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# Optimal Capacitor Placement in Distribution System with Random Variations in Load

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***Abstract:*** Capacitor placement is carried out in Distribution Systems for loss reduction and improving the voltage profile. In this work, random variations in load are considered for determining the capacitor placement. Sensitivity analysis is carried out for determining optimal locations and modified direct search algorithm is used for determining the sizes of capacitors.

The algorithm is tested on a practical distribution system. The system consists of 42 buses belonging to Tallarevu Mandal of East Godavari District of Andhra Pradesh. Random variations for 24 hours are considered on all 41 load buses for the analysis. For every hour, sensitivity analysis is done to determine the optimal locations for placing the capacitors. It is observed that the optimal locations are insensitive to load variations. Modified direct search algorithm is used for determining the sizes of capacitors. Optimal sizes are chosen in such a way that, it would result in best possible reduction in active power loss for all random load variations. Discrete sizes of capacitors are used for designing the capacitor placement.

***Index Terms:*** Capacitor placement, Radial Distribution System, Power Flow, Modified Direct Search Algorithm.

## 1. INTRODUCTION

Capacitor banks connected to distribution systems helps in reducing the active power loss and improves the voltage profile. The Load flow techniques used in Transmission Systems like Gauss-Siedel and Newton-Raphson techniques cannot be applied to the Distribution Systems because of high R/X ratio. The design of compensation systems for radial distribution system is modeled as non-linear optimization technique.

Ramalinga Raju et. al., [1] have developed direct search algorithm for capacitive compensation in radial distribution system. Wang et. al. implemented integer programming technique [2], and Tabu search was used by Huang et. al., [3] for optimal capacitor placement. Grainger implemented Equal area criterion [4] and Genetic Algorithm applied to capacitor placement by Delfanti [5] for determining optimal sizes of capacitors. D. Das applied Fuzzy-GA method for capacitor placement problem [6]. Sydulu et. al., applied Index Vector to capacitor placement problem [7], Prakash et. al., applied Particle Swarm Optimization for Optimal capacitor placement problem [8]. Carpinelli et. al., implemented non-linear programming technique for capacitor placement [9] on three phase unbalanced system.

The new two stage algorithm has been proposed for capacitive compensation in this work by combining the sensitivity analysis and direct search algorithm. Sensitivity analysis is used to identify optimal locations with random variations in load. Direct search algorithm determines the suitable sizes of capacitors resulting in minimum active power loss. Dependency of optimal location for capacitor placement on variations in load is addressed for the first time in this paper.

### 1.1. Objective Function

Minimization of total cost is considered as Objective function for optimization. The first part of it is cost of energy loss and second part is the purchase cost of capacitor. The objective is to minimize the total cost, S [6].

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$$\text{Minimum S} = \mathrm{K}_e \sum_{j=1}^{\mathrm{L}} \mathrm{T}_j \mathrm{P}_j + \sum_{i=1}^{\mathrm{ncap}} \mathrm{K}_c \mathrm{Q}_{ci} \tag{1}$$

Where $K_e$ is the energy Cost per each unit-kWhr, $T_j$ is the duration for which a $j^{th}$ load level. Twenty four load levels are considered in this work. They are assumed as hourly variations in load. $P_j$ is the active power loss during $j^{th}$ load level. $Q_{ci}$ is the size of the capacitor placed at $i^{th}$ bus. Different size capacitors would be suitable for different load levels at the optimal locations for minimizing the total cost function. $K_c$ is the purchase cost of capacitor per kVAr. Number of candidate locations is indicated by 'ncap'.

## 2. SENSITIVITY ANALYSIS

Potential locations for placing capacitors are obtained by Loss sensitivity factors [7]. Reduction in total active power loss per unit reactive power injection at each node is obtained by

Sensitivity factor.

$$\frac{\partial \mathrm{P}_{\mathrm{loss}}}{\partial \mathrm{Q}_2} = \frac{2 \times \mathrm{Q}_2 \times \mathrm{R}[j]}{\mathrm{V}_2^2} \tag{2}$$

Loss sensitivity factors, $\frac{\partial \mathrm{P}_{\mathrm{loss}}}{\partial \mathrm{Q}_2}$ are calculated using load flow, and values are arranged in descending order for all the lines. Normalized voltage magnitudes [7] are obtained by dividing the voltage with 0.95.

$$\text{Norm } [i] = \frac{\mathrm{V}[i]}{0.95} \tag{3}$$

Buses at which normalized voltages are less than 1.01 are considered as potential nodes for compensation. The sequence in which buses are to be prioritized for placing capacitors is given by Loss Sensitivity factors and values of voltages decide, whether a particular bus needs compensation or not.

## 3. DETERMINATION OF OPTIMAL SIZES OF CAPACITORS

Direct search algorithm [1] gives the optimal locations and sizes simultaneously. The algorithm actually makes selection of different groups of capacitors and searches for best location for each capacitor by searching all the possible locations. But, the optimal locations are already decided by sensitivity analysis for varying load conditions in the present case. Here, modified direct search algorithm is used which searches for best set of capacitors that gives the minimum active power loss within the selected optimal locations for all varying load conditions.

## 4. THE PROPOSED MODIFIED DIRECT SEARCH ALGORITHM

The algorithm proposed is for radial distribution system. Source bus is considered as slack bus and all other buses are considered as PQ buses. The algorithm proposed is presented in following steps for determining the optimal sizes of the capacitors.

1. Active power loss is determined for the uncompensated system is assumed to be maximum loss. This step is repeated for all loading conditions separately.
2. Reactive powers at all load buses are set to zeros and load flow study is conducted and total line loss is determined. This is considered as minimum possible loss to be aimed at. This step is carried out for all loading conditions.

3. To determine the optimal sizes of capacitors, a number of options have to be tried. In every option there will be a group of capacitors having different sizes. A tolerance index is chosen. The modulus of difference between losses under any option and minimum loss should be smaller than the tolerance index for convergence. All possible option are listed.
4. Let *m*(*k*) be the number of capacitors in the $k^{th}$ option, *k* ranging from 1 to *n* where '*n*' is the total number of options. *m*(1) , the first option is with single capacitor, the Q of which is nearest to the average of total kVAr of the system considering varying loading conditions. This is kept at the location which has got highest priority given by sensitivity analysis.
5. In one set of capacitors *m*(*k*), the first capacitor is kept at highest priority location given by sensitivity analysis. The second capacitor is kept at next priority location. This procedure is repeated for all capacitors.
6. The options *m*(2) to *m*(*n*) are sequenced taking more and more number of capacitors of smaller size such that the total compensation is nearest to the total KVAR of the system. System losses are found out for each combination.
7. This procedure is carried out for all varying loading conditions. Losses are determined and checked for tolerance. If the tolerance is acceptable, process can be terminated. If the tolerance limit is not met, the option that gives minimum average loss is chosen as the optimal solution.

## 5. RESULTS

Data for the 42 bus practical system is presented in Appendix. Table 1 shows the different options of sizes of capacitors considered for placement as per Modified Direct Search Algorithm. Random load variations are considered by multiplying all 41 loads with randomly generated numbers between 0 and 1. Optimal locations were identified with sensitivity analysis. They are found to be 4, 12, 10, 11, 5 in the order of priority.

**Table 1**
**Five Different Cases of Modified Direct Search Algorithm**

| *Optimal loc. (Bus Number)* | *Size of the capacitor in different options* | | | | |
|---|---|---|---|---|---|
| | *Case 1* | *Case 2* | *Case 3* | *Case 4* | *Case 5* |
| 4 | 450 | 300 | 450 | 300 | 150 |
| 12 | 300 | 300 | 150 | 150 | 150 |
| 10 | 150 | 150 | 150 | 150 | 150 |
| 11 | -- | -- | -- | 150 | 150 |
| 5 | -- | -- | -- | -- | 150 |
| Average $P_L$ (per hr) | 43.93 kW | 43.34 kW | 43.012 kW | 42.89 kW | 42.83 kW |

**Table 2**
**Hourly Active Power Loss with and without capacitor placement (kW)**

| *No. of the hour* | *Total active power loss with out capacitors* | *$P_L$ with 100% compensation in the system* | *After OCP-Case 1* | *After OCP-Case 2* | *After OCP-Case 3* | *After OCP-Case 4* | *After OCP-Case 5* |
|---|---|---|---|---|---|---|---|
| 1 | 50.03 | 39.87 | 42.19 | 41.56 | 41.13 | 41.11 | 41.08 |
| 2 | 45.07 | 35.93 | 38.5 | 37.68 | 37.24 | 37.23 | 37.21 |
| 3 | 46.08 | 36.76 | 39.25 | 38.52 | 37.93 | 38.06 | 38.05 |
| 4 | 56.7 | 45.12 | 47.21 | 46.74 | 46.52 | 46.25 | 46.21 |
| 5 | 46.25 | 36.9 | 39.44 | 38.72 | 38.11 | 38.29 | 38.27 |

| No. of the hour | Total active power loss with out capacitors | $P_L$ with 100% compensation in the system | After OCP-Case 1 | After OCP-Case 2 | After OCP-Case 3 | After OCP-Case 4 | After OCP-Case 5 |
|---|---|---|---|---|---|---|---|
| 6 | 50.56 | 40.29 | 42.41 | 41.78 | 41.48 | 41.41 | 41.38 |
| 7 | 53.36 | 42.51 | 44.85 | 44.29 | 43.93 | 43.84 | 43.81 |
| 8 | 38.87 | 31.09 | 34.16 | 33.3 | 32.22 | 32.81 | 32.8 |
| 9 | 54.18 | 43.14 | 45.31 | 44.78 | 44.5 | 44.35 | 44.31 |
| 10 | 58.12 | 46.24 | 48.14 | 47.68 | 47.63 | 47.28 | 47.24 |
| 11 | 57.79 | 45.96 | 48.07 | 47.58 | 47.52 | 47.13 | 47.1 |
| 12 | 55.9 | 44.45 | 46.53 | 45.97 | 45.94 | 45.5 | 45.47 |
| 13 | 48.84 | 38.92 | 41.3 | 40.62 | 40.18 | 40.16 | 40.14 |
| 14 | 57.76 | 45.91 | 48.01 | 47.49 | 47.52 | 47.03 | 47 |
| 15 | 56.49 | 44.98 | 46.9 | 46.45 | 46.25 | 46.05 | 46.01 |
| 16 | 52.74 | 41.98 | 44.08 | 43.44 | 43.35 | 43.05 | 43.03 |
| 17 | 55.3 | 44 | 46.01 | 45.47 | 45.38 | 45.02 | 44.98 |
| 18 | 52.56 | 41.92 | 44.27 | 43.81 | 43.09 | 43.28 | 43.24 |
| 19 | 62.28 | 49.5 | 51.42 | 51.05 | 51.12 | 50.63 | 50.58 |
| 20 | 54.12 | 43.07 | 45.3 | 44.73 | 44.52 | 44.26 | 44.22 |
| 21 | 59.56 | 47.38 | 49.44 | 49.04 | 48.89 | 48.53 | 48.48 |
| 22 | 53.47 | 42.62 | 44.72 | 44.2 | 43.83 | 43.75 | 43.71 |
| 23 | 41.77 | 33.36 | 36.1 | 35.22 | 34.56 | 34.77 | 34.77 |
| 24 | 48.03 | 38.31 | 40.72 | 40.07 | 39.46 | 39.59 | 39.56 |
| Average active power loss | 52.32 | 41.67 | 43.93 | 43.34 | 43.012 | 42.89 | 42.83 |

Table 2 shows hourly active power loss with different capacitor placements. Column 2 presents active power loss with out capacitor placement. Column 3 shows the minimum active power loss possible with the assumption of 100% capacitive compensation on all buses. Figure 1 shows the single line diagram of 42 bus system. Standard Capacitor Sizes available in the literature ( in kVAr ) are, 150, 300, 450, 600, 750,

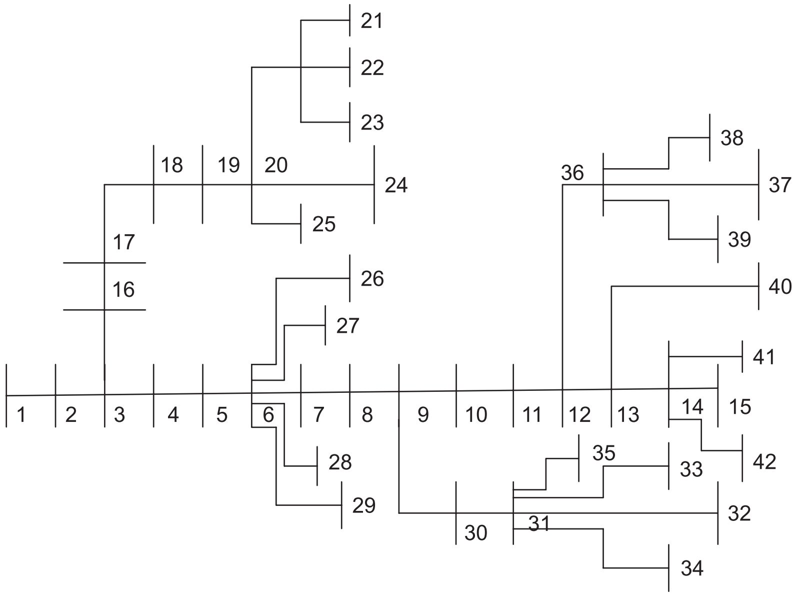

**Figure 1: Single line diagram of 42 Bus system**

900, 1050, 1200, 1350, 1500. Minimum active power loss is obtained with the fifth case, where 150 kVAr each is placed at the buses 4,12,10,11 and 5. For the first time, it is established in this paper that the optimal capacitor location is independent of load variations. The capacitor locations are fixed and average loss is found to be very nearer to the best possible active power loss that can be obtained with 100% compensation by capacitor placement (which is presented in column 3) of Table 2.

**Table 3**
**Voltage Profile on 42 Bus System**

| *Bus* | *Voltage* | *Bus* | *Voltage* | *Bus* | *Voltage* | *Bus* | *Voltage* |
|---|---|---|---|---|---|---|---|
| 2 | 0.999 | 12 | 0.936 | 22 | 0.993 | 32 | 0.96 |
| 3 | 0.996 | 13 | 0.932 | 23 | 0.993 | 33 | 0.96 |
| 4 | 0.978 | 14 | 0.932 | 24 | 0.993 | 34 | 0.961 |
| 5 | 0.972 | 15 | 0.931 | 25 | 0.993 | 35 | 0.96 |
| 6 | 0.97 | 16 | 0.995 | 26 | 0.97 | 36 | 0.931 |
| 7 | 0.966 | 17 | 0.994 | 27 | 0.97 | 37 | 0.931 |
| 8 | 0.965 | 18 | 0.994 | 28 | 0.97 | 38 | 0.931 |
| 9 | 0.964 | 19 | 0.993 | 29 | 0.97 | 39 | 0.931 |
| 10 | 0.958 | 20 | 0.993 | 30 | 0.961 | 40 | 0.932 |
| 11 | 0.952 | 21 | 0.993 | 31 | 0.961 | 41 | 0.931 |
|  |  |  |  |  |  | 42 | 0.931 |

**Table 4**
**Cost Analysis with and without capacitor placement**

|  | *Without Capacitor (Rs)* | *With Capacitor (Rs.)* |
|---|---|---|
| Energy Loss Cost | 18,83,900 | 15,43,140 |
| Capacitor cost | 0 | 2,25,000 |
| Total Cost | 18,83,900 | 17,68,140 |

Table 3 shows the voltage profile in the case 5. Table 4 shows the cost analysis considering the same random load is continued throughout the year. It is found that there is a saving of Rs. 1,15,760/- in one year.

## 6. CONCLUSIONS

Random load variations are considered by multiplying all 41 loads with randomly generated numbers between 0 and 1. Optimal locations were identified with sensitivity analysis. They are found to be 4, 12, 10, 11, 5 in the order of priority. It can be concluded from the above analysis, that the optimal location for placement of capacitor is independent of load variations in the Distribution System. They are fixed according to sensitivity analysis. The capacitors placed are fixed in all the five cases. The load flow is run for all five different cases of capacitor placement and fifth case is found to be the best case with minimum active power loss of 42.83 kW. Voltage profile and cost analysis are presented for the 5th case.

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## *Appendix*

**Table AI**
**Data of 11 kV Tallarevu Mandal Feeder**

| *Sl. No.* | *From bus* | *To bus* | *Length* | *R* | *X* | *P (kW)* | *Q (kVAr)* |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 0.05 | 0.03105 | 0.01778 | 76.5 | 37.05 |
| 2 | 2 | 3 | 0.22 | 0.13662 | 0.07823 | 11.475 | 5.4825 |
| 3 | 3 | 4 | 1.62 | 1.00602 | 0.57607 | 48.195 | 23.0265 |
| 4 | 4 | 5 | 0.52 | 0.32292 | 0.18491 | 11.475 | 5.4825 |
| 5 | 5 | 6 | 0.2 | 0.1242 | 0.07112 | 48.195 | 23.0265 |
| 6 | 6 | 7 | 0.4 | 0.2484 | 0.14224 | 76.5 | 37.05 |
| 7 | 7 | 8 | 0.2 | 0.1242 | 0.07112 | 12.24 | 5.848 |
| 8 | 8 | 9 | 0.1 | 0.0621 | 0.03556 | 48.195 | 23.0265 |
| 9 | 9 | 10 | 1.18 | 0.73278 | 0.419608 | 48.195 | 23.0265 |
| 10 | 10 | 11 | 1.12 | 0.69552 | 0.398272 | 48.195 | 23.0265 |
| 11 | 11 | 12 | 3.31 | 2.05551 | 1.177036 | 38.25 | 18.275 |
| 12 | 12 | 13 | 2.02 | 1.25442 | 0.718312 | 48.195 | 23.0265 |
| 13 | 13 | 14 | 0.56 | 0.34776 | 0.199136 | 12.24 | 5.848 |
| 14 | 14 | 15 | 1.3 | 0.8073 | 0.46228 | 48.195 | 23.0265 |
| 15 | 3 | 16 | 0.18 | 0.11178 | 0.064008 | 76.5 | 37.05 |
| 16 | 16 | 17 | 0.5 | 0.3105 | 0.1778 | 76.5 | 37.05 |
| 17 | 17 | 18 | 0.05 | 0.03105 | 0.01778 | 76.5 | 37.05 |
| 18 | 18 | 19 | 0.48 | 0.29808 | 0.170688 | 76.5 | 37.05 |
| 19 | 19 | 20 | 0.05 | 0.03105 | 0.01778 | 76.5 | 37.05 |
| 20 | 20 | 21 | 0.3 | 0.1863 | 0.10668 | 11.475 | 5.4825 |
| 21 | 20 | 22 | 0.3 | 0.1863 | 0.10668 | 11.475 | 5.4825 |

| *Sl. No.* | *From bus* | *To bus* | *Length* | *R* | *X* | *P (kW)* | *Q (kVAr)* |
|---|---|---|---|---|---|---|---|
| 22 | 20 | 23 | 0.3 | 0.1863 | 0.10668 | 11.475 | 5.4825 |
| 23 | 20 | 24 | 0.56 | 0.34776 | 0.199136 | 48.195 | 23.0265 |
| 24 | 20 | 25 | 1.02 | 0.63342 | 0.362712 | 48.195 | 23.0265 |
| 25 | 6 | 26 | 0.54 | 0.33534 | 0.192024 | 76.5 | 37.05 |
| 26 | 6 | 27 | 0.4 | 0.2484 | 0.14224 | 12.24 | 5.848 |
| 27 | 6 | 28 | 1.22 | 0.75762 | 0.433832 | 48.195 | 23.0265 |
| 28 | 6 | 29 | 1.46 | 0.90666 | 0.519176 | 48.195 | 23.0265 |
| 29 | 9 | 30 | 0.88 | 0.54648 | 0.312928 | 76.5 | 37.05 |
| 30 | 30 | 31 | 0.1 | 0.0621 | 0.03556 | 76.5 | 37.05 |
| 31 | 31 | 32 | 1.54 | 0.95634 | 0.547624 | 76.5 | 37.05 |
| 32 | 31 | 33 | 1.1 | 0.6831 | 0.39116 | 76.5 | 37.05 |
| 33 | 31 | 34 | 0.9 | 0.5589 | 0.32004 | 48.195 | 23.0265 |
| 34 | 31 | 35 | 2.1 | 1.3041 | 0.74676 | 76.5 | 37.05 |
| 35 | 12 | 36 | 2 | 1.242 | 0.7112 | 122.4 | 58.48 |
| 36 | 36 | 37 | 1.28 | 0.79488 | 0.455168 | 76.5 | 37.05 |
| 37 | 36 | 38 | 0.6 | 0.3726 | 0.21336 | 76.5 | 37.05 |
| 38 | 36 | 39 | 0.84 | 0.52164 | 0.298704 | 76.5 | 37.05 |
| 39 | 13 | 40 | 0.7 | 0.4347 | 0.24892 | 48.195 | 23.0265 |
| 40 | 14 | 41 | 0.77 | 0.47817 | 0.273812 | 76.5 | 37.05 |
| 41 | 14 | 42 | 0.72 | 0.44712 | 0.256032 | 48.195 | 23.0265 |