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Flower Pollination Algorithm and Loss Sensitivity Factors for optimal sizing and placement of capacitors in radial distribution systems

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ABSTRACT

In this paper, Flower Pollination Algorithm (FPA) is proposed for optimal allocations and sizing of capacitors in various distribution systems. First the most candidate buses for installing capacitors are suggested using Loss Sensitivity Factors (LSF). Then the proposed FPA is employed to deduce the locations of capacitors and their sizing from the elected buses. The proposed algorithm is tested on 10, 33 and 69 bus radial distribution systems. The obtained results via the proposed algorithm are compared with others to highlight the benefits of the proposed algorithm in reducing total cost and maximizing the net saving. Moreover, the results are introduced to verify the effectiveness of the proposed algorithm to enhance the voltage profiles for various distribution systems.

Introduction

In distribution networks, reactive power flows cause high power losses, high voltage drop and low power factor. These effects can be reduced by optimally installing of shunt capacitors [1]. Compensation of reactive power presents the basic role in power system planning to provide compatible locations of the compensation apparatus to guarantee the minimum cost of compensation with suitable voltage profiles [2].

Many techniques and optimization algorithms have been addressed in literature to deal with the problem of locations and sizing of capacitors in distribution systems. Genetic Algorithm (GA) [2], Particle Swarm Optimization (PSO) [3,4], Firefly Algorithm (FA) [5], Memetic Algorithm [6], Differential Evolutionary (DE) [7–9], Evolutionary Algorithm (EA) [10,11], Fuzzy Logic [12–15], Hybrid Algorithm [16], Heuristic Algorithm [17–19], Cuckoo Search Algorithm [20], Plant Growth Simulation Algorithm (PGSA) [21–23], Harmony Search (HS) [24], Ant Colony Optimization (ACO) [25], Mixed Integer Non Linear Programming (MINLP) [26], Artificial Bee Colony (ABC) [27], Teaching Learning Based Optimization (TLBO) [28] and Direct Search Algorithm (DSA) [29] are introduced as a solution to capacitor placement problem. However, these algorithms appear to be effective to deal with this problem, they may not guarantee reaching the optimal cost due to many reasons. In [4,5,10,20–22,24], the values of capacitors are treated as a continuous value. Moreover, the suggested objective function in [6,7,23,29] is so conventional and doesn't take all costs in consideration. The studies in [3,4,6,9,13,16,17,19,22–24,26] are limited to small scale system. Also, some use large number of buses to compensate [2,11,24]. On the other hand, the mentioned techniques have their own defects and have many parameters to assign that lead to large processing time [8,12–15,27]. Recently, the Flower Pollination Algorithm (FPA) is proposed in this paper to deal with the problem of optimal capacitor placement. It has only one key parameter p (switch probability) which makes the algorithm easier to implement and faster to reach optimum solution. Moreover, this transferring switch between local and global pollination can guarantee escaping from local minimum solution. In addition, it is clear from the literature survey that the application of FPA to solve the problem of capacitor location has not been discussed. This encourages us to adopt FPA to deal with this problem.

FPA technique is introduced in this paper in order to minimize the investment cost of new compensation sources and the active power losses with mitigating the voltage profiles for different distribution systems. The locations of the shunt capacitors problem are obtained at first by examinations the buses of higher LSF. Then FPA is introduced to decide the optimal locations and sizing of capacitors from specified buses. The effectiveness of the proposed

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Nomenclature

P_k, Q_k	the total effective active and reactive power supplied behind the bus 'k'
V_k	the magnitude of voltage at bus k
R_{ik}, X_{ik}	the resistance and reactance of transmission line between bus 'i' and 'k'
V_i	the magnitude of voltage at bus i
x_l^t	the pollen l
g_*	the current best solution found at the current generation
γ	scaling factor
$\Gamma(\lambda)$	the standard gamma function
p	switch probability
K_P	the cost per kW h
P_{Loss}	the total power losses after compensation
T	the time in hours
CB	the number of compensated buses
K_C	the cost per kVAr
K_I	the cost per installation
Q_{Ci}	the value of installed reactive power in kVAr
P_{Swing}	the active power of swing bus
Q_{Swing}	the reactive power of swing bus
L	the number of transmission line in a distribution system
$Pd(q)$	the demand of active power at bus q
$Qd(q)$	the demand of reactive power at bus q
N	the number of total buses
$V_{\min}$	the minimum voltage at bus i
$V_{\max}$	the maximum voltage at bus i
PF	Power Factor
$PF_{\min}$	the minimum power factor
$PF_{\max}$	the maximum power factor
PF_{sys}	the power factor at swing bus
$Q_{C\min}$	the minimum injected reactive power in kVAr
$Q_{C\max}$	the maximum injected reactive power in kVAr

List of abbreviations

FPA	Flower Pollination Algorithm
LSF	Loss Sensitivity Factors
SA	Simulated Annealing
TS	Tabu Search
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
PGSA	Plant Growth Simulation Algorithm
DSA	Direct Search Algorithm
TLBO	Teaching Learning Based Optimization
CSA	Cuckoo Search Algorithm
ABC	Artificial Bee Colony
ACO	Ant Colony Optimization
FA	Firefly Algorithm
MINLP	Mixed Integer Nonlinear Programming
HS	Harmony Search
DE–PS	Differential Evolution and Pattern Search
GSA	Gravitational Search Algorithm
IP	Interior Point

FPA is shown for three distribution systems. The results of the FPA are compared with various techniques to detect its superiority.

Loss Sensitivity Factors

Loss Sensitivity Factors (LSF) are employed in this paper to assign the candidate buses for capacitors installation [4]. The area of search is greatly reduced and consequently the time consumed in optimization process by using LSF. For a transmission line 'l' connected between 'i' and 'k' buses, as given in Fig. 1.

The active power loss in this line is specified by $I_l^2 R_{ik}$, which can be given by:

$$P_{ik\text{-}loss} = \frac{\left(P_k^2 + Q_k^2\right) R_{ik}}{(V_k)^2} \tag{1}$$

Also, the reactive power loss in this line is obtained below:

$$Q_{ik\text{-}loss} = \frac{\left(P_k^2 + Q_k^2\right) X_{ik}}{(V_k)^2} \tag{2}$$

The LSF can be computed from the following equations:

$$\frac{\partial P_{ik\text{-}loss}}{\partial Q_k} = \frac{2Q_k * R_{ik}}{(V_k)^2} \tag{3}$$

$$\frac{\partial Q_{ik\text{-}loss}}{\partial Q_k} = \frac{2Q_k * X_{ik}}{(V_k)^2} \tag{4}$$

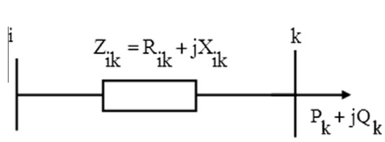

Fig. 1. Radial distribution system equivalent circuit.

These values are given from the base case load flow and are ordered in descending order for all transmission lines. Then, normalized voltages are obtained by dividing the base case voltages by 0.95. If the values of these voltages are less than 1.01 they can be considered as candidate buses for compensation devices [5].

Overview of Flower Pollination Algorithm

FPA was developed by Xin-She Yang in 2012 [30]. It is inspired by the pollination process of flowering plants. The main purpose of a flower is ultimately reproduction via pollination. Flower

Objective min or max $f(x), x = (x_1, x_2, \ldots\ldots\ldots, x_d)$
Initialize a population of n flowers/pollen gametes with random solutions
Find the best solution g_* in the initial population
Define a switch probability $p \in [0, 1]$
for $t = 1$: MaxGeneration (for all generations)
While $(l < n)$ (n no. of flowers in the population)
If rand $< p$,
Draw a (d-dimensional) step vector L from Lévy distribution
Global pollination via $x_l^{t+1} = x_l^t + \gamma L(\lambda)(g_* - x_l^t)$
else
Draw from a uniform distribution in [0, 1]
Do local pollination via $x_l^{t+1} = x_l^t + \varepsilon(x_n^t - x_p^t)$
end if
Evaluate new solutions
If new solutions are better, update them in the population
end while
Find the current best solution g_*
end for
Output the best solution found.

Fig. 2. Pseudo code of the proposed FPA.

Table 1
The used parameters.

K_P = 0.06 \$/kW h, $0.90 \leqslant \lvert V_i \rvert \leqslant 1.05$
T = 8760 h, 0.9 lagging $\leqslant PF_{sys} \leqslant 1$
K_C = 3 \$/kVAr, 50 kVAr $\leqslant Q_C \leqslant$ 1500 kVAr
K_I = 1000 \$

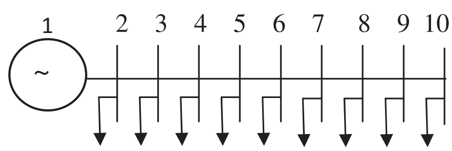

Fig. 3. The schematic diagram of the 10 bus system.

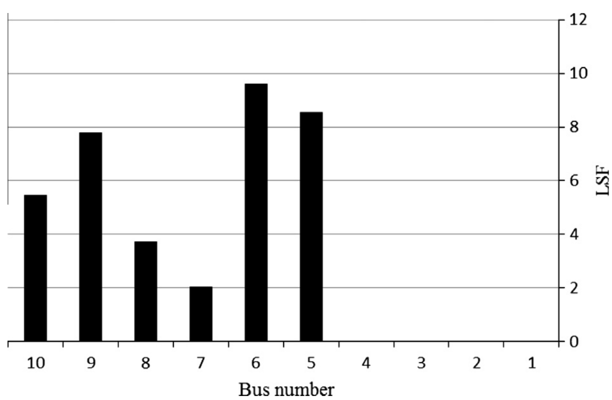

Fig. 4. The values of LSF for 10 bus system.

pollination is typically correlating with the transfer of pollen, which often associated with pollinators such as birds, insects, bats and other animals.

Pollination appears in two major forms: abiotic and biotic. Most of flowering plants depend on the biotic pollination process. In which the pollen is transferred by pollinators. The rest of pollination follows abiotic form that does not require any pollinators such as grass [31]. Wind and diffusion help in pollination process of such flowering plants. On the other hand, pollination can be achieved by self-pollination or cross-pollination. Self-pollination is the pollination of one flower from pollen of the same flower. Cross-pollination is the pollination from pollen of a flower of different plants [32].

The objective of flower pollination is the survival of the fittest and the optimal reproduction of plants in terms of numbers as well as the fittest. This can be considered as an optimization process of plant species. All of these factors and processes of flower pollination created optimal reproduction of the flowering plants [33]. FPA has been adopted in this paper to optimize capacitors allocation problems.

Flower Pollination Algorithm

For FPA, the following four steps are used [34]:

Step 1: Global pollination represented in biotic and cross-pollination processes, as pollen-carrying pollinators fly following Lévy flight [31].
Step 2: Local pollination represented in abiotic and self-pollination as the process does not require any pollinators.
Step 3: Flower constancy which can be developed by insects, which is on a par with a reproduction probability that is proportional to the similarity of two flowers involved.
Step 4: The interaction of local and global pollination is controlled by a switch probability $p \in [0, 1]$, lightly biased toward local pollination.

The above rules have to be converted into proper updating equations. For example at the global pollination step, the pollinators carry the flower pollen gametes, so the pollen can travel over a long distance. Therefore, global pollination step and flower constancy step can be represented by:

$$x_l^{t+1} = x_l^t + \gamma L(\lambda)\left(g_* - x_l^t\right) \tag{5}$$

In fact, $L(\lambda)$ the Lévy flights based step size that corresponds to the strength of the pollination. Since long distances can be covered using various distance steps, a Lévy flight can be used to mimic this behavior efficiently. That is, $L > 0$ from a Lévy distribution.

Table 2
Results for 10 bus system.

Items	Un-compensated	Compensated											
		Fuzzy reasoning [12]		PSO [4]		PGSA [21]		MINLP [26]		Discrete PSO [39]		Proposed FPA	
Year		1996		2007		2011		2014		2014		**2015**	
Total losses (kW)	783.77	704.883		696.21		694.93		673.44		701.2		**648.77**	
Loss reduction (%)	–	10.065		11.17		11.33		14.08		10.53		**17.22**	
Minimum voltage	0.8375	–		–		0.901		–		0.9002		**0.9168**	
Optimal location and size in kVAr	–	4	1050	6	1174	5	1200	5	400	4	3000	**6**	**1050**
		5	1050	5	1182	7	1200	7	2000	5	1500	**5**	**1050**
		6	1950	9	264	8	200	8	200	6	150	**9**	**450**
		10	900	10	566	9	407	9	1400	7	450	**10**	**450**
		–	–	–	–	–	–	–	–	8	600	–	–
		–	–	–	–	–	–	–	–	9	300	–	–
Total kVAr		4950		3186		3007		4000		6000		**3000**	
Annual cost (\$/year)	411949.5	389336.5		379,486		378276.2		369960.1		390550.72		**353993.5**	
Net saving (\$/year)	–	22,613		32463.5		33673.3		41989.45		21398.79		**57,956**	
% saving	–	5.5		7.9		8.2		10.2		5.2		**14.1**	
Worst losses		NA		NA		NA		NA		716.2		**661.4**	
Best losses		NA		NA		NA		NA		701.2		**648.77**	
Mean losses		NA		NA		NA		NA		708.4		**650.19**	
Variance		NA		NA		NA		NA		NA		**16.01**	
Standard deviation		NA		NA		NA		NA		4.4		**4.001**	

Bold items present the result obtained by the proposed algorithm.

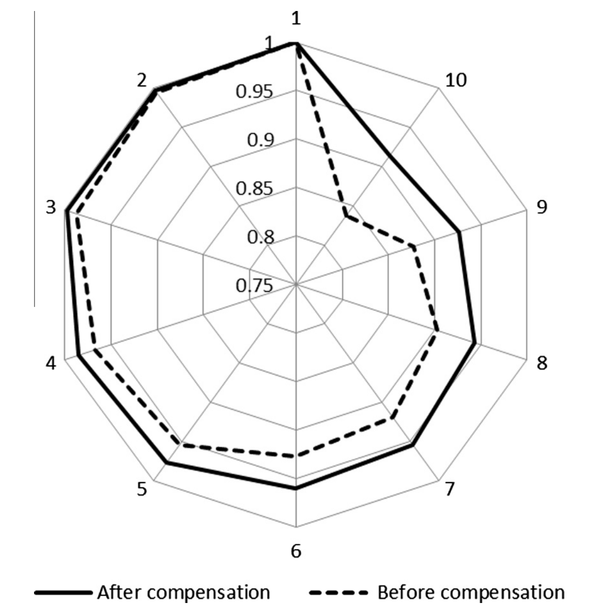

Fig. 5. The effect of compensated devices on voltages of 10 bus system.

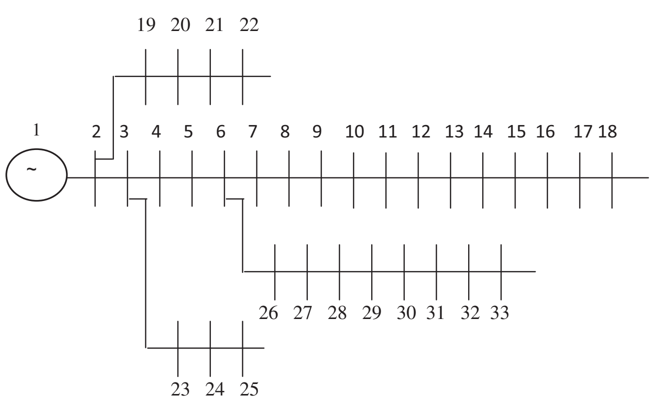

Fig. 6. The schematic diagram of the 33 bus system.

$$L \sim \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}, \quad (s \gg s_0 > 0) \tag{6}$$

$\Gamma(\lambda)$ is the standard gamma function, and this distribution is valid for large steps $s > 0$.

For the local pollination, both Step 2 and Step 3 can be represented as

$$x_l^{t+1} = x_l^t + \varepsilon\left(x_n^t - x_p^t\right) \tag{7}$$

where x_n^t and x_p^t are pollen from different flowers of the same plant species mimicking the flower constancy in a limited neighborhood. For a local random walk, x_n^t and x_p^t comes from the same species then ε is drawn from a uniform distribution as $[0,1]$.

In principle, flower pollination activities can occur at all scales, both local and global. In fact adjacent flower patches are pollinated by local flower pollen than those far away. In order to mimic this, one can effectively use a switch probability (Step 4) p to switch between common global pollination to intensive local pollination. One can use a value of $p = 0.5$ as an initially value. A preliminary parametric showed that $p = 0.8$ might work better for most applications.

The previous steps of FPA plus the switch condition can be summarized in the pseudo code shown in Fig. 2 while the parameters of FPA are given in appendix.

Objective function

The proposed objective function of optimal capacitor location problem is to minimize the total cost which is determined by the following equation:

$$Cost = K_P * P_{Loss} * T + K_I * CB + K_C * \sum_{i}^{CB} Q_{Ci} \tag{8}$$

where the constants are taken from [11].

Equality and inequality constraints

Eq. (8) is minimized whilst satisfying the following equality and inequality constraints.

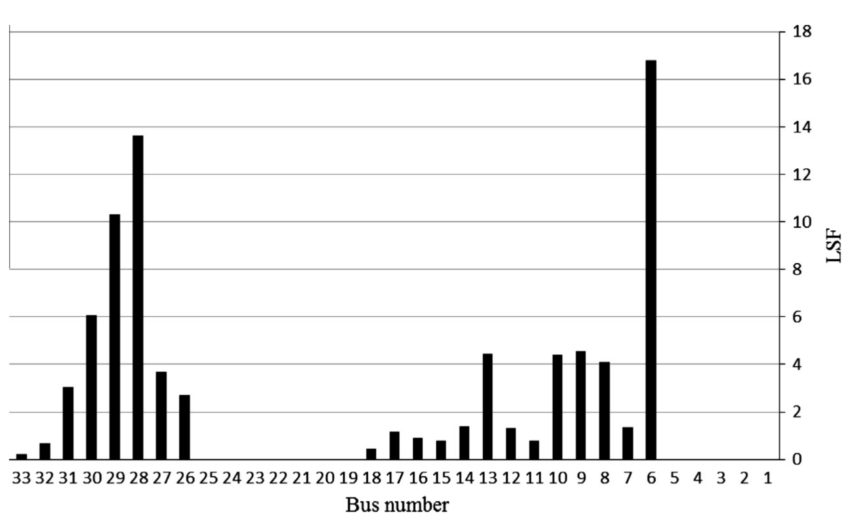

Fig. 7. The values of LSF for 33 bus system.

Table 3
Results for 33 bus system.

Items	Un-compensated	Compensated											
		GA [2]		PGSA [22]		GSA [40]		SA [40]		IP [40]		Proposed FPA	
Year		2005		2011		2015		2015		2015		**2015**	
Total losses (kW)	202.66	135.5		135.4		134.5		151.75		171.78		**134.47**	
Loss reduction (%)		33.14		33.19		33.63		25.12		15.24		**33.65**	
Minimum voltage	0.9131	0.9349		0.9463		0.9672		0.9591		0.9501		**0.9365**	
Optimal location and size in kVAr		8	300	6	1200	13	450	10	450	9	450	**6**	**250**
		15	300	28	760	15	800	14	900	29	800	**9**	**400**
		20	300	29	200	26	350	30	350	30	900	**30**	**950**
		21	300	–	–	–		–		–		–	
		24	300	–	–	–		–		–		–	
		26	300	–	–	–		–		–		–	
		28	300	–	–	–		–		–		–	
		27	600	–	–	–		–		–		–	
Total kVAr		2700		2160		1600		1700		2150		**1600**	
Annual cost ($/year)	106518.1	87318.8		80646.24		78493.2		87859.8		87859.8		**78477.4**	
Net saving ($/year)		19199.3		25871.9		28024.9		18658.3		18658.3		**28040.7**	
% saving		18		24.3		26.3		17.5		17.52		**26.33**	
Worst losses		NA		NA		NA		NA		NA		**138.85**	
Best losses		NA		NA		NA		NA		NA		**134.47**	
Mean losses		NA		NA		NA		NA		NA		**136.53**	
Variance		NA		NA		NA		NA		NA		**2.7145**	
Standard deviation		NA		NA		NA		NA		NA		**1.64**	

Bold items present the result obtained by the proposed algorithm.

Equality constraint

- Load flow constraint

Traditional methods such as Newton Raphson and Gauss Siedel cannot be used in distribution system due to ill condition [35]. Forward sweep algorithm has been introduced by Das et al. [36,37] to solve load flow problem of distribution systems. The equality constraint is given by the following equation:

$$P_{Swing} = \sum_{i=1}^{L} P_{Lineloss}(i) + \sum_{q=1}^{N} Pd(q) \tag{9}$$

$$Q_{Swing} + \sum_{b=1}^{CB} Q_C(b) = \sum_{i=1}^{L} Q_{Lineloss}(i) + \sum_{q=1}^{N} Qd(q) \tag{10}$$

Inequality constraints

- Voltage constraint

The magnitude of voltage at each bus must be limited by the following equation:

$$V_{\min} \leqslant |V_i| \leqslant V_{\max} \tag{11}$$

- Compensation constraint

The injected reactive power at each candidate bus should be less than its effective reactive power.

- Total reactive power constraint

It is noteworthy that the total injected reactive power is less than 0.75 of the total reactive power demand to sustain working of power system with lagging power factor and averting the leading one [11].

$$\sum_{b=1}^{CB} Q_C(b) \leqslant 0.75 \sum_{q}^{N} Qd(q) \tag{12}$$

- Power factor constraint

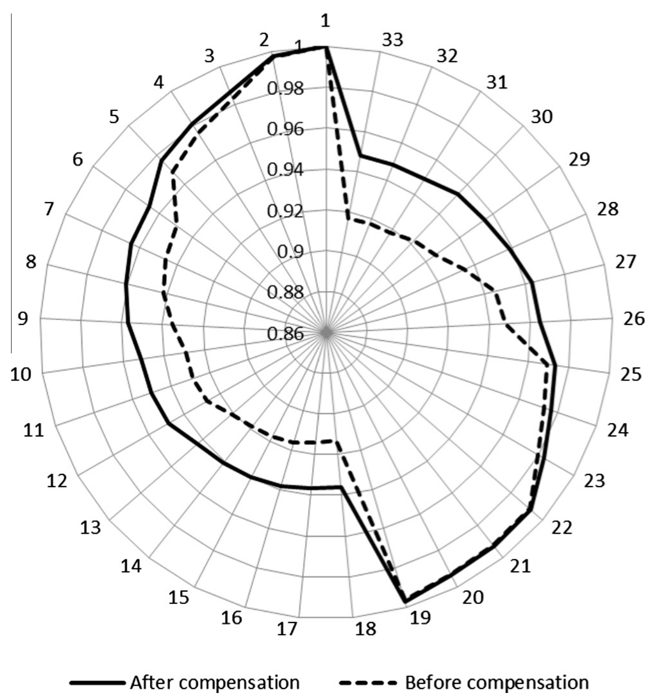

Fig. 8. The effect of compensated devices on voltages of 33 bus system.

Power Factor of overall system (PF_{sys}) should exceed the minimum value and less than the maximum value as shown by the following equation:

$$PF_{\min} \leqslant PF_{sys} \leqslant PF_{\max} \tag{13}$$

- Capacitor rating constraint

The injected kVAr of the installed capacitor is presented as a discrete value by step of 50 kVAr and specified by the following range:

$$Q_{C\min} \leqslant Q_C \leqslant Q_{C\max} \tag{14}$$

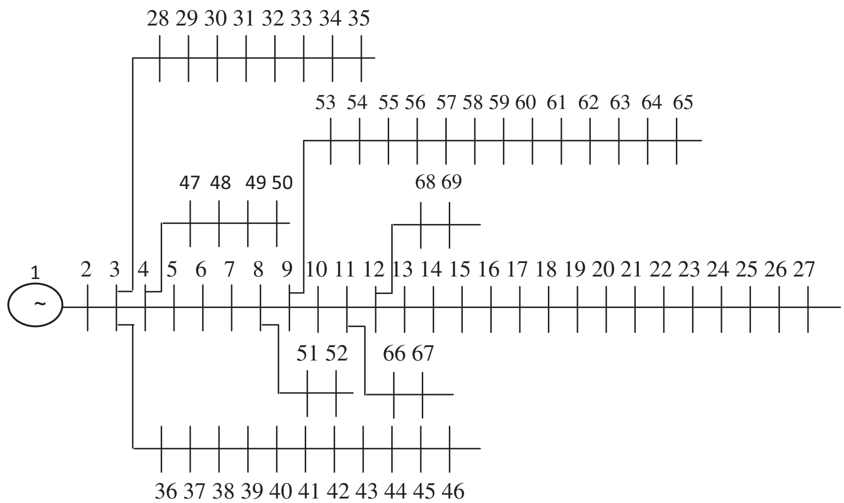

Fig. 9. Line diagram of the 69 bus system.

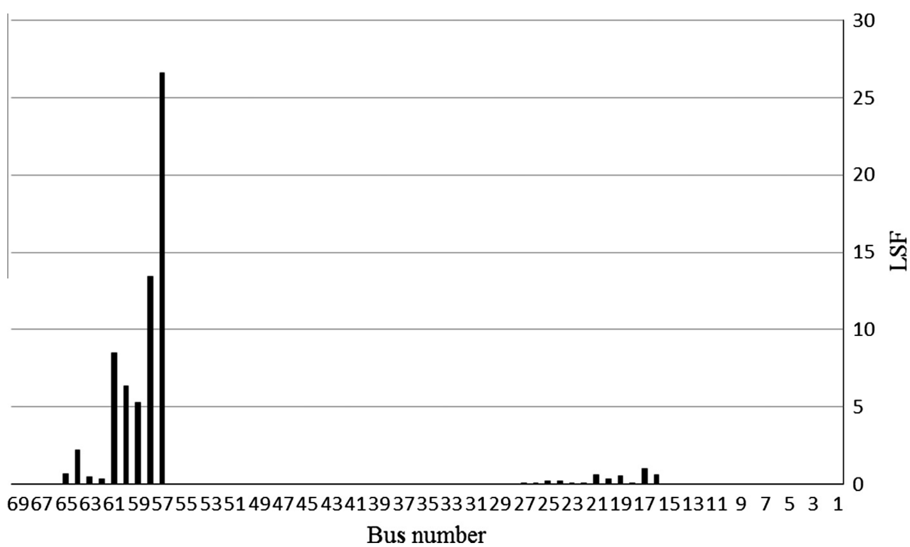

Fig. 10. The values of LSF for 69 bus system.

Results and discussion

The superiority of the proposed FPA with LSF is implemented to various distribution systems. The results of 10 bus, 33 bus and 69 bus radial distribution systems are given below in details. The proposed algorithm has been performed via Matlab [38]. The parameters used in calculation are given in Table 1 [11].

10 bus test system

First, the suggested algorithm is applied to 10 bus system as shown in Fig. 3. The system data are given in [36]. The total load for this system is (13151.77 + J 5176.6) kVA. Fig. 4 gives the candidate buses according to their LSF. The ordered of these buses are 6, 5, 9, 10, 8 and 7. For this system, FPA decides the optimum locations and their sizing from the candidate buses based on higher LSF. Four buses are selected for capacitor placements by FPA. The losses without compensation are 783.77 kW and are decreased to 648.77 kW due to capacitors installation as shown in Table 2. The percentage reduction in losses is increased to be 17.22%. The notability of the suggested FPA to reduce losses and decide the size of capacitors is demonstrated compared with those obtained in [4,12,21,26,39]. The minimum voltage before compensation is 0.8375 p.u. and this voltage is enhanced after compensation to be 0.9168 p.u. Fig. 5 shows the effect of installed capacitors on system voltages. The value of installed capacity of reactive power is 3000 kVAr. The value of total cost due to the proposed objective function 353993.5 $ which is the smallest one. Moreover, the net saving with the proposed FPA is 57956 $ which is the maximum one compared with other algorithms. Also, the percentage of net saving with the proposed FPA is equal to 14.1% which is the greatest one. In addition, the statistical performance of the proposed FPA is displayed in Table 2 to show the best, worst, mean, variance and standard deviations of the total losses for 50 runs.

33 bus test system

The second tested case via the suggested LSF and FPA is a 33 bus system. Fig. 6 gives the system diagram which consists of main feeders and three laterals. The system data are given in [37]. The

Table 4
Results of 69 bus system for different algorithms.

Items	Un-compensated	Compensated							
		PSO [4]	DSA [29]	TLBO [9]	Fuzzy GA [15]	DE–PS [11]	DE–PS [11]	Heuristic [18]	Proposed FPA
Year		2007	2012	2013	2008	2013	2013	2010	**2015**
Total losses (kW)	224.8949	152.48	147	146.35	156.62	146.1347	151.3763	148.48	**150.28**
Loss reduction (%)	–	32.2	34.64	34.92	30.4	35.02	32.7	34	**33.2**
Minimum voltage	0.9092	–	–	0.9313	0.9369	0.9327	0.9311	0.9305	**0.9333**
Optimal location and size in kVAr	–	46 241	61 900	12 600	59 100	61 950	57 150	8 600	**61 1350**
		47 365	15 450	61 1050	61 700	64 200	58 50	58 150	– –
		50 1015	60 450	64 150	64 800	59 150	61 1000	60 1050	– –
		–	– –	– –	–	65 50	60 150	– –	– –
		–	– –	– –	–	21 300	59 100	– –	– –
Total kVAr		1621	1800	1800	1600	1650	1450	1800	**1350**
Annual cost ($/year)	118204.8	88006.5	85663.2	85321.56	90119.5	86758.4	88913.4	86441.1	**84038.06**
Net saving ($/year)	–	30198.3	32541.56	32883.2	28085.3	31446.36	29291.4	31763.7	**34166.7**
% saving	–	25.6	27.53	27.82	23.8	26.6	24.8	26.9	**28.91**
Worst losses	–	NA	NA	146.92	NA	NA	NA	NA	**151.38**
Best losses	–	NA	NA	146.35	NA	NA	NA	NA	**150.01**
Mean losses	–	NA	NA	146.57	NA	NA	NA	NA	**151.11**
Variance	–	NA	NA	NA	NA	NA	NA	NA	**0.069**
Standard deviation	–	NA	NA	0.02134	NA	NA	NA	NA	**0.26**

Bold items present the result obtained by the proposed algorithm.

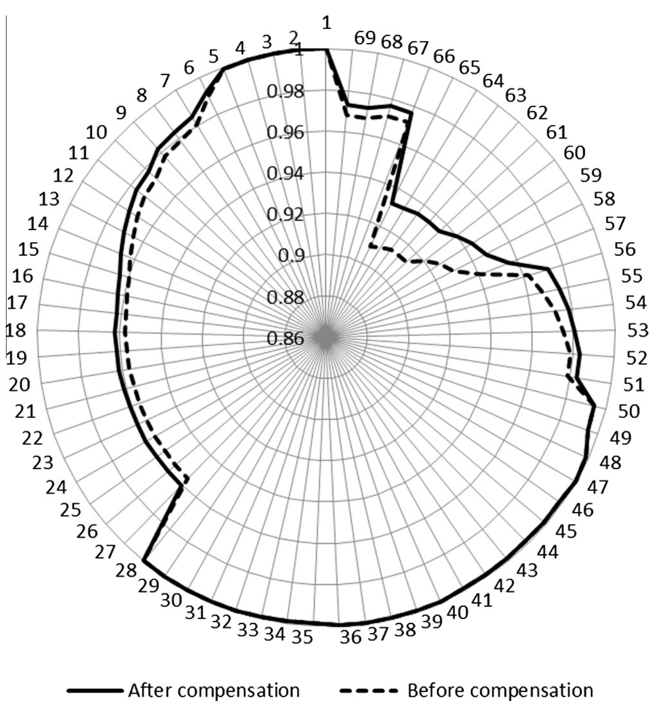

Fig. 11. The effect of compensated device on voltages of 69 bus system.

values of LSF for all buses are given in Fig. 7. Three buses are selected for capacitor placements by FPA. The notability of the proposed FPA to select the optimal locations and sizing of capacitors is verified compared with those obtained in [2,22,40]. The losses without compensation are 202.66 kW and are decreased to 134.47 kW due to compensation devices as shown in Table 3. Moreover, the minimum voltage has been increased from 0.9131 p.u. to 0.9365 p.u. The improvement of system voltages is given in Fig. 8 due to installed capacitors. The value of installed capacity of reactive power is 1600 kVAr which is the lowest one compared with other techniques. The value of total cost due to the proposed objective function is 78477.4 $ which is the smallest one. Moreover, the net saving with the proposed FPA is 28040.7 $ which is the maximum one compared with other algorithms. Also, the percentage of net saving with the proposed FPA is equal to 26.33% which is the greatest one. In addition, the statistical performance of the proposed FPA is displayed in Table 3 to show the best, worst, mean, variance and standard deviations of the total losses for 50 runs.

69 bus test system

The third tested case via the suggested algorithm is a 69 bus system. Fig. 9 gives the system diagram which consists of main feeders and seven branches. The system data are given in [41]. The order of candidate buses for this system according to their LSF values is 57, 58, 61, 60, 59, 64, 17, 65, 16, 21, 19, 63, 20, 62, 25, 24, 23, 26, 27, 18 and 22 as given in Fig. 10. Only one bus is selected by FPA for capacitor placements. The superiority of the proposed technique to solve the problem of optimal capacitor location compared with those obtained in [4,9,11,15,18,29] is confirmed. The losses without compensation are 224.8949 kW and are decreased to 150.28 kW due to compensation device as shown in Table 4. Moreover, the minimum voltage has been enhanced from 0.9092 p.u. to 0.9333 p.u. The improvement of system voltages is shown in Fig. 11 due to installed capacitor. The value of installed capacity of reactive power is 1350 kVAr which is the lowest one compared with other techniques. The value of total cost due to the proposed objective function is 84038.06 $ which is the smallest one. Moreover, the net saving with the proposed FPA is 34166.7 $ with percentage of 28.91% which is the maximum one compared with other algorithms. Also, the statistical performance of the proposed FPA is displayed in Table 4 to show the best, worst, mean, variance and standard deviations of the total losses for 50 runs.

Conclusions

In this paper, FPA has been successfully implemented with LSF for optimal location and sizing of shunted capacitors in various distribution systems. The designed problem has been formulated as an optimization task with computing cost of power losses, installation and vars. The effectiveness of the suggested approach is clarified by using different test systems. The results have been compared with those obtained using other algorithms. It is obvious from the comparison that the proposed approach provides a notable performance in terms of total cost and net saving. Applications of the proposed algorithm to large scale distribution power systems and unbalanced one with other techniques are the future scope of this work.

Appendix

The parameters of FPA are as follow: maximum number of iterations = 100, population size = 25, probability switch = 0.8, γ = 0.1 and $\lambda = 1.5$.

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