Alexandria Engineering Journal (2018) xxx, xxx–xxx

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ORIGINAL ARTICLE

Multi-objective simultaneous DG and DSTATCOM allocation in radial distribution networks using cuckoo searching algorithm

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Received 25 June 2016; revised 21 March 2017; accepted 30 January 2018

KEYWORDS

Distribution STATic COMpensator;
Distributed generation;
Cuckoo search algorithm;
Voltage stability index;
Loss sensitivity factor;
Radial distribution system

Abstract In this paper, authors proposed a new methodology based on bio-inspired Cuckoo Search Algorithm (CSA), which can significantly be envisaged with simultaneous allocation of Distributed Generation (DG) and Distribution STATic COMpensator (DSTATCOM) in the radial distribution systems (RDS). In the proposed method, optimal locations of the DG and DSTATCOM are determined by using Voltage Stability Index (VSI) and Loss Sensitivity Factor (LSF) respectively. The optimal size of DG and DSTATCOM are found by using a newly developed nature-inspired CSA in the RDS. Further, in the proposed method load flow calculations are carried out by using a fast and efficient Backward/Forward Sweep (BFS) algorithm. The objective function of the proposed method is derived in such a way that to minimize the system total power losses and enhancing the bus voltages. The effectiveness of the proposed method is tested by considering a well-known IEEE 33-bus and large 136-bus RDS. The attained results of the proposed method and comparison of different cases for allocation of DG and DSTATCOM are presented in result section. From the presented results, it can be clearly understood that the proposed method is able to significantly reduce the power losses and enhance the voltage profile of the RDS.

1. Introduction

The electric power system can be divided into four major components; generation, transmission distribution and utilities. Amongst these four components of the power system, the distribution network is the final and most critical link in the power system. It is well known that the reactance to resistance ratio is very high in the distribution levels which causes high power losses and voltage drops in the distribution feeders. Previous literature study shows that losses in the distribution power sector are as high as 13% [1]. To add to this misery, deregulation creates power quality issues such as voltage variations, distortion, voltage imbalance, voltage sag, voltage fluctuations and voltage instability in the distribution system [2,3]. From the consumer point of view, loss of power is one of the

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2018.01.001
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Please cite this article in press as: T. Yuvaraj, K. Ravi, Multi-objective simultaneous DG and DSTATCOM allocation in radial distribution networks using cuckoo searching algorithm, Alexandria Eng. J. (2018), https://doi.org/10.1016/j.aej.2018.01.001

most important issues to enhance the overall ability of power delivery. Extensive research has been performed by researchers to reduce the power loss in distribution systems.

The optimal allocation of DG and DSTATCOM have a valid effect on reducing the distribution system power losses and enhance the voltage profile. Different benefits of optimal allocation of DG and DSTATCOM simultaneously shows a great effect on reducing system power loss, voltage profile enhancement, power factor correction, load balancing, power quality improvement, on-peak operating costs reduction, releasing the overloading of distribution lines, system stability improvement, pollutant emission reduction, and increased overall energy efficiency. The power import from the substation can be reduced by using optimal generation of real and reactive power from DG and DSTATCOM in RDS thus it can control the feeder power flows. The optimal placement of DG and DSTATCOM which helps in terms of regulate the real and reactive power flows respectively in the RDS. So that, the system total power loss can be reduced at extent level with good voltage profile enhancement [25,26,42-45].

In recent years, the integration of DG has considerably increased in the RDS. The term "Distributed" or "Dispersed" Generation is described as small electric power generation that is directly linked to the systems. DG consists of induction generators, micro turbines, synchronous generators, reciprocating engines, fuel cells, combustion gas turbines, solar photovoltaic, wind turbines and other small power generation sources. The installation of DGs are usually less investment compared with constructing high priced new power plants and distribution and transmission lines. The main features of DGs are eco-friendly, power quality improvement and economic. In addition, it gives more reliable energy solutions than traditional generating methods [4,5]. Based on their abilities to inject active and reactive power, DG can be classified into following categories as presented by authors in [6]:

1. DG type A: DG injects real power (P) only,
2. DG type B: DG injects both real and reactive power (P&Q),
3. DG type C: DG injects real (P) power but absorbs reactive power,
4. DG type D: DG injects reactive power (Q) only.

On the other hand, Shunt capacitors are major devices which are generally used in distribution systems to compensate the reactive power in the RDS, but these shunt capacitors are not capable to constantly produce variable reactive power. Due to this, utility has to bare an additional cost of capacitors and for placing of capacitors at right places. In addition to this load balancing cannot be possible within it. Because it exhibits some operational problems like resonance [7]. To resolve above-mentioned drawbacks Distribution Flexible Alternating Current Transmission System (DFACTS) are used in distribution systems to compensate the reactive power requirements [8,9]. DSTATCOM is a notable DFACTS device which has been used to enhance the distribution system efficiency and reliability by providing reactive power support to reduce the total line losses and to enhance the voltage profile [10–12].

The problem of optimal allocation of DG and DSTATCOM in the RDS becomes a big consideration for power system researchers. Here is an extensive literature review of the accomplished power system researches which can be divided into following three categories:

1.1. Optimal DG allocation without DSTATCOMs

The number of optimization techniques have been used to find the optimal location and sizing of DGs in RDS, such as Bee Colony Algorithm (BCA) [13], Particle Swarm Optimization and Monte Carlo simulation (PSOMCS) [14], Genetic Algorithm (GA) [15], Honey Bee Mating Optimization Algorithm (HBMOA) [16], Quasi-Oppositional Teaching Learning Based Optimization (QOTLBO) [17], Backtracking Search optimization Algorithm (BSA) [18], Supervised Firefly Algorithm (SFA) [19], and Ant Lion Optimization Algorithm (ALOA) [20] have been considered with different objective function.

1.2. Optimal DSTATCOM allocation without DGs

Further, various research works have been carried out on the optimal allocation of DSTATCOM in the RDS. S. Jazebi et al. [8] used evolution algorithm for combined DSTATCOM and reconfiguration in the RDS for power loss minimization. The authors Seyed Abbas Taher et al. [9], proposed an Immune algorithm for the problem of DSTATCOM allocation to reduce the power and energy losses in the RDS. Yuvaraj.T et al. [21], considered bio-inspired bat algorithm for DSTATCOM allocation problem considering load variations to decrease the power loss reduction. The authors [22] have used power loss index and voltage stability factor for finding the DSTATCOM locations in the radial distribution networks. In addition to this the authors have considered UK 38 bus practical mesh distribution system to analysis the DSTATCOM with seasonal time varying loads. Further, the authors have considered different load models such as residential, commercial and industrial loads [23].

1.3. Optimal DG and DSTATCOM allocation simultaneously

From the literature, very few researchers have made an attempt [24–27] about the simultaneous allocation of DG and DSTATCOM in the RDS. The authors in [24] used an optimization technique based on a Particle Swarm Optimization (PSO) to allocate the DG and DSTATCOM simultaneously in the RDS for power loss reduction. In Ref. [25], the authors proposed Bacterial Foraging Optimization Algorithm (BFOA) to allocate the combined DG and DSTATCOM with a newly framed objective function in the RDS. The authors used DICA-NM hybrid algorithm for DG and DSTATCOM problem [26]. In Ref. [27] the exhaustive search method is utilized to solve the simultaneous allocation problem of DG and DSTATCOM in the RDS.

From the literature survey, it can be noticed that most of the optimization techniques have successfully been used to determine the location and sizing problem of DG and DSTATCOM in the RDS. However, many of them suffer from local optimality, low accuracy, calculation efficiency, slow convergence and require large computational time for simulation [7,24,25]. In addition to that all the authors have focused only on single load (medium) and the different load factors (light, medium, and peak) have not been investigated in the RDS [24–27]. These inspired the author to introduce a new, fast and efficient nature-inspired cuckoo search algorithm based optimization technique to resolve optimal DG and DSTATCOM placement in the RDS with different load factors.

Cuckoo search algorithm is a novel optimization algorithm in the field of Meta heuristic intelligence algorithms. CSA was proposed by Cambridge scholars Yang Xin She and Deb Suash [28]. This global search algorithm is inspired by the behaviors of cuckoos in locating nests and laying eggs and by the Lévy flight of insects. The major unique features of CSA which makes it popular in the field of optimization problems are: (i) the number of parameters involved in the CSA are less compare to other nature inspired optimization techniques like PSO and GA. Further it can be implemented to a wider range of optimization problems, (ii) the extensive property of CSA is elitism which helps to find the best solution with in the search space, (iii) Furthermore, the convergence of the system is insensitive to the parameter selection. Which can helps to reduces the tuning time of parameters for a specific problem, (iv) In addition, CSA is more generalized and robust for many optimization problems, comparing with other meta-heuristic algorithms like GA, PSO, ant colony algorithm etc., and (v) the property of Lévy flight in CSA makes the randomization more efficient as the step length is heavy tailed, and it is suitable for any step size [29–32]. Hence, CSA is considered as a promising algorithm which has more chances to provide best solution in compare with other optimization algorithms to solve the simultaneous allocation problem of DG and DSTATCOM in the RDS.

In this paper authors made an attempt to an impressive approach to identify the optimal allocation for DG and DSTATCOM allocation for total power loss reduction and bus voltage enhancement in the RDS. The cumulative voltage deviation (CVD) is utilized to indicate the voltage profile improvement. In addition in this paper an innovative method is proposed to implement an integrated approach of VSI, LSF and recently developed nature inspired cuckoo search algorithm to determine the optimal location and sizing of DG and DSTATCOM for power loss minimization and voltage profile enhancement for different loading conditions also evaluated to verify the system performance which will helpful to the Distribution Network Operators (DNOs) to select the DG and DSTATCOM size for a particular load level. In the proposed method VSI is used to find the optimal locations of DG and optimal locations of DSTATCOM is identified by using LSF. Recently developed bio-inspired CSA is implemented to find the optimal size of DG and DSTATCOM in the RDS. In the proposed optimization technique, different types of DG models and load factors are considered and analyzed on standard IEEE 33 and 136 bus systems to estimate the performance of the developed system.

2. Problem formulation

2.1. Load flow analysis

Generally, radial distribution systems have high resistance to reactance (R/X) ratio than transmission system. Therefore traditional power flow studies such as Gauss-Seidal, Newton-Raphson and Fast decoupled load flow studies are not appropriate for determining the line flows and voltages in RDS. The BFS algorithm is one of the efficient methods for power flow studies in RDS [33]. The main features of this power flow studies are simple, fast, requirement memory for processing is low with high efficiency and produce accurate solution over the entire process.

To work with proposed system here the authors considered two buses connected by a branch as apart in a RDS is depicted in Fig. 1, where the buses t and $t+1$ are the sending and receiving end buses respectively. The real power $\mathrm{P}_{\mathrm{t,t+1}}$ and reactive power $\mathrm{Q}_{\mathrm{t,t+1}}$ are flowing between buses t and $t+1$ can be calculated as:

$$P_{t,t+1} = P_{t+1,eff} + P_{Loss(t,t+1)} \tag{1}$$

$$Q_{t,t+1} = Q_{t+1,eff} + Q_{Loss(t,t+1)} \tag{2}$$

where $P_{t,t+1}$ and $Q_{t,t+1}$ are the active and reactive power flowing through in line between buses t and $t+1$, $P_{t+1,eff}$ and $Q_{t+1,eff}$ are the total effective real and reactive power supplied beyond the bus $t+1$,$P_{Loss(t,t+1)}$ and $Q_{Loss(t,t+1)}$ are the active and reactive power losses between buses t and $t+1$ respectively.

The current flow between buses t and $t+1$ can be calculated as

$$\mathrm{I}_{\mathrm{t,t+1}} = \left(\frac{\mathrm{P}_{\mathrm{t,t+1}} - j\mathrm{Q}_{\mathrm{t,t+1}}}{\mathrm{V}_{\mathrm{t+1}} \angle - \alpha_{\mathrm{t+1}}}\right) \tag{3}$$

Also,

$$\mathrm{I}_{\mathrm{t,t+1}} = \left(\frac{\mathrm{V}_{\mathrm{t}} \angle\alpha_{\mathrm{t}} - \mathrm{V}_{\mathrm{t+1}}\angle\alpha_{\mathrm{t+1}}}{R_{t,t+1} + jX_{t,t+1}}\right) \tag{4}$$

where V_t and V_{t+1} are the voltage magnitudes at nodes t and $t+1$ respectively. α_t and α_{t+1} are the voltage angles at nodes t and $t+1$ respectively. $\mathrm{R}_{\mathrm{t,t+1}}$ and $\mathrm{X}_{\mathrm{t,t+1}}$ are the resistance and reactance of the line section between buses t and $t+1$ respectively.

From the Eqs. (3) and (4), it can be derived that

$$V_t^2 - V_t V_{t+1}\angle(\alpha_{t+1} - \alpha_t) = (\mathrm{P}_{\mathrm{t,t+1}} - j\mathrm{Q}_{\mathrm{t,t+1}})(R_{t,t+1} + jX_{t,t+1}) \tag{5}$$

By equating the real and imaginary parts on both sides of Eq. (5), further equation can be written as:

$$V_t V_{t+1} * \cos(\alpha_{t+1} - \alpha_t) = V_t^2 - (\mathrm{P}_{\mathrm{t,t+1}} R_{t,t+1} + Q_{t,t+1} X_{t,t+1}) \tag{6}$$

$$V_t V_{t+1} * \sin(\alpha_{t+1} - \alpha_t) = Q_{t,t+1} R_{t,t+1} - \mathrm{P}_{\mathrm{t,t+1}} X_{t,t+1} \tag{7}$$

By performing square operation and adding the Eqs. (6) and (7), the new expression is derived and it is shown in Eq. (8)

$$V_{t+1}^2 = V_t^2 - 2(\mathrm{P}_{\mathrm{t,t+1}} R_{t,t+1} + Q_{t,t+1} X_{t,t+1}) + (R_{t,t+1}^2 + X_{t,t+1}^2)\left(\frac{\mathrm{P}_{\mathrm{t,t+1}}^2 + \mathrm{Q}_{\mathrm{t,t+1}}^2}{|\mathrm{V}_{\mathrm{t}}|^2}\right) \tag{8}$$

The active and reactive power loss in the line section between buses t and $t+1$ are calculated as

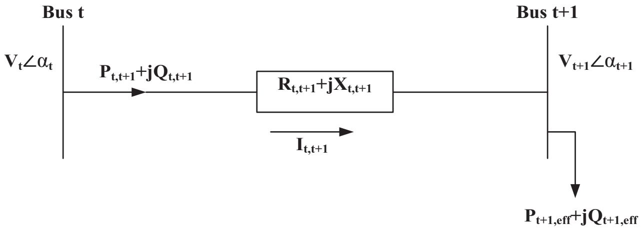

Fig. 1 One line diagram of distribution system.

$$\mathrm{P}_{\mathrm{Loss(t,t+1)}} = I_{t,t+1}^{2} * \mathrm{R}_{\mathrm{t,t+1}} \tag{9}$$

$$\mathrm{P}_{\mathrm{Loss(t,t+1)}} = \left(\frac{\mathrm{P}_{\mathrm{t,t+1}}^{2} + \mathrm{Q}_{\mathrm{t,t+1}}^{2}}{|\mathrm{V}_{\mathrm{t+1}}|^{2}} \right) * \mathrm{R}_{\mathrm{t,t+1}} \tag{10}$$

$$\mathrm{Q}_{\mathrm{Loss(t,t+1)}} = I_{t,t+1}^{2} * \mathrm{X}_{\mathrm{t,t+1}} \tag{11}$$

$$\mathrm{Q}_{\mathrm{Loss(t,t+1)}} = \left(\frac{\mathrm{P}_{\mathrm{t,t+1}}^{2} + \mathrm{Q}_{\mathrm{t,t+1}}^{2}}{|\mathrm{V}_{\mathrm{t+1}}|^{2}} \right) * \mathrm{X}_{\mathrm{t,t+1}} \tag{12}$$

The total active and reactive power losses in the distribution systems can be calculated by summation of losses in all line sections, which can be given as:

$$\mathrm{P}_{\mathrm{TL}} = \sum_{\mathrm{t=1}}^{\mathrm{Nb}} \mathrm{P}_{\mathrm{Loss\ (t,t+1)}} \tag{13}$$

$$\mathrm{Q}_{\mathrm{TL}} = \sum_{\mathrm{t=1}}^{\mathrm{Nb}} \mathrm{Q}_{\mathrm{Loss\ (t,t+1)}} \tag{14}$$

where Nb is total number of branches.

2.2. Power loss reduction using DG/DSTATCOM placement

The total losses reduced by DG/DSTATCOM allocation in the RDS is taken as the ratio of total power loss with and without DG/DSTATCOM placement in the RDS, and is given by

$$\Delta \mathrm{P}_{TL}^{\mathrm{DG/DST}} = \frac{\mathrm{P}_{TL}^{\mathrm{DG/DST}}}{\mathrm{P}_{\mathrm{TL}}} \tag{15}$$

The total power loss reduced by DG/DSTATCOM allocation in the RDS can be maximized by minimizing $\Delta \mathrm{P}_{TL}^{\mathrm{DG/DST}}$

2.3. Cumulative voltage deviation

To verify the superiority in voltage profile improvement of the system, the CVD at each bus has been considered, and it made as minimum in value at the extent level [1]. From the computations, it can be observed that the minimum value of Total CVD indicates good improvement in voltage profile of the RDS.

$$CVD = \left\{ \begin{array}{ll} 0, & if\ 0.95 \leqslant V_t \leqslant 1.05 \\ \sum_{t=1}^{N} |V_{ref} - V_t|, & else \end{array} \right\} \tag{16}$$

where N is total number of buses, V_t is the voltage magnitude at bus t and V_{ref} is the reference voltage (i.e. 1.0 p.u).

2.4. Voltage profile enhancement using CVD

The voltage profile of the system with DG/DSTATCOM allocation can be maximized by minimizing $\Delta \mathrm{CVD}^{\mathrm{DG/DST}}$. It is taken as the ratio of CVD before and after DG/DSTATCOM placement of the system, and it is expressed in the form of an equation given in (17),

$$\Delta \mathrm{CVD}^{\mathrm{DG/DST}} = \frac{\mathrm{CVD}_{after}^{\mathrm{DG/DST}}}{\mathrm{CVD}_{\mathrm{before}}} \tag{17}$$

where $\mathrm{CVD}_{\mathrm{before}}$ is the cumulative voltage deviation before DG/DSTATCOM placement and $\mathrm{CVD}_{after}^{\mathrm{DG/DST}}$ is the cumulative voltage deviation after DG/DSTATCOM placement in the RDS.

2.5. Objective function

As per the objective of proposed method for optimal DG and DSTATCOM placement to minimize the power losses and total CVD in the RDS. The objective function is derived as minimization function subject to various equality and inequality constraints to satisfy the electrical requirements of distribution network. Mathematically, the proposed multi-objective function is given blow:

$$Minimize(F) = Min\,(\beta_1 \Delta \mathrm{P}_{TL}^{\mathrm{DG/DST}} + \beta_2 \Delta CVD^{DG/DST}) \tag{18}$$

where β_1 and β_2 are the weighting factors related to power loss minimization and CVD minimization respectively.

$$\sum_{j=1}^{2} \beta_j = 1 \wedge \beta_j \in [0,\ 1] \tag{19}$$

The weights are selected in such a way that to give the corresponding priority to each impact indices for DG/DSTATCOM connection and depend on the required analysis (e.g., planning and operation) [34,35]. In addition, for the selection of weights also considered the experience of researchers and the concerns of distribution side utilities for the effective performance. Simultaneous DG and DSTATCOM allocation in the RDS has an extensive impact on the power loss reduction and voltage profile enhancement (by minimization CVD). At present, the power loss reduction is one of the major concerns at the RDS level due to its impact on the utilities' profit, since the voltage profile improvement (minimization of CVD) is less important than the power loss reduction. Hence, in this work the authors have taken the weight for the power loss minimization as 0.7 ($\beta_1 = 0.7$) and weight for the voltage profile enhancement as 0.3 ($\beta_2 = 0.3$).

The above objective function is derived subjected to following equality and inequality constraints:

a. Power balance constraints

Power balance constraints, which are equality constraints, can be formulated as follows

$$P_{TLoss} + \sum P_{D(t)} = \sum P_{DG/DST(t)} \tag{20}$$

where $P_{D(t)}$ is the power demand at bus t and $P_{DG/DST(t)}$ is the power generation using DG/DSTATCOM.

b. Voltage magnitude constraint

The voltage magnitude at each bus must be maintained within its limits and it is expressed as

$$V_t^{\min} \leqslant |V_t| \leqslant V_t^{\max} \tag{21}$$

where $V_t^{\min}$ is the minimum voltage limits of the buses and $V_t^{\max}$ maximum voltage levels of the buses.

c. Real power compensation

Real power constraint in which injected real power at each candidate bus must be within their permissible ranges

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$$P_{DG(t)}^{\min} \leqslant P_{DG(t)} \leqslant P_{DG(t)}^{\max} \quad t = 1, 2, \ldots nb \tag{22}$$

where $P_{DG(t)}^{\min}$ and $P_{DG(t)}^{\max}$ are the minimum and maximum real power limits of compensated bus t respectively.

d. Reactive power compensation

Reactive power constraint in which injected reactive power at each candidate bus must be within their permissible ranges.

$$Q_{DSTATCOM(t)}^{\min} \leqslant Q_{DSTATCOM(t)} \leqslant Q_{DSTATCOM(t)}^{\max} \quad t = 1, 2, \ldots nb \tag{23}$$

where $Q_{DSTATCOM(t)}^{\min}$ minimum reactive power limits of compensated bus t and $Q_{DSTATCOM(t)}^{\max}$ is the maximum reactive power limits of compensated bus t.

3. Optimal location of the DG/DSTATCOM

The estimation of optimal DG/DSTATCOM locations initially helps in significant reduction of search space process and CPU time for the optimization procedure. In this proposed method well known VSI and LSF are used to find the candidate location of the DG and DSTATCOM respectively.

3.1. Voltage stability index

The security level power system can be identified by using different voltage and power stability indices available in the literature like voltage stability index, power stability index, and loss sensitivity factor. In this section voltage collapse nodes can be identified by using new steady state VSI as presented by authors in [36]. The VSI at each node has been calculated using Eq. (24). The lesser value of VSI node has more chance to place DG. To prevent the voltage collapse in the RDS the VSI value should be maximized as much as possible.

$$\begin{aligned} VSI(t+1) = {} & |V_t|^4 - 4\left[P_{t+1,eff} * X_{t,t+1} - Q_{t+1,eff} * R_{t,t+1}\right]^2 \\ & - 4\left[P_{t+1,eff} * R_{t,t+1} + Q_{t+1} * X_{t,t+1}\right]|V_t|^2 \end{aligned} \tag{24}$$

3.2. Loss sensitivity factor

The installation of DSTATCOM with optimal locations can be determined by using LSF is presented in [37]. This will reduce the search space for the optimization work. The equations of LSF calculation can be derived by differentiating the Eq. (10) with respect to reactive power

$$\mathrm{LSF}(\mathrm{t}, \mathrm{t}+1) = \frac{\partial P_{\mathrm{Loss(t,t+1)}}}{\partial Q_{\mathrm{(t+1,eff)}}} = \left(\frac{2\mathrm{Q}_{\mathrm{t+1,eff}} * \mathrm{R}_{\mathrm{t,t+1}}}{|\mathrm{V}_{\mathrm{t,t+1}}|^2}\right) \tag{25}$$

From the above equation, sensitivity factors are calculated at each bus and the buses are arranged in descending order as per the values. Highest LSF value of bus has more chance to place DSTATCOM. By using CSA algorithm, the optimal size of DSTATCOM at the candidate buses are estimated.

4. Cuckoo search algorithm

4.1. Overview

CSA techniques is one of the most powerful technique available for solving global optimization problems. It is introduced by Yang and Deb [28] in the year of 2009. CSA method has been studied by several researchers for optimization problems [29–32]. This technique is mainly has two operators such as: (i) Direct search based on Levy flights (ii) Random search based on the probability for a host bird to discover an alien egg in its nest. The parameters used for optimization process and the values initialized for each parameter are given below:

n: Number of nests or different solutions (25).
p_a: Discovery rate of alien eggs/solutions (0.25).
n_d: Dimension Search Space (1 or 3).
l_b and u_b: The Lower and Upper bounds limits.

The steps involved in the optimization process of CSA are mainly consists three steps and are discussed clearly in the following:

Step 1#: In this step at initial, one egg will be laid at a time by every cuckoo, and dumps the egg in a randomly chosen nest.
Step2#: During the second step the best nests which have high quality of eggs (solutions) will be carried over to the forthcoming generation.
Step3#: At this stage the number of available host nests are fixed, and the egg laid by a cuckoo can be identified by the host bird.

The cuckoos are more attractive birds, these birds not only make beautiful sounds but also have capable to produce fantastic reproduction strategy. Some of the species in cuckoo like *ani* and *guira* lay their eggs in common nests, though they may remove other's eggs to rise the hatching probability of their own eggs. The cuckoo eggs may hatch earlier than that of their host eggs. When the first cuckoo eggs is hatched, the first action is to remove the host eggs by blindly pushing out the egg from the nest. The cuckoo chick 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 the 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 a non-negative random variables) know as Levy flights.

The cuckoo bird will find the best nest to lay their egg (solution) to maximize their eggs survival rate. Actually every cuckoo lays only one egg at a time. The high quality egg (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 p_a € [0, 1] and these eggs are thrown away or the nest is discarded, and the new nest is built at new location. The cuckoo randomly chooses the nest position to lay egg using Eqs. (26) and (27).

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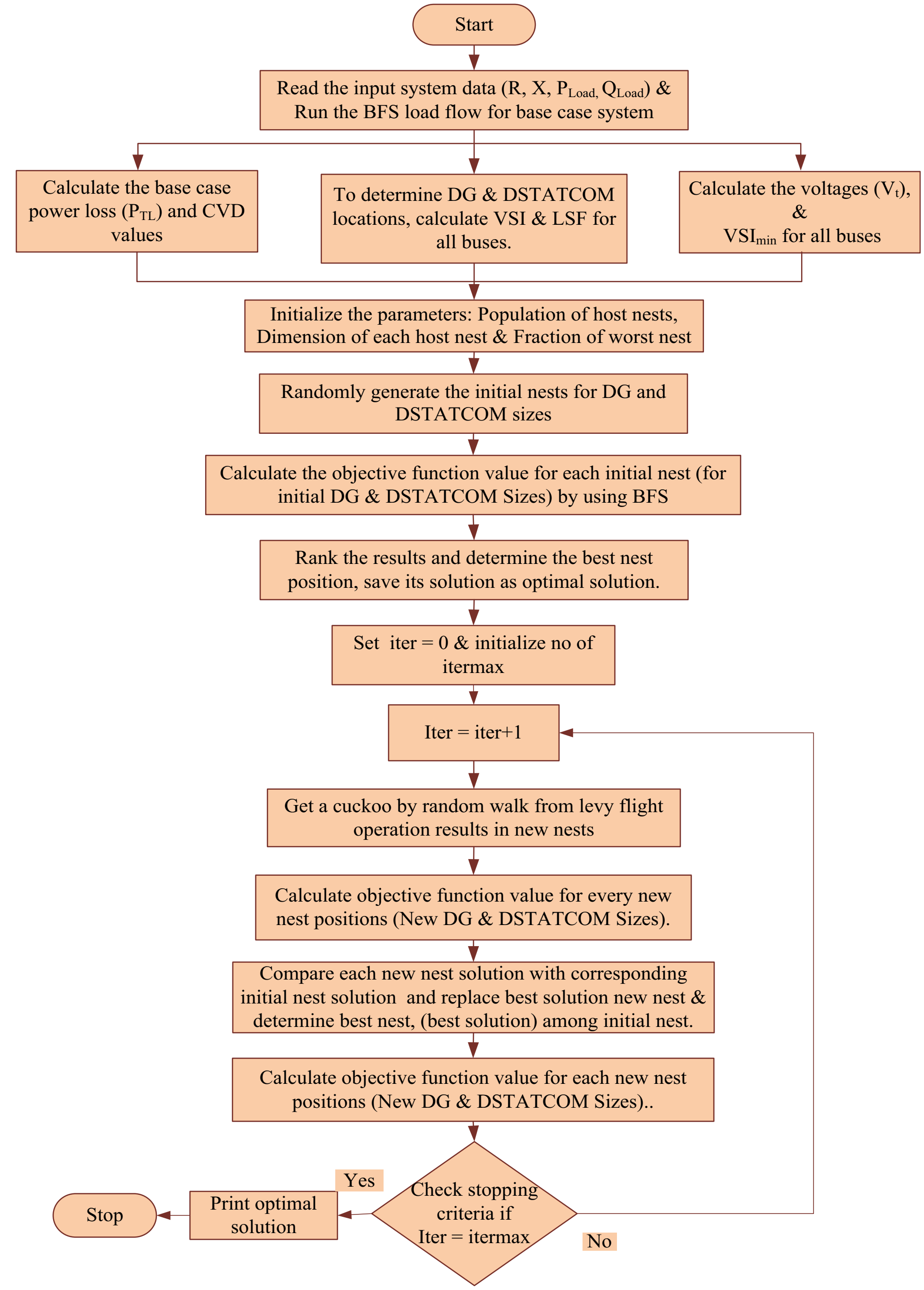

Fig. 2 Flowchart of the proposed method.

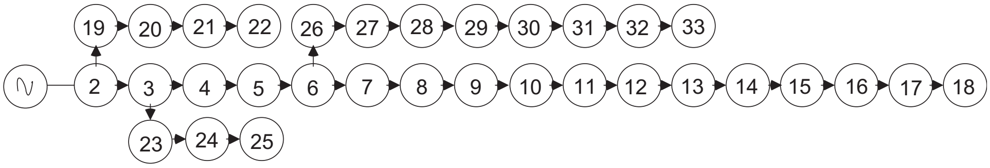

Fig. 3 One line diagram of IEEE 33-bus system.

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Table 1 Performance analysis of 33-bus system.

	Case I	Case II	Case III	Case IV	Case V
DG size in kW (Bus No)	–	750(14) 1100(24) 1050(30)	780(14) 1150(24) 1000(30)	–	750(14) 1100(24) 1000(30)
DSTATCOM size in kVAr (Bus No)	–	–	–	420(11) 460(24) 970(30)	420(11) 460(24) 970(30)
Power Factor	–	Unity Unity Unity	0.861 0.922 0.717	–	Unity Unity Unity
P_{Loss}(kW)	210.98	72.83	12.35	138.61	12
% Reduction in P_{Loss}	–	65.48	94.14	34.3	94.31
$V_{\min}$(p.u)	0.9037	0.9671	0.9930	0.9277	0.9910
$VSI_{\min}$(p.u)	0.6610	0.8667	0.9674	0.8026	0.9584
Total CVD	1.6229	0	0	0.8026	0
CPU (sec)	–	10.25	10.75	10.24	10.96

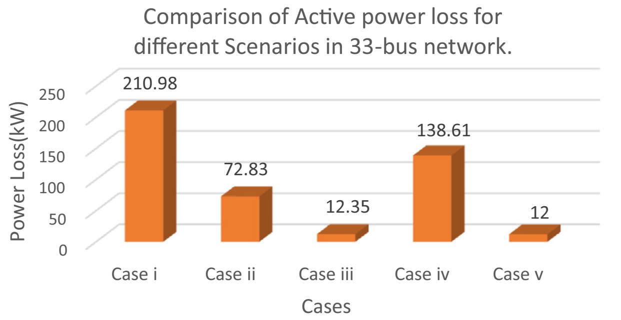

Fig. 4 Comparison of Active power loss for different cases in 33-bus network.

$$x_{pq}^{gen+1} = x_{pq}^{gen} + S_{pq} * Levy(\lambda) * \eta \tag{26}$$

$$Levy(\lambda) = \left| \frac{\Gamma(1+\lambda) * \sin(\frac{\pi*\lambda}{2})}{\Gamma(\frac{1+\lambda}{2}) * \lambda * S^{(\lambda-1)/2}} \right|^{1/\lambda} \tag{27}$$

where

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

The step size can be obtained using

$$S_{pq} = x_{pq}^{gen} - x_{fq}^{gen} \tag{28}$$

where

$p, f \in \{1, 2, \ldots, m\}$ and $q \in \{1, 2, \ldots, D\}$ are randomly chosen indexes.
f is chosen randomly but it's value should be different from p.

The host bird will identify the cuckoo egg and choose the high quality egg with probability of using Eq. (29)

$$pro_q = \left(\frac{0.9 * Fitness_q}{\max\left(Fitness\right)}\right) + 0.1 \tag{29}$$

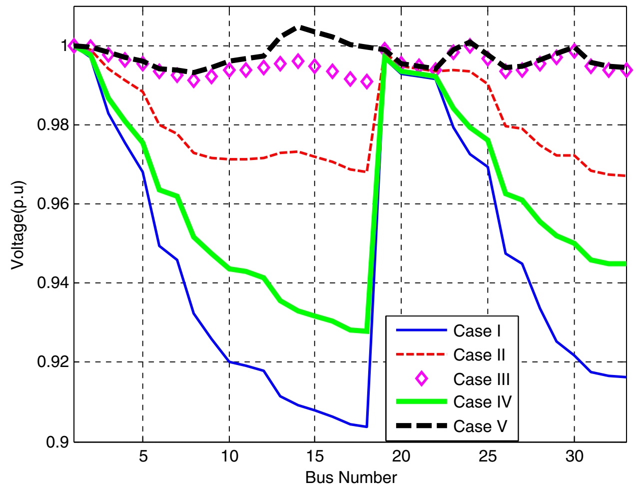

Fig. 5 Comparison of voltage profile for different cases in 33-bus network.

where $Fitness_q$ the fitness value of the solution and q is the proportional 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 built a new nest using Eq. (30). Otherwise the egg will grow and is alive for next generation.

$$nest_q = x_{q,\min} + rand\left(0, 1\right) * \left(x_{q,\max} - x_{q,\min}\right) \tag{30}$$

Based on approximation and idealization the step by step implementation of CSA optimization process is detailed in the form of flowchart and it is shown in Fig. 2.

5. Results and discussion

To demonstrate the superiority of the CSA method, extensive simulations are carried out for various test cases. For simulations a dedicated software program is developed in MATLAB by considering standard IEEE 33-bus and 136-bus RDS as test setup.

In each case, two types of DG models (Type-A & Type-B) are considered. The obtained results show that the proposed

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Table 2 Results for 33-bus System under different types of load factor.

	Load Factor					
	Light load (0.5)		Medium load (1.0)		Peak load (1.6)	
	B.C	A.C	B.C	A.C	B.C	A.C
Optimal DG size (kW) & Location	–	350(14) 480(24) 460(30)	–	750(14) 1100(24) 1000(30)	–	1150(14) 1650(24) 1600(30)
Optimal DSTATCOM size (kVAr) & Location	–	200(11) 180(24) 450(30)	–	420(11) 460(24) 970(30)	–	650(11) 830(24) 1550(30)
P_{loss}(kW)	48.78	**3.93**	210.98	**12**	603.43	**31.38**
$V_{\min}$(p.u)	0.9540	**0.9929**	0.9037	**0.9910**	0.8358	**0.9821**
$VSI_{\min}$(p.u)	0.8251	**0.9689**	0.6610	**0.9584**	0.4785	**0.9205**

Here B.C is Before Compensation and A.C is After Compensation. Bold values highlight the outputs (after compensation) using our method.

Table 3 Comparison of performances for 33-bus system.

	Method	DG/DSTATCOM size in kW/kVAr (Bus No)	Power factor	P_{Loss}(kW)	% Reduction in P_{Loss}
Multiple DGs (Type-A)	BSA[18]	632(12) 487(28) 550(31)	Unity	89.05	57.8
	QOTLBO[17]	880.8(12) 1059.2(24) 1071.4(29)	Unity	74.1	64.9
	BFOA[25]	779(14) 880(25) 1083(30)	Unity	73.53	65
	Proposed method	**750(14)** **1100(24)** **1050(30)**	**Unity**	**72.83**	**65.48**
Multiple DGs (Type-B)	BSA[18]	632(12) 487(28) 550(31)	0.86 0.71 0.70	29.65	85.97
	BFOA[25]	600(14) 598(25) 934(30)	0.89 0.83 0.88	27.50	86.97
	Proposed method	**780(14)** **1150(24)** **1000(30)**	**0.861** **0.922** **0.717**	**12.35**	**94.14**
Multiple DGs (Type-A) & DSTATCOMs	BFOA[25]	850(12) kW 750(25) 860(30) 400(12) kVAr 350(25) 850(30)	Unity	15.07	92.56
	Proposed method	**750(14) kW** **1100(24)** **1000(30)** **420(11) kVAr** **460(24)** **970(30)**	**Unity**	**12**	**94.31**
Single/Multiple DSTATCOMs	BFOA[25]	1102.7(30)	–	144.38	28.76
	Proposed method	**420(11)** **460(24)** **970(30)**	–	**138.61**	**34.3**

Bold values highlight the outputs (after compensation) using our method.

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CSA based optimization technique is feasible for real-time implementation.

- **Case I:** System without DG and DSTATCOM
- **Case II:** System with multiple DGs (Type A)
- **Case III:** System with multiple DGs (Type B)
- **Case IV:** System with multiple DSTATCOMs
- **Case V:** System with multiple DGs and DSTATCOMs.

5.1. IEEE 33-bus test system

For the verification of the proposed method as first case considered and it is IEEE 33-bus system as shown in Fig. 3. The system load and line data are taken from Ref. [38]. The real and reactive power loads for this system are 3.72 MW and 2.3 MVAr with a line voltage of 12.66 kV. The active power loss without any compensation in the RDS is 210.98 kW.

5.1.1. Case-I

Before compensation i.e., without DG or DSTATCOM installed in RDS and the active power loss is obtained as 210.98 kW. The minimum voltage, VSI and total CVD of the RDS are 0.9038, 0.6610 p.u and 1.5194 respectively.

5.1.2. Case-II

In this case, three DGs (Type-A) are optimally placed in 14th, 24th and 30th buses. The optimal locations are obtained by VSI and the optimal size of these DG locations are calculated by using CSA. The total power losses have been reduced from 210.98 kW to 72.83 kW after placement of DG with a minimum voltage of 0.9671 p.u.

5.1.3. Case-III

In this case, three DGs (Type-B) are optimally placed in 14th, 24th and 30th buses with optimal power factors 0.861, 0.922, 0.717 respectively. The total power loss has been reduced from 210.98 kW to 72.83 kW after placement of Type-B DG. This power loss reduction is high compared to Type- A, DG placement. The minimum VSI of this system is enhanced from 0.6610 p.u to 0.8667 p.u after DG placed.

5.1.4. Case-IV

Using CSA, the DSTATCOMs of rating 420, 460 and 970 kVAr are placed at the candidate locations 11, 24 and 30 respectively. The optimal locations can be obtained using VSI. As a result, the active power loss is decreased to 138.61 kW from 210.98 kW with a minimum voltage of 0.9277 p.u.

5.1.5. Case-V

In this case, three DGs and three DSTATCOMs are placed simultaneously at different optimal locations using VSI and LSF respectively. The sizing of the DG and DSTATCOM can be done by using CSA. The total power loss of the system has been reduced to 12 kW after placement of multiple DGs and DSTATCOMs in the RDS.

From the considered cases the case-V gives better power loss reduction and voltage profile enhancement compared to other cases. The minimum voltage and VSI of the system have been improved to 0.9839 p.u and 0.9663 p.u.

Power loss analysis:

Table 1, shows the optimal size, location, power loss, Total CVD and CPU time of 33-bus RDS under five different cases with implementation of proposed method. In each case, the power loss after placement of DG/DSTATCOM is compared with the base case power loss is depicted in Fig. 4. From the Table 1 and Fig. 4, it may be noted that higher level power loss reduction is possible if simultaneous DG (Type-A) and DSTATCOM are placed at the optimal location with optimal sizes in the RDS compared to other considered cases.

Voltage analysis:

The comparisons of voltage profile at various buses for the different cases considered in a 33-bus RDS is given in Fig. 5. It can be observed from the Fig. 5, case V gives higher voltage profile enhancement compared to other cases which is confirmed by the improvement in the CVD values before and after placement DGs and DSTATCOMs simultaneously. (See Table 1). This shows that the simultaneous DG and DSTATCOM placement in the radial distribution networks (Case V) is better than other cases considered in terms of quality of solutions.

In order to show the performance of the proposed method, the performance of CSA is compared with the results of BSA [18], QOTLBO [17] and BFOA [25] available in the literature and is presented in Table 3. From the table, it can be concluded that in all cases, the performance of the CSA method is better than other heuristic algorithms in terms of power loss reduction, voltage profile improvement, power factor improvement and convergence rate improvement.

The performance of the proposed method at three different load levels with and without compensation is presented in Table 2. The annual load profile is assumed to be piecewise segmented in three different load levels, i.e., light, medium and peak which is 50%, 100% and 160% of the nominal system load respectively and all the results obtained by using proposed method are compared with base case values. From this

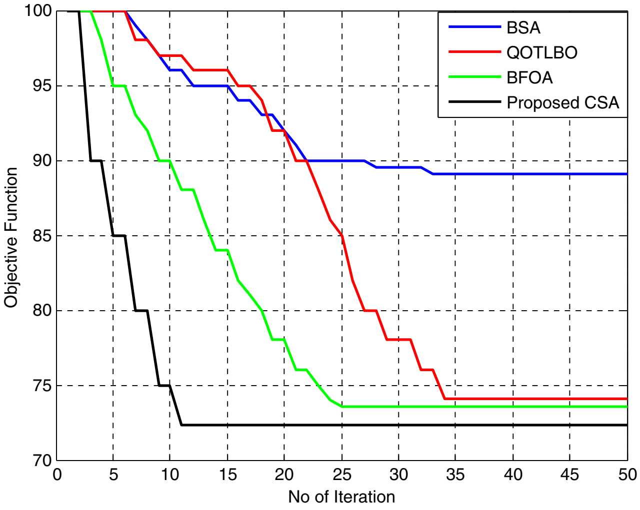

Fig. 6 Comparison of the convergence rate of CSA with other algorithms.

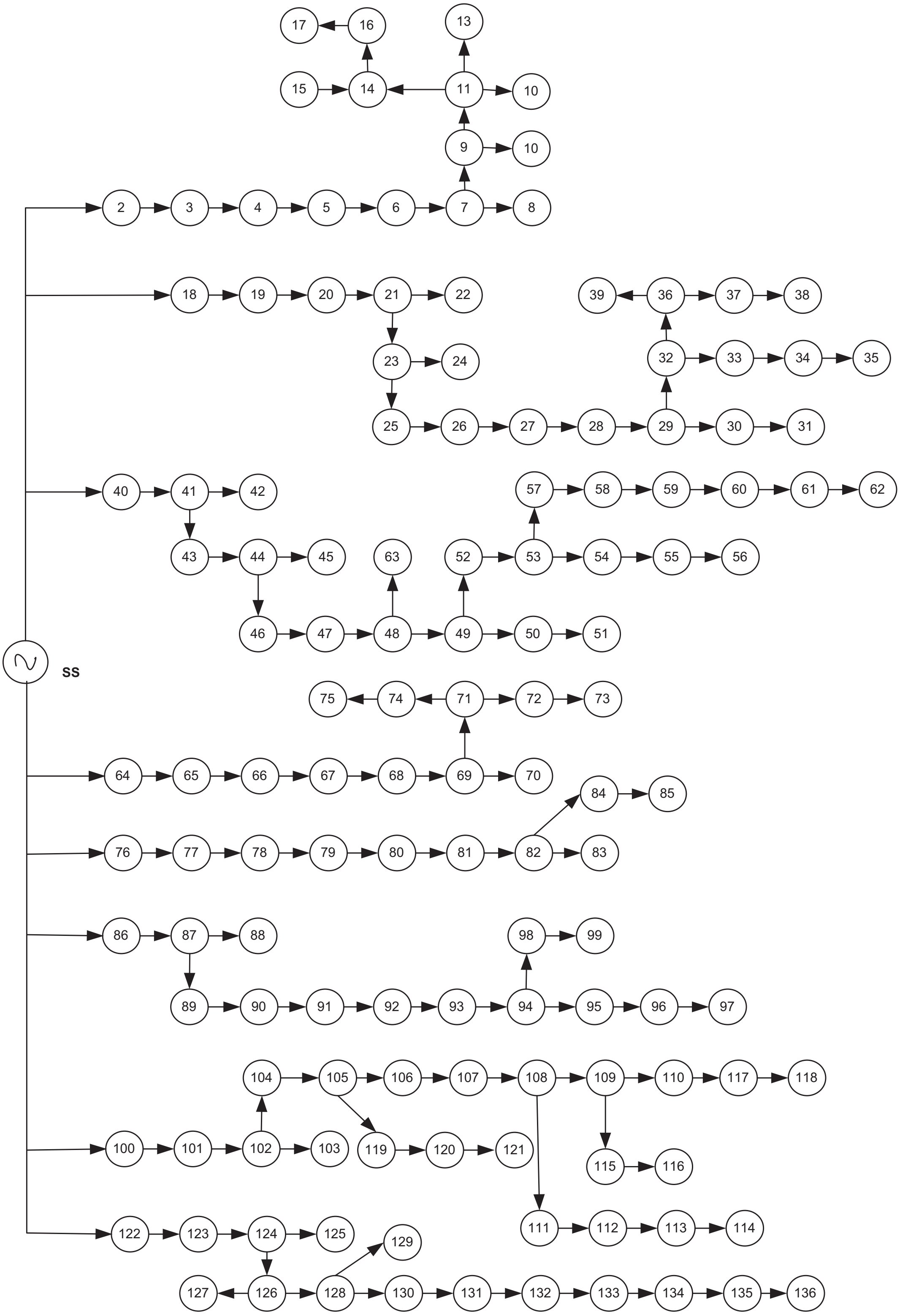

Fig. 7 One line diagram of IEEE 136-bus system.

comparison, it can be observed that the performance of the proposed CSA based optimization is better in terms of power loss reduction and voltage profile improvement.

The convergence rate of the cuckoo search algorithm is shown in Fig. 6. Since it was impossible to find the multi-objective programming with the same objective functions in literature, the single objective version of BSA, QOTLBO, and BFOA is plotted in Fig. 6. As seen, the CSA offers a better optimal solution with a reduced number of iterations.

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Table 4 Performance analysis of 136-bus system.

	Case I	Case II	Case III	Case IV	Case V
DG size in kW (Bus No)	–	2200(11) 1800(36) 2100(53) 1950(90) 2700(106)	2150(11) 1950(36) 2000(53) 1970(90) 2700(106)	–	2000(11) 1850(36) 2050(53) 2000(90) 2800(106)
DSTATCOM size in kVAr (Bus No)	–	–	–	950(11) 950(32) 930(52) 920(89) 1350(106)	980(11) 890(32) 860(52) 1000(89) 1150(106)
Power Factor	–	Unity Unity Unity Unity Unity	0.999 0.925 0.911 0.939 0.916	–	Unity Unity Unity Unity Unity
P_{Loss}(kW)	320.95	123.31	89.00	275.80	88.45
% Reduction in P_{Loss}	–	61.58	72.26	14.06	72.44
$V_{\min}$(p.u)	0.9290	0.9622	0.9700	0.9619	0.9708
$VSI_{\min}$(p.u)	0.6923	0.8532	0.8528	0.8031	0.8532
Total CVD	0.8787	0	0	0	0
CPU (sec)	–	12.55	12.85	12.58	12.96

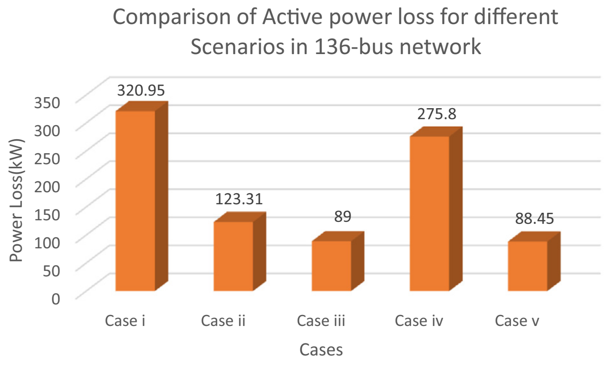

Fig. 8 Comparison of Active power loss for different cases in 136-bus network.

5.2. IEEE 136-bus test system

The second tested system is large and real 136 bus test system and it consists of 136-nodes with total real and reactive power loads of 18.314 MW and 7.933 MVAr, respectively. The main aim of this test system is to demonstrate the effectiveness and validity of the proposed CSA based technique when applied to large-scale power systems. The system load and line data are taken from Ref. [39]. The base case power losses of the test case are 320.95 kW and 702.95 kVAr respectively. The one line diagram of 136 system is depicted in Fig. 7.

5.2.1. Case-I

Without DG or DSTATCOM installed in radial distribution system and for the given total active power load, the active power loss is obtained as 320.95 kW. The minimum voltage and VSI of the radial distribution system are 0.9290 p.u and 0.6923 p.u respectively.

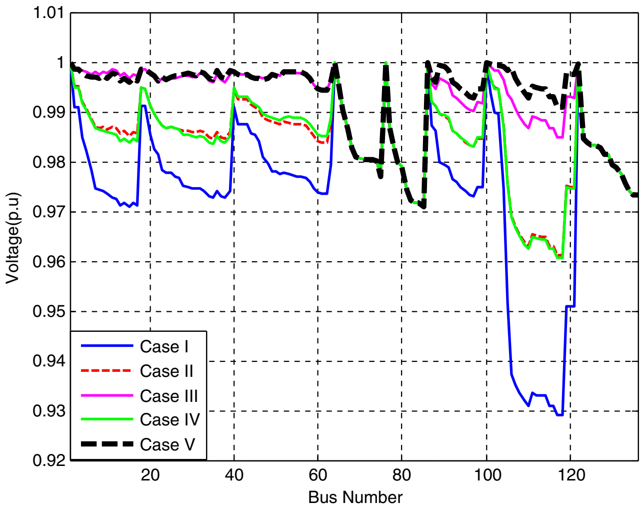

Fig. 9 Comparison of voltage profile for different cases in 136-bus network.

5.2.2. Case-II

In this case, multiple DGs operating at unity power factor (Type-A) are placed at the optimal locations. The total power loss has been reduced from 320.95 kW to 123.31 kW after multiple DG placement with minimum voltage of 0.9622 p.u. The minimum VSI of this system is improved from 0.6923 p.u to 0.8532 p.u after multiple DG placed.

5.2.3. Case-III

In this case, multiple DGs (Type-B) operating at optimal power factors are placed at the optimal locations. Using CSA, the DGs of rating 2150, 1950,2000,1970 and 2700 kW are placed at the optimal locations 11, 36,53,90 and 106 respectively. The power loss of this case is reduced to 89 kW from

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320.95 kW. The minimum voltage magnitude is increased from 0.9290 p.u to 0.9700 p.u.

5.2.4. Case-IV

In this case, five DSTATCOMs are optimally placed using LSF to improve the power loss reduction and voltage profile of the radial distribution system. The active power loss has been reduced to 275.8 kW with minimum voltage of 0.9619 p.u. The minimum VSI of the system is 0.8031 p.u.

5.2.5. Case-V

In this case, five DGs and five DSTATCOMs are optimally placed using VSI and LSF approach and sizing of these DG and DSTATCOMs can be find by using CSA. The size of the DGs and DSTATCOMs are 10.7 MW and 4.88 MVAr respectively. The total power loss after placement of multiple DG and DSTATCOM are 88.45 kW with minimum voltage of 0.9708 p.u. This is highest power loss reduction compared to other cases.

Power loss analysis:

Table 4, shows the optimal size, location, minimum bus voltage, Total CVD, CPU time and power loss of proposed 136-bus radial distribution network under five different Cases. In each Case, the power loss after placement of DG/DSTATCOM is compared with the base case power loss is depicted in Fig. 8. From the Table 4 and Fig. 8, it may be noted that more power loss reduction is possible when DG and DSTATCOM placed simultaneously in the radial distribution networks.

Voltage analysis:

The comparisons of voltage profile at various buses for the different cases considered in a 136-bus in the RDS is depicted in Fig. 9. It can be observed from the figure that improvement in the voltage profile by optimal placement of combined DG (Type-A DG) and DSTATCOM (Case V) is somewhat higher compared to other cases. This shows that the simultaneous DG and DSTATCOM placement in the radial distribution networks (Case V) is better than other cases considered in terms of power loss reduction and bus voltage profile enhancement.

The performance of the proposed method at three different load levels with and without compensation of 136 bus system is shown in Table 5. Table 6 shows a comparison of proposed CSA algorithm with BSA [40] and FPA [41], and the results ensure the validity and accuracy of CSA for large and real system optimization in terms of power loss reduction and voltage

Table 5 Results for 136-bus System under different types of load factor.

	Load factor					
	Light load (0.5)		Medium load (1.0)		Peak load (1.6)	
	B.C	A.C	B.C	A.C	B.C	A.C
Optimal DG size (kW) & location	–	1100(11) 900(36) 1000(53) 980(90) 1350(106)	–	2000(11) 1850(36) 2050(53) 2000(90) 2800(106)	–	3500(11) 2800(36) 3400(53) 3250(90) 3800(106)
Optimal DSTATCOM size (kVAr) & location	–	320(11) 450(32) 400(52) 360(89) 480(106)	–	980(11) 890(32) 860(52) 1000(89) 1150(106)	–	1500(11) 1450(32) 1600(52) 1400(89) 1800(106)
P_{loss}(kW)	77	**21.94**	320.95	**88.45**	865.6	**236.25**
$V_{\min}$(p.u)	0.9665	**0.9857**	0.9290	**0.9708**	0.9000	**0.9520**
$VSI_{\min}$(p.u)	0.8475	**0.9267**	0.6923	**0.8532**	0.5000	**0.7647**

Bold values highlight the outputs (after compensation) using our method.

Table 6 Comparison of performances for 136-bus system.

Multiple DGs (Type-A)	Base case	BSA[40]	FPA[41]	Proposed method
Optimal size (kW) & location	–	3068(106)	2624.3(11) 2875.3(106)	**2200(11)** **1800(36)** **2100(53)** **1950(90)** **2700(106)**
Power factor	–	Unity	Unity	**Unity**
P_{loss}(kW)	320.95	213.06	194.8	**123.31**
% Reduction in P_{loss}	–	33.61	39.3	**61.58**
$V_{\min}$(p.u)	0.9290	0.9712	0.9640	**0.9622**
$VSI_{\min}$(p.u)	0.6923	–	–	**0.8532**
Total CVD	0.8787	0	0	**0**

Bold values highlight the outputs (after compensation) using our method.

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profile enhancement. The authors could able to compare the case-II (Multiple DGs (Type-A)) only with other algorithms since IEEE 136 bus radial distribution system with other cases are not available in the literature.

Overall analysis:

Based on the above discussion, the maximum improvement in objective function is achieved when DGs and DSTATCOMs are placed simultaneously in the RDS; this is done under Case-V. Best results attained in case-V for objective functions are the most optimal values of all cases. Hence, it is concluded that the simultaneous allocation of DG and DSTATCOM is necessary to place in the RDS to achieve maximum power loss reduction and enhancement of voltage profile, etc.

6. Conclusion

In this paper, the authors proposed CSA-based optimisation procedure for solving the problem of combined DG and DSTATCOM allocations to minimize the system power losses and voltage profile enhancement with different load levels has been presented and investigated. In this proposed method VSI and LSF are utilized to search the optimal locations of DG and DSTATCOM. DG and DSTATCOM sizes can be found by using CSA among a large number of combinations by optimizing the objective function. The proposed method is implemented on 33-bus and 136-bus RDS and the results were compared with other methods available in the literature. The attained results showed that the proposed method has an accurate view of this important practical problem and causes the reduction in the total power loss and voltage profile enhancement in the RDS.

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Please cite this article in press as: T. Yuvaraj, K. Ravi, Multi-objective simultaneous DG and DSTATCOM allocation in radial distribution networks using cuckoo searching algorithm, Alexandria Eng. J. (2018), https://doi.org/10.1016/j.aej.2018.01.001