OPTIMAL CAPACITOR PLACEMENT IN RADIAL DISTRIBUTION SYSTEMS USING DIFFERENTIAL EVOLUTION

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Abstract: *This paper presents a novel approach that determines the optimal location and size of capacitors on radial distribution systems to improve voltage profile and reduce the active power loss. Capacitor placement & sizing are done by Loss Sensitivity Factors and Differential Evolution respectively. Loss Sensitivity Factors offer the important information about the sequence of potential nodes for capacitor placement. These factors are determined using single base case load flow study. Differential Evolution is well applied and found to be very effective in Radial Distribution Systems for capacitor placement. The proposed method has been successfully implemented on IEEE 10, 15, 34, 69 and 85 bus radial distribution systems.*

Key words: *Capacitor Placement, Radial Distribution Systems, Loss Sensitivity Factors, Differential Evolution.*

1. Introduction

As Distribution Systems are growing large and being stretched too far, leading to higher system losses and poor voltage regulation, the need for an efficient and effective distribution system has therefore become more urgent and important. In this regard, Capacitor banks are added on Radial Distribution system for Power Factor Correction, Loss Reduction and Voltage profile improvement.

With these various Objectives in mind, Optimal Capacitor Placement aims to determine Capacitor location and its size. Optimal Capacitor Placement has been investigated over decades. Early approaches were based on heuristic techniques. In the 80's, more rigorous approaches were suggested as illustrated by Grainger [1-2] and Baran Wu [3-4] formulated the Capacitor Placement as a mixed integer non-linear program. In the 90's combinatorial algorithms were introduced as a means of solving the Capacitor Placement Problem and neural network technique based papers [5] and [6] were investigated. Ng and Salama [7] have proposed a solution approach to the capacitor placement problem based on fuzzy sets theory. Using this approach, the authors attempted to account for uncertainty in the parameters of the problem. They model these parameters by possibility distribution functions. Chin [8] uses a fuzzy dynamic programming model to express real power loss, voltage deviation, and harmonic distortion in fuzzy set notation. Sundharajan and Pahwa [9] used genetic algorithm for capacitor placement. Simulated Annealing [10], Tabu Search [11], Ant colony optimization [12] and Particle Swarm Optimization [23, 26] searches are used for optimal capacitor placement problems. Salem Arif and Abdelhafid Hellal [27] have also used various meta- heuristic techniques for reactive power optimization problem.

In this paper, Capacitor Placement and Sizing are done by Loss Sensitivity Factors and Differential Evolution (DE) respectively. DE is used for estimation of required level of shunt capacitive compensation to improve the voltage profile of the system. The proposed method is tested on IEEE 10, 15, 34, 69 and 85 bus radial distribution systems and results are very promising. In this paper, Vector based Distribution Load Flow method (VDLF) [13] with Sparsity Technique [14] is used. With the support of sparsity technique the VDLF found to be very effective.

2. Loss Sensitivity Factors

A methodology is used to determine the candidate nodes for the placement of capacitors using Loss Sensitivity Factors. The estimation of these candidate nodes basically helps in reduction of the search space for the optimization procedure.

Consider a distribution line connected between 'p' and 'q' buses as shown in Fig 1.

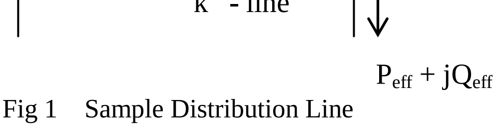

Fig 1 Sample Distribution Line

Active power loss in the k^{th} line is given by $[I_k^2]*R[k]$, which can be expressed as,

$$P_{lineloss}[q] = \frac{\left(P_{eff}^2[q] + Q_{eff}^2[q]\right)R[k]}{\left(V[q]\right)^2} \quad (1)$$

Similarly the reactive power loss in the k[th] line is given by

$$Q_{lineloss}[q] = \frac{\left(P_{eff}^2[q] + Q_{eff}^2[q]\right)X[k]}{\left(V[q]\right)^2} \quad (2)$$

Where,

$P_{eff}[q]$ = Total effective active power supplied beyond the node 'q'.

Q_{eff} [q] = Total effective reactive power supplied beyond the node 'q'.

Now, both the Loss Sensitivity Factors can be obtained as shown below:

$$\frac{\partial P_{lineloss}}{\partial Q_{eff}} = \frac{\left(2 * Q_{eff}[q] * R[k]\right)}{\left(V[q]\right)^2} \quad (3)$$

$$\frac{\partial Q_{lineloss}}{\partial Q_{eff}} = \frac{\left(2 * Q_{eff}[q] * X[k]\right)}{\left(V[q]\right)^2} \quad (4)$$

The Loss Sensitivity Factors ($\partial P_{lineloss}/\partial Q_{eff}$) are calculated from the base case load flows and the values are arranged in descending order for all the lines of the given system. A vector bus position 'bpos [i]' is used to store the respective 'end' buses of the lines arranged in descending order of the values ($\partial P_{lineloss}/\partial Q_{eff}$). The descending order of ($\partial P_{lineloss}/\partial Q_{eff}$) elements of "bpos[i]' vector will decide the sequence in which the buses are to be considered for compensation. This sequence is purely governed by the ($\partial P_{lineloss}/\partial Q_{eff}$) and hence the proposed 'Loss Sensitive Coefficient' factors become very powerful and useful in capacitor allocation or Placement. At these buses of 'bpos[i]' vector, normalised voltage magnitudes are calculated by considering the base case voltage magnitudes given by (norm[i]= V[i]/0.95). Now for the buses whose norm[i] value is less than 1.01 are considered as the candidate buses requiring the Capacitor Placement. These candidate buses are stored in 'rank bus' vector. It is worth note that the 'Loss Sensitivity factors' decide the sequence in which buses are to be considered for compensation placement and the 'norm[i]'decides whether the buses needs Q-Compensation or not. If the voltage at a bus in the sequence list is healthy (i.e., norm[i] >1.01) such bus needs no compensation and that bus will not be listed in the 'rank bus' vector. The 'rank bus' vector offers the information about the possible potential or candidate buses for capacitor placement.

Table 1

Loss Sensitivity Coefficients of a 15-bus distribution System

$\partial P_{lineloss}/\partial Q_{eff}$ **(descending)**	**Bus No.**	**Norm[i] V[i]/0.95**	**Base voltage**
0.029661	2	1.0224	0.971283
0.016437	6	1.0086	0.958232
0.015485	3	1.0069	0.956669
0.008526	11	0.9990	0.949952
0.006182	4	1.0009	0.949952
0.005266	12	0.9955	0.945829
0.004134	9	1.0188	0.967971
0.003141	15	0.99835	0.94844
0.002966	14	0.9985	0.948608
0.002811	7	1.0063	0.956008
0.001678	13	0.9942	0.944517
0.001613	8	1.007263	0.956954
0.001342	10	1.01768	0.966897
0.001256	5	0.99985	0.949918

Table 1 shows the active power line 'Loss Sensitivity Coefficients' placed in descending order along with its bus identification and normalized voltage magnitudes of 15 bus radial distribution system. Rank bus vector of 15-bus Radial Distribution System contains set of sequence of buses given as {6,3,11,4,12,15,14,7,13,8,5}.

Now sizing of Capacitors at buses listed in the 'rank bus' vector is done by using Differential Evolution based algorithm.

3. Differential Evolution

Differential Evolution (DE) is a population based optimization algorithm, proposed by Storn and Price [21], [22]. This has attracted several applications in the recent years due to its simple concept, easy implementation and quick convergence. DE has been successfully applied to a variety of continuous unconstrained optimization problems. It has few algorithm parameters to be selected, thus it is relatively easy to determine them. The algorithm draws inspiration from the field of evolutionary computation as it embeds implicit concepts, mutation, recombination and fitness based selection to evolve from an initially generated random population to a solution of problem of interest. It also borrows principles of Social Algorithms through the manner in which new individuals are generated. Unlike the typical binary chromosome of GA, an individual in DE is generally comprised of real valued chromosomes. Like other evolutionary algorithms, DE simplifies continuous optimization problems by allowing functional parameters to be represented as floating-point variables and is mutated with a simple arithmetic operation. DE's adaptive mutation scheme is easy to implement and simple to use. In the most successful implementation of DE, random vector differentials are added to the *best-so-far* solution in order to perturb it. Due to these features of DE, it takes less computational time to obtain the optimal solution for a combinatorial problem. The general elements of the DE are briefly explained as follows:

Initial Population: It is a set of 'n' number of randomly generated particles between (0, 1) for each generation 'G' represented as $X_i(G) = \{X_1, X_2 \dots X_n\}$

Mutation: For each target vector a mutant vector is generated $V_{i,G+1}$=gbest+ F* diff

Where, diff = $(X_{r1,G},- X_{r2,G}) + (X_{r3,G},-X_{r4,G})$ with r1, r2, r3 and r4 are random indexes ϵ {1,2,…n}

F is a real and constant factor ϵ {0, 2} which amplifies the differential variations.

Cross over: The mutated vector parameters are mixed with the parameters of another predetermined vector called as trail vector. Parameter mixing is often referred as crossover. To increase the diversity of the perturbed parameter vectors, crossover is used. where the trial vector is given by trail[i]= $\{U_{1i,G+1}, U_{2i,G+1}, U_{3i,G+1}, \dots U_{ni,G+1},\}$

4. Algorithm for Capacitor Placement Using Loss Sensitivity Factors and Differential Evolution

Step 1: Read the system data

Step 2: Run the base case distribution load flow and determine the active power loss (pl).

Step 3: Identify the Candidate buses for placement of capacitors using Loss Sensitivity Factors.

Step 4: Generate randomly 'n' number of particles, where each particle is represented as

$Q_{c,}[i] = Q_{min} + (Q_{max} - Q_{min})*$ rand( ) $i \in 1,2,\dots n$

where, rand( ) is a random number between (0,1)

Step 5: Initialize the candidate bus 'd' and gen=1

Step 6: Initialize the count i=1

Step 7: Determine the mutant vector $V_{i,G+1}$

Step 8: if rand( )<CR then assign trail[i]=$V_{i,G+1}$

Step 9: if rand( )>CR then assign trail[i]= $Q_c[i]$

Step10: Enforce the trial[i] within qmax and qmin limits.

Step11: Assign Q_{comp} =trail[i]

Step12: Run the load flows by placing the Q_{comp} at the candidate bus

Step13: Evaluate the fitness value fit[i]=1/(1+pl)

Step14: Store the 'gbest' fitness value among all the fitness values.

Step15: Repeat the steps from 7 to 14 until 'i' reaches to D particles

Step16: Sort the particles in the descending order of their fitness values.

Step 17: Find error= fitness of first particle-fitness of last particle

Step 18: If error<=tolerance then problem is said to be converged and store the corresponding Q_{comp} value else go to step 20.

Step19: Place the compensation Q_{comp} at the candidate bus 'i'.

Step20: Advance the generation count 'gen', if gen== genmax go to step 21 else go to step 6.

Step21: If the saving in active power loss > 3.4 KW then increment candidate bus –d else go to step 22.

Step22: Problem not converged in 'gen' iterations

Step23: Print the results and stop

5. Test Results

The proposed method for loss reduction by capacitor placement is tested on IEEE 10bus [15], IEEE 15bus [13], IEEE 34bus [15] and IEEE 69 bus [3] radial distribution systems. The various constants used in the proposed algorithm are population size (*n*) = 60, and Cross over (CR) = 0.751 and scaling mutant constant (*F*) =1.0.The 'Q^{min}' and 'Q^{max}' values used for various distribution test systems are given as

For 10 bus system : Q^{min} = 0 p.u., Q^{max} = 12 p.u.

For 15 bus system : Q^{min} = 0 p.u., Q^{max} = 5 p.u.

For 34 bus system : Q^{min} = 0 p.u., Q^{max} = 8 p.u.

For 69 bus system : Q^{min} = 0 p.u., Q^{max} = 0.8 p.u.

A. Test Case 1: IEEE 10-bus distribution system

Table 2 shows the test results of the proposed capacitor placement method for loss reduction on the IEEE 10-bus system. The results of proposed method are compared with the results of the Fuzzy Reasoning method [15] in which the total compensation placed is 4950 kvar with a loss reduction of 10.06 %. For the Particle Swarm Optimization (PSO) based method [23] it is 3186 kvar with a loss reduction of 11.17%. In case of the proposed Differential Evolution (DE) Optimization based method, the total compensation value is only 3130 kvar with a better loss reduction of 11.42%. It may be noted that there is a significant reduction in shunt compensation requirement with improved percentage of loss reduction.

Table 2
Test Results of IEEE 10- bus distribution system

Base Case Active Power Loss = 783.756 kW			
Bus No.	**Fuzzy Reasoning based [15]**	**PSO [23]**	**DE**
6	1950	1174	1200
5	1050	1182	1200
9	-------	264	730
10	900	566	-------
4	1050	-------	-------
Total kvar	4950	3186	3130
Loss (kW)	704.88	696.21	694.28
Loss Reduction (kW)	78.876	87.546	89.476

B. Test Case 2: IEEE 15-bus distribution system

From the results presented in Table 3, it is observed that the proposed DE based method has offered a better optimum solution in terms of potential locations and maximum loss reduction when compared to the results of the methods reported in [24], [18] and [23].

Table 3
Test Results of IEEE 15- bus distribution system

Base Case Active Power Loss = 61.78 kW				
Bus No.	**Method in [24]**	**Method in [18]**	**PSO [23]**	**DE**
6	300	388	321	500
3	150	805	871	454
11	150	----	---	178
4	300	----	---	---
Total kvar	900	1193	1192	1132
Loss(kW)	33.2	32.6	32.7	32.3
Loss Reduction (kW)	28.56	29.18	29.08	29.48

C. Test Case 3: IEEE 34-bus distribution system

Table 4 shows the case study results of the proposed capacitor placement method for loss reduction on the 34-bus system. Test results of the proposed method are compared with the results using Expert System (ES) method [25], Fuzzy Expert Systems (FES) method [20] and PSO based method [23]. It is observed that, the proposed capacitor placement method using DE technique has reduced the active power loss to 23.82%. This clearly indicates the better optimal solution is realized using DE based method. The results reported in [25] and [20] have offered sub-optimal solutions.

Table 4
Test Results of IEEE 34- bus distribution system

Base Case Active Power Loss = 221.67 kW				
Bus No.	**ES [25]**	**FES [20]**	**PSO [23]**	**DE**
19	-----	-----	781	800
22	900	-----	803	800
20	-----	-----	479	424
24	-----	1500	-----	-----
5	750	-----	-----	-----
17	-----	750	-----	-----
7	-----	450	-----	-----
Total kvar	1650	2700	2063	2024
Loss (kW)	173.6	168.98	168.89	168.86
Loss Reduction (kW)	48.07	52.69	52.78	52.81

D. Test Case 4: IEEE 69-bus distribution system

Table 5 shows the case study results of the proposed DE based capacitor placement method for loss reduction on the IEEE 69-bus system. For the Particle Swarm Optimization (PSO) based method [23] it is 1656 kvar with a loss reduction of 26.47%. In case of the proposed Differential Evolution (DE) Optimization based method, the total compensation value is only 1555 kvar with a better loss reduction of 26.49%. It may be noted that there is a significant reduction in shunt compensation requirement with improved percentage of loss reduction.

Table 5
Test Results of IEEE 69- bus distribution system

Base Case Active Power Loss = 224.97 kW		
Bus No.	**PSO[23]**	**DE**
46	697	766
47	959	789
50	-----	-----
Total kvar	1656	1555
Loss (kW)	165.41	165.36
Loss Reduction (kW)	59.56	59.61

E. Test Case 5: IEEE 85-bus distribution system

Table 6 shows the test results obtained using the proposed capacitor placement method. It is observed that Differential Evolution method has reduced the active power loss of the system to 49.05% where as the Particle swarm optimization method has reduced the active power loss only to 48.26%.

This proposed Differential Evolution based capacitor placement with Loss sensitivity Factors method saves not only initial investment on the capacitors but also running cost as it places the capacitors in a optimum number of locations.

Table 6
Test Results of IEEE 85- bus distribution system

Base Case Active Power Loss = 315.6 kW		
Bus No.	**PSO[23]**	**DE**
8	796	1700
58	453	250
27	901	150
29	-------	150
34	-------	150
52	-------	50
7	314	-------
Total kvar	2464	2450
Loss (kW)	163.3	160.77
Loss Reduction (kW)	152.3	154.83

6. Conclusion

In this paper, an algorithm that employs Differential Evolution, a meta heuristic parallel search technique is used for estimation of required level of shunt capacitive compensation to improve the voltage profile of the system and reduce active power loss. Loss Sensitivity Factors are used to determine the optimum locations required for compensation. The main advantage of this proposed method is that it systematically decides the locations and size of capacitors to realize the optimum sizable reduction in active power loss and significant improvement in voltage profile. Test results on IEEE 10, 15, 34, 69 and 85 bus systems are presented. The method places capacitors at less number of locations with optimum sizes and offers much saving in initial investment and regular maintenance.

7. Acknowledgement

The authors gratefully acknowledge the support and facilities extended by the Department of Electrical Engineering, National Institute of Technology, Warangal and Vaagdevi College of Engineering, Warangal (A.P) India.

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