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A Particle Swarm Optimization Algorithm based Power Loss Reduction in Radial Distribution Network by Optimal Capacitor Placement and Sizing

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ABSTRACT

Optimizing the placement and sizing of capacitors in electric distribution networks is a well-established technique that aims to minimize losses and enhance the voltage profile. The main focus of this study is to reduce power losses in radial distribution system by providing appropriate reactive power support. The methodology involves determining the optimal locations for ca- pacitor banks using a loss sensitivity factor-based method, which helps iden- tify suitable candidate bus locations. To determine the appropriate capacitor sizes, the Particle Swarm Optimization method is employed. Furthermore, a comprehensive explanation of the Backward-forward sweep algorithm is pro- vided for load flow analysis in radial distribution networks. The proposed algorithm offers several advantages. Firstly, it can be implemented using readily available software. Secondly, it ensures the attainment of globally optimal solutions while requiring relatively low computational effort compared to other meta-heuristic techniques commonly employed for the same purpose. In order to assess the efficacy of the proposed methodology, a series of tests were carried out on two benchmark radial distribution networks, comprising 33 and 69 buses respectively. The results of the study demonstrated that the suggested approach effectively reproduced the outcomes reported in the prior scholarly works for the 33 bus system. Furthermore, the methodology employed in the analysis of the 69 bus system produced innovative solutions that resulted in a 1.72% improvement compared to previously documented research outcomes. The placement of capacitors is a cost-effective approach, therefore, a detailed cost analysis is being discussed. In a separate instance, the technique of capacitor placement for minimizing power loss is integrated with the network reconfiguration method, under varying load conditions and the effects are examined in relation to improving the distribution system. The results indicate a significant reduction in power loss, nearly 50%, for both bus systems. Additionally, the voltage profile of both bus systems exhibits a further improvement of 5%.

Keywords: Capacitor Placement & Sizing, Particle Swarm Optimization, Backward/Forward sweep, Power Loss, Radial Distribution System.

I. INTRODUCTION

Distribution network losses are the single most expensive component of any electricity infrastructure. Due to the fast increase in power consumption, environmental limitations, and a competitive energy market situation, these systems are frequently run under highly loaded conditions, and the losses has become an increasing worry. The radial distribution system is the most fa- mous and extensively used network for electrical energy delivery, owing to its simple design and cheap cost implementation. However, because to increased system losses and poor voltage management, the voltage deviates from the rated value as we move farther away from the substation. The only way to improve delivery system efficacy is to minimise losses. Shilpa & Ganga

[1] have provided a succinct overview of various loss minimization meth- ods. There are other loss minimization techniques for distribution systems that can be found in the literature, but the three main techniques are dis- tributed generation (DG) allocation, network reconfiguration, and capacitor placement. The improvement of network reconfiguration or reactive power support through capacitor/DG location have historically been the

focus of loss reduction. However, the focus of this article is on building shunt capac- itor banks for reactive power compensation to reduce active power losses of the radial distribution network. However, a poor distribution of the capaci- tor banks would degrade the network’s characteristics. In order to decrease power losses and enhance the voltage profile, an appropriate approach for choosing the size and position of the capacitor banks must be developed.

The examination of the load flow is the initial phase in this procedure. Most research articles in the literature skip over this part and go straight to the capacitors’ location and dimensions. Standard load flow techniques including Gauss-Seidel (G-S), Newton-Raphson (N-R), and fast decoupled load flow are extensively used for the operation, control, and planning of power systems. It has been repeatedly shown that these methodologies may become ineffective when used to analyse radial distribution systems because of the particular features of such networks, including their radial topology, low X/R ratio, un-transposed lines, unbalanced loads, and single-phase & two-phase laterals. Thus, for the load flow analysis presented in section-II, the Backward and Forward Load Flow method was employed in this arti- cle even though it has not been mentioned by any other researcher in the literature.

The next stage in the procedure is to locate the capacitor’s ideal place- ment. The notion of loss sensitivity analysis was presented by Prakash [2]. The phrase ”sensitivity analysis” describes the process of identifying how ”sensitive” a parameter is to changes in the values of other model parameters or to changes in the model’s structure. According to its definition, it is ”the ratio $\Delta x/\Delta y$ of a small change Δx in one dependent variable (x) to a small change Δy in another independent or controllable variable (y)” [3]. A possible placement for the capacitor is established using this approach. In addition to this strategy, fuzzy logic [4],[5], [6] are also utilised in literature to determine the ideal location. However, the loss sensitivity factor (LSF) is a preferred option among researchers since it performs better than fuzzy logic in terms of computation simplicity and complexity.

Finding the size of the capacitor to be installed at the potential site is the process’s last phase. When inserting a shunt capacitor, Grainger and Lee

[7] created a strategy based on equal area criteria to reduce power loss. In a series of publications from [8] to [10], Baran & Wu proposed placement, type, and size of capacitors as independent algorithms. Up to the 1990s, capacitors were allotted on an individual feeder. Kalyuzhny [11] described a method that used a genetic algorithm to determine the best capacitor allocation. In 2004, Ghose & Goswami [12] considered variations in load while sizing a ca- pacitor, before which the load used to considered constant. Later, numerous researchers employed a variety of approaches to resolve this issue, such as the Parallel Tabu Search (TS) Algorithm introduced by Hiroyuki [13], which minimises power losses while determining the placement and size of the ca- pacitor in discrete numbers. D. Das [14] created a fuzzy genetic algorithm (GA) to find the ideal shunt capacitor values in the radial distribution system

. Yesim [15] suggested a fuzzy-based system in which the fuzzy expert system chooses the candidate bus for the capacitor position and the fuzzy optimisa- tion system determines the size of the capacitor. A plant growth modelling method was put into place by Srinivasa Rao [16] to minimise annual costs and minimise losses. Elsheikh [17] used discrete particle swarm optimisation approach and claimed to obtain better results than Prakesh [2], discussing the sizes and costs of commercially available capacitors, which makes cost analysis more simpler and more comparable. Some other methods used are Devabalaji[18] used a bacterial foraging optimisation algorithm, Mohammed Shuaib[19] used a gravitational search algorithm, and Abdelaziz[20] used a flower pollination algorithm to solve non-linear optimisation problems like ca- pacitor placement and sizing. The Particle Swarm Optimisation technique, which has been created as a solution strategy for the capacitor size problem, is presented in this paper in light of the above exciting research studies. The suggested algorithms were tested on IEEE standard 33 and 69 bus systems to demonstrate their efficiency.

This paper is set up as follows: Section I provides an introduction, Sec- tion II deals with an elaborate approach for load flow analysis, Section III addresses capacitor location and Section IV addresses capacitor sizing, Sec- tion V provides a detailed algorithm, and Section VI covers the findings and their analysis.

II. BACKWARD FORWARD SWEEP LOAD FLOW ALGORITHM

For the load flow analysis of a radial distribution network, the back- ward/forward sweep load flow algorithm is been developed. The Backward sweep involves the calculation of branch currents from the load end to the source end. The Forward sweep involves the calculation of node voltages from the source end to the load end. D.Das & D.P.Kothari[21] has proposed the load flow solution for radial distribution system in 1995 which involves only simple algebraic expression of voltage magnitudes, without any trigonometric functions or complex equations that required to be solved by any numerical methods. But these Equations are complex to understand and implement. Om pathak & Prem Prakesh[22] modified the load flow algorithm, which is much simpler and easy to understand. The methodology involves the BIBC (Bus Injection to Branch Current) & BCBV (Branch Current to Bus Voltage) matrix. The paper presents a detailed algorithm for the formation of BIBC and BCBV matrices which is not reported by any researcher in the literature.

The Fig-1 represents a simple 6-bus radial distribution system. If, I represents load current and B represents branch current. if, P_{Li} and Q_{Li} are the active and reactive load powers at i^{th} node. V_i is the i^{th} node voltage. At the initial steps all the bus voltages are treated/ set to 1pu and then the current injection at every node are calculated as,

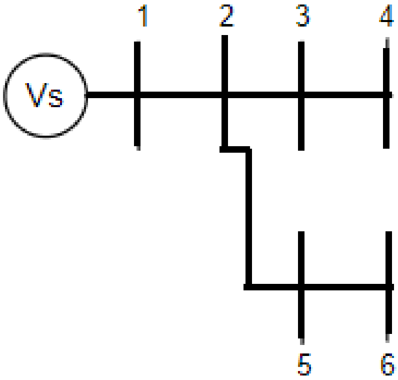

Figure 1: Simple Distribution System [22]

$$I = {}^{PLi + jQLi} \quad {}^{*} \text{ for, } i = 2, 3....6 \qquad (1)$$

In Backward Sweep, we apply KCL at far end node and move towards the source node & express the branch currents in terms of load currents as,

$B_5 = I_6$
$B_4 = I_5 + B_5 = I_5 + I_6$

$B_3 = I_4$ (2)
$B_2 = I_3 + B_3 = I_3 + I_4$
$B_1 = I_2 + B_2 + B_4 = I_2 + I_3 + I_4 + I_5 + I_6$

Writing the equations in the form of matrix, we have

$$\underset{[B]}{\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}} = \underset{[BIBC]}{\begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}} \underset{[I]}{\begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix}}$$

In short it can be represented as,

$$[B] = [BIBC][I] \qquad (4)$$

which relate branch currents interms of load currents (or) node currents. Since node-1 is source bus which is treated as 1pu, then remaining N-1 nodes will be equal to number of branches in the system. so, BIBC is a binary matrix of order (nbr,nbr), where, nbr represents number of branches and its elements are given as

$BIBC_{ij}$ = 1, if node − j lies after the branch – i
(5)
0, Otherwise

For example in equ-(3), the branch current B_2 has entries 1 corresponding to nodes 3&4, which implies nodes 3&4 exists after branch-2 in the radial network.

In Forward Sweep we Apply KVL to express bus voltages to voltage drops as

$V_2 = V_1 - B_1Z_{12} \Rightarrow V_2 = V_1 - B_1Z_{12}$
(6)
$V_3 = V_2 - B_2Z_{23} \Rightarrow V_3 = V_1 - B_1Z_{12} - B_2Z_{23}$
$V_4 = V_3 - B_3Z_{34} \Rightarrow V_4 = V_1 - B_1Z_{12} - B_2Z_{23} - B_3Z_{34}$
$V_5 = V_2 - B_4Z_{25} \Rightarrow V_5 = V_1 - B_1Z_{12} - B_4Z_{25}$
$V_6 = V_5 - B_5Z_{56} \Rightarrow V_6 = V_1 - B_1Z_{12} - B_4Z_{25} - B_5Z_{56}$

The voltage drop at each bus as compared to the 1^{st} bus is calculated and written as

$$\underbrace{\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix}}_{[\Delta V]} = \underset{[BCBV]}{\begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{24} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{24} & Z_{35} & 0 \\ Z_{12} & Z_{23} & Z_{24} & 0 & Z_{46} \end{bmatrix}} \underset{[B]}{\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}}$$

(7)

In short it can be represented as, $[\Delta V] = [BCBV][B]$

Where, ΔV represents drop in voltage at each node w.r.t source node voltage(1pu). The BCBV matrix is a complex impedance matrix of dimension (nbr,nbr). And it can be easily shown that

$$[BCBV] = [BIBC]^T\ [Z] \quad (8)$$

where [Z] is a diagonal matrix with all its diagonal entries equal to branch impedances. On substitution of [B] from equ-(3) the above expression can be rewritten as

$$[\Delta V] = [BIBC]^T\ [Z][BIBC][I] \qquad (9)$$

Equ-(9) gives the relationship between the bus voltage deviation from 1pu rated voltage interms of load currents. And the actual bus voltages are obtained from the following equation.

$$[V^k] = [V^0] + [\Delta V] \qquad (10)$$

Here, the superscript denotes the iteration count. For convergence of the load flow the maximum of voltage difference of two successive iterations should be less than the predefined tolerance and is given as,

$$\max[|V^{k+1}| - |V^{k}|] \leq \text{tolerance} \qquad (11)$$

Once the tolerance is reached the branch currents are calculated as per equ-(4) and losses are calculated using

$$P_{\text{Loss}} = \sum_{i=1}^{n} \mathrm{B}_i^2 \mathrm{R}_i$$

(12)

Where, n is number of busses, P_{Loss} is the total active power loss, B_i is the current flowing through the i^{th} Branch, R_i is the resistance of the i^{th} branch.

The primary goal of this study is to discover the best placement and size of a capacitor to insert in the distribution network to reduce power loss. This is performed by utilizing the Loss Sensitivity Analysis and Particle Swarm Optimization technique subject to operational constraints discussed in the next section.

III. PROBLEM FORMULATION

3.1 Objective Function

The main Objective of this paper is to minimize the active power losses in the radial distribution network by optimal placement of capacitors at potential location with appropriate size. Hence, the fitness function is given by

$$Minimum(P_{\text{Loss}}) = \sum_{i=1}^{n} \mathrm{B}_i^2 \mathrm{R}_i$$

(13)

3.2 Operational Constraints

The objective function is bound by the following constraints.

3.2.1 System total Reactive Power

The total reactive power compensation Q_C is less than total reactive power load of the system Q_L.

$$\sum_{i=1}^{NC} Q_{C_i} \leq \sum_{j=1}^{n} Q_{L_j}$$

(14)

Where, Q_C is the reactive power compensation, Q_L is the total reactive power load, NC is Number of capacitors & n is number of busses.

3.2.2 Capacitor Size

The Size of the capacitor at the candidate location is within the permis- sible range, given by the equation

$$Q_{min} \leq Q_i \leq Q_{max} \quad (15)$$

Where, Q_i = Size of capacitor of i^{th} candidate location, Q_{min} is the minimum size of capacitor, Q_{max} is the maximum size of capacitor. Table-1 displays the possible capacitor sizes as well as their annual expenses [17]. The Table is used to select the maximum and minimum capacitors.

Table 1: Available Capacitor sizes with their corresponding costs

Capacitor size (kvar)	150	300	450	600
Capacitor cost (Rs/kvar)	0.5	0.35	0.253	0.22
Capacitor size (kvar)	750	900	1050	1200
Capacitor cost (Rs/kvar)	0.276	0.183	0.228	017

IV. OPTIMAL LOCATION FOR CAPACITOR PLACEMENT THROUGH LOSS SENSI- TIVITY ANALYSIS

The loss sensitivity analysis is a method for determining the candidate position for capacitor installation based on the influence of nodal reactive power on the system's real power losses. It narrows the search space during optimization by anticipating which bus will have the greatest loss reduction when a capacitor is installed. As a result, the sensitive buses may be candidates for capacitor installation.

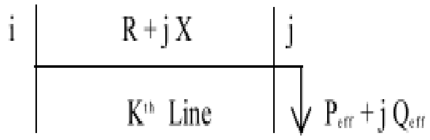

Figure 2: Sample Distribution Line [2]

This analysis is carried out by initially calculating the loss sensitive coefficients [2] as follows, Consider a distribution line as shown in Fig-2 connected between 'i' and 'j' buses. A Kth line is connected between the two buses. Power losses in this line is given by $(I_K)^2 * R_K$ which can be expressed as
eff

$$P_{Loss}(j) = \frac{P^2_{eff}(j) + jQ^2_{eff}(j)}{V_j^2} * R_K \qquad (16)$$

Where, P_{eff} (j) is the total effective active power load beyond node j. Q_{eff} (j) is the total effective reactive power load beyond node j. R_K is the line resistance of Kth line. V_j is the voltage at node j.
From equ-12 the LSF is calculated by taking a derivative of the equation
w.r.t the effective reactive power load.

$$LSF = \frac{dP_{Loss}}{dQ_{eff}} = \frac{2 * Q_{eff}(j) * R_{ij}}{(V_j)^2} \qquad (17)$$

The buses are listed in decreasing order using the computed LSF values. The decreasing order will decide the order in which the buses are to be considered for compensation. A normalized voltage vector (norm(i)) is now computed using base case voltage magnitudes provided, to determine whether a bus requires reactive power compensation or not.

$$norm(i) = \frac{V(i)}{0.95} \qquad (18)$$

Those buses having High normalized voltage (norm(i) 1.01) are healthy buses and such buses need no compensation. The buses having low normalized voltage (norm(i)<1.01) are selected as candidate buses for capacitor placement. The sizing of capacitors to be placed at these locations is done using Particle Swarm Optimization Algorithm.

V. PSO AND ITS APPLICATION TO CAPACITOR SIZING

5.1 Particle Swarm Optimization

The PSO algorithm starts by initializing a collection of particles that stand in for possible answers to the optimization issue. Within a predetermined search space, a particle's position and velocity are allocated at random for each particle. Each particle's position denotes a potential answer to the optimization issue, and its velocity denotes the speed and direction it is traveling in the search space. The particles are then assessed using a fitness function that is often established by specific problem being solved. Based on each particle's best position to date (P_{best}) and the best position of the group as a whole (G_{best}), the PSO algorithm dynamically adjusts each particle's position and velocity. The velocity of each particle in the swarm is adjusted in accordance with its own experience as well as the experience of the other particles, resulting in a collective movement in the direction of the ideal outcome[23], [24].

The velocity equation to update the position of the particle is given by

$$\begin{aligned} V_{ij}^{t+1} = K(w * V_{ij}^{t} + c1 * \text{rand}1(P_{ij}^{best} - X_{ij}^{t}) \\ + c2 * \text{rand}2(G_{j}^{best} - X_{ij}^{t})) \end{aligned} \qquad (19)$$

Where, K is the Constriction factor, c1 & c2 are the acceleration factors, i is the Particle number, j is the Control Variable, rand1 & rand2 are random numbers in the range [0, 1], w is inertia weight factor, X is the Current position of individual particle, P^{best} is the best position of individual particle, G^{best} is the best position among the swarm, V is the velocity of individual particle.
The Constriction factor [25] is given by

$$K = \frac{2}{\left|2 - C - \sqrt{C^2 - 4C}\right|} \quad (20)$$

where, $C = c1 + c2$ and $C \geq 4$

To avoid local convergence Clerc [25] assumed the values of c1 & c2 as 2.05 and the constriction factor comes out to be K = 0.729. Now, to keep local and global exploration in balance, the inertia weight is calculated as,

$$w^{t+1} = w_{max} - \frac{w_{max} - w_{min}}{t_{max}} \times t \quad (21)$$

where, t is current iteration, t_{max} is maximum number of iterations, w_{max} and w_{min} are taken as 0.9 and 0.4 [25].

Once the velocity is calculated, the particle's position is updated using the following equation.

$$X_{ij}^{t+1} = X_{ij}^{t} + V_{ij}^{t} \quad (22)$$

Where, X^{t+1} New position of the Particle, X^{t} Current Position of the Particle.

Flow chart shown in Fig-3 describes the step by step procedure to obtain the candidate location and size of the capacitor. The detailed algorithm is discussed in the next section.

VI. IMPLEMENTATION OF ALGORITHM FOR NETWORK POWER LOSS REDUCTION

1. Feed the input data:
   - a. Active & Reactive Power at each bus (Load data)
   - b. Transmission line resistance & reactance (Line data)
   - c. PSO parameters (number of particles, maximum number of iterations, acceleration constants & inertial weights)
2. Perform a base case load flow algorithm. Calculate the voltages at each node and the power losses as indicated in section II.
3. Use equ-(17) to determine the loss sensitivity coefficients for each bus and then arrange the buses in descending order of the coefficient's values.
4. Determine the candidate buses that need reactive power compensation by computing the normalized voltage vector according to equ-(18).
5. To calculate the size of the capacitor to be placed, randomly generate an initial swarm. Each individual particle in the swarm signifies a potential capacitor size. Using the capacitor values listed in Table-I, each member of the swarm is given a random initialization.
6. The position of the particles are represented as

$$X_{ij} = \begin{bmatrix} Q_{11} & Q_{12} & .. & .. & Q_{1j} \\ Q_{21} & Q_{22} & .. & .. & Q_{2j} \\ Q_{31} & Q_{32} & .. & .. & Q_{3j} \\ .. & .. & .. & .. & .. \\ Q_{i1} & Q_{i2} & .. & .. & Q_{ij} \end{bmatrix} \quad (23)$$

where, i represents number of particles and j is the number of candidate buses.

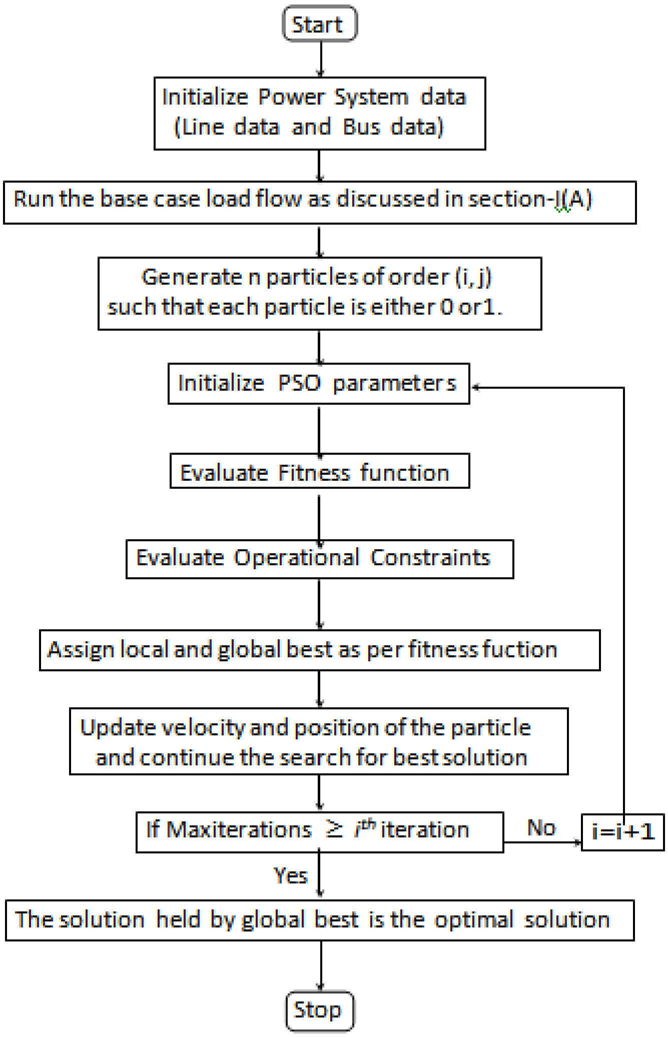

Figure 3: Calculation procedure for the proposed method

7. Set the iteration count = 1. Assume the capacitors of particle-1 from equ-(23) are placed at the candidate bus chosen in steps 3 and 4. Now, using equ-(24) update the reactive powers at these buses.

$$Q_L^1 = Q_L - Q_C \qquad (24)$$

where, Q_L is the reactive power load connected to the candidate bus.

Q_C is reactive power supplied by the capacitor.
Q^1L is the updated reactive power.

8. Run the load flow algorithm using the revised reactive powers, and then use equ-(12) to compute and store the active power loss. Similarly, for every particle in equ-(23), repeat steps 7 and 8.
9. Evaluate the particle's fitness value (Power loss) and compare it to the prior particle's best (P_{best}) value. If the current fitness value is higher than the P_{best} value, the P_{best} value should be assigned to the current value.
10. Determine the current greatest global best (G_{best}) value among the particle's individual best (P_{best}) values. Examine the current global position in relation to the prior global position. Set the global position to the current global position if it is better than the previous global position.
11. Generate the particle velocity (V_{ij}) for each element of the swarm using equ-(19) to equ-(21) and update the position of the particles using equ- (22).

12. Repeat the steps from 7 to 11 until the termination criteria (iteration count = maximum number of iterations) is achieved.

VII. RESULTS AND DISCUSSION

The proposed approach is programmed in MATLAB 2022b and runs on a PC with an 11th Gen Intel Core i5 processor with 8GB RAM. This study con- siders two test systems, 33 & 69 bus systems, to demonstrate the capabilities of the suggested approach for allocating capacitors and the results produced are compared with standard publications in the field. The substation voltage is estimated to be 1pu on a voltage base of 12.66 kV and 100 MVA. For the backward / forward sweep load flow analysis the convergence is set to 0.0001. For the PSO algorithm 20 particles & 200 iterations are considered and the results are run over 100 times for accuracy.

	33 Bus System					69 Bus System				
	Base Case	After Compensation				Base Case	After Compensation			
Location-Size(kvar)	-	29 - 450 30 - 750	29 - 150 30 - 750 7 - 750	29 - 150 30 - 750 7 - 750 28 - 150	29 - 150 30 - 750 7 - 450 28 - 300 12 - 300	-	60 - 600 63 - 750	60 - 600 63 - 600 64 - 150	60 - 450 63 - 600 64 - 150 20 - 300	60 - 150 63 - 450 64 - 450 20 - 450 58 - 300
Active Power load (kW)	3715	3715	3715	3715	3715	3801.89	3801.89	3801.89	3801.89	3801.89
Reactive Power load (kvar)	2300	2300	2300	2300	2300	2694.1	2694.1	2694.1	2694.1	2694.1
Powerloss (kW)	202.66	143.03	136.72	136.75	133.92	225	152.95	152.73	146.37	146.53
% Powerloss reduction	-	29.42%	32.53%	32.52%	33.91%	-	31.99%	32.10%	34.92%	34.85%
Minimum Voltage (pu)	0.913	0.925	0.932	0.933	0.937	0.909	0.931	0.931	0.931	0.931
Voltage Deviation	1.700	1.321	1.220	1.187	1.156	1.836	1.498	1.499	1.422	1.403
Total Compensation placed (kvar)	-	1200	1650	1800	1950	-	1350	1350	1500	1800
Total Powerloss Cost ($/year)	34047.71	24030.31	22969.26	22974.27	22500.001	37787.43	25696.94	25660.13	24591.754	24616.96
Capacitor installation Cost ($/year)	-	320.85	489	564	605.85	-	339	339	425.85	521.55

Total Annual Cost ($/year)	34047.71	24351.14	23458.26	23538.27	23105.85	37787.43	26035.94	25999.13	25017.604	25138.51
Net Saving ($/year)	-	9696.5	10589.45	10509.44	10941.86	-	11751.49	11788.301	12769.83	12648.92

Table 2: Analysis of 33 & 69 bus systems

Table 3: Results of 33 & 69 bus systems

Parameters	33 Bus System		69 Bus System	
	Before Reconfiguration	After Reconfiguration	Before Reconfiguration	After Reconfiguration
Location - Size (kvar)	-	29 - 150 30 - 750 7 - 450 28 - 300 12 - 300	-	60 - 450 63 - 600 64 - 150 20 - 300
Power Loss	202.66 kW	133.26 kW	225 kW	146.37 kW
% Power loss Reduction	-	33.91 %	-	34.92 %
Minimum Voltage	0.913 pu	0.937 pu	0.909 pu	0.931 pu
% Improvement in minimum voltage	-	2.62 %	-	2.42 %
Total Compensation	-	1950 kvar	-	1500 kvar

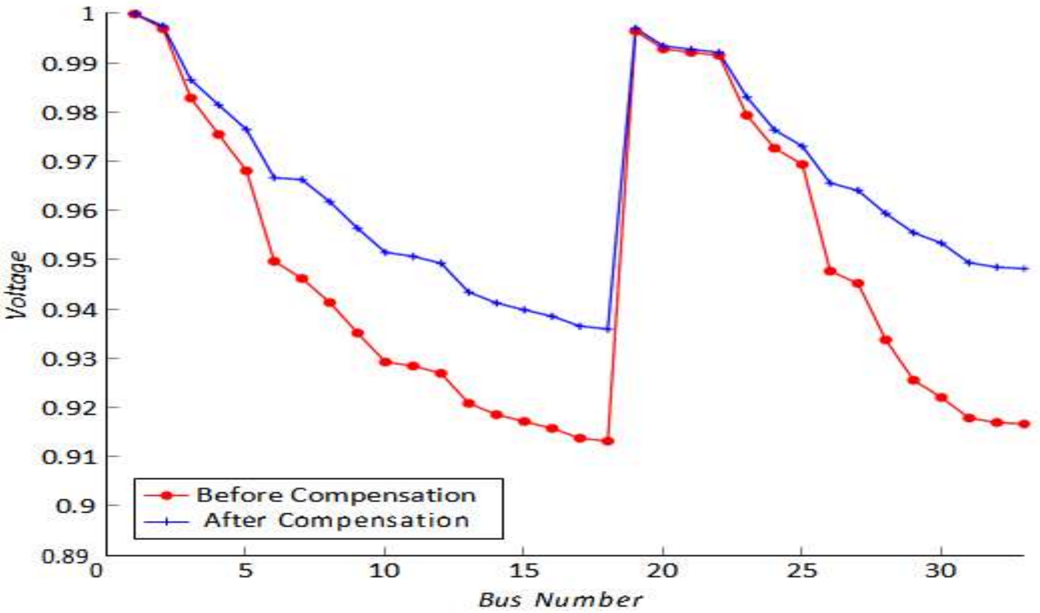

Figure 4: Voltage Profile of 33 Bus System Before & After Compensation

The results and analysis is divided in following sections: section A & B discusses the results of 33 & 69 bus systems. Section-C discusses the cost analysis, Section-D discusses about the placement under Network Reconfig- uration and Variable loading conditions.

7.1 Results and Analysis of 33 Bus System

The first case study for the proposed method is a radial distribution system with 33 buses. This system is comprised of a primary feeder and four laterals (sub-feeders). The single line diagram is depicted in Fig-6. The line and load information for the feeders is obtained from reference [4]. Loss-sensitive analysis is utilised to select the candidate bus location for the placement of capacitors. The order of the buses is determined by

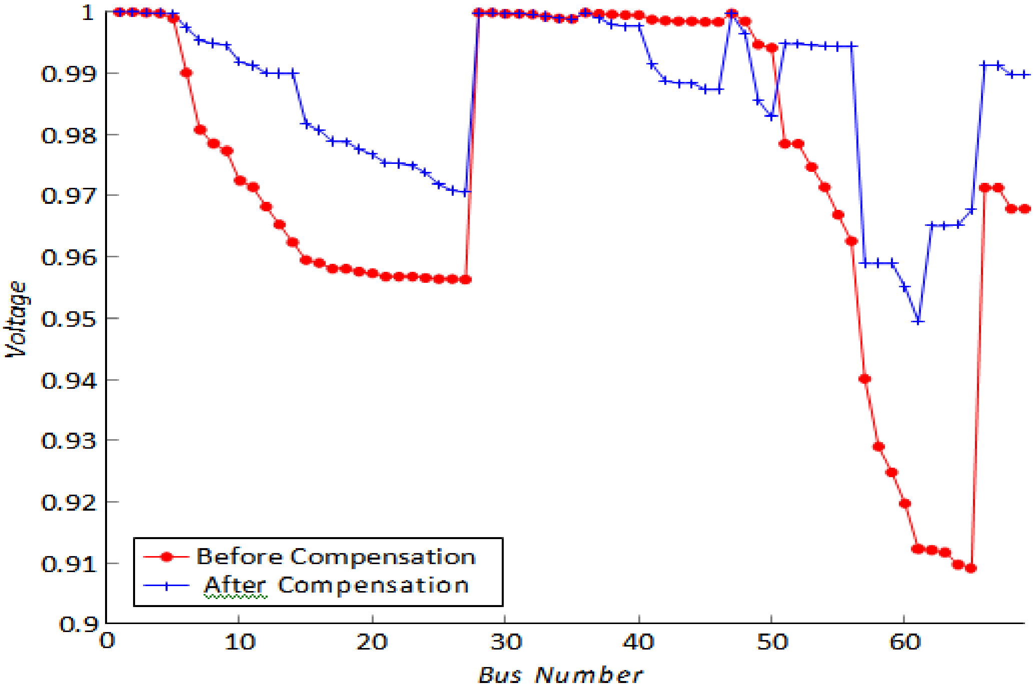

Figure 5: Voltage Profile of 69 Bus System Before & After Compensation

Table 4: Comparison of Various algorithms with proposed algorithm

33 Bus System					
Method	Power Loss (kW)			Location	Size (kW)
	Before	After	% PL		
PSO	**202.66**	**133.26**	**33.91%**	**29** **30** **7** **28** **12**	**150** **750** **450** **300** **300**
BPSO [28]	202.68	134.2	33.78 %	6 11 24 29	600 300 300 600

				32	300
FPA [20]	202.66	134.47	33.64 %	6 9 30	250 400 950
MILP [27]	202.67	132.2	34.77 %	13 24 30	350 550 1050
69 Bus System					
Method	Power Loss (kW)			Location	Size (kW)
	Before	After	% PL		
PSO	**225**	**146.37**	**34.92 %**	**60** **63** **64** **20**	**450** **600** **150** **300**
PSO [2]	225	152.48	32.23%	46 47 50	241 365 1015
FPA [20]	224.89	150.28	33.2 %	61	1350
MILP [27]	224.9	155.69	30.8 %	22 61 64	50 750 200

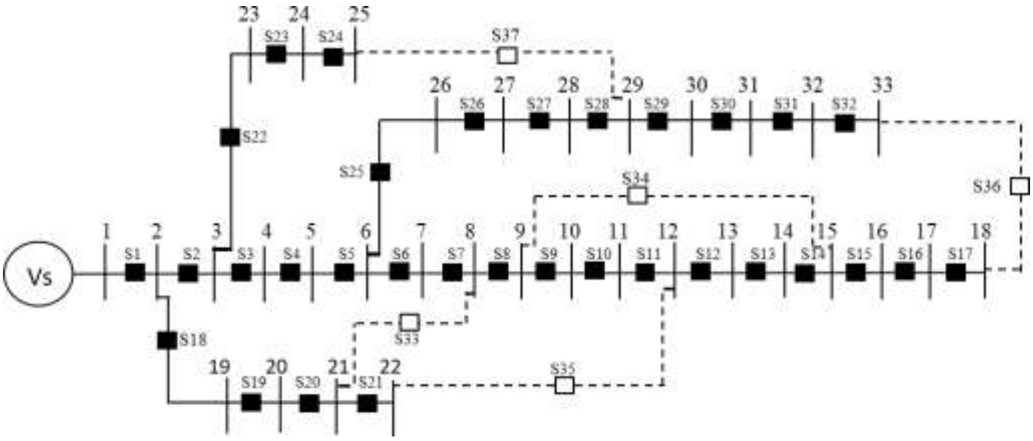

Figure 6: Single Line Diagram of 33 bus system[4]

their sensitivity value (29, 30, 7, 28, 12, 13, 31, 17, 16, and 27). Table- II presents the analysis for the placement of capacitors. PSO calculates the quantity of kvar to be injected based on the placement of candidate capacitors in varying locations. After comparing various parameters, the top five locations for placing the capacitor are chosen (i.e. 29, 30, 7, 28, 12) and their respective ratings are 150, 750, 450, 300, and 300 kvar. Fig-4 depicts the voltage profile before and after compensation. Initial power loss is 202.66 kW and is reduced to 133.26 kW using the proposed capacitor placement procedure. The results of the proposed method are displayed in Table-III, while Table-IV compares the results to those of BPSO [28], FPA [20], and MILP [27]. The minimum voltage before capacitor placement is 0.913 pu (bus 18); after capacitor placement, it is improved to 0.937 pu (bus18), and the voltage profile improves by 2.62 %. The voltage deviation has decreased from 1.75 to 1.156. A detailed cost analysis is provided in Table-II, and the annual savings resulting from capacitor installation is 10941.86 $/year.

7.2 Results and Analysis of 69 Bus System

The second case study for the proposed method is a radial distribution system with 69 buses. This system has one primary feeder and seven sec- ondary feeders. The line diagram is depicted in Fig-7. The line and load information for the feeders is obtained from reference [26]. Similar to the first test case, the Loss sensitive analysis method is used to determine the candidate bus location for capacitor placement. The order of the vehicles' sensitivity values is as follows: 60, 63, 64, 20, 23, 24, 25, 26, and 27. Table II presents the analysis for the placement of capacitors. PSO calculates the quantity of kvar to be injected based on the placement of candidate capaci- tors in varying locations. After comparing various parameters, the top four locations (i.e. 60, 63, 64, 20) are chosen to position the capacitor, and their ratings are 150, 600, 150, and 300 kvar. Fig-5 depicts the voltage profile of the system before and after compensation. The power loss before and af- ter capacitor installation is 225 and 146.37 kW, respectively. The minimum voltage prior to capacitor installation is 0.909 pu (bus 65) and increase to 0.931 pu (bus 65) after capacitor installation. Table-IV compares the results of the proposed method with those of the PSO method [2], FPA [20], and MILP [27]. The proposed method results in less power loss than all other methods, and the percentage reduction is 1.72 % greater than that reported in the literature.

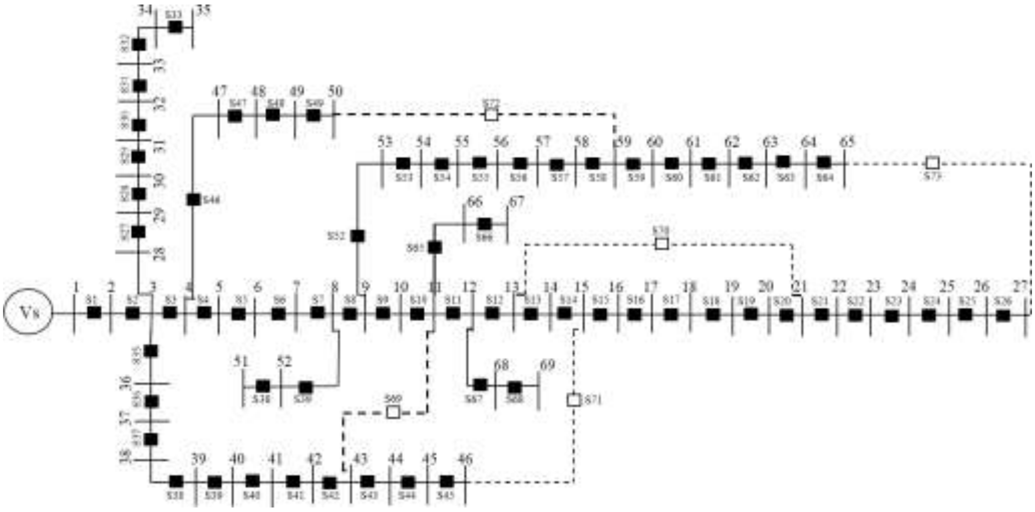

Figure 7: Single Line Diagram of 69 bus system[26]

7.3 Cost Analysis

The third case study deals with the economical aspects of the capacitor placement. The Capacitor placement and sizing is a highly cost effective work. In order that the distribution sector get maximum benefit at minimal cost for placing a capacitor bank, the cost analysis is essential. The cost analysis at the two test systems 33 & 69 bus systems is presented in Table-2.

The parameters in the table are calculated as below, The total cost of the system is a sum of total power loss cost and capacitor cost. The Power loss cost of the system is calculated as,

$$\text{Power loss Cost} = K_{PL}\, P_{Lose}$$

Where, K_{PL} is the annual cost per unit of power losses ($/kW). P_{Lose} is the total active power loss. Only fixed capacitors are considered for the analysis. The cost of capacitor can be divided into two parts: the installation cost and the maintenance cost.The capacitor basically is a maintenance free and very long life electrical plant. Therefore, we can assume that there is no equipment or parts to be replaced within the life of capacitor (typically 20 years). The total cost of capacitor installation during its working life can be calculated by the following equation.

$$\text{Capacitor cost} = K_c * Q_c$$

K_c is the capacitor annual cost ($/kvar). Table-1 shows the available capaci- tor sizes and the corresponding annual cost [17]. Q_c is the total compensation placed. So, the total cost of operation is given as

$$\text{Total Cost} = \text{Power loss Cost} + \text{Capacitor cost}$$

The annual cost of power loss K_{PL} is taken as 168 $/kW [20]. The annual capacitor installation cost is taken as per Table-1. The cost analysis for 33 & 69 bus systems is presented in Table-2.

For 33 bus system when 5 capacitors are installed, the net savings are 10941.86 $/year, despite the fact that the net capacitor installation cost is higher. However, it greatly reduces the total power loss cost, resulting in a greater net savings. Thus, the cost analysis plays a crucial role while deciding the number of capacitor to be placed. Comparatively, for a 69-bus system, placing four capacitors instead of five results in a net savings of 12769.83
$/year.

7.4 Capacitor Placement under Network Reconfiguration and varying load conditions

The fourth case study addresses the concept of combining the capacitor placement approach with other methods in the literature to minimize power losses in a distribution network at lower expenses. The two most common

Table 5: Capacitor placement under Network reconfiguration and load variations for 33 bus system

Parameters	Without Reconfiguration		With Reconfiguration	
	Base Case	Capacitor only	No Change in Capacitor Location	Change in Capacitor Location
100% Loading				
Location - Size (kvar)	-	29 - 150 30 - 750 7 - 450 28 - 300 12 - 300	29 - 300 30 - 450 7 - 300 28 - 150 12 - 450	29 - 150 30 - 450 28 - 300 31 - 300 17 - 300
Open Switches	33, 34, 35, 36, 37	33, 34, 35, 36, 37	7, 14, 9, 32, **37**	7, 14, 9, 32, **37**
Total Compensation	-	1950 kvar	1650 kvar	1500 kvar
Powerloss	202.66 kW	133.92 kW	95.5 kW	96.44 kW
% Power Loss	-	33.91%	52.87%	52.41%
75% Loading				
Location - Size (kvar)	-	29 - 300 30 - 450 7 - 300 28 - 150 12 - 300	29 - 450 30 - 450	30 - 600 31 - 450
Open Switches	33, 34, 35, 36, 37	33, 34, 35, 36, 37	7, 14, 9, 32, 28	7, 14, 9, 32, 28
Total Compensation	-	1600 kvar	900 kvar	1050 kvar

Powerloss	109.72 kW	75.88 kW	61.11 kW	62.07 kW
% Power Loss	-	30.83%	44.30%	43.42%
50% Loading				
Location - Size (kvar)	-	29 - 450 30 - 450	-	-
Open Switches	33, 34, 35, 36, 37	33, 34, 35, 36, 37	7, 14, 9, 32, 28	7, 14, 9, 32, 28
Total Compensation	-	900 kvar	-	-
Powerloss	47.06 kW	43.57 kW	33.725 kW	33.725 kW
% Power Loss	-	7.41%	28.33%	28.33%

Table 6: Capacitor placement under Network reconfiguration and load variations for 69 bus system

Parameters	Without Reconfiguration		With Reconfiguration	
	Base Case	Capacitor only	No Change in Capacitor Location	Change in Capacitor Location
100% Loading				
Location - Size (kvar)	-	60 - 450 63 - 600 64 - 150 20 - 300	60 - 450 63 - 150 64 - 150 20 - 150	60 - 450 58 - 450 56 - 300 57 - 150
Open Switches	69, 70, 71, 72, 73	69, 70, 71, 72, 73	**69**, **70**, 14, 56, 61	**69**, **70**, 14, 56, 61
Total Compensation	-	1500 kvar	1000 kvar	1350 kvar
Powerloss	225 kW	146.37 kW	76.3 kW	76.42 kW
% Power Loss	-	34.94%	66.08%	66.04%
75% Loading				
Location - Size (kvar)	-	60 - 300 63 - 600 64 - 300 20 - 300	-	-
Open Switches	69, 70, 71, 72, 73	69, 70, 71, 72, 73	**69**, **70**, 14, 56, 61	**69**, **70**, 14, 56, 61
Total Compensation	-	1500 kvar	-	-
Powerloss	120.94 kW	81.66 kW	54.249 kW	54.249 kW
% Power Loss	-	32.47%	55.14%	55.14%
50% Loading				
Location - Size (kvar)	-	60 - 450 63 - 450 64 - 300 20 - 300	-	-

Open Switches	69, 70, 71, 72, 73	69, 70, 71, 72, 73	**69**, **70**, 13, 58, 61	**69**, **70**, 13, 58, 61
Total Compensation	-	1500 kvar	-	-
Powerloss	51.58 kW	37.22 kW	23.6 kW	23.6 kW
% Power Loss	-	27.83%	54.23%	54.23%

methods for reducing power loss are capacitor placement and network recon- figuration. The fig-6 & fig-7 represents the single line diagram of 33 & 69 bus system. The dotted line represents tie line switches and the continuous line with black shaded boxes represents sectionalizing switches. The process of modifying the feeder structure with the use of tie line switches and sectional- izing switches, which must be closed and opened proportionately, is referred to as network reconfiguration. The reconfiguration algorithm is developed based on the technique discussed in the reference-[28]. The findings are re- ported in Tables 5 and 6. From Table-5 the 33, 34, 35, 36, 37 under base case represents the open tie line switches and the remaining switches (1 to 32) are the sectionalizing switches. After reconfiguring the network struc- ture switches in bold under ’with reconfiguration’ section represents the tie switches not operated while remaining are the sectionalizing switches opened for corresponding tie line switches closed. Similarly, Table-6 represents the 69 bus system with tie switches 69, 70, 71, 72, 73. Combining the two pro- cedures might sometimes provide better outcomes at a reduced cost. These outcomes are examined under various load circumstances.

In light of the reconfigured network structure, it is possible for the loca-tions of capacitors to undergo changes. Consequently, the paper also analyses this aspect. In the case of a 33-bus system, the reconfiguration of the network exhibits minimal impact on the placement of capacitors, with the overall level of compensation required remaining largely unchanged. The power loss is re- duced by 52% and the voltage profile is enhanced by approximately 5% as a result of combining the two methods. Now, when the load is reduced to 75% by combining the two methodologies, the required number of capaci- tors is reduced from 5 to 2, which can substantially reduce the cost burden while simultaneously improving the voltage profile. On,further load reduc- tion to 50% , after reconfiguration does not necessitate capacitor placement, as there are no buses with normalized voltage less than 1.01 (as discussed in section-III). Similarly, after network reconfiguration in a 69-bus system, the locations of capacitors change little, and the total amount of compensation required is nearly identical. By combining the two techniques, the power loss is decreased by 76%, and the voltage profile is enhanced by approximately 6%. When the burden is reduced to 75% and 50% after reconfiguration, capacitor placement is no longer necessary.

From the above analysis it clear that network reconfiguration method
is a cost efficient method for power loss reduction and yields better results when combined with optimal capacitor placement. so, a further research on network reconfiguration is underway by the author.

VIII. CONCLUSION

The paper presents an approach to place and size a capacitor on a ra- dial distribution network. The main objective is to reduce the active power losses and improve the voltage profile. For load flow calculations an efficient and simple method called backward/forward sweep load flow algorithm with the help of BIBC matrix and BCBV matrix is presented. It always guaran- tees convergence on any type of practical radial distribution network with a realistic X/R ratio. The Loss Sensitivity factor and Particle Swarm Opti- mization algorithms systematically decide the location, size, and the number of capacitors to be placed. Apart from these algorithms a detailed discussion is presented on the economical aspects of capacitor placement. An another case steady on capacitor placement under network reconfiguration at varying load conditions is also presented and analyzed the importance of combining both the method. The proposed methods are successfully applied on a 33 bus and 69 bus systems. The active power losses are reduced and there is a significant improvement in the voltage profile.

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