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ORIGINAL ARTICLE

Optimal capacitor placement in radial distribution systems using flower pollination algorithm

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Abstract In this paper, a new metaheuristic algorithm that mimics the pollination process of flowers and is known as the flower pollination algorithm (FPA) has been proposed for the solution of the optimal capacitor placement (OCP) problem in a radial distribution system (RDS). The objective of this problem is to minimize the total power loss and cost of capacitor installation by optimal location and sizing of the capacitors. OCP also improves the voltage profile. In this work, the power flow and losses in the network are obtained with the help of load flow analysis using data structures. The proposed FPA approach has been applied to solve 33-, 34-, 69- and 85 bus RDSs. The results obtained are compared with those of the analytical method, fuzzy real coded genetic algorithm, two stage fuzzy approach and teaching learning based optimization algorithms. The comparison shows that FPA is a highly suitable optimization approach for solving capacitor placement problems.

1. Introduction

The problem of optimal capacitor placement (OCP) in a radial distribution system (RDS) involves the determination of the locations and sizing of capacitors to be installed at the buses for minimizing the power loss and improving the voltage profile of the system. Several methods have been proposed for the solution of this OCP problem. A review and comparative study on the optimum shunt capacitor placement in distribution systems is presented in [1]. The mixed integer programming method to solve the OCP problem was initially presented by Baran and Wu [2]. The problem was first linearized and then solved using mixed integer linear programming approach in [3]. OCP in radial and mesh distribution systems using mixed integer non-linear programming (MINLP) approach has been proposed in [4]. An integrated approach based on the loss sensitivity factor (LSF) and voltage stability index (VSI) was used to determine the optimal location for capacitor placement and a bacterial foraging optimization algorithm (BFOA) was proposed for optimal sizing of capacitor banks in [5]. In addition to this, the authors in [5] have implemented BFOA under light, nominal and peak load conditions.

Two new bio-inspired or metaheuristic algorithms – the bat algorithm and cuckoo search algorithm – have been proposed for OCP problems in [6]. Sensitivity analysis for finding the optimal location and gravitational search algorithm for deter-

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mining the sizes of the capacitors have been used in [7]. A new fuzzy based approach for identification of buses for capacitor placement and simulated annealing technique for selection of capacitor sizes has been proposed in [8]. Two algorithms for OCP for improving voltage stability have been proposed in [9]. The first analytical algorithm used VSI for locating the candidate buses and then used the solution of linearized VSI formula for the shunt compensation to be provided. The second algorithm used a fuzzy expert system for capacitor placement and real coded genetic algorithm (FRCGA) for capacitor sizing. Teaching learning based optimization (TLBO) approach to minimize power loss and energy cost has been proposed for OCP in [10]. Reference [11] uses the cuckoo search algorithm for the solution of OCP. An artificial bee colony (ABC) approach to identify the optimal location and size has been proposed in [12]. The authors here have shown that their approach resulted in enhancement of the stability index and maximum net saving. In [13], a new particle swarm optimization (PSO) approach that uses Gaussian and Cauchy probability distributions based random numbers for velocity updating has been presented for OCP problems. In [14], a novel algorithm for OCP which hybridized the concepts of chaotic search opposition-based learning, and quantum mechanics has been proposed.

In [15], a loss sensitivity technique has been used to select the optimal locations and capacitor size is computed by optimizing the maximum loss saving equation with respect to capacitor currents. Several methods including the backward/-forward sweep method have been proposed and used for the load flow analysis in RDSs [16,17]. An improved backward/-forward sweep algorithm has been proposed in [18,19]. In [20], data structure has been used for load flow analysis in RDSs. Some of the loss sensitivity based approaches can be found in [21–23]. Reference [21] uses LSF for identifying the bus locations, and discrete PSO for sizing of capacitors. Reference [22] uses a two stage procedure, comprising loss sensitivity analysis for determining the optimal locations as the first stage, and ant colony optimization for optimal sizing as the second stage. Reference [23] too uses a two stage procedure, the first with LSF with VSI for bus location, and the second uses an improved harmony search algorithm for capacitor sizing.

Flower pollination algorithm (FPA), inspired from the pollination process of flowers, was proposed by Xin-She Yang in 2012 [24]. The applicability of FPA for solving both single objective and multi-objective optimization problems has been presented in [25]. In the current paper, four standard RDSs are considered for OCP using the FPA approach. To validate the results obtained, they are compared with those reported recently in the literature.

Reference [26] deals with the same optimal sizing and capacitor placement problem as in the current paper and the solution too is using the same algorithm (FPA) used in this paper. The difference between the work in [26] and this paper is that, in [26], the authors have used the power loss index (PLI) to determine the optimal bus location, and FPA to determine the capacitor sizing. Whereas, in this paper, FPA is used to determine both the optimal locations and the sizing. This obviates the need to calculate the PLI, and the problem can be solved more simply using just the FPA.

This paper is organized as follows: Section 2 presents the problem formulation of the OCP problem. Section 3 provides an overview of the FPA, and Section 4 provides the step by step procedure of the FPA implementation for the OCP problem. Section 5 contains the different test cases, simulation results and discussion, and the final Section 6 provides the concluding comments.

2. Problem formulation

Fig. 1 shows the single-line diagram of a RDS [2,3]. The set of recursive equations used for power flow computation are

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1} * \left(\frac{P_i^2 + Q_i^2}{|V_i|^2}\right) \tag{1}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1} * \left(\frac{P_i^2 + Q_i^2}{|V_i|^2}\right) \tag{2}$$

$$|V_{i+1}|^2 = |V_i|^2 - 2 * (R_{i,i+1} * P_i + X_{i,i+1} * Q_i) + \left(R_{i,i+1}^2 + X_{i,i+1}^2\right) * \left(\frac{P_i^2 + Q_i^2}{|V_i|^2}\right) \tag{3}$$

where

P_i, Q_i: real and reactive power flows into the receiving end of bus $i+1$ connecting bus i and bus $i+1$

P_{Li}, Q_{Li}: real and reactive power of load at bus i

$R_{i,i+1}, X_{i,i+1}$: The resistance and reactance of the line section between buses i and $i+1$, respectively. The power loss of the line section between buses i and $i+1$ is computed as

$$P_{\text{Loss}}(i, i+1) = R_{i,i+1}\frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{4}$$

The total power loss of the RDS, $P_{T,\text{loss}}$ is determined by adding the losses of all line sections in the system. This is given by

$$P_{T,\text{loss}} = \sum_{i=0}^{n-1} P_{\text{Loss}}(i, i+1). \tag{5}$$

The capacitors are installed at the buses in order to reduce the total power loss and limit the bus voltages within their specified limits. The shunt capacitor exists in a finite number of standard sizes which are integer multiples of the smallest size Q_0^c. Additionally, the annual cost per kVAR varies from one size to another. In general, large capacitor sizes are cheaper than smaller ones. The maximum allowable capacitor size placed at any bus location is limited to $Q_{\max}^c = LQ_0^c$, where L is an integer. At each capacitor location, there are L capacitor sizes $\{Q_0^c, 2Q_0^c, \ldots, LQ_0^c\}$ to choose from. $\{K_1^c, K_2^c, \ldots, K_L^c\}$ are their corresponding equivalent annual cost per kVAR.

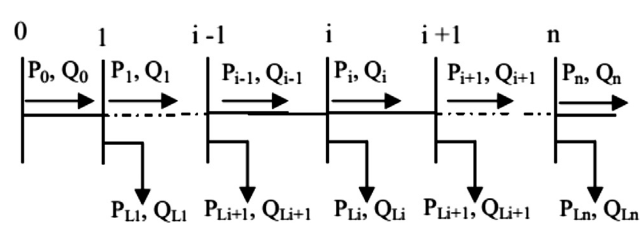

Fig. 1 Single-line diagram of a RDS.

The objective of the OCP problem is to minimize the real power loss, and cost of capacitor installation, besides improving the voltage profile, which is not represented in the objective function. This is subject to bus voltage limits and reactive power limits [8]. This is represented mathematically as the following nonlinear constrained optimization problem:

$$\min\ F = \min(\text{cost}) = K_P P_{T,\text{loss}} + \sum_{i=1}^{n} K_i^c Q_0^c = K_P P_{T,\text{loss}} + \sum_{i=1}^{n} Q_i^c \quad (6)$$

$$\text{s.t.}\, V_{\min} \leqslant V_i \leqslant V_{\max} \quad (7)$$

$$Q_i^c \leqslant \sum_{i=1}^{n} Q_{Li} \quad (8)$$

where K_P is the equivalent annual cost per unit of power loss in \$/(kW-year), $i = 1, 2, \ldots, n$ are the indices of buses selected for compensation, and $V_{\min}$ and $V_{\max}$ are the permissible minimum and maximum voltage limits, respectively. Q_i^c is the reactive power compensation at bus i.

3. Flower pollination algorithm

Xin-She Yang introduced the Flower Pollination Algorithm (FPA), inspired by the pollination process of flowering plants

Table 1 Possible choices of capacitor sizes and cost/(kVAR-year).

j	1	2	3	4	5	6	7
Capacitor size, Q_c (kVAR)	150	300	450	600	750	900	1050
Cost (\$/kVAR-year)	0.500	0.350	0.253	0.220	0.276	0.183	0.228
j	8	9	10	11	12	13	14
Capacitor size, Q_c (kVAR)	1200	1350	1500	1650	1800	1950	2100
Cost (\$/kVAR-year)	0.170	0.207	0.201	0.193	0.870	0.211	0.176

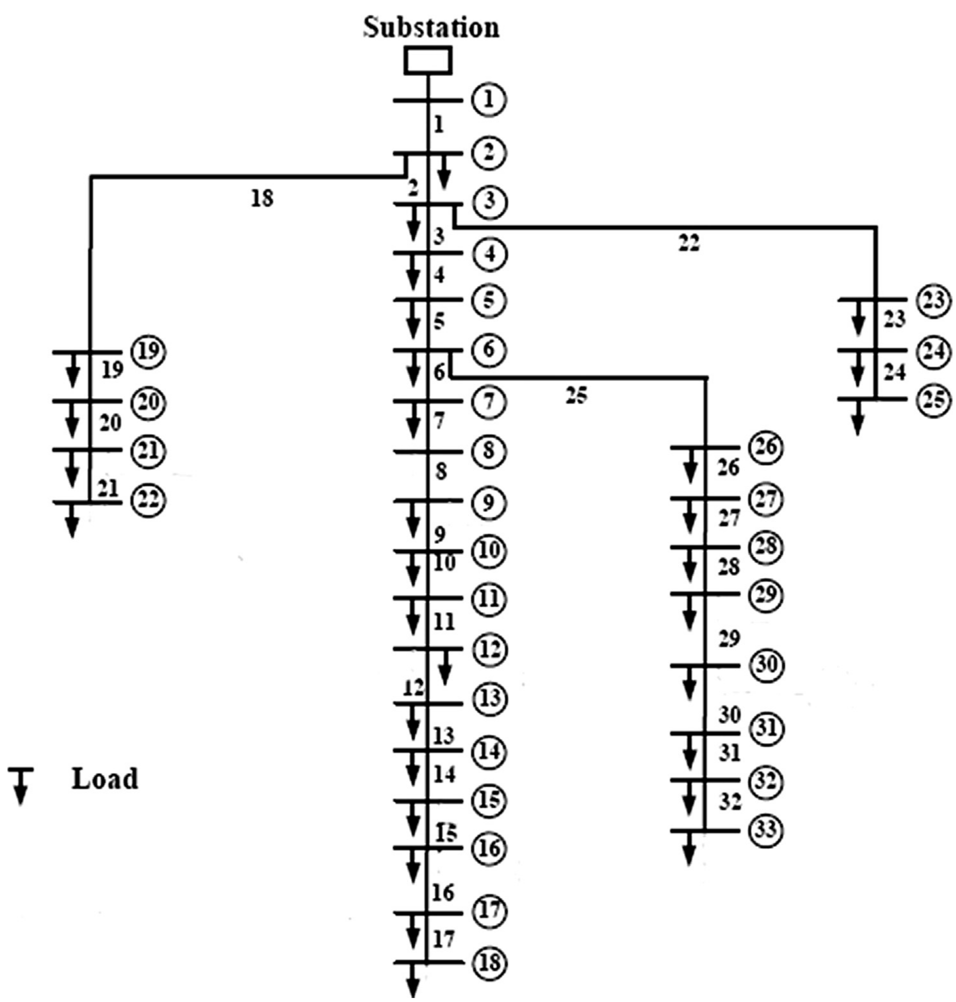

Fig. 2 Single line diagram of 33-bus RDS.

[24]. The author has shown the applicability of the FPA approach for solving optimization problems by its implementation on benchmark test functions such as Rosenbrock, Ackley, Rastrigin, and Griewank functions. The FPA approach was extended to solve multiobjective optimization problems in [25]. Flowering plants have been evolving for more than the past 125 million years [24]. The reproduction of plants is due to pollination of flowers. This pollination may be caused by pollen from a flower of the same plant or from some other plant. It is classified into two groups, (a) local pollination, using pollen of the same flower, and (b) cross pollination, using pollen from a flower of some other plant of same species. Local pollination occurs in the plant itself without the help of any insect. Cross pollination occurs with the help of pollinators such as insects.

For engineering optimization, the vector of control variables of the problem can be considered as a flower, and a group of flowers form a population of flowers (or solutions). For simplicity, we assume that each flower is equivalent to a pollen gamette, and thus there is no difference between pollen and flowers. Thus, a flower is considered as a solution vector. The cross pollination process, also termed as global pollination, involves insects whose behavior is addressed by Lévy flights. Lévy flight (L) behavior is governed and approximated as

$$L(\lambda) \sim \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}} \tag{9}$$

where the notation ~ means that L is drawn from a probability distribution on the right-hand side. λ is a constant that charac-

Table 2 Results and comparison for 33-bus RDS with and without OCP.

Description	Base case	Analytical method (IP*) [7]	Two stage method [15]	FRCGA [9]	FPA
Total loss (kW)	210.97	171.78	144.04	141.24	139.075
$C_{Location}$ (bus no.)	–	9, 29, 30	7, 29, 30	28, 6, 29, 8, 30, 9	30, 13, 24
C_{Size} (in kVAR)	–	450, 800, 900	850, 25, 900	25, 475, 300, 175, 400, 350	900, 450, 450
V_{min} (p.u)	0.9089	0.9501	0.9251	0.934	0.9327
Total kVAR	–	2150	1775	1725	1800
kVAR/kW loss reduction	–	54.86	26.52	24.74	25.04
Cost of kW loss (A) ($)	35442.96	28859.04	24198.72	23728.32	23364.6
Cost of capacitor (B) ($/(kVAR-year))	–	499.35	507.15	492.86	392.4
Total cost (C = A + B) ($)	35442.96	29358.39	24705.87	24221.18	23757.0
Net savings ($) (D = 35442.96 – C)	0.0	6084.57	10737.09	11221.78	11685.96
% Savings (E = D/35442.96)	0.0%	17.17%	30.29%	31.66%	32.97%
Best power loss (kW)	NA**	NA	NA	NA	139.075
Worst power loss (kW)	NA	NA	NA	NA	140.046
Mean power loss (kW)	NA	NA	NA	NA	139.57
Standard deviation	NA	NA	NA	NA	0.07793
Average computational time (s)	NA	NA	2.94	NA	7.75

* IP = interior point.
** NA = not available.

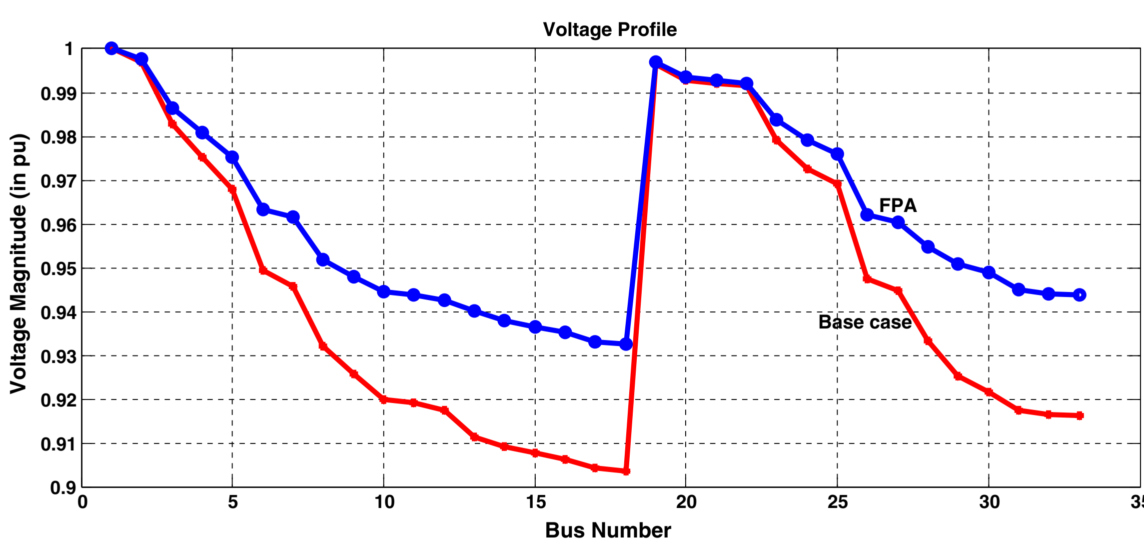

Fig. 3 Voltage profile of the 33-bus RDS without (base case) and with OCP.

terizes the flying angle, $\Gamma(\lambda)$ is the standard gamma function and $s > 0$ is the step size for the movement of the pollinator. This Lévy flight is used to find global pollination in the flower as

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \gamma L(\lambda)\left(\boldsymbol{g}_* - \boldsymbol{x}_i^t\right) \tag{10}$$

where $\boldsymbol{x_i} = [x_{1,i} \quad x_{2,i} \quad \ldots \quad x_{d,i}]$ is the ith flower that undergoes global pollination in iteration t, and $\boldsymbol{g}_*$ is the global best flower of the population. In some flowers local pollination may take place, which is given as

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \epsilon\left(\boldsymbol{x}_j^t - \boldsymbol{x}_k^t\right) \tag{11}$$

where $\boldsymbol{x}$ with suffixes i, j and k are the different flower positions in the population, and ϵ is a random number between zero and one.

For each flower, the type of pollination is decided by a switching probability p. If a random number corresponding to the flower is less than p, then global pollination is carried out; else local pollination is used. Global pollination provides the exploration capability, and local pollination provides the exploitation capability to the algorithm. The decision to explore or exploit is made by the switching probability p. In a minimization problem, the flower that yields the least value of the fitness function is selected as the global best flower. In each iteration, all the flowers undergo pollination. The program is stopped when there is no appreciable improvement in the minimum fitness value or until a predefined number of iterations.

4. FPA implementation for the OCP problem

Placement of capacitors in appropriate locations reduces the losses and improves the voltage profile. The control variables of the problem are of two types, namely the locations and size of capacitors. These two types of control variables form a flower (vector). For each flower, the control variables are updated and data structure (DS) based load flow [20] is executed to find the system losses and bus voltages. The loss output of the load flow is the fitness of the flower given by (6). The flower that gives the best fitness (the least or minimum loss) is chosen as the global best flower, and corresponds to the optimal values of the locations and sizes of the capacitors.

The step by step procedure of FPA to solve the OCP optimization problem is given below.

Step 0: Choose the population size N_P, maximum number of iterations, iter$_{\max}$, number of locations for capacitors to be installed, switch probability p, scaling factor γ, step size s, and lambda constant λ.

Generate the initial population of flowers or feasible solution vectors

$$\boldsymbol{P} = \begin{bmatrix} P^1 \\ P^2 \\ \vdots \\ P^{N_P} \end{bmatrix} = \begin{bmatrix} l_1^1 & l_2^1 & \ldots & l_{nc}^1 & Q_1^1 & Q_2^1 & \ldots & Q_{nc}^1 \\ l_1^2 & l_2^2 & \ldots & l_{nc}^2 & Q_1^2 & Q_2^2 & \ldots & Q_{nc}^2 \\ \vdots & \ldots & & & \vdots & \ldots & & \vdots \\ l_1^{N_P} & l_2^{N_P} & \ldots & l_{nc}^{N_P} & Q_1^{N_P} & Q_2^{N_P} & \ldots & Q_{nc}^{N_P} \end{bmatrix} \tag{12}$$

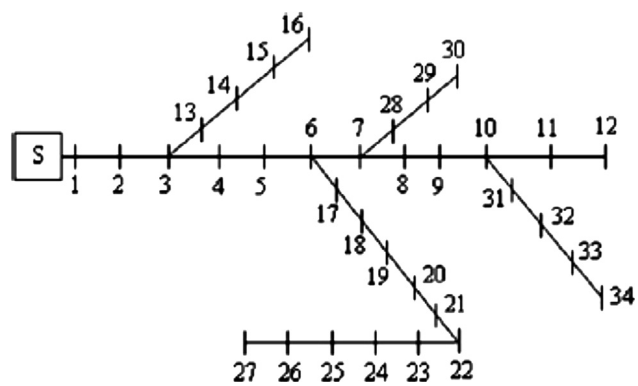

Fig. 5 Single line diagram of 34-bus RDS.

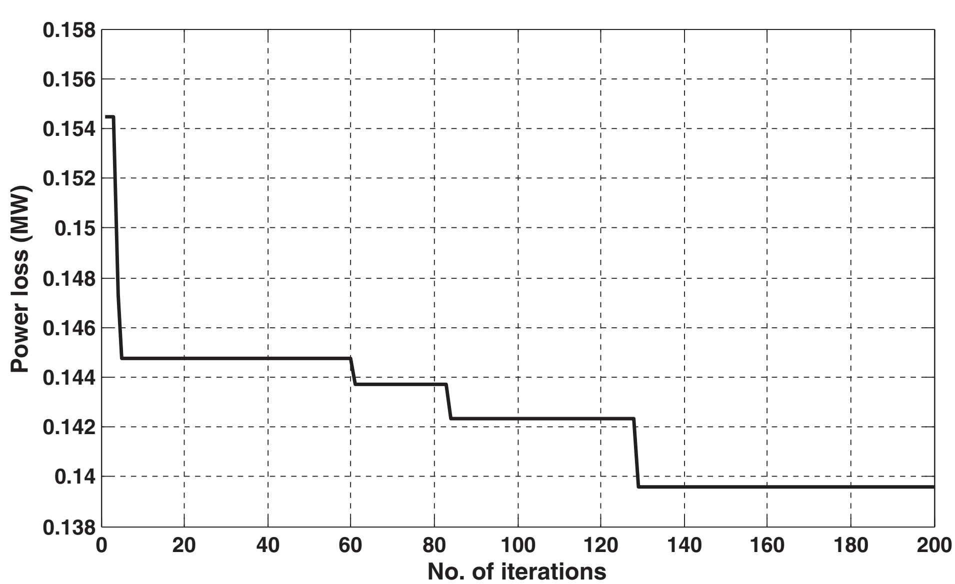

Fig. 4 Convergence of the solution by FPA approach for 33-bus RDS.

Table 3 Results and comparison for 34-bus RDS with and without OCP.

Description	Base case	PSO [29]	Two stage method [15]	Fuzzy-based approach [8]	Discrete PSO [21]	ACO [22]	FPA
Total loss (kW)	221.73	168.8	162.63	162	163.3	162.68	161.055
$C_{Location}$ (bus no.)	–	19, 22, 20	9, 19, 26	NA	19, 22, 26	9, 22, 25	10, 18, 24
C_{Size} (in kVAR)	–	781, 803, 479	400, 1000, 800	NA	1050, 300, 600	645, 719, 665	600, 1050, 900
V_{min} (p.u)	0.9416	0.9486	0.9494	0.951	0.9501	0.9501	0.9496
Total kVAR	–	2063	2200	3450	1950	2029	2550
kVAR/kW loss reduction	–	38.98	37.23	57.76	33.37	34.36	42.03
(A) Cost of kW loss ($)	37249.54	28358.4	27321.84	27,216	27,440	27,330	27056.4
(B) Cost of capacitor ($/(kVAR-year))	–	1577.6	NA	1005.3	483	1014.5	536.1
Total cost (C = A + B) ($)	37249.54	29,936	NA	28221.3	27,923	28344.5	27,592
Net savings ($) (D = 37249.54 – C)	0.0	7306	NA	8990.7	9295	9911	9657.04
% Savings (E = D/37249.54)	0.0%	19.61%	26.63%	24.13%	24.95%	26.61%	25%
Best power loss (kW)	NA	NA	NA	NA	163.1	–	161.055
Worst power loss (kW)	NA	NA	NA	NA	163.8	–	161.981
Mean power loss (kW)	NA	NA	NA	NA	163.4	–	161.496
Standard deviation	NA	NA	NA	NA	0.2	–	0.08002
Average computational time (s)	NA	NA	3.496	NA	NA	–	9.59

where

l is the location or the bus number.

Q is the available capacitor size in kVAR, in discrete values, to be installed.

nc is the total number of locations or buses at which capacitors are to be installed.

Step 1: Run the load flow for each flower and find the power loss in the distribution system. Evaluate fitness using the fitness or objective function given by (6). Identify the best solution or the global best flower (that which gives the least value of the objective function).

Step 2: Produce new bus locations and Q values: If rand $< p$, use global pollination, given by (11); else, use local pollination, given by (12). Round off each component of the new solution or flower to the nearest integer values. If any component of the solution violates the limits, fix it at the limit violated. This results in discrete values of capacitor ratings (in Table 1).

Step 3: Evaluate the new solutions or flowers. If new solutions are better, replace old solutions with these new solutions. Find the new global best flower. Repeat steps 2 and 3, until the stopping criterion is met.

5. Test cases, results and discussion

The applicability of the FPA approach is tested on four test cases comprising 33-, 34-, 69- and 85-bus RDSs. The optimal parameters used in the FPA approach are as follows. The switching probability p is taken as 0.6. The scaling constant is taken as 6. The value of λ is taken as1.5 and the constant γ is taken as 0.7 for local pollination. The population comprises twenty flowers. The simulation is stopped if there is no improvement in the solutions, that is, if $\frac{\text{fitness}(k)-\text{fitness}(k-1)}{\text{fitness}(k)} < \text{Tol} = 0.0001$. To avoid the possibility of endless execution of the program as per this criterion, the maximum number of iterations too is used as the other criterion, and is fixed as 200. These parameters are the same for all the four test cases in this paper. The bus voltage limits are taken as $V_{min} = 0.9$ p.u. and $V_{max} = 1.1$ p.u. In all the cases, the FPA has been run independently for 50 times with different, randomly generated initial solutions and the statistical results are listed in the corresponding tables.

The sizes of the capacitors installed at the buses are limited to discrete values that are given in Table 1. Their associated costs are also given in the table. The cost of real power loss is assumed to be 168 $/(kW-year) as in [7]. The FPA approach and the load flow solution used are implemented in MATLAB® software on a personal computer with 64 bit, 2.4 GHz, i3 processor and 4 GB RAM. The results of these four test cases are presented and discussed in the next section. The results obtained are compared with those reported in the literature such as the TLBO, two stage approach, fuzzy real coded genetic algorithm (FRCGA) and PSO.

5.1. 33-bus RDS

This RDS has 33 buses and 32 distribution lines with the total real and reactive power demands of 3715 kW and 2300 kVAR respectively [27]. All the calculations are done in per unit system, with the base values $S_{base} = 10$ MVA, and $V_{base} = 12.66$ kV. This radial system has low voltages at end buses due to heavy inductive loads. This low voltage may be improved by connecting capacitors to the buses which supply part of the reactive power demand, thereby reducing the current flow and the losses. Single line diagram of this system is given Fig. 2.

The base case or uncompensated power loss for this system is 210.97 kW. Optimization using the proposed FPA approach gives the optimal locations as bus numbers 30, 13, 24 and optimal sizes as 900, 450, 450 kVAR, respectively. These results are

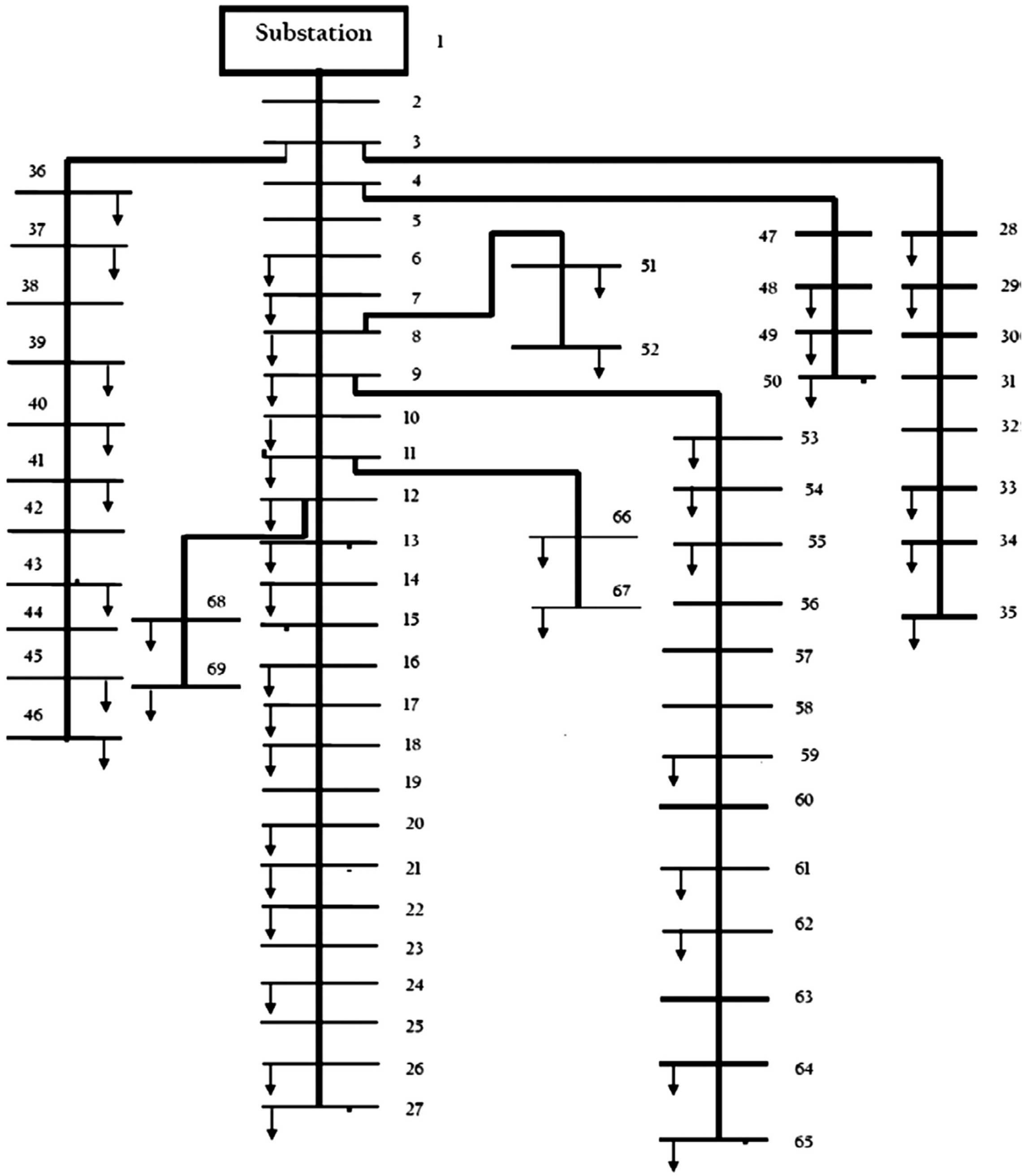

Fig. 6 Single line diagram of 69-bus RDS.

shown in Table 2. Also shown are the results obtained using analytical method (IP[1]), two stage method and FRCGA approach against which the proposed FPA method has been compared. After compensation, the best result for the real power loss is 139.075 kW for the FPA method, which is the least of all methods. After compensation, the minimum voltage is observed at bus #18 as 0.9327 p.u. This is better than the base case minimum voltage of 0.9089 p.u. From the table, it is to be noted that the net saving obtained by the FPA approach is $11685.96 which corresponds to a percentage saving of 32.97%, which is the highest of all. Also shown in the table is the kVAR compensation required per kW loss reduction. Since FPA is a stochastic optimization method, fifty trial runs of the method are made, and the best, worst and mean power loss, the standard deviation of these, and the average computation time are also shown in Table 2.

Fig. 3 shows the voltage profile of 33-bus RDS with and without OCP. It is seen that voltage profile at all the buses improves after compensation.

Fig. 4 shows the graph of the convergence of the solution with iterations for the FPA approach for the 33-bus RDS. It is seen that the solution converges gradually to its final value within the maximum number of iterations.

[1] Interior point.

Table 4 Results and comparison for 69-bus RDS with and without OCP.

Description	Base case	Analytical method(IP) [7]	Two stage method [15]	TLBO [10]	FPA
Total loss (kW)	225	163.28	148.91	146.35	145.86
$C_{Location}$ (bus no.)	–	11, 29, 60	19, 62, 63	12, 61, 64	11, 61, 22
C_{Size} (in kVAR)	–	900, 1050, 450	225, 900, 225	600, 1050, 150	450, 1350, 150
V_{min} (p.u)	0.9092	0.9532	0.9289	0.9313	0.9330
Total kVAR	–	2400	1350	1800	1950
kVAR/kW loss reduction	–	38.89	17.74	22.89	24.64
Cost of kW loss (A) ($)	37,800	27431.04	25016.88	24586.8	24504.48
Cost of capacitor (B) ($/(kVAR-year))	–	517.95	322.5	446.4	468.3
Total cost (C = A + B) ($)	37,800	27948.99	25339.38	25033.2	24972.78
Net savings ($) (D = 37,800 – C)	0.0	9851.01	12460.62	12766.8	12827.22
% Savings (E = D/37,800)	0.0%	26.06%	32.96%	33.77%	33.93%
Best power loss (kW)	NA	NA	NA	146.35	145.86
Worst power loss (kW)	NA	NA	NA	146.92	146.627
Mean power loss (kW)	NA	NA	NA	146.57	146.26
Standard deviation	NA	NA	NA	0.02134	0.05284
Average computational time (s)	NA	NA	5.361	15.76	18.36

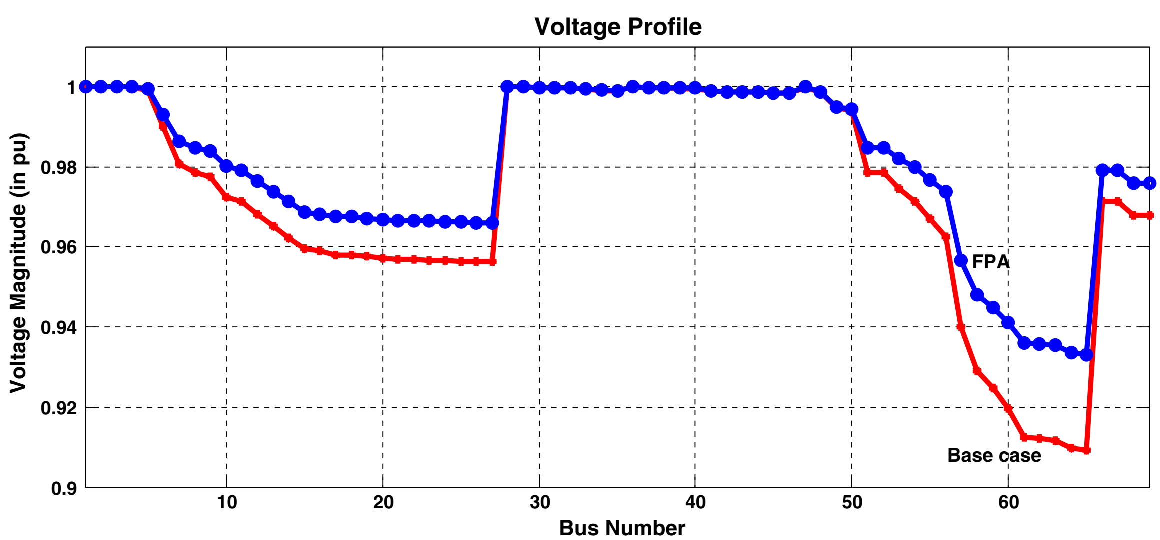

Fig. 7 Voltage profile of the 69-bus RDS without (base case) and with OCP.

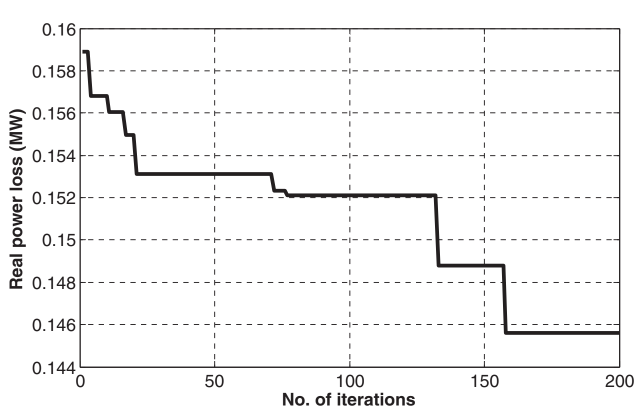

Fig. 8 Convergence of the solution by FPA approach for 69-bus RDS.

5.2. 34-bus RDS

The single line diagram of 34-bus RDS is shown in Fig. 5 [28]. It has 34 buses and 33 distribution lines. The per unit (p.u.) base values are S_{base} = 100 MVA, and V_{base} = 11 kV. The total real and reactive power demand of the system is 4636.5 kW and 2873.5 kVAR, respectively.

The base case power loss for this system is 221.73 kW. Optimization using the FPA approach gives the optimal locations as bus numbers 10, 18, 24 and sizes as 600, 1050, 900 kVAR, respectively. These results are shown in Table 3. For comparison, the results by the other recently reported methods of PSO, two stage method and fuzzy-based approach, discrete PSO, and ACO are also shown. The real power loss after compensation by the FPA method is 161.055 kW, which is the least of all methods. After compensation, the minimum voltage is observed as 0.9496 p.u.at bus #26. This is better than the base case minimum voltage of 0.9416 p.u. From the table it is seen

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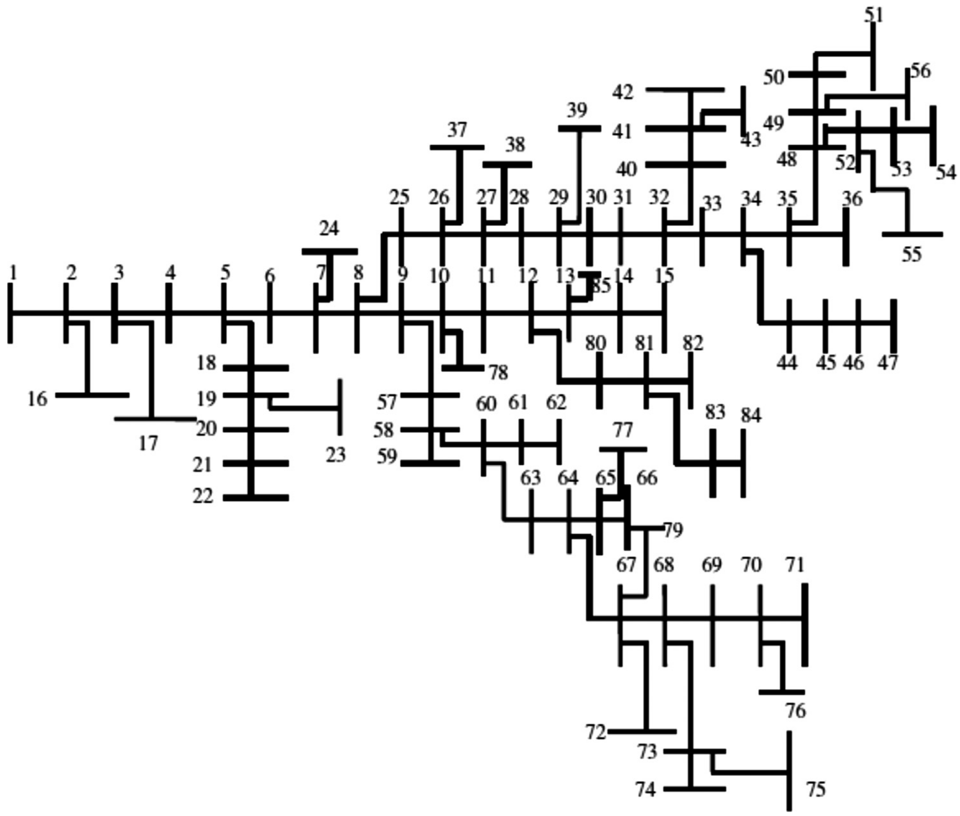

Fig. 9 Single line diagram of 85-bus RDS.

Table 5 Results and comparison for 85-bus RDS with and without OCP.

Description	Base case	PSO [29]	PGS [31]	MINLP [4]	BFOA [5]	FPA
Total loss (kW)	315.3278	163.32	161.4	159.87	152.25	151.807
$C_{Location}$ (bus no.)	–	7, 8, 27, 58	7, 8, 58	7, 8, 29, 58	9, 34, 60	8, 72, 36
C_{Size} (in kVAR)	–	324, 796, 901, 453	200, 1200, 908	300, 700, 900, 500	840, 660, 650	1200, 600, 600
V_{min} (p.u.)	0.8708	0.9153	0.9089	0.9171	0.9180	0.92359
Total kVAR	–	2474	2308	2400	2150	2400
kVAR/kW loss reduction	–	16.28	14.99	15.44	13.18	14.68
Cost of kW loss (A) ($)	52975.07	27437.76	27115.2	26858.16	25,578	25503.576
Cost of capacitor (B) ($/(kVAR-year))	–	1614	1470	779	370	468
Total Cost (C = A + B) ($)	52975.07	29051.76	28585.2	27,637	25,948	25971.576
Net savings ($) (D = 52975.07 – C)	0.0	23923.31	24389.87	25338.07	27027.07	27003.494
% Savings (E = D/52975.07)	0.0%	45.15%	46.04%	47.83%	51%	50.97%
Best power loss (kW)	–	–	–	–	–	151.807
Worst power loss (kW)	NA	NA	NA	NA	NA	152.67
Mean power loss (kW)	NA	NA	NA	NA	NA	152.26
Standard deviation	NA	NA	NA	NA	NA	0.057201
Average computational time (s)	NA	NA	NA	NA	NA	18.36

that the net saving obtained by FPA approach is $9657.04 which corresponds to a saving of 25%, which is comparable with other methods. Also shown in the table is the kVAR compensation required per kW loss reduction. As in the 33-bus test case, fifty trial runs of the method are made, and the best, worst and mean power loss, the standard deviation of these, and the average computation time are also shown in Table 3.

5.3. 69-bus RDS

The single line diagram of 69-bus RDS is shown in Fig. 6 [30]. It has 69 buses and 68 distribution lines. The per unit (p.u.) base values are S_{base} = 10 MVA, and V_{base} = 12.66 kV. The total real and reactive power demand of the system is 3801.89 kW and 2694.1 kVAR, respectively. Bus 3 has three

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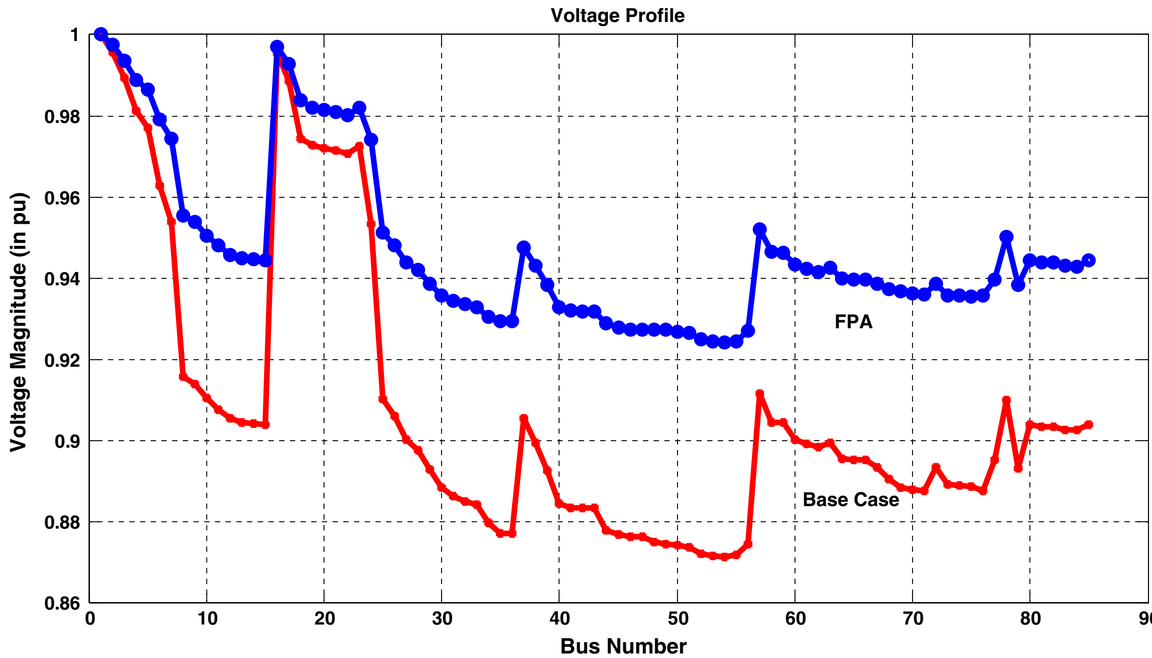

Fig. 10 Voltage profile of the 85-bus RDS without (base case) and with OCP.

branches and buses 4, 7, 9, 11 and 12 have two branches, and the other buses have only one branch connected to their next bus.

The base case power loss for this system is 225 kW. Optimization using the proposed FPA approach gives the optimal locations as bus numbers 11, 61, 22 and sizes as 450, 1350 and 150 kVAR, respectively. These results are shown in Table 4. The comparison of results with other methods such as IP (Analytical), two stage method and TLBO approach are also presented in the table. After compensation the real power loss is 145.86 kW. It can be seen that the loss obtained by the proposed FPA approach is the least of all other methods. After compensation, the minimum voltage is observed at bus #65 as 0.9330 p.u. This is better than the base case minimum voltage of 0.9092 p.u. From the table it is to be noted that the net saving obtained by FPA approach is $12827.22 which corresponds to a percentage saving of 33.93% is the highest of all. Also shown in the table is the kVAR compensation required per kW loss reduction. As in the previous test cases, fifty trial runs of the method are made, and the best, worst and mean power loss, the standard deviation of these, and the mean computation time are also shown in Table 4.

In [26], the optimal locations were found to be buses 61 and 21, and the capacitors were of 1250 kVAR and 250 kVAR respectively, and the power loss 145.77 kW. On simulation by the authors of this paper, the total loss for the uncompensated base case matches with the value reported in [26], but the total loss value after compensation is 147.04 kW, against the value of 145.777 kW reported in [26].

Fig. 7 shows the voltage profile of 69-bus RDS with and without OCP. It is seen that voltage profile at all the buses improves after compensation.

Fig. 8 shows the graph of the convergence of the solution with iterations for the FPA approach for the 69-bus RDS.

5.4. 85-bus RDS

The single line diagram of 85-bus RDS is shown in Fig. 9 [7]. It has 85 buses and 84 distribution lines. The total real and reactive power demand of the system is 2570.28 kW and 2621.936 kVAR, respectively. The per unit (p.u.) base values are S_{base} = 100 MVA, and V_{base} = 11 kV. The base case power loss is 315.3278 kW. Table 5 shows the optimal capacitor locations and sizes obtained by the FPA along with those of the other techniques including particle swarm optimization (PSO), plant growth simulation (PGS). The power loss after compensation, obtained by the FPA method is 151.807 kW, which is the least of all. The minimum voltage after compensation is observed at bus #53 as 0.92359 p.u. This is better than the base case minimum voltage of 0.8708 p.u. From the table it is to be noted that the net saving obtained by the FPA approach is $27003.494 which corresponds to a percentage saving of 50.97%, which is comparable to that by BFOA, and better than those by the other methods. Also shown in the table is the kVAR compensation required per kW loss reduction. As in the previous test cases, fifty trial runs of the method are made, and the best, worst and mean power loss, the standard deviation of these, and the mean computation time are also shown in Table 5.

Fig. 10 shows the voltage profile of 85-bus RDS with and without OCP. The Figure clearly shows the improvement in the voltage profile at all the buses after compensation.

6. Conclusion

In this paper, a novel approach using the new metaheuristic, flower pollination algorithm has been used for optimal placement and sizing of the capacitors in RDSs. The proposed approach has been tested on 33-, 34-, 69-and 85-bus systems. It is shown that OCP results in power loss minimization, maximization of the net annual cost savings and improvement in the voltage profile. The comparisons of the solutions obtained by the FPA approach with those by the other methods indicate that the proposed approach yields the least power loss for all the four test cases, and the net savings are comparable with the other methods.

The good results of this optimization is due to both the local and global search capabilities of the FPA approach. From this successful implementation of the FPA approach for OCP problems, it can be concluded that it is highly suitable for determining the optimal location and size of the capacitors in distribution networks. The application of FPA to other optimization problems in related areas can be considered for future work. In addition, since the results are obtained using fixed parameter settings for all algorithms, it would be useful to carry out a systematic study of parameter and sensitivity analysis. Further, it may be advantageous to develop an adaptive variant of the FPA so that even better performance may be achieved.

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