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Capacitive Compensation on Three Phase Unbalanced Radial Distribution System Using Index Vector Method

K.V.S. Ramachandra Murthy[1], M. Ramalinga Raju[2]
[1]G. V. P. College of Engineering, Visakhapatnam,
[2]JNTUK College of Engineering, Kakinada, India

ABSTRACT

Shunt capacitive compensation is one of the techniques used to improve the voltage profile of the system and reduce active power loss. In this paper Index Vector method is implemented for optimal capacitor placement on three phase unbalanced radial distribution system. Mutual inductance between the phases is taken into consideration for obtaining load flow solution of unbalanced distribution system. Three phase load flow solution for 25 bus system is obtained by using topology based method. Proposed technique is compared with alternate methods. In the second method, potential locations are obtained by sensitivity analysis (Loss Sensitivity Factors, LSF) and sizing is done by Particle Swarm Optimization (PSO). It is concluded that index vector method is superior to LSF – PSO technique.

Keywords: *Index Vector Method, Capacitive compensation, Radial distribution systems*

1. INTRODUCTION

In recent years, considerable attention has been focused in planning of a distribution system, to reduce the power and energy losses, to reduce the capital investment involved and to provide better quality supply to consumers. Improved modeling techniques and certain optimization and programming approaches has been presented to determine the best location, and suitable interconnections between sub-stations so as to meet the increasing demands more reliably and economically. In these approaches, shunt capacitors are introduced to reduce losses and to provide reactive power compensation.

Capacitors have been very commonly used to provide reactive power compensation in distribution systems. They are provided to minimize power and energy losses and to maintain the voltages within the acceptable limits. The amount of compensation provided is very much linked to the placement of capacitors, which is essentially determination of location and size of capacitors in radial distribution systems.

Index vector method is adopted [1] for capacitor placement by M.Sydulu *et al*. Sensitivity analysis and PSO based capacitor placement was done by K. Prakash *et al*. [2]. In this paper a Network Topology based Three Phase load flow for distribution Systems method used [3]. Load variation has not been considered by Sochuliavoka [4] for capacitor placement. Grainger used the equal area criterion for selecting the sites of fixed capacitors [5]. Carpinelli and Chiang implemented nonlinear programming method [7]. Wang implemented integer programming method [8].Investigation of capacitor placement for unbalanced distribution networks was done by Carpinelli, Wang and Chiang et al. [7–9]. However, unbalance in the 3 phases has not been considered in most of the previous works done by Hooshmand, Souza, and Mendes etc. [12-14]. On the other hand, the loss reduction has been accomplished only by using the fixed capacitors by Mendes [14].

2. DISTRIBUTION LOAD FLOW SOLUTION

Three phase line model is given by a 3X3 matrix as,

$$Z_{abcn} = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \quad (1)$$

The relations between the bus voltages and branch currents in Fig. 1 can be expressed as

$$\begin{bmatrix} V_A \\ V_B \\ V_V \end{bmatrix} - \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \begin{bmatrix} I_{Aa} \\ I_{Bb} \\ I_{Cc} \end{bmatrix} \quad (2)$$

For any phase which fails to present, the corresponding row and column in this matrix will contain null entries.

2.1 Formulation for the Model

2.1.1 Equivalent Current Injection

For distribution systems, the models which are based on the equivalent current injection as reported by J.H Teng and Lin. At each bus 'i' the complex power S_k is specified by,

$$S_i = P_i + j\,Q_i \tag{3}$$

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

$$I_i^k = I_i^r\left(V_i^k\right) + jI_i^i\left(V_i^k\right) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{4}$$

V_i^k is the node voltage at the k^{th} 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.

2.1.2 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 Kirchhoff's current law (KCL) to the distribution network. Then the branch currents can be formulated as a function of the equivalent current injections.

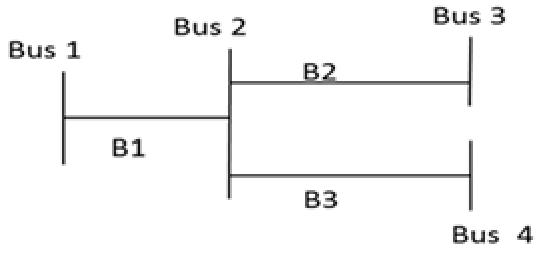

Fig. 1 Sample distribution system.

$$B_1 = I_2 + I_3 + I_4$$

$$B_2 = I_3 \quad ; \quad B_3 = I_4$$

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

$$[B] = [BIBC]\,[I] \tag{5}$$

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

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).

2.1.3 Branch - Current to Bus - Voltage Matrix (BCBV)

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

$$V_2 = V_1 - B_1 Z_{12} \quad ; V3 = V_2 - B_2 Z_{23}$$

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.

$$[\Delta V] = [BCBV][B] \tag{6}$$

That can be written as,

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 \\ Z_{12} & Z_{23} & 0 \\ Z_{12} & 0 & Z_{24} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} \tag{7}$$

$$[\Delta V] = [BCBV][BIBC][I] \tag{8}$$

That can be written as,

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 \\ Z_{12} & Z_{23} & 0 \\ Z_{12} & 0 & Z_{24} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{9}$$

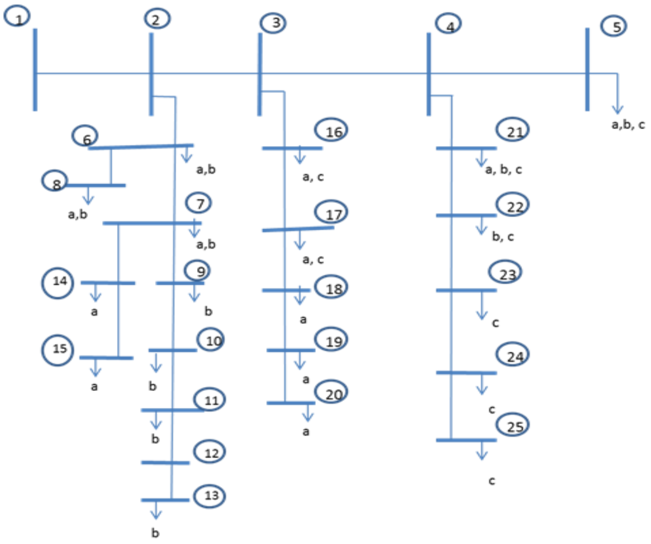

Fig. 2. Single line diagram of the 25 Bus system

3. INDEX VECTOR METHOD

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:

$$Min\ P_{loss} = R[k][\frac{P[k]^2+Q[k]^2}{V[n]^2}] \tag{10}$$

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

Index Vector based method is the conventional approach for optimal capacitor placement. Index Vector is formulated by running the base case load flow on a given radial distribution network, and calculating reactive component of current in the branches and reactive power load concentration at each node. Based on the elements of the Index Vector, this method identifies a sequence of nodes to be compensated. The sequence of priority of the nodes is mainly determined by the Index-Vector.

The Index-Vector for bus n is given by

$$Index[n] = \frac{1}{{V_n}^2} + \frac{I_q[k]}{I_p[k]} + \frac{Q_{eff}\,[n]}{totalQ} \tag{11}$$

where

Index[n] =”Index” for nth bus
V[n] = Voltage at nth bus
$I_q[k]$ = Imaginary component of current in kth branch
$I_p[k]$ = Real component of current in kth branch
Qeff[n] = Effective load at nth bus
TotalQ = Total reactive load of the given Distribution system
Value of capacitor bank to be placed is given by

$$Q_c = Index[n] * Q_{eff}[n]$$

After formulating the Index Vector multiply the index value by the load reactive power at that bus to estimate the size of the capacitor to be placed. Thus, the potential location and size of the capacitor to be placed are obtained directly. Arrange the Index vector in descending order so that highest priority bus will come first and the lowest priority bus will come at end. Now place the capacitor at the first potential location and run the load flow and estimate the losses. Then assume capacitors at first two potential locations and perform load flow again evaluate the corresponding losses. It may be observed that the loss will reduce. Repeat this with estimated capacitors at first “n” busses till losses reduce to minimum and for the first (n+1) potential locations the loss start increasing Then the estimated capacitors at first n potential locations will give optimal location and size for the given radial distribution system.

In this thesis, Index Vector method is used to find out potential locations and sizes in 25 bus unbalanced radial distribution system. As the three phase unbalanced system cannot be represented by single line diagram, Index vector method has to find optimal locations and sizes independently for each phase.

4. SENSITIVITY ANALYSIS AND PARTICLE SWARM OPTIMIZATION

4.1 Sensitivity Analysis

Loss sensitivity factors are calculated for determining the candidate nodes for placement of capacitors. Estimation of these sensitive nodes helps in reducing the search space.

$$\frac{\partial P_{loss}}{\partial Q_2} = \frac{2*Q_2*R[j]}{{V_2}^2} \tag{12}$$

Loss sensitivity factors, $\frac{\partial P_{loss}}{\partial Q_2}$ are calculated from the information obtained by load flow results, and values are arranged in descending order for all the lines. Normalized voltage magnitudes are calculated for all the buses. by the following formula.

$$Norm\ [i] = \frac{V[i]}{0.95}$$

Buses, whose normalized values are less than 1.01 are considered as candidate nodes requiring compensation. Loss Sensitivity factors decide the sequence of in which buses are to be considered for compensation placement and the normalized values of voltages decide, whether a particular bus needs compensation or not.

4.2 Particle Swarm Optimization

PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In every iteration, each particle is updated by following two "*best*" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called *pbest*. Another "*best*" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called *gbest*. When a particle takes part of the population as its topological neighbors, the best value is a local best and is called *lbest*. After finding the two best values, the particle updates its velocity and positions with following equation (13) and (14).

$$v[] = w*v[]+c_1*rand()*(pbest[] - present[])+c_2*rand()*(gbest[]- present[]) \quad (13)$$

$$present[] = present[] + v[] \quad (14)$$

where, *v*[] is the particle velocity, *persent*[] is the current particle (solution). *pbest*[] and *gbest*[] are defined as stated before. *rand* ( ) is a random number between (0,1). c_1, c_2 are learning factors. Usually $c_1= c_2 = 2$.

Dimension of particles: It is determined by the problem to be optimized.

Range of particles: It is also determined by the problem to be optimized, you can specify different ranges for different dimension of particles.

Vmax: it determines the maximum change one particle can take during one iteration. Usually we set the range of the particle as the V_{max} for example, the particle (x_1, x_2, x_3). x_1 belongs [*-10, 10*], then $V_{max} = 20$.

Learning factors*:* c_1 and c_2 usually equal to 2. However, other settings were also used in different papers. But usually c_1 equals to c_2 and ranges from [0, 4].

The stop condition: the maximum number of iterations the PSO executes and the minimum error requirement or the maximum number of iterations depends on the problem to be optimized.

Later, in order to improve PSO performance, a linear decreasing weight (LDW) parameter called inertia weight is developed and introduced by Shi and Eberhart.

where, *w* is the inertia weight. A large inertia weight facilitates a more powerful global search while a small inertia weight facilitates a more powerful local search. By linearly decreasing the inertia weight from a relatively large value to a small value through the course of the PSO run, the PSO tends to have more global search ability at the beginning of the run while having more local search ability near the end of the run

4.3 Evaluation of Fitness Function

$$Fit[i] = \frac{k_1}{(k_2+k_3*\frac{tqloss}{tota\ lQ})} \quad (15)$$

$$k_1 = 10, \quad k_2 = 1, \quad k_3 = 0.1$$

Population consists of 20 strings of capacitors, in each string 8 capacitor values are randomly chosen

5. RESULTS

Data for the 25 bus, 3 phase unbalanced system is shown in Table 6 in Appendix. An impedance matrix for different types of conductors is presented in Table 1. Total loads on various buses, phase wise shown in Table 6 in Appendix.

Load flow solution obtained by topology method proposed by J.H. Teng. Voltages after compensation by PSO are presented bus wise and phase wise in Table 5, as all the phases are not present on all the buses. Load flow takes four iterations to converge. Buses corresponding to various phases of different nodes are numbered from 1 to 41 for obtaining the voltages from the given algorithm. Optimal locations for the placement of capacitors is decided based on the value of the loss sensitivity factor of that node and the magnitude of the voltage at that node. Phase wise voltages without compensation are presented in Table 2. Table 7 presents the bus numbers, corresponding locations and their sizes obtained by index vector method.

Table 1. Impedance matrices for different types of conductors

Type	Impedance in ohms
1	0.3687+0.685i0.017+0.1515i 0.017+0.1515i 0.017+0.1515i 0.3687+0.685i 0.017+0.1515i 0.017+0.1515i 0.017+0.1515i 0.3687+0.685i
2 (ab- phases)	1+1i 0+0.25i 0+0.25i 1+1i
3 (bc- phases)	1+1i 0+0.25i 0+0.25i 1+1i
4 (ac- phases)	1+1i 0+0.25i 0+0.25i 1+1i
5 (a- only)	1.92+1.42i
6 (c- only)	1.92+1.42i
7 (b- only)	1.92+1.42i

Table 2. Bus wise phase wise voltages on 3 phases, before compensation.

Bus No.	a-phase	b-phase	c-phase
1	1	1	1
2	0.9896	0.9894	0.9894
3	0.9835	0.9854	0.9829
4	0.9813	0.9823	0.9783
5	0.9806	0.9816	0.9776
6	0.9787	0.9781	
7	0.9709	0.9699	
8	0.9766	0.9764	
9	0.9689	0.9637	
10		0.9553	
11		0.9488	
12		0.9455	
13		**0.9439**	
14	0.9638		
15	0.9585		
16	0.977		0.9796
17	0.9714		0.9776
18	0.9656		
19	0.9613		
20	**0.959**		
21	0.9798	0.98	0.9744
22		0.9773	0.9691
23			0.9627
24			0.9577
25			**0.9545**

5.1 Optimal Capacitor Placement by Index Vector Method

Using Index Vector method, four locations were identified on A Phase, five locations were identified on B Phase and Two locations were identified on 'C' phase. According to the algorithm, we go on placing the capacitor at appropriate location and run the load flow. We repeat the process till loss is decreased. The process is stopped as loss starts increasing.

5.2 Location for Capacitor Placement

Loss sensitivity factors are calculated for determining the candidate nodes for placement of capacitors. Estimation of these sensitive nodes helps in reducing the search space.

The sensitivity analysis is implemented on 25 bus unbalanced system. Those buses, whose voltages are less than 1.01 are chosen for compensation**.** Eight capacitor locations are found to be suitable for capacitor placement. The locations are 10b, 11b, 12b, 13b, 15a, 20a, 24c, 25c. So, optimal number of capacitors is 8.The value is given by the Particle Swarm Optimization Technique. Before compensation the active power loss is found to be: 40.23 kW**.**

Potential node numbers and corresponding locations are given in the table 3. Placement of capacitors by Particle Swarm Optimization shown in Table 4. Bus wise, phase wise voltages on 3 phases, after compensation by particle swarm optimization are presented in Table 5. Table 6 presents

Table 3. Potential locations for placement of capacitors using sensitivity analysis

sl.no	busno	actual location
1	21	10b
2	22	11b
3	26	15a
4	40	24c
5	23	12b
6	41	25c
7	33	20a
8	24	13b

Table 4. Optimal sizes of capacitors using PSO

Location	Values of the capacitors
10b	1.2936
11b	0.3062
12b	0.858

13b	0.0412
15a	1.6838
20a	1.5288
24c	1.7388
25c	0.0181
Total	7.4685
Loss after compensation 28.58 kW	

Table 5. Phase wise voltages after compensation by particle swarm optimization

	After compensation		
Bus No.	A-phase	B -phase	C - phase
1	1	1	1
2	0.9909	0.9912	0.9915
3	0.9858	0.9875	0.986
4	0.9838	0.9846	0.9824
5	0.9831	0.9839	0.9817
6	0.9818	0.9824	
7	0.9757	0.9764	
8	0.9797	0.9808	
9	0.9736	0.972	
10		0.9664	
11		0.9613	
12		0.9589	
13		**0.9574**	
14	0.9711		
15	0.968		
16	0.9809		0.9828
17	0.9768		0.9809
18	0.9735		
19	0.9712		
20	**0.9704**		
21	0.9825	0.9824	0.9794
22		0.9797	0.9757
23			0.9718
24			0.9689
25			**0.9658**

6. CONCLUSION

In this paper, 25 bus 3-phase radial distribution system with unbalanced loading is considered for analysis. Capacitor placement is done by two methods. In the First method, Index Vector used for identifying locations and size. Total 11 potential locations were identified in the first method. The minimum loss obtained is 26.90 kW whereas without compensation, the active power loss is found to be 40.23 kW.

To determine the effectiveness of this method, capacitor placement is also done by Sensitivity Analysis & PSO method. The sensitivity analysis method is used to determine suitable capacitor locations. Particle Swarm Optimization technique is used for finding the optimal values of the fixed capacitors in the locations given by Sensitivity Analysis. Eight capacitor locations are identified in the 25 bus system using the sensitivity analysis. Without compensation, the active power loss is found to be 40.23 kW and after compensation, it is found to be 28.58 kW. A considerable reduction in active power loss and improvement in voltage profile are observed after compensation in both the methods. But, loss reduction is more in Index Vector Method. It is concluded that index vector method is effective method compared to sensitivity analysis & PSO technique for capacitor placement on unbalanced distribution system.

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[15] K. V. S. Ramachandra Murthy is working as Associate Professor, G.V.P. College of Engineering, Visakhapatnam. Mail: murthykvs2000@yahoo.co.in

[16] M. Ramalinga Raju is working as Professor and Head of the Department in the Department of E.E.E., University college of Engg., J.N.T.U. Kakinada, India. Mail : rajumanyala@yahoo.com

APPENDIX

Table 6. 25 bus system data

Line no.	From bus	To bus	Type of the conductor	Load on receiving end bus		
				a-phase	b-phase	c-phase
1	1	2	1	0	0	0
2	2	3	1	0	0	0
3	3	4	1	0	0	0
4	4	5	1	40+30i	40+30i	40+30i
5	2	6	2	40+30i	60+45i	0
6	6	7	2	50+35i	50+35i	0
7	6	8	2	80+60i	60+45i	0
8	7	9	2	50+35i	40+30i	0
9	9	10	7	0	50+35i	0
10	10	11	7	0	80+60i	0
11	11	12	7	0	40+30i	0
12	11	13	7	0	40+30i	0
13	7	14	5	50+35i	0	0
14	14	15	5	133+100i	0	0
15	3	16	4	40+30i	0	50+35i
16	16	17	4	80+60i	0	50+35i
17	17	18	5	40+30i	0	0
18	18	19	5	50+35i	0	0
19	19	20	5	60+45i	0	0
20	4	21	1	40+30i	40+30i	40+30i
21	21	22	3	0	80+60i	50+35i
22	22	23	6	0	0	40+30i
23	23	24	6	0	0	50+35i
24	24	25	6	0	0	80+60i

Table 7. Compensation by index vector method

S. No.	**Bus No.**	**Locations chosen**	**Value of the capacitors**	**Loss after placing**
				Note : before –40.23kw
1A	17	15a	1.9187	37.27
2 A	20	17a	1.1593	35.71
3 A	8	8a	1.1073	35.25
4 A	24	20a	0.8427	34.35
5 A	6	7a	0.6811	34.42 (stop)
				Note : before –40.23kw
1B	13	11b	1.1729	36.71
2 B	28	22b	1.1064	36.13
3 B	05	6b	0.9119	35.59
4 B	09	8b	0.8254	35.36
5 B	07	7b	0.6892	35.25
6 B	12	10b	0.6844	35.36 (stop)
				Note : before –40.23kw
1C	32	25c	1.1368	37.74
2 C	29	22c	0.6712	37.28
3 C	31	24c	0.6635	37.47 (stop)
Minimum loss that can be obtained is **26.90 kW** with capacitors on all phases.				