18, 61)	8.3232	0.9945 (64)	93.25
	1072.1		302.49 558.52 848.28	293.17 491.50 904.98		82.418	0.9926 (64)	
	594.6		478.49 444.43 926.00	287.09 305.22 632.43		31.838	0.9923 (64)	

total optimal energy loss reduction is 91.56 % with improvement in minimum voltage from 0.9315 p.u. in base case to 0.9918 p.u. at bus 18. In case of 69 bus system, the tie switch numbers in the optimal configuration are 11,16,35,57,63 and the total optimal energy loss reduction is 93.25 % with improvement in minimum voltage from 0.9315 p.u. at bus 65 in base case to 0.9926 p.u. at bus 64.

5.2.9 Comparison

Table 5.20 shows the comparison of all the energy loss reduction methods with varying load. In case of IEEE-33 bus distribution system, if only capacitor placement is employed then the total energy loss can be reduced upto 26.55 %. If only network reconfiguration is implemented then the total energy loss can be reduced upto 31.10 %. If only DG placement is implemented then the total energy loss can be reduced upto 58.64 %. Simultaneous NR and capacitor placement results in energy loss reduction upto 46.27 %. Simultaneous NR and DG placement results in energy loss reduction upto 68.44 %. Simultaneous capacitor and DG placement results in energy loss reduction upto 92.04 %. Simultaneous implementation of all the three methods result in energy loss reduction upto 91.56 %.

In case IEEE-69 bus distribution system, if only capacitor placement is employed then the total energy loss can be reduced upto 26.57 %. If only network reconfiguration

TABLE 5.20: Comparison of Energy Loss Reduction Techniques with Varying Load

Case	33 Bus System	69 Bus System
	% Reduction In Energy Loss	% Reduction In Energy Loss
Capacitor Placement	26.55	26.57
NR	31.10	44.73
DG Placement	58.64	60.23
NR+ Capacitor	46.27	55.48
NR + DG	68.44	71.22
DG + Capacitor	92.04	95.35
NR+DG+ Capacitor	91.56	93.25

is implemented then the total energy loss can be reduced upto 44.73 %. If only DG placement is implemented then the total energy loss can be reduced upto 60.23 %. Simultaneous NR and capacitor placement results in energy loss reduction upto 55.48 %. Simultaneous NR and DG placement results in energy loss reduction upto 71.22 %. Simultaneous capacitor and DG placement results in energy loss reduction upto 95.35 %. Simultaneous implementation of all the three methods result in energy loss reduction upto 93.25 %.

The pivot chart of comparison of all the energy loss reduction methods in terms of % energy loss reduction is shown in the fig. 5.5.

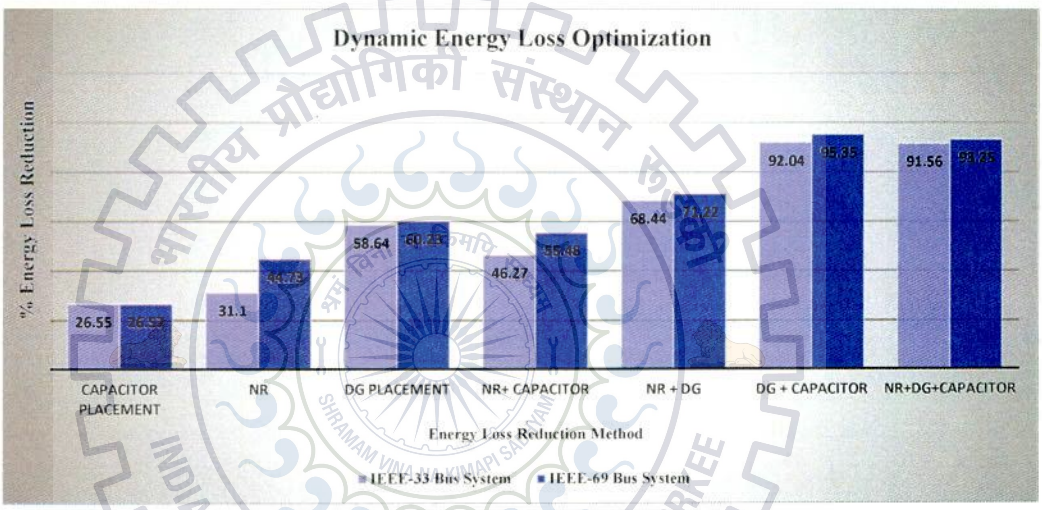

FIGURE 5.5: Comparison of Energy Loss Reduction Methods with Varying Load

5.3 Varying Load with Varying DG Output Condition

In this case the the load curve is divided as $[\,6 \quad 13 \quad 5\,]\,Hrs$ since the output of solar PV is available during the day time only. The average real and reactive power demand at each bus during the above three optimal intervals in per unit of peak load is $[\,0.3691 \quad 0.7358 \quad 0.6129\,]$ and $[\,0.3336 \quad 0.5276 \quad 0.4228\,]$ resp. Three DG (Solar PV units) of peak rating 802 kW, 1075 kW and 1064 kW are connected in 33-bus system at the buses 13, 24 and 30 resp. In 69-bus system three DG of peak rating 563 kW, 346 kW and 1716 kW are connected at the buses 11, 18 and 61 resp. These DG sizes are taken from the results of power loss optimization with only DG. The average DG output in the second interval is 0.6448 p.u. The results of each method are discussed below.

TABLE 5.21: Base Case of Varying Load with Varying DG Output

System	Without DG		With DG			% Energy Loss Reduction
	Energy Loss (kWh)	Min. Bus Voltage (Bus)	DG Size (Bus)	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	179.86	0.9618 (18)	802(13), 1075(24), 1064(30)	179.86	0.9618 (18)	58.05
	1279.6	0.9306 (18)		237.84	0.9718 (18)	
	334.93	0.9427 (18)		334.93	0.9427 (18)	
69 Bus	184.26	0.9678 (65)	563(11), 346(18), 1716(61)	184.26	0.9678 (65)	61.38
	1303.8	0.9397 (65)		180.78	0.9780 (65)	
	342.20	0.9501 (65)		342.20	0.9501 (65)	

5.3.1 Base Case

Table 5.21 shows the base case of the varying load condition with the varying DG output. In case of 33 bus system, the total energy loss without connecting the DG is 1794.4 kWh. The highest energy loss is in second interval and equal to 1279.6 kWh with lowest bus voltage of 0.9306 p.u. at bus 18. In case of 69 bus system, the total energy loss is 1830.3 kWh. The highest energy loss is in second interval and equal to 1303.8 kWh with lowest bus voltage of 0.9397 p.u. at bus 65. Here the energy loss in second interval is higher compared to the previous case because the length of the interval considered is more.

After connecting the DG units of above mentioned sizes at the candidate buses, the energy loss in case of 33 bus system reduces by 58.05 % as the DG output is available during peak load and the minimum bus voltage get improved from 0.9306 p.u. to 0.9718 p.u. at bus 18. In case of 69 bus system, the energy loss reduces by 61.38 % and the minimum bus voltage get improved from 0.9397 p.u to 0.9780 p.u. at bus 18.

5.3.2 Capacitor Placement

Table 5.22 shows the results of capacitor placement with the varying load and varying DG output condition. The amounts of reactive power to be injected at each candidate bus during each interval are shown in the table 5.22. In case of 33 bus system, the overall optimal energy loss reduction by both DG and capacitors is 68.71 % with improvement in minimum voltage from 0.9306 p.u. in base case to 0.9572 p.u. at bus 18. In case of 69 bus system, the overall optimal energy loss reduction by both DG and capacitors is

TABLE 5.22: Results of Capacitor Placement with Varying Load and Varying DG Output

System	Base Case Energy Loss (kWh)	Capacitor Placement Case				Overall % Energy Loss Reduction
		Size	Candidate Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	179.86	275.19, 305.99, 279.23	[13 24 30]	111.81	0.9748 (18)	68.71
	237.84	138.60, 91.90, 193.31		196.85	0.9788 (18)	
	334.93	283.36, 311.70, 404.03		252.74	0.9572 (18)	
69 Bus	184.26	132.91, 80.54, 555.49	[11 18 61]	110.04	0.9757 (65)	72.46
	180.78	83.65, 101.80, 238.45		133.69	0.9818 (65)	
	342.20	278.00, 279.57, 423.72		260.42	0.9572 (65)	

72.46 % with improvement in minimum voltage from 0.9397 p.u. in base case to 0.9572 p.u. at bus 65.

M.G. CENTRAL LIBRARY
ACC No. 624693
Date 15/9/16
IIT ROORKEE

5.3.3 Network Reconfiguration

Table 5.23 shows the results of NR with the varying load and varying DG output. In case of 33 bus system, the tie switch numbers in the optimal configuration are 7,9,34,36,28 and the overall optimal energy loss reduction is 68.53 % with improvement in minimum voltage from 0.9306 p.u. in base case to 0.9629 p.u. at bus 18. In case of 69 bus system, the tie switch numbers in the optimal configuration are 9,18,14,61,58 and the total optimal energy loss reduction is 6.50 % with improvement in minimum voltage from 0.9397 p.u. at bus 65 in base case to 0.9711 p.u. at bus 61.

TABLE 5.23: Results of NR with Varying Load and Varying DG output

System	Base Case Energy Loss (kWh)	Network Reconfiguration Case			Overall % Energy Loss Reduction
		Tie Switches In Optimal Configuration	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	179.86	7,9,34,36,28	131.15	0.9748(18)	68.53
	237.84		189.79	0.9807(18)	
	334.93		243.86	0.9629(18)	
69 Bus	184.26	9,18,14,61,58	95.888	0.9805(61)	76.50
	180.78		155.87	0.9767(62)	
	342.20		1.7833	0.9711(61)	

TABLE 5.24: Results of Simultaneous NR and Capacitor Placement with Varying Load and Varying DG output

System	Base Case Energy Loss (kWh)	Simultaneous NR and Capacitor Placement Case					Overall % Energy Loss Reduction
		Tie Switches In Optimal Conf.	Capacitor Size (kVAR)	Candidate Buses	Energy Loss (kWh)	Min. Bus Voltage (Bus)	
33 Bus	179.86	7,11,34,36,28	256.60,344.33 235.53	[13 24 30]	83.105	0.9844 (33)	74.75
	237.84		113.19,191.72 65.66		180.12	0.9829 (11)	
	334.93		258.04,517.07 503.39		189.83	0.9748 (18)	
69 Bus	184.26	9,13,43,58,63	350.48,174.39 324.62	[11 18 61]	67.76	0.9871 (62)	79.63
	180.78		52.13, 233.01 134.93		121.36	0.9833 (64)	
	342.20		855.90,379.83 367.99		183.65	0.9762 (62)	

5.3.4 Simultaneous Network Reconfiguration and Capacitor Placement

Table 5.24 shows the results of the simultaneous NR and capacitor placement with the varying load and varying DG output condition. The amounts of reactive power to be injected at each candidate bus during each interval are shown in the table 5.24. In case of 33 bus system, the tie switch numbers in the optimal configuration are 7,11,34,36,28 and the overall optimal energy loss reduction is 74.75 % with improvement in minimum voltage from 0.9315 p.u.in base case to 0.9748 p.u. at bus 18. In case of 69 bus system, the tie switch numbers in the optimal configuration are 9,13,43,58,63 and the overall optimal energy loss reduction is 79.63 % with improvement in minimum voltage from 0.9315 p.u. at bus 65 in base case to 0.9762 p.u. at bus 62.

5.3.5 Comparison

Table 5.25 shows the comparison of the energy loss reduction methods with varying load and varying DG output. In case of IEEE-33 bus distribution system, the energy loss reduction due to optimal DG placement is upto 58.05%. If the capacitor placement is employed in the presence of DG then the overall energy loss reduction is upto 68.51 %. If only network reconfiguration is implemented in the presence of solar PV then the overall energy loss can be reduced upto 68.31 %. Simultaneous NR and capacitor placement in the presence of solar PV results in energy loss reduction upto 74.75 %.

TABLE 5.25: Comparison of Methods with Varying Load and Varying DG output

Case	33 Bus System	69 Bus System
	% Reduction In Energy Loss	% Reduction In Energy Loss
Base (DG)	58.05	61.38
DG + Capacitor	68.71	72.46
DG + NR	68.53	76.50
DG +NR + Capacitor	74.75	79.63

In case of IEEE-69 bus distribution system, the energy loss reduction due to optimal DG placement is upto 61.38%. If the capacitor placement is employed in the presence of DG then the overall energy loss reduction is upto 72.46 %. If only network reconfiguration is implemented in the presence of solar PV then the overall energy loss can be reduced upto 76.50 %. Simultaneous NR and capacitor placement in the presence of solar PV results in energy loss reduction upto 79.63 %.

The pivot chart of comparison of the energy loss reduction methods in terms of % energy loss reduction is shown in the fig. 5.6.

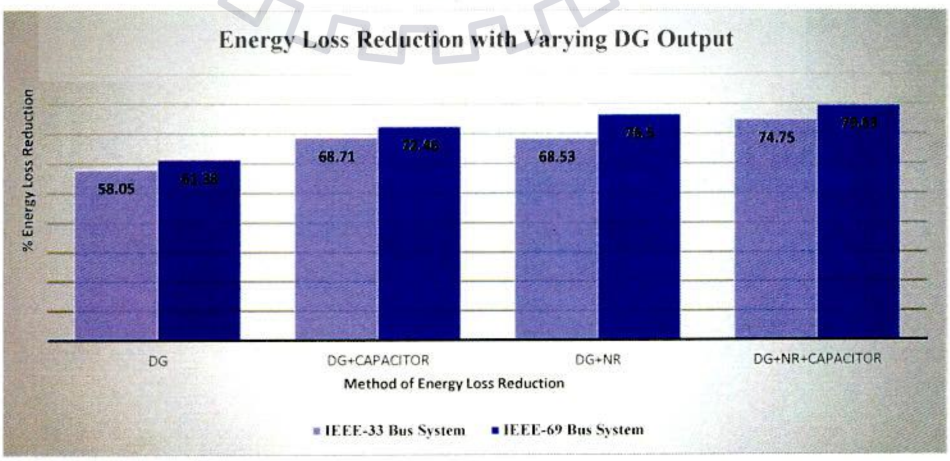

FIGURE 5.6: Comparison of Energy Loss Reduction Methods with Varying Load and varying DG output

Chapter 6

Conclusions

As a planning issue, the simultaneous DG and capacitor placement is the best method for power loss reduction in the radial distribution systems. As an operational issue, the simultaneous network reconfiguration, DG and capacitor placement is the best method for power loss reduction as the DG size required get reduced and it increases the degree of control. In case of energy loss reduction with varying loads, the effect of reconfiguration is negligible with fixed and controllable DG output but if the DG output is varying then reconfiguration and capacitor placement is the best method. Reduction in the power and energy losses automatically results in improvement of the voltage profile.

Bibliography

[1] Jen-Hao Teng, "A Direct Approach for Distribution System Load Flow Solutions," *IEEE Transactions on Power Delivery,* vol. 18, no. 3, pp. 882-887,July 2003.

[2] K. Desai, D. R. Brown, "Multiple Variable Sources of Reactive Power on Distribution System Feeders," *IEEE Transactions on Power Apparatus and Systems,* vol. 100, no. 11, pp. 4364-4372, 1981.

[3] J. J. Grainger, S. H. Lee, "Optimum Size and Location of Shunt Capacitors for Reduction of Losses on Distribution Feeders," *IEEE Transactions on Power Apparatus and Systems,* vol. 100, no. 3, pp. 1105-1118, 1981.

[4] Y. C. Huang, H. T. Yang and C. L. Huang, "Solving the Capacitor Placement Problem in a Radial Distribution System Using Tabu Search Approach," *IEEE Transactions on Power Systems,* vol. 11, no. 4, pp. 1868-1873, 1996.

[5] S. Sundhararajan and A. Pahwa, "Optimal Selection of Capacitors for Radial Distribution Systems using Genetic Algorithm," *IEEE Transactions on Power Systems,* vol. 9, no. 3, pp. 1499-1507, 1994.

[6] B. Milosevic and B. Miroslav, "Capacitor Placement for Conservative Voltage Reduction on Distribution Feeders," *IEEE Transactions on Power Delivery,* vol. 19, no. 3, pp. 1360-1367, 2004.

[7] D. Das, "Optimal Placement of Capacitors in Radial Distribution System using a Fuzzy-GA method," *Electrical Power and Energy System,* vol. 30, pp. 361-367, 2008.

[8] C. Wang and M. H. Nehrir, "Analytical Approaches for Optimal Placement of Distributed Generation sources in Power Systems," *IEEE Trans. on Power Systems,* vol. 19, no. 4, pp. 2068-2076, Nov. 2004.

[9] T. Gozel andM. H. Hocaoglu, "An Analytical Method for the Sizing and Siting of Distributed Generators in Radial Systems," *Elect. Power Syst. Res.,* vol. 79, no. 6, pp. 912-918, Jun. 2009.

[10] D. Q. Hung and N. Mithulananthan, "Multiple distributed generators placement in primary distribution networks for loss reduction," *IEEE Trans. Ind. Electron.,* vol. 60, no. 4, pp. 1700-1708, Apr. 2013.

[11] P. Vovos and J. Bialek, "Direct incorporation of fault level constraints in optimal power flow as a tool for network capacity analysis," *IEEE Trans. on Power Systems,* vol. 20, no. 4, pp. 2125-2134, Nov. 2005.

[12] A. Keane and M. OMalley, "Optimal utilization of distribution networks for energy harvesting," *IEEE Trans. on Power Systems,* vol. 22, no. 1, pp. 467-475, Feb. 2007.

[13] N. Khalesi, N. Rezaei, and M.-R. Haghifam, "DG allocation with application of dynamic programming for loss reduction and reliability improvement," *Int. J. Electr. Power Energy Syst.,* vol. 33, no. 2, pp. 288-295, Feb. 2011.

[14] R. S. Al Abri, E. F. El-Saadany, and Y. M. Atwa, "Optimal placement and sizing method to improve the voltage stability margin in a distribution system using distributed generation," *IEEE Trans. on Power Systems,* vol. 28, no. 1, pp. 326-334, Feb. 2013.

[15] H. Khan and M. A. Choudhry, "Implementation of distributed generation (IDG) algorithm for performance enhancement of distribution feeder under extreme load growth, *Int. J. Electr. Power Energy Syst.,* vol. 32, no. 9, pp. 985-997, Nov. 2010.

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

[17] K.-H. Kim, Y.J. Lee, S.B. Rhee, S.K. Lee, and S.K. You, "Dispersed generator placement using fuzzy-GA in distribution systems, *in Proc. IEEE Power Eng. Soc. Summer Meeting,* pp. 1148-1153, Jul. 2002.

[18] L. F. Ochoa, A. Padilha-Feltrin, and G. P.Harrison, "Time-series-based maximization of distributed wind power generation integration, *IEEE Trans. Energy Convers.,* vol. 23, no. 3, pp. 968-974, Sep. 2008.

[19] A. Soroudi and M. Ehsan, “Efficient immune-GA method for DNOs in sizing and placement of distributed generation units, *Eur. Trans. Electr. Power,* vol. 21, no. 3, pp. 1361-1375, Apr. 2011.

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

[21] M. H. Moradi and M. Abedini, “A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems, *Int. J. Electr. Power Energy Syst.*, vol. 34, no. 1, pp. 66-74, Jan. 2012.

[22] M. Gomez-Gonzalez, A. Lopez, and F. Jurado, “Optimization of distributed generation systems using a new discrete PSO and OPF, *Elect. Power Syst. Res.*, vol. 84, no. 1, pp. 174-180, Mar. 2012.

[23] C. Novoa and T. Jin, “Reliability centered planning for distributed generation considering wind power volatility, *Elect. Power Syst. Res.*, vol. 81, no. 8, pp. 1654-1661, Aug. 2011.

[24] N. G. A. Hemdan and M. Kurrat, “Efficient integration of distributed generation for meeting the increased load demand, *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 9, pp. 1572-1583, Nov. 2011.

[25] F. Rotaru, G. Chicco, G. Grigoras, and G. Cartina, “Two-stage distributed generation optimal sizing with clustering-based node selection, *Int. J. Electr. Power Energy Syst.*, vol. 40, no. 1, pp. 120-129, Sep. 2012.

[26] D. Shirmohammadi and H. W. Hong, “Reconfiguration of electric distribution networks for resistive line loss reduction, *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1492-1498, Apr. 1989.

[27] K.Y. Huang and H.C. Chin, “Distribution feeder energy conservation by using heuristics fuzzy approach, *Int. J. Elect. Power Energy Syst.*, vol. 24, pp. 439-445, 2002.

[28] D. Das, “A fuzzy multiobjective approach for network reconfiguration of distribution systems, *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 202209, Jan. 2006.

[29] Pavlos S. Georgilakis and Nikos D. Hatziargyriou, “Optimal Distributed Generation Placement in Power Distribution Networks-models, Methods, and Future Research, *IEEE Trans.Power Syst.*, vol. 28, no. 3, pp. 3420-3428, August 2013.

[30] Z. Rong, P. Xiyuan, H. Jinliang, and S. Xinfu, "Reconfiguration and capacitor placement for loss reduction of distribution systems, *in Proc. IEEE TENCON02,* pp. 1945-1949, 2002.

[31] C. F. Chang, "Reconguration and capacitor placement for loss reduction of distribution systems by ant colony search algorithm, *IEEE Trans. Power Syst.,* vol. 23, no. 4, pp. 1747-1755, Nov. 2008.

[32] V. Farahani, B. Vahidi and H. A. Abyaneh, "Reconguration and Capacitor Placement Simultaneously for Energy Loss Reduction Basedon an Improved Reconguration Method," *IEEE Trans. Power Syst.,* Vol. 27, No. 2, pp. 587-595, May 2012.

[33] R. S. Rao, K. Ravindra, K. Satish, and S. V. L. Narasimham, "Power loss minimization in distribution system using network reconfiguration in the presence of distributed generation, *IEEE Trans. Power Syst.,* vol. 28, no. 1, pp. 317-325, Feb. 2013.

[34] A. M. Imran , M. Kowsalya, D.P. Kothari, "A novel integration technique for optimal network reconfiguration and distributed generation placement in power distribution networks, *Elect. Power Energy Syst.,* vol. 63, pp. 461-472, 2014.

[35] H. R. Esmaeilian, R. Fadaeinedjad, "Energy Loss Minimization in Distribution Systems Utilizing an Enhanced Reconfiguration Method Integrating Distributed Generation, *IEEE Systems Journal,* to be published.

[36] S. Adhikari, Fangxing Li, "Coordinated V-f and P-Q Control of Solar Photovoltaic Generators With MPPT and Battery Storage in Microgrids, *IEEE Trans. Smart Grid,* vol. 5, no. 3, pp. 1270-1281, May 2014.

[37] Z. W. Geem, J. H. Kim, and G. V. Loganathan, "A new heuristic optimization algorithm: Harmony search, *Simulation,* vol. 76, no. 2, pp. 60-68, 2001.

[38] A. L. Shenkman, "Energy loss computation by statistical techniques, *IEEE Trans. Power Del.,* vol. 5, no. 1, pp. 254-258, Jan. 1990.

[39] V. Calderaro, V. Galdi, F. Lamberti, "A Smart Strategy for Voltage Control Ancillary Service in Distribution Networks, *IEEE Trans. Smart Grid,* vol. 3, no. 1, pp. 494-502, Jan. 2015.

Appendix

A) IEEE-33 Bus Radial Distribution System Data

Branch Number	Sending End Bus	Receiving End Bus	Branch Impedance		Load at Receiving End Bus	
			R(Ω)	X(Ω)	P(kW)	Q(kVAR)
1	1	2	0.0922	0.047	100	60
2	2	3	0.493	0.2511	90	40
3	3	4	0.366	0.1864	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.819	0.707	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	1.7114	1.2351	200	100
8	8	9	1.03	0.74	60	20
9	9	10	1.044	0.74	60	20
10	10	11	0.1966	0.065	45	30
11	11	12	0.3744	0.1298	60	35
12	12	13	1.468	1.155	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.591	0.526	60	10
15	15	16	0.7463	0.545	60	20
16	16	17	1.289	1.721	60	20
17	17	18	0.732	0.574	90	40
18	2	19	0.164	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.898	0.7091	420	200
24	24	25	0.896	0.7011	420	200
25	6	26	0.203	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.059	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.963	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.341	0.5302	60	40
33	8	21	2	2		
34	9	15	2	2		
35	12	22	2	2		
36	18	33	0.5	0.5		
37	25	29	0.5	0.5		

B) IEEE-69 Bus Radial Distribution System Data

Branch Number	Sending End Bus	Receiving End Bus	Branch Impedance		Load at Receiving End Bus	
			R(Ω)	X(Ω)	P(kW)	Q(kVAR)
1	1	2	0.0005	0.0012	0	0
2	2	3	0.0005	0.0012	0	0
3	3	4	0.0015	0.0036	0	0
4	4	5	0.0251	0.0294	0	0
5	5	6	0.366	0.1864	2.6	2.2
6	6	7	0.3811	0.1941	40.4	30
7	7	8	0.0922	0.047	75	54
8	8	9	0.0493	0.0251	30	22
9	9	10	0.819	0.2707	28	19
10	10	11	0.1872	0.0619	145	104
11	11	12	0.7114	0.2351	145	104
12	12	13	1.03	0.34	8	5
13	13	14	1.044	0.345	8	5.5
14	14	15	1.058	0.3496	0	0
15	15	16	0.1966	0.065	45.5	30
16	16	17	0.3744	0.1238	60	35
17	17	18	0.0047	0.0016	60	35
18	18	19	0.3276	0.1083	0	0
19	19	20	0.2106	0.069	1	0.6
20	20	21	0.3416	0.1129	114	81
21	21	22	0.014	0.0046	5	3.5
22	22	23	0.1591	0.0526	0	0
23	23	24	0.3463	0.1145	28	20
24	24	25	0.7488	0.2475	0	0
25	25	26	0.3089	0.1021	14	10
26	26	27	0.1732	0.0572	14	10
27	3	28	0.0044	0.0108	26	18.6
28	28	29	0.064	0.1565	26	18.6
29	29	30	0.3978	0.1315	0	0
30	30	31	0.0702	0.0232	0	0
31	31	32	0.351	0.116	0	0
32	32	33	0.839	0.2816	14	10
33	33	34	1.708	0.5646	19.5	14
34	34	35	1.474	0.4873	6	4
35	3	36	0.0044	0.0108	26	18.55
36	36	37	0.064	0.1565	26	18.55
37	37	38	0.1053	0.123	0	0
38	38	39	0.0304	0.0355	24	17
39	39	40	0.0018	0.0021	24	17
40	40	41	0.7283	0.8509	1.2	1

IEEE-69 Bus Radial Distribution System Data Contd...

Branch Number	Sending End Bus	Receiving End Bus	Branch Impedance		Load at Receiving End Bus	
			R(Ω)	X(Ω)	P(kW)	Q(kVAR)
41	41	42	0.31	0.3623	0	0
42	42	43	0.041	0.0478	6	4.3
43	43	44	0.0092	0.0116	0	0
44	44	45	0.1089	0.1373	39.22	26.3
45	45	46	0.0009	0.0012	39.22	26.3
46	4	47	0.0034	0.0084	0	0
47	47	48	0.0851	0.2083	79	56.4
48	48	49	0.2898	0.7091	384.7	274.5
49	49	50	0.0822	0.2011	384.7	274.5
50	8	51	0.0928	0.0473	40.5	28.3
51	51	52	0.3319	0.1114	3.6	2.7
52	9	53	0.174	0.0886	4.35	3.5
53	53	54	0.203	0.1034	26.4	19
54	54	55	0.2842	0.1447	24	17.2
55	55	56	0.2813	0.1433	0	0
56	56	57	1.59	0.5337	0	0
57	57	58	0.7837	0.263	0	0
58	58	59	0.3042	0.1006	100	72
59	59	60	0.3861	0.1172	0	0
60	60	61	0.5075	0.2585	1244	888
61	61	62	0.0974	0.0496	32	23
62	62	63	0.145	0.0738	0	0
63	63	64	0.7105	0.3619	227	162
64	64	65	1.041	0.5302	59	42
65	11	66	0.2012	0.0611	18	13
66	66	67	0.0047	0.0014	18	13
67	12	68	0.7394	0.2444	28	20
68	68	69	0.0047	0.0016	28	20
69	11	43	0.5	0.5		
70	13	21	0.5	0.5		
71	15	46	1	0.5		
72	27	65	1	0.5		
73	50	59	2	1		