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Full Length Article

Optimal sizing and locations of capacitors in radial distribution systems via flower pollination optimization algorithm and power loss index

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ABSTRACT

In this paper, a new and powerful algorithm called 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 Power Loss Index (PLI). Then the proposed FPA is employed to deduce the size of capacitors and their locations from the elected buses. The objective function is designed to reduce the total cost and consequently to increase the net saving per year. The proposed algorithm is tested on 15, 69 and 118-bus radial distribution systems. The obtained results via the proposed algorithm are compared with other algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Plant Growth Simulation Algorithm (PGSA), Direct Search Algorithm (DSA), Teaching Learning-Based Optimization (TLBO), Cuckoo Search Algorithm (CSA), Artificial Bee Colony (ABC) and Harmony Search Algorithm (HSA) to highlight the benefits of the proposed algorithm. Moreover, the results are introduced to verify the effectiveness of the suggested algorithm to minimize the losses and total cost and to enhance the voltage profile and net saving for various distribution systems.

1. Introduction

At the distribution level, about 13% of the generated power is lost as ohmic losses [1,2]. These losses can be diminished by installing shunt capacitors at appropriate positions. Moreover, the voltage profile, power factor and power system stability are improved. Thus, the optimal sizing and locations of these capacitors have a vital and irreplaceable role in distribution systems.

During last years, several algorithms and techniques are introduced to find the proper locations and optimal sizes of shunt capacitors. Nonlinear Programming [2], Simulated Annealing (SA) [3], Tabu Search (TS) [4], Genetic Algorithm (GA) [5], Particle Swarm Optimization (PSO) [6,7], Direct Search Algorithm (DSA) [8], Teaching Learning Based Optimization (TLBO) [9], Plant Growth Simulation Algorithm (PGSA) [1], Heuristic Algorithm [10], Cuckoo Search Algorithm (CSA) [11–13], Artificial Bee Colony(ABC) [14–16], Ant Colony Search Algorithm (ACO) [17,18], Bacteria Foraging (BF) [19], Firefly Algorithm (FA) [20], Harmony Search (HS) [21,22] and big bang-big crunch optimization [23] are developed to deal with the capacitor placement problem. However, these algorithms may fail to reach the optimal cost. In order to overcome these drawbacks, the Flower Pollination Algorithm (FPA) is proposed in this paper to solve 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.

FPA is proposed in this paper as a new optimization algorithm to diminish the total active power losses, the total cost and to reinforce the voltage profiles for different distribution systems. The locations of the shunt capacitors problem are obtained at first by examining the buses of higher Power Loss Index (PLI). Then FPA is introduced to decide the optimal locations and sizing of capacitors from specified buses. The effectiveness of the proposed algorithm in enhancing the voltage profile and reducing ohmic losses is shown for three distribution systems with different scales and topologies. The results of the FPA are compared with various algorithms to confirm its notability.

Abbreviations: FPA, Flower Pollination Algorithm; PLI, Power Loss Index; 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; HSA, Harmony Search Algorithm; SA, Simulated Annealing; TS, Tabu Search; ACO, Ant Colony Search Algorithm; BF, Bacteria Foraging; FA, Firefly Algorithm; HS, Harmony Search; DE, Differential Evolution.

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2. Overview of flower pollination algorithm

FPA was introduced in 2012 by Yang [24]. It was inspired by the pollination task of flowering plants. The main objective of a flower is basically reproduction using pollination. Flower pollination is correlating with the transfer of pollen, which is often associated with pollinators like birds and insects. Pollination appears in two main types: abiotic and biotic. Most flowering plants rely on the biotic pollination task, in which the pollen is transmitted by pollinators. The rest of pollination follows abiotic form that does not demand any pollinators like grass [25,26]. Wind and diffusion support in the pollination task of such flowering plants. On the other hand, pollination can be executed by self-pollination or cross-pollination. Self-pollination is the pollination of one flower from the pollen of the same flower or other flowers of the same plant. Cross-pollination is the pollination from the pollen of a flower of other plants.

The purpose of the FPA is the survival of the fittest and the optimal reproduction of plants in terms of numbers as well as the fittest [27]. This can be treated as an optimization task of plant species. All of these factors and tasks of flower pollination generated optimal reproduction of the flowering plants. Also, FPA proves its capability to solve various problems in power system [28–30]. Thus, it has been adopted in this paper to solve the problem of optimal sizing and locations of capacitors in distribution systems.

2.1. Flower pollination algorithm

For FPA, the following four steps are used:

Step 1: Global pollination represented in biotic and cross-pollination tasks, as pollen-carrying pollinators fly following Lévy flight [26].
Step 2: Local pollination appeared in abiotic and self-pollination as the task does not request any pollinators.
Step 3: Flower constancy which can be introduced by insects, which is on par with a reproduction probability that is proportional to the similarity of two flowers involved.
Step 4: A switch probability $p \in [0,1]$ is used to control the interaction of local and global pollination.

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

$$x_i^{t+1} = x_i^t + \gamma L(\lambda)(g_* - x_i^t) \quad (1)$$

In fact, $L(\lambda)$ the Lévy flights based step size that corresponds to the intensity of the pollination. Since long distances can be wrapped via many distance steps, a Lévy flight can be employed to imitate this behavior strongly. That is, $L > 0$ from a Lévy distribution.

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

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

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

$$x_i^{t+1} = x_i^t + \varepsilon (x_j^t - x_k^t) \quad (3)$$

where x_j^t and x_k^t are pollen from several flowers of the same plant species simulating the flower constancy in a limited neighborhood.

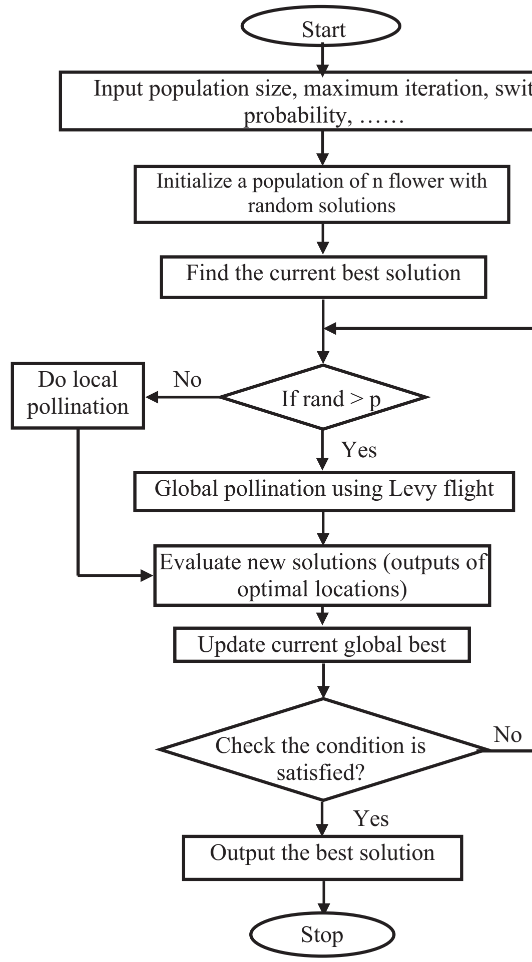

Fig. 1. Flow chart of FPA.

For a local random walk, x_j^t and x_k^t hail from the same species then ε is pulled from a uniform distribution as [0, 1].

In principle, flower pollination actions can take place at all levels, both local and global. In fact neighboring flower positions are pollinated by local flower pollen than those far away. In order to imitate this, one can utilize a switch probability p effectively to convert between general global pollination to intense local pollination. Initially, one can employ a value of $p = 0.5$. The flow chart of FPA is given in Fig. 1.

3. Problem formulation

3.1. Power loss index

In this paper, PLI is used to appoint the candidate buses for capacitors. The area of search is greatly reduced and consequently the time consumed in the optimization process. The disadvantage of this index is the necessary computations. It is required to perform load flow and determine the reduction in active power losses by injection reactive power at each bus except the swing one [13]. The PLI is calculated by the following expression.

$$\text{PLI(i)} = \frac{lr(i) - lr_{\min}}{lr_{\max} - lr_{\min}} \quad (4)$$

The buses of larger PLI will have the priority to be the candidate bus for installing compensator devices.

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3.2. Objective function

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

$$Cost = K_P * P_{Loss} * T + D\left(K_I * CB + K_C * \sum_{i}^{CB} Q_{Ci}\right) + K_o CB \quad (5)$$

where the constants are taken as in Reference 16.

The above equation is minimized while satisfying the following equality and inequality constraints.

3.2.1. Equality constraint

- Load flow constraint

Traditional methods such as Newton Raphson and Gauss Siedel cannot be used in the distribution system due to ill condition. Forward sweep algorithm has been introduced by Das et al. [31] to solve load flow problem of distribution systems. The equality constraint is given by the following equations:

$$P_{Swing} = \sum_{i=1}^{L} P_{Lineloss}(i) + \sum_{q=1}^{N} Pd(q) \quad (6)$$

$$Q_{Swing} + \sum_{b=1}^{CB} Q_C(b) = \sum_{i=1}^{L} Q_{Lineloss}(i) + \sum_{q=1}^{N} Qd(q) \quad (7)$$

3.2.2. Inequality constraints

- Voltage Constraint

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

$$0.90 \le V \le 1.05 \quad (8)$$

- 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 0.7 of the total reactive power demand to sustain working of power system with lagging power factor and averting the leading one.

$$\sum_{b=1}^{CB} Q_C(b) \le 0.7 \sum_{q}^{N} Qd(q) \quad (9)$$

- Power Factor Constraint

Power Factor (PF) should exceed the minimum value and less than the maximum value as shown by the following equation.

$$PF_{\min} \le PF \le PF_{\max} \quad (10)$$

4. Results and discussion

The superiority of the proposed FPA with PLI is implemented to various distribution systems. The results of 15, 69 and 118 bus radial distribution systems are given below in details. The proposed algorithm has been performed via Matlab [32].

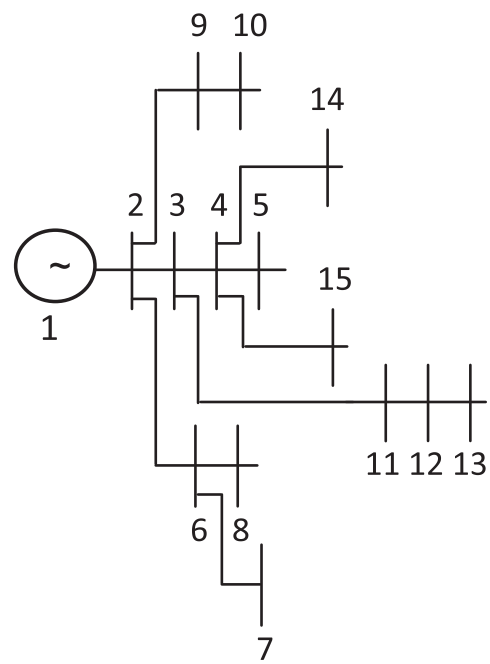

Fig. 2. The schematic diagram of the 15 bus system.

4.1. 15 Bus test system

The first tested case is 15 bus system as displayed in Fig. 2. The system data are given in Reference 33. The total load for this system is 1752 kVA with PF = 0.7. The losses without compensation are 61.9547 kW. Fig. 3 gives the candidate buses according to their PLI. The order of these buses are 15, 11, 4, 7, 6, 12, 14, 3, 8, 13, . . . 2. A comparison between two scenarios is performed and shown in Table 1. The first one selects the top three buses according to higher values of PLI to be the optimal locations. In the second scenario, FPA decides the optimum locations from the initial candidate buses based on higher PLI to reduce the number of compensated buses and their injected Vars. It is clear that the second scenario gives the better response in terms of costs and losses and therefore it is proposed in this paper for the other systems. The notability of the suggested FPA is demonstrated compared with other algorithms in References 6,34–37. The value of installed capacity of reactive power is 1000 kVAr. The minimum voltage is increased from 0.9424 to 0.9676 p.u. The losses with compensation are decreased to 30.7112 kW due to capacitors installation as given in Table 2. The percentage reduction in losses is increased to be 50.43%. Moreover, the value of total cost due to the proposed objective algorithm is 23001.78$ which is the smallest one. Also, the net saving with

Table 1
Comparison between two Scenarios.

Items	First Scenario		Second Scenario **(Proposed)**	
Total losses (kW)	34.32		**30.7112**	
Loss reduction (%)	44.6		**50.43**	
Minimum voltage	0.9661		**0.9676**	
Optimal location	4	350	**6**	**350**
and size in kVAr	11	300	**11**	**350**
	15	150	**15**	**300**
Total kVAr	800		**1000**	
Annual cost ($/year)	23899		**23001.78**	
Net saving ($/year)	8664.2		**9561.62**	
% saving	26.6		**29.36**	

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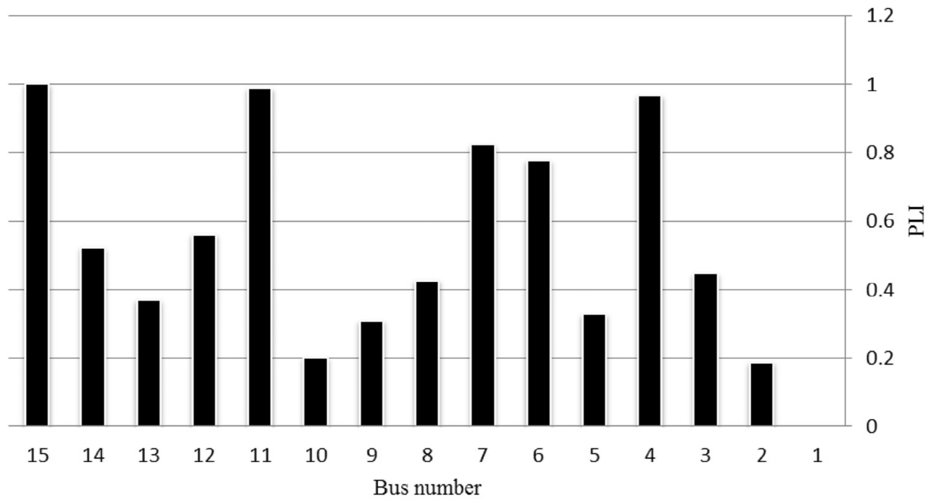

Fig. 3. PLI for the 15 bus system.

the proposed FPA is improved to 29.36% which is the maximum one compared with other algorithms. Finally, the improvement in system voltages due to installed capacitors is shown in Fig. 4.

4.2. 69 Bus test system

The second tested case via the suggested algorithm is a 69 bus system. Fig. 5 gives the system diagram which consists of main feeder and seven branches. The system data are shown in Reference 38. The order of candidate buses for this system according to their PLI values are 61, 64, 59, 65, 21, 12, 11, 62, 18, 17, 16, . . . as determined in Fig. 6. Two buses are considered for capacitor placements. The superiority of the proposed technique to solve the problem of optimal capacitor location is proved compared with those obtained in References 6,39–41. The losses without compensation are 224.8949 kW and are decreased to 145.777 kW due to compensation devices as shown in Table 3. Moreover, the minimum voltage has been enhanced from 0.9092 p.u to 0.9323 p.u. The improvement of system voltages is shown in Fig. 7 due to installed capacitors. The value of installed capacity of reactive power is 1500 kVAr. The

Table 2
Results for 15-bus system.

Items	Un-compensated	Compensated											
		FGA [34]		[35]		PSO [6]		DE [36]		[37]		**Proposed**	
Total losses (kW)	61.9547	30.4411		32.6		32.7		32.3		33.2		**30.7112**	
Loss reduction (%)	-	50.86		47.38		47.22		47.86		46.41		**50.43**	
Minimum voltage	0.9424	0.9677		-		-		-		-		**0.9676**	
Optimal location	-	4	200	3	805	6	871	3	454	3	150	**6**	**350**
and size in kVAr		6	100	6	388	11	321	6	500	4	300	**11**	**350**
		7	300					11	178	6	300	**15**	**300**
		11	300							11	150		
		15	200										
Total kVAr	-	1100		1193		1192		1132		900		**1000**	
Annual cost($/year)	32563.4	24599.8		24339.6		24387.1		24496.8		24429.9		**23001.78**	
Net saving ($/year)	-	7963.6		8223.8		8176.3		8066.4		8133.5		**9561.62**	
% saving	-	24.46		25.26		25.11		24.77		24.98		**29.36**	

Table 3
Results for 69-bus system.

Items	Un-compensated	Compensated									
		Fuzzy-GA [40]		DE [39]		PSO [6]		Heuristic method [41]		FPA	
Total losses (kW)	224.8949	156.62		151.3763		152.48		148.48		145.777	
Loss reduction (%)	-	30.4		32.7		32.2		34		35.2	
Minimum voltage	0.9092	0.9369		0.9311		-		0.9305		0.9323	
Optimal location and size in kVAr	-	59	100	57	150	46	241	8	600	61	1250
		61	700	58	50	47	365	58	150	21	250
		64	800	61	1000	50	1015	60	1050	-	-
		-		60	150	-		-		-	
		-		59	100	-		-		-	
Total kVAr		1600		1450		1621		1800		1500	
Annual cost ($/year)	118,204.8	90119.5		88913.4		88006.5		86441.1		85356.7	
Net saving ($/year)	-	28085.3		29291.4		30198.3		31763.7		32848.1	
% saving	-	23.8		24.8		25.6		26.9		27.8	

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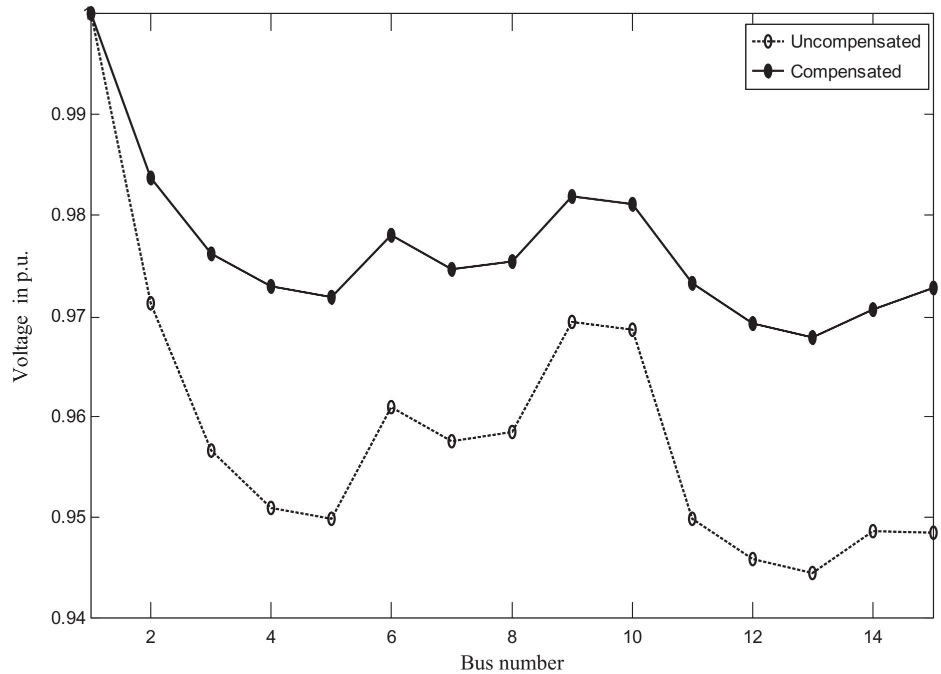

Fig. 4. Effect of compensation on system voltages.

value of total cost due to the proposed objective function is 85356.7$ which is the smallest one. Also, the percentage of net saving with the proposed FPA is equal to 27.8 % which is the greatest one compared with other techniques.

4.3. 118 Bus test system

The effectiveness of the proposed algorithm is investigated on 118 node test system which contains 117 branches as a large scale radial distribution network. The total load demand of this test system is 22709.72 kW and 17041.07 kVAr respectively. The system is operated with the nominal bus voltage of 11 kV, 100 MVA base. The nodes of 118 bus test system have been renumbered as shown in Fig. 8. The line data and load are given in References 42–44. Before compensation the active and reactive losses at nominal load are 1294.35 kW and 974.85 kVAr respectively. The values of PLI are given in Fig. 9. Based on the proposed algorithm, 9 nodes are identified as the most sensitive nodes for capacitor placements with net injection of 8300 kVAr. The locations and amount of injected vars are scheduled in Table 4 compared with References 13,16,22. The simulation results of optimal capacitor sizes and their corresponding locations, total active and reactive losses, net saving and minimum and maximum voltage excluding slack bus are summarized in Table 5. It is clear that the minimum voltage is increased from 0.8688 p.u. to 0.9002 p.u. The active and reactive power losses are reduced to 844.47 kW and 607.59 kVAr with percentage reduction of 34.76% and 37.67% respectively. Also, the overall PF is enhanced from 0.7879 to 0.92946. Moreover,

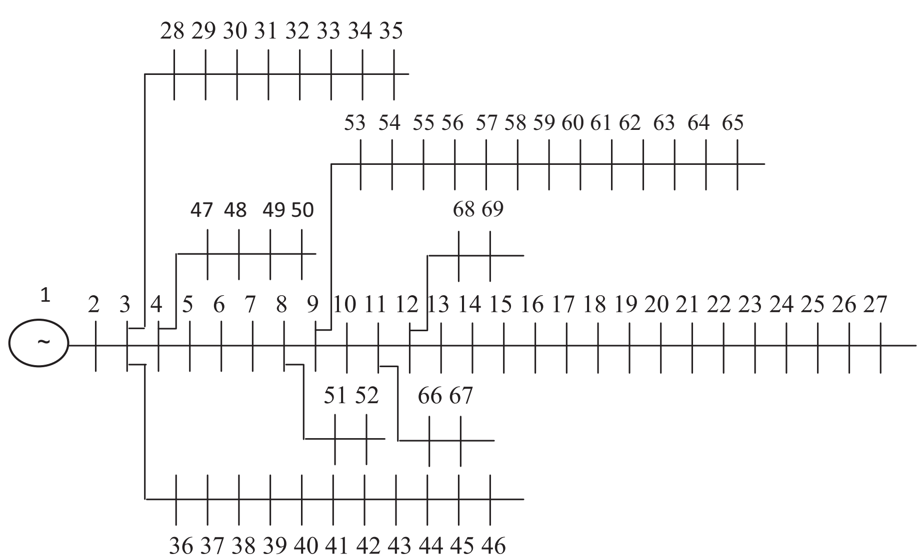

Fig. 5. The schematic diagram of the 69 bus system.

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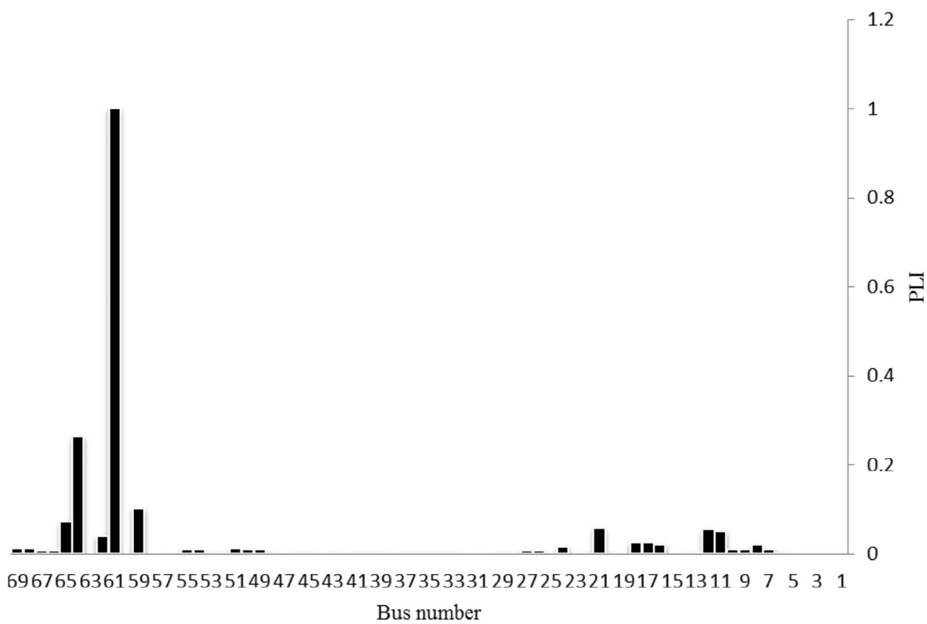

Fig. 6. The candidate buses ordered according to their PLI values.

Table 4
Optimal location and size in kVAr for 118-bus system.

	ABC [16]		CSA [13]		HSA [22]		**Proposed**	
Locations and injected kVAr	32	850	32	1500	79	714	**39**	**1500**
	35	1050	39	1500	77	170	**43**	**600**
	40	1300	40	550	76	192	**70**	**500**
	50	800	70	950	75	509	**74**	**1050**
	70	550	74	750	74	272	**86**	**900**
	73	1300	86	1050	73	432	**91**	**1500**
	79	1200	108	1500	72	386	**107**	**700**
	105	700	118	1200	113	974	**109**	**500**
	106	250			56	375	**118**	**1050**
	109	800			115	493		
	110	1200			54	377		
					53	425		
					111	641		
					52	753		
					112	793		
					51	349		
					71	513		
					110	281		
					50	165		
					70	626		
					49	488		
Total kVAr		**10,000**		**9000**		**9928**		**8300**

simulation results reveal the superiority of the proposed FPA to improve the net saving to 184163$ with percentage of 27.1% and to reduce the total cost to 496147.4$ compared with other algorithms. Finally, the effect of compensation can be seen on voltage profiles as indicated in Fig. 10.

5. Conclusions

In this paper, FPA has been successfully implemented to solve the problems of optimal locations and sizing of capacitors in distribution systems that have been established as an objective optimization task, with power losses, cost of installation, operation and injected vars are taken in consideration. The superiority of the proposed approach is clarified by using different large test systems. The contribution of this paper can be defined as

a) Application of FPA to solve capacitor location problem especially for large scale system.
b) Both locations and sizing of capacitors are optimized using FPA. The role of PLI is just reducing the research area.
c) Treating the value of capacitor as a discrete value not a continuous one as most papers. Moreover, the objective function

Table 5
Results for 118-bus system.

Items	Un-compensated	Compensated			
		ABC [16]	CSA [13]	HSA [22]	**Proposed**
Total losses (kW)	1294.35	854.39	858.89	926.1	**844.47**
Loss reduction (kW) (%)	-	33.99	33.64	28.26	**34.76**
Total losses (kVAr)	974.85	639.08	644.94	-	**607.59**
Loss reduction (kVAr) (%)	-	34.44	33.84	-	**37.67**
Minimum voltage	0.8688	0.90886	0.906	-	**0.9002**
Maximum voltage	0.9321	0.99741	0.997	-	**0.9962**
Total kVAr and No. of locations	-	10,000 11 locations	9000 8 locations	9928 21 locations	**8300 9 locations**
$PF_{overall}$	0.7879	0.9295	0.92	-	**0.92946**
Annual cost ($/year)	680310.4	505887.4	501392.6	549418.2	**496147.4**
Net saving ($/year)		174423	178917.8	130892.2	**184163**
% saving		25.64	26.3	19.24	**27.1**

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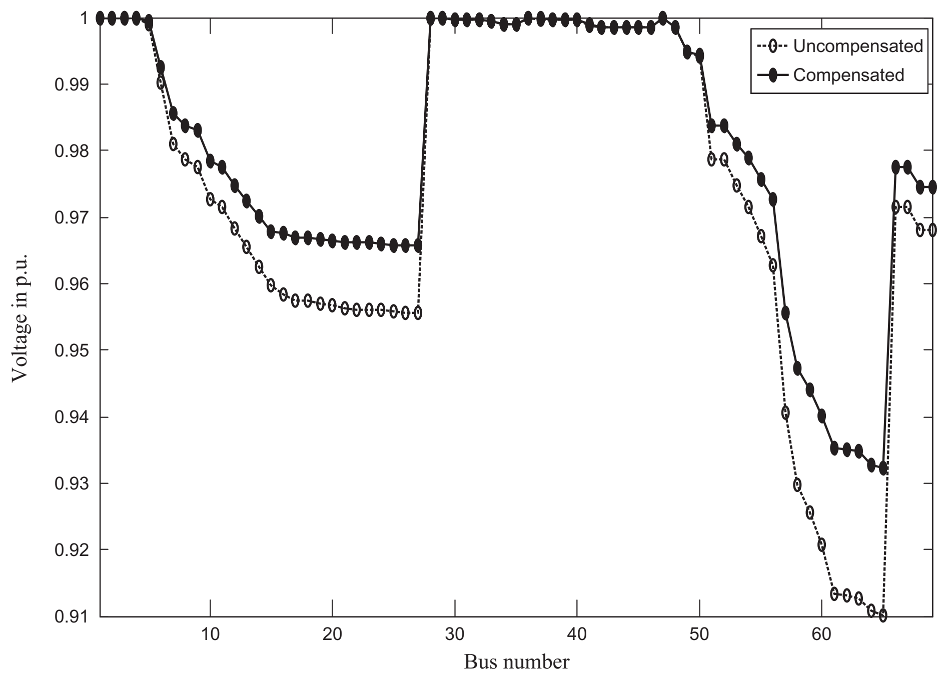

Fig. 7. The effect of compensated devices on voltage of 69 bus system.

that represents the total cost takes the installation and operating cost in consideration.

d) FPA outlasts other algorithms in solving the optimal locations and sizing of capacitors in distribution systems. Moreover, it provides a promising and preferable performance over other algorithms in terms of voltage profiles, active and reactive power losses, total cost and net saving.

Applications of the network reconfiguration and distributed generation with the most recent optimization algorithm to enhance the

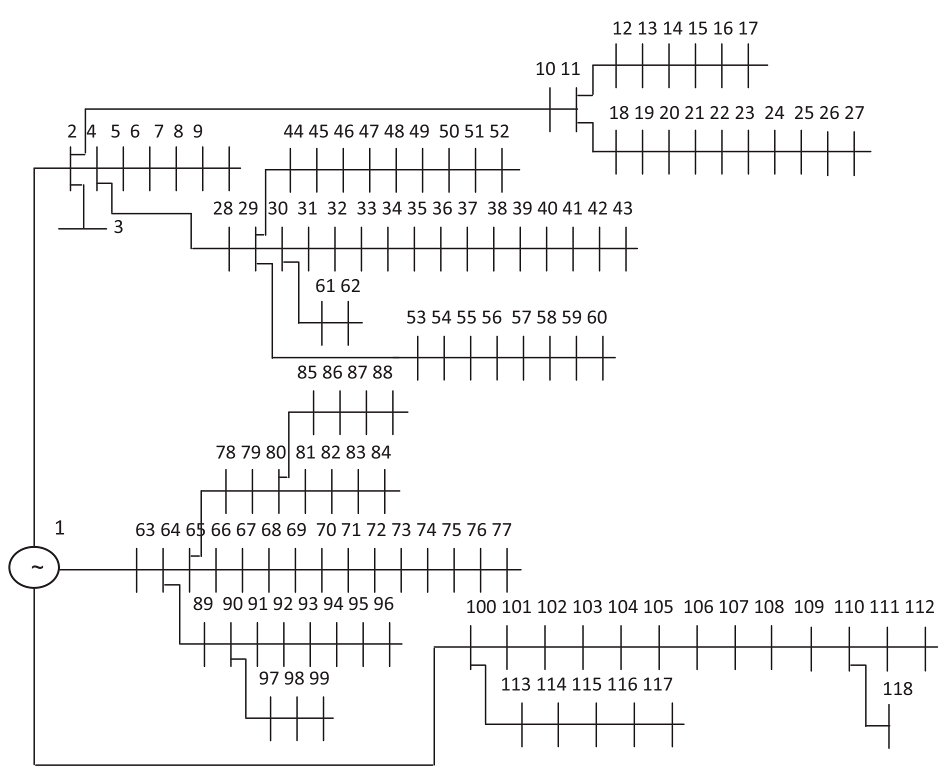

Fig. 8. The schematic diagram of the 118 bus system.

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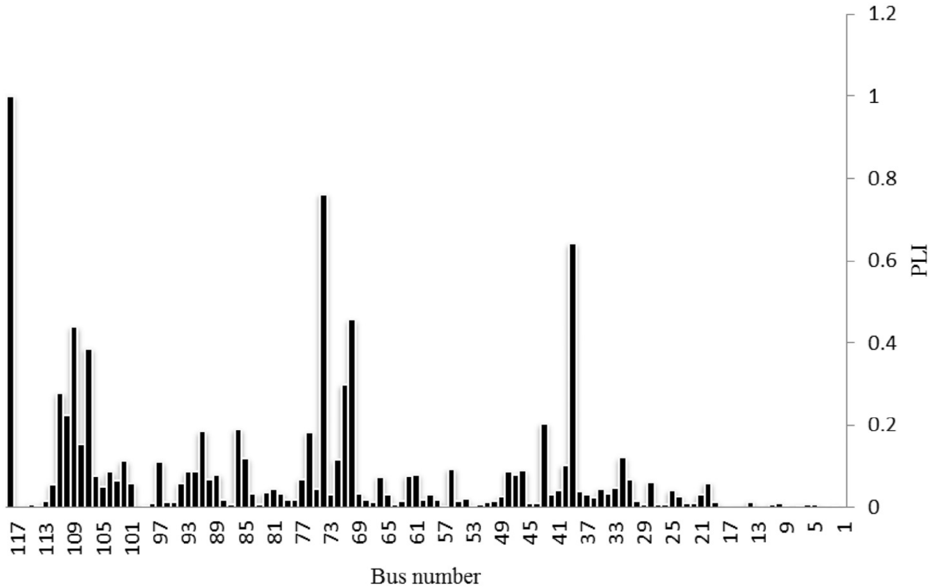

Fig. 9. PLI for the 118 bus system.

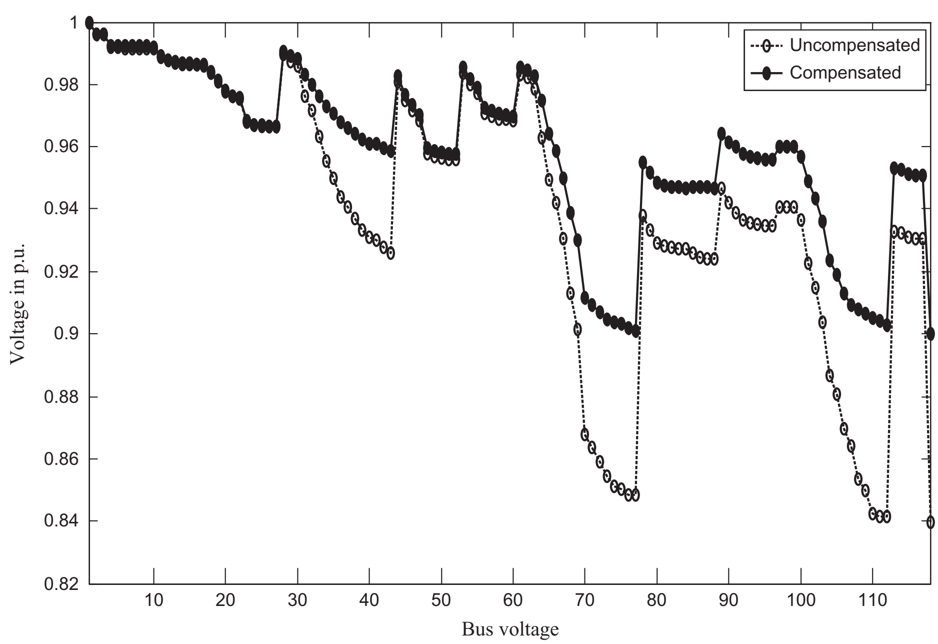

Fig. 10. Effect of compensation on system voltages.

voltage profiles and to reduce the ohmic losses are the future scopes of this work.

Nomenclature

lr_{max}	The maximum reduction in active power losses
lr_{min}	The minimum reduction in active power losses
$lr(i)$	The reduction in active power losses at bus i
x_i^t	The pollen i
g_*	The current best solution found at the current generation
γ	Scaling factor
$\Gamma(\lambda)$	The criterion gamma function i
p	Switch probability
K_P	The cost per kW-Hours and equals to 0.06$/kW-Hours
P_{Loss}	The total power losses after compensation
T	The time in Hours and equals to 8760
D	The depreciation factor and equals to 0.2
CB	The number of compensated buses
K_C	The cost per kVAr and equals to 25$/ kVAr
K_I	The cost per installation and equals to 1600$
Q_{Ci}	The value of installed reactive power in kVAr
K_o	The operating cost and equals to 300$/year/location
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

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N	The number of total buses
P_{Swing}	The active power of swing bus
PF	Power Factor
$PF_{\min}$	The minimum power factor, and it is equal to 0.9 lagging
$PF_{\max}$	The maximum power factor, and it is equal to 1
PF_{sys}	The power factor at swing bus

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