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# Optimal Capacitor Placement in Radial Distribution Systems Using Grasshopper Optimization for Power Loss and Energy Cost Minimization

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**Abstract:** *This paper applies the Grasshopper Optimization Algorithm (GOA), as a new approach to determine the optimal capacitor placement in radial distribution systems. The objective function is adapted to minimize both of power loss and energy cost. GOA is inspired from grasshoppers swarm motion. The grasshoppers can fly individually (which emulate the local searching in optimization techniques) or in swarm (which emulate the exploration of optimization techniques). The developed algorithm is validated based on different standard distribution systems such as 33-bus, 69-bus, and 85-bus test systems. However, the obtained results are compared with other algorithms to highlight the advantages of the developed approach. Numerical results stated that the GOA can generate optimal solutions for losses reduction and capacitor locations with quality better than many existing algorithms.*

**Keywords**: *Radial distribution system; Optimal capacitor placement; Power loss and energy cost minimization; Grasshopper optimization algorithm.*

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**Nomenclatures**

| | |
|---|---|
| $K_e$ | Energy cost per each KWh |
| $T_j$ | Duration for which jth load level operates |
| $P_j$ | Active power loss during jth load level |
| $K_c$ | Purchase cost of capacitor per KVAR |
| $Q_{ci}$ | Size of capacitor placed at the ith bus |
| $ncap$ | Number of capacitor locations. |
| $R_k$ | Resistance of line |
| $X_k$ | Reactance of line |
| $P_{loss}$ | Active power loss of line |
| $Q_{loss}$ | Reactive power loss of line |
| $P_{Tloss}$ | total network active loss |
| $P_{L,k}$ | Real power load fed through bus j |
| $Q_{L,k}$ | Reactive power load fed through bus j |
| $V_{max}$ | Maximum value of bus *k* voltage |
| $V_{min}$ | Minimum value of bus *k* voltage |
| $Q_{Ln}$ | Total load reactive power |
| $V_k$ | Bus voltage magnitude at bus *k*. |

| | |
|---|---|
| $g$ | gravitational constant |
| $\overrightarrow{e_g}$ | Unity vector towards the center of earth |
| $D_{ij}$ | Distance between *i* and *j* grasshoppers |
| $s\left(D_{ij}\right)$ | Represents the social force |

List of abbreviation

| | |
|---|---|
| GOA | Grasshopper Optimization Algorithm |
| PGS | Plant Growth Simulation |
| GA | Genetic Algorithm |
| DSA | Direct search algorithm |
| ACO | Ant colony optimization |
| IHA | Improved harmony algorithm |
| MOHEA | Multiobjective hybrid evolutionary algorithm |
| IP | Interior Point |
| FRCGA | Fuzzy-Real Coded GA |
| DEA | Differential Evolution Algorithm |
| GWO | Gray Wolf Optimizer |
| CSA | Cuckoo Search Algorithm |

| | | | |
|---|---|---|---|
| $P_l$ | Real power flow through the branch between bus *k* and *k+1* | TLBO | Teaching Learning Based Optimization |
| $Q_l$ | Reactive power flow through the branch between bus *k* and *k+1* | PSO | Particle Swarm Optimization |
| $R_l$ | Resistance of branch between bus *k* and *k+1* | MINLP | Mixed integer nonlinear programming |
| $X_l$ | Reactance of branch between bus *k* and *k+1* | BFOA | Bacterial foraging Optimization Algorithm |

## I. INTRODUCTION

Electrical power systems become more complicated and sophisticated systems. They contain of three primary components: the generation system, the transmission system, and the distribution system. Each component is essential to deliver the electrical energy from the generation site to the customer site. The major inductive loads are connected to the network through the distribution systems. This type of loads causes low voltage levels, high currents and power losses. However, studies have indicated that as much as 13% of the total generated power is lost as line losses [1]. Therefore, these losses must be diminished to improve the power system stability, power factor and voltage profile [2-4]. Connecting shunt capacitors is considered one of the basic methods which can be used to achieve that target [5], [6]. In general, the inappropriate locating of capacitors may be led to more voltage drop and higher losses. Moreover, the capacitor allocation problem has a combinatorial nature because capacitor locations and sizes are discrete variables [7]. Therefore several optimization algorithms have been proposed in recent years to solve that problem.

Recently many methods and optimization algorithm have been proposed in order to find the optimal capacitor placement problem [8]. Plant growth simulation algorithm PGS was presented for optimal allocation of capacitor with the objective of improving voltage profile and reduction of power loss. [1]. Genetic Algorithm GA was used to determine the optimal sizing of fixed and switched capacitor at different load levels [9–12]. Fuzzy based GA was used to find the optimal size with the multi objective of minimizing the energy cost and to enhance voltage profile of the system [13]. Direct search algorithm (DSA) was presented to find the optimal location and size of fixed and switched capacitor and it was tested on IEEE 22, 69, 85 bus radial distribution system with the objective of maximizing net savings and minimizing the power loss [14]. Ant colony optimization ACO algorithm was proposed to solve capacitor placement in radial distribution system [15]. Taher and Bagherpour proposed the hybrid honey bee colony optimization algorithm to place the shunt capacitor in IEEE 25, 37 bus radial distribution system to minimize power loss and maintains total harmonic distortion [16]. Baran and Wu introduced mixed integer programming for the capacitor placement [17]. Prakash and Sydulu introduced the particle swarm optimization to determine the optimal size of the capacitor bank to minimize the power loss [18]. Sayyad Nojavan et al. proposed mixed integer nonlinear programming approach to determine the optimal location and size of the capacitor to minimize the power loss and increased the net benefits [19]. Improved harmony algorithm IHA [20] is used to solve this problem depend on power loss index. Multiobjective hybrid evolutionary algorithm MOHEA [21] and improved harmony algorithm IHA [22] are introduced to solve the problem of the placement and size of the capacitor.

Grasshopper Optimization Algorithm (GOA) is a very new optimization technique GOA that has been introduced by Seyedali [23]. GOA is conceptualized from grasshoppers swarm motion where grasshoppers can move individually which emulate the local searching in optimization techniques or fly in swarm which emulate the exploration of optimization techniques. The mathematical model of grasshopper motion is described in [24], [25]. The GOA is a recent optimization technique and it has been under study. However, it should point out that GOA is similar to all new optimization technique where it has been tested with standard benchmark functions and also applied for finding the optimal shape for a 52-bar truss, 3-bar truss, and cantilever beam.

However, the application of GOA in solving the optimal capacitor placement problem for distribution systems has not been studied before. Hence, this paper develops the GOA in order to determine the optimal locations and sizes of capacitors and minimize the power losses and total cost of radial distribution systems considering different load levels. Three standard test systems; 33-bus, 69-bus and 85-bus systems are used to validate the effectiveness of the developed approach. In addition, the obtained results are compared with different well-known optimization algorithms to confirm the superiority of developed approach

The rest of paper is organized as follows: Section 2 presents the problem formulation. The GOA is described in Section 3. Section 4 presents the solution process of optimal capacitor placement problem using GOA. Section 5 presents the numerical results of developed GOA approach based on three standard radial distribution systems. Finally, the conclusions of paper are presented in Section 6.

## II. PROBLEM FORMULATION

### 2.1 Forward/ Backward sweep three phase load flow

Forward/backward sweep power flow method have been proven to be effective in analyzing radial distribution systems. However, this load flow method based on forward/backward sweep approach using Kirchhoff's voltage and current laws [26]. In general, the forward/backward sweep load flow algorithm includes the following steps:

First step: Identify different layers in the radial distribution network as described in Fig. 1.

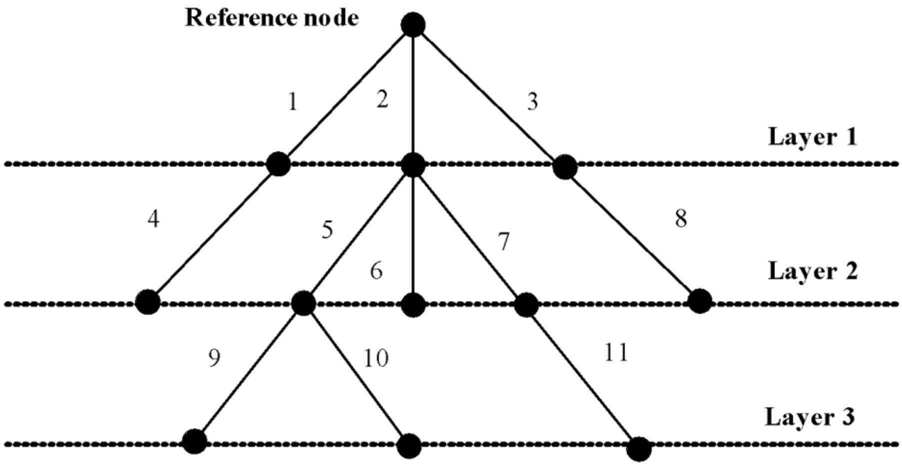

**Fig. 1** layers in radial distribution network (Step1)

Second step: Calculate the injected currents of each phase with the initial voltages for all nodes using (1).

$$I_i^s = \left(\frac{S_i^s}{V_i^s}\right)^* \quad (1)$$

Third step:

This step based on backward sweep approach. The total branch currents beginning from the lower to upper layers can be calculated. The current flowing through the line segment *l* can be calculated as given in (2).

$$J_l^s = -I_j^s + \sum_{m \in M} J_m^s \quad (2)$$

Final step: The forward sweep step (also known as the voltage update step). The node voltages are corrected beginning from the first layer towards the last layer as given in (3).

$$V_j^s = V_i^s - Z_{ij}^s J_l^s \quad (3)$$

The above steps are repeated until the load flow convergence is done.

### *1.1 Power loss calculation*

The power flow equations of distribution system can be simply obtained from Fig. 2 which represents the radial distribution system as follows:

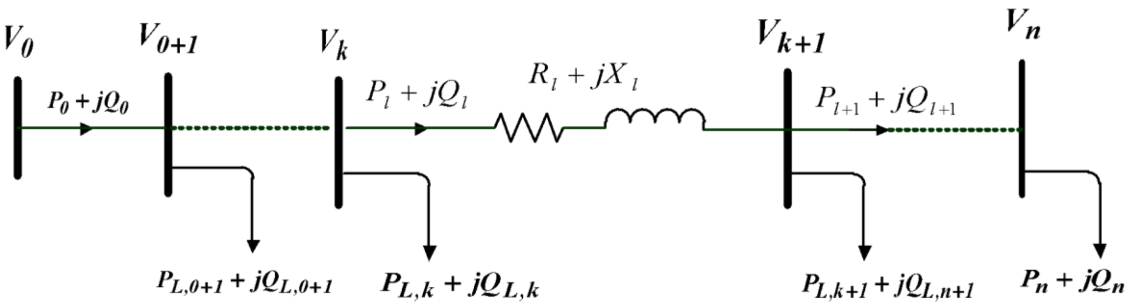

**Fig. 2** Single line diagram of a radial distribution system.

$$P_{l+1} = P_l - P_{L,k+1} - R_l\left(\frac{P_l^2 + Q_l^2}{|V_k|^2}\right) \quad (4)$$

$$Q_{l+1} = Q_l - Q_{L,k+1} - X_l \left(\frac{P_l^2 + j\,Q_l^2}{|V_k|^2}\right) \tag{5}$$

$P_l$ , $Q_l$,. $R_l$, $X_l$

Voltages of transmission line can be calculated from (6) as follows:

$$V_{k+1}^2 = V_k^2 - 2(R_l P_l + X_l Q_l) + (R_l^2 + X_l^2)\left(\frac{P_l^2 + Q_l^2}{|V_k|^2}\right) \tag{6}$$

The active and reactive power losses of *l*th line between buses *k* and *k+1* are given as:

$$P_{loss\,(k,k+1)} = R_l \left(\frac{P_l^2 + Q_l^2}{|V_k|^2}\right) \tag{7}$$

$$Q_{loss\,(k,k+1)} = X_l \left(\frac{P_l^2 + Q_l^2}{|V_k|^2}\right) \tag{8}$$

The total system loss can be calculated by summing all line losses as:

$$P_{T\ loss} = \sum_{k=1}^{n-1} P_{loss\,(k,k+1)} \tag{9}$$

The capacitor banks can be installed in distribution systems for enhancing the power quality and minimizing the total cost by injecting reactive power to the systems. Fig. 3 shows the single line diagram of radial distribution system including a shunt capacitor at bus *k+1*. However, the new value of the reactive power thought the transmission line can be calculated as:

$$Q_{k+1} = Q_k - Q_{L,k+1} - X_k \left(\frac{P_k^2 + Q_k^2}{|V_k|^2}\right) + Q_{C,k+1} \tag{10}$$

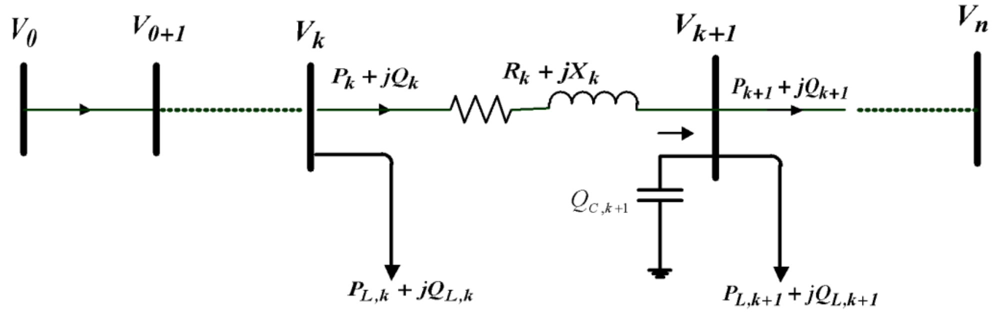

**Fig. 3** Radial distribution system with shunt capacitor.

## 2.2 Objective Function

The objective of optimal capacitor placement in distribution system is to optimize a certain objective functions such as; real power losses and total cost per year (including the energy power losses and the cost of installing capacitors), voltage profile, voltage stability index, subject to voltage and reactive power limits. In the current study, two objective functions; real power losses and total cost per year are investigated. The following mathematical statement can be performed to achieve these objective function:

$$f_1 = (P_{T\ loss}) \ , \tag{11}$$

$$f_2 = (Cost) \ . \tag{12}$$

In general, installation of capacitors in distribution network can improve the voltage profile and reduce current flow through the lines. Consequentially, the power loss, energy loss cost and energy efficiency of the network will be better. However, the installation of capacitors increases the investment cost. Therefore, the objective function in this case is to minimize the total cost which can be defined as [14]:

$$Cost = K_e \sum_{j=1}^{L} T_j P_j + \sum_{i=1}^{ncap} K_c Q_{ci} \tag{13}$$

## 2.3 Operational constraints

The above objective functions are subjected to the following constrains:

- Voltage limits

The bus voltage magnitude of each bus must be limited at its allowable ranges as:

$$V_{min} \le |V_k| \le V_{max} \tag{14}$$

The lower and upper values are taken as 0.90 and 1.05 p.u, respectively.

- Total reactive power limits

The total injected reactive power by capacitor banks must be less than or equal the total load reactive power as:

$$Q_{ci} \le Q_{Ln} \tag{15}$$

- Compensation limits

## III. GRASSHOPPER OPTIMIZATION ALGORITHM

GOA is a new efficient optimization technique that is inspired form the life style (movement, migration) of grasshopper in natural. The adult insects of grasshopper traveling together over long distance which mimics exploration of optimization technique. The nymphs have no wing so it move in small area which mimics the exploitation of optimization technique [23].

Grasshoppers are harmful insects that can destroy a wide area of the agriculture and crops. The grasshoppers swarm consists of million members which can cover wide area up to 1000 KM. The life cycle of grasshopper consists of three stages as depicted in Fig. 4. The grasshopper can be found in two phases. In the first phase the individual of grasshoppers avoid interaction together (solitary phase) while in another phase (gregarious phase), grasshoppers became sociable and form a swarm. The flying swarm of grasshoppers depend upon environmental consideration such as air temperature, sunshine and wind speed [27].

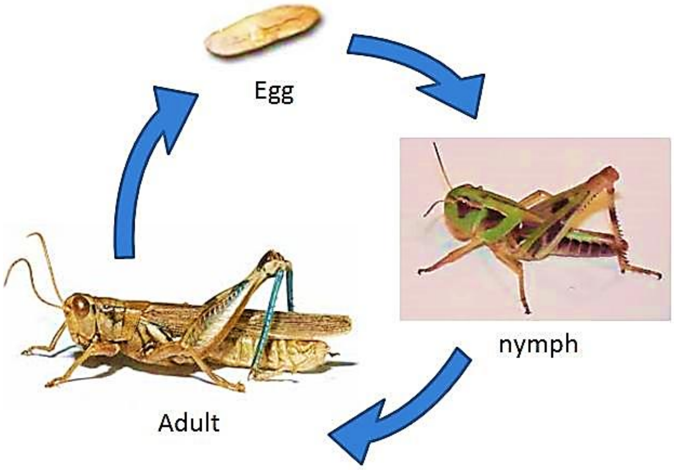

**Fig. 4** The life cycle of grasshopper.

The swarm of grasshopper moves in rolling motion. The groups are formed firstly by collection of insects which move in ground or locally and short flight. Then these groups became coordinated together and the insects share a common spatial orientation. However, the behavior of grasshopper swarm can be summarized as:

- The swarm flying with downwind.
- The grasshoppers in front of swarm settle on the ground.
- The settled insects start eating and resting.
- The swarm starts taking of gain to altitude.
- The grasshopper swarm navigation behavior aligned wind is depicted in Fig. 5.

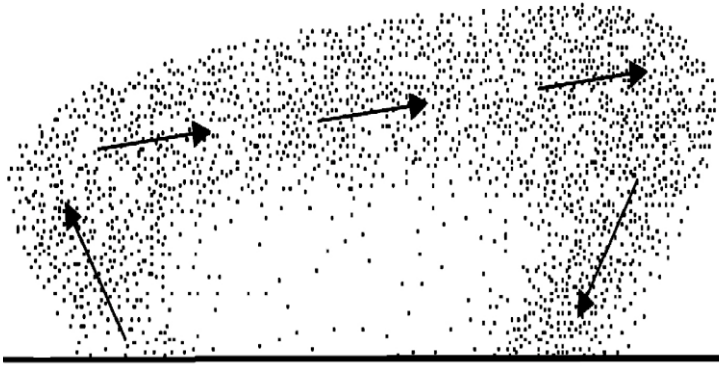

**Fig. 5** Motion of grasshopper swarm aligned with wind.

The grasshopper swarm behavior depends upon social interaction between grasshopper, the gravity force and the downwind advection. Hence mathematical behavior can be represented as [28]:

$$X_i = r_1 S_i + r_2 B_i + r_3 C_i \tag{16}$$

A social force between two grasshoppers is established biologically, where the repulsion forces is existed in order to prevent collisions over a short length scale and attraction force is existed for aggregation. The social interaction between grasshoppers can define as:

$$S_i = \sum_{j=1\ i\neq j}^{N} s\left(D_{ij}\right)\left(\frac{x_i - x_j}{D_{ij}}\right) \tag{17}$$

Where

$$D_{ij} = \left|x_i - x_j\right|$$

$$s\left(D_{ij}\right) = Fe^{\frac{D_{ij}}{l}} - e^{D_{ij}} \tag{18}$$

where $F$ is the intensity of attractive force and $l$ is the attractive length scale. The swarm motion is directly affected by the gravity force which can be found as:

$$B_i = -g\overrightarrow{e_g} \tag{19}$$

The wind advection effect on the motion swarm:

$$C_i = u\overrightarrow{e_w} \tag{20}$$

By substituting the value of $S_i$, $B_i$ and $C_i$ from (18), (19) and (20) in (16):

$$X_i = \sum_{j=1\; i\neq j}^{N} s\left(D_{ij}\right)\left(\frac{x_i - x_j}{D_{ij}}\right) - g\overrightarrow{e_g} + u\overrightarrow{e_w} \tag{21}$$

where, $N$ is number of grasshoppers. The previous equation is modified to be implemented for optimization problems and for enhancing the capability global searching of the algorithm. However, it can be modified as follows:

$$X_i^m = C\left(\sum_{j=1\; i\neq j}^{N} C\left(\frac{Up,m - Lp,m}{2}\right) s\left(D_{ij}\right)\left(\frac{x_i - x_j}{D_{ij}}\right)\right) + X_{best}^m \tag{22}$$

where, $U_p$ and $L_p$ are the upper and lower limits of the control variable, respectively. $x_{best}^m$ is the best position (the target position). $C$ is an adaptive coefficient decreased linearly for enhancing the search capability of GOA. It can be represented as follows:

$$C = C_{max} - T\frac{C_{max} - C_{min}}{T_{max}} \tag{23}$$

where, $C_{max}$, $C_{min}$ are the maximum and the minimum values of $C$, respectively. $T$ and $T_{max}$ are the current iterations and the maximum number of iterations, respectively. However, GOA algorithm can be summarized as follows:

**Step 1** : Determine the input data of GOA including number of the search agents (N), maximum number of iterations, $C_{min}$, $C_{max}$, $F$, $l$ and the upper and lower boundaries of control variables.

**Step 2** : Initialize the population of GOA as follows:

$$P_i^m = Lp(i,m) + rand * \left(Up(i,m) - Lp(i,m)\right) \tag{24}$$

**Step 3** : Calculate the fitness functions for each search agent.

**Step 4** : Determine the best position (target position) in term of the best fitness function.

**Step 5** : Update the position of search agent according to (21).

**Step 6** : Check the boundaries of the updated agents and bring the violated variable to accepted limit.

**Step 7** : Calculate the fitness function for the updated positions and determine the target position.

**Step 8** : Repeat steps form (5) to (7) until the stopping criterion is achieved (current iteration equals to maximum iteration).

**Step 9** : Find the best solution (target position) and the related fitness function.

## IV. SOLUTION PROCESS OF OPTIMAL CAPACITOR PLACEMENT PROBLEM USING GOA

The sizes and location of capacitors are considered as decision variables and used to form different objective functions. The implementing procedure of the developed GOA in solving the optimal capacitor placement problem can be summarized as follows:

**Step 1** : Read the line and bus data.

**Step 2** Initialize the maximum number of iterations, the number of capacitors, the number of the search agents ($N$), $C_{min}$, $C_{max}$, $F$, $l$ and the upper and lower boundaries of control variables.

**Step 3** : Select positions of capacitors randomly depending upon the capacitor numbers.

**Step 4** : Initialize randomly the size of the capacitors within the operating constraints as follows:

$$Q_i = Q_i^{min} + rand * \left(Q_i^{max} - Q_i^{min}\right) \tag{25}$$

**Step 5** Run the load flow to find the objective function (power losses or the total cost) then determine the best position (best locations and sizes of capacitors) in term of the best objective function.

**Step 6** : Normalize the distances between grasshoppers

**Step 7** : Update the position of search agent according to (21). In other words the locations and sizes of capacitor are updated with respected to the best solution.

**Step 8** If the stopping criterion is satisfied, stop and print the best solution, else go to Step 5.

However, the above steps can be summarized in the following flowchart.

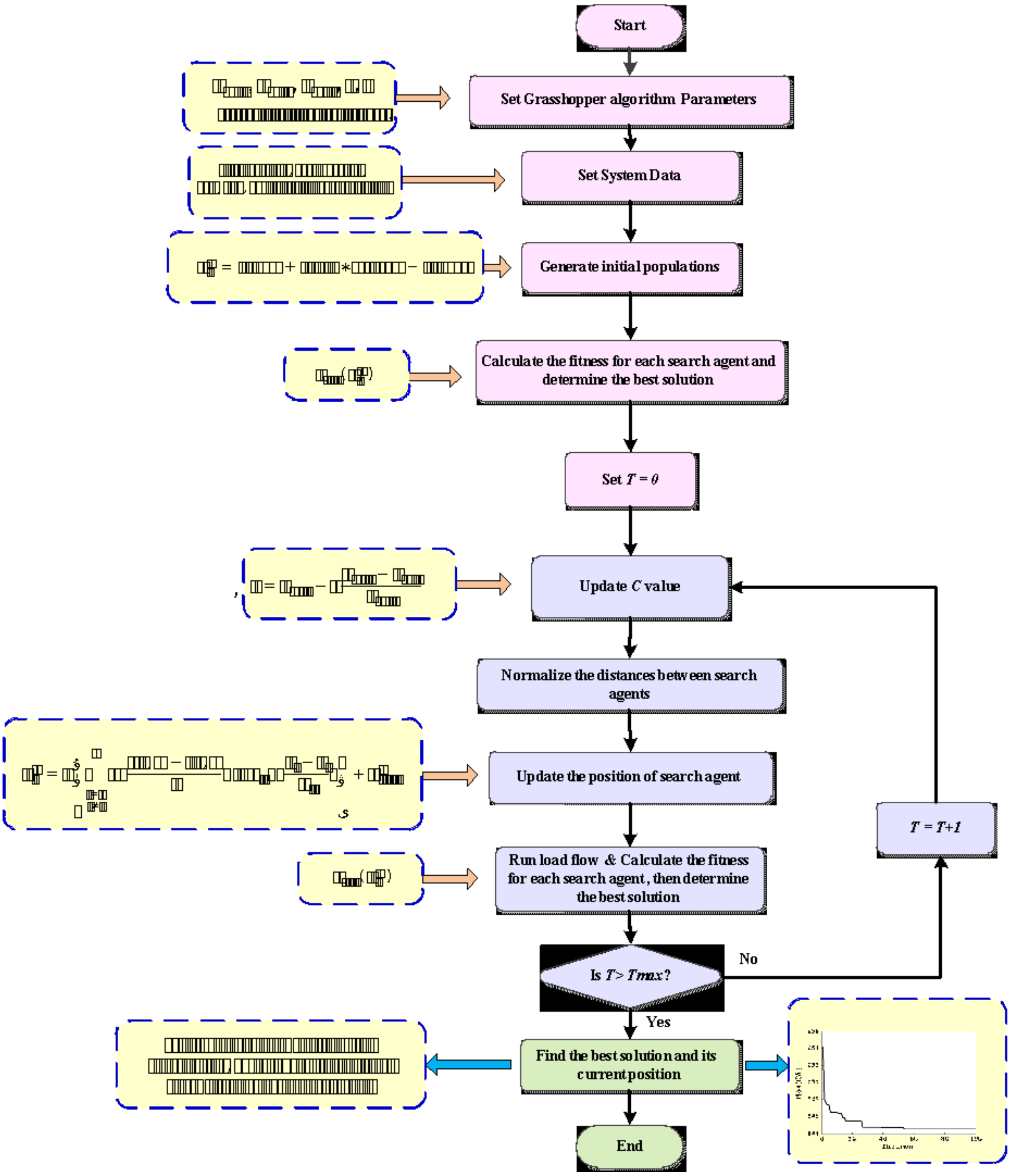

**Fig. 6** Flowchart of developed Grasshopper optimization algorithm for optimal capacitor placement in radial distribution systems

## V. NUMERICAL RESULTS

The developed GOA approach has been applied on different distribution radial test systems to observe its effectiveness and performance. Power loss and total cost are minimized for three standard test systems (33-bus, 69-bus and 85-bus radial distribution systems). The developed approach has been modelled and implemented using the MATLAB 7.14. All case studies are achieved using a personal computer having 2.5 GHz core i5 processor with 4 GB RAM. The number of compensated buses selected based on the size of test system.

The selected parameters of GOA algorithm are listed in Table 1. The available sizes of capacitors are given in Table 2. In all the mentioned test systems, GOA algorithm is performed 50 times and the best obtained results are reported and compared with other meta- heuristics optimization techniques.

**Table 1** The selected parameters of GOA.

| Parameter | $T_{max}$ | $C_{max}$ | $C_{min}$ | $F$ | $L$ |
|---|---|---|---|---|---|
| Value | 100 | 1 | 0.00004 | 0.5 | 1.5 |

**Table 2** The available capacitor sizes (KVAR).

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 150 | 300 | 450 | 600 | 750 | 900 | 1050 | 1200 | 1350 |
| 1500 | 1650 | 1800 | 1950 | 2100 | 2250 | 2400 | 2550 | 2700 |
| 2850 | 3000 | 3150 | 3300 | 3450 | 3600 | 3750 | 3900 | 4050 |

### 5.1 Power loss minimization.

In first case study, the developed GOA technique is tested to minimize the power loss of different standard test systems as 33-bus, 69-bus and 85-bus radial distribution systems. The results obtained based on GOA are compared with that obtained from different optimization methods.

### *5.1.1 33-bus test system*

To demonstrate the impact of developed GOA on medium scale of radial distribution system, 33-bus test system used in the first case study. The single line diagram of this test system given Fig. 7. The system voltage is 12.66 KV. However, the details of this system are given in [29]. In case of the system is working without capacitors, the minimum voltage magnitude is 0.9036 p.u at bus no. 18 and the total active power loss is 210.97 KW with annual energy losses cost about 35442.96 $. Based on the developed GOA, only three capacitors are allocated at optimal locations. Table 3 shows the power loss, minimum bus voltage, optimal locations and optimal size of capacitors obtained by different optimization techniques. From this table, it can be observed that installation of capacitors reduces the power loss significantly. However, the active power loss using GOA is reduced to be 138.772 KW. Consequentially, the total losses are reduced by 33.008 KW compared to Analytical interior point IP [30], 5.268 KW compared to GA [13], 2.468 KW compared to Fuzzy-Real Coded GA FRCGA [31], and 798 W compared to Differential Evolution Algorithm DEA [32], 1.648 KW compared to Gray Wolf Optimizer GWO. In addition, the system voltage profile is improved significantly in case on including the optimal capacitor placement compared with uncompensated case as shown in Fig. 8. This shows that the developed GOA is more effective than the other optimization techniques. Referring to Fig.9 it can obvious that the best objective function is obtained rapidly at the first 10th iterations. On other hand, the objective function with GWO reach to the best solution after 50th iterations

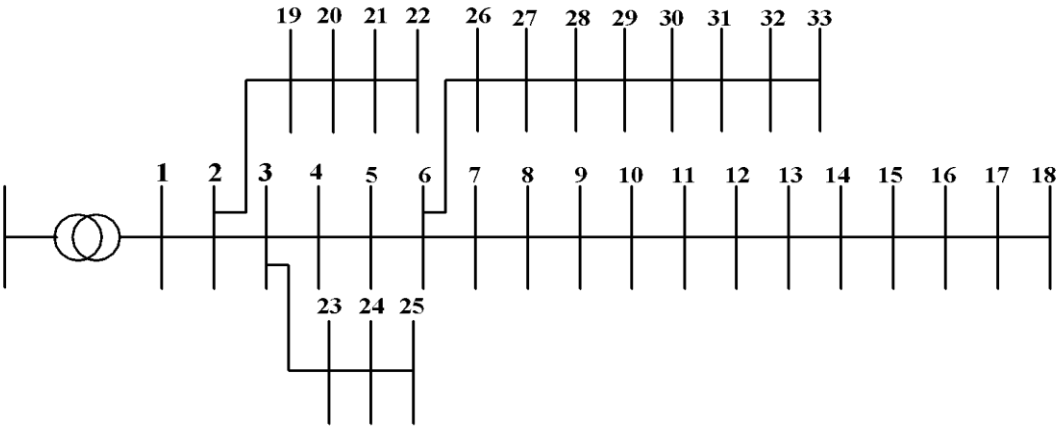

**Fig. 7** Single line diagram of 33-bus radial distribution system.

**Table 3** Optimal results of 33-bus network for power loss minimization

| | W/O Capacitor | With Capacitor | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | IP [30] | | GA [13] | | FRCGA [31] | | GWO | | DEA[32] | | GOA | |
| Optimal location & size of capacitors (KVAR) | | 9 | 450 | 7 | 850 | 6<br>8 | 475<br>175 | 12 | 450 | 5 | NA | 12 | 450 |
| | - | 29 | 800 | 29 | 25 | 9<br>28 | 350<br>25 | 4 | 300 | 27 | NA | 24 | 600 |
| | | 30 | 900 | 30 | 900 | 29<br>30 | 300<br>400 | 30 | 1050 | 28 | NA | 30 | 900 |
| Total KVAR | - | 2150 | | 1775 | | 1725 | | 1800 | | NA | | 1950 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Power loss kw | 210.97 | 171.78 | 144.04 | 141.24 | 140.42 | 139.57 | 138.772 |
| % reduction in power loss | 0 | 18.576 | 31.72 | 33.05 | 33.44 | 33.84 | 34.22 |
| Minimum voltage bus | 18 | 18 | NA | NA | 18 | 18 | 18 |
| Minimum voltage p.u. | 0.9038 | 0.9501 | NA | NA | 0.9307 | 0.93 | 0.9295 |

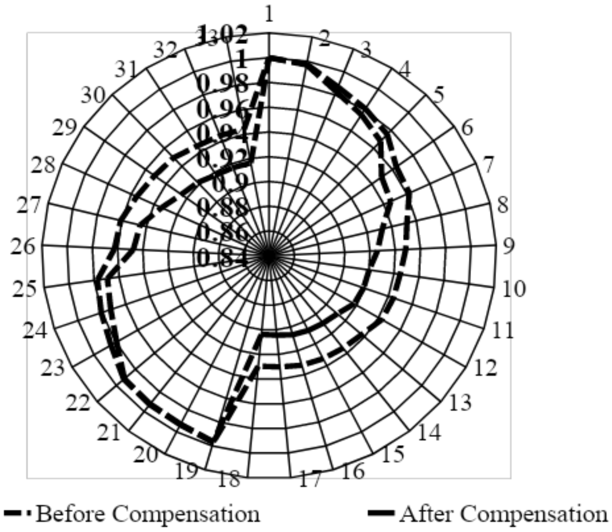

**Fig. 8** Voltage profile of 33-bus radial distribution system.

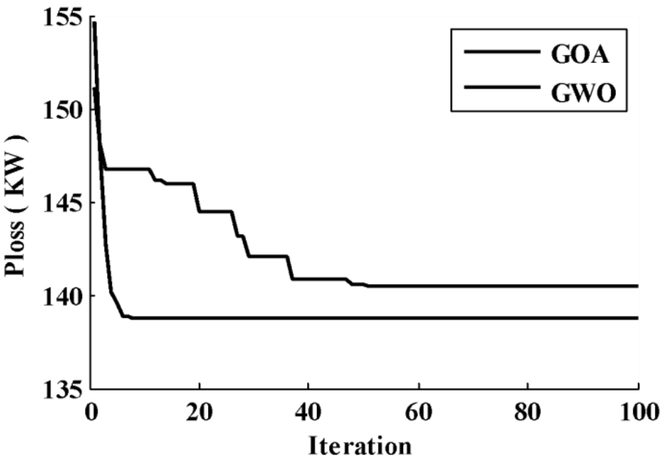

**Fig. 9** Convergence characteristics of the objective function for 33-bus radial distribution system

### *5.1.2 69-bus test system*

The developed GOA also validated using standard 69-bus radial distribution system, in case of taking the power loss minimization as an objective function. This test system is consisting of 69 buses and 68 branches as shown in Fig. 10. Its rated voltage is 12.66 kV and total system load is (1.896MW+j1.347MVAR). The details bus and line data are reported in [17]. The obtained KW loss without incorporating any capacitor equals to 224.96 KW and the lowest voltage is 0.9092 p.u. at bus no. 65. The optimal locations and sizes of capacitors with applying GOA are listed in Table 4. However, when applying the developed technique, the best active power loss is reduced to 145.404 KW. Meanwhile the percentage of power loss reduction is enhanced to be 35.37% which is the best value compared with other optimization algorithms as reported in Table 4. Moreover, the voltage profile is enhanced significantly with determining the optimal location and size of capacitors using GOA as shown in Fig. 11. The minimum voltage improved and became 0.9324 p.u which is compatible with the voltage constrains. However, the convergence characteristics for this case compared to GWO is shown in Fig.12.

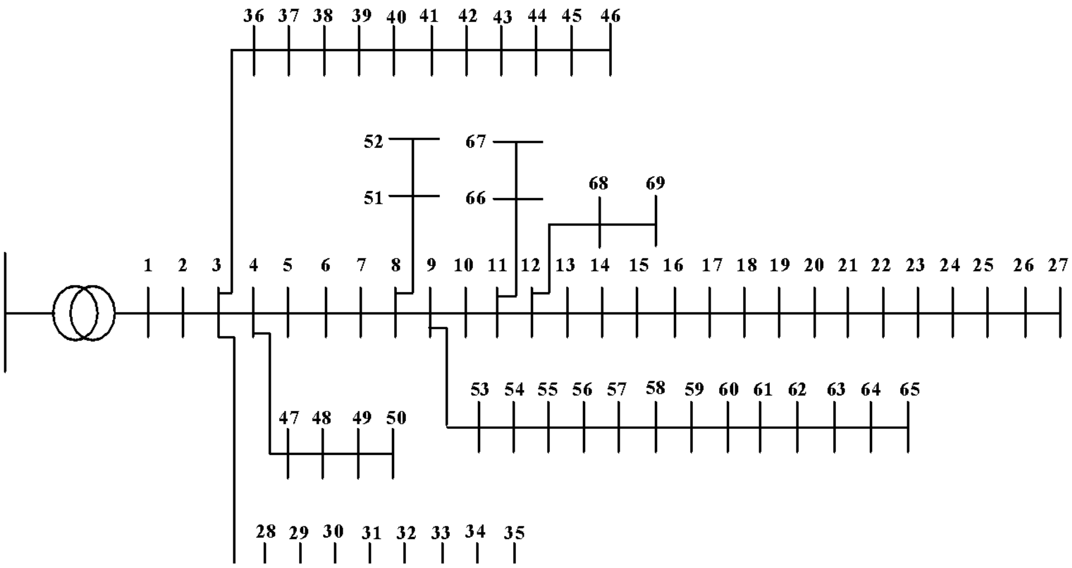

**Fig. 10** Single line diagram of 69-bus radial distribution system.

**Table 4** Optimal results of 69-bus network for power loss minimization

| | W/O Capacitor | With Capacitor | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | IP [30] | | A two stage[33] | | CSA[34] | | HMOEA [21] | | TLBO[35] | | GWO | | GOA | |
| Optimal location & size (KVAR) of capacitors | - | 11 | 900 | 19 | 225 | 62 | 1200 | 61 | 1150 | 12 | 600 | 16 | 450 | 12 | 450 |
| | | 29 | 1050 | 62 | 900 | 21 | 250 | 18 | 250 | 61 | 1050 | 61 | 1200 | 61 | 1200 |
| | | 30 | 450 | 63 | 225 | | | | | 64 | 150 | 9 | 300 | 21 | 150 |
| Total KVAR | - | 2400 | | 1350 | | 1450 | | 1400 | | 1800 | | 1950 | | 1800 | |
| Power loss KW | 224.96 | 163.28 | | 148.91 | | 148 | | 147.74 | | 146.36 | | 146.118 | | 145.4047 | |
| % reduction in power loss | 0 | 27.42 | | 33.8 | | 34.21 | | 34.33 | | 34.945 | | 35.05 | | 35.37 | |
| Minimum voltage bus | 65 | 65 | | 65 | | 65 | | 65 | | 65 | | 65 | | 65 | |
| Minimum voltage p.u. | 0.9092 | 0.9532 | | 0.9288 | | 0.93 | | 0.9288 | | 0.9312 | | 0.9313 | | 0.9308 | |

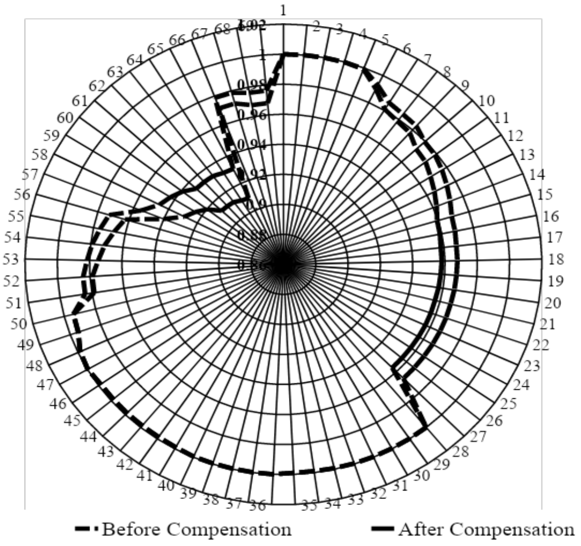

**Fig. 11** Voltage profile of 69-bus radial distribution system.

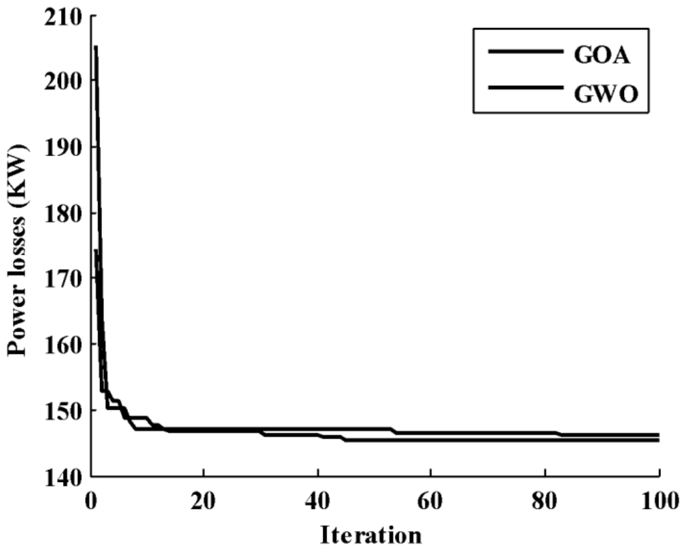

**Fig. 12** Convergence characteristics of the objective function for 69-bus radial distribution system

*5.1.3 85-bus test system*

To investigate the effectiveness of the developed GOA on large scale radial distribution systems, 85-bus test system is used. This system is operated with 100 MVA base and 11 KV rated voltage. Its single line diagram is shown in Fig. 13. All data of lines and loads are given in [36]. The total active power loss without incorporating capacitors in the system is 315.714 KW. The optimal results that obtained by GOA and other algorithms including optimal locations and sizes of capacitors are listed in Table 5. The active power loss is reduced to 148.9274 KW with percentage reduction of 52.83% with applying GOA. It should point out that the lowest bus voltage is increased from 0.8713 p.u. to 0.92182 p.u. Moreover, the voltage profile is significantly improved as shown in Fig. 14. Referring to Fig. 15, the GOA is performing well in stable and smooth convergence characteristics.

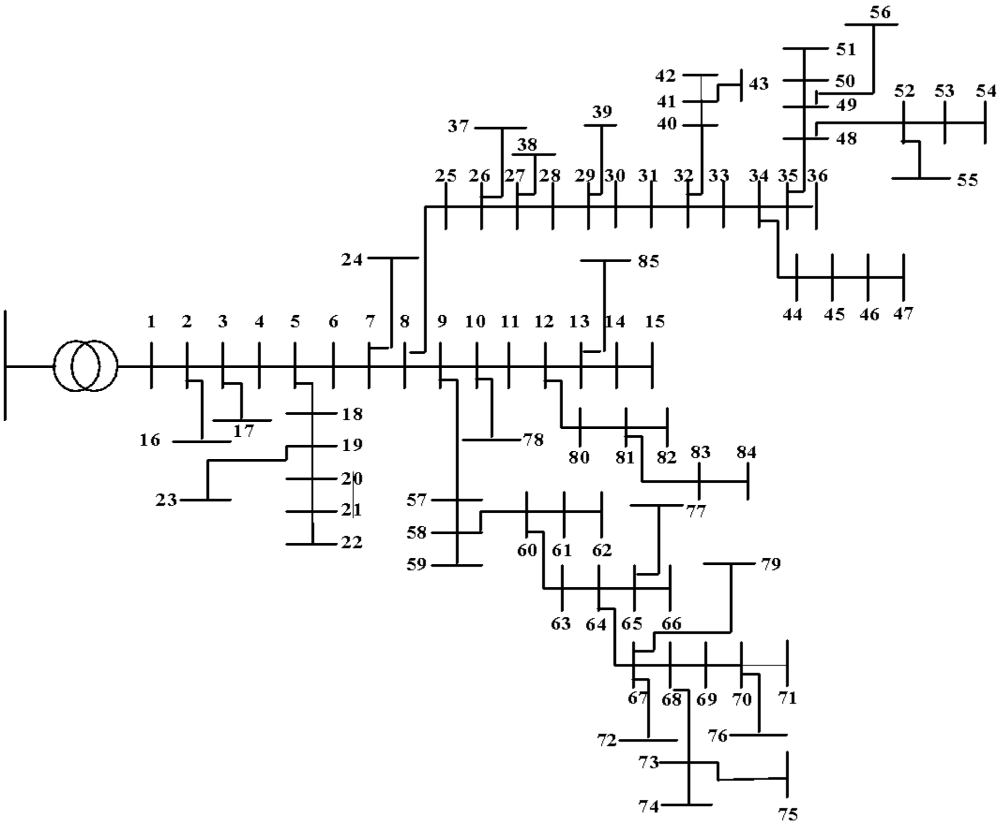

**Fig. 13** Single line diagram of 85-bus radial distribution system.

**Table 5** Optimal results of 85-bus network for power loss minimization

| | W/O Capacitor | With Capacitor | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | PGS [1] | | PSO [37] | | MINLP [38] | | BOFA [39] | | GWO | | GOA | |
| Optimal location and size (KVAR) of capacitors | - | 7 | 200 | 7 | 324 | 7 | 300 | 9 | 840 | 48 | 450 | 67 | 600 |
| | | 8 | 1200 | 8 | 796 | 8 | 700 | 34 | 660 | 9 | 900 | 34 | 600 |
| | | 58 | 908 | 27 | 901 | 29 | 900 | 60 | 650 | 68 | 450 | 26 | 600 |
| | | | | 58 | 453 | 58 | 500 | | | 29 | 450 | 12 | 450 |
| Total KVAR | - | 2308 | | 2474 | | 2400 | | 2150 | | 2250 | | 2550 | |
| Power loss KW | 315.714 | 174.0048 | | 163.32 | | 159.87 | | 152.25 | | 149.2728 | | 148.9274 | |
| % reduction in power loss | - | 44.82 | | 48.21 | | 49.03 | | 51.71 | | 52.72 | | 52.8288 | |
| Minimum voltage bus | 54 | 54 | | 54 | | 54 | | 54 | | 54 | | 54 | |
| Minimum voltage p.u. | 0.8713 | 0.9089 | | 0.9153 | | 0.9171 | | 0.918 | | 0.9235 | | 0.92182 | |

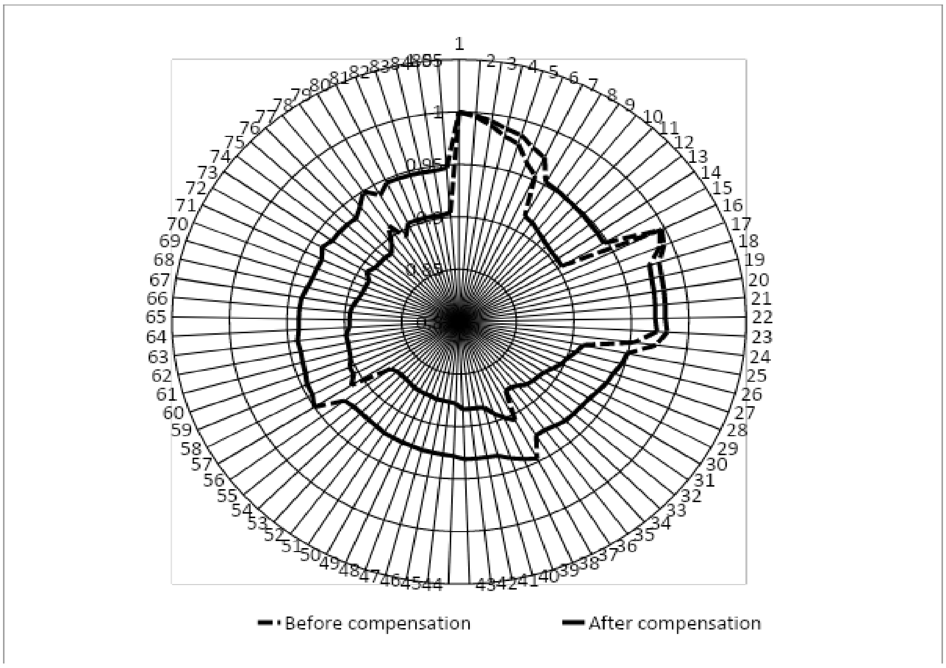

**Fig. 14** Voltage profile of 85-bus radial distribution system

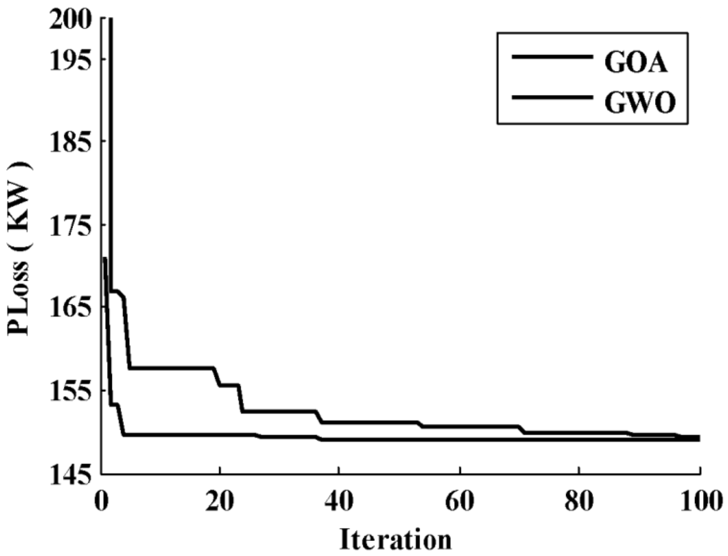

**Fig. 15** Convergence characteristics of the objective function for 85-bus radial distribution system.

### 5.2 Energy cost optimization.

To clarify the effectiveness of the developed GOA for minimizing the annual cost of real power loss and total capacitors, simulation studies carried out on standard 69-bus and 85-bus bus test systems. In this section, three different load demand patterns of light load 50%, nominal load (100%) and peak load (160%) are considered to show the performance of the developed technique. Duration of time for light load, nominal load and peak load are 2000 h, 5260 h and 1500 h, respectively [14]. Here, energy cost is assumed as US $ 0.06 per KWh and purchase cost of capacitor is taken as US $ 3.0 per KVAR [14].

#### *5.2.1 69-bus system.*

The developed GOA is applied on 69-bus system to determine the optimal location and size of capacitors to minimize the total energy cost. In case of the test system does not consist of compensation units, the active power loss for peak, nominal and light load are 652.40 KW; 224.96 KW, and 51.60 KW, respectively, while the minimum voltage level are 0.84449 p.u., 0.90919 p.u., and 0.95668 p.u, respectively. The total cost equals to 135,905$ [35]. The effect of optimal location and size of capacitors on the energy loss cost, capacitor cost and the total cost of the system are given in Table 6. Referring to the simulation results of Table 6, it is clear that the obtained results using GOA are better than the other reported algorithms such as the fuzzy GA [40], DSA [14], GWO and TLBO [35]. Due to the installing the capacitors in three locations the objective function decreased with respect to GWO as displayed in Fig.16.

**Table 6** Simulation results using fuzzy GA, DSA, TLBO and GOA for cost analysis (69-bus system)

| | W/O Capacitor | With Capacitor | | | | |
|---|---|---|---|---|---|---|
| | | Fuzzy GA [40] | DSA [14] | GWO | TLBO[35] | GOA |
| **Light load** | | | | | | |
| Optimal location & size (KVAR) of capacitors | - | 59 0<br>61 0<br>64 300 | 15 300<br>60 300<br>61 450 | 12 150<br>61 750<br>18 150 | 22 150<br>61 450<br>62 150 | 18 150<br>61 450<br>64 150 |
| Minimum voltage bus | 65 | 65 | 65 | 65 | 65 | 65 |
| Minimum voltage p.u. | 0.95668 | 0.9622 | 0.9683 | 0.9688 | 0.9662 | 0.9666 |
| Power loss KW | 51.6 | 40.48 | 35.52 | 34.87 | 34.43 | 34.36 |
| **Nominal load** | | | | | | |
| Optimal allocation and size (KVAR) | - | 59 100<br>61 700<br>64 800 | 15 450<br>60 450<br>61 900 | 12 150<br>61 1200<br>18 300 | 22 300<br>61 1050<br>62 300 | 18 300<br>61 1200<br>64 150 |
| Minimum voltage bus | 65 | 65 | 65 | 65 | 65 | 65 |
| Minimum voltage p.u. | 0.90919 | 0.93693 | 0.9318 | 0.9303 | 0.9321 | 0.9325 |
| Power loss KW | 224.96 | 156.52 | 147 | 145.776 | 146.8 | 146.45 |
| **Peak load** | | | | | | |
| Optimal allocation and size (KVAR) | - | 59 1100<br>61 800<br>64 1200 | 15 900<br>60 900<br>61 1800 | 12 150<br>61 1500<br>18 300 | 22 300<br>61 1050<br>62 750 | 18 300<br>61 1500<br>64 300 |
| Minimum voltage bus | 65 | 65 | 65 | 65 | 65 | 65 |
| Minimum voltage p.u. | 0.84449 | 0.90014 | 0.8936 | 0.8748 | 0.8795 | **0.8803** |
| Power loss KW | 652.40 | 460.5 | 427.3 | 426.15 | 417.38 | 416.32 |
| Energy loss cost ($) | 135,905 | 95727.00 | 89112.6 | 88544.37 | 88016.37 | 87813.82 |
| Capacitor cost ($) | 0 | 9300 | 10800 | 5850 | 6300 | 6300 |
| Total cost ($) | 135,905 | 105,027 | 99,912.6 | 94394.74 | 94316.37 | 94113.82 |

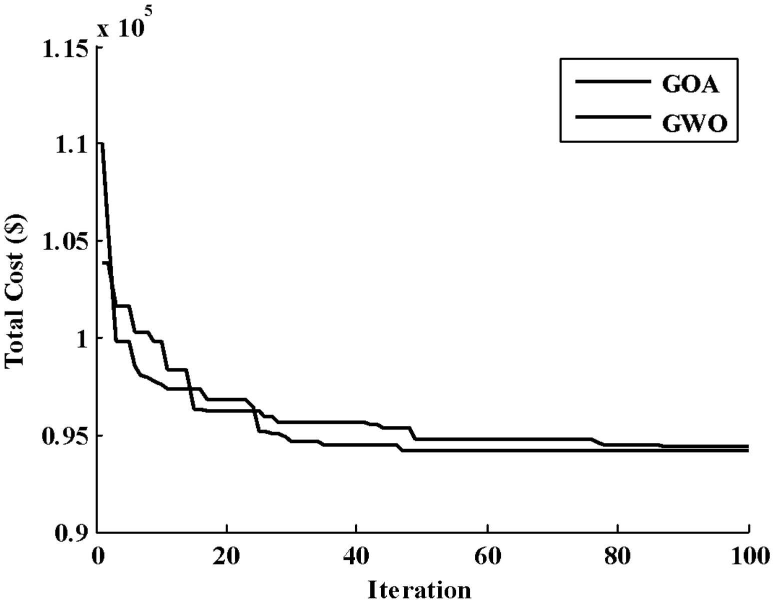

**Fig. 16** Convergence characteristics of the cost analysis for 69-bus radial distribution system.

### *5.2.2 85-bus system.*

Finally, the developed GOA is applied on 85-bus test system to find the optimal location and size of capacitors for minimizing the total cost. Without incorporating of compensation units, the minimum voltage level and the power loss of the system for peak, nominal and light load are 0.7722 p.u., 975.93 KW; 0.8713 p.u., 316.11 KW; and0.9397 p.u., 70.11 KW, respectively, and The total cost equals to 196,011$ [41]. The effect of the optimal location and size of capacitors on the energy loss cost, capacitor cost and the total cost of the system are listed in Table 7. The obtained cost using GOA technique is better than DSA [14], GWO and TLBO [35]. The total cost is decreased to optimal value as shown in Fig.17

**Table 7** Simulation results using DSA, TLBO and GOA for cost analysis (85-bus system).

| | W/O Capacitor | With Capacitor | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | DSA[14] | | GWO | | TLBO[35] | | GOA | |
| **Light load** | | | | | | | | | |
| Optimal location and size (KVAR) of capacitors | - | 6 | 0 | 35 | 0 | 15 | 0 | 21 | 150 |
| | | 8 | 0 | 70 | 0 | 23 | 150 | 26 | 0 |
| | | 14 | 150 | 52 | 150 | 26 | 150 | 27 | 150 |
| | | 17 | 150 | 32 | 0 | 32 | 150 | 37 | 0 |
| | | 18 | 0 | 4 | 0 | 36 | 150 | 39 | 0 |
| | | 20 | 0 | 11 | 150 | 38 | 0 | 46 | 150 |
| | | 26 | 0 | 73 | 150 | 45 | 0 | 53 | 150 |
| | | 30 | 150 | 63 | 0 | 52 | 0 | 56 | 150 |
| | | 36 | 300 | 15 | 150 | 57 | 150 | 62 | 0 |
| | | 57 | 150 | 8 | 150 | 61 | 0 | 65 | 150 |
| | | 61 | 0 | 31 | 150 | 64 | 150 | 67 | 0 |
| | | 66 | 150 | 27 | 150 | 73 | 150 | 70 | 150 |
| | | 69 | 150 | 49 | 0 | 82 | 0 | 80 | 150 |
| | | 80 | 0 | 19 | 150 | 84 | 150 | 81 | 0 |
| Minimum voltage bus | 54 | 54 | | 54 | | 54 | | 54 | |
| Minimum voltage p.u. | 0.9397 | 0.9629 | | 0.9626 | | 0.9616 | | 0.9663 | |
| Power loss kw | 70.11 | 34.76 | | 34.48 | | 34.11 | | 35.7186 | |
| **Normal load** | | | | | | | | | |
| Optimal allocation and size (KVAR) | | 6 | 150 | 35 | 0 | 15 | 150 | 21 | 300 |
| | | 8 | 150 | 70 | 150 | 23 | 300 | 26 | 150 |
| | | 14 | 150 | 52 | 150 | 26 | 300 | 27 | 150 |
| | | 17 | 150 | 32 | 150 | 32 | 150 | 37 | 150 |
| | | 18 | 150 | 4 | 150 | 36 | 150 | 39 | 150 |
| | | 20 | 150 | 11 | 450 | 38 | 150 | 46 | 150 |
| | | 26 | 150 | 73 | 150 | 45 | 150 | 53 | 300 |
| | | 30 | 300 | 63 | 450 | 52 | 150 | 56 | 0 |
| | | 36 | 450 | 15 | 0 | 57 | 300 | 62 | 150 |
| | | 57 | 150 | 8 | 0 | 61 | 150 | 65 | 150 |
| | | 61 | 150 | 31 | 150 | 64 | 300 | 67 | 150 |
| | | 66 | 150 | 27 | 300 | 73 | 150 | 70 | 150 |
| | | 69 | 300 | 49 | 150 | 82 | 150 | 80 | 300 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 80 | 150 | 19 | 150 | 84 | 0 | 81 | 150 |
| Minimum voltage bus | 54 | 54 | | 54 | | 54 | | 54 | |
| Minimum voltage p.u. | 0.8713 | 0.9224 | | 0.9213 | | 0.9241 | | 0.9229 | |
| Power loss kw | 316.11 | 144.01 | | 144.464 | | 143.2493 | | 145.0935 | |
| **Peak load** | | | | | | | | | |
| Optimal allocation and size (KVAR) | - | 6 | 150 | 35 | 300 | 15 | 150 | 21 | 300 |
| | | 8 | 300 | 70 | 300 | 23 | 0 | 26 | 150 |
| | | 14 | 150 | 52 | 150 | 26 | 300 | 27 | 150 |
| | | 17 | 150 | 32 | 300 | 32 | 450 | 37 | 150 |
| | | 18 | 300 | 4 | 150 | 36 | 150 | 39 | 300 |
| | | 20 | 300 | 11 | 300 | 38 | 150 | 46 | 150 |
| | | 26 | 150 | 73 | 150 | 45 | 150 | 53 | 300 |
| | | 30 | 450 | 63 | 450 | 52 | 300 | 56 | 300 |
| | | 36 | 900 | 15 | 300 | 57 | 300 | 62 | 300 |
| | | 57 | 300 | 8 | 300 | 61 | 150 | 65 | 300 |
| | | 61 | 300 | 31 | 300 | 64 | 450 | 67 | 150 |
| | | 66 | 300 | 27 | 300 | 73 | 300 | 70 | 300 |
| | | 69 | 600 | 49 | 150 | 82 | 450 | 80 | 300 |
| | | 80 | 450 | 19 | 0 | 84 | 0 | 81 | 150 |
| Minimum voltage bus | 54 | 54 | | 54 | | 54 | | 54 | |
| Minimum voltage p.u. | 0.7722 | 0.877 | | 0.866 | | 0.8647 | | 0.862 | |
| Power loss KW | 975.93 | 410.69 | | 411.66 | | 411.6 | | 415.9425 | |
| Energy loss cost ($) | 196,011 | 86586 | | 87294 | | 86346 | | 87513 | |
| Capacitor cost ($) | 0 | 13950 | | 10350 | | 11250 | | 9900 | |
| Total cost ($) | 196,011 | 100536 | | 97644 | | 97590 | | 97413 | |

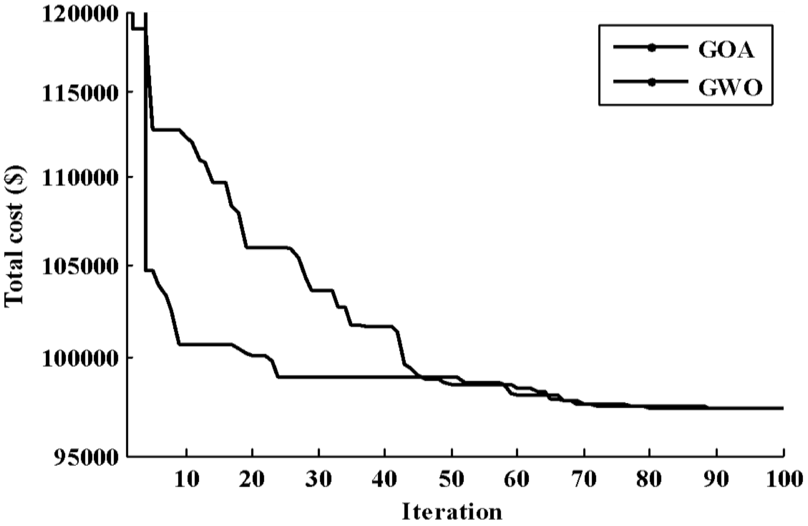

**Fig. 17** Convergence characteristics of the cost analysis for 85-bus radial distribution system.

## VI. CONCLUSION

This paper has applied one of the recently developed optimization techniques (grasshopper optimization algorithm (GOA)), in radial distribution systems to solve the problem of capacitors placement. Minimizing the total real power losses and annual energy cost are taken as objective functions which are considered an attractive economic issue. The developed GOA has been successfully applied on several standard distribution systems to prove its superiority and effectively compared with different well-known optimization techniques. IEEE 33-node, IEEE 69-node and IEEE 85-node test systems have been selected as small, medium and large scale radial distribution network, respectively. In all the mentioned test systems, the locations and sizes of capacitors are optimized to achieve the determined objective functions using the developed GOA algorithm. Furthermore, the nodes voltage has been improved. However, all numerical results obtained have been compared with other well-known optimization algorithms. GOA presents a favorable and promising performance with stable convergence over the other algorithms.

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