A Solution to Capacitor Placement Problem for the Minimization of Power Loss in Distribution Systems

Sarfaraz Nawaz, Ankush Tandon
Department of Electrical Engineering
Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur
Email- eesarfaraz1983@rediffmail.com

Abstract: **This paper investigates an approach that determines the desired locations of capacitors in a radial distribution system to improve voltage profile and reduce active power losses. Capacitor placements are done by power loss index and loss sensitivity factors. Loss Sensitivity Factors provide relevant information about the sequence of potential nodes for capacitor placement. In this paper load flow of pre-compensated distribution system is carried out. On the basis of load flow solutions, loss sensitivity factors (LSF) and power loss indices (PLI) indicating the potential locations for compensation are computed. From LSF and PLI, the candidate number of buses is identified for the placement of the capacitor. The proposed approach to find the locations of the capacitor placement by two different methods is tested on IEEE 34 & 69 bus radial distribution system and the net benefits were compared by utilizing these methods.**

Keywords: **Capacitor Placement, Radial Distribution Systems, Loss Sensitivity Factors and Power Loss Index.**

1. INTRODUCTION

A distribution system is an interface between the bulk power system and the consumers. As distribution systems are growing larger and being extended so far leading to higher system losses and poor voltage regulation. The need for an efficient and effective distribution system has therefore become more important. In distribution systems, the voltages at buses reduce when moved away from the substation and also the losses are high. The reason for decrease in voltage and high losses is the insufficient amount of reactive power which can be provided by the shunt capacitors. In this regard, capacitor banks are added on radial distribution system for improving power factor, loss reduction and voltage profile improvement. The literature on distribution system is very much diversified; a brief review on the subject of capacitor placement in distribution systems is presented [1]. In the past, considerable efforts were put into the capacitor placement problem. The early approaches to this problem include (i) Analytical Methods (ii) Numerical Programming Methods which uses iterative techniques to maximize and minimize an objective function (iii) Heuristics Techniques and (iv) Artificial Intelligence Methods which include genetic algorithm, artificial neural network, simulated annealing. The early *analytical methods* for capacitor placement were developed by Neagle and Samson [2] .They considered loss reduction by one capacitor bank placed along the feeder by considering uniformly distributed loads. Grainger and Lee [3] considered the problem as the non linear programming problem. They have optimized the net monetary savings associated with the reduction of power losses, through placement of fixed and switched shunt capacitors on primary distribution feeders.

Numerical Programming methods are iterative techniques and are used to maximize or minimize an objective function. Duran [4] considered the problem as dynamic programming problem and utilized a multistage maximizing process. He used discrete capacitors for the feeder with many sections of different wire sizes and concentrated loads. Baran and Wu [5] proposed a mixed Integer non linear programming method using decomposition technique. Using the same technique he determined the optimal size of capacitors placed on the nodes of a radial distribution system and minimized the power losses for a given load. Ponnavaikko and Rao [6] used a local optimization technique called the method of local variations by considering load growth, system capacity release and voltage rise at light load condition.

Heuristic Methods are developed through experience and judgment. The advantage of heuristic techniques is to decrease the exhaustive search space. Salam *et.al* [7] proposed a heuristic approach with varying load to reduce system losses by identifying sensitive nodes at which capacitors should be placed. Hamada *et al.* [8] introduced a new strategy for capacitor allocation handling the reduction in the section losses by adding a new voltage violation constraint.

Artificial methods include genetic algorithms, artificial neural network, simulation algorithm, fuzzy, particle swarm optimization (PSO), ant algorithm, Tabu search. Sattianadan et al. [9] have used PSO method for solving the problem of capacitor placement in radial distribution network. H. Kim and S.K Yu [10] have used genetic algorithm for obtaining the optimum values of shunt capacitor bank. They have treated the capacitors as constant reactive power loads. Anil Swarnkar [11] proposed Genetic Algorithms for finding the optimal number, location and sizing of fixed and switched shunt capacitors in radial distribution systems. By using this novel approach the objective cost function has been formulated to maximize the net annual savings by minimizing real power loss and optimizing the cost of annual investments on shunt capacitors. Huang *et al.* [12] introduced a Tabu Search-based method to solve the capacitor placement problem. A comparison has been made with simulated annealing method. Chiang *et al.* [13, 14] have used the method of simulated annealing to obtain the global optimum values of shunt capacitors for radial distribution networks. This methodology

Proposed here is used to determine the locations, the types and sizes of capacitors to be installed. Sirjani & Sharif [15] proposed Harmony search Algorithm for the optimal capacitor placement (OCP) problem. Rao & Narasimham [16] proposed the plant growth simulation algorithm to solve the OCP problem.

In this paper, capacitor placement is done by loss sensitivity factors and power loss index. High potential buses for capacitor placement are identified by the observations of power loss indices (PLI) and/or loss sensitivity factors (LSF) with weak voltage buses. These methods for capacitor placement were tested on IEEE 34 and 69 bus radial distribution systems. Both the systems are implemented on ETAP 7.0(Electrical Transient Analyzer Program).

The work carried out in this paper has been summarized in five sections. Section 1 presents the introductory details and summary of work carried out by various researchers. Section 2 gives the problem description and formulation. Section 3 describes power loss indices (PLI) and loss sensitivity factor (LSF) methods to identify the candidate buses for shunt capacitor placement. Section 4 presents the detailed simulation and the results pertaining to various test cases. The conclusions and the scope of further work are mentioned in section 5.

2. PROBLEM FORMULATION

Reactive power addition can be beneficial only in case if it is correctly applied. Correct application means choosing the correct position and size of reactive power support. It is not possible to achieve zero losses in a power system, but it is possible to keep them at minimum. The distribution network is usually compensated by either series or shunt capacitors. Series capacitors increase the maximum power limit while shunt capacitors have several benefits . Some of the benefits are: (i) reduce real and reactive power loss in the system (ii) increase voltage level at the load and power factor of source (iii) improve voltage regulation (iv) improve stability (v) improve power factor of the system (vi) decrease kVA loading on source generators etc. The real power loss in the network is given by

$$P_{Loss} = \sum_{i=1}^{n} |I_i|^2 \, R_i$$

Keeping the above objectives in mind the objective function is framed which is given by:

Minimize f= min (P_{Loss}) (1)

Subjected to $V_{min} \leq V_i \leq V_{max}$ (2)

Where P_{loss} is total real power loss of the system; $|I_i|$ is the magnitude of current in branch *i*;

V_{min} , V_{max} are bus minimum and maximum voltage limits respectively;

3. CANDIDATE BUS SELECTION

The candidate bus selection is done by two well known methods namely power loss indices (PLI) and loss sensitivity factor (LSF) [1].The buses having low voltage and high losses are most suitable for the placement of the capacitors in distribution system.

A. Power Loss Indices (PLI)

First, load flow solution for the original system is required to obtain the active power losses in the system without any compensation. Again, load flow solutions are required to obtain the power loss reduction by compensating the total reactive load at every bus of the distribution system taking one bus at a time except bus number 1 (slack bus). The loss reductions are then, linearly normalized into a [0, 1] range with the largest loss reduction having a value of 1 and the smallest one having a value of 0. PLI value for pth node can be obtained using the following equation:

$$\mathrm{PLI(p)} = \frac{\mathrm{Loss\ reduction(p)} - \mathrm{Loss\ reduction_{min}}}{\mathrm{Loss\ reduction}_{\ \mathrm{max}} - \mathrm{Loss\ reduction_{min}}}$$

B. Loss Sensitivity Factor (LSF)

To identify the location for capacitor placement in distribution system loss sensitivity factors have been used. The loss sensitivity factor is able to identify which bus will have the biggest loss reduction when a capacitor is placed. Consider a radial distribution line with an impedance R+jX and a load of $P_{eff}+jQ_{eff}$ connected between 'i' & 'j' buses as given in figure 3.1.

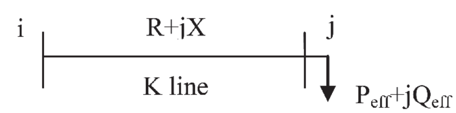

Fig. 3.1: A sample distribution line with load

The Loss Sensitivity Factors can be calculated as:

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

4. TEST RESULTS

In order to test the effectiveness and performance of proposed methods, it has been applied to IEEE 34 and 69 node radial test systems. Bus data and line data for 34 & 69-bus radial distribution are obtained from [5, 17]. Loss Sensitivity Factor and Power loss indices have been used to find out the potential buses for capacitor placement.

For simulation purpose, the following parameters have been used [1]:

1. Energy rate = 0.06 US $/kWh.
2. Capacitor installation cost 'C_i' = US $1000.
3. Capacitor rate 'C_v' = US $3.0/kVAr.
4. Yearly hours=8760

A. 69 Bus system

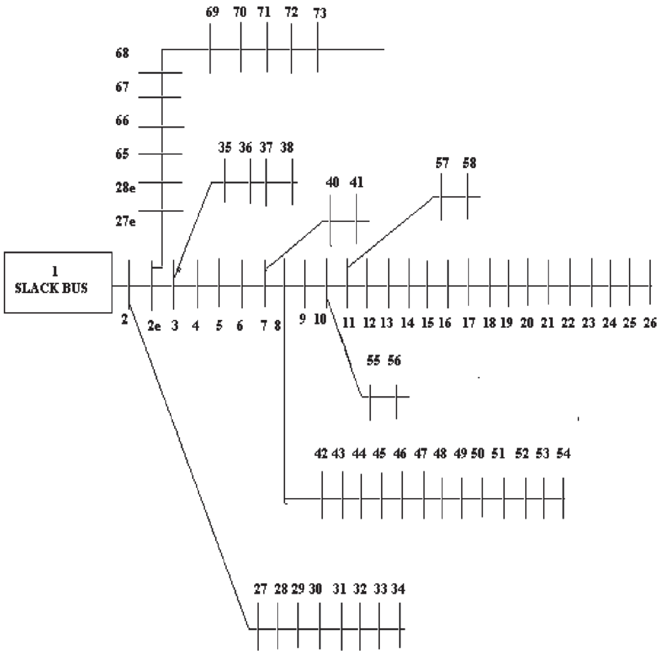

Fig. 4.1: 69-Bus Radial Distribution System [5]

The 69-bus test case radial distribution system is shown in figure 4.1. The data of the system are obtained from [5]. The 69 radial bus distribution system has been simulated using ETAP (Electronic Transient Analyzer Program) version 7.0.

Table 4.1 Results of 69-Bus radial feeder test case without and with OCP (5 higher potential buses)

Points of Comparison	Uncompensated	Compensated with utilizing PLI	Compensated with utilizing LSF
V_{min} (p.u.) at bus no	.922 at bus 54	.940 at bus 54	.939 at bus 54
V_{max} (p.u.) at bus no	1.00 at bus 1	1.00 at bus 1	1.00 at bus 1
P_{loss}, kW	167.1	117.2	121.3
Reductions in P_{loss}%	-	29.80%	27.40%
Q_{loss}, kVAR	77.3	55.6	57.2
Reductions in Q_{loss} %	-	28%	26%
Overall power factor	0.81	0.95	0.94
Total compensations	-	1650 kVAR	1450 kVAR
Compensation cost-A	-	$8950	$8,350
Energy saving cost-B	-	$26227	$24,072
Net benefits[B-A]	-	$17277	$15,722

The total load of the system is (3802 + j2694) kVA. Power loss indices and loss sensitivity factor have been used to identify the potential buses for shunt capacitor placement. The buses have been ordered according to the power loss index and loss sensitivity factor values $\partial Q_{lineloss}\,[j]/\partial Q_{eff}\,[j]$

for 69-bus system the potential buses are 50 , 53 ,48 , 54 , 20, 51 ,17 and 46, 47, 50, 49, 48 , 53 , 16 respectively.

The above system has following characteristics:

Number of buses = 69
Number of lines = 68
Slack Bus No =1
Base Voltage=12.66 KV
Base kVA=10 kVA

Table 4.1 shows that in case of uncompensated system the total system active power loss are 167.1 kW and the minimum system voltage $|V_{54}|$ = 0.922 p.u. at bus 54.The first five buses, having highest loss sensitivity values and Power loss index are selected as candidate buses, these candidate buses are (Bus No.46,47, 50, 49,48) and (Bus No.50,53,48,54, 20) .The capacitor sizes have been determined by using GA. Table 4.2 shows the optimal location and capacitor sizes using four candidate buses for 69-bus RDS (capacitor step size is taken as 50 kVAr)

Table (4.2): Optimal Location and Capacitor Sizes using four candidate buses for 69-Bus RDS (capacitor step size as 50 kVAr)

Bus nominations using PLI		Bus nominations using LSF	
Bus Number	Capacitor Size (KVAr)	Bus Number	Capacitor Size (KVAr)
50	950	46	150
53	200	47	50
48	150	50	1000
54	50	49	150
20	300	48	100

The capacitor placement results in the improvement in bus voltages and reduced power losses.
Table 4.1 shows that the active and the reactive power losses are reduced by 29.8% and 28% with the potential buses candidate using PLI. However the reductions were 27.4% and 26% with utilizing LSF. Moreover, the net savings are $17277.00 and 15722.00 with utilizing nominations of PLI and LSF, respectively (refer to Table 4.1). In addition to this, the overall system power is dramatically improved from 0.81 lagging (without any compensation) to 0.95 lagging and 0.94 lagging using PLI and LSF indicators, respectively.

B. 34 Bus System

The 34-bus test case four lateral radial distribution systems, as shown in figure 4.2. The data of the system are obtained from [17]. Simulations are carried out using ETAP.
The total load of the system is (4636 +j2873.5) kVA. Power loss indices and loss sensitivity factor methods have been used to identify the potential buses for shunt capacitor placement. The buses have been ordered according to the Power loss index and Loss Sensitivity Factor values $\partial Q_{lineloss}\,[j]/\partial Q_{eff}.[j]$
for 34-bus system the potential buses are 26, 25 , 24, 22, 23, 21, 20, 19, 27 and 19, 23, 20, 21, 22, 24, 25, 26, 27 respectively.

The 34 bus radial distribution system has following characteristics:

Number of buses = 34
Number of lines = 33
Slack Bus No =1
Base Voltage=11 kV
Base MVA=100 MVA

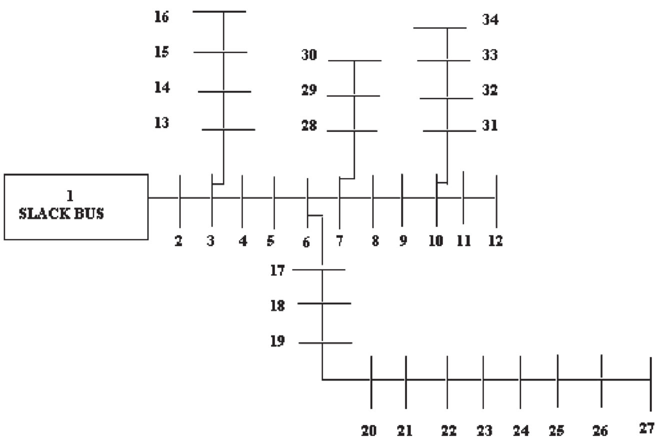

Fig. 4.1: 34 Bus Radial Distribution System [17]

Table 4.4 shows that in case of uncompensated system the total system active power loss are 171.1 (kW) and the minimum system voltage |V27| = 0.949 p.u. at bus 27. The first four buses, having highest loss sensitivity values and power loss index are selected as candidate buses. These candidate buses are (i.e. buses 19, 23, 20, 21) and (i.e. buses 26, 25, 24, 22). The capacitor sizes have been determined by using GA. Table 4.3 shows the optimal location and capacitor sizes using four candidate buses for 34-bus RDS (capacitor step size is taken as 50 kVAr).

Table (4.3): Optimal Location and Capacitor Sizes using four candidate buses for 34-Bus Radial Distribution System

Bus nominations using PLI		Bus nominations using LSF	
Bus Number	Capacitor Size (KVAr)	Bus Number	Capacitor Size (KVAr)
26	250	19	750
25	150	23	850
24	150	20	150
22	900	21	150

Table 4.4 clearly indicates the system overall power factor is significantly corrected from 0.856 lagging (no compensation) to 0.954 lagging and 0.961 lagging with utilizing PLI and LSF observations, respectively. It may be concluded, with utilizing LSF identifications, the better results are obtained compared to utilization of PLI nodes.

Table 4.4 Results of a 34-Bus radial feeder test case without and with OCP (4 higher potential buses)

Points of Comparison	**Uncompensated**	**Compensated with utilizing PLI**	**Compensated with utilizing LSF**
V_{min} (p.u.) at bus no	.9495 at bus 27	.95578 at bus 27	.95574 at bus 27
V_{max} (p.u.) at bus no	1.00 at bus 1	1.00 at bus 1	1.00 at bus 1
P_{loss}, kW	171.1	136.3	133.3
Reductions in P_{loss}%	-	20.3%	22.09%
Q_{loss}, kVAR	50.5	39.9	38.8
Reductions in Q_{loss} %	-	20.9%	23.16%
Overall power factor	.856	.954	.961
Total compensations	-	1450 kVAR	1900 kVAR
Compensation cost-A	-	$8350	$9700
Energy saving cost-B	-	$18290	$19867
Net benefits[B-A]	-	$9940	$10167

5. CONCLUSION

The work has been carried out to find the locations of capacitors to be placed in radial distribution system to maximize the saving after considering the energy loss cost and capacitor cost. The candidate locations for compensation are found using loss sensitivity factor and power loss indices calculated from base case load flow. The study has been carried out on 34 and 69 bus radial distribution system. The results obtained shows the optimal capacitor problem solved using LSF on 69 bus radial distribution system reduced the active and reactive power losses by 27.4% and 26% respectively. As utilizing PLI on 69 bus system the active and reactive power losses are reduced by 29.8% and 28% respectively. The net benefits by utilizing PLI and LSF on 69 bus system are $17277 and $15722.The simulation results clearly indicates the improvement in the voltage profile, reduction in active and reactive power losses, power factor has been improved where as the total cost can be minimized by injecting less VArs.

REFERENCES

[1] Attia A. El-Fergany,"Optimal capacitor allocations using evolutionary algorithms", IET Gener. Transm. Distrib.,Vol.7, Issue 6, pp. 593–601, 2013.

[2] N. M. Neagle and D.R. Samson, "Loss Reduction from Capacitors installed on Primary Feeders",AIEE Transactions,vol. 75, no. 3, pp. 950-959, 1956.

[3] J. J. Grainger and 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] H. Duran, "Optimum number, location, and size of shunt capacitors in radial distribution feeders, A dynamic programming approach", IEEE Trans. Power Apparatus and Systems, vol. 87, no. 9, pp. 1769–1774, Sept. 1968.

[5] M. E. Baran and F. F.Wu, "Optimal capacitor placement on radial distribution systems", IEEE Trans. Power Delivery, vol. 4, no. 1, pp. 725–734, Jan. 1989.

[6] M. Ponnavaikko and K. S. Prakasa Rao, "Optimal choice of fixed and switched shunt capacitors on radial distributors by the method of local variations", IEEE Trans. Power Apparatus and Systems, vol. 102, no. 6, pp. 1607–1615, June 1983.

[7] T. S. A. Salam, A. Y. Chikhani, and R. Hackam, "A new technique for loss reduction using compensating capacitors applied to distribution systems with varying load condition", IEEE Trans. Power Delivery, vol. 9,pp. 819–827, 1994.

[8] M. M. Hamada, M. A. A. Wahab, A. M. El-Sayed, H. A. Ramadan, " A proposed strategy for capacitor allocation in radial distribution feeders", in Conf. 12th Middle East Power Systems Conf., MEPCON, Aswan, Egypt, 12-15 March 2008.

[9] D. Sattianadan, Dr. M. Sudhkaran, K. Vijayakumar, S.Vidyasagar, "Optimal Placement of Capacitor in Radial Distribution System Using PSO" Second International Conference on Sustainable Energy and Intelligent System (SEISCON 2011), Dr. M.G.R. University, Maduravoyal, Chennai, Tamil Nadu, India. July 20- 22, 2011.

[10] H. Kim, S-K. You, "Voltage Profile Improvement by capacitor Placement and control in unbalanced distribution Systems using GA", IEEE power Engineering SocietySummer Meeting, 1999, Vol. 2, pp. 18-22.

[11] Anil Swarnkar, Nikhil Gupta and K. R. Niazi, "Optimal Placement of Fixed and Switched Shunt Capacitors for Large-Scale Distribution Systems using Genetic Algorithms".

[12] 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.

[13] H. D. Chiang, J. C. Wang, O. Cockings and H. D. Shin, " Optimal Capacitor Placements in Distribution Systems: Part 1: A New Formulation and the Overall Problem", IEEE Transactions on Power Delivery, vol. 5, no. 2, pp. 634-642, 1990.

[14] H. D. Chiang, J. C. Wang, O. Cockings and H. D. Shin, " Optimal Capacitor Placements in Distribution Systems: Part 2: Solution Algorithms and Numerical Results", IEEE Transactions on Power Delivery, vol. 5, no. 2, pp. 643-649, 1990.

[15] R.Sirjani , A. Mohamed and H. Shareef, "Optimal capacitor placement in a radial istribution system using harmony search algorithm", J. Appl. Sci., 10, (23),pp.2996- 3006, 2010.

[16] R. Rao and S.Narasimham, "Optimal capacitor placement in a radial distribution system using plant growth simulation algorithm", Int. J. Electr. Power Energy Syst., 1, pp. 123–130, 2008.

[17] M. Chis , M.M.A. Salama and S. Jayaram , "Capacitor Placement in distribution System using heuristic search strategies", IEE Gener. Transm. Distrib., 144, (3), pp.225 -130, 1997.

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