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Solving Optimal Capacitor Allocation Problem using DE Algorithm in Practical Distribution Networks

***Abstract**. In this paper, Differential Evolutionary (DE) algorithm has been proposed to determine optimal location, size, and number of capacitor banks in the radial distribution networks. Load of networks consist of different patterns, then in load modelling process three models have been introduced; constant and varying as well as effective loads. For capacitor installation, distribution networks are best option and as majority of distribution networks have radial topology; then DE algorithm has been tested on IEEE 10-bus radial distribution network and practical 73-bus radial distribution network of Ahvaz city in south of Iran. In this study, has been focused on cost and active power loss reduction as well as increment of minimum voltage using capacitor installation.*

***Streszczenie.** W artykule opisano wykorzystanie algorytmu DE (different evolutionary) do określania optymalnej lokalizacji, wielkości I liczby kondensatorów w sieci energetycznej. Jako obciążenie przyjęto trzy różne modele. Algorytm był testowany na IEEE 10-szynowej sieci promieniowej i 73 szynowej sieci w mieście Ahvaz w Iranie. (**Rozwiązywanie problemu optymalnej lokalizacji kondensatora w sieci energetycznej przy wykorzystaniu algorytmu ewolucyjnego DE**)*

Keywords: Differential Evolutionary Algorithm, Optimal Capacitor Placement Allocation, Practical Network, Radial Distribution Networks.
Słowa kluczowe: algorytm ewolucyjny, kondensator, sieć energetyczna

Introduction

Installation of capacitor in distribution network has many benefits; reducing reactive power consumption, improving voltage profile, improving PQ (Power Quality) (Optimal Capacitor Allocation Problem) problem, reducing annual cost. The OCAP is one of well search topics and many authors and researchers have suggested different approaches to solve OCAP in past lectures. Based on problem solve technique, we can classify these approaches in four main sets; i.e. heuristic, analytical, numerical programming, AI (Artificial Intelligence) methods. To review of past work about OCAP, we have focused on AI technique because our proposed approach is on of AI approach. Then, in this study; GA (Genetic Algorithm), PSO (Particle Swarm Optimization), IA (Immune Algorithm) and tabu search have analyzed and discussed.

GA is the most famous algorithm of EAs (Evolutionary Algorithms). In [1], GA introduced to solve OCAP, then in [2], has solved OCAP by GA and to calculate total energy loss a new fast method based on the computation of the moments of normalized daily load curves suggested. In developing process of GA, many improved GA have proposed; in [3], ESGA (Elite-based Simplex GA) hybrid approach using composition ESGA hybrid approach with multipop-GA compared with original GA to solve OCAP.

The high computational cost due to their slow convergence rate is one of main disadvantage of GA, then in [4] two different techniques proposed for speedup of GA. To determine optimal candid bus for installing capacitor banks, firstly the theory ISTN (Inherent Structure Theory of Networks) suggested. Second technique identifies the individual candidate bus at which the connection of a capacitor will give the maximum improvement of the voltage profile.

SIA (Swarm Intelligence Algorithm) consist of several algorithms that can used to solve optimization problem. PSO is most common approach in SIA. In 2004, Yu *et al.* was introduced to solve OCAP by considering varying load in presence harmonic distortion [5]. Etemadi and Fotuhi-Firuzabad studied parameters of reliability enhancement by optimal capacitor placement using PSO algorithm by considering reliability parameters [6]. Latter, Eajal and El-Hawary a discrete version of PSO has combined with a RDPF (Radial Distribution Power Flow) algorithm to form a HPSO (Hybrid PSO) algorithm for solving harmonics injected in unbalanced distribution systems [7]. Taher *et al.* have solved OCAP simultaneous with PQ improvement. Other contribution of the proposed PSO is improving particles in several steps for both converging more readily to the near global solution as well as improving satisfaction of the power quality constraints [8]. Also, Murthy *et al.* compared solution of OCAP by PSO and GA. Active and reactive power loss, and voltage magnitude is decision criteria. From this comparison in solution process of OCAP, PSO presents better results than GA [9].

IA is a branch of AI that has been used for solving OCAP placement in [10]. To show abilities of IA for solving OCAP, in addition to annual cost of system, computation time of IA has been compared with SA (Simulated Annealing) and MIP (Mixed Integer Programming).

Solving OCAP by DE (Differential Evolutionary) algorithm is main focus of this paper. In this study, in addition to cost, minimum voltage, active power loss and total installed capacitors have been selected as decision criteria. Also, in case study is considering load in three conditions. In first case, the system load is considered constant. Then, by attending to change of load daily, three load levels described. Third load condition is effective load. Test case of this paper is standard and practical networks. The 10-bus IEEE network has used for showing ability of the proposed algorithm than to other valid approaches and other test carried out on 73-bus Ahvaz network to illustrate ability of DE in practical cases.

Optimal Capacitor Placement Problem

OCAP is a nonlinear problem that is function of annual cost and is called conventional OF (Objective Function). In generally, this OF consist of two terms; first terms is sum invest of capacitor banks and capacity of installed capacitor banks multiply by corresponding cost. Second term is sum of active power loss (energy loss) of network multiply by corresponding cost.

Eqs. (1) and (2) are two OFs for constant and varying load, respectively. These OFs are same, only in second term of Eq. (2) cost of active power loss has been replaced by duration of each load level is multiplied energy cost.

(1) $$Min\left[\left(\sum_{i=1}^{NC} C_{\text{inv}} + C_{oper} \times Q_{Ci}\right) + C_{Ploss} \times \sum_{i=1}^{NB-1} P_{Loss}\right]$$

(2) $$Min\left[\left(\sum_{i=1}^{NC} C_{\text{inv}} + C_{oper} \times Q_{Ci}\right) + \sum_{h=1}^{TL} C_{Eloss} \sum_{i=1}^{NB-1}\left(P_{Loss,T_h} \times T_h\right)\right]$$

where, *NC NB*, *TL* are total the number of capacitors, bus and load levels respectively. Q_{ci} is capacity of capacitor bank. P_{Loss} and C_{Ploss} are total active power loss and related cost, respectively. $P_{Loss,Th}$ and T_h are duration of each load level and related power loss, respectively. C_{inv}, C_{oper} and C_{Eloss} are costs of investment, the operation of each capacitor bank and per energy loss, respectively.

The varying load levels has a effective load level, value of this level has been computed as follows [11],

(3) $$S_{Eff\,(i)} = \sum_{h=1}^{NLL} \frac{T_h \times P_{Loss,T_h}}{\sum_{h=1}^{NLL} T_h}$$

In this load condition, after calculate of magnitude of effective load level by Eq. (3) and obtain location and size of capacitors, these capacitors is placed in load flow program for system calculation in effective load. OCAP has five constraints that have been presented in [11].

DE Algorithm

DE algorithm is one of the EAs method that proposed in 1997 [12]. It is population based algorithm, and has five steps.

Step i) Initialization: First, initial matrix is generated with dimensions of the optimized variable as:

(4) $$u_{i,k}^{G} = u_{k\min} + rand\,[0,1] \times (u_{k\max} - u_{k\min})$$
$$i \in [1, PN\ ]\ , k \in [1, VN\ \ ]$$

In Eq. (4) u_{kmin} and u_{kmax} are lower and upper bound of the *j* variable, respectively, which are selected based on type of problem. *PN* and *VN* are population and the number of variable, respectively.

Step ii) Mutation: After generation of initial population, using mutation operator, vectors of population changed and are modified, randomly. In this process, three random vectors, U_a, U_b and U_c, placed in Eq. (5):

(5) $$U_{i(mut)}^{(G)} = U_a^{(G)} + SF\,(U_b^{(G)} - U_c^{(G)})\ , i = 1,...,PN$$

where, *a, b* and *c* are randomly selected from the set *{1,…,PN}*, that *a≠b≠c≠i* , and also *SF,* Scaling Factor, is a real and constant factor Є [0,2].

Step iii) Crossover: All population has not recombination ability, because corresponding fitness with these are far away global optimum, then crossover operator is applied. In crossover, if *CR* (Crossover Rate) is major than random number in range [0,1], vectors from mutation step are selected otherwise, selection is performed from initial population. *CR* is real value and in the range [0, 1].

(6) $$U_{ji(cross)}^{(G)} = \begin{cases} U_{ji(mut)}^{(G)} & if\ \ \rho_j \le CR\ \ or\ \ j = q \\ U_{ji}^{(G)} & otherwise \end{cases}$$
$$i = 1,...,\ PN\ \ ;\ \ j = 1,...,\ VN$$

where, ρ_j and *q* are chosen randomly from *[1,…,VN]*.

Step iv) Selection: Selection operator selects vectors corresponding with best solution for next generation as follows:

(7) $$U_i^{(G+1)} = \begin{cases} U_{i(cross)}^{(G)} & if\ \ f(U_{i(cross)}^{(G)}) \le f(U_i^{(G)})\ , \\ U_i^{(G)} & otherwise \end{cases}$$
$$i = 1,...,\ PN$$

where, $f(U_{i(cross)})$ and $f(U_i)$ are fitness corresponding with vectors of crossover and initialization steps, respectively.

Step v) Termination Criteria: The iterative process terminates when one of following two criteria is met, (1) An acceptable solution has been obtained, (2) The number of iteration reach to predetermined iteration number. We used second criteria for Termination of algorithm in this study.

Case Study

To illustrate ability of the DE algorithm, it has been tested on standard and practical network with three load conditions. The constant load condition has been tested on IEEE 10-bus standard network and varying and effective loads have been carried out on 73-bus region of Kian-pars network in Ahvaz city of Iran. The number of iteration and population are considered 400 and 40, respectively.For solution of OCAP, *VN* in Eq. (4) is the number of network buses and u_{kmin} and u_{kmax} are zero and the number of capacitor type. Total number of capacitor is 27 types and total installed capacitor banks are determined based on total reactive consumption of networks. Capacity and related cost of any capacitor types are accessible in [13].Cost per power loss and cost per energy loss are 168 *$/kW/year* and 0.06 *$/kWh/year*, respectively. Crossover rate, *CR*, is 0.1.

Scenario-1: 10-bus System with constant load

First network is IEEE 10-bus standard radial network as shown in Fig. 1. , the system data are given in [13]. The minimum and maximum voltages are 0.9 and 1.1 *p.u.*, whereas rated voltage corresponding with 23 *kV.*

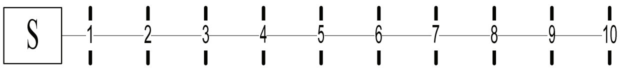

Fig. 1. 10-Bus Distribution Network

To illustrate the potential of the proposed DE algorithm for the solution of the OCAP, simulation results is compared with results of hybrid approach [11], PSO [14], fuzzy reasoning approach [15] and PGSA (Plant Growth Simulation Algorithm) [16]. This comparison has been listed in Table 1.

It can be seen that power loss of this network using DE based optimized capacitors banks is 113.6, 11.08, 26.01, 34.06, 24.73 kW less than power loss of before capacitor installation case and the represented approaches in [11], [14], [15] and [16], respectively. Minimum voltage of without capacitor case from 0.9929 *p.u.* has been raised to 1.007 *p.u*. by DE and hybrid algorithms. Finally, annual cost of DE is 16112, 757, 3020, 3945 and 2777 *$* less than cost of without capacitor and methods of [11], [14], [15] and [16], respectively.

Table 1. Results of Capacitor Placement on 10-Bus with Constant Load

Method	Total installed capacity (kVAr)	Power Loss (kW)	Min. Voltage (pu)	Cost ($)
W/O Cap.	-	783.8	0.8375	131675
Ref. [11]	10050	681.28	0.90014	116320
Ref. [14]	3186	696.21	-	118583
Ref.[15]	4950	704.26	-	119508
Ref.[16]	3007	694.93	-	118340
DE	12000	670.2	0.9014	115563

Figure 2 shows voltage profile of IEEE 10-bus system before capacitor installation and capacitor allocation by DE algorithm.

By DE algorithm, voltage profile in terminal buses is several times increased than the first buses. This concept confirms ability of DE technique to improvement of voltage profile by optimization of OCAP. Location and capacity of installed capacitors have been presented in Table 2.

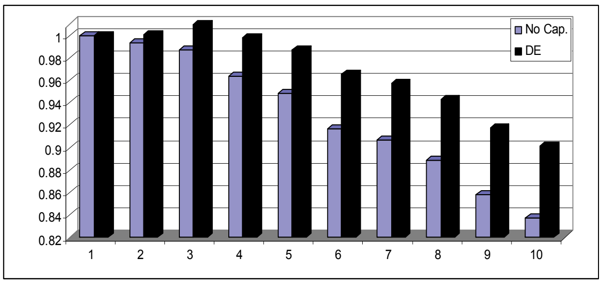

Fig. 2. Voltage Profile of 10-Bus Network

Table 2. Location/Size of Installed Capacitors on 10-Bus

Meth.	Optimal Location (Bus No.)- Optimal size (kVAr)					
Ref. [11]	3-3600	4-4050	5-450	6-1200	9-150	10-600
Ref. [14]	5-1174	6-1182	9-264	10-566	5-1174	-
Ref. [15]	4,5-1050	6-1950	10-900	-	-	-
Ref. [16]	5,6-1200	9-200	10-407	-	-	-
DE	3-4050	4-2100	5-2100	6,7-600	8,9-150	10-450

Scenario-2: 73-bus Kian-Pars distribution network with varying load condition

In this case, three load levels have been defined; i.e. first load level with 1.0 *p.u.* for 1000 *h* duration, second load level with 0.8 *pu* load for 6780 *h* duration and third load level with 0.5 *p.u.* for 1000 *h* duration. These load levels are applied on 73 bus distribution network of Kian-Pras region of Ahvaz city in south of Iran. Single diagram of this system with nominal voltage 11 *kV* is depicted in Fig. 3 [17].

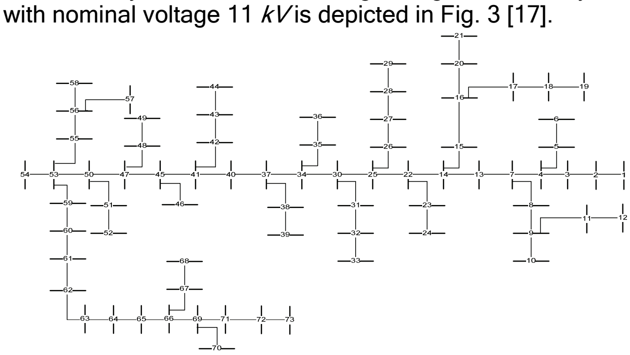

Fig. 3. 73-Bus Distribution Network

Simulation results are listed in Table 3. Location and size of installed capacitor is shown in Table 4.

Table 3. Results of Capacitor Placement on 73-Bus with Varying Load

Method	Load Level (p.u.)	Total installed capacity (kVAr)	Min Volt. (p.u.)	Power Loss (kW)	Cost ($)
W/O Cap.	1.0	-	0.95215	264.47	15868
	0.8	-	0.96209	155.07	62896
	0.5	-	0.97664	59.091	3545
DE	1.0	4800	0.97428	174	11738
	0.8	4800	0.98214	108.85	45753
	0.5	2100	0.98433	44.066	3537

Table 4. Location and Size of Installed Capacitors on 73-Bus with Varying Load

1.0 p.u.		0.8 p.u.		0.5 p.u.	
Size	Location	Size	Location	Size	Location
150	8, 12, 49, 54, 63	150	5, 10, 34, 40, 43, 46, 51, 59, 60	150	9, 14, 17, 31, 38, 47, 55, 60, 70
300	19, 50, 70	450	13, 31, 67	300	25
900	30, 45, 48	300	20, 21, 57, 61	450	27
450	71	900	38	-	-

It is evident that power loss of network using DE algorithm is 90.47, 46.22 and 15.025 kW less than power loss of without capacitor state in 1.0, 0.8 and 0.5 *pu* load levels, respectively. Minimum voltage before capacitor placement has been raised from 0.95215 to 0.97428, 0.96209 to 0.98214 and 0.97664 to 0.98433 *p.u.* in 1.0, 0.8 and 0.5 *p.u.* load levels, respectively. System costs using DE method is 4130, 17143 and 8 *$* less than costs of network without capacitor in 1.0, 0.8 and 0.5 p.u. load levels, respectively. The voltage profile of 73-bus network has been illustrated in Fig. 4.

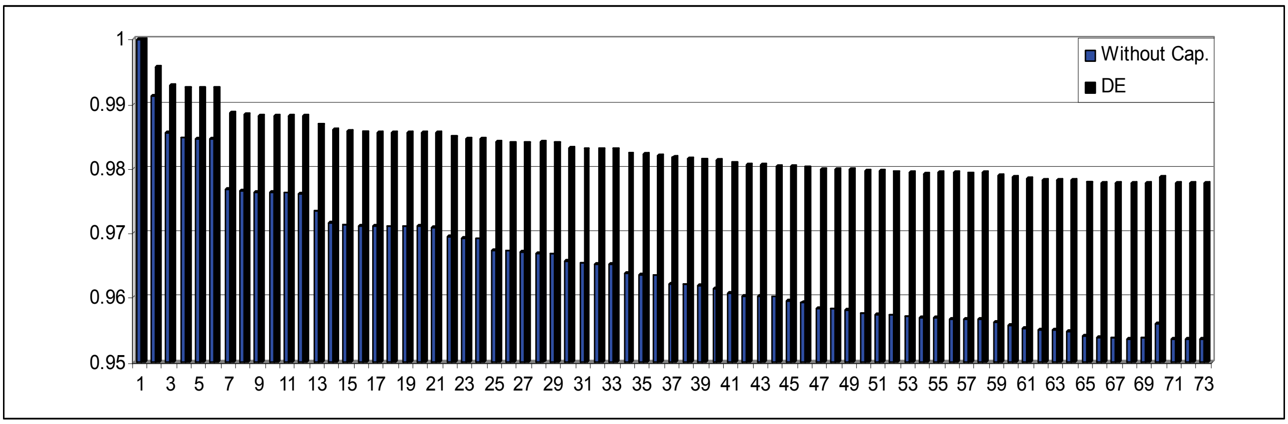

Fig. 4. Profile Voltage of 73-Bus Network

Scenario-3: 73-bus Kian Pars distribution network with effective load condition

The three load levels in scenario 2 have an effective level that is imposed on network. Value of effective load in this scenario is 0.78858 *p.u.* that is computed using Eq. (12).

Table 5. Results of Capacitor Placement on 73-bus Network with Effective Load

Parameter	value
Total installed capacity (kVAr)	4200
Power Loss (kW)	106.63
Min.Voltg. (p.u)	0.98049
Cost ($)	19348

Table 6. Location and Size of Installed Capacitors on 73-bus Network with Effective Load

DE	
Size	Location
150	2, 14, 26, 29, 36, 39, 41, 54, 61, 62, 63, 69
300	54
600	20, 34
900	57

Table 7. Results of Effective Load in Each Load Level using Effective Load Method

Load level	Power Loss (kW)	Min.Voltg. (p.u)	Cost ($)
1.0	178.63	0.97028	12151
0.8	109.92	0.97994	46017
0.5	47.364	0.9941	4276

Table 8. Energy Loss Before and After Compensation

Method	Energy loss
W/O Cap.	1352.83
DE	953.89

Conclusion

In this paper, a novel method based on evolutionary algorithm i.e. DE algorithm is proposed for optimal placement and sizing of capacitor in radial distribution networks. Cost, Minimum voltage, total installed capacity and power loss are considered as decision criteria. Results of simulation have been compared to other recently reported methods in literature. It can be concluded that:

i) ***Minimum voltage:*** Increasing minimum voltage which is occurred in terminal bus in radial networks is one of main issue. It was shown that by DE algorithm increment of minimum voltage in terminal bus is several times than other buses. This fact is clear in 73-bus network test system, especially.

ii) ***Power (energy) loss:*** This decision criteria has largest impact on annual cost; reduction of power (energy) loss by the proposed DE approach is considerable than the other reported methods.

iii) ***Cost:*** Main target of capacitor installation is reduction annual cost, thus objective function of optimal capacitor allocation problem is formulated as function of cost. Using the proposed DE algorithm, the cost is reduced in all cases for all load patterns in comparison to other represented approaches.

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