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RESEARCH ARTICLE

DIFFERENTIAL EVOLUTION FOR OPTIMAL CAPACITOR PLACEMENT IN RADIAL DISTRIBUTION SYSTEM

***Chandram Karri**

Department of Electrical and Electronics Engineering, S R Engineering College, Warangal, Telangana, India

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ABSTRACT

In this paper, Differential Evolution (DE) has been proposed for optimal sizing of capacitors to reduce the power loss and to improve the voltage profile in a radial electric distribution system. Power Loss Index is used for finding the potential buses in the electric distribution system and then the DE is used to determine the sizing of capacitors that are to be placed at the potential locations in order to reduce the power losses and to improve the voltage profile. The proposed approach has been implemented and tested on various standard test cases such as 10- bus and 85- bus systems. The simulation results obtained by the proposed approach have been compared with uncompensated system in terms of the power loss. Also the results have been compared with the existing methods available in literature. It has been found from the various test cases that the proposed approach provides best solution in terms of the power loss.

INTRODUCTION

An electric distribution system is a link between the sub-transmission system and the consumers of electric power (Kersting, 2012). The electric distribution systems have numerous nonlinear loads, which significantly affect the quality of power supplies. Active power loss minimization and enhancing the voltage profiles at each bus is one of the major challenges in radial distribution network. Power losses are more in the distribution system due to the flow of reactive currents. Capacitor placement is one of the most effective and useful methods in reducing the power loss and improving the voltage profile in distribution system networks (Divya and Siva Krishna Rao, 2013). Installation of capacitors is beneficial only when those are placed at potential locations in order to reduce the power losses and to improve the voltage profile at each bus in the system. To achieve the benefits of loss reduction and voltage profile improvement under various operating constraints, the optimal location and size of capacitors to be placed at different load levels has to be determined. Mathematically, the optimal capacitor placement is a combinatorial optimization problem because it involves the optimization of size of the capacitor to minimize the power loss and improve the voltage profile.

****Corresponding author: Chandram Karri***
Department of Electrical and Electronics Engineering, S R Engineering College, Warangal, Telangana, India.

Various bio-inspired algorithms have been proposed over several years in different fields in engineering (Binitha and Siva Sathya, 2012). A load flow technique for radial distribution networks has been developed in (Das*et al.,* 1995). Loss sensitivity factors are used in (Prakash and Sydulu, 2008) to determine the potential location of capacitors required for compensation. A forward and backward sweep algorithm for evaluating the node voltages iteratively has been presented in (Vinoth Kumar, and Selvan, 2008). A MATLAB program for load flow analysis using Gauss-Siedel method has been developed in (Srikanth*et al.,* 2013). The bus-injection to branch-current matrix and the branch-current to bus-voltage matrix have been used in (Jen Hao Teng 2003) to obtain unbalanced three phase load flow solutions. A simple three phase load flow method to solve three-phase unbalanced radial distribution system (RDS) has been developed.Past decade many heuristic and modern heuristic methods have been applied for capacitor placement problem. In (Prakash. K and Sydulu, 2007), Capacitor placement and sizing are done by Loss Sensitivity Factors and Particle swarm optimization. Self-adaptive harmony search algorithm is used in (Rani*et al.,* 2013) to determine the capacitor sizes in order to reduce the power loss and improve the voltage profile. A direct search algorithm for capacitive compensation in radial distribution systems has been proposed in (Ramalinga*et al.,* 2012) and the results are compared with results of particle swarm optimization and genetic algorithm. The total distribution loss is significantly lesser than the one obtained in the other two methods. In (Das, 2008), multi-objective approach for determining the optimum values of fixed and switched shunt capacitors to improve the voltage profile and maximizing the net savings in a radial distribution system has been suggested. The Cuckoo search algorithm has been proposed in (Attia*et al.,* 2014) for solving capacitor placement problem to minimize the system losses and to improve the voltage profiles at different load levels. Teaching learning based optimization (Sneha Sultana and Provas Kumar Roy, 2014) is proposed for capacitor placement problem. Mixed integer non-linear programming is suggested in (Sayyad Nojavan*et al.,* 2014) for optimal placement of capacitors.In the recent past, the Differential evolution (Nasimul Noman and Hitoshi Iba, 2008; Sudhakar*et al.,* 2017) has been proposed to solve different problems such as economic dispatch, unit commitment and optimal power flow in optimal operation of power system. It is found that the DE is very powerful technique in solving the complex problem. In capacitor placement problem, there is a need to reduce the power loss by selecting the proper sizing of the capacitors. Hence, in this paper, DE has been used.Rest of the paper is organized as follows. Section II provides the problem formulation of capacitor placement. Section III describes overview of differential evolution algorithm. Section IV provides the details about the proposed approach. Section V presents the case studies on distribution networks and simulation results. Section VI outlines the conclusions.

Capacitor Placement Problem in Radial Distribution system

The objective of the optimal capacitor placement problem is to determine the location and size of the capacitors to be installed in the radial distribution system. This results in power loss reduction and voltage profiles improvement at each bus.

Objective function

The objective function is to minimize the power loss in the electric distribution system network.

The power loss of a distribution system is calculated as:

$$P_{loss} = \sum_{i=1}^{n} I_i^2 R_i \quad \text{.. (1)}$$

where I_i and R_i are the current and resistance of circuit branch i; n is the number of circuit branches. A low P_{loss} value indicates economic operation of a network.

Constraints

The objective function is subjected to the following constraint.
Voltage constraints: To provide quality electrical supply, the voltage magnitude at each bus after the placement of the capacitors must be within a permissible range and is expressed as

$$V_{min} \leq V \leq V_{max} \quad \text{.. (2)}$$

where V_{min} and V_{max} are taken as 0.95 pu and 1.05 pu respectively.

Differential Evolution

Differential Evolution (DE) is a population based stochastic algorithm introduced by Storn and Price in 1995. It is a bio-inspired algorithm and another paradigm in Evolutionary Algorithm (EA) family. This method is more suitable for highly nonlinear, non-convex and non-smooth global optimization problems. DE algorithm has several advantages like easy implementation, fast convergence, reliable, accurate, robust and, little parameter tuning. Similar to the other members of the EA family it has four stages such as: initialization, crossover, mutation and selection operators. Brief description of each stage is provided below.

Initialization

It is the first stage in the DE algorithm. The population is initialized randomly over the entire search space and cover upper and lower bounds $X_{max}$and X_{min} respectively.

Where

$$X_{max} = \{X_{1,max}, X_{2,max}, X_{3,max}, \ldots\ldots, X_{D,max}) \quad \text{............ (3)}$$

$$X_{min} = \{X_{1,min}, X_{2,min}, X_{3,min}, \ldots\ldots, X_{D,min}) \quad \text{............ (4)}$$

The j^{th} component of the i^{th} individual is defined as

$$x_{i,j} = x_{j,min} + rand * (x_{j,max} - x_{j,min}) \quad \text{.......………… (5)}$$

Where i = 1,2 …. N_p , j = 1,2,….. D

Mutation

Second step of the DE algorithm is mutation process. It is to introduce the next generation child’s into the population. It plays an important role in the reproduction cycle. Mutation is performed by choosing three individuals in a random manner from the population.

If X_{r1}, X_{r2}, and X_{r3} are random variables, the mutation performed during G^{th} generation as

$$V_i^{G+1} = X_{rbest}^G + F * (X_{r2}^G - X_{r3}^G) \quad \text{…………………….. (6)}$$

Where V_i^{G+1} is the perturbed mutated individual, X_{rbest}^G is the best individual among the three individual random variables. The difference of the remaining two random numbers is scaled by a factor F, which controls the amplification of the two individuals to improve convergence process by avoiding search stagnation.

Crossover

This stage involves binary crossover between the target vector $X_{i,j}$ and mutant vector $V_{i,j}$, to produce new off-spring’s. The trail vectors are produced according to

$$u_{i,j}^{G+1} = \begin{cases} V_{ij}^{G+1} \; if rand(0,1) \leq CR \\ X_{ij}^G otherwise \end{cases} \quad \text{……………………… (7)}$$

Where CR is a user defined crossover constant that controls the diversity of the population and avoids getting trapped into the local optima.

Selection

Selection procedure is performed among the trail vector and the updated target vector to select the best set of individuals for the next generation. Each solution has equal chance ofbeing selected as parents. If the trail vector f ($\boldsymbol{U_{i,G}}$) has better value, then it replaces the target vector f ($\boldsymbol{X_{i,G}}$) with the trail vector as per the equation given below.

$$X_{i,G+1} = \begin{cases} U_{i,G} iff (U_{i,G}) \le f(X_{i,G} \\ X_{i,G} otherwise \end{cases} \quad \text{.......................... (8)}$$

Proposed Approach

Three stages are involved in the proposed approach. Initially, distribution load flow is run for the base case system, in order to find the power loss and voltage profile then PLI is used to determine the potential buses and differential evolution is finally used to find the optimal sizing of the capacitors. Brief information about the above methods is provided here.

A. Distribution Load Flow

Generally distribution networks are radial and the R/X ratio is very high. Load flow analysis of distribution systems is different from the load flow analysis of transmission systems. Because of this, distribution networks are ill conditioned and conventional Newton-Raphson (NR) and fast decoupled load flow (FDLF) methods are inefficient at solving such networks. The figure shows a two bus system, where sending end voltage is known and receiving end voltage is to be obtained.

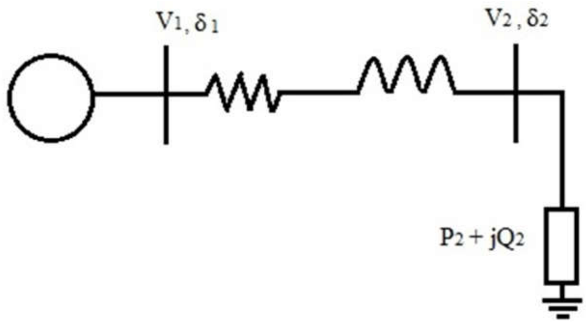

Fig. 1. Two bus radial distribution system

P_2 and Q_2 are effective active and reactive powers at node 2 in the Fig. 1. The magnitude of voltage and loss calculation is performed. The same equations are used along with the matrices developed from network topology method. For distribution systems, the models which are based on the effective load at every node is very convenient. At each bus 'i' the complex power S is specified by:

$$S_i = P_i + Q_i \quad \text{.. (9)}$$

P_i and Q_i are the real power and imaginary powers at i^{th} node.Bus-injection to branch current matrix (BIBC): Effective load at node [N] can be obtained by,

[N] = [BIBC][S] .... (10)

The constant BIBC matrix has entries of 1, -1 and 0 only. For a distribution system with m-branch sections and n-load buses, the dimension of the BIBC is m*n. The bus, where there is no load need not enter into matrix [S]. Line loss to node power matrix (LLNP): End nodes will not have to supply any line loss component. So, they will have all zeroes in their corresponding rows. Node 2 will have to supply all the line losses except branch-1 loss. S_L is the column matrix containing all line losses.

[N']=[LLNP][S_L] .... (11)

Effective load at each node = N + N'

Algorithm for the load flow solution

1. Read the system data, V_1= 1.0 pu. Line losses are assumed to be zero in the first iteration.
2. Build BIBC matrix and LLNP matrix
3. Obtain $P_{effective}$ + j*$Q_{effective}$ at each node using [N] = [BIBC][S], N represents the part of load powers in the effective load at various nodes, S is the column matrix of all loads
4. Initialize iteration count = 1
5. Obtain receiving end voltages
6. Calculate power loss on all lines using the formulae:

$$P_{loss}[j] = \frac{P_2^2+Q_2^2}{V_2^2} R[j] \quad \text{.................................... (12)}$$

$$Q_{loss}[j] = \frac{P_2^2+Q_2^2}{V_2^2} X[j] \quad \text{.................................... (13)}$$

$$S_{loss} = P_{loss} + jQ_{loss} \quad \text{.................................... (14)}$$

7.Multiply the power loss column matrix, S_L with LLNP matrix to get N' matrix. N' represents the part of line losses in the effective load at various nodes.

8. Effective load at each node = N + N'

B.Determining Potential buses using Power Loss Index (PLI)

The candidate locations for capacitor placement are determined using power loss index (PLI). 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.

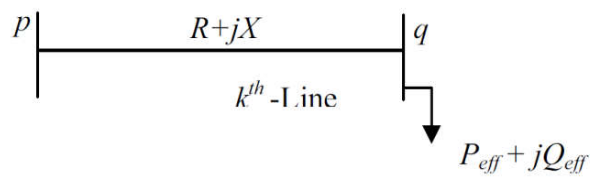

Fig. 2. Radial distribution system with load

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

$$P_{lineloss}[q] = \frac{P_{eff}^2[q]+Q_{eff}^2[q]}{V^2[q]} R[k] \quad \text{...................... (15)}$$

Similarly the reactive power loss in the kth line is given by

$$Q_{lineloss}[q] = \frac{P_{eff}^2[q]+Q_{eff}^2[q]}{V^2[q]} X[k] \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

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'.

The load flow (LF) runs are necessary to obtain the loss reduction (LR) by compensating the total reactive load at every bus of the distribution system taking one bus at a time, except slack bus with Q totally compensated at that node from resulted power without any compensation provided. PLI value for the mth node can be obtained using

$$PLI(m) = \frac{LR(m)-LR_{min}}{LR_{max}-LR_{min}} \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

The buses of higher PLI and lower bus voltage values have more chances of being identified as candidate locations. One drawback of this method is the calculation burden, as the LF requires running for times equal number of buses before starting the optimization process. The following are the steps to be implemented to find out the high potential buses for capacitor allocations using PLI:

- Run LF and obtain initial real power loss and bus voltages.
- Do for all buses, except slack bus. Inject capacitive reactive power equal to load reactive power. Run LF and obtain real power loss. Calculate LR = (initial real power loss–real power loss) and store.
- Obtain maximum and minimum LRs.
- Calculate PLI for all buses, except slack.
- Sort the values of PLI for respective buses in descending order.
- The buses whose voltage is less than 95% are identified as candidate buses for capacitor placement.

C. Differential Evolution for Sizing of the capacitor

The sizing of capacitors is done at the potential locations obtained by PLI. The DE algorithm is implemented by taking size (kvar) of capacitor as an individual in the population. The number of decision variables is the number of locations at which capacitor is to be placed. The procedure for implementing the DE algorithm in solving optimal capacitor placement problem summarized in the following steps.

Step 1: Import line data and load data of the radial distribution system.
Step 2: Run DLF for the given data to find the voltage profiles and power losses at different buses.
Step 3: Using PLI, find the potential locations for capacitor placement.
Step 4: Randomly generate the DE population and initialize the parameters.
Step 5: Perform mutation and crossover steps and run DLF for whole population.
Step 6: Compare the power loss of new generation with the previous one for each individual. Replace the one with lesser power loss compared to previous ones.
Step 7: If maximum iterations are reached, then stop. Otherwise repeat steps 5-7

Case Studies and Simulation results

The proposed approach has been developed in MATLAB (R2012 A) on Laptop (Intel R i3, 2.10 Ghz, 4 GB RAM). It has been tested on various test cases such as 10-bus and 85-bus systems in order to prove the applicability of the proposed approach. All case studies including the simulation results have been presented in the following sections.Control parameters used during execution of differential algorithm are given below.

Population =50
Maximum iterations =100
Scaling factor (F)=0.0005
Cross over constant (CR) = 0.6

A. 10- Bus system

The data of 10 bus system is taken from (Sultana et al., 2014). The 10- bus system is shown in Fig. 3. The line and bus data of 10 bus system are given in Table 1 and 2. The base voltage of the 10-bus system is 23 kV.

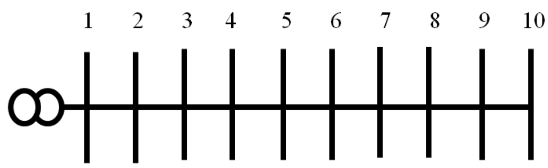

Fig. 3. 10-bus system

Table 1.Line data of 10- bus system

Sending end node	Receiving end node	R (ohm)	X (ohm)
1	2	0.1233	0.4127
2	3	0.014	0.6057
3	4	0.7463	1.205
4	5	0.6984	0.6084
5	6	1.9831	1.7276
6	7	0.9053	0.7886
7	8	2.0552	1.164
8	9	4.7953	2.716
9	10	5.3434	3.0264

Table 2. Bus data of 10- bus system

Bus No.	P (KW)	Q (KVAR)
1	0	0
2	1840	460
3	980	340
4	1790	446
5	1598	1840
6	1610	600
7	780	110
8	1150	60
9	980	130
10	1640	200

The initial active power loss for given line data and load data is 742.61 KW. The ideal power loss in the absence of any reactive power flow in the system is 654.33 KW.Voltages and rotor angles of the un-compensated and compensated systems are shown in Fig. 4 and Fig. 5.

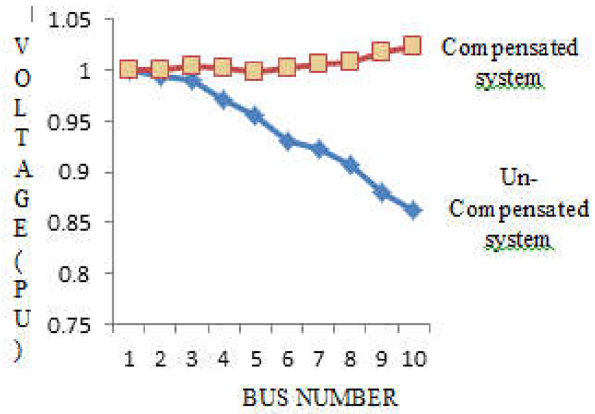

Fig. 4. Voltage profiles of un-compensated and compensated systems for 10-bus system

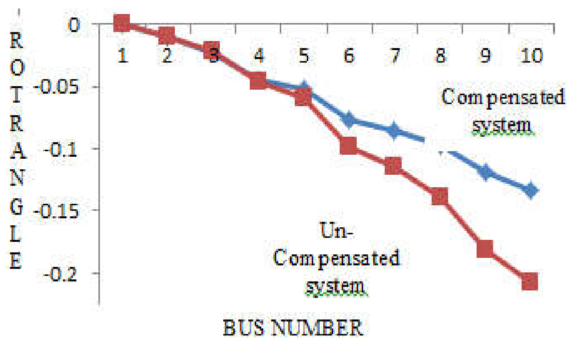

Fig. 5. Rotor angles of un-compensated and compensated systems for 10-bus system

Iteration versus Power loss of DE algorithm is shown in Fig. 6.

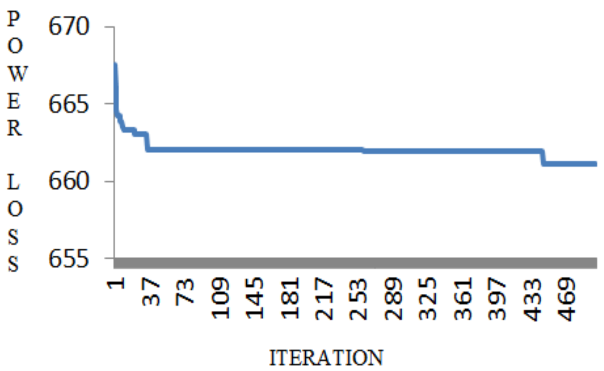

Fig. 6. Iteration versus Power loss of a 10 bus system

Placement and sizing by the DE is given in Table 3.

Table 3. Placement and size of capacitors

Bus position	Kvar needed
9	927.30
10	955.13

Power losses of un-compensated system and compensated system are presented in Table 4.

Table 4. Power losses of un-compensated system and compensated system of 10- bus system

Bus Number	Uncompensated Power loss		Compensated Power loss	
	Active loss (in KW)	Reactive loss (in KVAR)	Active loss (in KW)	Reactive loss (in KVAR)
2	44.76	149.82	32.79	109.74
3	3.78	163.53	2.78	120.11
4	167.78	270.90	125.76	203.06
5	107.11	93.30	82.76	72.09
6	181.08	157.75	181.08	157.75
7	45.53	39.66	45.53	39.66
8	72.02	40.79	72.02	40.79
9	83.55	47.32	83.55	47.32
10	37.00	20.96	35.26	19.97

The power loss obtained by using proposed algorithm is 661.524 KW. The results of the proposed method are compared with the results of PSO (Prakash and Sydulu, 2007), Plant Growth Simulation algorithm (Srinivasa Rao and Narasimham, 2008) and MINLP (Sayyad Nojavan*et al.,* 2014) and provided in Table 5.

Table 5. Results comparison

	POWER LOSS OF AFTER COMPENSATION			
	PSO	PGSA	MINLP	DE
LOSS (KW)	696.21	694.93	673.44	661.52
REDUCTION (%)	11.17	11.33	14.08	10.92
LOCATION	6,5,9,10	6,5,9,10	5,7,8,9	9,10
SIZE in kvar	1174, 1182, 264 and 566	1200, 1200, 200 and 407	400, 2000, 200 and 1400	927.30 and 955.13

B. 85-bus system

The proposed Differential Evolution method for capacitor placement has been applied to a 85-bus radial distribution test system (Das*et al.,* 1995). The base voltage of the 85-bus system is 11 kV.The active power loss of un-compensated system is 315 kW. The active power loss in the absence of any reactive power in the system is 140.51 kW. The power loss obtained by using proposed algorithm is 140.74 kW. The sizing and location of the capacitors for the proposed method are shown in Table 6. The performance of algorithm (power loss) with number of iterations is shown in Fig. 7.

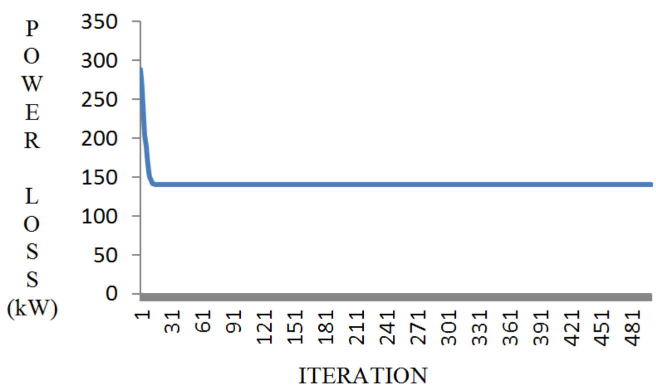

Fig. 7. Iteration versus Power loss of a 85 bus system

The results of the proposed method are compared with the results of PSO (Prakash and Sydulu, 2007), Plant Growth Simulation (Srinivasa Rao and Narasimham, 2008) and MINLP (Sayyad Nojavan*et al.,* 2014) and provided in Table 7.

Table 6. Placement and size of capacitors

Bus	Kvar needed	Bus	Kvar needed
8	30.2	34	28.679675
9	32.12	35	47.234913
10	34.2	36	64.763771
11	32.22	37	69.462544
12	25.35	38	71.552337
13	33.03	39	70.638356
14	50.12	40	33.480968
15	1066.42	41	40.447859
25	31.2287	42	45.018434
26	34.6079	43	64.749004
27	27.9623	44	39.824675
28	31.3831	45	45.140466
29	21.5782	46	33.886959
30	25.8622	47	31.706061
31	30.3488	48	28.946317
32	23.1724	49	43.458351
33	29.8169	50	60.207861

Table 7. Results comparison

	Compensated power loss			
	PSO	PGSA	MINLP	DE
Total Loss (Kw)	163.32	161.4	159.87	140.74
Loss Reduction (%)	48.27	48.88	49.36	55.32

Conclusion

In this paper, Differential Evolution is used for estimation of required level of shunt capacitive compensation to reduce the power loss and to improve voltage profile. Power loss index is used to determine the optimum locations required for compensation. The proposed approach has been tested on various test cases like 10- bus and 85 -bus systems. It has been observed from the simulation results that the DE provides very good results in terms of less number of locations with optimum sizes and offers much saving in initial investment and regular maintenance.

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