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PROPOSED STRATEGY FOR CAPACITOR ALLOCATION IN RADIAL DISTRIBUTION FEEDERS

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ABSTRACT

Capacitors in power systems are generally used to supply reactive power for the purpose of loss minimization and voltage profile improvement. The main objective of this study is to present a new strategy for capacitor allocation in radial distribution systems. Presently, the capacitor placement problem is widely solved by using heuristic optimization methods. In this study sizes and locations of capacitors are selected in order to achieve the maximum reduction in total losses of the system. This reduction is not seen in all branches at times, but the loss in any individual branch of the system is not allowed to increase than it was before the capacitor is placed. This work is done applied to 34-bus distribution system. The results of this proposed strategy are compared with original previous work mentioned to show its validity. Power loss and voltages in buses for both cases are obtained by simple load flow technique.

KEYWORDS: Capacitor Allocation Techniques, Distribution Feeders, Loss Reduction

INTRODUCTION

Electric distribution systems are becoming large and complex leading to higher system losses and poor voltage regulation. Studies indicate that almost 13% of the total power generated is consumed as I 2 R losses at the distribution level[1]. Shunt capacitors are widely installed in radial distribution systems to reduce losses, power factor correction, voltage profile management, power flow control and improve voltage stability. The I2R heating due to load and fault current is usually the largest single contributor to total temperature[2]. So the sectional ohmic losses should be decreased to improve the thermal capacity of feeder conductors. However, the benefits of compensation depend greatly on the placement and size of the added capacitors. This paper presents capacitor allocation strategy for reactive power compensation which deals with decreasing the sectional losses in each branch hence improving the thermal capacity of feeder conductors.

In the literature, many techniques have been reported for solving the optimal capacitor placement problem in distribution systems. These techniques may be classified in the following categories: analytical, numerical programming, heuristic and artificial intelligence based. Among these techniques, the heuristic based techniques have been widely applied in solving the optimal capacitor placement problem. Published literature describing capacitor allocation algorithms are abundant. Grainger et al. pioneered the analytical methods [3]. In ref [3], fixed and switched capacitors are placed for optimizing the net monetary savings associated with the reduction of power and energy losses, both the capacitor locations and sizes are treated as continuous variables. A new voltage dependent methodology for shunt capacitor compensation of primary distribution feeders is presented in ref[4]. Ponnavaikko and Rao [5]

Used a numerical method called the method of local variations and further expanded the problem to include the effects of load growth, and switched capacitors for varying load. Similarly, Baran and Wu[6] formulated the capacitor placement problem using mixed integer programming. The optimal selection and placement of capacitor banks using binary particle swarm optimization(PSO) is integrated with the estimation of harmonic levels in ref [7]. Methods based on heuristic search techniques are introduced for distribution system loss reduction by reconfiguration [8],[9]. Abdel-Salam et al. [10] proposed a heuristic technique based on ideas from [8],[9] to identify a section in the distribution system with the highest losses due to reactive load currents and then pinpoint the sensitive node in that section having the greatest effect on the system loss reduction. Sizes of capacitors placed on the sensitive nodes are then determined by maximizing the power loss reduction from capacitor compensation. M. Chis et al. [11] improved the work of [10] by determining the sensitive nodes that have the greatest impact on loss reduction for the entire distribution system directly and by optimizing for the capacitor sizes based on maximizing the net economic savings from both energy and peak power loss reduction. In addition, the method in [11] also accounts for varying loads of the distribution system considered. Most of these studies consider the loss reduction for the capacitor allocation problem[3-11], but these studies take in consideration the reduction of total losses not the reduction in the individual section loss. The general capacitor placement problem in distribution feeders consists of determining the optimal location, type (fixed or switched), and size of capacitors such that power and energy losses are minimized while taking the cost of the capacitor into account. For simplifying the problem fixed capacitors are only considered in this paper and aims to implement the proposed strategy, and compare its results with so called exact solution in ref [12] to show the validity of this strategy. For this case, the problem is considered as a nonlinear integer optimization problem and the Newton-Raphson power flow method is used to calculate the cost function.

PROBLEM FORMULATION AND IMPLEMENTATION

In this section, the implementation and the results of the proposed strategy are shown, also implementation of the exact solution in [12]. Then their performance is compared.

Ref. [12] presents review and implementation of previous strategies and comparison between them and the so called exact solution. The best results were offered by the exact solution; so this was the reason for choosing to compare the results of the suggested strategy by the results of the exact solution. These two methods are applied to two feeders with 9 and 34 buses.

The objectives of the capacitor placement are to reduce the power loss and keep voltages within the prescribed limits with minimum cost.

To solve the optimal capacitor placement and sizing problem for radial distribution networks, a suitable power flow method called as the backward/forward sweep power flow (Teng, 2000) is used for computing the power loss. In this power flow method, the relationship between the bus current injections and the branch currents is represented by the matrix [BIBC] which is given as:

$$B] = [BIBC]\ [I] \tag{1}$$

where [I] is the bus current injection vector and [B] is the branch current vector.

The relationship between the branch currents, [B] and bus voltages, [ΔV] is represented by the matrix [BCBV]. The matrices [BIBC] and [BCBV] are then multiplied to obtain the relationship between the voltage deviation, [AV] and the bus current injections [I], which is represented by the matrix [DLF] and given as:

$$\Delta V] = [BCBV]\ [B] = [BCBV]\ [BIBC]\ [I] = [DLF]\ [I] \tag{2}$$

[DLF] is also known as the voltage drop to bus current injection matrix.

The backward/forward sweep power flow method at the k iteration considers the following equations

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

(3)

[ΔVk+1] = [D L F] [Ik] (4)

Problem Formulation

The total power loss $P_{t\ loss}$ is given by

$$P_{t\ loss} = \sum_{i=0}^{n-1} P_{loss}\,(i, i+1) \quad (5)$$

where, i is the bus number and n is the total number of buses.

Considering investment cost, there is a finite number of standard capacitor sizes that are integer multiples of the smallest size Qc. The cost per kVAr varies from one size to another. Generally, large sizes are cheaper than smaller ones. Let the maximum permissible capacitor size be limited

$$Q_{max} = L \times Q_o \quad (6)$$

Where, Qo is the smallest capacitor size in Table I and L is an integer which is resulted by dividing the maximum allowed capacitor size for this feeder Qmax with the smallest value Qo. Then at each selected location, there are L sizes to choose from

Let K1, K2, ….KL be the corresponding capital investment per kVAr. Assuming that only capacitor banks are used for voltage excursions, the cost function S can be selected as:

$$S = K_p \times P_{t\ loss} + \sum_{j=1}^{k} K_j\, Q_j \quad (7)$$

where, Kp is the cost per power loss ($/kW/year) and j=1,2,…k represents the selected buses. The objective function (7) is to be minimized subject to

$$V_{min} \le V_i \le V_{max} \qquad i=1,2,\ldots,n \quad (8)$$

For the test feeder, Kp is selected to be U.S. $ 168/kW [12], and the voltage limits are Vmin=0.9 p.u and Vmax=1.1 p.u. commercially available capacitor sizes with U.S. $/kVAr are used in the analysis. For reactive power compensation, the maximum capacitor size Qmax should not exceed the total reactive loads (i.e., 4186 kVAr). So applying for (6) results in 27 possible capacitor sizes shown in table II with corresponding cost/kVAr [13]. The values of the choices are derived from table I by assuming a life expectancy of ten years(the operating costs are neglected) [12].

Table 1: [13] Available Three-Phase Capacitor Sizes and Costs

Size(kVAr)	150	300	450	600	900	1200
Cost ($)	750	975	1140	1320	1650	2040

The Proposed Strategy

In this strategy as it is mentioned before the optimal sizes and placements of the capacitors are ones that minimize (7), satisfy (8) and also satisfy (9) (i.e. give minimum cost and minimum sectional ohmic losses and satisfy the voltage constraint)

$$P_{k+1(\sec loss)} \le P_{k(\sec loss)}$$

where, k+1 is the case after the capacitor placement and k is the case before the capacitor placement. The solution algorithm of this method can be summarized as follows:

- Perform the load flow solution for the original feeder to get the branch(sectional) losses and other necessary data.
- Begin putting Qc equal the smallest value in Table II at the far end bus(i.e. bus no. n) from the substation, and perform the load flow
- Compare the sectional losses in each branch of the feeder that were resulted from step 2 with that were resulted from step 1.
- If the sectional losses in each branch are less than or equal to that of the prior case then try with the next value of Qc from 27 standard values of Qc, perform the load flow, and compare the sectional losses as in step 3, but now compare it with the sectional losses that were resulted with the prior value of Qc is placed.
- Repeat steps 4 with the different values of Qc placed at this bus until reaching the optimal value of Qc(i.e. minimize (7), satisfy (8) and (9)).
- If the sectional losses in any branch of the feeder is more than that of the prior case then remove the value of Qc and put the prior value of Qc
- With optimal Qc placed at the far end perform the load flow and check the voltage profile. If $0.9 \leq Vbus \leq 1.1$ then stop otherwise try with the next bus(i.e. bus no (n-1)) and so on until $Vmin \geq 0.9$

A schematic diagram for these steps is shown in Figure 1

Exact Solution [12]

As it was stated at [12]; the solution algorithm of this method can be summarized as follows:

- Bus (K2) where the next optimal Qc2 will be placed.
- With Qc1 and Qc2 placed at buses K1 and K2, repeat steps 1 and 2 and so on until candidate buses are exhausted.
- If the minimum voltage is still < 0.9; try to increase Qc of the candidate node that is very far from the substation. This will increase the voltage such that $0.9 \leq Vi \leq 1$ p.u.
- With Qc1 and Qc2 placed at buses K1 and K2, repeat steps 1 and 2 and so on until candidate buses are exhausted.
- If minimum voltage is still <0.9; try to increase Qc of the candidate node that is very far from the substation. This will increase the voltage such that $0.9 \leq Vi \leq 1$ p.u.

The Test Feeder [12]

The method discussed before, is applied to 34-bus radial distribution test system. This test system has a main feeder and four laterals. The data of the feeder is taken from [12]. The single line diagram, the load data and feeder- line parameters for the system are shown in Appendix A.

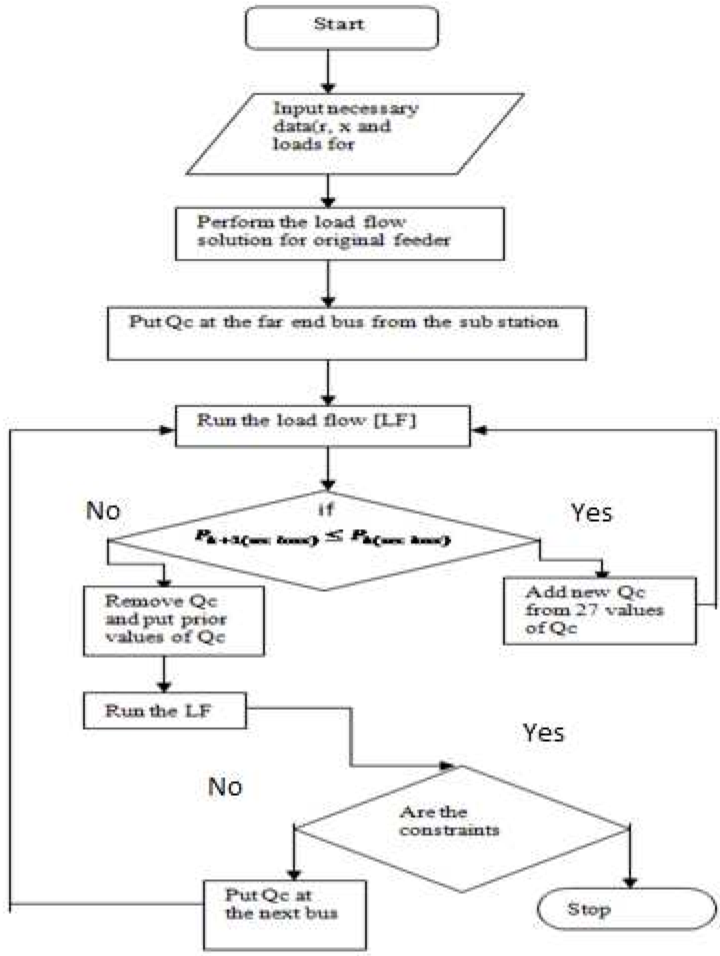

Figure 1: Flow Chart for New Strategy

The system voltage is 11kV. Before compensation, the cost is U.S. $ 327212, based on the previously defined cost function. The active and reactive losses are 221.5kW and 65.04kVAr respectively, and the voltage limits in p.u. are 0.9417≤Vi≤1. The results are summarized in Table 3.

Table 2: Possible Choice of Capacitor Sizes and Cost/KVAr

J	1	2	3	4
Qc	150	300	450	600
$/KVAr	0.5	0.35	0.253	0.22
J	5	6	7	8
Qc	750	900	1050	1200
$/KVAr	0.276	0.183	0.228	0.17
J	9	10	11	12
Qc	1350	1500	1650	1800
$/KVAr	0.207	0.201	0.193	0.187
J	13	14	15	16
Qc	1950	2100	2250	2400
$/KVAr	0.211	0.176	0.197	0.17
J	17	18	19	20
Qc	2550	2700	2850	3000
$/KVAr	0.189	0.187	0.183	0.18
J	21	22	23	24
Qc	3150	3300	3450	3600
$/KVAr	0.195	0.174	0.188	0.17
J	25	26	27	
Qc	3750	3900	4050	
$/KVAr	0.183	0.182	0.179	

DISCUSSIONS OF RESULTS

TABLE III shows the results of the two methods for the feeder and it is observed that the total active loss for the feeder is 0.158 MW which is less than exact solution (0.1655 MW). Also the fixed cost (the cost of the installed capacitors only) and the running cost (the cost of the total power losses only) are less than that of the exact solution. So the proposed strategy offers more cost saving and more loss reduction than the exact solution.

The voltage profile for the proposed strategy for 34-bus system is the best case and it is clear from the Figure (2). The sectional losses for the two methods and the original case for the feeder is shown in Figure (3). It is clear that the sectional loss resulting by using the proposed strategy is always less than that of original case(i.e. case without using Qc's), but the sectional loss resulting from the exact solution offers violation in section (2-3) (i.e. the loss in this section is more than that of the original case)

CONCLUSIONS

The prior studies for capacitor allocation problem have not considered increasing of sectional losses that may occur with capacitor allocation scenario. This work treats this problem by adding a new constraint which ensures that the losses in any branch of the feeder will never increase during installing of capacitors at the candidate buses.

It has been shown that the proposed strategy's results are the best; which ensures the superiority of this strategy

Table 3: Results for the Methods Applied to the 34- Bus Feeder

	Without Qc	Method in Ref [12]	The Proposed Strategy
Total power loss in MW	0.2215	0.1655	0.158
Total Cost in $	37212	28250	27909
Max voltage in p.u.	1	1	1
Min voltage in p.u	0.9417	0.951	0.951
Summation of all Qc in MVAr	0	2.1	3
Loss reduction in kW	0	56	63.5
Cost saving in $	0	8962	9303
Saving %	0	24.08	25
Loss reduction in %	0	25.28	28.668

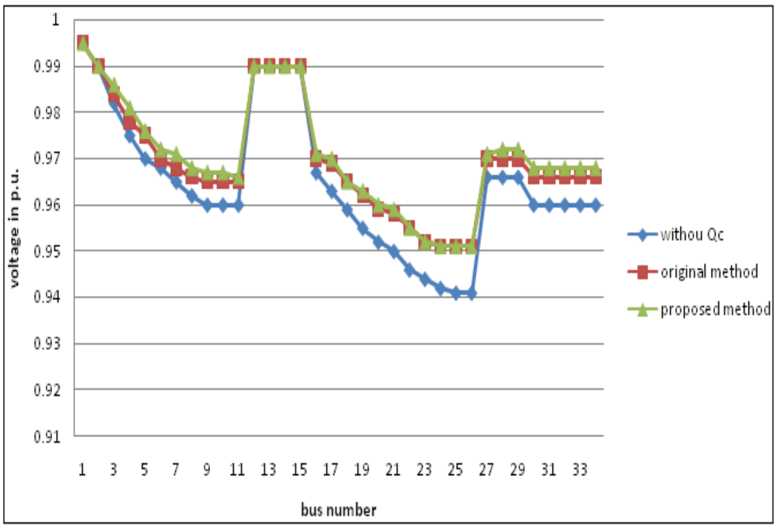

Figure 2: Voltage Profile of 34 Bus System

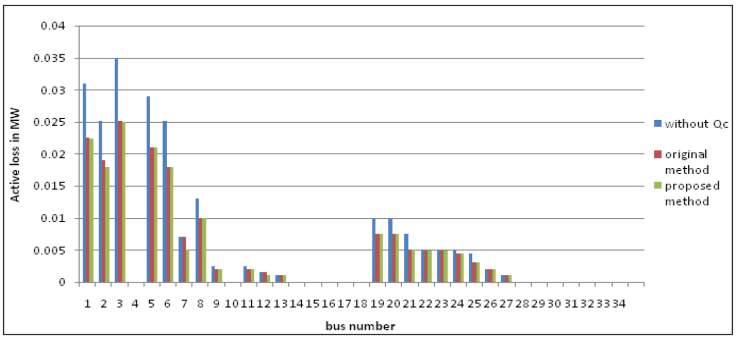

Figure 3: Losses in Each Section of 34 Bus System

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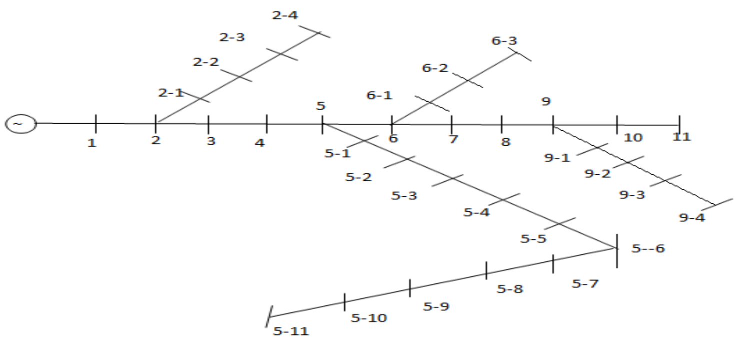
APPENDICES

Appendix A: Line diagram of 34 bus test system



The Load Data and Feeder Data of 34 Bus Test System [12]

Table 4

No.	Load		Sectional Parameters				Length km
	P (KW)	Q (Kvar)	Bus No From	Bus No To	Ri,i+1 (Ω/km)	Xi,i+1 (Ω/km)	
1	320	142.5	0	1	0.195	0.08	0.6
2	0	0	1	2	0.195	0.08	0.55
3	230	142.5	2	3	0.299	0.083	0.55
4	230	142.5	3	4	0.299	0.083	0.5
5	0	0	4	5	0.299	0.083	0.5
6	0	0	5	6	0.524	0.09	0.6
7	230	142.5	6	7	0.524	0.09	0.4
8	320	142.5	7	8	0.524	0.09	0.6
9	0	0	8	9	0.524	0.09	0.4
10	230	142.5	9	10	0.524	0.09	0.25
11	137	84	10	11	0.524	0.09	0.2
2_1	72	45	2	2_1	0.524	0.09	0.3
2_2	72	45	2_1	2_2	0.524	0.09	0.4
2_3	72	45	2_2	2_3	0.524	0.09	0.2
2_4	13.5	7.5	2_3	2_4	0.524	0.09	0.1
5_1	230	142.5	5	5_1	0.299	0.083	0.6
5_2	230	142.5	5_1	5_2	0.299	0.083	0.55
5_3	230	142.5	5_2	5_3	0.378	0.086	0.55
5_4	230	142.5	5_3	5_4	0.378	0.086	0.5
5_5	230	142.5	5_4	5_5	0.378	0.086	0.5
5_6	230	142.5	5_5	5_6	0.524	0.09	0.5
5_7	230	142.5	5_6	5_7	0.524	0.09	0.5
5_8	230	142.5	5_7	5_8	0.524	0.09	0.6
5_9	230	142.5	5_8	5_9	0.524	0.09	0.4
5_10	230	142.5	5_9	5_10	0.524	0.09	0.25
5_11	137	85	5_10	5_11	0.524	0.09	0.2
6_1	75	48	6	6_1	0.524	0.09	0.3
6_2	75	48	6_1	6_2	0.524	0.09	0.3
6_3	75	48	6_2	6_3	0.524	0.09	0.3
9_1	57	34.5	9	9_1	0.524	0.09	0.3
9_2	57	34.5	9_1	9_2	0.524	0.09	0.4
9_3	57	34.5	9_2	9_3	0.524	0.09	0.3
9_4	57	34.5	9_3	9_4	0.524	0.09	0.2