ARTICLE IN PRESS
Ain Shams Engineering Journal (2016) xxx, xxx–xxx

Ain Shams University
Ain Shams Engineering Journal
www.elsevier.com/locate/asej
www.sciencedirect.com

ELECTRICAL ENGINEERING

# An efficient method for solving the optimal sitting and sizing problem of capacitor banks based on cuckoo search algorithm

**K.R. Devabalaji** *, **T. Yuvaraj**, **K. Ravi**

*School of Electrical Engineering, VIT University, India*

Received 3 June 2015; revised 12 March 2016; accepted 12 April 2016

**KEYWORDS**
Cuckoo search algorithm;
Power loss minimization;
Voltage stability index;
Voltage profile index;
Distribution system

**Abstract** In this paper, a new approach to determine the optimal location and sizing of capacitor is being analyzed and the objective function is formulated to minimize power losses and voltage profile of the system subjected to equality and inequality constraints. Voltage stability index (VSI) is implemented to pre-determine the optimal location of capacitor. The newly developed Cuckoo Search Algorithm (CSA) is proposed to determine the optimal size of the capacitor. To check the feasibility of the proposed method, it is tested on IEEE 34-bus and 69-bus radial distribution system with different load factors. The simulated results demonstrate well the performance and effectiveness of the proposed method.


## 1. Introduction

In the radial distribution system, the capacitors are optimally located for the power loss minimization and enhancing voltage stability. It is estimated that 13% of the total power generation is dissipated as $I^2R$ loss in the distribution networks. Hence the capacitor placement will help to decrease the intake of power from the feeder [1,2]. Improper placement of the capacitor will lead to reduce the benefits of the system and even endanger the entire system control [3–7]. To locate the shunt capacitors in the distribution systems, one has to find the optimal location, optimal size and number of capacitors to be installed such that maximum benefits of the system can be achieved while satisfying all the constraints. The main difficulty in placement of shunt capacitor in radial distribution systems lies in determining the optimal size and location of the shunt capacitors. Recently many methods and optimization algorithms have been proposed in order to find the optimal allocation of capacitors [8]. Plant growth optimization was implemented to allocate the capacitor in radial distribution system with the objective of improving voltage profile and reducing the power losses. [9]. Genetic Algorithm had been used to find the optimal sizing of the fixed and switched capacitor at various load levels [10–13]. Direct search algorithm (DSA) had been introduced to find the optimal location and size of capacitor and it is tested on IEEE 22, 69, 85-bus radial distribution

* Corresponding author at: School of Electrical Engineering, VIT University, Vellore, Tamil Nadu 632014, India. Tel.: +91 9047290894.
E-mail addresses: eeedevabalaji@gmail.com (K.R. Devabalaji), yuvaraj4252@yahoo.com (T. Yuvaraj), k.ravi@vit.ac.in (K. Ravi).
Peer review under responsibility of Ain Shams University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2016.04.005
2090-4479 © 2016 Faculty of Engineering, Ain Shams University. Production and hosting by Elsevier B.V.

**Nomenclature**

| | |
|---|---|
| $P_{Lm}$ | real power load at bus $m$ |
| $P_m$ | real power flowing out of bus $m$ |
| $P_{m+1,eff}$ | total effective real power load fed through the bus $m + 1$ |
| $I_m$ | equivalent current injected at node $m$ |
| $R_m$ | resistance of the line section between buses $m$ and $m + 1$ |
| $P_{loss}(m, m+1)$ | real power loss in the line connecting buses $m$ and $m + 1$ |
| $n$ | total number of buses |
| nb | total number of the branches |
| $Q_{Lm}$ | reactive power load at bus $m$ |
| $Q_m$ | reactive power flowing out of bus $m$ |
| $Q_{m+1,eff}$ | total effective reactive power load fed through the bus $m + 1$ |
| $V_m$ | voltage magnitude at bus $m$ |
| $X_m$ | reactance of the line section between $m$ and $m + 1$ |
| $P_{T,Loss}$ | total power losses of the system |
| $P^{cap}_{T,Loss}$ | total power loss of the system after capacitor placement |
| $P_{cap,m}$ | reactive power supplied by capacitor |
| $V_{m,\min}$ | minimum voltage limits at bus $m$ |
| $V_{m,\max}$ | maximum voltage limits at bus $m$ |
| $Q^{\min}_{cm}$ | minimum reactive power limits of compensated bus $m$ |
| $Q^{\max}_{cm}$ | maximum reactive power limits of compensated bus $m$ |
| $\Delta P^{cap}_{TL}$ | total power losses of the system after capacitor placement |

system with the objective function of maximizing net savings and minimizing the power losses [14]. Taher and Bagherpour propose the hybrid honeybee colony optimization algorithm to place the shunt capacitors in IEEE 25, 37 bus radial distribution systems to minimize the power losses by maintaining total harmonic distortion at prescribed level [15]. Antunes et al. proposed the non-dominated sorting genetic algorithm to solve the optimal capacitor placement in radial distribution systems for reactive power compensation [16]. Baran and Wu introduced mixed integer programming for the capacitor placement [17]. Chis et al. had chosen more sensitivity nodes for optimal location and sizing by heuristic search strategies to maximize the net savings [18]. Mohammad et al. introduced the supervisory control and data acquisition system (SCADA) with fuzzy based decision making to calculate the suitable capacitors required to enhance the power factor according to the measured parameters [19]. Prakash and Sydulu introduced the particle swarm optimization to determine the optimal size of the capacitor bank to minimize the power losses [20]. Nojavan et al. proposed mixed integer nonlinear programming approach to determine the location and size of the capacitor to minimize the power losses and increasing the net benefits [21].

Cuckoo Search Algorithm (CSA) [22] is one of the new nature-inspired algorithms that has been proposed recently to solve complex optimization problems. CSA can be used to efficiently solve global optimization problems [23] as well as NP-hard problems that cannot be solved by exact solution methods [24]. The most powerful feature of CS is its use of Lévy flights to update the search space for generating new candidate solutions. This mechanism allows the candidate solutions to be modified by applying many small changes during the iteration of the algorithm. This in turn makes a compromised relationship between exploration and exploitation which enhance the search capability [25]. To this end, recent studies proved that CSA is potentially far more efficient than GA and PSO [26]. In addition, it is simple and population based stochastic optimization algorithm. Moreover, it requires less control parameters to be tuned. Also, it is a compatible optimization tool for power system controller design. Such feature has motivated the use of CSA to solve different kinds of engineering problems such as multi-objective scheduling problem [27], reliability optimization problems [28], DG allocation in distribution network [29], economic dispatch [30], network reconfiguration and distributed generation allocation in distribution network [31].

In the present work, a fast and new technique to determine the optimal location and sizing of capacitors to minimize the power losses and to enhance the voltage profile in the radial distribution system with different load factors has been proposed. The novelty of this work is implementing an integrated approach of VSI and recently developed meta-heuristic cuckoo search algorithm to determine the optimal location and sizing of capacitor for the sake of power loss minimization and voltage profile enhancement. It is validated that CSA gets better results faster when compared with other classical algorithm. In addition to that CSA is capable of searching global optima solution. The proposed method has been tested on different radial distribution systems and the results are presented. In order to show the effectiveness of the proposed method, the results obtained by the proposed method are compared with the results of other existing methods.

## 2. Problem formulation

### *2.1. Load flow analysis*

The direct approach for distribution system load flow solution is used to find the power losses and also the voltage at each branch [32]. The single line diagram of a sample distribution system is shown in Fig. 1.

The voltage at node $m + 1$ is given by

$$V_{m+1} = V_m - I_m * (R_m + jX_m) \tag{1}$$

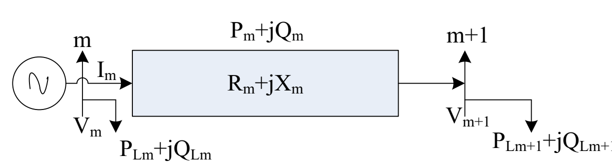


**Figure 1** Sample distribution system.

$$I = [BIBC] * [i] \tag{2}$$

where BIBC is the Bus current Injection to Branch Current matrix.

$$i_m = \frac{(P_{Lm} + jQ_{Lm})^*}{V_m} \tag{3}$$

The real and reactive power losses in the line section between buses $m$ and $m+1$ are calculated by using the following equation

$$P_{loss}(m, m+1) = \left(\frac{P_m^2 + Q_m^2}{|V_m|^2}\right) * R_m \tag{4}$$

$$Q_{loss}(m, m+1) = \left(\frac{P_m^2 + Q_m^2}{|V_m|^2}\right) * X_m \tag{5}$$

The total real and reactive power losses of the system can be easily found by summing of all the branch power losses and it is expressed in Eq. (6).

$$P_{T,Loss} = \sum_{m=1}^{nb} P_{Loss}(m, m+1) \tag{6}$$

### 2.2. Power loss reduction using capacitor placement

The net power losses reduced by capacitor placement is taken as the ratio of total power loss before and after capacitor placement of the system, and is given by

$$\Delta P_{TL}^{cap} = \frac{P_{T,loss}^{cap}}{P_{T,Loss}} \tag{7}$$

Net power loss reduced by capacitor placement in the system can be maximized by minimizing $\Delta P_{TL}^{cap}$.

### 2.3. Voltage profile index

If the capacitor is placed optimally, it results in improving the voltage profile of the system. Suppose the index is closer to zero, then the network will operate in safe mode. The Voltage profile index [33] is given by,

$$\Delta V_D = \max\left(\frac{V_1 - V_m}{V_1}\right) \quad v \quad m = 1, 2, \ldots, n \tag{8}$$

where $V_1$ is the voltage at the generating station ($V_1 = 1.0$ p.u.).

It is advised to keep the index value ($\Delta V_D$) closer to zero and thereby improves voltage stability and network performance.

### 2.4. Objective function of the problem

The objective function ($F$) of the proposed work is formulated to minimize the total power loss and voltage profile index of the distribution system.

The mathematical formulation of the objective function [33] is given by

$$\text{Minimize} \quad (F) = \min(\Delta P_{TL}^{cap} + \Delta V_D) \tag{9}$$

Subjected to the following operating constraints.

*Power Balance*

$$P_{ss} = \sum_{m=2}^{n} P_{Lm} + \sum_{m=1}^{nb} P_{Loss}(m, m+1) - \sum_{m=1}^{nb} P_{cap,m}$$

*Voltage deviation limit*

$$V_{m,\min} \leqslant |V_m| \leqslant V_{m,\max}$$

*Reactive power compensation*

$$Q_{cm}^{\min} \leqslant Q_{cm} \leqslant Q_{cm}^{\max}, \quad m = 1, \ldots, N_B$$

## 3. Optimal location

The voltage stability index is used to pre-identify the location of the capacitor. Initially the optimal location is determined by using VSI. However the calculation of VSI is dependent on the network topology, configurations, loading, etc. In order to overcome this issue the algorithm will search the optimal number of buses and select them for capacitor placement. The optimal size of the capacitor will be obtained using cuckoo search algorithm.

### 3.1. Voltage stability index for capacitor placement

There are many indices used to check the power system security level. In this section a new steady state voltage stability index is used in order to identify the node, which has more chance to voltage collapse [33,34]. The voltage stability index at each node is calculated using Eq. (10). The node which has the low value of VSI is the weakest node and the voltage collapse phenomenon will start from that node. VSIs are calculated from the load flow for all the buses of the given system and the values are arranged in ascending order. The VSIs choose the sequence in which the buses are to be considered for capacitor allocation. Therefore to avoid the possibilities of voltage collapse, the VSI of nodes should be maximized.

$$\begin{aligned} VSI(m+1) = {} & |V_m|^4 - 4[P_{m+1,eff} * X_m - Q_{m+1,eff} * R_m]^2 \\ & - 4[P_{m+1,eff} * R_m + Q_{m+1} * X_m]|V_m|^2 \end{aligned} \tag{10}$$

## 4. Cuckoo search algorithm

A more recent meta-heuristic search algorithm, Cuckoo Search Algorithm (CSA) has been developed by Yang [22]. CSA has two main operators. One is direct search based on Levy flights and another one is random search based on the probability for a host bird to discover an alien egg in its nest.

CSA consists of three steps. They are

(i) Every cuckoo lays one egg at a time, and dumps its egg in a randomly chosen nest.
(ii) The best nests with high quality of eggs will carry over to the next generation.
(iii) The number of available host nests is fixed, and the egg laid by a cuckoo is discovered by the host bird.

Please cite this article in press as: Devabalaji KR et al., An efficient method for solving the optimal sitting and sizing problem of capacitor banks based on cuckoo search algorithm, Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.04.005

Cuckoos are attractive birds, it not only makes beautiful sound, but also has fantastic reproduction strategy. Some of the species in cuckoo such as *ani* and *guira* lay their eggs in common nests, though they may remove others eggs to raise the hatching probability of their own eggs. The cuckoo eggs may hatch earlier than those of their host eggs. When the first cuckoo egg is hatched, the first action is to remove the host eggs by blindly pushing out the egg from the nest. The cuckoo chicks may also mimic the call of host chick to increase the feeding opportunity.

The term Levy flight was introduced by Benoit Mandelbrot, who used this term for one specific definition of the distribution of step size. Naturally most of the animals search (cuckoo bird will search for host nest) their food in a random manner (the next step is always based on the current location and the probability of moving to the next location). It can be modeled with a Levy distribution (a continuous probability distribution for non-negative random variables) known as Levy flights.

The cuckoo bird will find the best nest to lay their eggs (solution) to maximize their egg's survival rate. Actually every cuckoo lays one egg at a time. The high quality eggs (Optimal value) which are more similar to the host bird's eggs have more chance to develop (next generation) and became a mature cuckoo. Unhealthy eggs (not optimal value) are identified by host bird with a probability Pa € [0, 1] and these eggs are thrown away or the nest is discarded, and the new nest is built at new location. A randomly distributed initial population of host nest is generated and then the population of solutions is subjected to repeat cycles of the search process of the cuckoo birds.

The parameters used in cuckoo search algorithm are

Number of nests or different solutions ($n$) = 25.
Discovery rate of alien eggs/solutions (pa) = 0.25.
Levy coefficient ($\lambda$) = 0.5

The cuckoo randomly chooses the nest position to lay eggs using Eqs. (11) and (12) [35,36].

$$X_{pq}^{gen+1} = X_{pq}^{gen} + S_{pq} * Levy(\lambda) * \alpha \quad (11)$$

$$Levy(\lambda) = \left| \frac{\Gamma(1+\lambda) * \sin\left(\frac{\pi*\lambda}{2}\right)}{\Gamma\left(\frac{1+\lambda}{2}\right) * \lambda * S^{(\lambda-1)/2}} \right|^{1/\lambda} \quad (12)$$

where $\lambda$ is constant ($1 < \lambda \leqslant 3$)
$\alpha$ is a random number generated between $[-1, 1]$.
$\Gamma$ is gamma function.
$S > 0$, it is step size.

The step size can be obtained using

$$S_{pq} = X_{pq}^{gen} - X_{fq}^{gen} \quad (13)$$

where $p, f \in \{1, 2, \ldots, m\}$ *and* $q \in \{1, 2, \ldots, D\}$ are randomly chosen indexes.

$f$ is chosen randomly but its value must be different from $p$.

The host bird will identify the cuckoo egg and choose the high quality egg with probability of using Eq. (14)

$$pro_q = \left(\frac{0.9 * fit_q}{\max(fit)}\right) + 0.1 \quad (14)$$

where $fit_q$ is the fitness value of the solution.

$q$ is the proportionality index to the quality of egg in the nest position $q$.

If the host bird identify the cuckoo egg, then the host bird may throw the egg away or leave that nest and build a new nest using Eq. (15). Otherwise the egg will grow and is alive for next generation.

$$nest_q = X_{q,\min} + rand(0,1) * (X_{q,\max} - X_{q,\min}) \quad (15)$$

### 4.1. Steps to be followed for optimization

*Step 1:* Run load flow analysis.
*Step 2:* Obtain the base power losses and Voltage at each bus.
*Step 3:* Run the VSI to find the candidate location for capacitor.
*Step 4:* Set the lower and upper limits for the constraints.
*Step 5:* Initiate random population of n host nests, $X_i$ for amount of kVAr to be injected within limits.
*Step 6:* Obtain cuckoo randomly using Levy flights, $i$
*Step 7:* Evaluate its fitness ($F_i$) according to objective function.
*Step 8:* Get a nest randomly from population $j$.
*Step 9:* If $F_i > F_j$, else go to step 11. If no go to step 12.
*Step 10:* Let $j$ be the solution.
*Step 11:* Replace $j$ with the new solution.
*Step 12:* If a fraction of nest is replaced by new nests then create a new nest at new location with the help of Levy flights.
*Step 13:* Choose the best current nests.
*Step 14:* Allow the current best solution to the next generation.
*Step 15:* If maximum iteration is not reached then go to step 6, otherwise it is the best nest (optimal solution).
*Step 16:* Display optimal solution.

These are the steps involved to minimize $F$.

## 5. Numerical results

To demonstrate the effectiveness of the proposed method using VSI and CSA, it is applied to 34-bus and 69-bus radial distribution systems. The voltage at the substation is assumed to be 1 p.u. The first bus in this system is considered as feeder of electric power from generation/transmission network. The rest of the buses are considered as a candidate location of capacitor. The maximum limit of the capacitor unit is 100% of the total kVAr loading of this network. The maximum number of capacitor installed is limited to three. Since beyond this limit, there is no significant improvement in power loss reduction. The parameters used to calculate net savings per year are the energy rate $C_e$ = \$0.06/kW h, Installation cost of capacitor $C_{cl}$ = \$ 1600/location, purchase cost of capacitor $C_e$ = \$ 25/kVAr, operating cost is \$ 300/year/location, depreciation factor ($\gamma$) is 20%, operating hour per year is 8760 [37].

### 5.1. IEEE 34-bus radial distribution system

The schematic diagram of the IEEE 34-bus radial distribution system is shown in Fig. 2. The IEEE 34-bus radial distribution system consists of 34 buses and 33 branches. The line data and

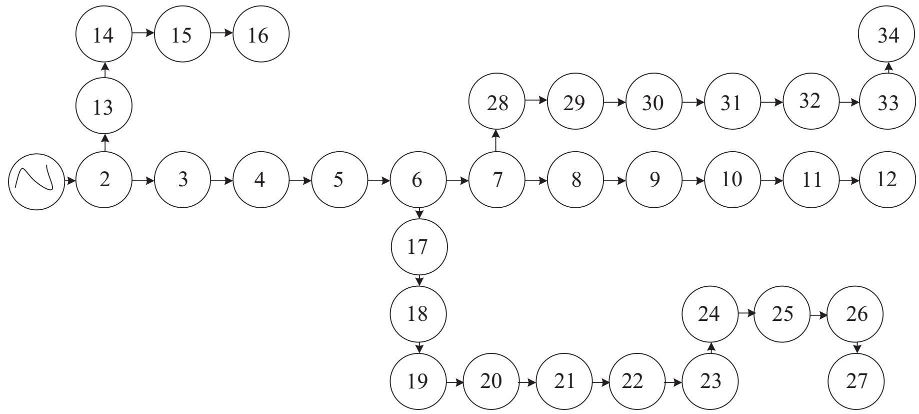


**Figure 2** IEEE 34 radial distribution system.

**Table 1** Optimal result of 34-bus network.

| | Base case | Heuristic method (18) | PSO (20) | PGS (9) | MINLP (21) | Proposed method |
|---|---|---|---|---|---|---|
| Optimal size and location | – | 1400 (26), 750 (11), 300 (17), 250 (4) | 781 (19), 803 (22), 479 (20) | 1200 (19), 639 (22), 200 (20) | 300 (4), 600 (10), 100 (14), 500 (18), 300 (22), 1000 (27) | 10 (650), 19 (850), 25 (700) |
| Total kVAr | – | 2700 | 2063 | 2039 | 2800 | 2200 |
| $P_{loss}$ (kW) | 221.286 | 167 | 168.5 | 168.7 | 162.9 | 160.3 |
| % reduction in $P_{loss}$ | – | 24.53% | 23.85% | 23.76% | 26.38% | 27.6% |
| $V_{\min}$ (p.u) | 0.9420 | 0.9515 | 0.9500 | 0.9496 | 0.9513 | 0.9503 |
| $VSI_{\min}$ (p.u) | 0.7875 | NA | NA | NA | NA | 0.8152 |
| Net savings/year ($) | – | 12,553 | 15,569 | 15,584 | 12,968 | 19,194 |
| Computational time (s) | – | NA | NA | NA | NA | 8.2 |

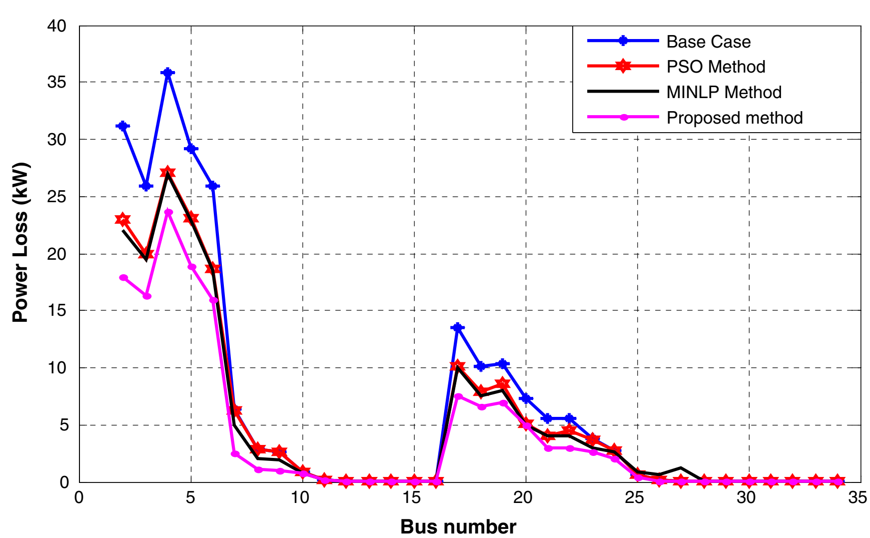


**Figure 3** Comparison of performance of line losses for 34-bus radial distribution system.

load data of this system are taken from [37]. The base values are 100 MVA, 11 kV and the real and reactive power loads of this system are 4636.5 kW and 2873.5 kVAr. In this case the maximum limit of the capacitor bank is 100% of the total kVAr loading of this network (2874 kVAr at full load). The minimum bus voltage and maximum bus voltage of the system are 0.9420 p.u and 0.9999 p.u. respectively. The optimal location and size of this system are chosen as 10 (650), 19 (850), 25 (700). Compared with the heuristic method in which they were able to reduce power losses to 167 kW with total

**Table 2** Simulation results of different loading conditions (34-bus system).

| | Load factors | | | | |
|---|---|---|---|---|---|
| | (0.5) | (0.75) | (1.0) | (1.25) | (1.6) |
| Optimal size and location | 10 (300), 19 (400), 25 (300) | 10 (520), 19 (650), 25 (510) | 10 (650), 19 (850), 25 (700) | 10 (900), 19 (1120), 25 (860) | 10 (1100), 19 (1500), 25 (1100) |
| Total kVAr | 1000 | 1680 | 2200 | 2880 | 3700 |
| $P_{loss}$ (kW) | 38.7 | 88.3 | 160.3 | 255.58 | 432 |
| $V_{min}$ (p.u) | 0.9753 | 0.9631 | 0.9503 | 0.9373 | 0.9184 |
| $VSI_{min}$ (p.u) | 0.9048 | 0.8597 | 0.8152 | 0.7701 | 0.7111 |

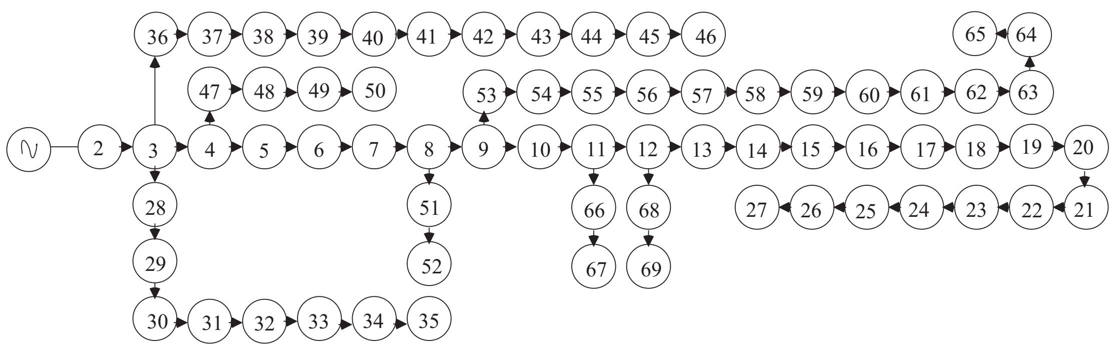

**Figure 4** The schematic diagram of the 69-bus radial distribution system.

**Table 3** Optimal result of 69-bus network.

| | Base case | GA [13] | PSO [20] | DSA [14] | TLBO [39] | Proposed method |
|---|---|---|---|---|---|---|
| Optimal size and location | – | 61 (700), 64 (800), 59 (100) | 46 (241), 47 (365), 50 (1015) | 61 (900), 15 (450), 60 (450) | 12 (600), 61 (1050), 64 (150) | 18 (350), 61 (1150), 65 (150) |
| Total compensation | – | 1600 | 1621 | 1800 | 1800 | 1650 |
| $P_{loss}$ (kW) | 225 | 156.62 | 152.48 | 147.00 | 146.35 | 146.1 |
| % reduction in $P_{loss}$ | – | 30.39% | 32.23% | 34.67% | 34.95% | 35.07% |
| $V_{min}$ (p.u) | 0.9090 | NA | NA | NA | 0.9321 | 0.9321 |
| $VSI_{min}$ (p.u) | 0.6822 | NA | NA | NA | NA | 0.7451 |
| Net savings/year ($) | – | 26,081 | 28,152 | 30,137 | 30478.4 | 31359.9 |
| Computation time (s) | – | NA | NA | NA | NA | 8.6 |

reactive compensation of 2700 kVAr, using PSO method the losses were reduced to 168.5 kW with injecting 2063 kVAr and by PGS method, the authors were able to reduce power losses to 168.7 kW with total reactive support of 2039 kVAr. Finally using MINLP method, the losses were reduced to 162.9 kW with the total reactive support of 2800 kVAr. However, in the proposed method, the losses are reduced to 160.3 kW with reactive compensating of 2200 kVAr which results better when comparing with other existing techniques as shown in Table 1. It is found that the net savings using proposed method are $ 19,194 which is better when compared to $ 12,968 by MINLP, $ 15,584 by PGS $ 15,569 by PSO, and $ 12,553 by Heuristic method. Finally all the constraints such as voltage magnitude and reactive power limits were checked and found that all the limits are within the allowable tolerance. The performance analysis of line losses of proposed method over other techniques is shown in Fig. 3 also it shows that the proposed method has achieved better power loss reduction when compared with other methods. This system is also analyzed under different load factors such as 0.5, 0.75, 1.0, 1.25 and 1.6 and it is shown in Table 2. The base case power losses of different load factors (0.5, 0.75, 1.0, 1.25 and 1.6) are 52.75 kW, 121.49 kW, 221.28 kW, 354 kW, and 603 kW respectively. From Table 2, it is concluded that the proposed method power loss reduction has been improved when compared with base case.

### 5.2. IEEE-69 bus radial distribution system

The 69-bus radial distribution system is analyzed in this case. The line data and bus data are available from [38] with a real and reactive load of 3801 kW and 2694.6 kVAr and the base

**Table 4** Simulation results of different loading conditions (69-bus system).

| | Load factors | | | | |
|---|---|---|---|---|---|
| | (0.5) | (0.75) | (1.0) | (1.25) | (1.6) |
| Optimal size and location | 18 (150), 61 (500), 65 (150) | 18 (240), 61 (820), 65 (80) | 18 (350), 61 (1150), 65 (150) | 18 (420), 61 (1420), 65 (160) | 18 (600), 61 (1800), 65 (200) |
| Total kVAr | 800 | 1140 | 1650 | 2000 | 2600 |
| $P_{loss}$ (kW) | 34.45 | 79.74 | 146.1 | 236.57 | 408.5 |
| $V_{\min}$ (p.u) | 0.9675 | 0.9487 | 0.9320 | 0.9123 | 0.8839 |
| $\mathrm{VSI}_{\min}$ (p.u) | 0.8709 | 0.8044 | 0.7451 | 0.6813 | 0.5954 |

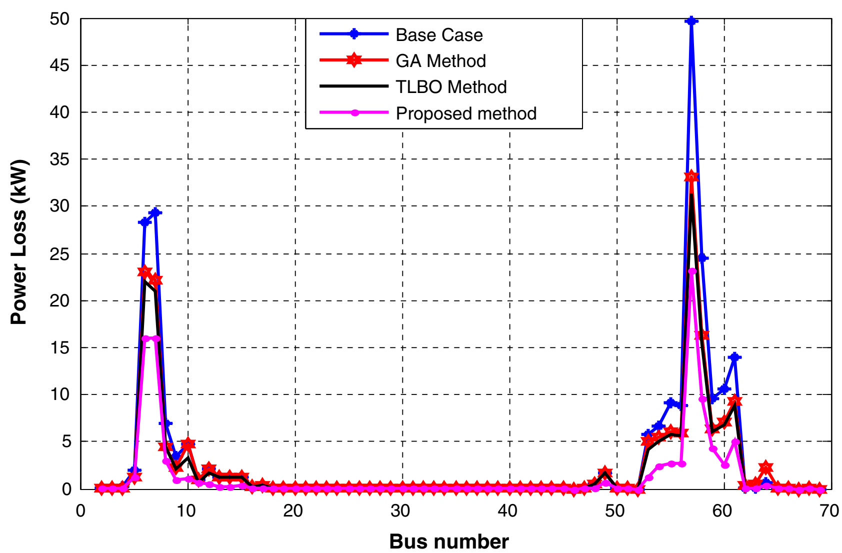


**Figure 5** Comparison of performance of line losses for 69-bus radial distribution system.

values are 100 MVA, 12.66 KV. The real and reactive power losses of the base case are 225 kW and 102.2 kVAr. In this case the maximum limit of the capacitor unit is 100% of the total kVAr loading of this network (2695 kVAr at full load). The schematic diagram of this system is as shown in Fig. 4. It is planned to install three capacitors in this system. The optimal location and size of capacitors for this system are chosen as 18 (350), 61 (1150), 65 (150). The total kVAr used in the proposed method is less when compared with other techniques at the same time the real and reactive power losses are also less. The real power losses obtained from the proposed method are 146.1 kW which is less when compared to 146.35 kW by TLBO, 147 kW by PSO and 156.62 kW by GA. The net savings for the proposed method are $ 31359.9 which is better than the other techniques compared in the Table 3. The optimal results of other algorithm compared in this paper are executed using proposed power flow equation. The Table 3 shows the comparison of numerical values of proposed method with the other techniques and Table 4 shows the numerical results of proposed method with different load Factors (0.5, 0.75, 1.0, 1.25 and 1.6). The base case power losses of different load factors (0.5, 0.75, 1.0, 1.25 and 1.6) are 51.6 kW, 121.03 kW, 225 kW, 369 kW, and 652.5 kW respectively. From Table 4, it is concluded that the proposed method power loss reduction has been improved when compared with base case. The performance analysis of line losses of proposed method over other techniques is shown in Fig. 5. From Fig. 5, it is clear that the performance of the proposed CS algorithm is better compared to other existing methods in terms of quality of solutions.

## 6. Conclusion

Capacitor placement in the distribution system is used to compensate the reactive power which leads to minimization of power losses, enhancement of the voltage profile, improving the system stability, etc. It is necessary to place the capacitors at optimal locations with optimal size to ensure the maximum benefits of the system. In this article, the new method of finding the optimal location is proposed and the optimal size is determined by using newly developed CSA. The proposed method is applied to IEEE 34-bus, 69-bus radial distribution system with different load factors. The main advantage of using CSA is that it does not require spending more effort in tuning the control parameters, as in case of GA, PGS, MINLP, DSA and other Evolutionary algorithms. The simulated results obtained using CSA are compared with the other existing techniques, and the results show that the performance of the proposed method for minimization of power loss and voltage profile and maximization of net savings is found to

Please cite this article in press as: Devabalaji KR et al., An efficient method for solving the optimal sitting and sizing problem of capacitor banks based on cuckoo search algorithm, Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.04.005

be better than the other existing methods. The proposed method can be easily applied to any large scale particle radial distribution system.

## References

[1] Lee SH, Grainger JJ. Optimum placement of fixed and switched capacitors on primary distribution feeders. IEEE Trans Power Apparatus Syst 1981;PAS-100(1):345–52.
[2] Devabalaji KR, Ravi K. Optimal size and siting of multiple DG and DSTATCOM in radial distribution system using Bacterial Foraging Optimization Algorithm. Ain Shams Eng J 2015.
[3] Mohamed Imran A, Kowsalya M. Optimal size of multiple distributed generators in distribution system using bacteria foraging optimization. Swarm Evol Comput 2014:58–65.
[4] Chiang H. Optimal capacitor placement in distribution system. IEEE Trans Power Deliv 1989;4(1):725–34.
[5] Baran M, Wu F. Optimal placement on radial distribution. IEEE Trans Power Deliv 1989:725–34.
[6] Haque MH. Capacitor placement in radial distribution system for loss reduction. IEE Proc, Gener Transm Distrib 1999:501–5.
[7] Devabalaji KR, Ravi K, Kothari DP. Optimal location and sizing of capacitor placement in radial distribution system using bacterial foraging optimization algorithm. Int J Electr Energy Syst 2015;71:383–90.
[8] EI-Fergany Attia A, Almoataz Y Abdelaziz. Efficient heuristic-based approach for multi-objective capacitor allocation in radial distribution networks. IET Gener Transm Distrib 2013:70–80.
[9] Srinivasas Rao R, Narasimham SVL, Ramalingaraju M. Optimal capacitor placement in radial distribution system using plant Growth Simulation Algorithm. Int J Electr Power Energy Syst 2011;33:1133–9.
[10] Das D. Reactive power compensation for radial distribution networks using genetic algorithm. Int J Electr Power Energy Syst 2002;24:573–81.
[11] Swarup KS. Genetic algorithm for optimal capacitor allocation in radial distribution system. In: Proc. sixth WSEAS int. conf. evolutionary computation, Lisbon, Portugal; 2005. p. 152–59.
[12] Levitin G, Kalyuzhny A, Shenkaman A. Optimal capacitor allocation in distribution system using genetic algorithm and a fast energy loss computation technique. IEEE Trans Power Deliv 2000;15(2):623–8.
[13] Sydulu M, Reddy VVK. Index and GA based optimal location and sizing of distribution system capacitor. In: IEEE power engineering society general meeting; 2007, 24th–28th June. p. 1–4.
[14] Raju MR, Murthy KVSR, Avindra KR. Direct search algorithm for capacitive compensation in radial distribution system. Int J Electr Power Energy Syst 2012;42(1):24–30.
[15] Taher SA, Bagherpour R. A new approach for optimal capacitor placement and sizing in unbalanced distorted distribution systems using hybrid honey bee colony algorithm. Int J Electr Power Energy Syst 2013;49:430–48.
[16] Antunes CH, Pires DF, Barrico C, Gomes A, Martins AG. A multi-objective evolutionary algorithm for reactive power compensation in distribution network. Appl Energy 2009;86(7–9):977–84.
[17] Baran ME, Wu FF. Optimal placement on radial distribution systems. IEEE Trans Power Deliv 1989;4(1):725–34.
[18] Chis M, Salama MMA, Jayaram S. Capacitor placement in distribution systems using heuristic strategies. In: Proc Inst. Elect. Gen. Transm. Dist., vol.144, No.2; 1997. p. 225–30.
[19] Mohammad WF, Tawalbeh N, AL-Aubidy KM. Fast power loss computation and shunt capacitor insertion using fuzzy logic technique. Am J Appl Sci 2007;4(1):37–41.
[20] Prakash K, Sydulu M. Particle Swarm optimization based capacitor placement on radial distribution system. In: Proceedings of IEEE power Engineering Society General Meeting; 2007. p. 1–5.
[21] Nojavan Sayyad, Jalali Mehdi, Zare Kazem. Optimal allocation of capacitors in radial/mesh distribution systems using mixed integer nonlinear programming approach. Electr Power Syst Res 2013:119–24.
[22] Yang XS, Deb S. Cuckoo search via Levy flights. In: Proc. world congress on nature & biologically inspired computing (NaBIC 2009). USA: IEEE Publications; 2009. p. 210–4.
[23] Yang X-S, Deb S. Cuckoo search: recent advances and applications. Neural Comput Appl 2014;24:169–74.
[24] Dejam S, Sadeghzadeh M, Mirabedini SJ. Combining cuckoo and tabu algorithms for solving quadratic assignment problems. J Acad Appl Stud 2012;2:1–8.
[25] Walton S, Hassan O, Morgan K, Brown MR. A review of the development and applications of the cuckoo search algorithm. In: Yang X-S, Cui Z, Xiao R, Gandomi AH, Karamanoglu M, editors. Swarm intelligence and bio-inspired computation. Oxford: Elsevier; 2013. p. 257–71.
[26] Yang X-S, Deb S. Engineering optimisation by cuckoo search. Int J Math Modell Numer Optim 2010;1:330–43.
[27] Chandrasekaran K, Simon Sishaj P. Multi-objective scheduling problem: hybrid approach using fuzzy assisted cuckoo search algorithm. Swarm Evol Comput 2012;5:1e16. August.
[28] Valian Ehsan, Tavakoli Saeed, Mohanna Shahram, Haghi Atiyeh. Improved cuckoo search for reliability optimization problems. Comput Ind Eng 2013;64(1):459e68.
[29] Moravej Zahra, Akhlaghi Amir. A novel approach based on cuckoo search for DG allocation in distribution network. Int J Electr Power Energy Syst 2013;44(1):672e9.
[30] Basu M, Chowdhury A. Cuckoo search algorithm for economic dispatch. Int J Energy 2013;60(1):99–108.
[31] Nguyena Thuan Thanh, Truong Anh Viet, Phung Tuan Anh. A novel method based on adaptive cuckoo search for optimal network reconfiguration and distributed generation allocation in distribution network. Int J Electr Power Energy Syst 2016;78:801–15.
[32] Teng Jen-Hao. A direct approach for distribution system load flow solutions. IEEE Trans Power Deliv 2003;18(3):882–7.
[33] Mohamed Imran A, Kowsalya M, Kothari DP. A novel integration technique for optimal network reconfiguration and distributed generation placement in power distribution networks. Int J Electr Power Energy Syst 2014:461–72.
[34] Yuvaraj T, Ravi K, Devabalaji KR. DSTATCOM allocation in distribution networks considering load variations using bat algorithm. Ain Shams Eng J 2015.
[35] Nguyen Thang trung, Vo Dieu Ngoc, Truong Anh Viet. Cuckoo Search algorithm for short-term hydrothermal scheduling. Appl Energy 2014:276–87.
[36] Bhandari Ashish Kumar, Singh Vineet Kumar, Kumar Anil, Singh Girish Kumar. Cuckoo search algorithm and wind driven based study of satellite image segmentation for multilevel thresholding using kapur's entropy. Expert Syst Appl 2014:3538–60.
[37] EI-Fergancy Attia A, Abdelaziz Almoataz Y. Efficient heuristic-based approach for multi-objective capacitor allocation in radial distribution networks. IET Gener Trans Distrib 2014;8(1):70–80.
[38] Sahoo NC, Prasad K. A fuzzy genetic approach for network reconfiguration to enhance voltage stability in radial distribution systems. Energy Convers Manage 2006;47:3288–306.
[39] Sultana Sneha, Roy Provas Kumar. Optimal capacitor placement in radial distribution systems using teaching learning based optimization. Int J Electr Power Energy Syst 2014;54:387–98.

Please cite this article in press as: Devabalaji KR et al., An efficient method for solving the optimal sitting and sizing problem of capacitor banks based on cuckoo search algorithm, Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.04.005

**K.R. Devabalaji** received the B.E and M.E Degree, both in electrical engineering, from Anna University, Tamil Nadu, India. Presently, he is a full time Research scholar in the school of Electrical engineering, VIT University, Vellore, India. His research interests are optimal allocation of D-FACTS in distribution systems.

**K. Ravi** Received the B.E, M.E and Phd, all in Electrical Engineering, from Anna University, Tamil Nadu, India. He had more than 15 years of teaching experience. He is an Associate professor in the School of Electrical Engineering, VIT University, Vellore, Tamil Nadu, India. His research interests are optimal allocation of FACTS devices, Optimal Power Flow.

**T. Yuvaraj** received the B.E and M.E Degree, both in electrical engineering, from Anna University, Tamil Nadu, India. Presently, he is a full time Research scholar in the school of Electrical engineering, VIT University, Vellore, India. His research interests are optimal allocation of D-FACTS in distribution systems.

Please cite this article in press as: Devabalaji KR et al., An efficient method for solving the optimal sitting and sizing problem of capacitor banks based on cuckoo search algorithm, Ain Shams Eng J (2016), http://dx.doi.org/10.1016/j.asej.2016.04.005