Optimal Capacitor Placement in Radial Distribution Systems Using Flower Pollination Algorithm

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Abstract: **Optimal capacitor placement is carried out in distribution systems for active power loss reduction and improving voltage profile. In this paper, Flower Pollination Algorithm (FPA) is be implemented for optimal allocations and sizing of capacitors in various distribution systems. First the candidate buses for installing capacitors will be suggested using Power Loss Index (PLI). Then the FPA is employed to deduce the size of capacitors and their locations from the selected buses. The objective function is designed to reduce the total cost and consequently to increase the net saving per year. The proposed algorithm will be tested on 15, 69 and 85 bus radial distribution systems. The voltage profile and reduction in active power loss are observed on the three test systems.**

Keywords: **Flower pollination algorithm, optimal capacitor placement, radial distribution systems**

I. INTRODUCTION

The topology based load flow program is used in this paper. This involves construction of two network matrices based on topology and matrix operations. Computationally this method is very efficient. This method requires less computer memory. Convergence is guaranteed for all types of practical radial network with a realistic X/R ratio. Constant power Load modeling is considered in this work. This method can also be used for composite load modeling.

In the recent past, attention has been focused in reduction of losses in distribution system which results in saving of capital investment. There are various methods to determine the interconnections between sub-stations so as to increase the reliably. In these approaches, shunt capacitors are introduced to reduce losses, improve voltage profile by providing reactive power.

There are several methods for loss reductions in distribution systems. Fixed load and varying loads have been considered uniformly distributed load for optimal capacitor placement. Many works have considered reactive power compensation that used on a simple line feeder that had no lateral tree or a simple lateral feeder without branches. All these may not be considered as realistic distribution systems.

In this paper power loss indices have been obtained for capacitor placement. This method identifies the potential nodes for capacitor placement in distribution systems. These nodes are very small fraction of total load buses. As capacitor placement is non-linear optimization problem Flower Pollination Algorithm (FPA) is used for selecting the optimal size of the capacitors.

It has been established that more than 70% of the system losses occur in the primary and secondary distribution system, while transmission lines account for less than 30% of the total losses. Therefore the distribution systems must be properly planned to ensure less losses.

FPA was introduced in 2012 by Yang. It was inspired by the pollination process of flowering plants. The main objective of a flower is basically reproduction using pollination. Flower pollination is correlating with the transfer of pollen, which is often associated with pollinators like birds and insects. Pollination appears in two main types: abiotic and biotic. Most flowering plants rely on the biotic pollination task, in which the pollen is transmitted by pollinators. The rest of pollination follows biotic form that does not demand any pollinators like grass.

Wind and diffusion both support the pollination process of such flowering plants. Pollination can be executed by two ways. They are self-pollination or cross-pollination. Self pollination is the pollination of one flower from the pollen of the same flower or other flowers of the same plant. Cross-pollination is the pollination from the pollen of a flower of other plants. The purpose of the FPA is the survival of the fittest and the optimal reproduction of plants in terms of numbers as well as the fittest. This can be treated as an optimization task of plant species. All of these factors and tasks of flower pollination generated optimal reproduction of the flowering plants. Also, FPA proves its capability to solve various problems in power system. Thus, it has been adopted in this paper to solve the problem of optimal sizing and locations of capacitors in distribution systems. In this paper, the main aim has been to implement flower pollination algorithm for optimal capacitor placement. This section introduces the load flow algorithm, optimal capacitor placement and flower pollination algorithm.

Abdelaziz et al proposed Flower Pollination Algorithm for optimal sizing of capacitors which is the basis of this work [1]. Flower pollination is an intriguing process in the natural system. Its evolutionary characteristics can be used to design new optimization techniques. Xin-She Yang proposed novel flower pollination algorithm, inspired by the pollination process of flowers [2]. The proposed method by JoyaI Isac et al is applied to 12 bus and 34 bus radial distribution system. Results show robustness of proposed method [3].

Kartikeya Sarma et al presented a new method which applies an artificial bee colony algorithm (ABC) for capacitor placement [4]. Muthukumar et al aimed to minimize the power loss in radial distribution by injecting reactive power [5]. Abdelazizl et al implemented GA for optimal location of FACTS devices [6]. Flower pollination algorithm is suggested by Almoataz et al for robust tuning of a static VAR compensator to minimise power system oscillations [7]. Prasad et al proposed methodology based on fuzzy-genetic approach [8]. A new formulation of the general capacitor placement problem taking into consideration of operational constraints at different load levels is presented by Hsiao-Dong Chiang et al [9]. D. Das et al presented a novel method for solving radial distribution networks [10]. Abul Wafa et al have used a graphical approach for developing load flow equations in matrix form to satisfy the need of distribution automation [11]. Teng and Lin developed topology based load flow for distribution systems [12]. No importance is given for initial guess solution by Das et al and other related research works [13].

Shirmohammadi et all developed a compensation-based power flow technique [14]. Stevens et al have proposed the ladder method for load flow [15]. Goswami et al and Basu have presented a direct solution method for solving radial and meshed distribution networks [16]. They have derived the fundamental equations for solving a load flow problem of a distribution network using a single-line equivalent [17]. The main limitation of this method is that no node in the network is the junction of more than three branches i.e., one coming and two outgoing branches[18]. Ghosh has proposed a method suitable for both radial and mesh configurations. It being a Z-bus based method, the sparsity structure cannot be exploited which is the greatest disadvantage [19]. Gautami and K V S Ramachandra Murthy worked on load flow solution of exponential and composite loads using topology based loadf flow [20].

II. TOPOLOGY BASED LOAD FLOW SOLUTION

2.1 Equivalent current injection: For distribution systems, the models which are based on the equivalent current injection as reported by Shirmohammadi et al., (1988), Chen et al. (1991.) and Teng and Lin (1994) are more convenient to use. At each bus 'k the complex power S_k is specified by,

$$S_i = P_i + j\,Q_i \tag{4}$$

Corresponding equivalent current injection at the k-th iteration of the solution is given by,

$$I_i^k = I_i^r(V_i^k) + jI_i^i(V_i^k) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{5}$$

V_i^k is the node voltage at the kth iteration.

I_i^k is the equivalent current injection at the k-th iteration.

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

Bus-Injection to Branch-Current matrix: (BIBC)

The power injections can be converted into equivalent current injections using the equation (4). The set of equations can be written by applying Kirchoff's current law (KCL) to the distribution network [20]. Then the branch currents can be formulated as a function of the equivalent current injections.

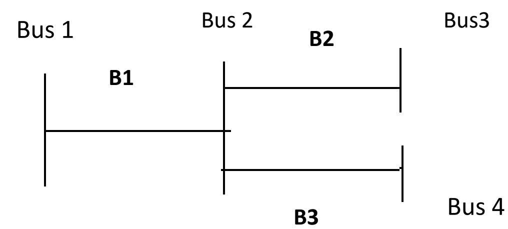

Fig. 2 Sample distribution system.

$$B_1 = I_3 + I_4$$

$$B_2 = I_3$$

$$B_3 = I_4$$

Where, I_2, I_3 and I_4 are load currents respectively at buses 2, 3 and 4

[B] = [BIBC] [I] (6)

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

The constant BIBC matrix has non-zero entries of +1 only. For a distribution system with m-branch sections and n-buses, the dimension of the BIBC is m x (n-1).

2.2 Branch-Current to Bus-Voltage Matrix :

The relation between the branch currents and bus voltages can be obtained by following equations.

$$V_2 = V_1 - B_1 Z_{12}$$

$$V_3 = V_2 - B_2 Z_{23}$$

where V_2, V_3 are the voltages at node 2 and node 3. Z_{23} is the impedance between 2 and 3 nodes. The above equations can also be written as ,

$$V_1 - V_2 = Z_{12} B_1$$

$$V_1 - V_3 = Z_{12} B_1 + B_2 Z_{23}.$$

In general, $[V_1] - [V_k] = [Z]\,[B]$ where Z matrix will have elements in the transposed matrix of BIBC matrix. V_1 matrix contains all elements equal to 1.0pu.

$$[\Delta \boldsymbol{V}] = [\boldsymbol{BCBV}][\boldsymbol{B}] \tag{7}$$

That can be written as,

$$\begin{bmatrix} \boldsymbol{V_1} \\ \boldsymbol{V_1} \\ \boldsymbol{V_1} \end{bmatrix} - \begin{bmatrix} \boldsymbol{V_2} \\ \boldsymbol{V_3} \\ \boldsymbol{V_4} \end{bmatrix} = \begin{bmatrix} \boldsymbol{Z_{12}} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{Z_{12}} & \boldsymbol{Z_{23}} & \boldsymbol{0} \\ \boldsymbol{Z_{12}} & \boldsymbol{0} & \boldsymbol{Z_{24}} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} \quad \textbf{(8)}$$

$$[\Delta \mathbf{V}] = [\mathbf{BCBV}][\mathbf{BIBC}][\mathbf{I}] \quad \textbf{(9)}$$

That can be written as,

$$\begin{bmatrix} \boldsymbol{V_1} \\ \boldsymbol{V_1} \\ \boldsymbol{V_1} \end{bmatrix} - \begin{bmatrix} \boldsymbol{V_2} \\ \boldsymbol{V_3} \\ \boldsymbol{V_4} \end{bmatrix} = \begin{bmatrix} \boldsymbol{Z_{12}} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{Z_{12}} & \boldsymbol{Z_{23}} & \boldsymbol{0} \\ \boldsymbol{Z_{12}} & \boldsymbol{0} & \boldsymbol{Z_{24}} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad \textbf{(10)}$$

As already presented in the previous sections, two important steps involved in this algorithm are, **[B] = [BIBC] [I]** : matrix [I] is current injections. Branch currents expressed in terms of bus current injections.

$[\Delta \boldsymbol{V}] = [\boldsymbol{BCBV}][\boldsymbol{B}]$: Voltage deviations expressed in terms of branch currents.

$I_i^k = I_i^r(V_i^k) + jI_i^i(V_i^k) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^*$ Conversion of Power injections into current injections. From the above two equations, $[\Delta \boldsymbol{V}] = [\boldsymbol{BCBV}][\boldsymbol{BIBC}][\boldsymbol{I}]$

III. IMPLEMENTATION OF FLOWER POLLINATION ALGORITHM

Optimal Location for placement of capacitor is obtained by sensitivity analysis. Optimal sizes of capacitors is obtained by using local flower pollination algorithm for 15 Bus, 33 Bus and 69 Bus Systems. Sample program is presented in the Appendix 5. Data for the loadflow for 15 Bus, 33 Bus, 69 Bus and 85 Bus Systems is presented in Appendix 1 to Appendix 4 respectively.

3.1. Objective Function

The Objective function in the capacitor placement problem comprises of the minimization of the total real power losses in the given Radial Distribution System. The Objective function is given by:

$$Min\ P_{loss} = R[k]\left[\frac{P[k]^2 + Q[k]^2}{V[n]^2}\right] \quad (1)$$

where

P[k], Q[k] =Real and reactive power in the Branch k

V[n] =Voltage at node n

R[k] =Resistance of the branch k

3.2 Power Loss Indices:

Using the load flow program power loss reduction of the system is obtained when reactive power injections are completely compensated at every node taking one node at a time. The loss reductions are then linearly normalized into [0 1] range with largest loss reduction having a value of 1 and smallest one having a value of 0. This procedure is obtained to every node of the distribution system under consideration. Loss reduction at a particular node is obtained by subtracting active power loss obtained from load flow with Q completely compensated at that node from power loss without any compensation provided. PLI for the nth node is obtained by,

$$PLI_{\,(\mathrm{n})} = \frac{\text{Loss reduction}_{\,(\mathrm{n})} - \text{Loss reduction}_{\,\min}}{\text{Loss reduction}_{\,\max} - \text{Loss reduction}_{\,\min}} \quad (2)$$

3.3 Flower Pollination algorithm

For the local pollination, both Step 2 and Step 3 can be symbolized as

$$X_i^{t+1} = X_i^t + \varepsilon\left(X_j^t - X_k^t\right)$$

where X_i^t and X_k^t are pollen from several flowers of the same plant species simulating the flower constancy in a limited neighbourhood. For a local random walk, X_j^t and X_k^t hail from the same species then ε is pulled from a uniform distribution as [0, 1]. In principle, flower pollination actions can take place at all levels, both local and global. In fact neighbouring flower positions are pollinated by local flower pollen than those far away. In order to imitate this, one can utilize a switch probability p effectively to convert between general global pollination to intense local pollination. Initially, one can employ a value of p = 0.5.

MATLAB implementation of flower pollination algorithm :

```
for t=1:50
  poly(t,1)= poly(t,1)+rand()*(pbest(1)-poly(t,1));
  poly(t,2)= poly(t,2)+rand()*(pbest(2)-poly(t,2));
  poly(t,3)= poly(t,3)+rand()*(pbest(3)-poly(t,3));
  end
```

3.4 Analysis on 15 Bus System

On 15 Bus systems, three optimal locations were identified using power loss index method. They are Bus No. 6, 11, 15. Optimal sizes were obtained using flower pollination algorithm. The values of capacitors are presented in the Table 1. On 15 Bus system, loss without compensation is 61.80 kW and after compensation, active power loss is 31.7 kW. Voltage profile before and after are presented in Table 2. Fig. 1 shows the single line diagram of 15 Bus systems. Fig.2 shows the voltages before and after compensation.

Table 1: Optimal locations and sizes of capacitors on 15 Bus system

Optimal Location (Bus No.)	Optimal Size
6	347
11	354
15	295

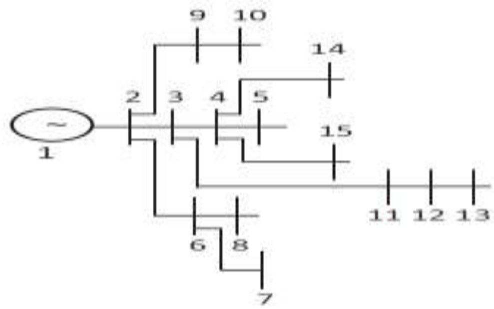

Fig. 1. 15 Bus system

Table 2 : Voltages on 15 Bus System before and after compensation

Bus No	before compensation	after compensation
2	0.9713	0.9798
3	0.9567	0.9696
4	0.9509	0.9655
5	0.9499	0.9646
6	0.9581	0.971
7	0.9559	0.969
8	0.9568	0.9698
9	0.9679	0.9766
10	0.9669	0.9756
11	0.9499	0.9657
12	0.9457	0.9621
13	0.9444	0.9609
14	0.9486	0.9634
15	0.9484	0.9645

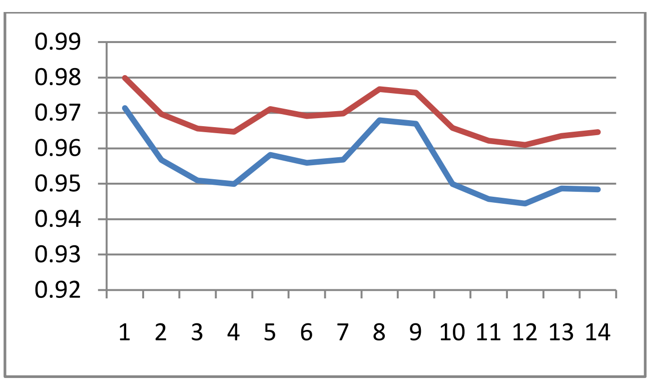

Fig. 2 Voltage profile before and after capacitor placement on 15 Bus system

3.5 Analysis on 33 Bus System

On 33 Bus system, three optimal locations were identified using power loss index method. They are Bus No. 32, 30, 14. Optimal sizes were obtained using flower pollination algorithm. The values of capacitors are presented in the Table 3. On 33 Bus system, loss without compensation is 210.74 kW. and after compensation, active power loss is 149.81 kW. Voltage profile before and after are presented in Table 4. Fig. 3 shows the voltages before and after compensation.

Table 3 : Optimal locations and sizes of capacitors on 33 Bus system

Optimal Location (Bus No.)	Optimal Size (kVAr)
32	740
30	420
14	140

Table 5 : Optimal locations and sizes of capacitors on 69 Bus system

Optimal Location (Bus No.)	Optimal Size (kVAr)
61	238
21	240

Table 4. Voltages on 33 Bus systems before and after compensation

Bus No.	Before compensation (pu)	After compensation (pu)
2	0.997	0.9974
3	0.9828	0.9853
4	0.9752	0.9791
5	0.9677	0.9731
6	0.9496	0.9584
7	0.9452	0.9552
8	0.9314	0.9422
9	0.925	0.9363
10	0.919	0.9308
11	0.9182	0.93
12	0.9168	0.9287
13	0.9105	0.923
14	0.9079	0.9206
15	0.9064	0.9191
16	0.9049	0.9177
17	0.9026	0.9156
18	0.9019	0.915
19	0.9965	0.9969
20	0.9927	0.9932
21	0.9919	0.9925
22	0.9912	0.9918
23	0.9792	0.9818
24	0.9724	0.9753

25	0.969	0.972
26	0.9476	0.9571
27	0.9449	0.9554
28	0.9341	0.9477
29	0.9263	0.9423
30	0.9224	0.9401
31	0.918	0.9352
32	0.917	0.9338
33	0.9167	0.9336

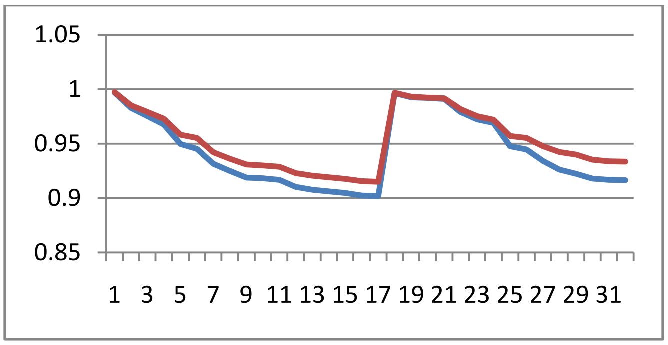

Fig. 3. Voltage profile before and after capacitor placement on 33 Bus system

3.6 Analysis on 69 Bus System

On 69 Bus system, three optimal locations were identified using power loss index method. They are Bus No. 61, 21. Optimal sizes were obtained using flower pollination algorithm. The values of capacitors are presented in the Table 5. On 69 Bus systems, loss without compensation is 225 kW and after compensation, active power loss is 147.1 kW. Voltage profile before and after are presented in Table 6. Fig. 4 shows the single line diagram of 69 Bus systems. Fig. 5 shows the voltages before and after compensation.

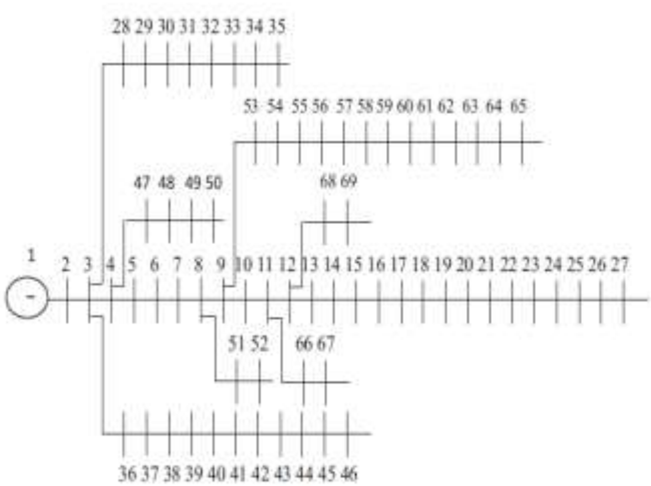

Fig. 4. Single line diagram 69 Bus system

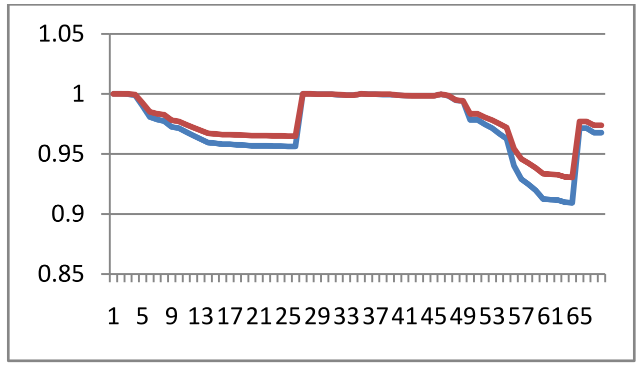

Fig. 5. Voltage profile before and after capacitor placement on 69 Bus systems

IV. CONCLUSIONS

In this paper, Flower Pollination Algorithm (FPA) is implemented for optimal allocations and sizing of capacitors in various distribution systems. The candidate buses for installing capacitors are identified using Power Loss Index (PLI). Then the local FPA is employed to deduce the size of capacitors and their locations from the elected buses. The objective function is designed to reduce the total active power loss. The proposed algorithm is tested on 15, 33 and 69 bus radial distribution systems.

On 15 Bus systems, three optimal locations were identified using power loss index method. They are Bus No. 6, 11, 15. Optimal sizes were obtained using flower pollination algorithm. On 15 Bus system, loss with out compensation is 61.80 kW and after compensation, active power loss is 31.7 kW.

On 33 Bus system, three optimal locations were identified using power loss index method. They are Bus No. 32, 30, 14. Optimal sizes were obtained using flower pollination algorithm. On 33 Bus systems, loss with out compensation is 210.74 kW. and after compensation, active power loss is 149.81 kW.

On 69 Bus system, three optimal locations were identified using power loss index method. They are Bus No. 61, 21. Optimal sizes were obtained using flower pollination algorithm. On 69 Bus system, loss without compensation is 225 kW and after compensation, active power loss is 147.1 kW.

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