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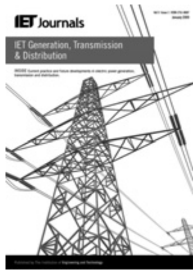

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Capacitor allocations in radial distribution networks using cuckoo search algorithm

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Abstract: In the present work, a cuckoo search optimisation-based approach has been developed to allocate static shunt capacitors along radial distribution networks. The objective function is adopted to minify the system operating cost at different loading conditions and to improve the system voltage profile. In addition to find the optimal location and values of the fixed and switched capacitors in distribution networks with different loading levels using the proposed algorithm. Higher potential buses for capacitor placement are initially identified using power loss index. However, that method has proven less than satisfactory as power loss indices may not always indicate the appropriate placement. At that moment, the proposed approach identifies optimal sizing and placement and takes the final decision for optimum location within the number of buses nominated with minimum number of effective locations and with lesser injected VArs. The overall accuracy and reliability of the approach have been validated and tested on radial distribution systems with differing topologies and of varying sizes and complexities. The results shown by the proposed approach have been found to outperform the results of existing heuristic algorithms found in the literature for the given problem.

Nomenclatures and Symbols

N	total number of network buses
N_B	number of effective buses having compensations
n	total number of lines
P_{loss}	total network active loss
Q_{loss}	total network reactive loss
$\lvert V_i \rvert$	voltage magnitude of bus i
$\lvert V_j \rvert$	voltage magnitude of bus j
$P_{L_a}(i)$	average total active power loss after compensation for time interval i
C_e	average rate of energy cost
C_{ci}	installation cost
C_{co}	operating cost
T_i	time interval
L	load level
n_l	number of load buses
P_{slack}	active power supplied from the slack bus
Q_{slack}	reactive power supplied from the slack bus
$P_D(i)$	active power demand of load at bus i
$Q_D(i)$	reactive power demand of load at bus i
$P_L(j)$	active power loss at branch j
$Q_L(j)$	reactive power loss at branch j
$Q_C(i)$	amount of reactive power at bus i
$V_{i,\min}$	lower permissible voltage limit at bus i
$V_{i,\max}$	upper permissible voltage limit at bus i
$Q_{Ci}^{\min}$	lower reactive power limit of compensated bus i
$Q_{Ci}^{\max}$	upper reactive power limit of compensated bus i
S_{li}	actual line flow of line i
S_{li}^{rated}	rated line transfer capacity
$\text{PF}_{\min}$	lower limit of overall system power factor at substation (slack bus)
$\text{PF}_{\max}$	upper limit of overall system power factor at substation (slack bus)
λ_{VC}	penalty function for voltage limit constraint
λ_{PFC}	penalty function for power factor constraint
λ_{LFC}	penalty function for line power flow constraint
λ_{CC}	penalty function for maximum total compensation constraint
$X_{\text{p,min}}$	minimum limits of the parameter to be optimised
$X_{\text{p,max}}$	maximum limits of the parameter to be optimised
D	number of parameters to be optimised
m	total population of nest position

1 Introduction

Reactive power addition can be beneficial only when correctly applied. Correct application means choosing the correct position and size of the reactive power support. It is not possible to achieve zero losses in a power system, but it is possible to keep them to a minimum [1–3] to reduce the system overall costs. However, the minimisation of losses does not guarantee the maximisation of benefits unless the problem is well formulated. Numerous methods for solving this problem with a view to minimising losses have been suggested in the literature based on both traditional mathematical methods and more recent heuristic approaches.

A comprehensive survey of the literature from the past decade focusing on the various heuristic optimisation techniques applied to determine the optimal capacitor placement (OCP) and size is presented in [4]. Several heuristic tools that facilitate solving optimisation of capacitor placement problems that were previously difficult or impossible to solve have been developed in the past decade. Such as tabu search [5], particle swarm optimisation (PSO) algorithm [6, 7], the harmony search algorithm [8], ant colony optimisation-based algorithm [9, 10], a simulated annealing technique [11], genetic algorithm (GA) [12], a GA-fuzzy [13], bacterial foraging with a PSO algorithm [14], plant growth simulation algorithm [15], an immune-based optimisation technique [16], the integration of differential evolution (DE) and pattern search (PS) [17] and big bang-big crunch optimisation [18].

Swarm intelligence is an innovative computational way to solving hard problems. This discipline is inspired by the behaviour of social insects such as fish schools and bird flocks and colonies of ants, termites, bees and wasps. In general, this is done by imitating the behaviours of the biological creatures within their swarms and colonies [19, 20].

Cuckoo search algorithm (CSA) has been developed by simulating the intelligent breeding behaviour of cuckoos [21]. Strictly speaking, CSA is a population-based algorithm similar to GA and PSO, but it uses some sort of elitism. Secondly, the randomisation is more efficient as the step length is heavy tailed, and any large step is possible. Moreover, the number of parameters to be tuned is less than GA and PSO, and thus it is potentially more generic to adapt to a wider class of optimisation problems and used as an optimisation tool, in solving complex, non-linear and non-convex optimisation problems [22]. For example, and more recently, CSA has been applied to located and size distributed generator [23], to solve non-convex economic dispatch problem [24] and to capacitor placement on distribution problem [25].

A conceptual comparison of the CSA with PSO, DE and artificial bee colony algorithm (ABC) suggests that CSA and DE algorithms provide more robust results than PSO and ABC algorithms [26]. One of the interests of this article is to examine the efficiency of the CSA. In this manuscript, a CSA-based algorithm is utilised to ascertain the optimal size (fixed and switched) and select optimum locations of shunt static capacitors at different loading patterns. High potential buses for capacitor placement are initially identified by the observations of power loss index (PLI) with weak-voltage buses. The proposed method improves the voltage profile and reduces system losses in addition to enhancing voltage stability. The method has been tested and validated on a variety of radial distribution systems and the detailed results are presented. The distribution power flow suggested in [27] is used in this study.

2 Cumulative voltage deviation (CVD)

To have a good voltage performance, the voltage deviation at each bus must be made as small as possible. CVD is utilised to indicate the voltage profile improvement

$$\mathrm{CVD} = \begin{cases} 0, & \text{if } 0.95 \le V_i \le 1.05 \\ \sum_{i=1}^{N} \left|1 - V_i\right|, & \text{else} \end{cases} \tag{1}$$

3 Objective function formulation

The main objectives of capacitor allocations in the distribution system are to minimise the active power losses, to minimise the overall operating cost and to enhance the system voltage profile subject to specific operating constraints. The objective function is mathematically formulated and adopted as constrained optimisation problem

$$\text{minimise}\left\{C_e \sum_{i=1}^{L} P_{\mathrm{La}}(i) T_i + C_c \sum_{j=1}^{N_B} Q_c(j) + \left(C_{ci} + C_{co}\right) N_B\right\} \tag{2}$$

Subject to the satisfaction of the active and reactive power flow balance equations and a set of inequality constraints

$$\text{power balance:} \quad \left.\begin{aligned} P_{\mathrm{slack}} &= \sum_{i=1}^{n_l} P_D(i) + \sum_{j=1}^{n} P_L(j) \\ Q_{\mathrm{slack}} + \sum_{i=1}^{N_B} Q_C(i) &= \sum_{i=1}^{n_l} Q_D(i) + \sum_{j=1}^{n} Q_L(j) \end{aligned}\right\} \tag{3}$$

$$\text{bus voltage: } V_{i,\min} \le \left|V_i\right| \le V_{i,\max}, \quad i = 1 \ldots N \tag{4}$$

$$\text{reactive compensation: } Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, \quad i = 1 \ldots N_B \tag{5}$$

$$\text{line capacity: } S_{li} \le S_{li}^{\mathrm{rated}}, \quad i = 1 \ldots n \tag{6}$$

$$\text{total compensation: } \sum_{i=1}^{N_B} Q_C(i) \le \sum_{j=1}^{n_l} Q_D(j) \tag{7}$$

$$\text{overall system power factor: } \mathrm{PF}_{\min} \le \mathrm{PF}_{\mathrm{overall}} \le \mathrm{PF}_{\max} \tag{8}$$

A penalty factor associated with each violated constraint is burdened to the objective function in order to force the solution to stay away from the infeasible solution space; to respect the inequality constraints. Therefore the optimal solution is established when no constraints are violated or even within an acceptable tolerance and the objective function is minimised.

The penalty function can be formulated as follows

$$\text{penalities} = \lambda_{\mathrm{VC}} + \lambda_{\mathrm{PFC}} + \lambda_{\mathrm{LFC}} + \lambda_{\mathrm{CC}} \tag{9}$$

where (see (10) at the bottom of next page)

ψ_V, ψ_{PF}, ψ_L and ψ_C are the penalty function weights having large positive value.

4 Identification of potential buses using PLI

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 (11)

$$\mathrm{PLI}(m) = \frac{\mathrm{LR}(m) - \mathrm{LR}_{\min}}{\mathrm{LR}_{\max} - \mathrm{LR}_{\min}} \tag{11}$$

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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 calculations burden as the LF requires running for times equal number of buses before starting the optimisation process'.

The following are the steps to be implemented to find out the high potential buses for capacitor allocations using PLI:

(1) Run LF and obtain initial real power loss and bus voltages.
(2) Do for all buses, except slack bus.
(a) Inject capacitive reactive power equal to load reactive power.
(b) Run LF and obtain real power loss.
(c) Calculate LR = (initial real power loss–real power loss) and store.
(3) Obtain maximum and minimum LRs.
(4) Calculate PLI using (11) for all buses, except slack.
(5) Sort the values of PLI for respective buses in descending order.
(6) The buses whose voltage is less than 95% are identified as candidate buses for capacitor placement.

5 Fixed and switched-shunt capacitors

In radial distribution networks, wide ranges of various electric loads such as residential loads, industrial loads, commercial loads and street lamps are handled. Besides, each of these loads has many fluctuations within a year, which creates many difficulties in modelling of the load in the networks. The radial feeders are experienced with variation of load conditions along the day and with seasons; typically, light, medium and full load levels may be obtained by multiplying the base load uniformly by factors of 0.5, 0.75 and 1.00 for time percentages of 25, 35 and 40%, respectively. Constant power and linear loads are supposed in this study with the assumption of that the level of harmonics is within an acceptable limit.

From practical and economical point of view, in finding the values of capacitors, the selection criterion should not be the capacitors' fixed reactive powers because their reactive power varies by variation of the feeder's voltage [3]. In order to properly compensate the reactive power demand that changes from minimum to maximum and to be switched off at the load minimum. When the load varies during the day, the switched capacitors should be properly sized to avoid any stress on the system insulation because of voltage rises.

6 Cuckoo search algorithm and capacitor placement

CSA is one of the most recently defined algorithms by Yang and Deb [21, 22]. CSA is following three idealised rules: (i) each cuckoo lays one egg at a time, and dump its egg in randomly chosen nest; (ii) the best nests with high quality of eggs will carry over to the next generations; and (iii) the number of available host nests is fixed, and the egg laid by a cuckoo is discovered by the host bird.

The cuckoo bird searches the most suitable nest to lay eggs (solution) in order to maximise their eggs survival rate. Each cuckoo lays one egg at a time. The eggs (high quality of eggs, that is, near to optimal value) which are more similar to the host bird's eggs have the chance to develop (next generations) and become a mature cuckoo. Foreign eggs (away from optimal value) are detected by host birds with a probability $\text{Pa} \in [0,1]$ and these eggs are thrown away or the nest is discarded, and a completely new nest is built, in a new location. The mature cuckoo form societies and each society have its habitat region to live in. The best habitat from all of the societies will be the destination for the cuckoos in other societies. Then they immigrate towards this best habitat. A randomly distributed initial population of host nest is generated and then the population of solutions is subjected to repeated cycles of the search process of the cuckoo birds. The cuckoo randomly chooses the nest position to lay egg using (12) and (13)

$$X_{pq}^{\text{gen}+1} = X_{pq}^{\text{gen}} + s_{pq} \times \text{Lévy}(\lambda) \times \alpha \tag{12}$$

$$\text{Lévy}(\lambda) = \left| \frac{\Gamma(1+\lambda) \times \sin\left(\frac{\pi \times \lambda}{2}\right)}{\Gamma\left(\frac{1+\lambda}{2}\right) \times \lambda \times s^{(\lambda-1)/2}} \right|^{1/\lambda} \tag{13}$$

where λ is a constant ($0.25 < \lambda \le 3$) and α is a random number generated between $[-1, 1]$, Γ is gamma function. Also $s > 0$ is the step size which should be related to the scales of the problem of interests. If s is too large, then the new solution generated will be too far away from the old solution (or even jump out of the bounds). Then, such a move is unlikely to be accepted. If it is too small, the change is too small to be significant, and consequently such search is not efficient. Therefore a proper step size is important to maintain the search as efficiently as possible. Hence, the step size is calculated using (14)

$$s_{pq} = X_{pq}^{\text{gen}} - X_{fq}^{\text{gen}} \tag{14}$$

where $p, f \in \{1, 2, \ldots, m\}$ and $q \in \{1, 2, \ldots, D\}$ are randomly chosen indexes. Although f is determined randomly, it has to be different from p.

The host birds identified the alien egg (solution away from the optimal value) and chose the high quality of egg with the

$$\left.\begin{aligned}
\lambda_{\text{VC}} &= \psi_V \left[\sum_{i=1}^{N} \max\left(0, \ \langle |V_i| - V_{i,\max} \rangle\right) + \sum_{i=1}^{N} \max\left(0, \ \langle V_{i,\min} - |V_i| \rangle\right) \right] \\
\lambda_{\text{PFC}} &= \psi_{\text{PF}} \left[\max\left(0, \ \langle \text{PF}_{\text{overall}} - \text{PF}_{\max} \rangle\right) + \max\left(0, \ \langle \text{PF}_{\min} - \text{PF}_{\text{overall}} \rangle\right) \right] \\
\lambda_{\text{LFC}} &= \psi_{\text{L}} \left[\sum_{i=1}^{n} \max\left(0, \ \langle S_{\text{l}i} - S_{\text{l}i}^{\text{rated}} \rangle\right) \right] \\
\lambda_{\text{CC}} &= \psi_{\text{c}} \left[\max\left(0, \ \langle \sum_{i=1}^{N_{\text{B}}} Q_{\text{C}}(i) - \sum_{j=1}^{n_{\text{l}}} Q_{\text{D}}(j) \rangle\right) \right]
\end{aligned}\right\} \tag{10}$$

probability value associated with that quality of egg, using (15)

$$\text{pro}_p = \left(\frac{0.9 \times \text{fit}_p}{\max(\text{fit})}\right) + 0.1 \quad (15)$$

where fit_p is the fitness value of the solution p which is proportional to the quality of egg in the nest position p '[which is obtained from (2)]'. The egg is discovered by the host bird by comparing randomly (i.e. probability Pa ∈ [0,1]) with Pro_p. If the host bird discovers the alien egg, the host bird can either throw the egg away or abandon the nest, and build a completely new nest using (16). Otherwise, the egg grows up and is alive for the next generation

$$\text{nest}_p = X_{p,\min} + \text{rand}(0,\ 1) \times \left(X_{p,\max} - X_{p,\min}\right) \quad (16)$$

Good converge behaviour can be obtained if the three control parameters namely cuckoo nest population size, maximum generation and ë, can be optimally tuned. Setting of these cuckoo parameters optimally would also yield better solution and lesser computational time.

In a summary, pseudo-code for CSA with Lévy flight expresses as follows [22]:

1. Generate initial population of n host nests.
2. Repeat till stopping criteria is met
(a) Randomly select a cuckoo using Lévy flight using (12).
(b) Calculate its fitness (F_i) according to (2).
(c) Randomly select a nest.
(d) Calculate its fitness (F_j) according to (2).
(e) If ($F_i < F_j$), then replace the nest j with the cuckoo i.
(f) A fraction p_a of nest is replaced by new nests.
(g) Calculate fitness and keep best nests.
(h) Store the best nest as optimal fitness value.
3. Obtain the current best nest as optimal solution.

The procedure of the CSA-based algorithm to solve OCP can be illustrated in the flowchart diagram of Fig. 1.

7 Numerical results and simulations

In order to test the effectiveness and performance of the proposed CSA-based algorithm, it has been applied to several distribution radial test systems. Owing to the article space limitations, two radial distribution systems: the 69-bus and 118-bus radial distribution systems with different load levels are selected for reporting to examine the applicability of the proposed approach. The pre-identification and the estimation of high-potential buses significantly help in the reduction of the search space for

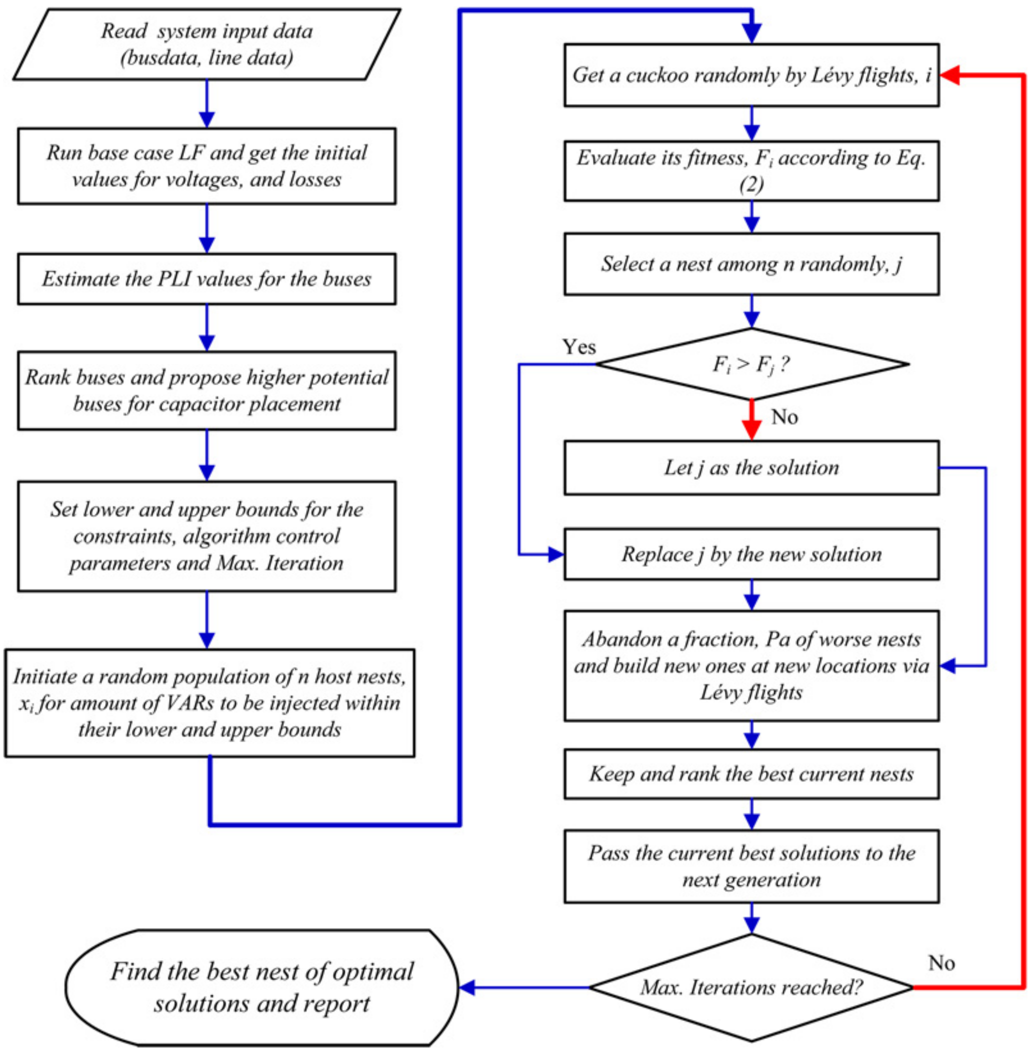

Fig. 1 *Flowchart of CSA-based algorithm and capacitor allocations*

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the optimisation procedure. Setting the lower limit of capacitor range to 0, will permit the proposed CSA-based approach to select the optimum locations within the range of bus nominations initially identified by the PLI method which has to be set manually by the user; just to set the number of buses due for search.

After intensive trials with nominating 10–25% of total network number of buses after ranking using the PLI is guaranteeing the optimal or near to optimal solutions (these percentage numerical figures are obtained after many trials). For small size networks, user may nominate/set the initial number of higher potential buses to 20–25% of network buses and for medium size, nominate 15–20% of network buses. However, for large-scale radial networks, set the number of potential buses for capacitor placement to 10–15% of network buses.

It is well known that PLI observations, may not lead to the optimum locations. Owing to the fact that the PLI calculations depend on the network topology, configurations, loading etc. and to tackle these limitations, the algorithm will search the optimum number of buses and select them for capacitor placements. The proposed method has been programmed and implemented using MATLAB codes [28].

It is assumed for all test cases, variation of load conditions are considered with good approximation as follows; light, medium and full by multiplying the base load uniformly by a factor of 0.5, 0.75 and 1.00 for time percentages of 25, 35 and 40%, respectively. For all calculations, rates stated in Table 1 are recycled for the purpose of obtaining net savings with the assumption that the cost of capacitor's purchase is linearly proportional to the size of capacitor. In addition, the net yearly savings are calculated by

$$\begin{aligned} &\text{net yearly savings} \\ &\quad = \text{yearly energy cost savings} \\ &\qquad - \text{cost of capacitors} \\ &\qquad \times (\text{purchase, operation and maintenance})/\text{year} \end{aligned} \tag{17}$$

7.1 Sixty-nine-bus test system numerical results and simulations

This 69-bus test case has seven lateral radial distribution system with data obtained from [29]. The load of the system is (3801.4 + j2693.6) kVA which is shown in Fig. 2.

The calculated ranked PLI values with lower voltages: {61, 64, 59, 65, 21, 62, 18, 17, 16, 24, 27, 26, 22, 20, 63, …}. Parameters adopted for the CSA-based algorithm for the test case of a 69-bus, and the required inequality constraints to be satisfied and respected are given in Table 2.

For sake of comparisons with recent heuristic algorithms, set the number of initial higher potential buses estimated by PLI to 9. After running the proposed optimisation algorithm for the case of 100% load level to select the optimal locations and determine the capacitor optimal sizes, the outcome leads to only two locations for capacitor placement which are buses 21 and 62 with optimum capacitor ratings of 250 and 1200 kVAr, respectively. The results of the proposed method compared with the results of DE [30], PSO [6] and DE–PS [17] for the reactive compensation required and relevant bus allocations are numerically tabulated in Tables 3 and 4.

Table 1 Proposed rate for energy, purchase, operation and maintenance costs

SN	Item	Proposed rate
1	average energy cost	\$0.06 kWh
3	purchase cost	\$3 kVAr
4	installation cost	\$1000 location
5	operating cost	\$300 year/location
6	hours per year	8760

Table 2 Control parameters adopted for the CSA algorithm and target setting for the constraints – 69-bus test case

Item	Proposed setting
number of nests	90
discovery rate of alien eggs	0.25
Levy coefficient, λ	0.5
cycles	100
bus voltage constraint	$0.95 \le V_i \le 1.05$
power factor constraint	$0.90 \le PF_{overall} \le 0.98$
allowable capacitor range	0–1500 kVAr with step of 50 kVAr

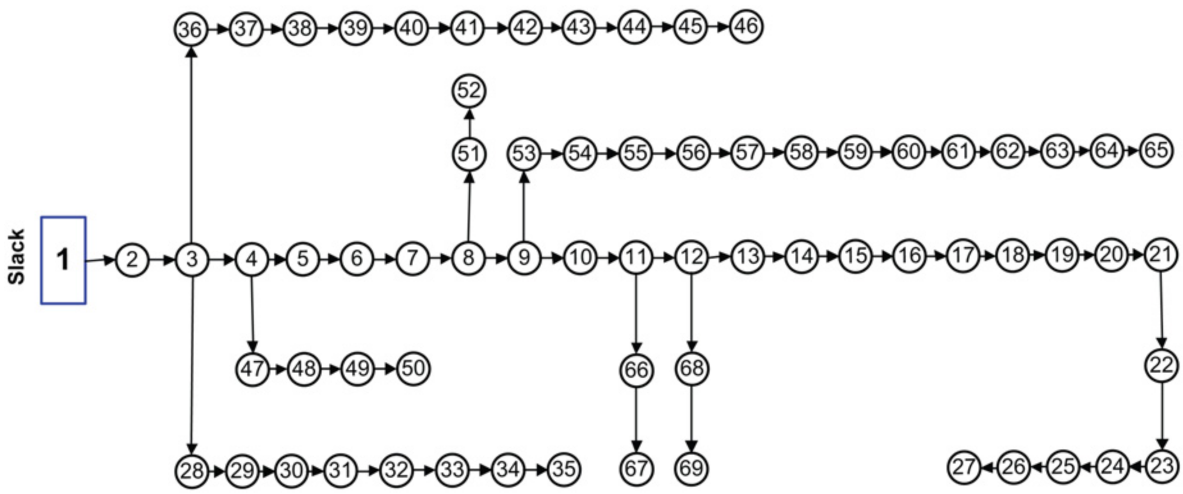

Fig. 2 *One-line diagram of a 69-bus test radial distribution system*

Table 3 Optimal location of capacitor placement and value of capacitor size in KVAr – full 100% load level

Method	Proposed approach	PSO [6]	DE [30]	DE-PS [17]
location and size in kVAr	(21, 250) (62, 1200)	(59, 1015) (61, 241) (65, 365)	(16, 200) (60, 700) (61, 500)	(21, 300) (59, 150) (61, 950) (64, 200) (65, 50)
total KVAr placed	1450	1621	1400	1650

The system overall power factor is significantly corrected from 0.821 lagging (base case at 100% load level) to 0.949 lagging with capacitor allocations, respectively. The voltage profile of a 69-bus radial distribution system without and with compensations for the case of 100% load level is depicted in Fig. 3.

The CSA is performing well in stable and smooth convergence, which proves the good characteristics of the proposed CSA-based algorithm as shown in Fig. 4.

In spite of the OCP is planning aspect in nature and the processing time is not considered a concern. The central

Table 4 Results and comparisons of a 69-bus radial feeder test case without and with OCP – 100% load patterns

Point of comparison	Without OCP	Compensated			
		Proposed approach	PSO [6]	DE [30]	DE-PS [17]
V_{min}, pu[a]	0.909	0.930	0.934	0.928	0.931
V_{max}, pu[a]	1.00	1.00	1.00	1.00	1.00
CVD	0.731	0.527	0.488	0.526	0.500
P_{loss}, kW	224.90	147.95	156.14	149.55	146.13
reductions in P_{loss}, %	–	34.21	30.57	33.50	35.02
Q_{loss}, kVAr	102.12	69.04	71.95	67.78	68.06
reductions in Q_{loss}, %	–	32.39	29.54	33.63	33.35
$PF_{overall}$	0.821	0.949	0.961	0.945	0.963
ΣQ_C, kVAr	–	1450 (2 locations)	1621 (3 locations)	1400 (3 locations)	1650 (5 locations)
net savings/year	–	\$33 494.90	\$29 301.00	\$31 504.00	\$29 951.50
computational time, s	0.1	125.80	NA	92.38	48.46
search space, potential buses	–	9	3	3	5

[a]Reported values of V_{min} and V_{max} are shown excluding the slack bus # 1

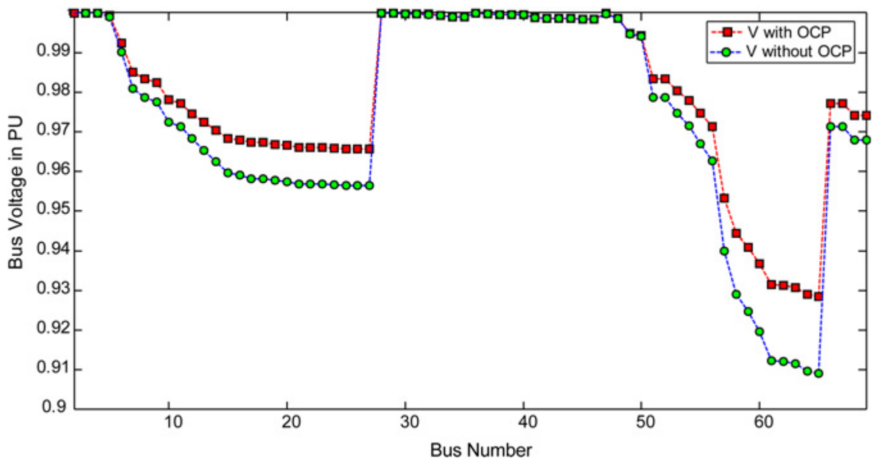

Fig. 3 *Bus voltage profile for a 69-bus radial distribution feeder with and without OCP (two locations) – 100% load level*

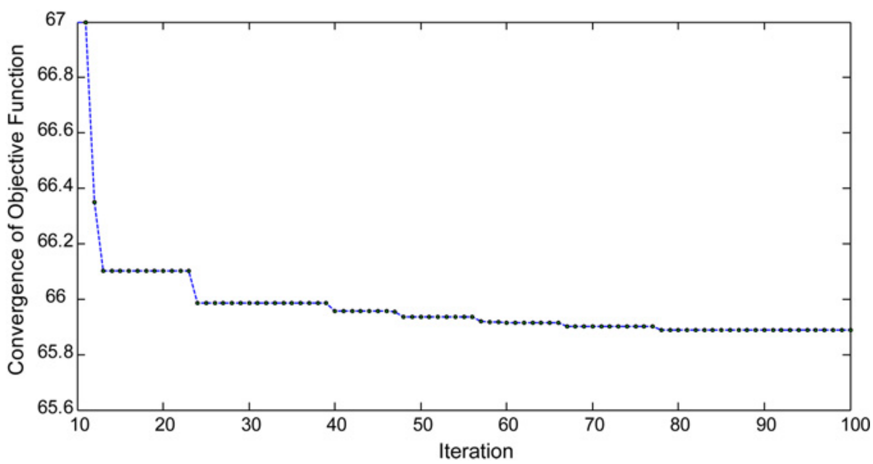

Fig. 4 *Convergence trend of the objective for the case of a 69-bus loss minimisation*

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processing unit (CPU) time used to reach the optimal solution by the proposed CSA-based method is approximately 125.80 s (including LF runs) which is higher than the reported CPU time of other methods as depicted in Table 4. On the other hand, the obtained results using CSA-based proposed methodology is much better in terms of lesser injected VArs with less places and better loss minimisation (see Tables 3 and 4).

Table 5 shows the system conditions when capacitor placement is implemented as per the optimal solutions of each load level. It may be noted that the required voltage regulation at the light, medium and the full load levels has been obtained from Table 5. Moreover, real power LRs at different load levels have been achieved and fixed capacitors and switchable on the load level are depicted as well.

The constraints have been checked for reactive power limits, node voltages and branch security flows and found within acceptable limits.

Table 5 System conditions without and with capacitors placement for the 69-node case – different load levels

Load level		Uncompensated	Compensated	Compensation values and location
light 50%	V_{min}, pu[a]	0.9567	0.966	600 kVAr at bus 62
	V_{max}, pu[a]	1.00	1.00	
	P_{loss}, kW	51.58	35.89 (30.42% reduction)	
	Q_{loss}, kVAr	23.54	16.75 (28.83% reduction)	
	average P.F.	0.82	0.93	
medium 75%	V_{min}, pu[a]	0.934	0.9486	950 kVAr at bus 62
	V_{max}, pu[a]	1.00	1.00	
	P_{loss}, kW	120.97	83.19 (31.23% reduction)	
	Q_{loss}, kVAr	55.07	38.72 (29.70% reduction)	
	average P.F.	0.82	0.94	
full 100%	V_{min}, pu[a]	0.909	0.930	1450 kVAr (250 kVAr at bus 21 and 1200 kVAr at bus 62)
	V_{max}, pu[a]	1.00	1.00	
	P_{loss}, kW	224.90	147.95 (34.21% reduction)	
	Q_{loss}, kVAr	102.12	69.04 (32.39% reduction)	
	average P.F.	0.82	0.95	
final fixed and switched values – optimal solution in kVAr	fixed	600 kVAr located at node 62		
	switched	250 kVAr located at node 21 and 600 kVAr located at node 62		
annual net savings		$18 239.60		

[a]Reported values of V_{min} and V_{max} are shown excluding the slack bus no. 1.

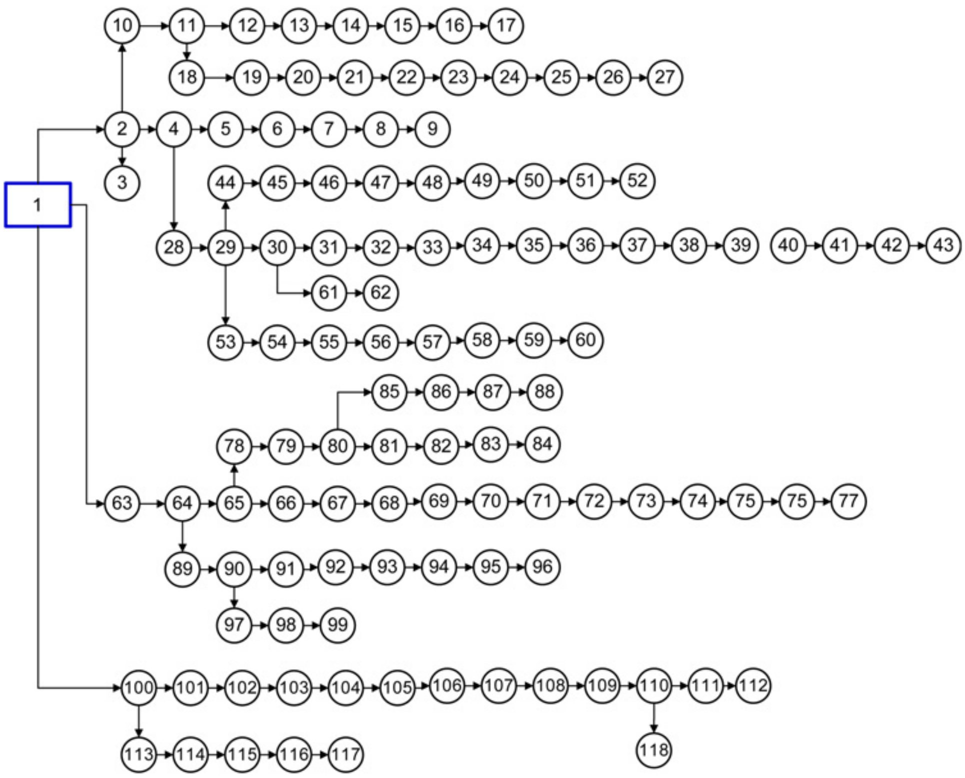

Fig. 5 *Single-line diagram of the 118-bus radial distribution system (the bus number is reordered)*

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Table 6 Control parameters adopted for the CSA algorithm and targets for the constraints

Item	Proposed settings
number of nests	150
discovery rate of alien eggs	0.25
Levy coefficient, λ	0.5
cycles	100
bus voltage constraint	$0.90 \le V_i \le 1.05$
power factor constraint	$0.90 \le PF_{overall} \le 0.98$
allowable capacitor range	0–1500 kVAr with step of 50 kVAr

7.2 One hundred and eighteen-bus test system results and simulations

This proposed approach has been applied to a large radial distribution system with 118-nodes, as shown in Fig. 5 to assess the performance of CSA with higher number of control variables. The network layout, including line data and load data, and its physical characteristics are summarised and obtained from [31]. This network has a total load of (22.7097 + j17.0422) MVA.

The most likely buses for capacitor placements pre-identified are {118, 39, 74, 70, 109, 107, 71, 111, 43, 110, 86, 76, 32, 108, 40, …}. Table 6 shows the parameters adopted for the CSA algorithm for the test case of a 118-node radial distribution and the required constraints.

Set the number of initial higher buses range resulted by the PLI observations to 15, to let the proposed algorithm to select the optimal locations and amount of compensations required accordingly. The approach has selected eight buses for optimal capacitor allocations with the relevant amount of reactive compensation required per each location which is depicted in Table 7 for all the proposed load patterns/levels. Once again, this proves the ability of the proposed approach to allocate capacitors at a minimum number of locations.

Table 7 Optimal locations and sizes (fixed and switched) for the 118- nodes test case at different load levels

bus/location	light	32	39	40	70	74	86	108	118	total
KVAr		0	1100	0	350	500	450	0	1000	3400
bus/location	medium	32	39	40	70	74	86	108	118	total
KVAr		900	1500	0	600	750	700	750	1100	6300
bus/location	full	32	39	40	70	74	86	108	118	total
KVAr		1500	1500	550	950	750	1050	1500	1200	9000
final optimal ratings	fixed: (39, 1100), (70, 350), (74,500), (86, 450) and (118, 1000)									
(location and size)	switched: (32, 1500), (39, 400), (40, 550), (70, 600), (74,250), (86, 600), (108, 1500) and (118, 200)									

Table 8 Summaries and results for the case of a 118-node radial distribution with different load levels

Point of comparison	Uncompensated/load level			Compensated/load level		
	Light	Medium	Full	Light	Medium	Full
V_{min}, pu[a]	0.939	0.905	0.869	0.955	0.933	0.906
V_{max}, pu[a]	0.998	0.997	0.996	0.999	0.998	0.997
CVD	0.467	1.839	3.697	0	0.948	1.621
P_{loss}, kW	296.77	695.92	1294.35	208.96	471.01	858.89
reductions in P_{loss}%	—	—	—	29.59	32.32	33.64
Q_{loss} kVAr	224.83	525.78	974.85	158.56	355.02	644.94
reductions in Q_{loss}, %	—	—	—	29.48	32.48	33.84
$PF_{overall}$	0.79	0.79	0.79	0.87	0.91	0.92
ΣQ_C kVAr	—	—	—	3400	6300	9000
net savings					$107 063.80	

[a]Reported values of V_{min} and V_{max} are shown excluding the slack bus no. 1.

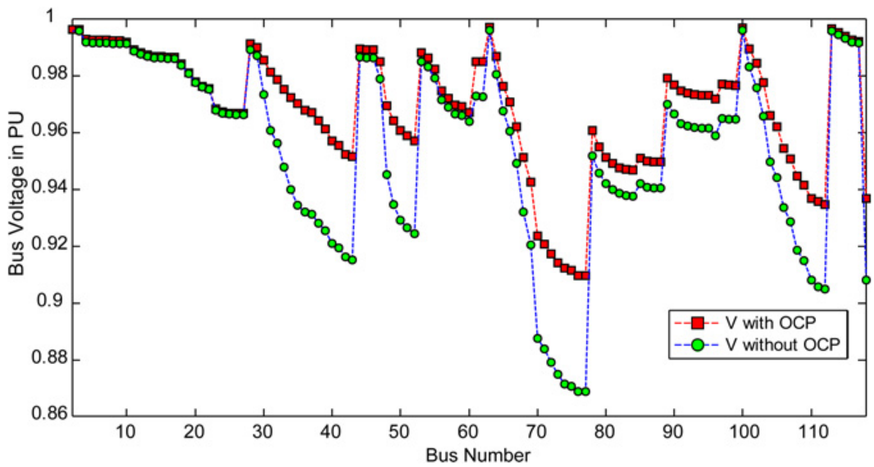

Fig. 6 *Bus voltage profile of a 118-bus radial distribution feeder with and without OCP at full load*

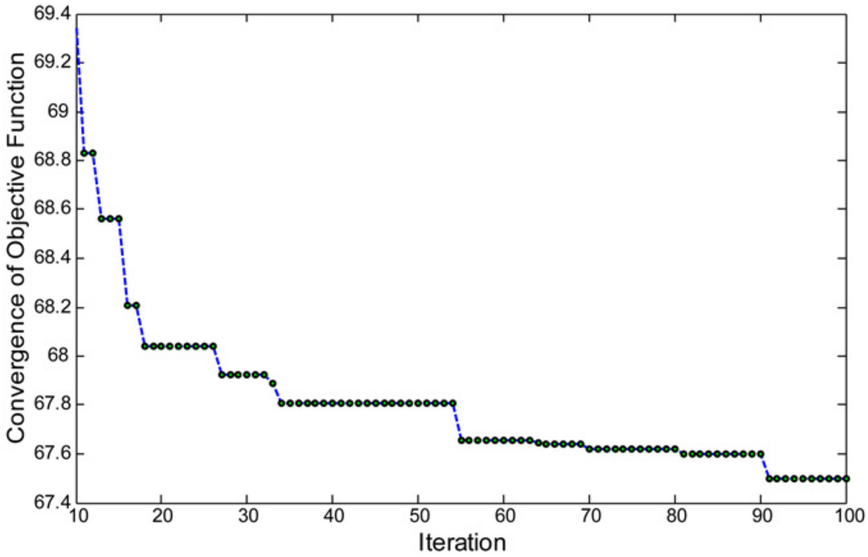

Fig. 7 *Convergence characteristic of the objective function for the case of 118-bus network*

The summaries and numerical results are tabulated and shown in Table 8.

The reductions in the peak active and reactive losses are 33.64 and 33.84%, respectively, for the 100% load conditions. However, the overall power factor has been enhanced from 0.7879 lagging to 0.915 lagging. Fig. 6 shows the improvement in the bus voltage profile before and after capacitor installations.

Fig. 7 shows the trend of objective function convergence characteristics. The CPU time used to reach the optimal solution by the proposed method is approximately 800 s including LF runs which is considered a concern for this CSA-based approach and working to shorten it to an acceptable range.

The results show that $33 494.90 annual net savings for 69-bus system with 100% loading during the year. However, in case of the load variations are tied up, the cost net savings is $18 239.60 and for the case of 118-bus, $107 063.80 is possible as shown in Tables 4, 5 and 8, respectively, and bus voltages are also improved notably.

8 Conclusions

The application of the CSA-based optimisation approach for solving the problem of capacitor allocations (sizing and location) to minimise the system losses at different load levels and to improve system voltage profile has been presented and investigated. The obtained results indicate that the proposed method has a realistic view to this important practical problem and causes the reduction in the power loss and annual energy consumption in the network which is attractive in the economic point of view. It has also improved the feeder's nodes voltage and controls the voltage in a favourable manner using fixed and switched capacitor stages. The realised results pointed up good performance and robustness of CSA-based approach in power distribution systems optimisation problems that make it preliminary competitive with the other methods in terms of the quality of the solution and stable convergence. On the other hand, it is worth to highlight that one main issue with this CSA-based approach is the time required by CPU that is still relatively high compared with other heuristic's methods due to higher search space.

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