INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
K. S. Sambaiah and T. Jayabarathi, Vol.9, No.1, March, 2019

Optimal Allocation of Renewable Distributed Generation and Capacitor Banks in Distribution Systems using Salp Swarm Algorithm

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Received: 12.10.2018 Accepted: 19.11.2018

Abstract – Recent advances in power generation technologies using renewable energy resources, changes in utility infrastructure and government policies tend to increase the interest in a renewable-based distributed generation units (DGs) in a distribution system. To obtain reduced power loss, voltage deviation and improved bus voltage stability in distribution systems, it is mandatory to control optimal power flow of both active and reactive power. Therefore, optimal allocation of DGs and CBs plays a vital role in distribution systems performance enhancement. Where optimal allocation of DGs reduce active power loss and optimal allocation of capacitor banks (CBs) improve bus voltages. This paper proposes a salp swarm algorithm (SSA) for optimal allocation of DGs and CBs. The main aim of the proposed algorithm is to attain technical, economic and environmental benefits. The proposed algorithm is based on the salps swarming behavior in oceans when navigating and foraging. To assess the performance of the proposed SSA three different cases considered: optimal allocation of only DGs, only CBs and simultaneous DGs and CBs. The proposed algorithm is tested on IEEE 33 and 69 bus radial distribution systems. The simulated results illustrate the efficiency of the proposed algorithm when compared to other existing optimization algorithms. Also, the proposed algorithm has achieved technical benefits of reduced power loss, voltage deviation, and improved bus voltage stability, the economic benefit of reduced total electrical energy cost and environmental benefit of reduced emissions.

Keywords Salp swarm algorithm, Optimal DGs allocation, Capacitor banks, Distributed generation, Solar and wind DGs, Power loss, bus voltage improvement.

1. Introduction

Present scenario witness that the demand for electrical energy is rapidly increasing day by day due to population exploitation and urbanization. Traditional electrical energy production system utilizes fossil fuels. However, excess utilization of fossil fuels causes fuel exhaustion and affects the environment. Renewable energy technologies are emerging as a changeover from centralized to decentralized electric power generation with new initiatives and policies on renewable energy across the world. Due to unpredicted changes in electric power demand, distribution facilities inadequacy and various techno-economic constraints renewable based distributed generation units (DGs) are utilized to generate electric power. Moreover, the integration of DGs into an existing power distribution network has technical, economic and environmental benefits. The significant impacts of DGs integration are reported to be rising due to deregulation of the electricity market.

Optimal allocation of DGs has technical benefits of reduced power loss and bus voltage deviation, environmental benefits of reduced pollution and system emissions, and economic benefits of reduced operational cost. Where non-optimal allocation causes power quality issues, creates harmonics, exceed bus voltage limits and increase power loss [1]. Integration of CBs in a distribution network produces reactive power that improves bus voltages of load buses and reduces power losses. Thus, the essential reactive power drawn from the substation or main grid is reduced. Some type of DGs causes voltage fluctuations in the network these can be reduced by effective utilization of (fixed-switched) CBs [2,3].

Therefore, the integration of both DGs and CBs reduce line power losses, improve bus voltages and thereby the overall distribution network performance enhances. To achieve the aforementioned benefits appropriate allocation of DGs and CBs is need to be investigated and a suitable optimization tool has to be chosen [4]. Various techniques have been implemented for solving optimal distributed generation units (ODGs) allocation problem in distribution networks. In [5], authors have proposed a new analytical method and a fuzzy logic for ODGs allocation in distribution networks with minimization of real power loss as the main objective. Moradi et al. [6] describe a novel algorithm which is a combination of genetic algorithm (GA) and particle swarm optimization (PSO) is used for ODGs allocation in distribution networks for network loss minimization. A meta-heuristic harmony search algorithm (HSA) is proposed to solve the ODGs allocation problem considering loss minimization as an objective [7]. An exhaustive search algorithm (ESA) has been proposed for single and multiple ODGs allocations for minimization of both active and reactive power losses [8]. Rama et al. [9] have proposed a loss sensitivity factor (LSF) analysis for finding the DGs location and nature-inspired intelligent water drop (IWD) optimization algorithm is used for DGs size.

Mohamed et al. [10] have considered various load models while solving ODGs allocation problem in which they used LSF for DGs location and a bacterial foraging optimization algorithm (BFOA) is used for DGs size. In [11], a hybrid optimization algorithm is proposed for ODGs allocation which is a combination of ant colony optimization (ACO) and artificial bee colony (ABC) as a multi-objective optimization technique. Murthy et al. [12] proposed a new voltage stability index technique for single ODGs allocation in presence of load growth. In [13], a new backtracking search optimization algorithm (BSOA) based on swarm intelligence with a single control parameter is proposed for ODGs allocation in a radial distribution system (RDS). In [14], authors have proposed bat algorithm (BA) for solar photovoltaic (SPV) system allocation and intermittent generation pattern of solar irradiance is modeled using an appropriate probabilistic distribution function. In [15], authors have presented a loss sensitivity factor (LSF) analysis for finding the DGs location and an invasive weed optimization (IWO) algorithm for DGs size. Satish et al. [16] proposed a multiple DG allocation technique which is a combination of PSO and improved analytical method. In [17], a new hybrid grey wolf optimizer (HGWO) is used for optimal allocation of various DG types (based on power injected from the DGs) with power loss minimization as an objective. Chithradevi et al. [18] proposed a new meta-heuristic optimization algorithm called stud krill herd algorithm (SKHA) is used for ODGs allocation in distribution networks.

Optimal capacitor banks (OCBs) allocation in distribution networks offers various technical benefits like reducing the cost of power losses, energy losses and improves power quality in the presence of voltage and current harmonics [19].

Several optimization techniques have been employed for solving OCBs allocation problem such as analytical, classical/numerical, heuristic/meta-heuristic and artificial intelligence methods [20]. Prakash et al. [21] have proposed LSF analysis gives a sequence of nodes potential for finding the OCBs location and PSO algorithm is used for OCBs size. In [22], along with LSF, a plant growth simulation algorithm (PGSA) which is free from parameter tuning is proposed for OCBs sizing. A clustering-based optimization (CBO) algorithm creates a simple search which iteratively loops on system buses and allocates CBs optimally to minimize the overall cost of power/energy and CBs is proposed in [23].

Ahmed et al. [24] proposed an analytical method for ranking the system buses based on voltage stability index (VSI) and a fuzzy real coded GA for OCBs sizing for achieving the maximum net money savings on power/energy loss and CBs expenditure. In [25] a combination of LSF and VSI is used for OCBs location and a BFOA technique is proposed for OCBs sizing in a load varying environment. A combination of two bio-inspired algorithms are BA and cuckoo search (CS) are proposed for OCBs allocation with network power loss reduction and maximization of net savings in [26]. Sneha et al. [27] proposed teaching and learning based optimization (TLBO) algorithm is used for OCBs allocation and to achieve minimized cost of power/energy loss. Reduction of power losses and capacitor costs as the main objective in [28] author proposed PSO algorithm for OCBs allocation based on various operators such as Gaussian, Cauchy probability distribution functions and a chaotic load pattern sequences of the distribution system. Mohamed et al. [29] have proposed LSF which reduce the search space and to attain at the accurate location for CBs and gravitational search algorithm (GSA) is used for OCBs size. In [30], a newly developed crow search algorithm (CSA) is proposed for solving the OCBs allocation problem in the distribution network.

Mohamed et al. [31] used LSF for obtaining the location of combined DGs and CBs and BFOA is used for obtaining ODGs and OCBs sizing. Saonerkar et al. [32] proposed GA for obtaining the optimal allocation of combined DGs and CBs in distribution networks. In [33], intersect mutation differential evolution (IMDE) algorithm is proposed for simultaneous allocation of DGs and CBs considering current flow in safe operating limits. Partha et. al. [34] proposed an evolutionary algorithm based on decomposition (EA/D) for combined allocation of DGs and CBs with reduced power loss and maintaining distribution system reliability as a multi-objective optimization. In [35], the author proposed Gbest-guided ABC (GABC) for simultaneous allocation of DGs and CBs in a distribution network with a varying load demand. Advantages of renewable energy resources based DG allocation and modeling techniques have been presented in [41 – 48].

Adel et al. [36] proposed a water cycle algorithm for simultaneous allocation of DGs and CBs in the distribution network and to obtain techno-economic and environmental benefits. Summary of various methods for optimal DGs and

CBs allocation in distribution systems is presented in Table 1.

Table 1
Summary of various methods for optimal DGs and CBs allocation in distribution systems

Author(s) [Ref]	Objective Function(s)	Method	Benefits	DGs / CBs	Test system	Year
Injeti et. al. [5]	Minimization of real power loss	Analytical and Fuzzy	Technical	DGs	33 and 69 bus	2011
Moradi et. al. [6]	Minimization of network power losses, improve voltage stability and achieve better voltage regulation	GA / PSO	Technical	DGs	33 and 69 bus	2012
Rao et. al. [7]	Minimization of real power loss	HSA	Technical	DGs	33 and 69 bus	2013
Mahmoud et. al. [8]	Minimization of real and reactive power loss	ESA	Technical	DGs	6, 14 and 30 bus	2015
Prabha et. al. [9]	Minimization of total line losses	LSF and IWD	Technical	DGs	10, 33 and 69 bus	2015
Mohammed et. al. [10]	Minimization of network power loss and operational costs	LSF and BFOA	Technical and Economic	DGs	33 and 69 bus	2014
Kefayat et. al. [11]	Minimization of power losses, total energy cost, and total emissions	ACO-ABC	Technical, Economic and Environmental	DGs	33 and 69 bus	2015
Murthy et. al. [12]	Minimization of power losses, total energy cost, and total emissions	New VSI	Technical, Economic and Environmental	DGs	12, 69 and 85 bus	2015
Attia et. al. [13]	Minimization of real power loss	BSOA	Technical	DGs	33 and Portuguese 94 bus	2015
Suresh et. al. [14]	Minimization of power loss	BA	Technical	DGs	33 bus	2016
Prabha et. al. [15]	Minimization of real power loss	LSF and IWO	Technical	DGs	33 and 69 bus	2016
Satish et. al. [16]	Minimization of power loss	PSO	Technical	DGs	33 and 69 bus	2016
Sanjay et. al. [17]	Minimization of power loss	HGWO	Technical	DGs	33, 69 and Indian 85 bus	2017
ChithraDevi et. al. [18]	Minimization of line losses	SKHA	Technical	DGs	33, 69 and Portuguese 94 bus	2017
Prakash et. al. [21]	Minimization of active power loss	LSF and PSO	Technical	CBs	10, 15, 34, 69 and 85 bus	2007
Rao et. al. [22]	Minimization of power loss	PGSA	Technical	CBs	10, 34 and 85 bus	2011
Jovica et. al. [23]	Minimization of power losses and total energy cost	CBO	Technical and Economic	CBs	22, 34, 69 and 85 bus	2014
Ahmed et. al. [24]	Minimization of power losses and total energy cost	LSF and Fuzzy real coded GA	Technical and Economic	CBs	33 bus	2014
Devabalaji et. al. [25]	Minimization of power loss	LSF and VSI with BFOA	Technical	CBs	34 and 85 bus	2015
Injeti et. al. [26]	Minimization of power loss and maximization of net savings	BA and CS	Technical and Economic	CBs	34 and 85 bus	2015
Sultana et. al. [27]	Minimization of power losses and total energy cost	TLBO	Technical and Economic	CBs	22, 69, 85 and 141 bus	2014
Chu-Sheng et. al. [28]	Minimization of energy loss and total energy cost	PSO	Technical and Economic	CBs	9 bus	2015
Shuaib et. al. [29]	Minimization of power loss and maximization of net savings	LSF and GSA	Technical and Economic	CBs	33 and 69 bus	2015
Alireza et. al. [30]	Minimization of power loss and maximization of net savings	CSA	Technical and Economic	CBs	33 and 69 bus	2016
Mohamed et. al. [31]	Minimization of real power loss	BFOA	Technical	DGs and CBs	33 bus	2014
Saonerkar et. al. [32]	Minimization of power loss	GA	Technical	DGs and CBs	33 bus	2014
Amin et. al. [33]	Minimization of power loss	IMDE	Technical	DGs and CBs	33 and 69 bus	2016
Partha et. al. [34]	Minimization of power loss	EA/D	Technical	DGs and CBs	33, 69, 119 and practical 83 bus	2017
Mukul et. al. [35]	Minimization of power loss	GABC	Technical	DGs and CBs	33 and 85 bus	2017
Adel et. al. [36]	Minimization of power losses, total energy cost, and total emissions	WCA	Technical, Economic and Environmental	DGs and CBs	33 and 69 bus	2018

The present study proposes the salp swarm algorithm (SSA) to obtain the optimal allocation of simultaneous DGs and CBs in the distribution network. The major contribution of the present paper is realized as follows:

i.) Studying the integration of renewable DGs and CBs in the distribution network and to enhance the technical, economic and environmental benefits.
ii.) Three technical objectives that satisfied are: reducing power loss, voltage deviation and improving bus voltage stability.
iii.) Two economic issues considered as two objectives as minimization of generated power costs and cost of CBs.
iv.) Another major objective is the environmental benefit of emission reduction with the clean operation.
v.) Three operational cases considered here are only DGs, only CBs and simultaneous allocation of DGs and CBs in distribution network using SSA.
vi.) Proposed SSA is applied to real and standard distribution systems.

This paper is structured as follows: Section 2 provides the problem formulation. Proposed SSA for solving optimal DGs and CBs allocation problem is presented in section 3. Simulation results obtained by the proposed method applied on two standard distribution systems and discussion is presented in section 4. The conclusion of the present paper is outlined in section 5.

2. Problem Formulation

The objective functions (OFs), operational equality and inequality constraints that need to be satisfied for optimal DGs and CBs allocation in distribution networks as follows.

2.1. Objective functions

The proposed technique aims to achieve three OFs that are technical, economic and environmental OFs.

2.1.1. *Technical OF*

In this section, the three technical OFs are considered. The aim of the first objective (f_1) is to minimize the network total real power loss (P^{Tloss}). Fig. 1 shows the RDS single line diagram (SLD) with N_{bus} number of buses and the main feeder.

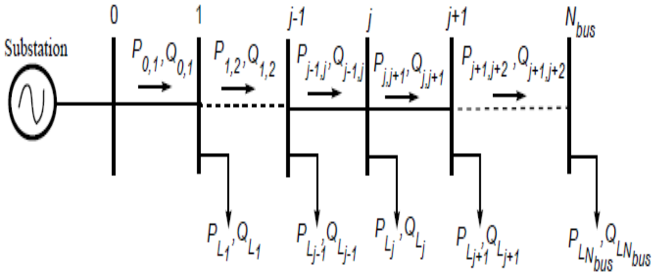


Fig. 1. SLD of an RDS [17]

The real and the reactive power loss in the line section between j and $j+1$ buses, can be expressed by the formula [17]:

$$P^{loss}_{j,j+1} = \frac{P^2_{j,j+1}+Q^2_{j,j+1}}{|V_j|^2} R_{j,j+1} \tag{1}$$

$$Q^{loss}_{j,j+1} = \frac{P^2_{j,j+1}+Q^2_{j,j+1}}{|V_j|^2} X_{j,j+1} \tag{2}$$

$$P^{Tloss} = \sum_{j=0}^{N_{bus}-1} \frac{P^2_{j,j+1}+Q^2_{j,j+1}}{|V_j|^2} R_{j,j+1} \tag{3}$$

$$f_1(x) = min\ (P^{Tloss}) \tag{4}$$

The aim of the second objective (f_2) is to minimize the voltage deviation that can be expressed as [10]:

$$f_2(x) = min\left(\frac{V_1 - V_j}{V_1}\right) \forall\ j = 2, \dots, N_{bus}\ and\ V_1 = 1.05 \tag{5}$$

As mentioned above voltage stability index (VSI) is one of the most significant indices which is here the third objective (f_3) that can be expressed as [11]:

$$VSI_j = |V_1|^4 - 4\left[P_j * X_j - Q_j * R_j\right]^2 - 4\left[P_j * X_j + Q_j * R_j\right]|V_1|^2 \tag{6}$$

$$f_3(x) = min\left(\frac{1}{VSI_j}\right) \tag{7}$$

2.1.2. *Economic OF*

The power generation costs minimization is considered as economic OF (f_4) that can be expressed as [11] and [2]:

$$f_4(x) = min\left(C_{sub} + C_{CB} + \sum_{i=1}^{T_{DG}} C_{DG,i}\right) \tag{8}$$

where,

$$C_{sub} = P_{G,grid} * Price_{grid} \tag{9}$$

$$C_{CB} = \frac{\sum_{i=1}^{Tcap}(e_i + C_{cap,i}|Q_{cap,i}|)}{lifetime*8760} \tag{10}$$

$$C_{DG,i} = a + b \tag{11}$$

$$a = \frac{capital\ cost * capacity * P_{DG,i}}{lifetime*8760*LF} \tag{12}$$

$$b = (fuel\ cost + O\&M\ cost) * P_{DG,i} \tag{13}$$

2.1.3. *Environmental OF*

The most frequently produced pollutants by the grid and other forms of DGs (non-renewable) are carbon dioxide (CO_2), Sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Therefore, minimization of pollutants emission is an environmental objective (f_5) and that can be expressed as:

$$f_5(x) = min\left(\sum_{i=1}^{T_{DG}}(E_i^{DG}) + E^{grid}\right) \tag{14}$$

$$E_i^{DG} = (CO_2^{DG} + SO_2^{DG} + NO_x^{DG}) * P_{DG,i} \tag{15}$$

$$E^{grid} = \left(CO_2^{grid} + SO_2^{grid} + NO_x^{grid}\right) * P_{G,grid} \tag{16}$$

2.2. *Constraints*

In order to perform optimal DGs and CBs allocation in the distribution network, the system needs to satisfy certain security constraints. The mathematical representation of those constraints is presented in the following subsections.

2.2.1. *Equality constraints*

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

$$P_{demand} = \sum_{i=1}^{T_{DG}} P_{DG,i} + P_{G,grid} \tag{17}$$

$$Q_{demand} = \sum_{i=1}^{T_{DG}} Q_{DG,i} + Q_{G,grid} \tag{18}$$

2.2.2. *Inequality constraints*

2.2.2.1. *Bus voltage limits*

The bus voltage at each bus (V_j) must be within the specified limits i.e., minimum and maximum bus voltage limits are *0.95* and *1.05 p.u.*

$$0.95 \le V_j \le 1.05\ ; \tag{19}$$

2.2.2.2. *Capacitor installation limits*

The total reactive power generated from the CBs (Q^{CB}_{total}) must be less than total reactive power demand of the distribution system (Q_{demand}).

$$Q^{CB}_{total} < Q_{demand} \tag{20}$$

2.2.2.3. *Generation operation limits*

The real and reactive power generated is within the specified limits.

$$P_{DG,i}^{min} < P_{DG,i} < P_{DG,i}^{max} \; ; \; Q_{DG,i}^{min} < Q_{DG,i} < Q_{DG,i}^{max} \tag{21}$$

2.2.2.4. *Operating power factor limits of DGs*

The operating power factor of DGs must be within the limits to minimize losses.

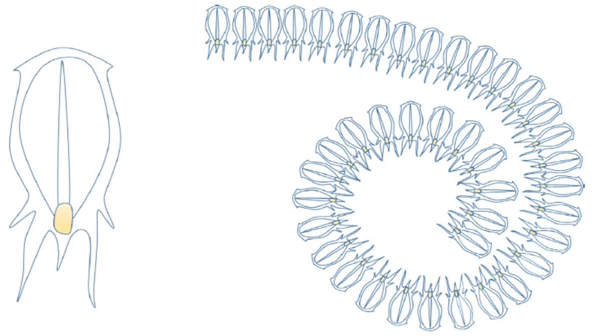
$$0.8 \leq PF \leq 1 \tag{22}$$

3. Proposed Salp Swarm Algorithm

3.1. *Salp swarm algorithm*

In 2017 Mirjalili et al. [37] proposed salp swarm algorithm. It is inspired by navigating and foraging behavior of salps in oceans. The structure of the salp is shown in Fig. 2(a). Salps often used to swarm in deep oceans called salp chain. This salp chain is illustrated in Fig. 2(b). The main reason for this salp chain behavior is to achieve better locomotion using quick coordinated variations and foraging.

For mathematically modeling the salp chains, firstly the population has to be divided into two groups: leader and the followers. The leader salp is in front of the salp chain, remain salps are treated as followers. The leader guides the follower's salps to follow each other.



(a) (b)

Fig. 2. (a) Single salp, (b) salp swarming (salp chain) [37]

Same as other swarm-based methods, the location of the salps is well-defined in n-dimensional search space where n is the variable number of a specified problem. Hence, the location of all salps is saved in a two-dimensional matrix called *X*. It is also considered that in the search space there is a food source called *F* as the swarm's target. The following equation is proposed to update the location of the leader:

$$X_d^1 = \begin{cases} F_d + C_1\left((ub_d - lb_d)C_2 + lb_d\right), & C_3 \geq 0 \\ F_d - C_1\left((ub_d - lb_d)C_2 + lb_d\right), & C_3 < 0 \end{cases} \tag{23}$$

where, X_d^1 is the first salp (leader) location in the d^{th} dimension, F_d is the food source location in the d^{th} dimension, lb_d and ub_d indicates the lower and upper bounds of the d^{th} dimension, C_2 and C_3 are random numbers.

In the above Eq. (23), the leader only updates its location with respect to the food source. The most significant parameter in SSA is coefficient C_1which balances the exploration and exploitation is expressed as:

$$C_1 = 2 * e^{-\left(\frac{t}{T}\right)^2} \tag{24}$$

where T is the maximum number of iterations and t is the current iteration.

The parameter C_2 and C_3 are uniformly generated random in numbers in the interval [*0,1*]. Based on newton's law of motion the location of the followers is updated as:

$$X_d^i = \frac{1}{2}at_m^2 + v_0 t_m \tag{25}$$

where, $i \geq 2$, X_d^i represents the location of i^{th} follower salp in the d^{th} dimension, t_m is time, initial speed is $v_{the\,0}$.

However, the time in the above Eq. (25) is iterations, and the above Eq. (25) can be re-written as follows:

$$X_d^i = \frac{1}{2}\left(X_d^i + X_d^{i-1}\right) \tag{26}$$

where $i \geq 2$, X_d^i represents the location of i^{th} follower salp in the d^{th} dimension.

With Eqs. (23) and Eq. (26), the salp chain is simulated.

The sequence of steps required to solve an optimization problem using SSA is shown below:

Step 1: Generate the initial population of the salps as *X* considering lower and upper bounds.

$$X = \begin{bmatrix} x_1^1 & x_2^1 \cdots & \cdots & x_d^1 \\ x_1^2 & x_2^2 \cdots & \cdots & x_d^2 \\ \vdots & \vdots \,\vdots\vdots & \vdots\vdots & \vdots \\ \vdots & \vdots & & \vdots \\ x_1^n & x_2^n \cdots & \cdots & x_d^n \end{bmatrix} \tag{27}$$

Step 2: Calculate the fitness of each salp, and find the best salp location towards the food source. Assign salp with the best location as a leader which helps followers to attain targeted food source.

Step 3: The coefficient of C_1 change its value for every iteration using Eq. (24). The location of the leader salp is updated using Eq. (23) and the follower salps location is updated using Eq. (26) in every dimension.

Step 4: Any salp going out of the search region is brought back using the boundary conditions.
Step 5: Steps 2 – 4 repeated until reaching the satisfactory end criterion ($iter < iter_{max}$).

Step 6: Overall best (optimal) solution is the final solution.

3.2. *Implementation of proposed SSA for optimal DGs and CBs allocation*

Step 0: Initialize the search agents, the maximum number of iterations, the total number of dimensions which gives location and size of DGs and CBs. Generate the initial search agents of a size which satisfies all the constraints listed in section 2.2. Thus, the solution set of simultaneous DGs and CBs allocation is formulated as follows:

$$X = \begin{bmatrix} l_1^1 & l_2^1 & l_3^1 & DG_1^1 & DG_2^1 & DG_3^1 & l_1^1 & l_2^1 & l_3^1 & CB_1^1 & CB_2^1 & CB_3^1 \\ l_1^2 & l_2^2 & l_3^2 & DG_1^2 & DG_2^2 & DG_3^2 & l_1^2 & l_2^2 & l_3^2 & CB_1^2 & CB_2^2 & CB_3^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ l_1^n & l_2^n & l_3^n & DG_1^n & DG_2^n & DG_3^n & l_1^n & l_2^n & l_3^n & CB_1^n & CB_2^n & CB_3^n \end{bmatrix}$$
(28)

Step 1: Input the test system data which includes the bus and line data. Calculate the load flow of the entire system using load flow study program [38].

Step 2: Run the load flow study program and calculate power loss for each search agent generated. Evaluate the fitness value using the Eq. (4). Calculate the best search agent position using the Eq. (23) for the first iteration.

Step 3: Update the value of C_1 using the Eq. (24). For each and every iteration update location of leader salp and follower salp by Eq. (23) and Eq. (26).

Step 4: Adjust the salps variables based on upper and lower bounds. Calculate the best fitness value (objective function).

Step 5: Check for the stopping criterion. If yes display the fitness (objective function) value and corresponding values of DGs and CBs location and sizes. Otherwise, repeat the steps 1 to 4.

The implementation of the proposed SSA for optimal DGs and CBs allocation in distribution system flowchart is shown in Fig. 3.

4. Simulation Results and Discussion

The load flow analysis is carried out by BIBC method proposed by Teng et al. [38] in 2003. The proposed SSA is applied to two distribution networks. These are IEEE 33-bus system with the real and reactive power demand of 3,715 kW and 2,300 kVAr having the base case power loss of 202.6 kW [39] and IEEE 69-bus system with the real and reactive power demand of 3,802 kW and 2,694 kVAr having the base case power loss of 225 kW [40]. The algorithm parameters initialized for both the test systems are common (i.e. population size is 1000 and number of search agents is 50). Load flow analysis is carried out in MATLAB® environment in the personal computer with 8 GB RAM and i7 intel processor configured. The proposed SSA is developed for optimal DGs and CBs allocation in the distribution network.

4.1. Case studies

The proposed SSA is tested for four different cases to illustrate the proposed method effectiveness and to study the impact of DGs and CBs integration in the network performance.

Case 1: Power loss minimization as single OF, considering only optimal DGs allocation.

Case 2: Power loss minimization as single OF, considering only optimal CBs allocation.

Case 3: Power loss minimization as single OF, considering optimal DGs and CBs allocation simultaneously.

Case 4: Multiobjective optimal allocation of DGs and CBs. Three technical objectives (f_1, f_2, f_3) are considered. A weighted aggregation technique is utilized for implementing the multiobjective function (MOF).

$$OF = \min\,(w_1 * f_1 + w_2 * f_2 + w_3 * f_3) \qquad (29)$$

Case 5: Multiobjective optimal allocation of DGs and CBs. MOF is used to optimize the technical, economic and environmental benefits (f_1, f_4, f_5). Therefore, the MOF is formulated as follow:

$$OF = \min\,(w_1 * f_1 + w_2 * f_4 + w_3 * f_5) \qquad (30)$$

where, $w_1 + w_2 + w_3 = 1$ (31)

The properties like economic and environmental are depended on DG types. The characteristics of the grid and the different DGs are presented in Table 2 [36]. However, to increase the DGs integration levels two types of DGs are considered (SPV and wind turbine (WT)). At the substation, the generated power cost is considered as 0.044 $/kWh [11]. The corresponding values of e_i is 1000 and $C_{cap,i}$ is 30,000 $/Mvar, respectively [2].

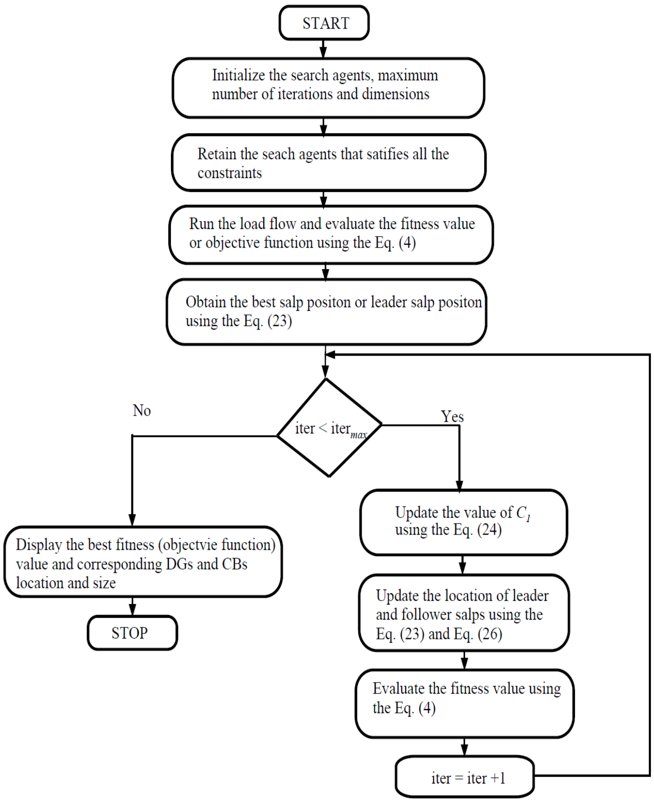


Fig. 3. Flowchart of the proposed SSA for optimal DGs and CBs allocation.

Table 2. Grid and DGs characteristics [36]

DG type	Capacity (MW)	Installation cost ($/kW)	Fuel cost ($/kWh)	O & M cost ($/kWh)	Life-time (years)	Emission factors (lb/MWh)		
						CO_2	SO_2	NO_x
Grid	25	-	0.044	-	25	2031	11.6	5.0
SPV	1	3985	-	0.01207	20	-	-	-
WT	5	1822	-	0.00952	20	-	-	-

4.2. IEEE 33-bus system

The results of case 1 are presented in Table 3 where the optimal DGs allocation is determined using the proposed SSA. The three DGs of size 753.6, 1100.4 and 1070.6 kW are allocated at buses 13, 23 and 29, respectively. The results obtained for this case are compared with other existing optimization techniques. The obtained results show the effectiveness of the proposed SSA in finding optimal DGs allocation. The proposed SSA achieved the total real power loss reduction to be 71.456 kW and a reduction of 131.144 kW (64.73%) compared to the base case. The minimum value of voltage (0.9686) is obtained on bus 33.

Table 3. Optimal DGs allocation in the 33-bus system (case 1)

Optimization technique	DGs size (kW) and location	Power loss (kW)	Min. voltage (*p.u.*)
Fuzzy and analytical [5]	2590 (6)	111	0.9423 (18)
GA [6]	1500 (11), 422.8 (29), 1071.4 (30)	106.3	0.981 (25)
PSO [6]	1176.8 (8), 981.6 (13), 829.7 (32)	105.35	0.980 (30)
GA/PSO [6]	925 (11), 863 (16), 1200 (32)	103.4	0.980 (25)
HSA [7]	572.4 (17), 107 (18), 1046.2 (33)	96.76	0.967 (29)
IWD [9]	600.3 (9), 300 (16), 1011.2 (30)	85.78	0.9696 (30)
BFOA [10]	633 (17), 90 (18), 947 (33)	98.3	0.964
ACO-ABC [11]	754.7 (14), 1099.9 (24), 1071.4 (30)	75.4	0.9735
BSOA [13]	632 (13), 487 (28), 550 (31)	89.05	0.9554
BA [14]	816.3 (15), 952.35 (25), 952.35 (30)	75.05	0.98 (18)
IWO [15]	624.7 (14), 104.9 (18), 1056 (32)	85.86	0.9716 (29)
PSO and analytical [16]	790 (13), 1070 (24), 1010 (30)	72.89	NA
HGWO [17]	802 (13), 1090 (24), 1054 (30)	72.784	NA
SKHA [18]	801.8118 (13), 1091.385 (24), 1053.6346 (30)	72.785	0.9687 (33)
WCA [36]	854.6 (14), 1101.7 (24), 1181 (29)	71.052	0.973 (33)
SSA	**753.6 (13), 1100.4 (23), 1070.6 (29)**	**71.456**	**0.9686 (33)**

Table 4 presents the optimal results of case 2. The proposed SSA is used to obtain optimal CBs allocation. The bus locations for CBs installation are 10, 23 and 29 with their corresponding sizes of 450, 450 and 1050 kVAr, respectively.

However, the size of the CBs is considered here as multiple of 150. The results obtained for case 2 from the proposed SSA is compared with other existing techniques. The results show the proposed SSA efficiency in finding optimal CBs allocation. The proposed SSA achieved the total real power loss reduction to be 132.3588 kW and a reduction of 70.2412 kW (34.67%) compared to the base case. The minimum value of voltage (0.9366) is obtained on bus 18.

Table 4. Optimal CBs allocation in the 33-bus system (case 2)

Optimization technique	CBs size (kVAr) and location	Power loss (kW)	Min. voltage (*p.u.*)
GSA [29]	450 (13), 800 (15), 350 (26)	134.5	0.9672
CSA [30]	600 (11), 300 (33), 450 (24), 600 (30)	131.5	0.943
PSO [30]	900 (2), 450 (7), 450 (31), 300 (15), 450 (29)	132.48	0.945
BFOA [31]	349.6 (18), 820.6 (30), 277.3 (33)	144.04	0.936
IMDE [33]	475 (14), 1037 (30)	139.7	0.942 (18)
EA/D [34]	469 (12), 1057 (30)	135.74	0.9363 (18)
WCA [36]	397.3 (14), 451.1 (24), 1000 (30)	130.912	0.951 (18)
SSA	**450 (10), 450 (23), 1050 (29)**	**132.35**	0.9366 (18)

The results of case 3 is presented in Table 5 and that shows the superiority of proposed SSA for finding optimal DGs and CBs allocation simultaneously when compared to case 1 and 2. In case 3 three DGs are located at buses 13, 23 and 29 and three CBs are located at buses 13, 23 and 29, respectively. The proposed SSA achieved the total real power loss reduction to be 11.8 kW and a reduction of 190.8 kW (94.18%) compared to the base case. The minimum value of voltage (0.9918) is obtained on bus 7.

Table 5. Optimal DGs and CBs allocation in the 33-bus system (case 3)

Optimization technique	DGs size (kW) and location	CBs size (kVAr) and location	Power loss (kW)	Min. voltage (*p.u.*)
BFOA [31]	542 (17), 160 (18), 895 (33)	163 (18), 541 (30), 3 38 (33)	41.41	0.9783
GA [32]	250 (16), 250 (22), 500 (30)	300 (15), 300 (18), 300 (29), 600 (30), 300 (31)	71.25	0.971
IMDE [33]	1080 (10), 896.4 (31)	254.8 (16), 932.3 (30)	32.08	0.979 (25)
EA/D [34]	840 (13), 1140 (30)	453 (12), 1040 (30)	28.47	0.98 (25)
GABC [35]	1098 (28), 132 (29), 609 (30)	300 (16), 150 (17), 150 (18)	93.72	0.9629
WCA [36]	973 (25), 1040 (29), 563 (11)	465 (23), 565 (30), 535 (14)	24.688	0.980 (33)
SSA	**746.6 (13), 1078.9 (23), 1049.2 (29)**	**300 (13), 600 (23), 1050 (29)**	**11.8**	**0.9918 (7)**

The performance of the proposed algorithm for power loss minimization as a single objective for different cases with best, average and worst values of power loss and its standard deviation is presented in Table 6.

Table 6. Best, average and worst values of power loss achieved by the proposed algorithm (for 20 trail runs)

	Best	Average	Worst	Standard deviation
Case 1	**71.45**	71.45	71.45	0.00
Case 2	**132.35**	133.02	135.40	0.8917
Case 3	**11.8**	12.95	15.91	2.65

Table 7 shows the simultaneous DGs and CBs allocation for minimizing power loss and for evaluating the corresponding value of voltage deviation and inverse VSI. The bus voltage profile at each bus for different cases are compared and illustrated in Fig. 4. The convergence characteristics of the proposed algorithm are illustrated in Fig. 5. In addition, the allocation of DGs and CBs with adjustable power factor gives better results.

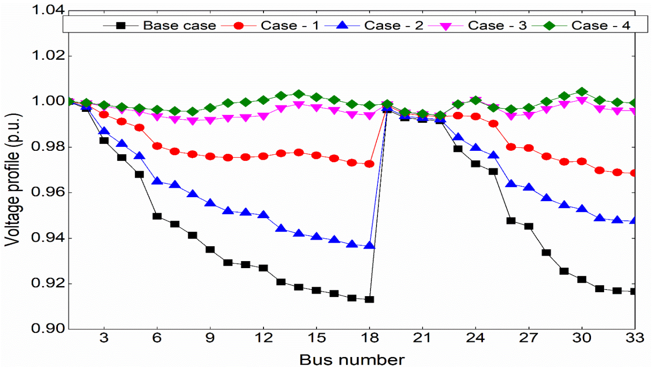


Fig. 4. Bus voltage profile at each bus in the 33 - bus system for different cases.

The technical, economic and environmental benefits of simultaneous DGs and CBs allocation in 33 – bus distribution network is presented in Table 8. Here, gas turbine (GT) is not considered. Obtained results illustrate the overall emission is reduced by 67.76% due to the integration of renewable DGs (SPV with 919.65 and 636.4; and WT with 894.34 kW. Also, the power loss is reduced by 19.62 kW and the power generation cost is reduced by 21.68%.

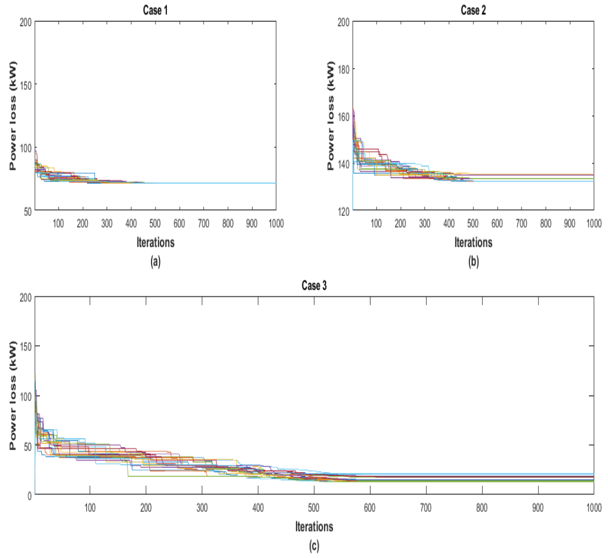


Fig. 5. Convergence characteristics of the proposed algorithm for 33 – bus system for (a) Only DGs (b) Only CBs (c) Simultaneous DGs and CBs allocation.

Table 7. Simultaneous DGs and CBs allocation for evaluating voltage deviation, and inverse VSI (case 4)

Optimization technique	Objective function			DGs size (kW) and location	DGs operating Power factor	CBs size (kVAr) and location	Min. voltage (*p.u.*)
	f_1 (kW)	f_2 (p.u.)	f_3 (p.u.)				
WCA [36]	19.848	0.041	0.015	991.7(11), 982.3(31), 1652 (24)	0.905 0.985 0.959	325 (19), 311.6 (23), 543.2 (30)	0.989 (18)
SSA	**12.70**	**0.086**	**0.0314**	**746.6 (13), 1078.1 (23), 1047.1 (29)**	**0.948 0.948 0.948**	**150 (1), 600 (3), 150 18)**	**0.9924 (33)**

Table 8. Simultaneous DGs and CBs allocation for evaluating technical, economic and environmental benefits (case 5)

		Grid	SPV	WT	GT	CB	Power loss (kW)	Cost ($/h)	Emission (lb/h)
Base case	Active (kW)	3715 (1)	-	-	-	-	202.6	304.8966	8.0267e+06
	Reactive (kVAr)	2300 (1)	-	-	-	-			
WCA [36]	Active (kW)	1541 (1)	639.7 (27) 714.9 (32)	647.6 (25)	200.8 (18)	-	28.9615	249.3429	3.4045e+06
	Reactive (kVAr)	657.2 (1)	277.6 (27) 438.5 (32)	146.7 (25)	51.6 (18)	300 (15) 0 (26) 450 (19)			
SSA	Active (kW)	1264 (1)	636.4 (13) 919.65 (23)	894.34 (29)	-	-	**19.62**	**238.8**	**2.5882e+06**
	Reactive (kVAr)	497 (1)	390.35 (13) 564.1 (23)	548.56 (29)	-	150 (11) 0 (29) 150			

						(23)			

4.3. IEEE 69-bus system

The results of case 1 and case 2 are presented in Table 9 and Table 10, respectively. It can be noticed from the results that the power loss obtained by proposed SSA is better than the other methods. The power loss obtained in case 1 is 69.41 kW and in case 2 is 145.365 kW. Here, power loss obtained in case 2 is little higher when compared to WCA. However, in [36] author considered CBs capacity as a continuously varying variable which is not possible in a practical scenario. The minimum value of bus voltage for case 1 and case 2 are 0.9789 and 0.9308 found at bus 65.

Table 9. Optimal DGs allocation in the 69-bus system (case 1)

Optimization technique	DGs size (kW) and location	Power loss (kW)	Min. voltage (*p.u.*)
Fuzzy and analytical [5]	1870 (61)	83.2	0.9091 (61)
GA [6]	929.7 (21), 1075.2 (62), 984.8 (64)	89	NA
PSO [6]	1199.8 (61), 795.6 (63), 992.5 (17)	83.2	NA
GA/PSO [6]	910.5 (21), 1192.6 (61), 884.9 (63)	81.1	NA
HSA [7]	1302.4 (63), 369 (64), 101.8 (65)	86.77	0.967*
BFOA [10]	295.4 (27), 447.6 (65), 1345.1 (61)	75.23	0.9808 (61)
HGWO [17]	527 (11), 380 (17), 1718 (61)	69.425	0.98*
WCA [36]	775 (61), 1105 (62), 438 (23)	71.5	0.987 (65)
SSA	**380 (17), 527 (10), 1718 (60)**	**69.41**	**0.9789 (65)**

Table 11 shows the case 3 results of simultaneous DGs and CBs allocation in the 69 bus system. In case 3, three DGs are allocated at buses 10, 19 and 60 with an active power generation capacity of 518, 358 and 1673.5 kW, respectively. In addition, three CBs are allocated at buses 11, 48 and 60 with the reactive power generation capacity of 600, 600 and 1200 kVAr, respectively. The power loss obtained by the proposed SSA is better than other existing techniques.

Table 10. Optimal CBs allocation in the 69-bus system (case 2)

Optimization technique	CB size (kVAr) and location	Power loss (kW)	Min. voltage (*p.u.*)
PSO [21]	241 (46), 365 (47), 1015 (50)	152.48	NA
CBO [23]	150 (12), 150 (16), 150 (21), 150 (59), 750 (61), 150 (62), 150 (64),	145.35	0.9305*
TLBO [27]	600 (12), 1050 (61), 150 (64)	146.35	0.9313 (65)
GSA [29]	150 (13), 150 (26), 1050 (15)	145.9	0.952*
WCA [36]	270 (18), 1288.2 (61), 213.4 (69)	144.53	0.95 (65)
SSA	**300 (17), 1200 (60), 300 (10)**	**145.26**	**0.9308 (65)**

Table 11. Optimal DGs and CBs allocation in the 69-bus system (case 3)

Optimization technique	DGs size (kW) and location	CBs size (kVAr) and location	Power loss (kW)	Min. voltage (*p.u.*)
IMDE [33]	479 (24), 1738 (62)	1192 (61), 109 (63)	13.83	0.9915 (68)
EA/D [34]	495 (11), 379 (18), 1675 (61)	375 (11), 230 (21), 1196 (61)	6.28*	0.9943 (50)
WCA [36]	540.8 (17), 2000 (61), 1159.2 (69)	1187.9 (2), 1237.3 (62), 269.7 (69)	33.339	0.994 (50)
SSA	**358 (19), 518 (10), 1673.5 (60)**	**600 (11), 600 (48), 1200 (60)**	**4.837**	**0.9971 (65)**

The performance of the proposed algorithm for power loss minimization as a single objective for different cases with best, average and worst values of power loss and its standard deviation is presented in Table 12.

Table 12. Best, average and worst values of power loss achieved by the proposed algorithm (for 20 trail runs)

	Best	Average	Worst	Standard deviation
Case 1	**69.41**	70.43	72.96	1.1590
Case 2	**145.26**	146.03	147.58	0.7819
Case 3	**4.837**	9.89	18.93	3.3585

Table 13 shows the simultaneous DGs and CBs allocation for minimizing power loss and evaluating the corresponding values of voltage deviation and inverse VSI. The bus voltage profile at each bus for different cases are compared and illustrated in Fig. 6. The convergence characteristics of the proposed algorithm are illustrated in Fig. 7. In addition, the allocation of DGs and CBs with adjustable power factor gives better results.

Table 13. Simultaneous DGs and CBs allocation for evaluating voltage deviation, and inverse VSI (case 4)

Optimization technique	Objective function			DGs size (kW) and location	DG operating Power factor	CBs size (kVAr) and location	Min. voltage (*p.u.*)
	f_1 (kW)	f_2 (p.u.)	f_3 (p.u.)				
WCA [36]	18.7048	0.0082	0.0313	106.3 (19), 1041.4 (36), 1824.7 (61)	0.877 0.916 0.904	18.8 (15), 457.8 (33), 558.6 (22)	0.994 (50)
SSA	**3.3876**	**0.0041**	**0.0149**	**508.3 (10),** **364.7 (18),** **1673.8 (60)**	**0.9963** **0.9963** **0.9963**	**3600 (2),** **150 (35),** **150 (36)**	**0.9965 (64)**

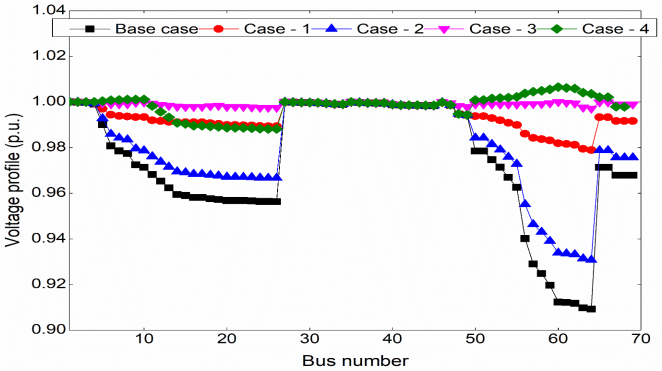


Fig. 6. Bus voltage profile at each bus in the 69 - bus system for different cases.

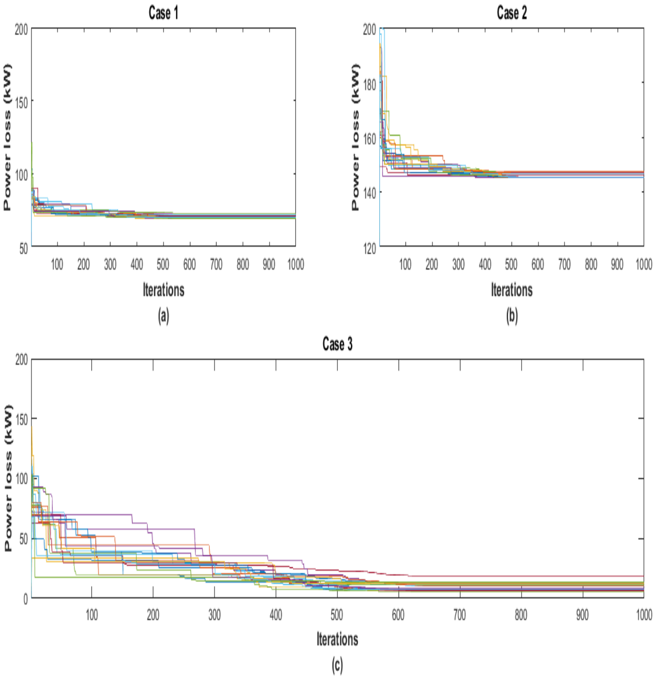


Fig. 7. Convergence characteristics of the proposed algorithm for 69 – bus system for (a) Only DG (b) Only CBs (c) Simultaneous DG and CBs allocation.

The technical, economic and environmental benefits of simultaneous DGs and CBs allocation in 69 – bus distribution network is presented in Table 14. Obtained results illustrate the overall emission is reduced by 57.75% and production cost is reduced from 309.7134 to 261.48 $/h.

Table 14. Simultaneous DGs and CBs allocation for evaluating technical, economic and environmental benefits (case 5)

		Grid	SPV	WT	GT	CB	Power loss (kW)	Cost ($/h)	Emission (lb/h)
Base case	Active (kW)	3,802 (1)	-	-	-	-	225	309.7134	8.2508e+06
	Reactive (kVAr)	2694 (1)	-	-	-	-			
WCA [36]	Active (kW)	1746.7 (1)	102.4 (58) 731.4 (66)	703 (63)	540.5 (64)	-	22.36	297.47	4.247e+06
	Reactive (kVAr)	294.6 (1)	35.2 (58) 291.3 (66)	274.2 (63)	313 (64)	600 (23) 600 (62) 300 (42)			
SSA	Active (kW)	1702.6 (1)	729.76 (17) 665.38 (49)	704.8 (60)	-	-	**6.062**	**261.48**	**3.4863e+06**
	Reactive (kVAr)	366 (1)	324.945 (17) 407.785 (49)	244.8 (60)	-	150 (3) 600 (11) 600 (60)			

The line power losses in 33 and 69 bus system for different cases are illustrated in Figs. 8 – 9, respectively. The line power loss is reduced drastically from base case to case – 4 due to optimal DGs and CBs allocation with adjustable power factor.

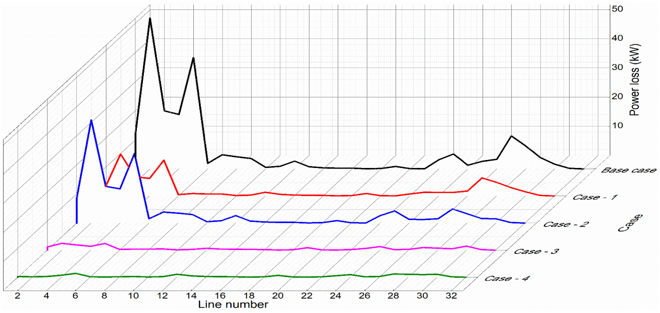


Fig. 8. Illustration of line power loss in IEEE 33-bus system for different cases.

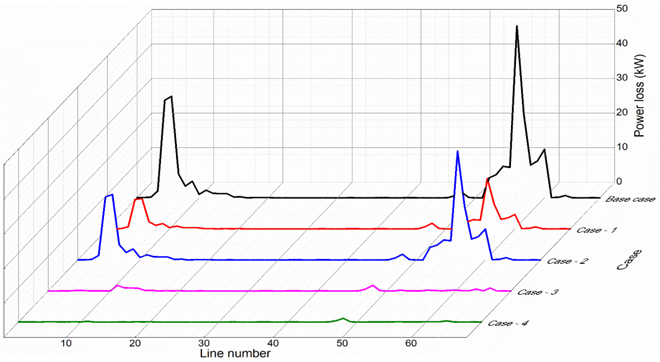


Fig. 9. Illustration of line power loss in IEEE 69-bus system for different cases.

The reduced power loss achieved by the proposed SSA for different cases is illustrated in Fig. 10. Fig. 11. Illustrates the power purchase cost reduction from the grid using the proposed SSA and compared with the base case and the WCA.

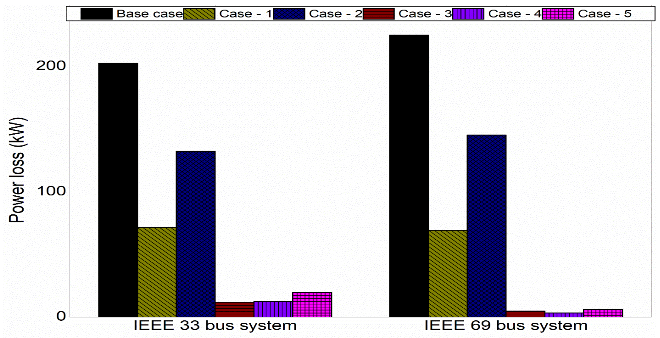


Fig. 10. Illustration of power loss reduction using the proposed SSA for different cases.

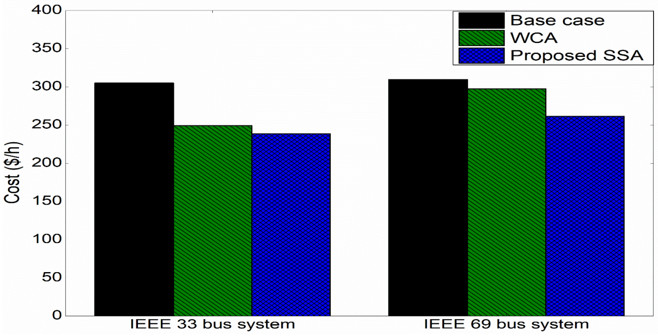


Fig. 11. Illustration of power purchase cost reduction using the proposed SSA for test systems.

The performance of the proposed SSA in the reduction of emissions compared with the base case and the WCA is illustrated in Fig. 12.

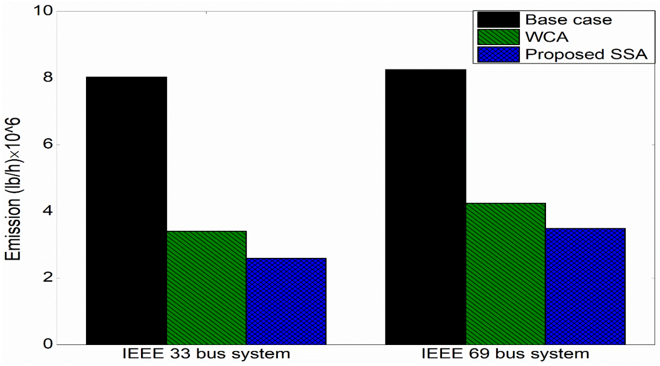


Fig. 12. Illustration of emission reduction using the proposed SSA for test systems.

5. Conclusion

Salp swarm algorithm has been proposed to solve optimal DG and CBs allocation problem in the distribution system. The main aim of the proposed SSA is to maximize the technical, economic and environmental benefits. The proposed SSA is applied to two standard distribution networks for five different operational cases and compared the obtained results with existing optimization techniques. The proposed SSA is very efficient in solving optimal allocation problem when compared with other optimization techniques. It is observed that the optimal allocation of only DG and only CBs has significantly reduced power loss of the test systems. However, the major reduction in network power losses and the substantial benefits has been obtained with the simultaneous allocation of DG and CBs. Overall power loss is reduced by 90%, the cost is reduced by 21% and the emission is reduced by 67%, as in case 5 for 33 bus system. Future research on the topic can include other sources of energy like fuel cells and battery storage.

Nomenclature

P^{Tloss}	network total real power loss	N_{bus}	total network buses
$P^{loss}_{j,j+1}$ and $Q^{loss}_{j,j+1}$	real and reactive power loss in the line section between buses j and $j+1$	N_{br}	total network branches
$P_{j,j+1}, Q_{j,j+1}$	real and reactive power flow between buses j and $j+1$	T_{cap}	total number of CBs
V_1	slack bus voltage	T_{DG}	total number of DG
V_j	voltage at j^{th} bus	$O\ \&\ M$	operation and maintenance
$R_{j,j+1}$ and $X_{j,j+1}$	resistance and reactance of line section between buses j and $j+1$	E^{grid}	emission produced by the grid
VSI_j	voltage stability index at node j	E_i^{DG}	emission produced by i^{th} DG
P_j	real power injected at node j	Q_j	reactive power injected at node j
$P_{G,grid}$	real power production at the substation	Q^{CB}_{total}	total reactive power injected by CBs
$Q_{G,grid}$	reactive power production at the substation	P_{demand}	the total real power demand of the distribution system
$Price_{grid}$	power generation cost at the substation	Q_{demand}	the total reactive power demand of the distribution system
$C_{DG,i}$	power generation cost of i^{th} DG	$P^{min}_{DG,i}, P^{max}_{DG,i}$	minimum and maximum real power generation limits of i^{th} DG
$P_{DG,i}$	real power generated by i^{th} DG	$Q^{min}_{DG,i}, Q^{max}_{DG,i}$	minimum and maximum reactive power generation limits of i^{th} DG

w_1, w_2 and w_3	Weight factors are 0.5, 0.25 and 0.25, respectively

Acknowledgments

The second author thanks VIT for providing ‘VIT SEED GRANT’ for carrying out this research work.

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