Optimal capacitor placement in distribution systems for power loss reduction and voltage profile improvement using Modified Cuckoo Search algorithm

Gurpreet Kaur[1], Shivani Sehgal Mehta[2], Dr. Chintu Rza[3]
1. M.Tech Student, 2.Assistant Professor, 3.Assistant Professor
Department of electrical engineering, DAVIET, Jalandhar [1,2,3]

Abstract: This paper discusses a novel and effective method for placing capacitors in radial distribution networks that regulate the optimum locations and size of capacitor with goal of refining the voltage profile and decreasing power losses. The solution procedure has two parts: in part one, the loss sensitivity factors are utilised to select the candidate locations for the capacitor placement and in part two modified cuckoo search algorithm is used to guess the ideal size of capacitors at the optimum buses determined in part one. The chief benefit of the proposed method is that it does not necessitate any exterior control parameters. The additional advantage is that it grips the objective function and the constraints separately, evading the worry to regulate the barrier factors. The proposed procedure is applied to diverse standard test systems as 34-bus and 85-bus radial distribution systems. The solutions obtained by the proposed method are compared with other methods.

Keywords—Distribution systems, Capacitor placement, loss reduction, Loss sensitivity factors, cuckoo search

1 Introduction

The chief parts of the unified system are the power generation, transmission and distribution systems. The key loads such as industrial, commercial and domestic are linked to the network through the distribution systems. Consequently, the eminence of the service is founded on the continuousness of power and upholding the supply voltage inside certain bounds with stated frequency. Owing to the quick spread in the loads, the extended distance of radial structure and the high R/X ratio of transmission lines, the improvement of the voltage profile and power loss lessening, the system consistency and the power factor are the challenge in the distribution system. To crack these difficulties with energy saving, cost reducing, increased in power quality and reliability, the shunt capacitors are installed on the radial feeders for injection of reactive power. Consequently, the optimal locations and sizes of capacitors in distribution systems can be expressed as a constrained optimisation problem.

Many optimisation techniques were applied to solve the optimal capacitor placement problem. Lee et al. [1] presented the optimal capacitors placement using the particle swarm optimisation algorithm with operators based on Gaussian and Cauchy probability distribution functions. In [2, 3], a two stage method was used to solve the optimal capacitor placement problem based on the loss sensitivity factors (LSF) to determine the optimal locations and the plant growth simulation algorithm (PGSA) to estimate the optimal sizes of capacitors. However, the optimal solution may not be obtained because the optimisation technique is restricted only to find the sizes of capacitors. Bhattacharya and Goswami [4] used the fuzzy based method for identification of probable capacitor nodes of radial distribution system, while the simulated annealing (SA) technique was utilised for final selection of the capacitor sizes. Etemadi and Fotuhi-Firuzabad [5] used the PSO algorithm to find the optimal capacitor placement with separate objective functions. Prakash and Sydulu [6] used the LSF and the PSO algorithm to find the optimal locations and sizing of capacitors, respectively. Reddy and Sydulu [7] presented a power loss index (PLI) based location and an index and genetic algorithm (GA) based sizing for the capacitor placement problem. Raju et al. [8] presented the direct search algorithm (DSA) to find the optimal locations and sizes of fixed and switched capacitors to maximise the net savings and minimise the active power loss.

Tabatabaei and Vahidi [9] introduced the optimal locations and sizes of capacitors using the fuzzy decision making and the bacteria foraging algorithm (BFA), respectively. Reddy and Veera [10] presented two stage methodology based on the fuzzy approach and GA to find the optimal locations and sizing of capacitors, respectively. Sultana and Roy [11] used the teaching learning based optimisation (TLBO) approach to find the optimal placement of capacitors in radial distribution systems. In [12, 13], the authors presented PLI to determine the high potential buses for capacitor placement. Then, the optimal sizing and placement of capacitors were obtained using accelerated PSO in [12] and cuckoo search algorithm in [13]. Nojavan et al. [14] presented a mixed integer non-linear programming approach for capacitor placement in radial/mesh distribution systems. Xu et al. [15] used the mixed-integer programming and the net present value criterion to find the optimal placement of capacitor banks and to evaluate the cost benefit of the capacitor installation project. El-Fergany [16] presented PLI and/or LSF to determine the high potential buses for capacitor placement. Then, the differential evolution and pattern search (DE-PS) algorithm was used to find the optimal locations and sizes of capacitors.

In this paper, Capacitor Placement and Sizing is done by Loss Sensitivity Factors and modified Cuckoo search (MCS) respectively. The loss sensitivity factor is able to predict which bus will have the biggest loss reduction when a capacitor is placed. Therefore, these sensitive buses can serve as candidate locations for the capacitor placement. MCS 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 34 and 85 bus radial distribution systems and results are very promising.

2 Problem formulation

The problem of optimal capacitor placement in radial distribution systems for diminish the total energy cost and maximising the saving can be formulated as:

$$\text{Min } S = K_P P_{\text{Loss}}^{\text{Total}} + K_c Q_c^{\text{Total}} = K_p \sum_{i=1}^{N_b-1} P_{\text{Lossi}} + K_c \sum_{j=1}^{N_c} Q_{cj} \qquad (1)$$

where, S is the total costs (\$/year),K_P is the annual cost per unit of power loss (\$/kW-year),K_c is the total capacitor purchase and installation cost (\$/kVAR), $P_{\text{Loss}}^{\text{Total}}$ and Q_c^{Total} are the total power loss and capacitors reactive power, respectively. PLossi is the power loss in line i, QCj is the total reactive power injected at location j, Nb is the total number of buses and NC is the optimal number of capacitors placement. Therefore, the annual total cost of capacitors can be calculated as:

$$\text{Total Capacitor Cost} = \frac{K_c * Q_c^{\text{Total}}}{\text{Life Expectancy}} \ \$/year \qquad (2)$$

The objective function (1) is subjected to the following constraints:

(a) Operational constraints

- Bus voltage constraint

The voltage at each bus (Vi) must be within their permissible minimum and maximum limits as: $V_i^{\min} < V_i < V_i^{\max}$ (3)

- Power flow constraint

  The power flow in each line (PFk) must be less than the maximum limit of power flow in this line ($PF^{\max}{}_k$) as:

  $$|PF_k| < PF_k^{\max} \qquad (4)$$

- Overall power factor constraint

  The overall system power factor (pfoverall) must be greater than or equal to the minimum limit of power factor (pf min) as:

  $$|PF_{\text{overall}}| > PF_{\text{overall}}^{\min} \qquad (5)$$

(b) Capacitor constraints

- Number of capacitors constraint

  This constraint aims to reduce the number of capacitors placement. Therefore, the optimal number of capacitors (N_C) must be less than or equal to the maximum number of possible locations ($N_c^{\max}$) as:

  $$N_{\mathrm{c}} \leq N_{\mathrm{c}}^{\max} \tag{6}$$

- Capacitor size constraint

  The reactive power injection must be within their feasible minimum and maximum limits as:

  $$Q_{\mathrm{cj}}^{\min} \leq Q_{\mathrm{cj}} \leq Q_{\mathrm{cj}}^{\max} \tag{7}$$

- Total reactive power constraint

  The total reactive power injection ($Q_{\mathrm{c}}^{\mathrm{total}}$) must be less than or equal the total load reactive power ($Q_{\mathrm{l}}^{\mathrm{total}}$) as:

  $$Q_{\mathrm{c}}^{\mathrm{total}} \leq Q_{\mathrm{l}}^{\mathrm{total}} \tag{8}$$

loss sensitivity indices (LSIs)

Two LSIs are adopted in this paper from [17] to rank the load buses according to their severity for efficient detecting the candidate load buses for the installation of capacitors. The objective of the candidate load buses is to reduce the search space in the optimisation procedure.

Backward/forward sweep (BFS) algorithm

The BFS algorithm is popular for load flow distribution system due to it's simplicity, quick and robust convergence and low memory prerequisite for processing with efficiencies and answer accuracies computational. The BFS algorithm involves mainly an iterative three basic steps based on Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL). The three steps are named as the nodal current calculation, the backward sweep and the forward sweep and they are repeated until the convergence is achieved. The BFS utilises as a simple and flexible radial distribution system numbering scheme in order to numbering each branch in the feeder, lateral and sub-lateral. The BFS algorithm can be applied to find the load flow results by following steps mentioned in [17].

Cuckoo Search (CS) Algorithm

CS algorithm is based on the obligate brood parasitic behaviour of some cuckoo species in combination with theLevy flight behaviour of some birds and fruit flies. Some species of Cuckoo birds lay their eggs in communal nests. If a host bird discovers the eggs are not their own, they will either throw these alien eggs away or simply abandon its nest and build a new nest elsewhere. CS, can be described using following three idealized rules:

a) Each cuckoo lays one egg at a time, and dump its egg in randomly chosen nest

b) The best nests with high quality of eggs will carry over to the next generations

c) The number of available host nests is fixed, and the egg laid by a cuckoo is discovered by the host birth a probability pa ∈ [0, 1]. [18]

Modified Cuckoo search (MCS) algorithm

In the real world, if a cuckoo's egg is very similar to a host's eggs, then this cuckoo's egg is less likely to be discovered, thus the fitness should be related to the difference in solutions. Therefore, it is a good idea to do a random walk in a biased way with some random step sizes. Both, original, and modified code use random step sizes. Compared to the original code, we use different function set for calculating this step size. In the original code, step size is calculated using following code expression:

*r*nests [permute1 [i]][j]- nests [permute2 [i]][j]* (1)

where *r* is random number in [0,1] range, *nests* is matrix which contains candidate solutions along
with their parameters, *permute1* and *permute2* are different rows permutation functions applied on
nests matrix.In order to calculate the step size, instead of Equation 4, we used:

*r*nests [sorted [i]][j] - nests [permute [i]][j]* (2)

The difference is that instead of *permute1*, we used *sorted* function. This function sorts *nests* matrix by fitness of contained solutions. In this way, higher fitness solutions have slight advantage over solutions with lower fitness. This method keeps the selection pressure (the degree to which highly fit solutions are selected) towards better solutions and algorithm should achieve better results. That does not mean that high fitness solutions will flood population and the algorithm will stuck in local optimum. At a first glance, it seems that there are some similarities between CS and hill-climbing in respect with some large scale randomization. But, these two algorithms are in essence very different. Firstly, CS is population-based algorithm in a way similar to GA and PSO, but it uses some sort of elitism and/or selection similar to that used in harmony search. Secondly, the randomization is more efficient as the step length is heavy-tailed, and any large step is possible. And finally, the number of tuning parameters is less than in GA and PSO, and thus CS can be much easier adapted to a wider class of optimization problems. [19]

Optimal capacitor placement using MCS algorithm.

The heuristic guide function of the problem is the inverse of the objective function in (1) at iteration t + 1 as:

$$N(t+1)=1/\sum_{i=1}^{Nb} F(x) \qquad 9$$

The MCS parameters are adjusted to find their optimal values. The MCS algorithm can be applied to find the optimal capacitor placement using the following steps:

Step1: Intialisation
Insert the follows

- Insert the control variables that represent the capacitor locations randomly between 0 and 1 in the cases of fixed, switched and the combination of fixed and switched capacitors.
- Insert the control variables that represent the capacitor sizes between the minimum and maximum limits (150 and 1200 kVAR) in the cases of fixed, switched and the

combination of them. In the case of fixed capacitors, these values are distributed randomly in the search space. In the case of switched capacitors, these values are distributed increasingly from the minimum limit to the maximum limit with fixed step (150 kVAR). In the combination of fixed and switched capacitors, a two-search space is used in parallel for fixed and switched capacitors.

- Insert the MCS parameters, number of cuckkos,etc.
- Create a search space with dimensions (Ncuckkos × 2Ncan), where Ncan is the number of candidate buses for capacitor placement. Thus, the control variable xi initially can be represented randomly as:

$$x_i^{\text{initial}} = [x_1, x_2, x_3, \ldots\ldots, x_{\text{can}}, y_1, y_2, \ldots, y_{\text{can}}]$$

where, xi refers to the states of capacitors locations and yi refers to the sizes of capacitors.

- Create the initial population of cuckoos with the same dimensions of search space which contains the elements with very small values to give the same chance of searching for all cuckoos.

Step 2: Provide first position
Each cuckoo is positioned on the initial state randomly within the reasonable range of each control variable in a search space with one ant at each position in the length of randomly distributed values

Step 3: Evaluation
The initial value of objective function is obtained by applying the BFS algorithm without reactive power compensation.

Step 4: Search space updating
The search space is updated by applying the final form of the cuckoo tour matrix on the search space in order to rearrangement the positions of control variables.

Results & discussion

The proposed methodology using the multi-stage method is applied on two standard radial distribution systems in order to solve the optimal capacitor placement problem. These test systems are 34-bus [2, 4] and 85-bus [11].Kp is assumed to be 168 $/(kw-year) and KC is assumed to be 5 $/kVAR, with a life expectancy of 10 years, where the maintenance and running costs are neglected. The limit of voltage magnitude is taken between 0.95 for 34-bus systems, while the voltage limit is 0.90 and 1.1 p.u. for 85-bus system. The maximum number of possible locations (N_c^{max}) is assumed to be 4 for 34-bus test systems. N_c^{max} is 15 for 85-bus test system, because the voltage magnitude at 46 buses without compensation is lower than the minimum voltage limit, means that there is a violation of the minimum voltage limit at 54.12% of the total number of system buses. The maximum limits of power flow (PFmax) are 5 and 3 for 34-bus, 85-bus and test systems, respectively. The minimum limit of overall power factor (pf min overall) is 0.9 lagging for all test systems. The substation is located at bus number 1 for all test systems with constant voltage (1 p.u.).

Two different types of capacitors are considered to find the optimal solution, which are:
1) Fixed capacitors with minimum and maximum limits are 150 and 1200 kVAR.
2) Switched capacitors with standard commercial available sizes are from 150 to 1200 by step 150 kVAR.

Two case studies are employed to check the capability of the proposed method as:
Case 1: Optimal locations and sizes of fixed capacitors.

Case 2: Optimal locations and sizes of switched capacitors.

Table1: Results for 34 bus test system

	Uncompe- -nsated	Compensated															
		PGSA[2]		BFA[9]		GA[10]		APSO[12]		ACO[17]				Modified CS			
										Case1		Case2		Case1		Case2	
total losses (kW)	221.67	169.167		169.07		168.955		168.023		162.68		164.508		169.2961		159.8445	
loss reduction (%)	---	23.69		23.73		23.78		24.2		26.61		25.79		23.62		27.89	
minimum bus voltage(p.u.)	0.9417	0.9492		0.9503		0.9491		0.9416		0.9501		0.9501		0.9497		0.95038	
maximum bus voltage(p.u.)	0.9941	0.995		0.9942		0.9948		0.9949		0.995		0.9949		0.99485		0.99528	
optimal locations and sizes in kVAR	---	19	1200	9	600	7	1629	19	1050	9	645	9	450	9	288	5,9	750 ,750
		20	200	22	900	--	--	25	750	22	719	19	450	23	452	22	750
		22	639	--	--	--	--	--	--	25	665	25	1050	25	916	25	450
total capacitors power (kVAR	----	2039		1500		1629		1800		2029		1950		1655.95		2700	
Annual cost ($/year)	37241	28420		28404		28384		28228		27330		27637		28441.738		26853.877	
total capacitors cost ($/year)	--	1019.5		750		814.5		900		1014.5		975		827.9745		1350	
net savings ($/year)	--	8821		8837		8857		9013		9911		9604		8799		10388	

Table2: Results for 85 bus test system

	Uncomp-ensated	Compensated																	
		PGSA[2]		PSO[6]		GA[7]		DSA[8]		TLBO[11]		ACO[17]				Modified CS			
												Case1		Case2		Case1		Case2	
total losses (kW)	315.714	174.912		163.32		146.061		144.01		143.18		143.347		143.874		172.421		145.2051	
loss reduction (%)	--	44.6		48.27		53.74		54.39		54.65		54.6		54.43		45.38		54	
minimum bus voltage(p.u.)	0.8713	0.909		0.9156		0.9246		0.9185		0.9242		0.9244		0.922		0.88792		0.90697	
maximum bus voltage(p.u.)	0.9957	0.9973		0.9974		0.9973		0.9975		0.9976		0.9976		0.9975		0.99744		0.99818	
optimal locations and sizes in kVAR	---	7	200	7	324	26	48.44	6	150	4	300	4	185	7	150	29	525.4	8	450
		8	1200	8	796	28	214.1	8	150	7	150	7	150	8	300	58	541.3	4	1200
		58	908	27	901	37	103.1	14	150	9	300	9	210	19	300	68	133.6	30	1200
				58	453	38	120.3	17	150	21	150	13	150	27	300	69	131.8	26	1200
						39	178.1	18	150	26	150	18	280	32	300	44	162.5	5	600
						51	100	20	150	31	300	26	320	48	300			31	1200
						54	212.5	26	150	45	150	31	250	61	300			58	150
						55	101.6	30	150	49	150	35	205	68	300			33	300
						59	4.688	36	450	55	150	53	200	80	300			12	450
						60	157.8	57	150	61	300	61	250					49	150
						61	112.5	61	150	68	300	68	330					67	450
						62	104.7	66	150	83	150	80	196					68	1200
						66	9.375	69	300	85	150							69	1200
						69	100	80	150									17	1200
						72	67.19											45	150
						74	112.5												
						76	71.88												
						80	356.3												
						82	31.25												
Annual cost ($/year)	53040	29385		27438		24.538		24194		24054		24082		24171		28966.7363		24394.4579	
total capacitors cost ($/year)	---	1154		1237		1103.1		1275		1350		1363		1275		614.5979		5550	
net savings ($/year)	----	23655		25602		28502		28846		28986		28958		28869		24073.26		28645.54	

Conclusion

This paper offered a well-organized multi-stage procedure based the MCS algorithm to find out the best locations and sizes of capacitors placement for reducing power losses and improving voltage profile in radial distribution systems. First, the LSIs have been used to select the contender locations for the capacitors to decrease the search space for the optimisation process. Then, the MCS algorithm has been used to bargain the optimal locations and sizes of capacitors at two case studies based on fixed, and switched capacitors. The BFS load flow algorithm has been used for the load flow calculations. The projected method has been tested on small- and large-scale distribution systems. The optimum results by means of the proposed process have been equated with other methods and have been demonstrated that the competence of the proposed procedure to find the optimal solutions with least power loss and voltage profile improvement. Consequently, the proposed procedure signifies a probable tool to decrease the system losses and helps their operators in smart grid environment.

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