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Gbest-Guided Artificial Bee Colony Optimization Algorithm-Based Optimal Incorporation of Shunt Capacitors in Distribution Networks under Load Growth

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Abstract: In this work, a new technique is introduced for optimal incorporation of shunt capacitors (SCs) in distribution networks. This technique has been compared to other sensitivity-based approaches such as loss sensitivity factor, index vector method, power loss index, and index of voltage stability. In the proposed technique, the optimal positions as well as the ratings of SCs are identified through an optimization algorithm. In sensitivity-based approaches, the positions of SCs are determined through a sensitivity approach and the optimal ratings of SCs are computed through an optimization algorithm. The main target of this study is to minimize the total annual cost and power loss of the network under load growth. This has been done through the population-based Gbest-guided artificial bee colony (GABC) optimization technique. Furthermore, the outcomes obtained through the GABC algorithm are compared to those from the iteration particle swarm optimization algorithm. The whole work along with the proposed methodology has been demonstrated on standard 34-bus and 118-bus distribution networks for SC placement. The results show that it reduces the total annual expense of the network to a great value. Consequently, it improves the total power loss reduction, enhances the voltage profile and power factor, and reduces the total voltage deviation. The obtained numerical outcomes through the proposed technique have been compared with the published literature outcomes to show the viability and superiority of the algorithm.

Keywords: Optimal capacitor placement, IPSO, GABC algorithm, LSF, IVS, PLI, IVM, load growth.

1 Introduction

Shunt capacitors (SCs) are mainly used for providing reactive power compensation in distribution networks to diminish power loss, enhance the voltage profile and power factor, and also to improve the network stability and reliability [15]. In the optimal SC placement (OSCP) problem, the target of electrical power utility is to determine the optimal positions and ratings of SCs for achieving the above-mentioned objectives. However, some studies available in the literature indicate that if the locations and sizes are not identified correctly, it may increase the power loss as well as deteriorate the voltage level of the system.

In the past, many researchers have worked on combined schemes of sensitivity approaches and optimization algorithms for solving the SC placement problem. The locations of SCs are identified through a sensitivity-based approach, and the ratings are determined via any one of the optimization techniques. Refs. [2, 17, 31] presented the influence of SC placement on power loss, voltage profile, total annual cost, and power factor of distribution networks. Recently, population-based heuristic and meta-heuristic optimization techniques have been broadly employed to solve the SC installation problem. Refs. [7, 16, 31, 32] implemented a genetic algorithm (GA) to identify the optimal allocations and ratings of SCs simultaneously for minimization

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of active power loss and increment in net savings. Refs. [12, 22, 26] applied the particle swarm optimization (PSO) algorithm and its variant for solving the SC placement task. Refs. [11, 13] applied a loss sensitivity factor (LSF) technique to find SC allocations, and the optimal ratings of these were evaluated using the artificial bee colony (ABC) algorithm to reduce the total cost of the network. Fuzzy-based GA has been demonstrated to determine the optimal ratings of SCs for reduction of total power loss and voltage level improvement [1, 18]. In Ref. [29], the optimal locations and ratings of SCs have been recognized through the LSF approach and gravitational search algorithm (GSA), respectively. Refs. [4, 20] implemented the ant colony optimization (ACO) algorithm for solving the OSCsP problem. In Ref. [28], the LSF approach was utilized for location identification, and the ratings of SCs were determined using the plant growth simulation algorithm (PGSA). Ref. [27] introduced a direct search algorithm for providing optimal SC compensation in distribution networks at different loading conditions. Ref. [10] applied an LSF and power loss index (PLI) approach to evaluate optimal allocations as well as ratings of SCs through an evolutionary algorithm (EA). In Ref. [30], the authors implemented a teaching-learning-based optimization algorithm for optimal incorporation of SCs in distribution networks at different load levels. Similarly, Ref. [8] utilized a bacterial foraging optimization (BFO) algorithm to solve capacitor placement problem. In the present research work, the Gbest-guided artificial bee colony (GABC) optimization algorithm is utilized. This algorithm is already implemented for well-known power system problems, i.e. optimal power flow, unit commitment, and economical load dispatch. In addition, the solution search equations of the algorithm are also better in exploration and exploitation. They are capable of finding the most optimal solution to the problem. These features encouraged the authors to implement the algorithm for solving the OSCsP problem. Hence, this technique has been selected as the preferred method.

In this study, various sensitivity-based approaches, i.e. LSF, index vector method (IVM), PLI, and index of voltage stability (IVS), are utilized for identifying the optimal allocations of SCs, and the respective sizes of SCs are determined through an optimization algorithm. The obtained numerical outcomes of these approaches are compared to the numerical results of the proposed methodology. For checking the performance of the GABC algorithm in terms of optimal solution, the numerical outcomes are compared to those of the iteration PSO (IPSO) algorithm. This typical task has been demonstrated on 34-bus and 118-bus distribution networks with and without including load growth. In addition, the numerical outcomes obtained through the proposed methodology are compared with those of the other intelligent techniques that are available in the published literature.

The contributions of this work were as follows:

- A backward/forward load flow program is formulated for determining the power loss, voltages, and currents of distribution networks.
- A new methodology is introduced for identifying capacitor allocation as well as size through the GABC algorithm under load growth.
- The impact of SCs on the total power loss, voltage profile, and total voltage deviation is analyzed/examined year wise under load growth.

2 Mathematical Problem Formulation

Optimal reactive power compensation in distribution networks is essential. If there is improper allocation and size selection, it may increase the total annual cost and power loss, and deteriorate the voltage level. Moreover, the target of this work is to minimize the total annual expense of the system by incorporating SCs at optimal allocations. As a result, it reduces the power loss and improves the voltage profile and increment in net saving. In many studies, most of the authors used the traditional objective function, which is indicated in Eq. (1). However, in this paper, this objective function has been modified by incorporating the capacitor installation cost, operation cost, and maintenance cost, as defined using Eq. (2).

2.1 Objective Functions

2.1.1 Traditional Total Annual Cost Fitness Function

The traditional fitness function of the total annual cost is associated with the cost of power loss and capacitor incorporation [19]. It is defined using Eq. (1):

$$\text{Minimization cost} = K_{\text{PL}} \sum P_{\text{loss}} T_i + \sum_{j=1}^{N_B} K_j^c Q_j^c. \quad (1)$$

2.1.2 Modified Total Annual Cost Fitness Function

The above traditional fitness function [Eq. (1)] has been modified by introducing the capacitor fixed cost and capacitor operations and maintenance cost. This objective function can be expressed as follows:

$$\text{Minimization cost} = K_{\text{PL}} \sum_{b=1}^{br} P_{\text{loss},b} T_i + \sum_{j=1}^{N_B} K_j^c Q_j^c + N_B (C_{\text{inst}} + C_{\text{opr}}). \quad (2)$$

2.2 Operating Constraints

2.2.1 Power Flow Calculations

The equivalent single line diagram of a radial distribution network is shown in Figure 1. The basic backward/forward load flow program has been utilized for calculating real and reactive power flow between the buses and terminating bus voltage using Eqs. (3), (4), and (5), respectively:

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1} \times \frac{(P_i^2 + Q_i^2)}{|V_i|^2}. \quad (3)$$

$$Q_{i+1} = Q_i + Q_j^c - Q_{Li+1} - X_{i,i+1} \times \frac{(P_i^2 + Q_i^2)}{|V_i|^2}. \quad (4)$$

$$|V_{i+1}|^2 = |V_i|^2 - 2(R_{i,i+1} \times P_i + X_{i,i+1} \times Q_i) + (R_{i,i+1}^2 + X_{i,i+1}^2) \times \frac{(P_i^2 + Q_i^2)}{|V_i|^2}. \quad (5)$$

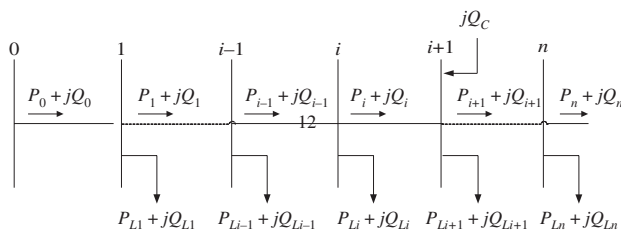


Figure 1: Equivalent Branch of an Electrical Distribution Network.

2.2.2 Voltage Limit

In order to maintain system stability, the voltage level of each bus should lie within the minimum and maximum range. It can be defined using Eq. (6):

$$V_{\min} \leq V_i \leq V_{\max}. \quad (6)$$

2.2.3 Line Current Limit

The line current limit of each branch should not exceed the rated value of current.

$$I_{i,i+1} \leq I_{i,i+1}^{\text{rated}} \forall i \in S_{\text{Br}}. \quad (7)$$

2.2.4 Reactive Power Compensation Limit

The maximum capacitive compensation limit provided through SCs should not be beyond the total reactive demand of the network, and it is expressed as follows:

$$Q_j^c \leq Q_L. \quad (8)$$

Some assumptions have been considered in the above analysis.

- It is assumed that the test network is balanced and free from harmonics.
- In a distribution network, the first bus is assumed as a slack/substation bus and its voltage is 1 pu.
- SCs cannot be placed at the substation bus because there is no load connected across it.

3 Various Approaches for Capacitor Placement

3.1 Proposed Approach

A new approach is introduced to identify candidate buses as well as the sizes of SCs in distribution networks simultaneously for capacitor installation. The load flow calculations are required to evaluate the total power loss, bus voltage, and branch current of the network, and these are associated with the fitness function. The SC locations and sizes are considered as decision variables in the optimization algorithm. Therefore, these are defined in the available search space of the optimization algorithm using Eq. (9). The optimal fitness function value totally depends upon the random selection of decision variables within the specified upper and lower limits. Out of several combinations, one combination shows the minimum function value, which would be the optimal location for capacitor placement. For obtaining the optimal solution, the optimization algorithm should be run multiple times. An optimal topology that has been used in this study can be represented as follows:

$$\text{Dim.} = \left[\underbrace{\text{Cap_Location}}_{\text{Location}} \quad \underbrace{\text{Cap_Size}}_{\text{Size}} \right]. \quad (9)$$

Here, Cap_Location and Cap_Size are the capacitor location and capacitor size, respectively. The capacitor locations and sizes are defined in a 1×2 column matrix.

3.2 IVM

This method has been implemented to identify optimal buses for SC placement in distribution networks. A load flow program is necessary to evaluate the real and imaginary components of current across each branch. The IVM value for the i^{th} bus can be evaluated using Eq. (10). Based on the values, this method identifies candidate buses for SC installation [24].

$$\text{IVM}(i) = \frac{1}{V_i^2} + \frac{I_q(k)}{I_p(k)} + \frac{Q_{\text{eff}}(i)}{Q_L}. \quad (10)$$

The following are the steps for implementation of the IVM approach to find candidate buses for SC placement:

- Step 1: Run the load flow program without SC installation.
- Step 2: Store the values of voltages of each bus as well as the real and imaginary components of the current of each branch.
- Step 3: Then, calculate the IVM values of all buses using Eq. (10) and sort these in a decreasing manner.
- Step 4: Evaluate the normalized voltage, $\text{norm}(i) = V_i/0.95$, for all buses. Those buses that have higher IVM values and least normalized voltage <1.01 are picked up as candidate buses for SC integration.

3.3 LSF

This technique has been employed to find the sensitivity of each bus of the distribution network [28]. It is helpful for mitigating the search space of the algorithm during the optimization process. The LSF values for real and reactive power support is determined using Eqs. (11) and (12), respectively:

$$\frac{dP_{i,i+1}^{\text{line loss}}}{dQ_{\text{eff}}(i)} = \frac{2 \times Q_{\text{eff}}(i) \times R_{i,i+1}}{|V_i|^2}. \quad (11)$$

$$\frac{dQ_{i,i+1}^{\text{line loss}}}{dQ_{\text{eff}}(i)} = \frac{2 \times Q_{\text{eff}}(i) \times X_{i,i+1}}{|V_i|^2}. \quad (12)$$

The steps for implementation of the LSF approach are as follows:

- Step I: Calculate the LSF for all buses from base case load flow using Eq. (13):

$$\text{LSF} = dP_{i,i+1}^{\text{line loss}} / dQ_{\text{eff}}(i). \quad (13)$$

- Step II: Sort the LSF values of all buses in descending order and store them in bus position vector.
- Step III: Then, evaluate the normalized voltage for each bus, $\text{norm}(i) = V_i/0.95$.
- Step IV: Choose those buses with normalized voltage <1.01 as candidate buses for SC installation.

The possible standard sizes of SCs with cost in \$/kVar are available in Ref. [23], which have been utilized to determine the total annual cost of the network.

3.4 PLI

The PLI approach has been implemented to determine candidate buses for capacitor installation. The load flow is required to find loss reduction (LR) values by compensating the total reactive load across each bus,

considering one bus at a time excluding the slack bus [14]. The PLI value for the i^{th} bus is evaluated using Eq. (14):

$$\text{PLI}(i) = \frac{\text{LR}(i) - \text{LR}_{\min}}{\text{LR}_{\max} - \text{LR}_{\min}}. \quad (14)$$

Those buses having higher PLI values are chosen as candidate buses for SC installation. The procedure for implementation of the PLI approach is as follows:

- Step 1: Run the load flow program of base case and evaluate real power losses.
- Step 2: Provide reactive power compensation across each bus, which is equal to the entire reactive load of the network.
- Step 3: Run the load flow and calculate the real power loss and store these values.
- Step 4: Calculate $\text{LR} = (\text{base case real power loss} - \text{real power loss of each bus after compensation})$ and store the value.
- Step 5: Evaluate the maximum and minimum LR. Then, compute the PLI values of each bus using Eq. (14).
- Step 6: Sort these PLI values in descending order. Those buses with voltage < 0.95 pu are selected as candidate buses for capacitor installation.

3.5 IVS

The IVS is a numerical solution to compute the security level of the distribution system. The purpose of IVS is to calculate the stability of the buses and locate sensitive buses in the network [3]. Voltage collapse begins at the most sensitive bus and expand to other sensitive buses. IVS at bus $i + 1$ can be determined using Eq. (15):

$$\text{IVS}_{(i+1)} = |V_i|^4 - 4\{P_{i+1}R_{i,i+1} - Q_{i+1}X_{i,i+1}\}^2 - 4\{P_{i+1}R_{i,i+1} + Q_{i+1}X_{i,i+1}\}|V_i|^2. \quad (15)$$

The condition for stable operation of the network is $\text{IVS}_{(i+1)} \geq 0$, whereas $i = 1, \dots, (N_B - 1)$. Those buses having minimum IVS values are selected as the most sensitive buses for capacitor placement.

To determine the sensitive buses for capacitor allocation, the following steps are taken:

- Step 1: Calculate IVS values for all buses through a base case load flow program.
- Step 2: Sort these IVS values in ascending order. Those buses having the least IVS values are chosen as candidate buses for SC installation.

4 Voltage Deviation

Bus voltage is one of the most important factors for maintaining power quality. The variation in voltage level results in poor performance of the electrical system. The voltage deviation can be calculated using Eq. (16):

$$V_{\text{deviation}} = \sum_{i=1}^{N_B} \frac{V_{\text{rated}} - V_i}{V_{\text{rated}}}. \quad (16)$$

5 Load Growth Modeling

Feeder load growth is a natural phenomenon, and this may be increased due to the addition of new load on the existing load. An increment in load demand may increase the whole network power loss and deteriorate

the voltage profile. For the future point of view, if the load increases beyond the feeder capacity, a new facility has to be created such as expansion of existing substation or addition of new feeders to maintain the power quality. In this work, the load growth concept is considered from Ref. [6]. The compensation increases with the load growth to fulfill the increased load demand. The load growth model for active and reactive load is expressed using Eqs. (17) and (18), respectively:

$$P_{\text{Load}}(t) = \sum_i^{N_B} P_{\text{Load}}(i) \times (1 + gw)^t, \quad (17)$$

$$Q_{\text{Load}}(t) = \sum_i^{N_B} Q_{\text{Load}}(i) \times (1 + gw)^t, \quad (18)$$

where $P_{\text{Load}}(i)$ and $Q_{\text{Load}}(i)$ are the active and reactive loads of the i^{th} bus, respectively. $P_{\text{Load}}(t)$ and $Q_{\text{Load}}(t)$ are the active and reactive loads of the t^{th} year.

6 Optimization Algorithms

6.1 Conventional PSO

This algorithm was proposed by Eberhart and Kennedy in 1995 [9]. In this algorithm, the population is known as swarm and it is generated in a random manner, and the swarm consists of individuals named as particles. Each and every particle moves in the search space for finding an optimal solution. In this, the particles have two important parameters, such as position (x_i) and velocity (v_i). The position and velocity of the i^{th} particle in available d -dimensional search space is defined as $x_i^k = x_{i1}^k, x_{i2}^k, \dots, x_{id}^k$ and $v_i^k = v_{i1}^k, v_{i2}^k, \dots, v_{id}^k$, respectively. In each and every iteration, the i^{th} particle fitness is calculated, i.e. $P_{\text{best},i}^k = P_{\text{best},i1}^k, P_{\text{best},i2}^k, \dots, P_{\text{best},id}^k$. $P_{\text{best},i}$ is the best position that has been visited through the i^{th} particle unto the current iteration (k). Moreover, the fitness position associated with the best particle ($P_{\text{best},i}^k$) is considered as particle best position (x_i^k). The global best fitness value ($G_{\text{best},i}^k$) is the best solution among the $P_{\text{best},i}^k$ in a group of i^{th} particles at iteration (k). Thus, the new position of particles (x_i^{k+1}) is updated, given by Eq. (19) based on the velocity (v_i^{k+1}) values using Eq. (20):

$$v_i^{k+1} = v_i^{k+1} + c_1 r_1 (P_{\text{best},i}^k - x_i^k) + c_2 r_2 (G_{\text{best}}^k - x_i^k). \quad (19)$$

$$x_i^{k+1} = v_i^{k+1} + x_i^k. \quad (20)$$

6.2 IPSO

In the iteration-based PSO method, a new parameter I_{best} is incorporated into the velocity equation for improving the solution quality. It was developed by Lee and Chen [21]. This I_{best} value is the P_{best} value that has been chosen in random manner among all particles in the current population. Moreover, another coefficient, “ c_3 ,” called dynamic accelerating constant, has also been introduced and is evaluated using Eq. (21). Hence, the final updated velocity equation can be defined using Eq. (22):

$$c_3 = c_1 (1 - e^{c_1 k}). \quad (21)$$

$$v_i^{k+1} = v_i^{k+1} + c_1 r_1 (P_{\text{best},i}^k - x_i^k) + c_2 r_2 (G_{\text{best}}^k - x_i^k) + c_3 (I_{\text{best}}^k - x_i^k). \quad (22)$$

6.3 GABC Algorithm

The GABC algorithm is one of the prevalent meta-heuristic optimization techniques; it is inspired by the social nature of honeybees for searching a food source. This was developed by Zhu and Kwong [33] in 2010. It consists of a combination of three varieties of bees, namely employed bee, onlooker bee, and scout bee, where onlooker and scout bees are considered as unemployed bees. An employed bee searches and exploits a food source position while the onlooker bees wait in the hive. Employed bees distribute information with the onlooker bees regarding a food source position. As per the information received via the employed bees, the onlooker bees find a better food source location [33]. The probability to select a particular food source through the onlooker bee is evaluated using Eq. (23). The location of each food source indicates the feasible outcomes of the defined optimization task:

$$P_{\text{prob},i} = \frac{\text{fit}_i}{\sum_k^N \text{fit}_k}, \quad (23)$$

where fit_i represents an objective function value of the i^{th} position solution and $k \in \{1, 2, \dots, dv\}$. The term dv belongs to the total number of decision variables. The scout bees identify a better food source position in a random manner using Eq. (24):

$$\gamma_{ij} = \gamma_{\min,j} + \text{rand}(\gamma_{\max,j} - \gamma_{\min,j}), \quad (24)$$

where $\gamma_{\min,j}$ and $\gamma_{\max,j}$ indicate the maximum and minimum values of the j^{th} variable at the i^{th} solution, and rand indicates the random number, which lies between 0 and 1. The entire population has a solution. Equation (25) represents the solution of the i^{th} food source:

$$\gamma_i = \{\gamma_{i1}, \gamma_{i2}, \dots, \gamma_{id}\}. \quad (25)$$

The searching process of the GABC algorithm is classified into four simple steps, as follows: (i) initialization of parameters, (ii) employed bee phase, (iii) onlooker bee phase, and (iv) scout bee phase. In the first step, the candidate solution is determined in a random manner using Eq. (24). Both employed and onlooker bees search a new food source position using Eq. (26):

$$\gamma_{\text{new},ij} = \gamma_{ij} + \phi_{ij}(\gamma_{ij} - \gamma_{kj}) + c(\gamma_j + \gamma_{ij}). \quad (26)$$

Here, ϕ_{ij} represents the uniform random number $[-1, 1]$, $\gamma_{\text{new},ij}$ indicates the updated food source position, γ_{kj} is a food source that is related to the employed bees or nearer to γ_{ij} , c is a random number between $[0, 2]$, and γ_j represents a global best solution of the present cycle.

6.4 Implementation of the GABC Algorithm for the OSCsP Problem

This section indicates the application and implementation of GABC algorithm to solve the optimal SC installation problem in distribution networks. The necessary steps to solve this problem are as follows:

- Step I: Initialize the power system data and the parameters of the GABC algorithm, i.e. load and line data, operating voltage and base MVA, number of employed bees, number of onlooker bees, limit, total number of iterations (MCN), etc.
- Step II: Calculate the size of SCs using Eq. (24). These are the random sizes of SCs, γ_{ij} . Then, convert them into standard ratings via the pseudo code below:

$$\begin{aligned}
& \text{if } C_{s1} \leq \gamma_{ij} \leq C_{s2} - \frac{C_{s2} - C_{s1}}{2} \\
& \quad \gamma_{ij} = C_{s1} \\
& \text{else if } C_{s2} - \frac{C_{s2} - C_{s1}}{2} \leq \gamma_{ij} \leq C_{s3} - \frac{C_{s3} - C_{s2}}{2} \\
& \quad \gamma_{ij} = C_{s2} \\
& \quad \vdots \\
& \text{else if } C_{s(n-1)} - \frac{C_{s(n-1)} - C_{s(n-2)}}{2} \leq \gamma_{ij} \leq C_{sn} - \frac{C_{sn} - C_{s(n-1)}}{2} \\
& \quad \gamma_{ij} = C_{s(n-1)} \\
& \text{else if } \gamma_{ij} \geq C_{sn} - \frac{C_{sn} - C_{s(n-1)}}{2} \\
& \quad \gamma_{ij} = C_{sn} \\
& \text{end}
\end{aligned}$$

Here, C_{s1} , C_{s2} , ..., $C_{s(n-1)}$ and C_{sn} are the standard sizes of the capacitor.

- Step III: Run the GABC optimization algorithm including load flow program, and evaluate fitness function value (2). Initially, the iteration count is set as 1 and is repeated till the MCN is reached.
- Step IV: In this step (employed bee phase), modify the randomly generated solution in the above step using Eq. (26).
- Step V: After the employed bee phase, modify the value and repeat step III.
- Step VI: Apply a greedy search mechanism and memorize the best solution obtained from steps II and IV, and discard the worst one.
- Step VII: Onlooker bee phase. In this step, the onlooker bee selects an employed bee food source location and evaluates the probability to find a better food source using Eq. (23).
- Step VIII: After the onlooker bee phase, the values become modified. Using these modified capacitor values, execute step III. Apply the greedy mechanism and memorize the best solution obtained from steps VI and VIII, and discard the worst.
- Step IX: In the scout bee phase, if the result quality is not mended in predefined trials, the values are discarded. Then, the scout bees find a better solution in a random manner using Eq. (24).
- Step X: Memorize the best obtained solution and increment the iteration cycle: $\text{iter} = \text{iter} + 1$. If $\text{iter} < \text{MCN}$, go to step IV; otherwise, stop and display the best optimal solution.

The flowchart diagram of the GABC algorithm for solving the SC installation problem is illustrated in Figure 2.

7 Numerical Results and Discussion

This methodology is demonstrated on 34-bus and 118-bus distribution networks for SC installation at optimal allocation for total annual cost minimization. Thereby, it reduces the network power loss and improves the voltage level simultaneously. In addition, the numerical outcomes obtained through the proposed methodology have been compared with the other intelligent algorithms available in the published literature. The adopted control parameters of the GABC and IPSO algorithms are indicated in Tables 1 and 2, respectively, for obtaining the optimal solution. The complete simulation has been carried out in MATLAB environment.

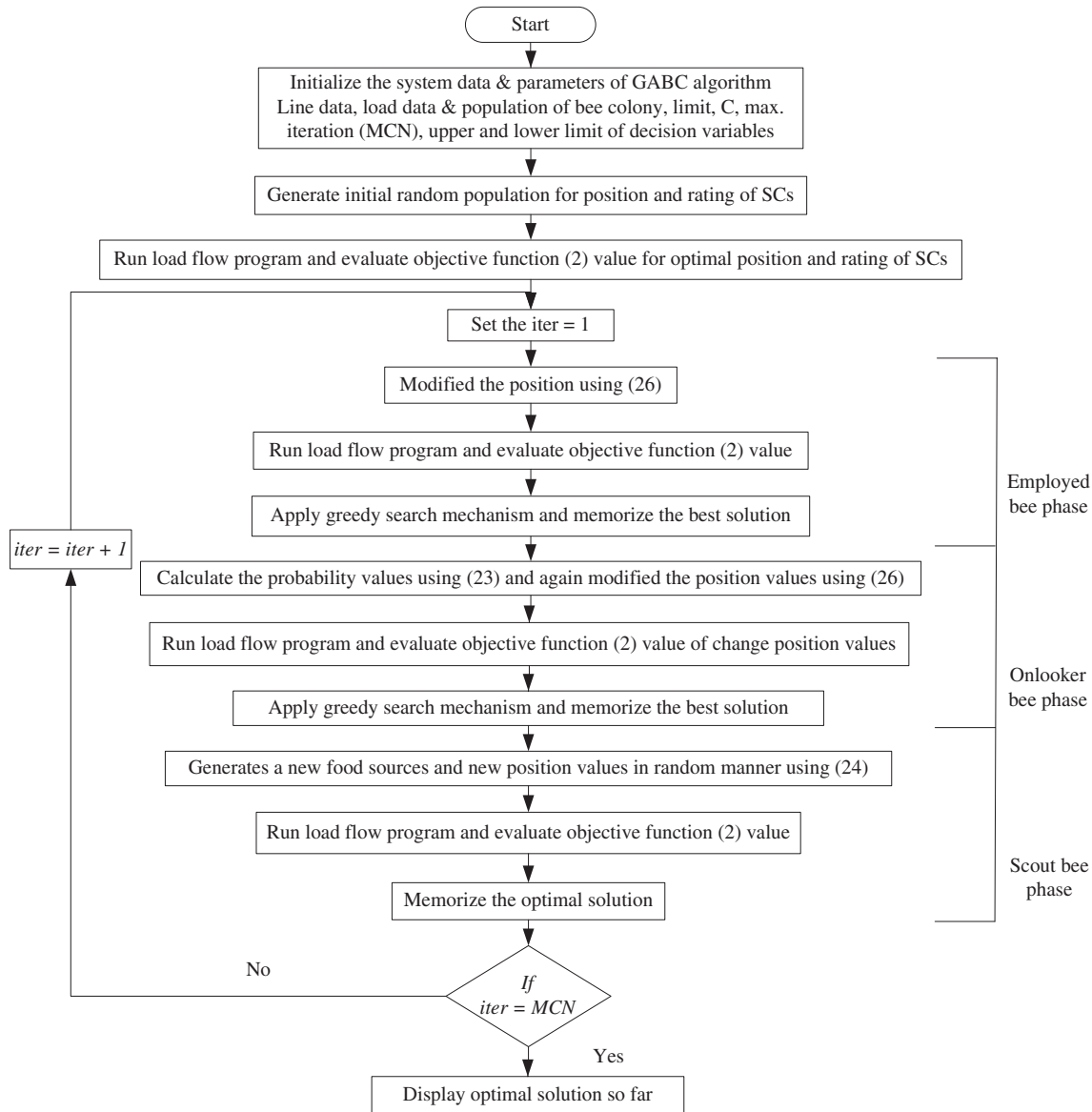


Figure 2: Flowchart of the GABC Algorithm to Solve the OSCSP Problem.

Table 1: Adopted Control Parameters of the GABC Optimization Algorithm.

Parameters	Colony size	Employed bees	Onlooker bees	Food source	Limit	C	MCN
Values	150	150	$3 \times \text{employed bees}$	$0.5 \times \text{employed bees}$	3	1.5	100

Table 2: Adopted Control Parameters of the IPSO Algorithm.

Parameters	Population size	c_1	c_2	MCN
Values	100	2.05	0.25	100

7.1 Thirty-Four-Bus Radial Distribution System

This standard test network contains 34 buses and 33 branches, and has one main feeder and four laterals (subfeeder). The total network details, i.e. load and line data, have been taken from Ref. [5]. The total network load is 4.636 + 2.873 MVA, the rated voltage is 11 kV, and the base is 100 MVA.

Proposed Approach: In this, the optimal allocations and sizes of SCs are determined simultaneously through optimization algorithms for minimizing the total annual cost of the system. As a result, it improves the power loss reduction and enhances the voltage level significantly. The numerical outcomes obtained through optimization algorithms with and without consideration of load growth are tabulated in Table 3. Between the two algorithms, the GABC algorithm generates better-quality solutions.

IVM: The IVM approach is applied for determining optimal buses for SC placement. Those buses with higher IVM values and lower normalized voltage are chosen as candidate buses for SC installation. These buses are {23, 24, 25, and 26} and the optimal sizes of SCs on these respective buses are evaluated using optimization algorithms. The detailed numerical outcomes obtained through different optimization algorithms with and without considering load growth are tabulated in Table 4. Between the two algorithms, GABC provides good-quality solutions.

LSF: This methodology is applied to find the sensitivity of the buses of the distribution network. Those buses with higher LSF values and lower normalized voltage are chosen as candidate buses for SC placement. These buses are {19, 20, 21, and 22}, and the optimal sizes of SCs on these buses are evaluated through optimization algorithms. The obtained numerical outcomes via both optimization algorithms are tabulated in Table 5.

PLI: In this, the locations of SCs are determined through the PLI approach. Those buses with high PLI values and voltage <0.95 pu are chosen as candidate buses for SC installation, and these are {22, 25, 26, and 27}, and the respective size on these buses is evaluated through optimization algorithms. The numerical results obtained through various algorithms are mentioned in Table 6. From the numerical outcomes, it is noted that both optimization algorithms show the same results.

Table 3: Simulation Results of the 34-Bus Distribution Network after SC Placement Using the Proposed Approach.

Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	221.74	160.28	159.33	477.95	349.02	345.65
Loss reduction (%)	–	27.72	28.14	–	26.98	27.68
Capacitor size (location)	–	450 (8)	900 (5)	–	450 (8)	900 (9)
		900 (16)	600 (9)		1050 (16)	600 (18)
		450 (21)	600 (20)		750 (21)	600 (21)
		600 (24)	600 (24)		600 (24)	750 (24)
Σ kVar	–	2400	2700	–	2850	2850
Total cost (US\$)	116,548.18	89,966.36	89,506.47	251,208.91	189,339.02	187,509.99
Saving (%)	–	22.81	23.20	–	24.63	25.36
Power factor	0.85	0.995	0.999	0.8500	0.98	0.98
$V_{\min}$ (pu)	0.9417	0.9503	0.9506	0.9142	0.9251	0.9256
Σ Voltage deviation (pu)	1.2044	1.0187	1.0169	1.7672	1.5060	1.5040

Table 4: Simulation Results of the 34-Bus Distribution Network after SC Placement Using the IVM Approach.

Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	221.74	173.83	173.84	477.95	373.12	373.21
Loss reduction (%)	–	21.61	21.60	–	21.93	21.91
Capacitor size (location)	–	1050 (23)	900 (23)	–	1350 (23)	1200 (23)
		150 (24)	300 (24)		300 (24)	450 (24)
		150 (25)	150 (25)		150 (25)	150 (25)
		150 (26)	150 (26)		300 (26)	300 (26)
Σ kVAr	–	1500	1500	–	2100	2100
Total cost (US\$)	116,548.18	97,032.02	96,993.22	251,208.91	201,876.30	201,857.97
Saving (%)	–	16.74	16.78	–	19.64	19.64
Power factor	0.85	0.9588	0.9588	0.8500	0.957	0.957
$V_{\min}$ (pu)	0.9417	0.9493	0.9424	0.9142	0.9255	0.9256
Σ Voltage deviation (pu)	1.2044	1.0458	1.0456	1.7672	1.534	1.534

Table 5: Simulation Results of the 34-Bus Distribution Network after SC Placement Using the LSF Approach.

Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	221.74	169.29	169.14	477.95	362.66	362.62
Loss reduction (%)	–	23.65	23.72	–	24.12	24.13
Capacitor size (location)	–	750 (19)	900 (19)	–	1500 (19)	1200 (19)
		300 (20)	300 (20)		150 (20)	300 (20)
		150 (21)	150 (21)		150 (21)	300 (21)
		600 (22)	600 (22)		900 (22)	900 (22)
Σ kVAr	–	1800	1950	–	2700	2700
Total cost (US\$)	116,548.18	94,698.27	94,577.01	251,208.91	196,428.19	196,372.27
Saving (%)	–	18.75	18.85	–	21.81	21.83
Power factor	0.85	0.9742	0.9807	0.8500	0.98	0.98
$V_{\min}$ (pu)	0.9417	0.9493	0.9498	0.9142	0.9259	0.9261
Σ Voltage deviation (pu)	1.2044	1.033	1.028	1.7672	1.509	1.508

Table 6: Simulation Results of the 34-Bus Distribution Network after SC Placement Using the PLI Approach.

Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	221.74	171.71	171.71	477.95	368.46	368.46
Loss reduction (%)	–	22.56	22.56	–	22.91	22.91
Capacitor size (location)	–	1200 (22)	1200 (22)	–	1500 (22)	1500 (22)
		150 (25)	150 (25)		450 (25)	450 (25)
		150 (26)	150 (26)		150 (26)	150 (26)
		150 (27)	150 (27)		150 (27)	150 (27)
Σ kVAr	–	1650	1650	–	2250	2250
Total cost (US\$)	116,548.18	95,882.06	95,882.06	251,208.91	199,426.36	199,426.36
Saving (%)	–	17.73	17.73	–	20.61	20.61
Power factor	0.85	0.9669	0.9669	0.8500	0.963	0.963
$V_{\min}$ (pu)	0.9417	0.9497	0.9497	0.9142	0.9258	0.9258
Σ Voltage deviation (pu)	1.2044	1.039	1.039	1.7672	1.527	1.527

IVS: In this, those buses with the least IVS values are chosen as candidate buses for SC placement. The candidate buses for SC installation are {24, 25, 26, and 27}, and the respective sizes of SCs on these buses are computed through optimization algorithms. From Table 7, it is observed that both optimization algorithms give the same solution including load growth.

The obtained numerical outcomes through the proposed technique using the GABC algorithm are compared with the other published intelligent algorithms available in the published literature, i.e. ABC, PGSA, heuristic search, mixed-integer non-linear program (MINLP), GA, BFO, and PSO, as tabulated in Table 8. These realized numerical results indicate that the proposed technique is superior to other computation techniques. The minimum system voltage is appreciably improved after optimal compensation. In addition, Table 9 indicates the simulation results comparison between various approaches after incorporating the SCs. The percentage loss reduction is 28.14% and the percentage annual saving is 23.20% without consideration of load growth. In the presence of load growth, it becomes 27.68% and 25.36%, respectively. Among all approaches, the proposed approach shows better results. During load growth, the system draws more real and reactive power from the substation. As a result, the total network load increases, the power loss increases, and the voltage profile deteriorates. Year-wise load growth analysis and comparison without any compensation are mentioned in Table 10. In the same manner, year-wise load growth analysis and comparison after optimal compensation are mentioned in Table 11. Year-wise voltage profile comparisons without and with optimal capacitive compensation under load growth are depicted in Figure 3. The computation time of the CPU to find good-quality solution through the proposed methodology is nearly 43.02 s, including load flow. Furthermore, the simulation results of the 118-bus distribution system obtained through various approaches are indicated in Tables 12–16 after SC installation. Figure 4 indicates the performance comparison between the GABC and IPSO algorithms for the 34-bus and 118-bus distribution systems with and without considering load growth.

8 Conclusion

In this paper, a new methodology is introduced to identify the optimal allocation and size of SCs simultaneously through optimization algorithms for minimizing the total annual cost of the system. From Tables 8 and 9, it is noted that the proposed methodology shows better outcomes as compared to the other sensitivity-based approaches. In addition, after optimal SC installation, the total annual expense of the network

Table 7: Simulation Results of the 34-Bus Distribution Network after SC Placement Using the IVS Approach.

Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	221.74	176.62	176.62	477.95	379.16	379.26
Loss reduction (%)	–	20.35	20.35	–	20.67	20.65
Capacitor size (location)	–	900 (24)	900 (24)	–	1500 (24)	1200 (24)
		150 (25)	150 (25)		150 (25)	450 (25)
		150 (26)	150 (26)		150 (26)	150 (26)
		150 (27)	150 (27)		150 (27)	150 (27)
Σ kVar	–	1350	1350	–	1950	1950
Total cost (US\$)	116,548.18	98,423.16	98,423.16	251,208.91	205,015.38	205,007.43
Saving (%)	–	15.55	15.55	–	18.39	18.39
Power factor	0.85	0.95	0.95	0.8500	0.95	0.95
$V_{\min}$ (pu)	0.9417	0.9491	0.9491	0.9142	0.9253	0.9254
Σ Voltage deviation (pu)	1.2044		1.054	1.7672	1.543	1.543

Table 8: Simulation Results and Comparison with Other Intelligent Techniques after SC Placement for the 34-Bus System.

Particulars	Uncompensated					Compensated				
			ABC [11]	PGSA [28]	Heuristic based [12]	MINLP [25]	GA [32]	PSO [26]	BFO [8]	GABC
Real power loss (kW)	221.74		167.76	169.13	168.01	163.22	164.94	168.88	160.97	159.33
Loss reduction (%)	—		24.34	23.73	24.23	26.39	25.62	23.84	27.41	28.14
Reactive power loss (kVAr)	65.12		48.88	48.98	48.98	47.40	48.51	48.92	47.23	46.70
Loss reduction (%)	—		24.94	24.78	24.78	27.21	25.51	24.88	27.47	28.29
Capacitor size (location)	—		1050 (19)	1200 (19)	1050 (19)	300 (4)	300 (5)	781 (19)	625 (10)	900 (5)
			800 (24)	200 (20)	750 (25)	600 (10)	300 (9)	479 (20)	640 (20)	600 (9)
				639 (22)		100 (14)	300 (12)	803 (22)	610 (25)	600 (20)
						500 (18)	600 (22)			600 (24)
						300 (22)	300 (26)			
						1000 (27)				
Σ kVAr			1850	2039	1800	2800	1800	2063	1875	2700
Total cost (US\$)	116,548.18		91,236.00	93,241.98	91,350.63	94,334.35	93,744.97	93,224.96	88,948.19	89,506.47
Saving (%)	—		21.72	20.00	21.62	19.06	19.56	20.01	23.68	23.20
Power factor	0.85		0.98	0.98	0.97	0.999	0.97	0.985	0.988	0.999
$V_{\min}$ (pu)	0.9417		0.9495	0.9492	0.9495	0.9521	0.9479	0.9496	0.9499	0.9506
Σ Voltage deviation (pu)	1.204		1.032	1.026	1.034	1.021	1.039	1.025	1.023	1.0169

Table 9: Simulation Results Comparison among Various Approaches after SC Placement.

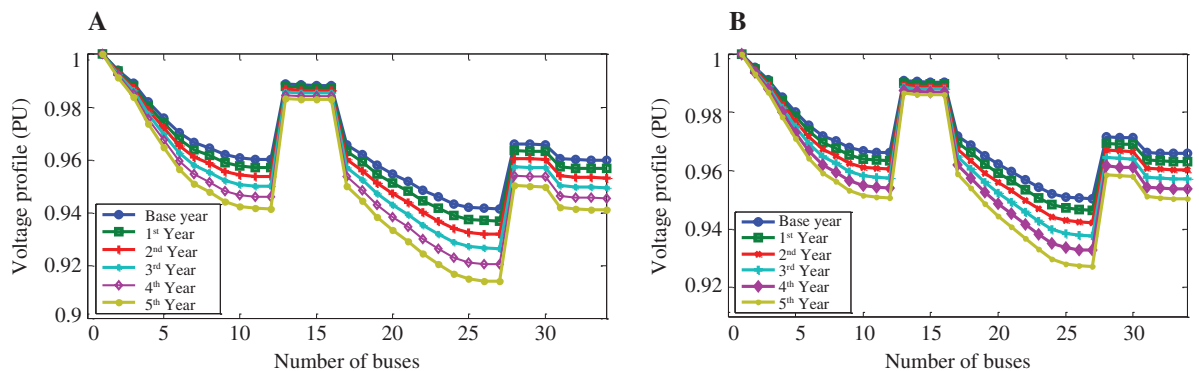
Particulars	Proposed approach	IVM	LSF	PLI	IVS
Total losses (kW)	159.33	173.84	169.14	171.71	176.62
Loss reduction (%)	28.14	21.60	23.72	22.56	20.35
Total cost (US\$)	89,506.47	96,993.22	94,577.01	95,882.06	98,423.16
Saving (%)	23.20	16.78	18.85	17.73	15.55
Power factor	0.999	0.9588	0.9807	0.9669	0.95
$V_{\min}$ (pu)	0.9506	0.9424	0.9498	0.9497	0.9491
Σ Voltage deviation (pu)	1.0169	1.0456	1.028	1.039	1.054

Table 10: Year-wise Analysis on the 34-Bus Distribution System without OSCsP.

Particulars	Base year	1 st year	2 nd year	3 rd year	4 th year	5 th year
Total real power load (kW)	4636.5	4984.24	5358.06	5759.91	6191.90	6656.29
Total reactive power load (kVAr)	2873.5	3089.01	3320.69	3569.74	3837.47	4125.28
Real power loss (kW)	221.74	258.17	300.79	350.70	409.22	477.95
Reactive power loss (kVAr)	65.12	75.81	88.31	102.95	120.11	140.25
Total cost (US\$)	116,548.18	135,696.33	158,095.63	184,327.94	215,088.14	251,208.92
$V_{\min}$ (pu)	0.9417	0.9371	0.9320	0.9266	0.9206	0.9142
Σ Voltage deviation (pu)	1.2044	1.2994	1.4025	1.5142	1.6355	1.7672

Table 11: Year-wise Analysis on the 34-Bus Distribution System after OSCsP Using the GABC Algorithm.

Particulars	Base year	1 st year	2 nd year	3 rd year	4 th year	5 th year
Real power loss (kW)	159.33	185.29	215.86	251.90	294.78	345.65
Reactive power loss (kVAr)	46.70	54.30	63.28	73.91	86.54	101.58
Capacitor size (location)	900 (5)	900 (5)	750 (9)	750 (9)	900 (9)	900 (9)
	600 (9)	600 (9)	900 (16)	900 (17)	600 (18)	600 (18)
	600 (20)	750 (20)	600 (21)	600 (21)	600 (21)	600 (21)
	600 (24)	600 (24)	600 (24)	600 (24)	750 (24)	750 (24)
Σ kVAr	2700	2850	2850	2850	2850	2850
Total cost (US\$)	89,506.47	103,226.78	119,291.30	138,234.72	160,769.99	187,509.99
$V_{\min}$ (pu)	0.9506	0.9466	0.9421	0.9371	0.9319	0.9256
Σ Voltage deviation (pu)	1.0169	1.0963	1.1856	1.2813	1.3880	1.5040

**Figure 3:** Voltage Profile of the 34-Bus Distribution System.

(A) Before compensation considering load growth. (B) After compensation considering load growth.

Table 12: Simulation Results of the 118-Bus Distribution Network after SC Placement Using the Proposed Approach.

Particulars	Without Load Growth			With Load Growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	1296.55	832.83	794.31	2932.34	1817.86	1746.16
Loss reduction (%)	–	35.77	38.74	–	38.01	40.45
Capacitor size (location)	–	600 (21)	900 (21)	–	1800 (19)	1500 (19)
		450 (30)	1350 (30)		150 (21)	1800 (30)
		1050 (31)	750 (36)		1800 (30)	1650 (40)
		1350 (36)	750 (40)		1800 (31)	1800 (47)
		150 (40)	300 (42)		1800 (48)	1500 (51)
		1050 (42)	600 (48)		1800 (58)	1050 (57)
		300 (48)	1500 (49)		150 (70)	1800 (71)
		1650 (49)	600 (58)		1800 (73)	600 (74)
		1350 (73)	1350 (70)		1800 (77)	1050 (77)
		600 (79)	450 (73)		1800 (78)	1650 (80)
		600 (89)	1500 (79)		1800 (95)	1800 (90)
		1200 (95)	900 (95)		1800 (100)	1800 (99)
		300 (106)	1050 (100)		150 (106)	900 (106)
		1650 (108)	1350 (106)		1800 (108)	1800 (108)
		900 (110)	1350 (110)		1800 (110)	1200 (110)
Σ kVAr	–	13,200	14,700	–	22,050	21,900
Total cost (US\$)	681,465.61	460,074.56	440,175.64	1,541,240.38	979,232.99	941,520.55
Saving (%)	–	32.49	35.41	–	36.46	38.91
Power factor	0.80	0.986	0.99	0.8	0.99	0.99
$V_{\min}$ (pu)	0.8688	0.9057	0.9097	0.7978	0.8613	0.8654
Σ Voltage deviation (pu)	5.2429	4.1242	4.0677	7.8518	6.0175	6.0303

Table 13: Simulation Results of the 118-Bus Distribution Network after SC Placement Using the IVM Approach.

Particulars	Without Load Growth			With Load Growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	1296.55	968.34	964.16	2932.34	2190.89	2177.04
Loss reduction (%)	–	25.31	25.64	–	25.28	25.76
Capacitor size (location)	–	150 (34)	900 (34)	–	150 (34)	1500 (34)
		150 (46)	150 (46)		150 (46)	150 (46)
		150 (47)	150 (47)		1800 (47)	150 (47)
		150 (48)	150 (48)		150 (48)	300 (48)
		1800 (49)	1350 (49)		1800 (49)	1800 (49)
		150 (52)	300 (52)		150 (52)	450 (52)
		150 (55)	450 (55)		1200 (55)	600 (55)
		150 (56)	600 (56)		150 (56)	900 (56)
		150 (77)	900 (77)		1800 (77)	1500 (77)
		1800 (78)	300 (78)		150 (78)	600 (78)
		150 (79)	450 (79)		1800 (79)	600 (79)
		150 (80)	600 (80)		150 (80)	900 (80)
		600 (93)	900 (93)		1800 (93)	1500 (93)
		150 (94)	150 (94)		150 (94)	150 (94)
		1800 (110)	1500 (110)		1800 (110)	1800 (110)
Σ kVAr	–	7650	8850	–	13,200	12,900
Total cost (US\$)	681,465.61	530,424.03	528,340.03	1,541,240.38	1,173,854.52	1,166,498.79
Saving (%)	–	22.16	22.47	–	23.84	24.31
Power factor	0.80	0.9241	0.9407	0.8	0.9452	0.9425
$V_{\min}$ (pu)	0.8688	0.8767	0.8776	0.7978	0.8154	0.8136
Σ Voltage deviation (pu)	5.2429	4.3545	4.2868	7.8518	6.3287	6.3553

Table 14: Simulation Results of the 118-Bus Distribution Network after SC Placement Using the LSF Approach.

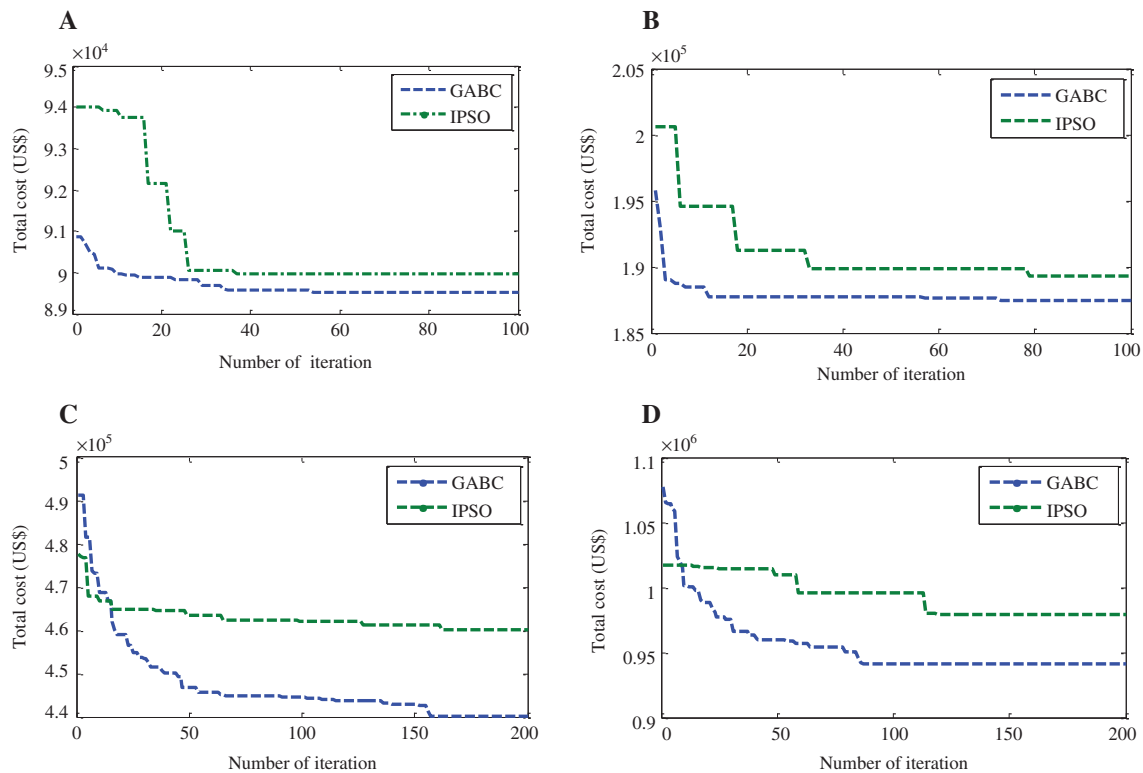
Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	1296.55	859.55	833.59	2932.34	1866.29	1834.15
Loss reduction (%)	–		35.71	–		37.45
Capacitor size (location)	–	150 (33)	600 (33)	–	600 (33)	1200 (33)
		1800 (35)	1500 (35)		1500 (35)	1500 (35)
		150 (45)	450 (45)		1050 (45)	750 (45)
		150 (46)	600 (46)		1200 (46)	1500 (46)
		1800 (49)	1500 (49)		1800 (49)	1500 (49)
		1800 (54)	1200 (54)		1350 (54)	1500 (54)
		1800 (71)	1200 (71)		1350 (71)	1500 (71)
		150 (76)	450 (76)		300 (76)	900 (76)
		1800 (86)	1350 (86)		1800 (86)	1500 (86)
		150 (94)	750 (94)		1050 (94)	1050 (94)
		1800 (101)	1500 (101)		1800 (101)	1500 (101)
		150 (110)	1200 (110)		1500 (110)	1500 (110)
		1800 (111)	900 (111)		1500 (111)	1500 (111)
		150 (114)	150 (114)		600 (114)	450 (114)
		150 (115)	150 (115)		450 (115)	150 (115)
Σ kVar	–	13,800	13,350	–	17,850	18,000
Total cost (US\$)	681,465.61	474,237.21	460,443.26	1,541,240.38	1,004,059.13	987,246.50
Saving (%)	–	30.41	32.43	–	34.85	35.94
Power factor	0.80	0.99	0.99	0.80	0.98	0.98
$V_{\min}$ (pu)	0.8688	0.9115	0.9086	0.7978	0.8457	0.8624
Σ Voltage deviation (pu)	5.2429	4.1267	4.1197	7.8518	6.1737	6.1223

Table 15: Simulation Results of the 118-Bus Distribution Network after SC Placement Using the PLI Approach.

Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	1296.55	921.17	908.98	2932.34	2021.86	2009.19
Loss reduction (%)	–	28.95	29.89	–	31.05	31.48
Capacitor size (location)	–	1800 (52)	1800 (52)	–	1800 (52)	1800 (52)
		1050 (70)	750 (70)		1800 (70)	1200 (70)
		150 (71)	150 (71)		150 (71)	300 (71)
		150 (72)	150 (72)		150 (72)	150 (72)
		150 (73)	300 (73)		150 (73)	600 (73)
		150 (74)	150 (74)		150 (74)	150 (74)
		150 (75)	150 (75)		150 (75)	150 (75)
		150 (76)	150 (76)		150 (76)	150 (76)
		150 (97)	900 (97)		150 (97)	900 (97)
		150 (98)	150 (98)		1800 (98)	600 (98)
		1800 (109)	1200 (109)		150 (109)	1650 (109)
		150 (110)	900 (110)		1800 (110)	1350 (110)
		150 (111)	150 (111)		1050 (111)	150 (111)
		150 (112)	150 (112)		150 (112)	150 (112)
		150 (117)	150 (117)		150 (117)	300 (117)
Σ kVar	–	6450	7200	–	9750	9600
Total cost (US\$)	681,465.61	505,481.88	499,114.88	1,541,240.38	1,084,528.37	1,077,756.89
Saving (%)	–	25.82	26.76	–	29.63	30.07
Power factor	0.80	0.91	0.92	0.8	0.91	0.91
$V_{\min}$ (pu)	0.8688	0.9087	0.9091	0.7978	0.8637	0.8641
Σ Voltage deviation (pu)	5.2429	4.3981	4.3595	7.8518	6.5039	6.5272

Table 16: Simulation Results of the 118-Bus Distribution Network after SC Placement Using the IVS Approach.

Particulars	Without load growth			With load growth		
	Uncompensated	Compensated		Uncompensated	Compensated	
		IPSO	GABC		IPSO	GABC
Total losses (kW)	1296.55	937.30	911.02	2932.34	2006.97	1994.78
Loss reduction (%)	–	27.71	29.73	–	31.56	31.97
Capacitor size (location)	–	1800 (50)	1500 (50)	–	1800 (50)	1500 (50)
		150 (51)	150 (51)		1050 (51)	1200 (51)
		150 (52)	150 (52)		150 (52)	150 (52)
		150 (53)	600 (53)		150 (53)	450 (53)
		150 (70)	900 (70)		1800 (70)	1500 (70)
		150 (71)	300 (71)		150 (71)	150 (71)
		150 (72)	150 (72)		150 (72)	150 (72)
		150 (73)	150 (73)		150 (73)	600 (73)
		150 (74)	150 (74)		150 (74)	150 (74)
		150 (75)	150 (75)		150 (75)	150 (75)
		150 (76)	150 (76)		150 (76)	150 (76)
		1800 (109)	1200 (109)		1800 (109)	1500 (109)
		150 (110)	900 (110)		1800 (110)	1350 (110)
		150 (111)	150 (111)		150 (111)	300 (111)
		150 (112)	150 (112)		150 (112)	150 (112)
Σ kVar	–	5550	6750	–	9750	9450
Total cost (US\$)	681,465.61	513,794.74	500,078.34	1,541,240.38	1,076,700.16	1,070,222.56
Saving (%)	–	24.60	26.62	–	30.14	30.56
Power factor	0.80	0.89	0.91	0.8	0.92	0.91
$V_{\min}$ (pu)	0.8688	0.8923	0.9079	0.7978	0.8572	0.8615
Σ Voltage deviation (pu)	5.2429	4.4723	4.3515	7.8518	6.4728	6.4538

**Figure 4:** Convergence Characteristic Performance of GABC and IPSO.

(A) For 34 buses without load growth. (B) For 34 buses with load growth. (C) For 118 buses without load growth. (D) For 118 buses with load growth.

is reduced significantly and, thereby, it improves the voltage level and power factor, and reduces the total voltage deviation and increment in net annual saving with and without considering load growth. To check the viability and feasibility of the proposed methodology, it has been compared to other implemented optimization algorithms. Moreover, the numerical outcomes also have been compared with those of the other intelligence techniques that are available in the published literature to show the effectiveness of the proposed technique.

Nomenclature

K_{PL}	Power loss constant (0.06 kWh)
P_{loss}	Active power loss
T_i	Annual load duration (8760 h)
N_B	Number of buses
K_j^c	Capacitor purchase cost (\$/kVAr)
br	Number of distribution segments
Q_j^c	Size of capacitor (kVAr)
C_{inst}	Capacitor installation cost (US\$1000)
C_{opr}	Capacitor operation and maintenance cost (US\$300)
P_{i+1} and Q_{i+1}	Active and reactive power flow at $(i+1)^{th}$ bus
$R_{i,i+1}$	Resistance between i^{th} and $(i+1)^{th}$ bus
V_i	Voltage of i^{th} bus
$X_{i,i+1'}$	Reactance between i^{th} and $(i+1)^{th}$ bus
V_{i+1}	Receiving end voltage of $(i+1)^{th}$ bus
P_L and Q_L	Entire real (kW) and reactive (kVAr) network load
$I_{i,i+1}$	Current flow between i^{th} and $(i+1)^{th}$ bus
$I_{i,i+1}^{rated}$	Rated value of current between i^{th} and $(i+1)^{th}$ bus
S_{Br}	Set of all branches
$I_p(k)$ and $I_q(k)$	Real and imaginary current component for k^{th} branch
$Q_{eff}(i)$	Supply effective reactive power beyond bus i (pu)
$norm(i)$	Normalized voltage of i^{th} bus (pu)
$P_{i,i+1}^{line loss}$ and $Q_{i,i+1}^{line loss}$	Real and reactive power loss between i^{th} and $(i+1)^{th}$ bus
$PLI(i)$	Power loss index of i^{th} bus (pu)
$LR(i)$	Loss reduction of i^{th} bus
LR_{min} and LR_{max}	Minimum and maximum value of loss reduction
$IVS_{(i+1)}$	Index of voltage stability of $(i+1)^{th}$ bus (pu)
V_{rated}	Nominal rated voltage 1 pu
V_{min} and V_{max}	Minimum and maximum bus voltage limit
c_1 and c_2	Constant parameters
r_1, r_2	Random number
c_3	Dynamic acceleration constant
fit_k	Fitness value of every cycle
$P_{prob,i}$	Probability of food source

Bibliography

- [1] A. R. Abul'Wafa, Optimal capacitor placement for enhancing voltage stability in distribution systems using analytical algorithm and Fuzzy-Real Coded GA, *Int. J. Electr. Power Energy Syst.* **55** (2014), 246–252.

- [2] M. E. Baran and F. F. Wu, Optimal sizing of capacitors placed on a radial distribution system, *IEEE Trans. Power Delivery* **4** (1989), 735–743.
- [3] M. Chakravorty and D. Das, Voltage stability analysis of radial distribution networks, *Int. J. Elec. Power Energy Syst.* **23** (2001), 129–135.
- [4] J. -P. Chiou, C. -F. Chang and C. -T. Su, Ant direction hybrid differential evolution for solving large capacitor placement problems, *IEEE Trans. Power Syst.* **19** (2004), 1794–1800.
- [5] M. Chis, M. Salama and S. Jayaram, Capacitor placement in distribution systems using heuristic search strategies, *IET Gener. Transm. Dis.* **144** (1997), 225–230.
- [6] D. Das, Maximum loading and cost of energy loss of radial distribution feeders, *Int. J. Electr. Power Energy Syst.* **26** (2004), 307–314.
- [7] M. Delfanti, G. P. Granelli, P. Marannino and M. Montagna, Optimal capacitor placement using deterministic and genetic algorithms, *IEEE Trans. Power Syst.* **15** (2000), 1041–1046.
- [8] K. Devabalaji, K. Ravi and D. Kothari, Optimal location and sizing of capacitor placement in radial distribution system using Bacterial Foraging Optimization Algorithm, *Int. J. Electr. Power Energy Syst.* **71** (2015), 383–390.
- [9] R. C. Eberhart and J. Kennedy, A new optimizer using particle swarm theory, in: *Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, pp. 39–43, 1995.
- [10] A. El-Fergany, Optimal capacitor allocations using evolutionary algorithms, *IET Gener. Transm. Dis.* **7** (2013), 593–601.
- [11] A. A. El-Fergany, Involvement of cost savings and voltage stability indices in optimal capacitor allocation in radial distribution networks using artificial bee colony algorithm, *Int. J. Electr. Power Energy Syst.* **62** (2014), 608–616.
- [12] A. A. El-Fergany and A. Y. Abdelaziz, Efficient heuristic-based approach for multi-objective capacitor allocation in radial distribution networks, *IET Gener. Transm. Dis.* **8** (2014), 70–80.
- [13] A. A. El-Fergany and A. Y. Abdelaziz, Capacitor placement for net saving maximization and system stability enhancement in distribution networks using artificial bee colony-based approach, *Int. J. Electr. Power Energy Syst.* **54** (2014), 235–243.
- [14] A. El-Fergany and A. Y. Abdelaziz, Capacitor allocations in radial distribution networks using cuckoo search algorithm, *IET Gener. Transm. Dis.* **8** (2014), 223–232.
- [15] J. J. Grainger and S. Lee, Optimum size and location of shunt capacitors for reduction of losses on distribution feeders, *IEEE Trans. Power App. Syst.* **3** (1981), 1105–1118.
- [16] M. -R. Haghifam and O. Malik, Genetic algorithm-based approach for fixed and switchable capacitors placement in distribution systems with uncertainty and time varying loads, *IET Gener. Transm. Dis.* **1** (2007), 244–252.
- [17] M. Haque, Capacitor placement in radial distribution systems for loss reduction, *IET Gener. Transm. Dis.* **146** (1999), 501–505.
- [18] Y. -T. Hsiao, C. -H. Chen and C. -C. Chien, Optimal capacitor placement in distribution systems using a combination fuzzy-GA method, *Int. J. Electr. Power Energy Syst.* **26** (2004), 501–508.
- [19] Y. -C. Huang, H. -T. Yang and C. -L. Huang, Solving the capacitor placement problem in a radial distribution system using tabu search approach, *IEEE Trans. Power Syst.* **11** (1996), 1868–1873.
- [20] D. Kaur and J. Sharma, Multiperiod shunt capacitor allocation in radial distribution systems, *Int. J. Electr. Power Energy Syst.* **52** (2013), 247–253.
- [21] T. -Y. Lee and C. -L. Chen, Unit commitment with probabilistic reserve: an IPSO approach, *Energy Convers. Manag.* **48** (2007), 486–493.
- [22] C. -S. Lee, H. V. H. Ayala and L. dos Santos Coelho, Capacitor placement of distribution systems using particle swarm optimization approaches, *Int. J. Electr. Power Energy Syst.* **64** (2015), 839–851.
- [23] S. Mekhamer, S. Soliman, M. Moustafa and M. El-Hawary, Application of fuzzy logic for reactive-power compensation of radial distribution feeders, *IEEE Trans. Power Syst.* **18** (2003), 206–213.
- [24] V. Murthy and A. Kumar, Comparison of optimal DG allocation methods in radial distribution systems based on sensitivity approaches, *Int. J. Electr. Power Energy Syst.* **53** (2013), 450–467.
- [25] S. Nojavan, M. Jalali and K. Zare, Optimal allocation of capacitors in radial/mesh distribution systems using mixed integer nonlinear programming approach, *Electr. Power Syst. Res.* **107** (2014), 119–124.
- [26] K. Prakash and M. Sydulu, Particle swarm optimization based capacitor placement on radial distribution systems, in: *IEEE Power Engineering Society General Meeting*, pp. 1–5, 2007.
- [27] M. R. Raju, K. R. Murthy and K. Ravindra, Direct search algorithm for capacitive compensation in radial distribution systems, *Int. J. Electr. Power Energy Syst.* **42** (2012), 24–30.
- [28] R. S. Rao, S. Narasimham and M. Ramalingaraju, Optimal capacitor placement in a radial distribution system using plant growth simulation algorithm, *Int. J. Electr. Power Energy Syst.* **33** (2011), 1133–1139.
- [29] Y. M. Shuaib, M. S. Kalavathi and C. C. A. Rajan, Optimal capacitor placement in radial distribution system using gravitational search algorithm, *Int. J. Electr. Power Energy Syst.* **64** (2015), 384–397.
- [30] S. Sultana and P. K. Roy, Optimal capacitor placement in radial distribution systems using teaching learning based optimization, *Int. J. Electr. Power Energy Syst.* **54** (2014), 387–398.
- [31] S. Sundhararajan and A. Pahwa, Optimal selection of capacitors for radial distribution systems using a genetic algorithm, *IEEE Trans. Power Syst.* **9** (1994), 1499–1507.

- [32] K. Swarup, Genetic algorithm for optimal capacitor allocation in radial distribution systems, in: *Proceedings of the Sixth WSEAS International Conference on Evolutionary Computation, Lisbon, Portugal*, pp. 152–159, 2005.
- [33] G. Zhu and S. Kwong, Gbest-guided artificial bee colony algorithm for numerical function optimization, *Appl. Math. Comput.* **217** (2010), 3166–3173.