Current Journal of Applied Science and Technology

40(12): 43-58, 2021; Article no.CJAST.65925
ISSN: 2457-1024
(Past name: British Journal of Applied Science & Technology, Past ISSN: 2231-0843, NLM ID: 101664541)

Simultaneous Placement and Sizing of Distributed Generation Units and Shunt Capacitors on Radial Distribution Systems Using Cuckoo Search Algorithm

Sunday Adeleke Salimon[1*], Gafari Abiola Adepoju[1], Isaiah Gbadegesin Adebayo[1], Oluwadamilare Bode Adewuyi[2] and Saheed Oluwasina Amuda[3]

[1]Department of Electronic and Electrical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.
[2]Department of Electrical and Electronics Engineering, First Technical University, Ibadan, Nigeria.
[3]Department of Technical Education, Emmanuel Alayande College of Education, Oyo, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. Author SAS helped in conceptualization, collected resources, simulation and wrote the manuscript. Author GAA helped in conceptualization, search resources, investigation and supervised the study. Author IGA performed data interpretation, investigation, validation and supervision. Author OBA collected resources, did investigation and helped in data validation. Author SOA collected resources. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2021/v40i1231380
Editor(s):
(1) Dr. Elena Lanchares Sancho , University of Zaragoza, Spain.
Reviewers:
(1) Sajjan Kumar , Jadavpur University, India.
(2) G. Senthil Kumar, SCSVMV Deemed to be University, India.
Complete Peer review History: http://www.sdiarticle4.com/review-history/65925

Received 03 January 2021
Accepted 04 March 2021
Published 04 June 2021

Original Research Article

ABSTRACT

This paper presents a Cuckoo Search (CS) algorithm-based methodology for simultaneous optimal placement and sizing of Shunt Capacitors (SCs) and Distributed Generations (DGs) together in radial distribution systems. The objectives of the work are to minimize the real power and reactive power losses while maximizing the voltage stability index of the distribution network subjected to equality and inequality constraints. Different operational test cases are considered namely installation of SCs only, DGs only, SCs before DGs, DGs before SCs, and SCs and DGs at one

---

*Corresponding author: E-mail: sunnydexs.sa@gmail.com;

time. The proposed method has been demonstrated on standard IEEE 33-bus and a practical Ayepe 34-bus radial distribution test systems. The highest percentage power loss reduction of 94.4% and other substantial benefits are obtained when SCs and DGs are optimally installed simultaneously. Simulated results obtained from the proposed technique are compared with other well-known optimization algorithms and found to be more effective.

Keywords: Cuckoo search; shunt capacitors; distributed generation units; real and reactive power losses; voltage stability index.

1. INTRODUCTION

Most distribution systems are usually radial in nature for simplicity of operation. The Radial Distribution System (RDS) are fed from the substation which receives power from the centralized generating stations through interconnected transmission network. The end users of electricity receive supply from the substation through RDS which is a passive network, meaning that the power flow is unidirectional. The high resistance to reactance ratio of the distribution lines compared to that of the transmission results in the low voltage and high current characteristics of the distribution system [1]. This leads to large voltage drops, low voltage stability and as the main problem huge power losses in the RDS. About 13% of the total power generated is expended as losses at the distribution system which represent the largest power loss portion among the three power system sections which are the generation, transmission and distribution [2]. The shunt capacitor placement and the usage of distributed generation unit are among those efforts used to mitigate this problem.

The power losses can be said to consist of two integral parts based on the active and reactive components of the branch currents. The losses produced by reactive component of the branch currents can be reduced by the installation of shunt capacitor (SC). This is because the installed shunt capacitor supplies a part of the reactive power demands thereby reducing a portion of the power loss in the distribution system. Capacitive compensation reduces power loss, improves voltage profile and stability of system, increases the power factor and releases the kVA capacity of the distribution equipment [3]. Some type of DGs causes voltage fluctuations in the network and these can be reduced by effective utilization of shunt capacitors [4,5]. The extent of these benefits depends on the deliberate placement and sizing of the shunt capacitor (SC) as improper placement may lead to further power losses, voltage instability and jeopardise the system operation [6]. The optimal placement and sizing of capacitor to harness these aforementioned benefits is a significant matter that has been investigated in many previous studies.

Distributed Generation (DG) units are employed at the distribution level to supply power and reduce power losses produced by the active component of the branch currents. Optimal allocation of DG units has technical benefits of reduced power loss, improved voltage profile and voltage stability, economic benefits of reduced operational costs and environmental benefits of reduced pollution and system emission. Whereas non-optimal allocation causes power quality issues, creates harmonics, exceeds bus voltage limits and increase power loss [7]. Several models and methods in previous studies have been suggested for solution of the optimal placement and sizing of DGs in other to maximize these benefits.

Integration of both DG unit and shunt capacitor in a radial distribution system will significantly reduce the power losses, improve the bus voltages and voltage stability. This will enhance the distribution network performance and raise the overall efficiency and reliability of the power system. From previous works, it has been discovered that the major reduction in network power losses and substantial benefits has been obtained with simultaneous allocation of DGs and CBs. Many studies have been done in the field of optimal allocation of DG units and SCs with different aims as stated in the subsequent paragraphs.

Valipour KE et al. [8] presented an approach on Biogeography based optimization algorithm for the simultaneous power quality improvement and optimal placement and sizing of capacitor banks and DGs in the presence of voltage harmonic in radial distribution networks with the aim of minimizing the power losses, voltage profile and total harmonic distortion improvement. The result revealed that the methodology was effective in reduction of the power technical parameters. Saonerkar AK et al. [9] has presented Genetic Algorithm for minimization of power loss, improvement in voltage profile and branch currents using network reconfiguration, capacitor placement and optimum number of DG units in on standard IEEE 33 bus. Kowsalya M et al. [10] proposed Bacterial Foraging Optimization to find the optimal sizes of DGs and Capacitors while sensitivity analysis was used to obtain the locations on a standard IEEE 33-bus radial distribution system. The results result revealed that the performance of BFOA is better than the other methods compared.

Khodabakhshian A et al. [11] presented Intersect Mutation Differential Evolution (IMDE) to optimally locate and determine the size of the DGs and capacitors in distribution network simultaneously with the objective of minimizing the power loss and loss expenses. The simulation result shows the efficiency of the proposed methodology when compared with other algorithms. [12] has proposed multi-objective Evolution algorithm based on decomposition (MOEAD) to simultaneously minimize the real power loss and the net reactive power flow in distribution system when reinforced with DGs and SCs. It was tested on the standard 33-bus, 69-bus, 119-bus and a practical 83-bus distribution network. The simulation result shows the efficiency of the method when compared with equivalent optimization methods.

Dixit, M et al. [13] proposed Gbest-guided Artificial Bee Colony algorithm to minimize the total active power loss of the system through DG and capacitor placement simultaneously. In their method, Index Vector Method (IVM) and Power Loss Index (PLI) approach is utilized to determine the suitable location of DGs and SCs. The proposed methodology was validated on standard IEEE 33-bus distribution network. The simulation result revealed that the methodology is capable of minimizing real power loss which lead to reduction in total annual cost, voltage deviation and improvement in voltage profile. Adel A et al. [14] has proposed Water Cycle Algorithm (WCA) as single and multi-objective frameworks for optimal placement and sizing of combined DGs/CBs in distribution networks with the aim of maximizing technical, economic and environmental benefits. The result revealed the effectiveness of the proposed WCA when compared with other optimization algorithms. Gampa SR et al. [15] proposed fuzzy GA for simultaneous optimal allocation and sizing of DGs and SCs in distribution networks with the objective of active and reactive power reduction and improvement of branch current capacity, voltage profile and voltage stability. The simulation results outperformed GA-based conventional multi-objective approach and loss sensitivity-based methods. Sambaiah KS et al [16] has proposed Salp Swarm Algorithm (SSA) to solve optimal DG and CBs allocation problem in the distribution system with the aim of maximizing the technical, economic and environmental benefits. The proposed SSA is very efficient in solving optimal allocation problem when compared with other optimization techniques.

The simultaneous placement and sizing of DG units and capacitor allocation is a discrete, non-linear and non-differentiable optimization problem, hence the Cuckoo Search Algorithm (CSA) is employed to solve the optimization problem in this paper considering real power loss, reactive power loss and minimum voltage stability index as the objective functions. The performance of the CSA was investigated by various case studies on the standard IEEE 33-bus and a real Nigerian Ayepe 34-bus radial distribution networks.

2. PROBLEM FORMULATION

2.1 Load Flow for Radial Distribution Network

Distribution load flow plays important role in finding the solution for the DG units and SCs placement problem. Due to the fact that distribution networks are generally radial in nature and the R/X ratio is very high, the conventional Gauss Seidel, Newton Raphson and Fast decoupled load flow methods are inefficient in performing the load flow of the network. The backward/forward sweep load flow utilized in [17] has been used in this paper.

2.2 Objective Function

The recommended objective function of the multi-objective optimization is considered as below:

$$\text{Min F} = c_1 P_{loss} + c_2 Q_{loss} + c_3 \frac{1}{VSI_{min}} \quad (1)$$

$$\sum_{i=1}^{3} c_i = 1 \quad (2)$$

Where P_{loss} and Q_{loss} are the total real and reactive power losses of the network after the installation of the DG units and the capacitors respectively and VSI_{min} is the minimum value of the voltage stability index after installation of the DG units and the capacitors. The VSI is determined to measure the value of the voltage stability in the radial distribution network. Inspecting the VSI performance exposes the weak buses with minimum VSI undergoing huge voltage drops. The VSI as obtained from [18] is given by:

$$\text{VSI(ni)}= |V_{mi}|^4 - 4[P_{ni}(ni)R_{ni} + Q_{ni}(\text{ni})X_{ni}]\ |V_{ni}|^2 - 4[P_{ni}(ni)R_{ni} + Q_{ni}(\text{ni})X_{ni}]^2 \quad (3)$$

where V_{mi} is the sending node voltage; while V_{ni}, P_{ni}, Q_{ni}, R_{ni} and X_{ni} are voltage, real power, reactive power, resistance, and reactance for the receiving node.

The objective function is subject to equality and inequality constraints.

2.3 The Equality Constraints

The equality constraints refer to the balance of real and reactive power flow in the distributions system.

$$P_{Gi} - P_{Di} - \sum_{i=1}^{N} V_i V_j Y_{ij} \cos\left(\theta_i - \delta_i - \delta_j\right) = 0 \quad (4)$$

$$Q_{Gi} - Q_{Di} - \sum_{i=1}^{N} V_i V_j Y_{ij} \sin\left(\theta_i - \delta_i + \delta_j\right) = 0 \quad (5)$$

Where j = 2,…N, P_{Gi} and P_{Di} are the real power generated/demand at the ith bus; Q_{Gi} and Q_{Di} are the reactive power generated/demand at the ith bus; V_i and V_j are the voltage magnitudes at the i^{th} and j^{th} bus; θ_i is the angle of the ij^{th} element in the admittance matrix; δ_i and δ_j are the voltage angle at the i^{th} and j^{th} bus.

2.4 Inequality Constraints

(1) Shunt capacitor limits: The reactive power (Q_{sc}) injected at each candidate bus is given by its minimum and maximum compensation limit.

$$Q_{sc,min} \leq Q_{sc} \leq Q_{sc,max} \quad (6)$$

(2) Total injected reactive power limit: The total reactive power injected is not to exceed the total reactive power demand (Q_T) in radial distribution system:

$$\sum_{n=1}^{NSC} Q_{scn} < Q_T \quad (7)$$

(2) Bus bar voltage limits: The voltage magnitude at each bus must be maintained within its limits and is expressed as follows:

$$V_{n,min} \leq |V_n| \leq V_{n,max} \quad (8)$$

(3) DG limits: As the DG capacity is naturally limited by the energy resources at any given location and the capacity of the given distribution network, the active and reactive power for DG was formulated as a discrete value with 100-kW increment and restricted by the lower and upper limit, as:

$$P_{DGn,min} \leq P_{scn} \leq P_{DGn,max} \quad (9)$$

2.5 Cuckoo Search Algorithm

Cuckoo search is one of the latest nature-inspired metaheuristic algorithms proposed by Yang et al. [19]. It is inspired by the aggressive reproduction of cuckoo species combining with behaviour of Levy flight. The female cuckoo lays her fertilized eggs in nests of other host birds. In this way, the host birds unwittingly raise her brood. If a cuckoo egg in a nest of a host bird is discovered, the host bird will throw it out or abandon her nest and start her own brood elsewhere. In the CS algorithm, each egg of host birds in a nest represents a solution, and a cuckoo egg represents a new solution. If a new solution is better than the one in the nest, the worse one will be replaced. For simplicity in describing the CS, we now use the following three idealised rules [20]:

(i) Each cuckoo lays one egg at a time, and dumps it in a randomly chosen nest.
(ii) The best nests with high quality of eggs (solutions) will carry over to the next generations.
(iii) The number of available host nests is fixed, and a host can discover an alien egg with probability Pa [0,1]. In this case, the host bird either throw the egg away or abandon the nest so as to build a completely new nest in a new location.

The new solutions (new position), $x^{(t+1)}$ for say cuckoo I, a Levy flight is described by the following equation:

$$x_i(k+1) = x_i(k) + \alpha \oplus \text{Levy}(\lambda) \quad (10)$$

Where α>0 is the step size, which should be related to the scale of the problem interest. The product ⊕ means entry-wise multiplications [21]. The Levy flight essentially provides a random walk while the random step length is drawn from a Levy distribution

$$\text{Levy(u)} = t^{-1-\beta},\ 0 < \beta \leq 2 \tag{11}$$

The step size generating new nest is different from α and is defined as follows:

$$S(k) = \alpha(x_i(\text{k}) - x_j(\text{k}))\oplus\text{Levy}(\beta) \tag{12}$$

The update of position of x_i is given by

$$x_i(k+1) = x_i(k) + r_i S_i(k) \tag{13}$$

Where r_i is a random number generated by the uniform distribution in interval [0,1]. The CS algorithm employs a discovery probability p_a to replace the nests abandoned by the hosts. Then, the update law is defined as follows:

$$x^* = \begin{cases} x_i + r^*\ if\ P_a > p_a \\ \quad x_i\ else \end{cases} \tag{14}$$

Where p_a is the discovery probability to create a new nest, and P is a random number in interval [0,1], while r^* is the step size to generate new nest is different from that of equation (8), and its defined by

$$r^* = rand(x_i - x_j)\ x_i,\ x_j\ \in [1,\text{n}] \tag{15}$$

2.6 Implementation of Placement and Sizing of DG Units and SCs Using CSA

This paper reports the successful application of CSA for simultaneous allocation of DGs and SCs to minimize the objective function. The details of the solution procedure are provided below:

Step 1: Initialize the CSA parameters (number of nests, n=25, step size, α=1, maximum number of iterations, $K_{max} = 200,$ probability to discover foreign eggs, $p_a = 0.6$) and enter the input data (Number of buses, Load demand active (kW) and reactive (kVAr) power at each bus, shunt capacitor limits, DG limits, bus voltage limits (V_{min} and V_{max}) and distribution line impedances (resistance and reactance)). Calculate the load flow of the entire system using the backward/forward sweep technique for the base case.

Step 2: Generate the initial population of the hoist nest which satisfies all the constraints listed in equations (4) to (9). The solution set of simultaneous DGs and SCs is formulated as follows:

$$X = \begin{bmatrix} l_1^1 & l_2^1 & l_3^1 & DG_1^1 & DG_2^1 & DG_3^1 & l_1^1 & l_2^1 & l_3^1 & SC_1^1 & SC_2^1 & SC_3^1 \\ l_1^2 & l_2^2 & l_3^2 & DG_1^2 & DG_2^2 & DG_3^2 & l_1^2 & l_2^2 & l_3^2 & SC_1^2 & SC_2^2 & SC_3^2 \\ \vdots & & & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ l_1^n & l_2^n & l_3^n & DG_1^n & DG_2^n & DG_3^n & l_1^n & l_2^n & l_3^n & SC_1^n & SC_2^n & SC_3^n \end{bmatrix} \tag{16}$$

Step 3: Run the load flow of the solutions contained in X to obtain the total active power losses (P_{loss}) and the voltage at each buses (V_{bus}). Calculate the objective function using equation (1) and determine the fitness function of each nest (solution) using equation:

$$FF = \{Min\ F + \textstyle\sum_{i=1}^{N_b}(penalty\ factor) \times (V_i - V_{max})^2 + \sum_{i=1}^{N_b}(penalty\ factor) \times (V_i - V_{min})^2\} \tag{17}$$

Where the penalty factor is assigned as follows for radial distribution systems.

$$penalty\ factor = \begin{cases} \quad 0 & if\ constraints\ are\ not\ violated \\ 500 \times Min\ F \times iteration^2 & if\ constraints\ are\ violated \end{cases} \tag{18}$$

Step 4: Generation of Cuckoo: A cuckoo, $x^{\text{i(t+1)}}$ which is a new solution is generated by Levy flight as given in equation (11).

Step 5: Evaluate the cuckoo, `1new solution, using the load flow to obtain its P_{loss} and V_{bus}. Calculate the objective function for the cuckoo using equation (1) and its fitness function, FF using equation (17) to determine the quality of the cuckoo.

Step 6: Replacement: A nest is selected among n randomly, if the quality new solution in the selected nest is better than the old solution, it is replaced by the new solution (cuckoo).

Step 7: Generation of new nest: The worst nests are abandoned based on the probability (p_a) and new ones are built using Levy flight.

Step 8: The stopping criterion is set to a tolerance value of 1×10^{-6} and maximum generation of 100 iterations in case of a divergent result. If the maximum number of iterations is reached or specified accuracy level is achieved, the iterative process is terminated and the result of the CSA displayed. Otherwise, go to step 4 for continuation.

3. RESULTS AND DISCUSSION

The proposed CSA is applied to two distribution networks. These are the standard IEEE 33-bus and Ayepe 34-bus radial systems. The minimum and maximum bus voltage limits are fixed at 0.95 and 1.05, the minimum and maximum shunt capacitor limits at 150 kVAr and 1800 kVAr, and the minimum and maximum DG limits at 100 kW and 2000 kW respectively. The loads are treated as constant power and considered as balanced. The operating power factor of the DG considered is one.

In this paper, four different test cases were explored which are as follows:

Case 1: The base case without installation of DG and Shunt capacitor (SC)
Case 2: Shunt Capacitors (SCs) only were optimally installed in the distribution system
Case 3: DG units only were optimally installed in the distribution system
Case 4: SCs were first optimally installed before the DG units were installed in the distribution system.
Case 5: DG units were first optimally installed before the SCs were installed in distribution system.
Case 6: DG units and SCs were optimally installed by the CS in the distribution system at the same time.

All the six operational test cases are considered for two different distribution networks.

3.1 The Standard IEEE 33-Bus Radial Distribution System

The IEEE 33-bus system is a standardized test system with a base voltage and base MVA of 12.66kV and 100MVA respectively. The power of all network buses is assumed to be delivered by the substation placed at node 1. The line and load data are gotten from [22]. The total real power loads and reactive loads on the 33 radial distribution system are 3.715 MW and 2.3 Mvar respectively while the single line diagram is shown in Fig. 1. The simulation results of the six test cases after running the algorithm are tabulated in Table 1 while the characteristics of the voltage profile and the VSI are illustrated in Figs. 2 and 3 respectively.

In Table 1, it can be seen that the real power loss, reactive power loss and the minimum VSI for the base case (case 1) are 210.99 kW, 143.13 kVar and 0.6689, respectively.

For case II, the optimal shunt capacitor sizes (buses) in kVAR are 495 (11), 500 (24) and 946 (30) with real and reactive power loss reduction of 72.34 kW (34.28%) and 48.72 kVAR (34.04%) respectively as compared to the base case. The results are compared with existing methods in Table 2. Even though some of the existing methods gave a better result, the result of the proposed method is still comparable, significant and efficient.

For case III, optimal sizes of the DGs (and buses) obtained after running the code are 791 (14), 1086 (24), 1041 (30) with real and reactive power loss reduction of 138.17 kW (65.49%) and 92.42 kVAR (64.57%) respectively as compared with base case. The results are compared with existing methods in Table 3. The comparison shows the efficiency of the proposed method even though the real power loss for WIPSO-GSA is better and some of the minimum voltage of other methods are better but the record values of CS is still in range.

Cases IV-VI involves the placement and sizing of SCs and DGs simultaneously. In Case IV, the three SCs are first optimally installed before the three DGs while in case V, the three DGs are first optimally installed before the SCs. For Case VI, the proposed algorithm optimally installed both the three SCs and the three DGs at the same time. After running the algorithm, case IV gave optimal sizes of the SCs in KVAR as 495 (11), 500 (24), 946 (30) and that of the DGs in KW as 783 (14), 1050 (24), 1018 (30) with real power loss equal to 12.07 kW while the reactive power loss is 9.89 kVAR. The real and the reactive power loss reduction are 198.92 (94.28%) and 133.24 (93.09%) respectively as compared to the base case. For case V, the optimal sizes of the SCs first installed are 397 (13), 518 (24), 971 (30) and followed by optimal DGs sizes of 791 (14), 1086 (24), 1041 (30) with real and reactive power loss of 11.2kW and 9.82kVAR. The real and reactive power loss reduction obtained are 199.17 kW (94.4%) and 133.31 (93.14%) as compared to base case. For case VI, the optimal sizes of the SCs obtained are 462 (12), 678 (24), 987 (30) while that of the DGs are 838 (13), 890 (25), 903 (30) with real and reactive power loss reduction of 197.50 (93.61%) and 131.61 (92.65%) respectively.

Comparison of cases four, five and six shows that optimal installation of the three DGs before the three SCs gave the lowest power and objective function from Table 1. The optimal installation of SCs and DGs are compared with other techniques in Table 4. Though the different techniques have different aims and objective functions but the total real power loss and the minimum voltage recorded are still comparable. The proposed CS gave the highest real power loss reduction and minimum voltage in comparison with the other techniques which establishes the efficiency of this proposed method.

The voltage profile and VSI values of all the six cases are illustrated in Figs. 2 and 3 respectively. The voltage profile and the VSI values were poor before the installation of the SCs and DGs but were significantly improved after the installation of SCs and/or DGs. The best voltage profile and VSI values were obtained when both SCs and DGs were optimally installed in the distribution network. The convergence characteristic for case VI is shown in Fig. 4. The performance of the proposed algorithm over 20 independent runs of simulation for all the cases with best, average and worst values of objective function and its standard deviation is presented in Table 5. The results show that the algorithm is very precise which indicates its output consistency.

3.2 AYEPE 34-Bus Radial Distribution Network

The real network used to test the algorithm is the Ayepe 34-bus radial distribution network of the Ibadan Electricity Distribution Company (IBEDC), Ibadan, Nigeria. The total real power loads and reactive loads on the 34 bus network are 4.12 MW and 2.05 Mvar respectively. The line data, load data, load profile, single line and other necessary information are found in [38]. The single-line diagram of the Ayepe 34-Bus feeder is as depicted in Fig. 5. The simulation results of the six test cases are tabulated in Table 1 while the characteristics of the voltage profile and the VSI are illustrated in Figs. 2, 3 respectively.

Table 1. Summary of results of the six test cases for standard IEEE 33-bus distribution network

	Base case	SCs only	DGs only	SCs before DG	DGs before SCs	DGs and SCs sim.
SCs size (kVAR)		495(11), 500(24), 946(30)		495(11), 500(24), 946(30)	397(13), 518(24), 971(30)	462(12), 678(24), 987 (30)
DGs size (kW)			791(14), 1086(24), 1041(30)	783(14), 1050(24), 1018(30)	791(14), 1086(24), 1041(30)	838(13), 890(25), 903(30)
Ploss (kW)	210.99	138.54	72.82	12.07	11.82	13.49
Qloss(kW)	143.13	94.41	50.71	9.89	9.82	10.52
Min VSI	0.6689	0.7554	0.8784	0.9701	0.9766	0.9659
P. Reduction		72.34	138.17	198.92	199.17	197.50
Q. Reduction		48.72	92.42	133.24	133.31	131.61
% Ploss		34.28	65.49	94.28	94.40	93.61
% Qloss		34.04	64.57	93.09	93.14	92.65
Min Voltage	0.9038(18)	0.9321(18)	0.9681(33)	0.9935(8)	0.9924(8)	0.9921(13)
Fmin		102.26	54.06	9.43	9.26	10.43

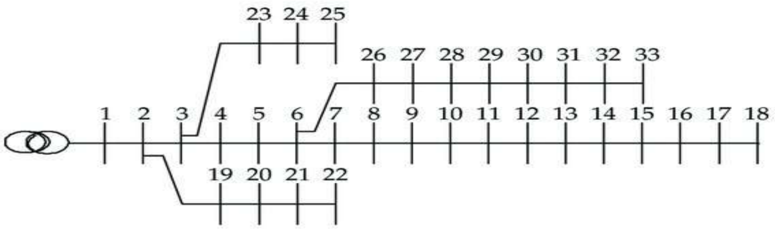

Fig. 1. Standard IEEE 33-bus radial distribution network

Table 2. Optimal SCs allocation in the standard IEEE 33-bus distribution network

Optimization technique	CBs size (kVAr) and location	Base ploss (kW)	Ploss (kW)	Ploss reduction	Vmin
GSA [23]	450 (13), 800 (15), 350(26)	202.6	134.5	68.1 (33.6%)	
CSA [24]	600(11), 300(33), 450(24), 600(30)	202.6	131.5	71.1 (35.1%)	0.943
BFOA[10]	349.6(18), 820.6(30), 277.3(33)	211	144.04	66.96 (33.1%)	0.936
PSO [25]	900(2), 450(7), 450(11), 300(15), 450(29)	202.6	132.48	69.52 (34.5%)	
IMDE [11]	475(14), 1037(30)	202.6	139.7	62.9 (31.0%)	
WCA [14]	397.3(14), 451.1(24), 1000(30)	202.6	130.91	71.69 (35.4%)	0.951 (18)
WIPSO-GSA[26]	0.69(6), 0.31(14), 0.77(30)	211	134.01	76.98 (36.5%)	0.9292
SSA [16]	450(10), 450(23), 1050(29)	202.6	132.35	70.25 (34.7%)	0.9366 (18)
SSA[27]	397.3(14), 451.1(24), 1000(30)	202.6	130.91	71.69 (35.4%)	0.951 (18)
Proposed method CS	450(11), 400(24), 950(30)	211	138.54	72.45 (34.3%)	0.9321 (18)

From Table 6, the real power loss, reactive power loss and the minimum VSI for the base case (case 1) are 762.64 kW, 146.37 kVar and 0.4746, respectively.

For case II, the optimal shunt capacitor sizes (buses) in kVAR are 574 (8), 1010 (13) and 392 (15) with real and reactive power loss reduction of 174.64 kW (22.90%) and 33.52 kVAR (22.90%) respectively as compared to the base case. The minimum VSI recorded is 0.5184. For case III, optimal sizes of the DGs (and buses) obtained after running the code are 958 (9), 1867 (14), 946 (22) with real and reactive power loss reduction of 174.64 kW (84.10%) and 23.27 kVAR (84.10%) respectively as compared with base case. The minimum VSI is significantly improved from 0.4746 (base case) to 0.9615.

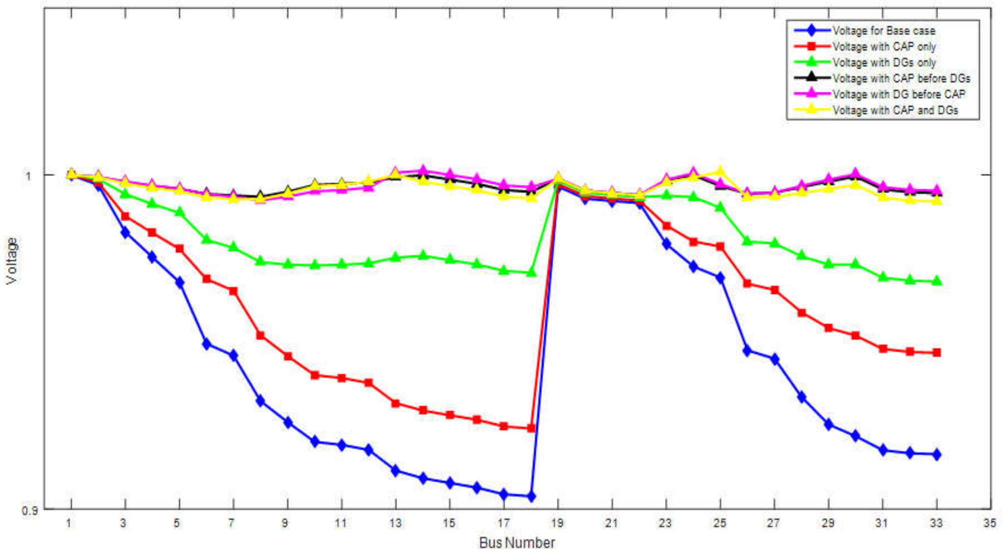

Fig. 2. Voltage Profile for the Standard IEEE 33-Bus Distribution Network

For Case IV, the obtained optimal sizes of the SCs in KVAR are 574 (8), 1010 (13), 392 (15) and that of the DGs in KW are 938 (9), 1674 (13), 1038 (22) with real power loss equal to 10.42 kW while the reactive power loss is 1.99 kVAR. The real and the reactive power loss reduction are 752.22 (94.28%) and 144.38 (93.09%) respectively as compared to the base case. The minimum VSI is significantly improved to 0.9900.

For case V, the optimal sizes of the SCs first installed are 1867(14), 946(22), 958(9) and followed by optimal DGs sizes of 704(21), 420(34), 625(11) with real and reactive power loss of 10.58 kW and 2.02 kVAR. The real and reactive power loss reduction obtained are 752.06 kW (98.61%) and 143.35 (98.62%) as compared to base case. The minimum VSI is improved to 0.9927.

For case VI, the optimal sizes of the SCs obtained are 591(10), 612(27), 555(22) while that of the DGs are 1176(21), 1774(14), 818(6) with real and reactive power loss reduction of 752.06 (98.61%) and 144.34 (98.61%) respectively. The minimum VSI obtained is 0.9814.

Table 3. Optimal DGs allocation in the standard IEEE 33-bus distribution network

Optimization technique	**DGs size (kW) and location**	**Base ploss (kW)**	**Ploss (kW)**	**Ploss reduction (%Red.)**	**Vmin**
FWA[28]	589.7(14), 189(18), 1014.6(32)	202.6	86.6	116 (57.3%)	0.968
BFOA[10]	633(17), 90(18), 947(33)	211	98.3	112.7 (53.4%)	0.964
HSA[29]	572.4(17), 107(18), 1046.2(33)	202.6	96.76	105.84 (52.2%)	0.967
TM[30]	587.6(15), 195.7(25), 783(33)	202.6	91.305	111.3 (54.9%)	0.958
ACO-ABC [31]	754.7(14), 1099.9(24), 1071.4(30)	202.6	75.4	127.2 (62.8%)	0.9735
PSO[25]	1176.8(8), 981.6(13), 829.7(32)	202.6	105.35	97.25 (48.0%)	0.980(30)
BSOA[32]	632(13), 487(28), 550(31)	202.6	89.05	113.55 (56.0%)	0.9554
BA [33]	816.3(15), 952.35(25), 952.35(30)	202.6	75.5	127.1 (62.7%)	0.98(18)
IWO [34]	624.7(14), 104.9(18), 1056(30)	202.6	85.86	127.1 (57.6%)	0.9716(29)
IMDE [11]	840(14), 1130(30)	211	84.28	126.72 (60.06%)	0.971 (33)
WOA [35]	1072.8 (30), 772.5 (25), 856.7 (13)	202.6	73.75	137.24 (65.0%)	0.9688(33)
WIPSO-GSA [26]	900(13), 1110(24), 1040(30)	211	72.12	138.87 (65.8%)	0.967 (18)
WCA [14]	854.6(14), 1101.7(24), 1181(29)	202.6	71.05	131.55 (64.9%)	0.973(33)
SSA [16]	753.6(13),1100.4(23), 1070(29)	202.6	71.46	131.55 (64.73%)	0.9686 (33)
SSA [27]	854.6(14), 1101.7(24), 1181(29)	202.6	71.05	131.55 (64.9%)	0.973(33)
OTCDE [36]	801.8(13), 1091(24), 1053.6(30)	211	72.79	138.21 (65.5%)	0.9687(33)
Proposed CS	791(14),1086(24), 1041(30)	211	72.82	138.18 (65.5%)	0.9681(33)

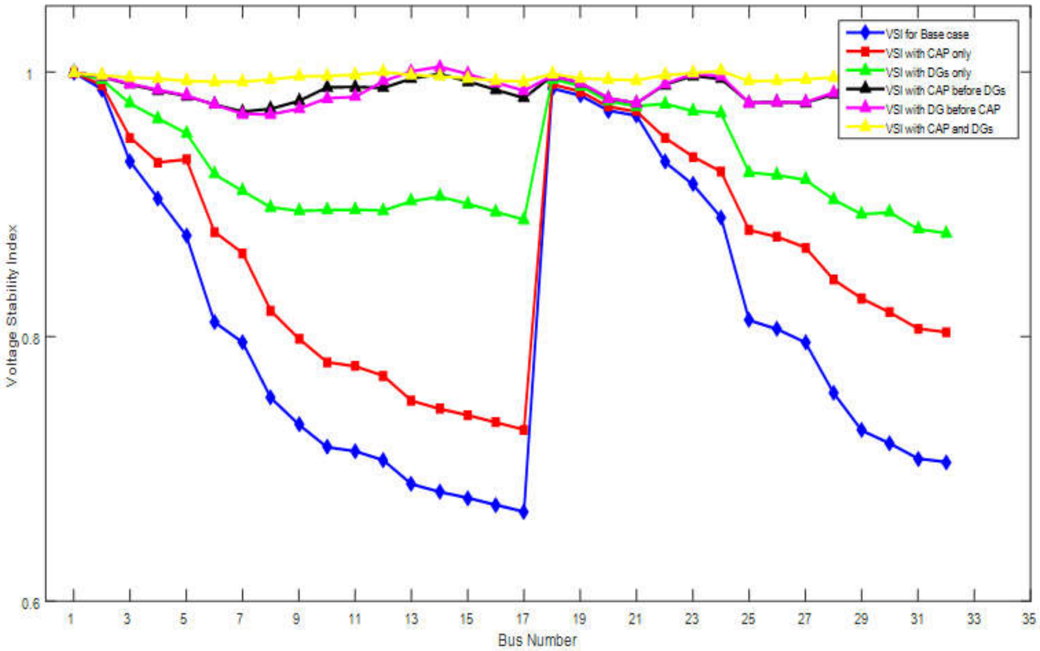

Fig. 3. VSI values of all cases for the standard IEEE 33-bus distribution network

Table 4. Optimal SCs and DGs allocation in the standard IEEE 33-bus distribution network

Optimization Technique	CBs size (kVAr) and location	DGs size (kW) and location	Base Ploss (kW)	Ploss (kW)	Ploss Red.	Vmin
BFOA [10]	163(18), 541(30), 338(33)	54(17), 160(18), 895(33)	202.6	41.41	161.19 (80.4%)	0.9783
GA [9]	300(15), 300(18), 300(29), 600(30), 300(31)	250(16), 250(22), 500(30)	202.6	71.25	131.35 (64.8%)	0.971
GABC [13]	300(16), 150(17), 150(18)	1098(28), 132(29), 609(30)	211	93.72	117.28 (55.6%)	0.9629
IMDE [11]	254.8(16), 932.3(30)	1080(10), 896.4(31)	211	32.08	178.91 (84.8%)	0.979 (25)
WCA [14]	465(23), 565(30), 535(14)	973(25), 1040(29), 563(11)	202.6	24.69	177.91 (87.8%)	0.980 (33)
PFA [37]	400(13), 400(24), 1000(30)	783(13), 982(24), 1024(33)	211	12.02	198.98 (94.3%)	0.9919
SSA [16]	300(13), 600(23), 1050(29)	747(13), 1079(23), 1049(29)	202.6	11.8	190.8 (94.2%)	0.9918(7)
SSA [27]	465(23), 565(30), 535(14)	973(25), 1040(29), 563(11)	202.6	24.69	177.91 (87.8%)	0.980 (33)
WIPSO-GSA [26]	510(10), 550(24), 770(30)	800(13), 1070(24), 1020(30)	211	13.25	197.74 (93.72%)	0.9807 (25)
Proposed CS	397(13), 518(24), 971(30)	791(14), 1086(24), 1041(30)	211	11.82	199.17 (94.4%)	0.9924 (8)

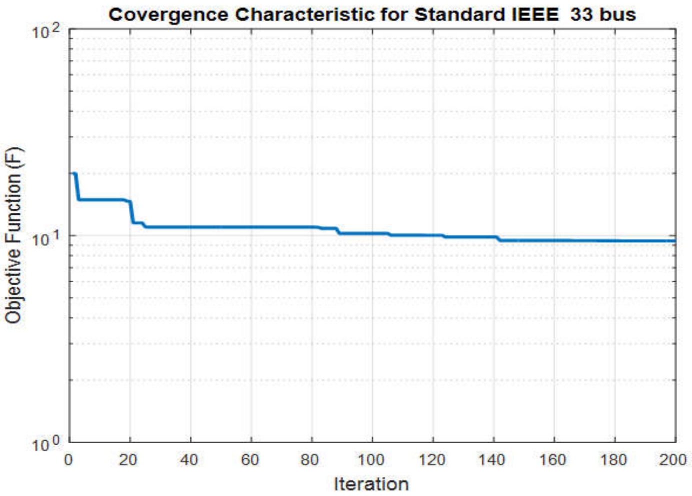

Fig. 4. Convergence characteristic of standard IEEE 33-bus for case VI

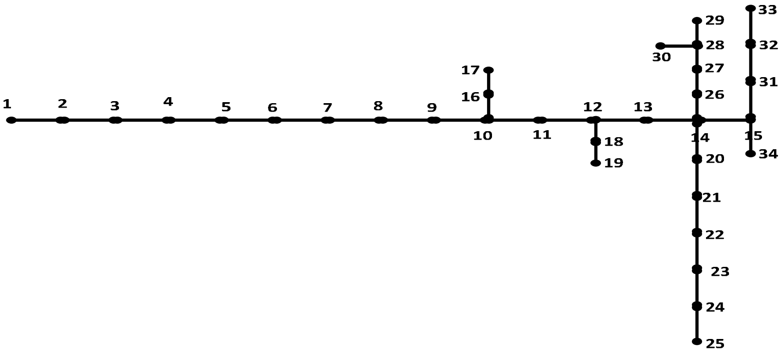

Fig. 5. AYEPE 34-bus radial distribution network

Table 5. Simulation results of algorithm over 20 independent runs for IEEE 33-bus

	Min F			
	Best (Minimum)	**Worst (Maximum)**	**Average**	**Std. Dev**
SCs only	102.26	102.90	102.63	0.2473
DGs only	54.06	55.92	55.51	0.5390
SCs b4 DGs	9.42	10.11	9.76	0.1955
DGs b4 SCs	9.26	9.52	9.37	0.0917
SCs and DGs	10.43	15.92	14.49	1.4068

The voltage profile and VSI values of all the six cases for the Ayepe 34-bus radial distribution network are illustrated in Figs. 6 and 7 respectively. The voltage profile and the VSI values were poor before the installation of the SCs and DGs but were significantly improved after the installation of SCs and/or DGs. The best voltage profile and VSI values were obtained when both SCs and DGs were optimally installed in the distribution network. This shows the effectiveness of simultaneous optimal installation of SCs and DGs using the proposed method to improve the voltage of the radial distribution network with very high power loss reduction. The convergence characteristic for case VI is shown in Fig. 4. The performance of the proposed algorithm over 20 independent runs of simulation for all the cases with best, average and worst values of objective function and its standard deviation is presented in Table 7. The results show that the algorithm is very precise which indicates its output consistency.

Table 6. Summary of results of the six test cases for AYEPE 34-bus radial distribution network

	Base case	**SCs only**	**DGs only**	**SCs before DG**	**DGs before SCs**	**DGs and SCs sim.**
SCs size (kVAR)		392(15), 574(8), 1010(13)		392(15), 574(8), 1010(13)	1867(14), 946(22), 958(9)	591(10), 612(27), 555(22)
DGs size (kW)			1867(14), 946(22), 958(9)	1674(13), 938(9), 1038(22)	704(21), 420(34), 625(11)	1176(21), 1774(14), 818(6)
Ploss (kW)	762.64	588.0	121.27	10.42	10.58	10.58
Qloss (kW)	146.37	112.85	23.27	1.99	2.02	2.03
Min VSI	0.4746	0.5184	0.9615	0.9900	0.9927	0.9814
P. Reduction		174.64	641.37	752.22	752.06	752.06
Q. Reduction		33.52	123.1	144.38	143.35	144.34
% Ploss		22.90	84.10	98.63	98.61	98.61
% Qloss		22.90	84.10	98.64	98.62	98.61
Min Voltage	0.8295(25)	0.8482(25)	0.9885(33)	0.9977(3)	0.9983(3)	0.9953(33)
Fmin		375.75	77.62	6.86	6.95	6.96

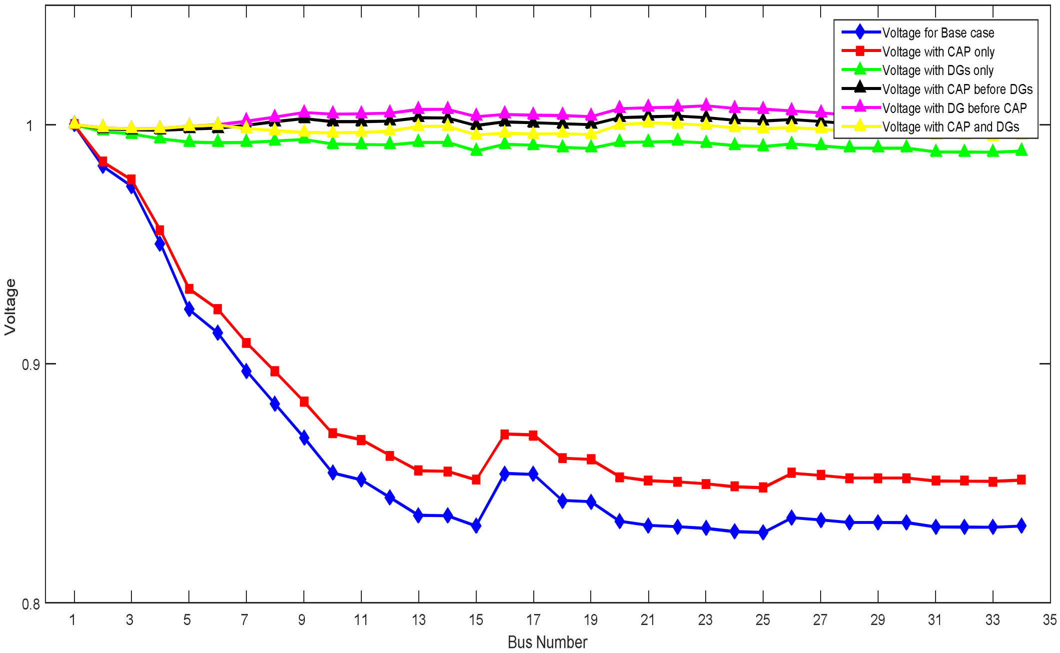

Fig. 6. The voltage profile of the AYEPE 34-bus for the six test cases

Table 7. Simulation results of algorithm over 20 independent runs for AYEPE 34-bus

		Min F		
	Best (Minimum)	**Worst (Maximum)**	**Average**	**Std. Dev.**
SCs only	102.26	102.90	102.63	0.2473
DGs only	54.06	55.92	55.51	0.5390
SCs b4 DGs	9.42	10.11	9.76	0.1955
DGs b4 SCs	9.26	9.52	9.37	0.0917
SCs and DGs	10.43	18.64	15.73	2.5782

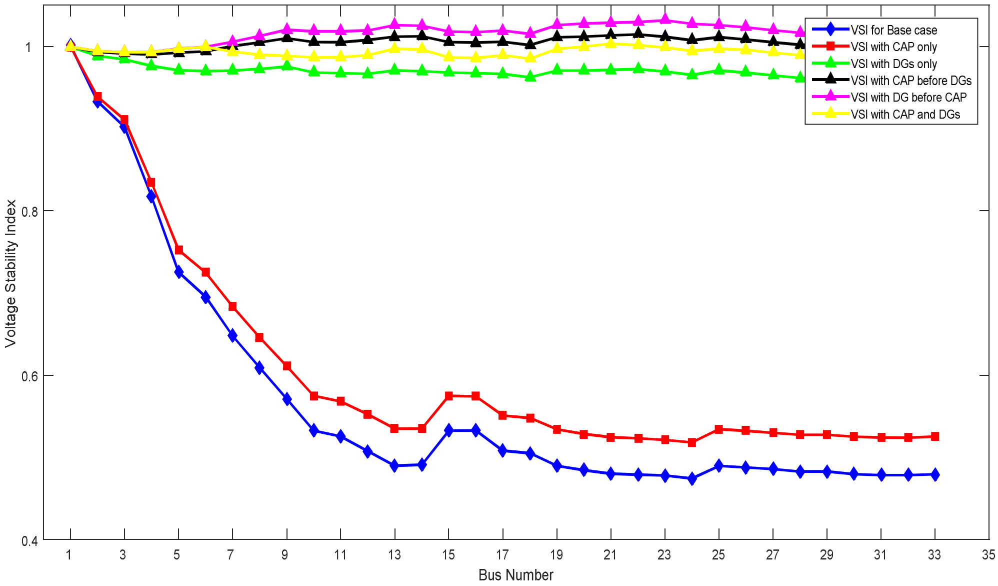

Fig. 7. The VSI values of the Ayepe 34-Bus for Six Test Cases

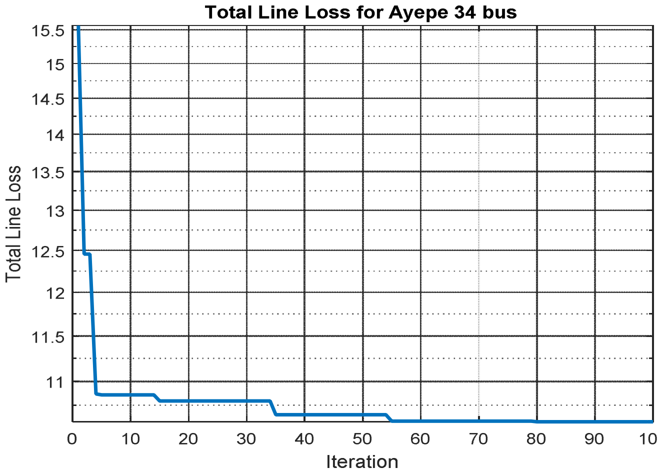

Fig. 8. Convergence characteristic of AYEPE 34-bus for DGs and SCs placement

4. CONCLUSION

Cuckoo Search algorithm has been proposed for simultaneous optimal placement and sizing of shunt capacitors and distributed generation units with the objectives of minimizing the power losses and the inverse of the voltage stability index. The proposed method is tested on standard IEEE 33-bus for the purpose of comparison with other optimization techniques and a real Nigerian Ayepe 34-bus radial distribution system with six different operational cases considered. The proposed CS algorithm is very efficient in solving optimal allocation problem when compared with other optimization techniques. It is observed that the optimal allocation of only SCs and only DGs has significantly reduced power loss and improved the voltage profile of the distribution systems. However, the major reduction in network power losses and the substantial benefits has been obtained with the simultaneous allocation of SCs and DGs. Future research on this topic can include economic and environmental objective functions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Moradi MH, Abedini M. Optimal multi-distributed generation, trans, location and capacity by genetic algorithms. 4th International Power Engineering and Optimization Conference (PEOCO). 2010;400-404.
2. Rao RS, Narasimham SVL, Ramakingaraju M. Optimal capacitor placement and in a radial distribution systems using plant growth simulation algorithm. Int. J. Electr. Power Energy Syst. 2011;33:1133-1139.
3. Elsheikh A, Abouelseoud Y, Elsherif A. Optimal placement and sizing of capacitor in radial electric power systems. Alexandra Engineering Journal. 2014;53(2014) 809-816.
4. Shaheen AM, El-Sehiemy RA, Farrag SM. “Adequate planning of shunt power capacitors Involving transformer capacity release benefit”. IEEE Systems Journal. 2018;12(1):373-382,.
5. Kongtonpisan S, Chaitusaney S. Loss reduction in distribution system with photovoltaic system by considering fixed and automatic switching capacitor banks using genetic algorithm. Asia-Pacific Power and Energy Engineering Conference, Shanghai. 2012;1-4.
6. Sun Q, Li Z, Zhang H. Impact of distributed generation on voltage profile in distribution system. In Proceedings of the International Joint Conference on Computational Sciences and Optimization. 2009;249–252.
7. Adefarati T, Bansal RC. Integration of renewable distributed generators into the distribution system: A review. IET Renewable Power Generation. 2016; 10(7):873-84.
8. Valipour KE, Dehghan E, Shariatkhah MH. Optimal placement of capacitor banks and distributed generation for losses reduction and voltage THD improvement in distribution networks based on BBO algorithm. International Research Journal of Applied and Basic Sciences. 2013;4(7):1663-1670.
9. Saonerkar AK, Bagde BY. Optimized DG placement in radial distribution system with reconfiguration and capacitor placement using genetic algorithm. In proc. Int. Conf. Adv. Commun. Contr. Comput. Technol. 2014;1077–1083.
10. Kowsalya M. Optimal distributed generation and capacitor placement in power distribution networks for power loss minimization. In proc. Int. Conf. Adv. Electr. Eng. 2014;1–6.
11. Khodabakhshian A, Andishgar MH. Simultaneous placement and sizing of DGs and shunt capacitors in distribution systems by using IMDE algorithm. Int. J. Elect. Power Energy Syst. 2016;82:599–607.
12. Biswas RP, Mallipeddi R, Suganthan Gehan PN, Amaratunga AJ. A multiobjective approach for optimal placement and sizing of distributed generators and capacitors in distribution network. Applied Soft Computing Journal. 2017;1-26.
    DOI:http://dx.doi.org/10.1016/j.asoc.2017.07.004.
13. Dixit M, Kundu P, Jariwala HR. Incorporation of distributed generation and shunt capacitor in radial distribution system for techno-economic benefits. Eng. Sci. Technol. Int. J. 2017;20(2):482–493.
14. Adel A, Abou El-Ela, Ragab A, El-Sehiemy, Ahmed Samir Abbas. Optimal placement and sizing of distributed generation and capacitor banks in distribution systems using water cycle algorithm. IEEE Systems Journal. 2018;1-9.
15. Gampa SR, Das D. Simultaneous optimal allocation and sizing of distributed generations and shunt capacitors in distribution networks using fuzzy GA methodology. Journal of Electrical Systems and Information Technology. 2019;6:4.
    DOI: https://doi.org/10.1186/s43067-019-0003-2.
16. Sambaiah KS, Jayabarathi T. Optimal allocation of renewable distributed generation and capacitor banks in distribution systems using salp swarm algorithm. International Journal of Renewable Energy Research. 2019;9(1):96-102.
17. Salimon SA, Aderinko HA, Fajuke FI, Suuti KA. Load flow analysis of nigerian radial distribution network using backward/forward sweep technique. Journal of VLSI Design and its Advancement. 2019;2(3):1-11.

18. Tan WS, Hassan MY, Majid MS, Rahman HA. Allocation and sizing of DG using cuckoo search. IEEE International Conference on Power and Energy (PECon), Kota Kinabalu Sabah, Malasia. 2012;133–138.
19. Yang XS, Deb S. Cuckoo search via levy flights. In Nature and Inspired Biologically Computing, World Congress. 2009;210-214.
20. Yang XS, Deb S. Engineering optimization by cuckoo search. Int J. Mathematically Modelling and Numerical Optimization. 2010;1:330-343.
21. Yang XS, Deb S. Multiobjective cuckoo search algorithm for design optimization. Computers and Operations Research. 2011;40(6):1616-1624.
22. Das D, Kothari D, Kalam A. Simple and efficient method for load flow solution of radial distribution network. International Journal Electrical Power Energy System. 1995;17(5):335-346.
23. Shuaib YM, Kalavathi MS, CCA Rajan CCA. Optimal capacitor placement in radial distribution system using gravitational search algorithm. Int. J. Elect. Power Energy Syst. 2015;64(2015):384–397.
24. Askarzadeh A. Capacitor placement in distribution systems for power loss reduction and voltage improvement: A new methodology. Iet Gener. Transmiss. Distrib. 2016;10(14):3631–3638.
25. Moradi MH, Abedini M. A Combination of Genetic Algorithm and Particle Swarm optimization for Optimal DG Location and Sizing in Distribution Systems. International Journal of Electrical Power Energy System. 2012; 34(1):66–74.
26. Arulraj R, Kumarappan N. Optimal economic-driven planning of multiple DG and capacitor in distribution network considering different compensation coefficients in feeder's failure rate evaluation. Engineering Science and Technology, an International Journal. 2019;22:67–77.
DOI:https://doi.org/10.1016/j.jestch.2018.08.009.
27. Mohammad Dehghani, Zeinab Montazeri, Malik OP. Optimal sizing and placement of capacitor banks and distributed generation in distribution systems using spring search algorithm. International Journal of Emerging Electric Power Systems. 2020;1-9:10.
1515/ijeeps-2019-0217.
28. Imran AM, Kowsalya M, Kothari DP. A novel integration technique for optimal network reconfiguration and distributed generation placement in power distribution networks. Int. J. Elect. Power Energy Syst. 2014;63:461–472.
29. R. S. Rao, K. Ravindra, K. Satish, and S. V. L. Narasimham, (2013). Power Loss Minimization in Distribution System using Network Reconfiguration in the presence of Distributed Generation," IEEE Trans. Power Syst., 28(1): 317–325.
30. Meena NK, Swarnkar A, Gupta N, Niazi KR. "A taguchi-based approach for optimal placement of distributed generations for power loss minimization in distribution system", in Proc. IEEE Power Energy Soc. Gen. Meeting. 2015;1–5.
31. Kefayat M, Ara AL, Niaki SN. A hybrid of ant colony optimization and artificial bee colony algorithm for probabilistic optimal placement and sizing of distributed energy resources. Energy Conversion and Management. 2015;92:149-161.
32. El-Fergany A. Optimal allocation of multi-type distributed generators using backtracking search optimization algorithm. Int. J. Elect. Power Energy Syst. 2015;64:1197–1205.
33. Sudabattula SK, Kowsalya M. Optimal allocation of solar based distributed generators in distribution system using Bat algorithm. Perspectives in Science. 2016;8:270-272.
34. Prabha DR, Jayabarathi T. Optimal placement and sizing of multiple distributed generating units in distribution networks by invasive weed optimization algorithm. Ain Shams Engineering Journal. 2016;7(2):683-694.
35. Prakash DB, Lakshminarayana C. Multiple DG placements in radial distribution system for multi-objectives using whale optimization algorithm. Alexandria Eng. J; 2018.
DOI:https://doi.org/10.1016/j.aej.2017.11.003.
38. Kumar S, Mandal KK, Chakraborty N. A novel opposition-based tuned-chaotic differential evolution technique for techno-economic analysis by optimal placement of distributed generation. Engineering Optimization. 2020;52(2):303-324.

36. Sudabattula SK, Suresh V, Subramaniam U, Almakhles D, Padmanaban S, Leonowicz Z, et al. Optimal allocation of multiple distributed generators and shunt capacitors in distribution system using flower pollination algorithm. IEEE Conference Proceedings; 2019. DOI: 10.1109/EEEIC.2019.8783417
37. Adepoju GA, Salimon SA, Aderinko HA, Bisiriyu AO. Optimal placement and sizing of distributed generation in a Nigerian distribution network using cuckoo search algorithm. Current Journal of Applied Science and Technology. 2019;38(6): 1-12.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/65925