Journal of Operation and Automation in Power Engineering
Vol. 3, No. 2, Summer & Fall 2015, Pages: 131-146
http://joape.uma.ac.ir

Application of Multi Objective HFAPSO Algorithm for Simultaneous Placement of DG, Capacitor and Protective Device in Radial Distribution Network

H. Shayeghi*, M. Alilou
Department of Technical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

ABSTRACT
In this paper, simultaneous placement of distributed generation, capacitor bank and protective devices are utilized to improve the efficiency of the distribution network. The objectives of the problem are reduction of active and reactive power losses, improvement of voltage profile and reliability indices and increasing distribution companies' profit. The combination of firefly algorithm, particle swarm optimization and analytical hierarchy process is proposed to solve the multi-objective allocation problem. The proposed method is implemented on IEEE 69-bus and also an actual 22-bus distribution systems in Tehran-Iran. Test results approve the effectiveness of the proposed method for improved reliability and network performance of the distribution network.

Keywords: Analytical hierarchy process, Capacitor banks, Distributed generation, Hybrid firefly algorithm and particle swarm optimization, Multi-objective optimization, Protective device.

1. INTRODUCTION

Nowadays, the penetration of distributed generation (DG) units in distribution networks has been increased rapidly. The advantages of DG include reduction of transmission and distribution operations cost, environmental pollutions' decrement and reduction of power loss, improvement of system reliability and betterment of power quality [1]. In spite of all the benefits of DG installation, it changes the direction of flow and fault current level of the system; therefore protection plans of the distribution system become unbalanced [2]. The distribution system operator always has special attention to the reactive power; because it has an effect on the system losses, voltage profile and also network performance. Capacitor bank is the usual and cheapest method to compensate the reactive power [3].

Studies of the distribution system area that used the DG, capacitor bank and protective device in order to increase the efficiency of the network can be divided into four categories. The first category is about studies in which DG units are utilized to improve system parameters [4-7].Ref. [4] reported an algorithm for calculation of proper size and placement of DG units considering economic goals such as minimizing total costs of system's planning, including investment, operation and maintenance costs of DG or maximizing profit in deregulated environments. The authors applied in [6] a combination of genetic algorithm (GA)

Received:2 May 2015 Revised: 4 June 2015
Accepted: 26 June 2015
*Corresponding author:
H. Shayeghi (E-mail: hshayeghi@uma.ac.ir)

Nomenclature

S_{loss}	Loss index	C_{DG_oper}	Operation cost of DG ($)
V_P	Voltage profile index	C_{DG_main}	Maintenance cost of DG ($)
S_{rel}	Reliability index	${P_{l\_ins}}^y$	P_{l_ins} in each year (MW)
$Benefit$	Distribution company profit ($)	${P_l}^y$	P_l in each year (MW)
L_{end}	Power loss index after installation	d_1	Cost of produced active power ($\$/MW\ h$)
L_{ins}	Power loss index before installation	h	1 year period (hours)
P_l	Active power loss after installation (MW)	$Infr$	The inflation rate
Q_l	Reactive power loss after installation (Mvar)	T	Planning period (year)
P_{l_ins}	Active power loss before installation (MW)	${Q_{l\_ins}}^y$	Q_{l_ins} in each year (Mvar)
Q_{l_ins}	Reactive power loss before installation (Mvar)	${Q_l}^y$	Q_l in each year (Mvar)
R_i	Resistance of branch i	d_2	Cost of produced reactive power ($\$/Mvar\ h$)
X_i	Reactance of branch i	${ENS_{ins}}^y$	ENS without devices in each year
I_i	Current of branch i	ENS^y	ENS with devices in year
N_{br}	Branch number	MP	Market price ($\$/MW\ h$)
pro_{end}	Voltage profile after installation	C_b	Breaker cost ($)
pro_{ins}	Voltage profile before installation	C_s	Sectionaliser cost ($)
V_i	Voltage of bus i (pu)	N_b	Breaker number
V_b	Nominal voltage (1 pu)	N_s	Sectionaliser number
n	Bus number	N_C	Capacitor bank number
$AENS_{end}$	Reliability indices after installation	Q_C	Capacity of capacitor bank (Kvar)
$AENS_{ins}$	Reliability indices before installation	C_{cfb}	Cost of capacitor fixed bank ($\$/Kvar$)
N_i	Customer number of bus i	N_{DG}	DG number
r_i	Failure rate of bus i (f/yr)	P_{DG_i}	Capacity of DG (MW)
u_i	Average annual unavailability of bus i	C_{ins}	DG installation cost ($\$/MW$)
$L_{a(i)}$	Average load of bus i (KW)	C_{oper}	DG operation cost ($\$/MW\ h$)
B_{LA}	Active power loss reduction benefit ($)	C_{main}	DG maintenance cost ($\$/MW\ h$)
B_{LR}	Reactive power loss reduction benefit ($)	V_{min}	Minimum voltage at bus (pu)
B_{ENS}	Energy not supplied reduction benefit ($)	V_{max}	Maximum voltage at bus (pu)
C_P	Protective device cost ($)	${P_{DG}}^{min}$	Minimum capacity of DG (MW)
C_C	Capacitor bank cost ($)	${P_{DG}}^{max}$	Maximum capacity of DG (MW)
C_{DG_ins}	Installation cost of DG ($)	W_i, k_i, C_i	Penalty coefficients

and particle swarm optimization (PSO) for optimal location and sizing of DG maximizing profit in deregulated environments. Authors applied in [6] a combination of GA and PSO for optimal location and sizing of DG in distribution systems to minimize network power losses, with better voltage regulation and improving voltage stability.

Studies that used capacitor banks to increase the efficiency of the system are placed in the second group [8-11]. The proposed technique in [8] finds optimal locations for shunt capacitor banks from the daily load curve and it determines the suitable values of fixed and switched capacitors. An improved bi-strategy differential evolutionary algorithm which has been used to find optimal location and size of capacitor banks in a radial distribution system with varying load conditions was reported in [11]. In third category studies was investigated on the allocation protective device on the distribution network and plan protection schemes for improvement of technical indicators [12-

14]. In [12] a procedure based on genetic algorithm was suggested for optimal allocation of sectionalizing switches in radial distribution systems. Reference [14] was proposed the modified shuffled frog leaping algorithm for the optimal placement of manual and automatic switches in distribution automation systems. The last groups of studies are combination of instruments to improve network indicators [15-18]. In Ref. [15] the authors determined the optimal placement of DG and capacitor by applying PSO technique to minimize the real power losses. The authors investigated in [16] simultaneously DG and capacitor placement in the radial distribution network to minimize the energy losses with time varying loads. Reference [17] was reported a fuzzy multi objective approach for optimal placement of sectionalizing switches in the presence of distributed generation units. Simultaneous allocation of DGs and switches in distribution networks is done using genetic algorithm in [18].

1.1. General view of the proposed scheme

As mentioned above, the different studies about placement of DG, capacitor bank and protective devices in distribution network has been done, but so far study on the simultaneous placement of these devices due to the complexity of the issue has not been done. Imagining a network without protective device is illogical because if a fault happens anywhere on the system, the entire network will be blackout. Protective device doesn't have an effect on the indices such as loss and voltage profile but it improves the value of the reliability indices to an acceptable level. When along with protective devices, DG placement is done too; beside the most significant improvement of reliability parameters, network's other technical indices such as loss and voltage profile will be improved. In this paper, the most important goal in the placement of protective equipment along with DG and a capacitor bank in the distribution system is forming islanded areas in the occurrence of a fault; therefore two devices including breaker and sectionaliser are utilized. Breaker as the final protective device is placed at the beginning of the feeder and sectionaliser is placed on the branch or sub-branch of the system according to the location of DG and capacitor bank, so that the maximum stability is obtained when a fault happens.

For further understanding of the problem, sample circuit shown in the Fig. 1 can be used. If DG is considered alone, when a fault happens in any branch of the feeder, main breaker disconnects the network and the reliability indices cannot improve. On the other hand, if sectionaliser is located alone on the network, when a fault occurs in sectionaliser's downstream (In the depicted section), sectionaliser will act and so blackout will not happen in the upstream loads. But, if the fault occurs in upstream, breaker and sectionaliser will isolate the fault and so downstream loads will be turned off because there aren't energy source for downstream loads. Of course, after creating the islanded area, power flow of the region should be done; if the problem constraints are not violated, the island will continue to work, otherwise like upstream network, loads of island will be interrupted. Moreover, the placement of capacitor in the protective area can help in powering DG and also improving stability of island region. In the second case, placement of capacitor in the entire system alongside with the injected power by the DG, altogether improve indices such as loss reduction and voltage profile.

Therefore, in this paper, a multi-objective method is provided to evaluate the DG, capacitor and sectionaliser locating and sizing in distribution

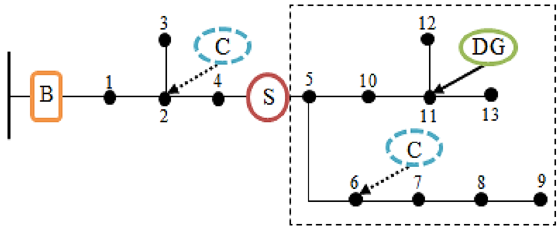

Fig. 1. Typical network for describing protection issue (B: Breaker, S: Sectionaliser, C: Capacitor bank)

network, simultaneously, using the proposed hybrid firefly algorithm and particle swarm optimization alongside with the analytical hierarchy process. The objectives of the problem are reduction of active and reactive network losses, improvement of voltage profile and reliability indices and increasing distribution company profit. The proposed method is implemented on IEEE 69-bus and an actual 22-bus distribution systems. Evaluation of the results shows improvement of indices during the simultaneous placement of different devices and reflect the high efficiency of the proposed method to improve the performance of distribution networks.

2. OBJECTIVE FUNCTION

In this paper, three-objective function is considered for optimal allocation problem which are reducing network loss, improving voltage profile and reliability index. Mathematically, the main multi-objective function is formulated as:

$$objective\ function\text{: min } \{S_{loss},\ V_P,\ S_{rel}\} \quad (1)$$

In which, S_{loss} is distribution network loss index, V_P is voltage profile index and S_{rel} is reliability index. Mathematical formulation for different term of the objective function is given by:

2.1. Power loss

Power loss as the most important index composed of active and reactive power loss is defined as:

$$S_{loss} = L_{end}/L_{ins} \quad (2)$$

$$L_{end} = C_p P_l + C_q Q_l \quad (3)$$

$$L_{ins} = C_p P_{l\_ins} + C_q Q_{l\_ins} \quad (4)$$

The function for calculating active and reactive power loss is:

$$loss_P = \sum_{i=1}^{N_{br}} R_i |I_i|^2 \quad (5)$$

$$loss_Q = \sum_{i=1}^{N_{br}} X_i |I_i|^2 \quad (6)$$

2.2. Voltage profile

One of the advantages of proper location and sizing of the DG and capacitor bank is the improvement voltage profile. This index indicates bus voltage deviation from nominal voltage. So as this indicator is closer to zero, the network performance is better. It can be defined as:

$$V_P = pro_{end}/pro_{ins} \quad (7)$$

For calculation the voltage profile at each stage the Eq. (8) is used.

$$pro = \sum_{i=1}^{n} (V_i - V_b)^2 \quad (8)$$

2.3. Reliability

Reliability of system is its ability to perform the task in the system under certain operating and environmental conditions for a specific timeframe. In distribution system, the reliability is related to the outages of consuming power and disruption of equipment's performance [19]. System average interruption frequency index (SAIFI), system average interruption duration index (SAIDI) and average energy not supplied index (AENS) (see Ref. 19 for more details) are reliability indices of load points that are used for defining the reliability index. So, the reliability index is defined as follows:

$$S_{rel} = C_{r1} \times \frac{SAIFI_{end}}{SAIFI_{ins}} + C_{r2} \times \frac{SAIDI_{end}}{SAIDI_{ins}} + C_{r3} \times \frac{AENS_{ens}}{AENS_{ins}} \quad (9)$$

2.4. Problem constraints

The following constraints must be met during the implementation of the proposed algorithm:

1. The following range for voltage of the buses is allowable:

$$V_{min} \le V_i \le V_{max} \quad (10)$$

2. The utilized DG unit must have the allowable size as the following range:

$$P_{DG}{}^{min} \le P_{DG\_i} \le P_{DG}{}^{max} \quad (11)$$

3. Maximum number of DG, capacitor bank and sectionaliser for placement is known.

4. More than one sectionaliser cannot be located in each branch.

3. BENEFIT FUNCTION

Economic is the integral part of decision making in all daily activities. The power grid also is not exempt from this. So beside technical objectives, economic issues must be considered in developing or improving the network. For this reason, the benefit function is defined according to Eq. (12).

$$Benefit = (B_{LA} + B_{LR} + B_{ENS}) - (C_P + C_C + C_{DG_{ins}} + C_{DG_{oper}} + C_{DG_{main}}) \quad (12)$$

The components of benefit function are described below.

3.1. Active power loss reduction benefit

Optimal placements of DG and capacitor bank have a positive impact on reducing power loss. Active power reduction benefit for each year is as follows:

$$B_{LA_{year}} = ({P_{l\_ins}}^y - {P_l}^y) \times d_1 \times h \quad (13)$$

To calculate the total profit from reducing active loss in the period of operation, the following equation is used:

$$B_{LA} = B_{LA_{year}} \times \sum_{t=1}^{T} (1 + Infr)^t \quad (14)$$

3.2. Reactive power loss reduction benefit

Optimal allocation DG and capacitor bank in the proper place in distribution system reduce reactive power. For this reason, effect of reactive loss reduction in benefit function is considered. The reactive power loss reduction benefit can be defined as:

$$B_{LR_{year}} = ({Q_{l\_ins}}^y - {Q_l}^y) \times d_2 \times h \quad (15)$$

$$B_{LR} = B_{LR_{year}} \times \sum_{t=1}^{T} (1 + Infr)^t \quad (16)$$

3.3. Energy not supplied reduction benefit

By optimal placement of DG, capacitor and sectionaliser in the distribution system, island region is created when fault occurs. So, the energy not supplied is reduced. Of course, meeting network constraints such as the bus voltage limit, results in stability of the island. Energy not supplied reduction benefit for each year is given by:

$$B_{ENS_{year}} = ({ENS_{ins}}^y - ENS^y) \times (MP - d_1) \times h \quad (17)$$

The total profit from reducing energy not supplied in the period of operation using the Eq. (18) is calculated:

$$B_{ENS} = B_{ENS_{year}} \times \sum_{t=1}^{T} (1 + Infr)^t \quad (18)$$

3.4. Protective device cost

This fee includes the costs that the distribution company pays for purchasing and maintaining the protective devices. The cost of protective devices (breaker and sectionaliser) is calculated by Eq. (19).

$$C_P = \sum_{i=1}^{N_b} C_b + \sum_{j=1}^{N_s} C_s \quad (19)$$

3.5. Capacitor bank cost

Capacitor bank's fees are composed of the costs related to the purchase, install and maintenance of them. With respect to the fact that capacitor bank is considered as fixed capacity, the capacitor bank cost is:

$$C_C = \left(\sum_{i=1}^{N_C} Q_C \times C_{cfb}\right) \times \sum_{t=1}^{T} (1 + Infr)^t \quad (20)$$

3.6. Distribution generation cost

The DG costs is composed of installation, operation and maintenance cost. These costs are calculated as follows:

$$C_{DG_{ins}} = \sum_{i=1}^{N_{DG}} P_{DG_i} \times C_{ins} \quad (21)$$

$$C_{DG_{oper}} = \left(\sum_{i=1}^{N_{DG}} P_{DG_i} \times C_{oper} \times h\right) \times \sum_{t=1}^{T} (1 + Infr)^t \quad (22)$$

$$C_{DG_{main}} = \left(\sum_{i=1}^{N_{DG}} P_{DG_i} \times C_{main} \times h\right) \times \sum_{t=1}^{T} (1 + Infr)^t \quad (23)$$

4. OPTIMIZATION ALGORITHM

In this paper, multi-objective optimization for the simultaneous placement and sizing of DG, capacitor bank and sectionaliser are applied. In the proposed method to solve the non-linear problem, the combination of hybrid firefly algorithm and particle swarm optimization and analytical hierarchy process are proposed.

4.1. Hybrid Firefly Algorithm and Particle Swarm Optimization (HFAPSO)

Intelligent algorithms typically are inspired their performance from nature. In Firefly Algorithm (FA), which is inspired from the social behavior of firefly, an absorption power is considered for each artificial firefly and worms move toward the firefly with greater absorbency power. Finally, an insect is selected as the most attractive one, which is the optimal solution for the problem. In this algorithm, the location of each particle is based on strong absorption of particles, when the brightness of the j^{th} firefly is more than the i^{th} firefly is updated as follows (see Ref. [20] for more details):

$$\acute{x}_i = x_i + \beta_0 e^{-\gamma r^2}\left(x_j - x_i\right) + \alpha\varepsilon_i \tag{24}$$

Particle Swarm Optimization (PSO) is a stochastic global optimization technique which uses swarming behaviors observed in flocks of birds, schools of fish or swarms of bees, in which the intelligence is emerged. In PSO, the particles move around according their velocity and position. Equations (6, 7) are used to update the velocity and position of the particles [21].

$$\acute{V}_i = \omega V_i + c_1 r_1\left(x_{i_{best}} - x_i\right) + c_2 r_2(g_{best} - x_i) \tag{25}$$

$$\acute{x}_i = x_i + \acute{V}_i \tag{26}$$

The proposed HFAPSO algorithm uses the mechanism of FA and PSO ability. Although, FA converges very quickly than PSO in running, but it is often outperformed by PSO for long simulation runs, when the PSO finds better solutions. With combination two algorithms, the space of particles' motion is limited due to global communication between particles in the FA and simple search mechanism with high accuracy in the PSO. Also, with updated two steps in any iteration, the probability of algorithm diversion is reduced and also more optimal results in less time than other algorithms are obtained. Therefore, combination of FA and PSO algorithms increases the convergence rate and accuracy. This hybrid algorithm also has appropriate performance in complex issues. This algorithm initially uses PSO and then FA update particles' location. The proposed hybrid algorithm steps are as follows:

Step 1: Generate the initial position and velocity of all particles

Step 2: Calculate the objective function of all the particles

Step 3: Evaluate the objective function and select the personal best and global best ($x_{i_{best}}, g_{best}$)

Step 4: Apply PSO method and update the velocity and position of particles (Eqs. (25), (26))

Step 5: Calculate the objective function of all the particles

Step 6: Apply FA and update the particle's position (Eq. (24))

Step 7: Repeat the searching process from step 2 until current iteration reaches the predetermined maximum iteration number.

For analyzing the results of the HFAPSO algorithm, they are compared with results of PSO and FA algorithms. The results and analysis exist in the appendix on some test functions. According to the results, the proposed HFAPSO than the PSO and FA algorithms is able to provide more accurate results. The HFAPSO has high convergence rate and in this algorithm the optimum result is obtained in less number of iterations than the PSO and FA techniques. Thus, the proposed HFAPSO has merit in terms of exploration.

For multi-objective optimization, the method used in reference [22] and non-dominated sorting is used. In this method, particles in terms of all objective functions are compared with every other particle in the population. Since the possibility of a particle to be excellent in all terms of criteria, is low; particles are updated as non-dominated and sorted according to the lack of excellence. In other words, non-dominated front is used to sort the population in the proposed multi-objective algorithm. The first and last fronts are the highest and lowest ranked, sequentially.

4.2. Analytical Hierarchy Process (AHP)

After obtaining the Pareto optimal set solution, according to the importance of various indices of the system, the AHP method is used for the ultimate goal of the decision. AHP is a methodology for finding the optimal solution in the issues in which user is faced with several conflicting criteria and should select the most appropriate issue between the various schemes proposed [23].

Due to the importance of consumers and to improve the number of subscribers who are satisfied by the received service from the network, reliability index has the highest weight. Loss and voltage profile have the equal and lower weight. Profit also allocated less weight than technical indicators. Therefore, the defined criteria of judgmental matrix are presented in Table 1. To obtain the final weight of the criteria, the arithmetic mean method is used [23]. The final weight of criteria also can be seen in Table 1. Finally, in order to choose the best result Eq. (27) is used.

$$final_{function} = W_{loss} \times loss + W_v \times vol_{profile} + W_{rel} \times Rel + W_B \times Benefit \quad (27)$$

5. ALLOCATION ALGORITHM

To achieve the best result; at first, objective function, including the network loss, voltage profile and reliability, as multi-objective function is optimized using the proposed HFAPSO technique.

Table 1. Judgment matrix and Final weight of indices in the AHP

Judgment matrix				
Index	Reliability	Loss	Voltage profile	Benefit
Reliability	1	2	2	3
Loss	0.5	1	1	1.5
Voltage	0.5	1	1	1.5
Benefit	0.33	0.66	0.66	1
Final Weight	0.4290	0.2145	0.2145	0.1419

At every stage, according to the location of DG units, capacitor and sectionalisers, island regions are determined. After determining island areas, power flow is done in these regions; if voltage at the buses is not violated the voltage constraints, the island will continue to work, otherwise it will be interrupted. After applying intelligent algorithm and improving the objective functions, in order to select optimal location, size and number of devices, AHP mechanism based on profit function is applied.

Using the above mentioned method, the complete algorithm for simultaneous allocation of DG, capacitor bank and sectionaliser in the distribution system is shown in Fig. 2. In this figure, column 1 is initial actions. In this step, actions such as selecting the number of devices and primary calculation of objectives are done. Column 2 is related to the main loop which uses the proposed HFAPSO algorithm to optimize the objective functions consist of network loss, voltage profile and reliability indices. In any iteration of the main loop, the problem constraints are also evaluated. Finally, in the last column, optimal solution equal to best particle is selected using the AHP method. In this step, the profit function is also applied.

6. NUMERICAL RESULTS AND DISCUSSION

In this section, the proposed algorithm for simultaneous allocation of DG, capacitor and sectionaliser are applied on IEEE 69-bus radial distribution test system [24] and actual 22-bus distribution system in Tehran-Iran [25].

Table 2. Capacity and yearly cost of fixed capacity bank

$Q_c\ (Kvar)$	150	300	450	600	750	900
$C_{cfb}\ (\frac{\$}{Kvar})$	0.500	0.350	0.253	0.220	0.276	0.183
$Q_c\ (Kvar)$	1050	1200	1350	1500	1650	1800
$C_{cfb}\ (\frac{\$}{Kvar}$	0.228	0.170	0.207	0.201	0.193	0.187
$Q_c\ (Kvar)$	1950	2100	2250	2400	2550	2700
$C_{cfb}\ (\frac{\$}{Kvar}$	0.211	0.176	0.197	0.170	0.189	0.187
$Q_c\ (Kvar)$	2850	3000	3150	3300	3450	3600
$C_{cfb}\ (\frac{\$}{Kvar}$	0.183	0.180	0.195	0.174	0.188	0.170

Here, DG is considered as a PQ load which provides active and reactive power. The DG's operating power factor is set at 0.85. The capacity and yearly fixed cost of capacitor bank are given in Table 2. Commercial information of network and devices is tabulated in Table 3. Table 4 shows the values of the remaining parameters used in the study.

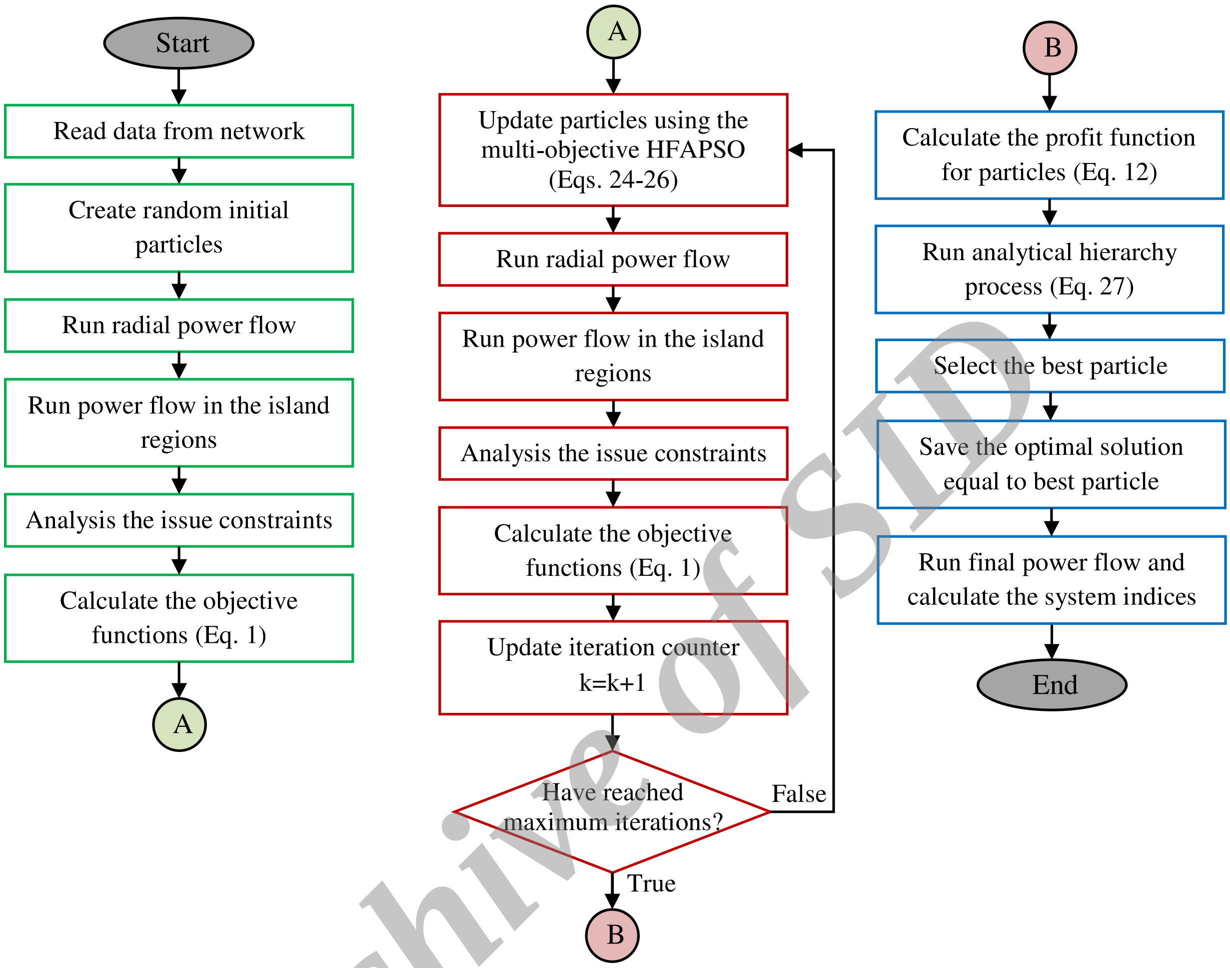

Fig. 2. Flow chart of the proposed method for simultaneous placement of DG, capacitor and sectionaliser

Table 3. Commercial information of network and devices

Parameter	Unit	Value
d_1	$\$/MW\,h$	14
d_2	$\$/MVar\,h$	4
MP	$\$/MW\,h$	28
C_b	$\$$	3250
C_s	$\$$	6500
C_{ins}	$\$/MW$	318000
C_{oper}	$\$/MW\,h$	29
C_{main}	$\$/MW\,h$	7
$Infr$	%	10
h	$hours$	8760
T	$year$	5
Annual load growth rate	%	5

In this network, maximum allowed number of DG, capacitor and sectionaliser to locate in the network, is 4 pcs of each. To obtain the best location and sizing of devices, the multi-objective optimization process and simultaneous improvement of the indicators (Eq. 1) are used.

Table 4. Simulation parameters

Index	Value	Index	Value
C_p	0.6	C_q	0.4
k_1	0.33	k_2	0.33
k_3	0.34	c_1 ,c_2	2
β_0	2	α	0.2
V_{min}	0.9 (pu)	V_{max}	1.1 (pu)
$P_{DG}{}^{min}$	0.1 (MW)	$P_{DG}{}^{max}$	2.5 (MW)

Figure 4 shows simultaneous improvement of the goals after applying the proposed method for placement of DG, capacitor and sectionaliser. According to assumed maximum allowed number of devices that can be used to locate in the network, there are 64 modes of devices. To select the optimal number of devices, the proposed algorithm as given in Sec. 5 is used to locate different number of devices. After using the proposed method for placement of devices in all scenarios, and using the AHP method and comparing the final results; top 10 results are shown in Table 5. Table 6 shows the objective function's value after installation of different number of DG, capacitor and sectionaliser at top 10 results.

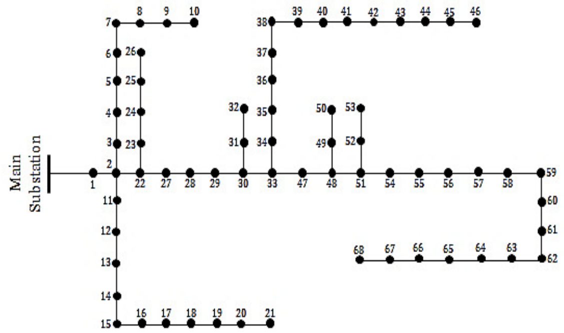

Fig. 3. Single line diagram of the 69-bus distribution system

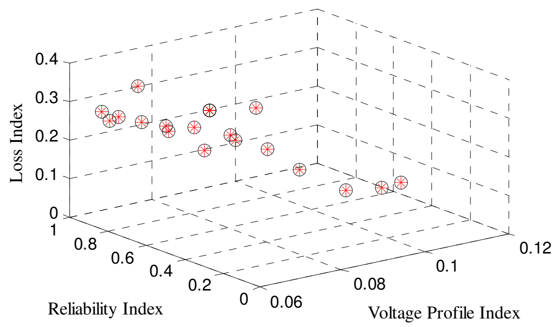

Fig. 4. Multi-objective optimization with HFAPSO for simultaneous placement of devices (non-dominated solutions)

Simulation results show the effectiveness of the proposed method in reducing network loss (86-96 %), improving voltage profile (97-99 %) and reliability (77-84 %) and increasing profit. In the last column of Table 6, the final weight of choice is determined according to the AHP method so that larger weight is the desirable response.

Table 5. Top 10 results of simultaneous placement of DG, capacitor bank and sectionaliser in the 69 bus system

Top 10 No	DG No	Capacitor No	Sectionaliser No	Placement data	Distributed generation (Position: bus number Capacity: MW)				Capacitor (Position: bus number Capacity: Mvar)				Sectionaliser (Position: branch number)			
1	3	2	3	Position	42	15	55		18	37			47	51	37	
				Capacity	1.91	0.458	0.6709		0.15	0.6						
2	4	3	3	Position	42	49	22	55	15	37	39		38	51	18	
				Capacity	1.489	0.1	0.523	0.561	0.45	0.45	0.15					
3	4	4	4	Position	42	33	37	55	23	31	22	36	34	26	47	31
				Capacity	1.5	0.1	0.1	0.625	0.15	0.15	0.45	0.15				
4	2	4	4	Position	54	42			49	43	38	37	31	38	48	23
				Capacity	0.586	1.792			0.15	0.15	0.15	0.15				
5	3	1	2	Position	49	55	42		47				40	48		
				Capacity	0.1	0.568	1.746		0.6							
6	3	1	3	Position	46	43	55		33				19	36	48	
				Capacity	0.1	1.626	0.409		0.3							
7	2	3	3	Position	42	55			31	38	31		39	18	51	
				Capacity	1.894	0.677			0.6	0.6	0.15					
8	4	3	4	Position	37	42	51	48	34	33	27		48	26	46	39
				Capacity	0.1	1.48	1.37	0.1	0.15	0.45	0.45					
9	4	1	4	Position	43	48	42	15	26				39	21	16	30
				Capacity	0.305	1.368	1.311	0.1	0.3							
10	4	2	3	Position	26	42	19	48	36	31			48	25	39	
				Capacity	0.917	1.645	0.1	1.428	0.15	0.45						

Table 6. Technical and commercial parameters after installation top 10 results in the 69 bus system

Top 10 No	DG No	Capacitor No	Sectionaliser No	Placement data							
				Active loss (MW)	Reactive loss (Mvar)	Voltage profile	SAIFI	SAIDI	AENS	Benefit ($)	Final weight
Initial network				0.2249	0.1021	0.0993	2.234	1.8163	0.3997	-	-
1	3	2	3	0.0118	0.0100	0.0007	0.4141	0.2933	0.0655	4,753,539,076	0.1246
2	4	3	3	0.0097	0.0091	0.0012	0.4531	0.3049	0.0682	4,713,366,776	0.1179
3	4	4	4	0.0095	0.0086	0.0011	0.4892	0.3339	0.0754	4,612,595,434	0.1116
4	2	4	4	0.0097	0.0088	0.0011	0.4820	0.3266	0.0731	4,644,699,937	0.0979
5	3	1	2	0.0085	0.0082	0.0002	0.4916	0.3314	0.0746	4,623,263,421	0.0979
6	3	1	3	0.0105	0.0095	0.0025	0.5029	0.3446	0.0771	4,589,487,346	0.0939
7	2	3	3	0.0203	0.0137	0.0015	0.4531	0.3049	0.0682	4,713,725,985	0.0919
8	4	3	4	0.0205	0.0128	0.0014	0.4601	0.3015	0.0676	4,721,186,410	0.0905
9	4	1	4	0.0133	0.0084	0.0009	0.5231	0.3436	0.0763	4,596,879,545	0.0900
10	4	2	3	0.0145	0.0060	0.0008	0.4909	0.3110	0.0694	4,691,209,479	0.0837

According to this, placement No. 1 is selected as the optimal place and proper number of devices. Consequently, the placement of 3 DG units, 2 capacitor banks and 3 sectionalisers alongside the one main breaker, having the highest final weight, is the proper number and optimal place of devices on the network by the proposed method.

To assess the impact of the proposed method, analysis of the network structure is necessary. According to the load information of network, it can be observed that the 69-bus system with 17064 subscribers, consumes 3801.59 kW active power and 2693.6 Kvar reactive power. In terms of load, the network can be divided into three parts.

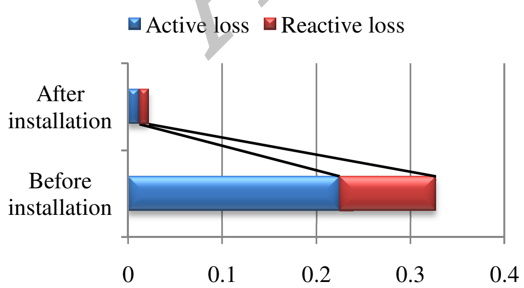

Fig. 5. Comparingactive and reactive loss, before and after installation of equipment

Before the 33^{th} bus, consumes 30 percent of total power of the network. After the 47^{th}bus, to which about 20 percent of the subscriber and network load is connected. Sub branches connected to 33^{th} bus, with having 8000 customers consume about 50 percent of the power to supply the circuit. Also, bus number 42 is the most consumed buses with consumption 1244 kW and 888 kVar by 5680 subscriber in the network.

According to the network structure, sub branch connected to 33^{th}bus is one of the best options to locate equipment, in order to form an island area and improve the reliability of grid when fault occurred. DG unit is located in this area, on the bus number 42 as the most consumed buses in the network. This placement improves the stability of island area and also has a positive impact on the other technical indicators. So, it can be said that the simultaneous connection of DG unit and capacitor bank at this overloaded branch, is reduced the load density of lines to decrease the network loss and improve the voltage profile. Similarly, it can be said that places of other devices with respect to the network structure as the optimal locations. Active and reactive power losses are reduced 94.75% and 90.2%, respectively by connecting these devices (placement No.1) to distribution system; details of active and reactive power losses at the network, before and after installation of devices is shown in Fig. 5.

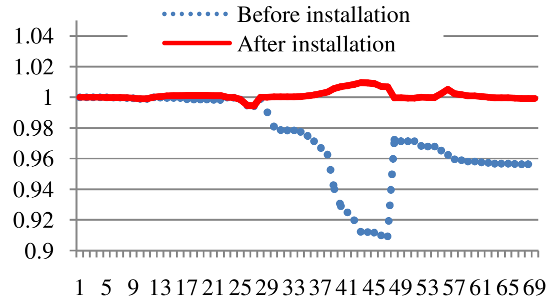

Fig. 6. Voltage level for 69 bus system before and after installation devices

Also voltage profile is improved very much (about 99%) with placement of DG, capacitor and sectionaliser simultaneously. Fig. 6 depicts voltage level of each bus in the 69 bus system. The details of voltage variation include the minimum and maximum voltage at the buses, range of voltage changing, average and variance of voltage at the radial distribution network, before and after installation of instruments are presented in Table 7. Simultaneous placement of devices, with 83.26% and 98.8% reduction in range of voltage changing at the buses and variance of voltage, respectively is caused to enhance the voltage stability of buses and to improve the voltage profile in the radial network. Although, DG and capacitor bank alone can improve the voltage profile, however, simultaneous placement of this device is more effective.

Table 7. Details of voltage at the 69-bus radial distribution system, before and after installation devices

Index	Minimum voltage $(min_V), pu$	Maximum voltage $(max_V), pu$	Range of voltage changing $(max_V - min_V)$	Average	Variance
Before installation	0.9092 at bus 46	1 at bus 1	0.0908	0.97338	0.00073037
After installation	0.9943 at bus 26	1.0095 at bus 42	0.0152	1.0012	0.0000087125

Table 8. Effect of various parameters on the rate of profit

Index	Value
B_{active_loss}	197,162
$B_{reactive\_loss}$	24,381
B_{ENS}	4,762,108,177
$Cost_{Device}$	8,790,644
$Total\ Benefit$	4,753,539,076

The profit function is related to the reduction of network loss and improvement of network reliability; thus, with improving technical parameters of the network, profit of distribution company also is increased. The effects of various parameters on the rate of benefit are presented in Table 8. Based on this Table, reducing the energy not supplied has the greatest effects on increasing the company profit. This effect is one of the main reasons for increasing attention of experts to improve network reliability and ENS indices.

6.1. Actual 22 bus distribution system

The other system under study is an actual system of Tehran Distribution Company in Iran which is shown in Fig. 7 [25]. The system has 22 buses and 21 lines. In this network the allowed maximum number of DG, capacitor bank and sectionaliser to locate in the network, is 3 pcs of each.

To obtain the best location and size of devices, the multi-objective optimization and simultaneous improvement of the indicators (Eq. 1) are used.

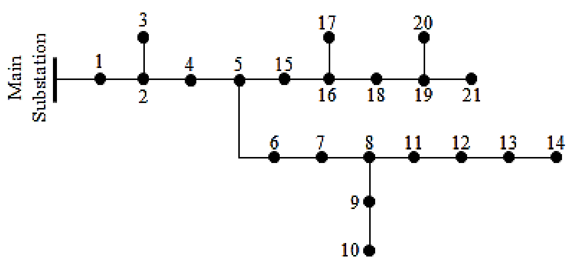

Fig. 7. Single line diagram of the actual 22 bus distribution system in Tehran-Iran

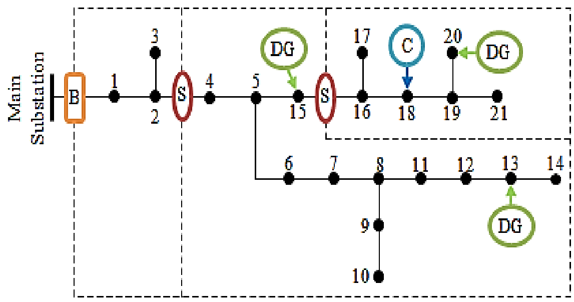

Fig. 8. Actual distribution system with optimal devices are selected by the proposed method

According to allowed maximum number of devices that can be used to be located in the network, there are 27 modes for a number of devices. To select the optimal number of devices, the proposed algorithm is used to locate different number of devices. After using the proposed method for all scenarios, the AHP method is applied and final results are compared with each other.

Consequently, the placement of 3 DG units, 1 capacitor bank and 2 sectionalisers alongside the main breaker is the proper number with having the highest final weight. Optimal place of devices on the actual system by the proposed method is shown in Fig. 8. According to Fig. 8, DG units are placed on nodes 13, 15 and 20 which their sizes are 1.355 MW, 2.5 MW and 1.096 MW, respectively. The capacitor bank of 0.15 Mvar is placed in node 18. Also, beside the main breaker, two sectionalisers are placed in branches 4 and 16. Now, with regard to the location of equipment, performance of the proposed algorithm on the distribution network can be discussed.

The actual 22 bus distribution system with 2126 subscribers, consumes 1672.34 kW active power and 1036.441 kVar reactive power. In terms of load, the network can be divided into two parts: The main branch of the network, which consumes 44.76% of total power of the network by the 853 customers. Sub branch connected to bus 5 having 1273 customers, consumes55.24% of the power to supply the circuit. Also,20^{th}bus with consumption of 372 kW and 230.55 kVar by280 subscribers is the most consumed bus in the actual system.

Table 9. Amount of reliability indicators before and after installation

	SAIFI	SAIDI	AENS
Initial	9.9529	29.8588	74.4183
Proposed method	1.5502	4.6506	10.1509

According to the Fig.8 and analysis of the network structure, it can be said that the proposed algorithm has the appropriate performance. By connecting these devices to the actual 22 bus distribution system, network will be divided into 3 protection area. Thus, with creation of island region when fault occurred, system's reliability will improve about 85%. The details of reliability indicators are presented in Table 9.

Location of DG units and capacitor bank somehow improves stability of island areas, and also other technical indices of system such as network loss and voltage profile are improved. This system in initial state has 0.1677 MW and 0.0967MVar active and reactive losses, respectively. Loss index is reduced to 94.56% in the actual system by connection of these devices.

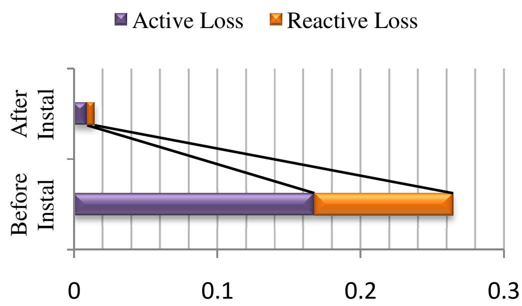

Fig. 9. Comparing active and reactive loss, before and after installation of equipment in actual system

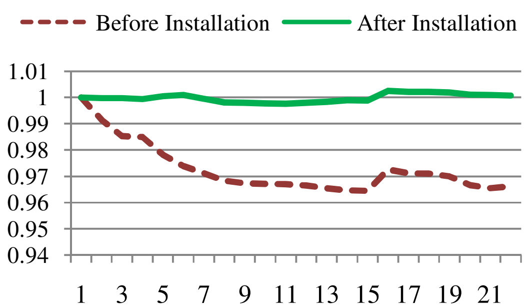

Fig. 10. Voltage level for actual system before and after installation devices

Details of active and reactive power losses, before and after installation, are shown in Fig. 9. Finally, system's active and reactive power losses using the proposed method and placement of devices in optimal location are equal to 0.0091 MW and 0.0053 Mvar, respectively.

The proposed method also has appropriate performance in improving the voltage profile. The value of voltage profile index before and after installation of devices is equal to 0.0183 and 5.107E-5, respectively. This index is improved about 99%using the proposed algorithm; therefore, network stability has been improved considerably. This result is clearly demonstrated in Fig. 10.

The statistical details of voltage variation, before and after installation of instruments are presented in Table 10. Simultaneous placement of devices, with 86.2% and 97.3% reduction in range of voltage changing at the buses and variance of voltage, respectively is caused to increase the voltage stability at the buses and to improve the voltage in the actual system.

Table 10. Details of voltage at the actual radial distribution system, before and after installation devices

Index	Minimum voltage $(min_V), pu$	Maximum voltage $(max_V), pu$	Range of voltage changing $(max_V - min_V)$	Average	Variance
Before installation	0.9645 at bus 15	1 at bus 1	0.0355	0.97267	8.709E-5
After installation	0.9976 at bus 11	1.0025 at bus 16	0.0049	0.99984	2.328E-6

Table 11. The details of company benefit in each year

Year	Income	Cost	Benefit
1	1,701,735,505	315,323	1,701,120,181
2	1,965,504,652	171,819	1,965,332,833
3	2,270,158,034	189,001	2,269,969,034
4	2,522,032,713	207,901	2,621,824,812
5	3,028,447,988	228,691	3,028,219,298
Total	11,587,878,892	1,112,735	11,586,766,157

As illustrated before, technical indices of system include of network loss, voltage profile and reliability are improved. Whatever the technical indicators of system improved further, the profit of distribution company will be greater. System's profit using the proposed method after operation period is equal to 11,856,766,157 $. The details of company benefit during the operation period are presented in Table 11.It can be seen that optimal allocation of devices using the proposed method, in addition to compensating equipment's cost, increases the profit of distribution system each year. Consequently, it is evident that the proposed algorithm has also appropriate effect on improving the economic index.

7. CONCLUSION

In this paper, in order to increase the efficiency of the distribution system, simultaneously placement and sizing of DG, capacitor and sectionaliser has been studied as the multi-objective optimization problem. The objectives of the problem are reduction of active and reactive power losses, improvement of voltage profile and reliability indices and increasing distribution company profit. To optimize and select the best result, combination of the proposed HFAPSO algorithm and AHP mechanism is applied. To evaluate the proposed method, it is implemented on IEEE 69-bus and an actual 22-bus radial distribution systems. From the simulation results, following points can be concluded:

1. Protection devices only have an impact on network reliability. While, DG units and capacitor banks impact on the network loss and voltage profile in addition to reliability indices.

2. DG and capacitor are commonly located near the load center, which improve the stability of island areas; on the other hand technical indicators of the network are improved by reducing the load density of lines. Sectionalisers are located near the sources and increase system reliability by creating island regions, so in fault happening, the least amount of energy not supplied is achieved.

3. DG, capacitor and sectionaliser lonely can be increased the performance and efficiency of the

distribution system; however, using the proposed method and simultaneous placement is more effective.

4. By applying the proposed algorithm, proper number of devices is determined. In addition to technical advantages, an economic saving or benefit is also obtained after planning period.

5. The proposed HFAPSO algorithm in comparison with original algorithms is faster and more accurate. By using AHP mechanism and the relative priority of indicators, the best number, location and capacity of the equipment can be obtained.

Appendix

In this section, the proposed intelligent algorithm is examined. The HFAPSO algorithm is benchmarked using unimodal and multimodal benchmark functions. These test functions are the classical functions utilized by many researchers [26, 27] and are presented in Table I.

For verifying the results, the proposed hybrid HFAPSO algorithm is compared with PSO and FA techniques. The PSO, FA and HFAPSO algorithms were run 20 times on each benchmark test function with identical conditions (Iteration: 200, Dimension: 30). The statistical results, including average, best and standard deviation, are reported in Table II.

According to the results of Table II, the proposed HFAPSO is able to provide more accurate results than PSO and FA algorithms. Fig. I shows the convergence results on various objective functions.

Table I. Benchmark functions

Functions

$$f_1(x) = \sum_{i=1}^{n} i x_i^4 + random[0,1]$$

$$f_2(x) = \sum_{i=1}^{n} [x_i^2 - 10\cos(2\pi x_i) + 10]$$

$$f_3(x) = -20\exp\left(-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}\right) - \exp\left(\frac{1}{n}\sum_{i=1}^{n}\cos(2\pi x_i)\right) + 20 + e$$

$$f_4(x) = \frac{1}{4000}\sum_{i=1}^{n} x_i^2 - \prod_{i=1}^{n}\cos\left(\frac{x_i}{\sqrt{i}}\right) + 1$$

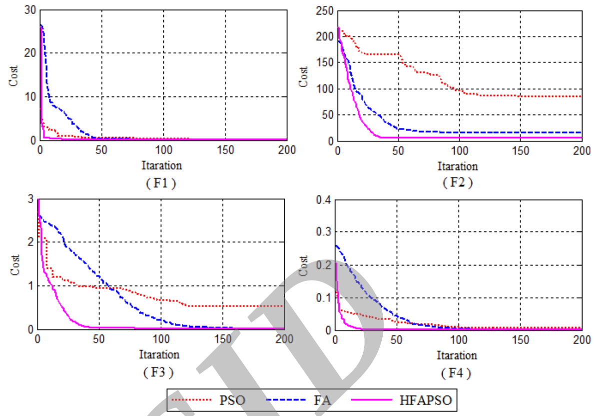

Fig. I. Convergence plot for various fitness functions

Table II. Results of benchmark functions

Algorithm		Benchmark functions			
		F1	F2	F3	F4
PSO	Average	0.15886	76.4478	0.53016	0.00868
	Best	0.10670	66.9697	0.43140	0.00770
	Std	0.03849	6.33846	0.04115	0.00062
FA	Average	0.08276	12.6496	0.00658	0.00216
	Best	0.06180	10.9595	0.00510	0.00130
	Std	0.01113	1.26107	0.00108	0.00051
HFAPSO	Average	0.01405	3.11510	0.00439	1.618E-4
	Best	0.01130	2.00480	0.00380	1.385E-4
	Std	0.00183	0.82972	0.00027	2.117E-5

It can be said that the HFAPSO has high convergence rate than PSO and FA, in which the optimum result is obtained in less number of iteration. Thus, the proposed HFAPSO has merit in terms of exploration.

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