Feeder Reconfiguration and Capacitor Allocation in Presence of Non-linear Loads Using New P-PSO Algorithm

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Abstract: This paper proposes a new particle swarm optimization (PSO) algorithm for combined problem of capacitor placement and network reconfiguration simultaneously in the presence of non-linear loads. Here, the minimizing cost of real power losses and capacitor installation and also improving the power quality criteria have been pursued as the goals of an optimization problem. In the proposed method, to achieve better control on the algorithm's exploration and exploitation capabilities, particles velocity will be dependent upon both particle's fitness and time. Perturbation module is adopted to perform perturbation on some particles and provide extra diversity to jump out from local optima and avoid premature convergence. The proposed model is implemented on two typical networks including 33-bus IEEE standard well-known test system and a 77-bus radial distribution network of Sirjan, Iran. Through showing numerical results, the performance of the presented method will be discussed in comparison to previously proposed ones. The numeric comparison also indicates that simultaneously capacitor placement and network reconfiguration lead to far better results than they are considered non-simultaneously. Furthermore, in regard to harmonic distortion, as a term of a multi-objective function, it also improves the power quality of the network during the reconfiguration and capacitor placement procedures.

1. Introduction

The subject of minimizing distribution systems losses has gained a great deal of attention due to the high cost of electrical energy. Accordingly, much of current research on distribution automation has focused on the minimum-loss configuration problem and installation of capacitor banks to reduce the power system losses. Capacitors are widely used in distribution systems for reactive power compensation, achieving power and energy loss reduction and improving service quality via voltage regulation. The issue of capacitor banks placement in distribution systems has been one of the most prominent research priorities during past decades [1]-[4]. Regarding the capacitor placement, the optimal size and location of capacitors should be determined by different aims such as minimizing the cost of capacitor installation and the cost of real power losses. Therefore, a wide variety of methods have been suggested for capacitor placement problem that include classic ones such as non-linear programming [1] and modern ones like genetic algorithm [2], simulated annealing [3], and particle swarm optimization [4].

Reconfiguration is the process by which the distribution system structure is changed through the opening and closing of the switches. Different methods have been developed to solve reconfiguration problem in distribution networks [5-10]. Use of reconfiguration technique for service restoration and power loss reduction is proposed in [11]. In most of papers, the capacitor placement and network reconfiguration problems have been studied separately, and few papers have investigated them simultaneously [12], [13]. In addition, in most of these papers, the effects of voltage and current harmonics have not been taken into account. In [12], a new method based on ant colony search algorithm has been proposed to solve the combinational problem of feeder reconfiguration and capacitor placement with the aim of minimizing the system power losses. In [13], a joint optimization algorithm has been proposed for combining the capacitor placement and network reconfiguration problems and different load patterns have been considered to show the practical application of this method.

In a real distribution network, the considerations of the power quality issues are indispensable in optimal operation problem of the network, due to the high penetration of the non-linear loads. Without considering harmonic sources in the network, the operation of network may lead to resonance between the shunt capacitors and the inductive elements in the network and in consequence high distortion levels [14]. Therefore, in [10] and [15] the importance of non-linear loads has been taken into account in capacitor placement problem. Besides the impact of capacitor placement on the system harmonics, the reconfiguration process also affects the harmonic level of distribution network. Therefore, it is necessary to consider harmonic condition of networks during the reconfiguration process of distribution networks. In [16] network reconfiguration and capacitor placement are modelled in the form of a multi-objective problem with four scenarios. These studies show that simultaneous implementation of feeder reconfiguration and capacitor placement is more effective than considering them separately. This problem is very complex and has a very large solution space, and several constraints then require the use of appropriate and good optimization method. The PSO is a relatively powerful intelligence evolution algorithm for solving optimization problems. PSO has also been found to be robust in solving problems featuring non-linearity, non-differentiability, and high dimensionality. So, different topologies of PSO has been used in distribution system reconfiguration and capacitor placement problems [17-23]. In the current paper, new PSO algorithm with perturbation is proposed. Despite the competitive performance of PSO, it is noted the tendency of PSO swarm to converge prematurely in the local optima, due to its rapid convergence on the best position found so far at the early stage of optimization. Once the swarm congregates at such position, little opportunity is afforded for the population to explore for other solution possibilities by designing perturbation module. This leads to the entrapment of the swarm within the local optima of search space and thus premature convergence occurs. Another challenging issue that needs to be addressed is the proper control on the exploration and exploitation searching of PSO. In proposed P- PSO new formulation for swarm velocities is designed and the problem is modelled by this proposed method in different six scenarios. In order to indicate the importance of considering THD parameter in multi-objective function, first, the optimization problem is solved for single-objective function based on cost minimization. Then the multi-objective function included THD parameter and costs of losses and capacitor placement is considered for solving the optimization problem. In the proposed model, decrease in cost (including the reduction of costs in losses and capacitors setting), and improvement in total harmonic distortion (THD) of network are considered as the goals of optimization problem. The proposed model is implemented on two typical distribution networks; 33-bus IEEE standard test system and 77-bus distribution system from Sirjan-Iran. For examining the effectiveness of proposed P-PSO algorithm, the results are compared with Fuzzy-HS, HS, ACO and PSO methods and show that the proposed P-PSO algorithm is very effective to optimize complex problem with most profit and best convergence characteristic. The simulation results also confirmed that simultaneous implementation of network reconfiguration and capacitor placement is more effective than considering them separately. Since in this model, THD is considered as a part of objective function, not only it provides further improvement in THD parameter but also facilitates the implementing of designer’s ideas on capacitor placement and network reconfiguration from the perspective of system distortion level.

2. Mathematical expression of problem

The problem of optimal reconfiguration and capacitor placement is a nonlinear multi-objective problem with different constraints which must be considered in solving the problem. In this paper, both economic issue and power quality concept are considered as the objectives of the optimization problem. The mathematical expression of the problem is described as follows:

2.1 Objective function

In order to reduce the harmonic distortion in network with high harmonic distortion, total bus voltage harmonic distortion is considered as a part of objective function. The objective function that should be minimized as shown in Eq. (1) aims at minimizing the total cost due to capacitor placement and power losses, and harmonic distortion considering a one-year time horizon:

$$\boldsymbol{F = minimize}\begin{pmatrix} \boldsymbol{f_1 = K_p P_{loss} + \sum_{i=1}^{n_c} K_{ci} Q_{ci}} \\ \boldsymbol{f_2 = \sum_{i=1}^{n} \mu_{i,ave}} \end{pmatrix} \quad 1)$$

In the above equation, f_1 is the cost of power losses and capacitors and f_2 is a function of annual total harmonics distortion of system buses. P_{loss} is the total annual real power losses, Q_{ci} is the reactive power injection for the i^{th} capacitor; K_p and K_{ci} are the annual cost per unit of the real power loss and the reactive power injection by the i^{th} capacitor respectively; n is the total number of bus; Q_{ci} is the reactive power injection for the i^{th} capacitor; n_c is the total number of shunt capacitors to be installed. The total annual real power loss is calculated through the following equation:

$$P_{loss} = \sum_{l=1}^{NT} P_{loss,l} * \alpha_l \quad (2)$$

Where NT is the number of load levels in piecewise linear estimation of load duration curve, α_l is the percentage of hours of the year at which the distribution system operates with load level l, and $P_{loss,l}$ is total real power loss for load level l that calculated as [24]:

$$P_{loss,l} = \sum_{i=1}^{n_b} P^1_{loss,i,l} + \sum_{i=1}^{n_b} \sum_{h=h_0}^{h_{max}} P_{loss,i,l}{}^{(h)} \quad (3)$$

Where $P^1_{loss,i,l}$ is real power loss in fundamental harmonic at branch i and load level l, $P_{loss,i,l}{}^{(h)}$ is real power loss at harmonic h, load level l and branch i, n_b, h_0 and h_{max} are the number of branches of the network, the smallest order of harmonic and highest order of harmonic, respectively. The fundamental and harmonic component of real power loss are computed using conventional fundamental (PF) and harmonic power flow (HPF), respectively.

For further decreases in THD, THD is considered as a part of objective function, not only it provides further improvement in THD parameter but also facilitates the implementing of designer's ideas on capacitor placement and network reconfiguration from the perspective of harmonic condition of the system. The desired value for THD ($\mathrm{THD_d}$) is equal to 5% [24].

$\mu_{i,ave}$ is defined as average of annual total harmonics distortion of bus i voltage as shown in Eq. (4):

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$$\mu_{i,ave} = \sum_{l=1}^{NT} THD_{i,l} * \alpha_l \tag{4}$$

Where $THD_{i,l}$ is total harmonic distortion of bus i voltage at load level l and calculated as follows,

$$THD_{i,l} = \begin{cases} THD_i & for\ THD_i > THD_d \\ 0 & else \end{cases} \tag{5}$$

The general total harmonic distortion formulation of bus i is as follows:

$$THD_i(\%) = \frac{\sqrt{\sum_{h=h_0}^{h_{max}} \left|V_i^{(h)}\right|^2}}{\left|V_i^{(1)}\right|} \tag{6}$$

Where $\left|V_i^{(1)}\right|$ and $\left|V_i^{(h)}\right|$ are fundamental and harmonic voltage rms values of the ith bus.

Objective function that should be minimized is shown in Eq. (7):

$$f(x) = \alpha_1 f_{1n} + \alpha_2 f_{2n} \tag{7}$$

$\alpha_1$and $\alpha_2$which are selected based on experience are the weighting factors for power losses and capacitor costs and voltage THD respectively. f_{1n} and f_{2n} are normalized values of f_1 and f_2 respectively that are calculated through following equation.

$$f_{in}(x) = \frac{f_{i,max} - f_i}{f_{i,max} - f_{i,min}}$$

8)

That $f_{i,max}$ and $f_{i,min}$ are the maximum and minimum value of f_i respectively.

2.2 Constraints

The objective function is restricted by four constraints; bus voltage constraint, distribution network constraint, number and size of shunt capacitors constraint, and current constraint. Particles that satisfy the constraints and lead to minimum objective function are the best in population.

- Voltage constraint: The magnitude of voltage in each bus must be kept within the following range:

$$V_{min} \le |V_i| \le V_{max}\ , \qquad i = 1, 2, \dots, n$$

9)

Where V_{min} and V_{max} are the minimum and maximum value of bus voltage respectively.

- Current constraint: The magnitude of current in each line must be less than current carrying capacity of the conductor in line ($I_l(max)$):

$$I_l < I_l(max) \tag{10}$$

- Since the harmonic analysis is of interest during the optimization process, the rms value of i^{th} bus voltage can be calculated using the following equation:

$$|V_i| = \sqrt{\left|V_i^{(1)}\right|^2 + \sum_{h=h_0}^{h_{max}} \left|V_i^{(h)}\right|^2} \tag{11}$$

- Distribution network constraint: Since the distribution networks are usually operated in the radial form it is essential to look over the radial form of network through the optimization process.
- Number and size of capacitors constraint: The capacitors are generally manufactured in the standard sizes. Hence, the size of capacitors must be chosen from integer discrete values. It should be paid attention that the total injected reactive power of capacitors must not exceed from the total reactive demand of network.

3. Optimization techniques

3.1 Basic PSO Algorithm

In basic PSO, each particle that is roaming through the *D* dimensional problem hyperspace represents the potential solution for a specific problem. For particle *i* two vectors, i.e. position vector $\mathrm{X_i} = [\mathrm{X_{i1}}, \mathrm{X_{i2}}, \dots, \mathrm{X_{iD}}]$ and velocity vector $\mathrm{V_i} = [\mathrm{V_{i1}}, \mathrm{V_{i2}}, \dots, \mathrm{V_{iD}}]$ are used to represent its current state. Additionally, each particle *i* can memorize its personal best experience ever encountered (i.e. cognitive experience), represented by the personal best position vector $\mathrm{P_i} = [\mathrm{P_{i1}}, \mathrm{P_{i2}}, \dots, \mathrm{P_{iD}}]$. The position attained by the best particle in the society (i.e. social experience) is represented as $\mathrm{P_g} = [\mathrm{P_{g1}}, \mathrm{P_{g2}}, \dots, \mathrm{P_{gD}}]$. Mathematically, at iteration $(t + 1)$ of the searching process, the *d*-th dimension of particle *i*'s velocity, $\mathrm{V}_{\mathrm{i,d}}(\mathrm{t} + 1)$ and position $\mathrm{X}_{\mathrm{i,d}}(\mathrm{t} + 1)$ are updated as follows:

$$V_{id}(t+1) = V_{id}(t) + c_1 r_1 (P_{id}(t) - X_{id}(t)) + c_2 r_2 \left(P_{gd}(t) - X_{id}(t)\right) \tag{12}$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \tag{13}$$

Where c_1 and c_2 are the acceleration coefficients; r_1 and r_2 are two random numbers generated from a uniform distribution within the range of [0, 1]. Particles velocity is clamped to a maximum magnitude of V_{max} to prevent swarm explosion. When minimizing the fitness function *f* in *D* dimensional search space, particle *i*'s P_i position in iteration $(t + 1)$ is updated as follows [25]:

$$P_i(t+1) = \begin{cases} X_i(t+1), & if\ f\big(X_i(t+1)\big) < f(\,P_i(t)) \\ P_i(t) & other\ wise \end{cases} \tag{14}$$

Meanwhile P_i with lowest fitness is assigned as P_g.The implementation of basic PSO algorithm is illustrated in Fig.1.

```
Generate initial swarm and set up parameters for each particle;
Reset t = 0 ;
while t <max-generation do
    for each particle i do
        Update the velocity V_i and position X_i using Equations (12) and (13);
        Fitness evaluation is performed on the updated X_i of particle i;
        if f(X_i)<f(P_i) then
            P_i = X_i;  f(P_i) = f(X_i);
            if f(X_i)<f(P_g) then
                P_g = X_i;  f(P_g) = f(X_i);
            end if
        end if
    end for
    t = t + 1;
end while
```

Fig. 1 *Basic PSO algorithm*

3.2 Proposed P-PSO Algorithm

Despite the competitive performance of PSO, researchers have noted the tendency of PSO swarm to converge prematurely in the local optima, due to its rapid convergence on the best position found so far at the early stage of optimization [26]. Once the swarm congregates at such position, little opportunity is afforded for the population to explore for other solution possibilities by designing perturbation module. This leads to the entrapment of the swarm within the local optima of search space and thus premature convergence occurs. Another challenging issue that needs to be addressed is the proper control on the exploration and exploitation searching of the PSO. So new PSO is characterized by:

3.2.1 Velocity calculation

In proposed model to achieve better control on the algorithm's exploration and exploitation capabilities, particles velocity is dependent on both particle's fitness and time. More specifically, particles with better (i.e. lower) fitness value are assigned with lower ω_i that favour the exploitation, whilst particles with worse (i.e. higher) fitness value is encouraged for the exploration by assigning them with higher ω_i. Mathematically, particle i's inertia weight, i.e. ω_i is calculated as follows:

$$\omega_i = c_1\big((\omega_{max} - \omega_{min}\,) * G_i + \omega_{min}\,\big) + c_2\left((\omega_{max} - \omega_{min}) * \frac{maxiter - iter}{maxiter} + \omega_{min}\right)$$

15)

Where ω_{max} and ω_{min} represent the maximum and minimum inertia weights, respectively, i.e. $\omega_{max} = 0.9$ and $\omega_{min} = 0.4$; G_i represents the fitness dependent weight value that determines ω_i of particle i as shown:

$$G_i = \frac{f(P_i) - f_{min}}{f_{max} - f_{min}} \tag{16}$$

Where f_{max} and f_{min} represent the maximum and minimum personal best fitness values that exist in the population. Equation (12) shows that the particle with smaller fitness has smaller and thus is assigned with smaller ω_i and vice versa. To this end, we update the particle i's velocity, V_i as follows:

$$V_i(t+1) = \omega_i V_i + \sum\nolimits_{P_k \in N_i} c_k r_k (P_k - X_i) \tag{17}$$

where P_k represents the personal best position of neighboring particles that exist in particle i's neighborhood; N_i represents the number of neighbouring particles available for particle i; c_k represents the acceleration coefficient that equally distributed among the N_i neighboring particles, calculated as, $c_k = c/N_i$ where; $c = 4.1$, r_k represents the random number in the range of [0, 1].

3.2.2 Perturbation module

To alleviate the premature convergence issue, a perturbation module is adopted to perform perturbation on the P_g particle and provide extra diversity for it to jump out from local optima, if its fitness is not improved for m successive function evaluations (FEs). The m value that used to trigger perturbation module should not be set too large or too small, as the former wastes the computation resources, whilst the latter degrades algorithm's convergence speed. Herein, m is set as 5. In perturbation module, one of the d-dimension of P_g particle i.e. $P_{g,d}$ is first randomly selected and it is then perturbed randomly by a normal distribution as follows:

$$P_{gd}^{per} = \begin{cases} P_{gd} + r_4\left(X_{max,d} - X_{min,d}\right) & if\ r_3 > 0.5 \\ P_{gd} - r_4\left(X_{max,d} - X_{min,d}\right) & if\ r_3 \leq 0.5 \end{cases} \tag{18}$$

Where P_{gd}, is the perturbed P_g; r_3 is a random number with the range of [0, 1] and generated from uniform distribution; r_4 is a random number generated from the normal distribution of $N \sim (\mu, \sigma^2)$ with mean value of $\mu = 0$ and standard deviation of $\sigma = R$, respectively. R represents the perturbation range that linearly decreased with the number of FEs as follows:

$$R = R_{max} - (R_{max} - R_{min})\frac{fes}{FE_{max}} \tag{19}$$

Where R_{max} and R_{min} are the maximum and minimum perturbation ranges, respectively; fes is the FEs number used; max FE is the predefined maximum FEs. The newly perturbed P_g particle, i.e. P_g^{per} is then evaluated and examined. It will replace P_g if $f(P_g^{per}) < f(P_g)$.

if $f_c \leq m$ then

$\mathrm{P_g^{per}} = P_g$

Randomly select a dimension, d to perform perturbation;

Calculate the range of perturbation, R, using equation (19);

Perform the perturbation on $\mathrm{P_{gd}^{per}}$, using equation (18);

Fitness evaluation is performed on the $\mathrm{P_g^{per}}$ particle;

    if $\mathrm{f(P_g^{per})} < f\mathrm{(P_g)}$ then

$P_g = \mathrm{P_g^{per}}; \mathrm{f(P_g)} = \mathrm{f(P_g^{per})}$;

    end if

end if

Fig. 2. *Perturbation module*

Implementation of EBP module is shown in Fig. 2. The proposed and original PSO is shown as a flowchart in Fig 3. Blocks have dashed boarders, shows changes to the proposed method compared to the conventional PSO.

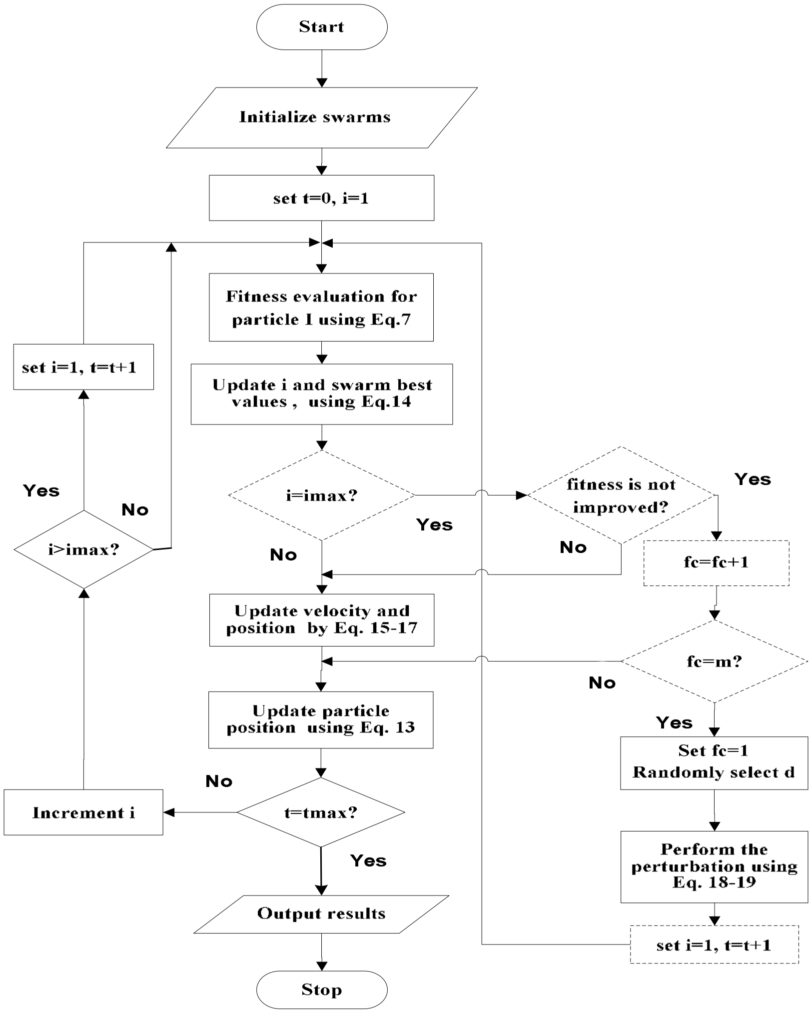

Fig 3. *Proposed PSO flowchart*

4. Solution Method

As mentioned before the optimal capacitor placement and sizing considering network reconfiguration is a non-linear optimization problem with several numbers of local optimum points. Therefore it is necessary to solve this problem with a very robust and precise algorithm to avoid trapping in local optimum point instead of global optimum point in minimum time.

The goal is to find appropriate tie switches (open switches), number, location and size of capacitors in order to mitigate cost and improve THD profile. Due to analysis of harmonics in the distribution network, harmonic power flow (HPF) is utilized to calculation the magnitude of different voltage and current harmonics [15]. Furthermore, the nonlinear loads are model as current sources for each harmonic. It should be noticed that in this paper, modelling of non-linear loads are performed only by the aim of investigating the impacts of network reconfiguration and capacitor placement on harmonic condition of distribution system. Hence, the magnitudes of harmonics are not adapted to real non-linear load patterns. However, in the cases which are more practical, the detailed data of real non-linear loads are required to have precise analysis. In order to solve network reconfiguration more efficiently, loop selection method is used [27]. So a single tie switch is selected from each fundamental loop of the network. Therefore, the number of variables reduces. Table 1 compares the variables of the PSO to P-PSO algorithm. PSO and P-PSO algorithms then used to solve problem with objective function and constraints from Eq. (1-11). To start the procedure, the initial swarm is generated containing random binary strings. Each particle of the swarm indicates the condition of loops selection sequence, the condition of capacitor installation on each node, and the size of located capacitors (4 bits for 1-10 number of 150 kVAr capacitors). Thus, if the number of decision variables (search space dimension) is considered D and population size considered P, then the initial swarms dimension will be P × D. At last, the stop condition of this algorithm is met when no improvement is observed in final solution. Fig 4 shows solution method.

Table 1 *PSO Parameters used During the Simulation*

P-PSO	PSO
Number of particles P =30	Number of particles P =30
$\omega_{max} = 0.9$, $\omega_{min} = 0.4$	$c_1 = c_2 = 2$
$maxiter = 120$	$V_{max} = 0.9$, $V_{min} = 0.4$
$m = 5$	

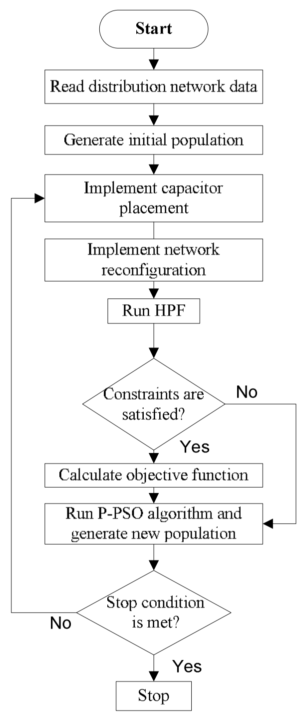

Fig 4. *Solution method flowchart*

5. Results and discussion

The proposed simultaneous network reconfiguration and capacitor placement algorithm using proposed P-PSO optimization method has been implemented in MATLAB2011a. Two case studies are chosen to illustrate the effectiveness of this combinational optimization problem; An IEEE 33-bus distribution network with single supply feeder and constant loads per yaer, and 77-bus distribution network from Sirjan- Iran with variable loads per year. The standard values of commercial capacitors with their relevant costs are available in [10]. The annual cost per unit of the real power loss is considered as 168 US$/kW/year. For each example, the results are compared through six following scenarios:

- **Scenario 1:** The system is evaluated in normal operating condition.
- **Scenario 2:** The system is analyzed after shunt capacitor installation.
- **Scenario 3:** The system is reconfigured without compensating.
- **Scenario 4:** Reconfiguration process is performed after shunt capacitor installation.
- **Scenario 5:** Shunt capacitor installation process is performed after reconfiguration.
- **Scenario 6:** The processes of network reconfiguration and capacitor placement are carried out simultaneously.

In order to indicate the importance of considering THD parameter in objective function, first, the optimization problem is solved for single-objective function based on cost minimization. Then the multi-objective function included THD parameter and costs of losses and capacitor placement is considered.

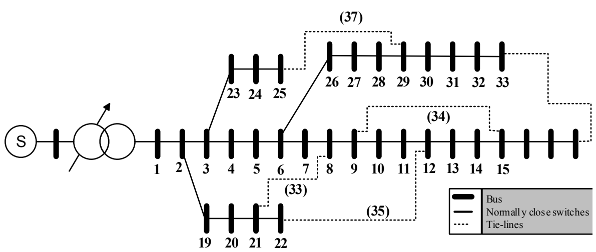

Fig. 5. The IEEE 33-bus test distribution system

Table 2 *Non-linear load data for the 33-bus system*

Non-linear bus number	Non-linear load type	kW	kVAr
13	PWM-ASD	60	35
25	Six-Pulse Variable frequency drive	420	200
30	Six-Pulse	200	600

5.1 Case study I

Figure 5 shows a distribution system in which there are totally 33 buses and 5 tie-switches, and the system voltage is 12.66 kV. The total active and reactive demands are 3.715 MW and 2.3 MVAR, respectively and the loads are supposed to be constant. Other data of 33-bus IEEE test system are available in [28]. Power flow calculations are carried out in per unit, with Sbase = 100 MVA and Vbase = 12.66 kV. This system consists of three non-linear loads in specified buses as indicated in table 2 with the harmonic spectrum given in [16].

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1) Single-objective solution: Minimizing the active power loss and capacitor cost are merely the goal of single-objective solution. The results obtained for aforementioned scenarios are shown in Table 3.

As it can be seen from Table 3, the real power losses are calculated as 201.872 kW in base condition of network. For solving optimization problem through single-objective solution, the weighting factors in (1) are adjusted as α_1= 1 and α_2= 0.

Table 3 *Simulation results for single-objective problem (Case study I)*

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Real power losses (kW)	201.872	137.072	136.927	99.254	93.4915	93.391
Minimum bus voltage (pu)	0.9082	0.947	0.938	0.956	0.963	0.9609
Maximum THD (%)	13.9167	13.894	14.874	13.437	9.5926	12.9947
SATHD (%)	6.8118	8.456	7.0027	6.7412	6.7386	6.8600
NEB	22	23	12	16	17	19
Total cost ($)	33.914	23.55	24.62	23.112	19.521	18.025
Tie switches	33,34,35,36,37	33,34,35,36,37	7,11,12,28,36	7, 11, 14,28, 32	7,10,12,32,37	7,10,14,31,37
Capacitor Location (Bus no.)	-	13,24,29,31	-	20,24,31	3,8,31	5,20,24,29,31
Size of capacitors (×150 kVAr)	-	3,3,4,3	-	4,4,3	5,4,7	1,4,3,5,1

In each scenario, different indices are defined. SATHD represents the system average total harmonic distortion that is calculated using following equation [29]:

$$SATHD = \frac{\sum_{i=1}^{n} L_i THD_i}{L_T} \tag{20}$$

Where L_T is total connected kVA of the loads served from the system and L_i is connected kVA of the loads served from bus ith. It is worthwhile to note that SATHD is not intended as an exact representation of the quality of service provided to each customer. It can be used as a benchmark against which quality levels of different distribution systems can be compared. In Table 3, NEB represents the number of buses that their THD values have exceeded from standard value 5%. The obtained results for harmonic parameters demonstrate that both capacitor installation and network reconfiguration affect the harmonic condition of network. Without considering harmonic condition in the objective function, the capacitor placement may largely distort the harmonic condition of network as the SATHD and NEB parameters are increased from 6.81818 and 22 in scenario1 to 8.456 and 23 in scenario 2, respectively. Along with capacitor placement, network reconfiguration may also distort the harmonic condition of network. However, in single-objective solution of this case study, the reconfiguration process incidentally doesn't improve the harmonic condition of networks. The obtained results for scenarios 4, 5 and scenario 6 represent that the simultaneous performing the network reconfiguration and capacitor placement without considering harmonic condition index in the objective function distorts the harmonic condition level of network. This deduction can be attained by focusing on the obtained results for harmonic parameters in scenario 6. As it can be seen, the SATHD and NEB parameters are increased to 6.86 and 19 in scenario 6.

Table 4 *Simulation results for multi-objective problem (Case study I)*

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Real power losses (kW)	201.872	136.52	135.089	133.228	115.523	100.9007
Fitness Function f	0.5	0.2394	0.238	0.1201	0.1159	0.1002
Minimum bus voltage (pu)	0.9082	0.941	0.941	0.948	0.9496	0.9561
Maximum THD (%)	13.9167	10.233	9.923	10.0471	9.0314	8.9947
SATHD (%)	6.8118	5.749	5.835	3.3282	3.1645	3.0314
NEB	22	8	6	5	5	4
Total cost ($)	33.914	23.085	23.441	18.42	18.37	18.023
Tie switches	33,34,35,36,37	33,34,35,36,37	7,10,12,32,37	7, 9, 14, 32, 37	7,11,12,28,36	7,8,17,31,34
Capacitor Location (Bus no.)	-	7,18,20,24,29,31	-	13,24,29,31	30, 23, 11, 6	11, 18,20, 24, 29
Size of capacitors (×150 kVAr)	-	1,3,1,4,3,2	-	3,3,4,3	6, 3, 1, 1	1,4,1,3,5

2) Multi-objective solution: However, the THD index is not completely disregarded. As it is stated before, the weighting factors are determined by network designer. The results obtained through six defined scenarios are shown in Table 4. For solving optimization problem through multi-objective solution, the weighting factors in (Eq. 5) for both case studies are adjusted as α_1= 0.7 and α_2= 0.3.

In comparison with single-objective solution, the total cost obtained for each scenario is slightly increased in multi-objective solution. However, as it is expected, the values of harmonic parameters are significantly improved in multi-objective solution due to considering THD index as a term of multi-objective function.

As it is obvious from the results, in scenario 2, optimal cost in $ is improved from 33.914 (base condition) to 23.085, by optimal capacitor placement and sizing. In scenario 3, optimal cost is improved to 23.441$, by only reconfiguration. However, in scenario 6, which is dedicated to capacitor installation and network reconfiguration simultaneously, the optimal cost is improved to 18.023$. Both network reconfiguration and capacitor installation can reduce cost and improve THD index as well. It can be deduced from simulation results that simultaneous study of capacitor placement and network reconfiguration results in more improvement in cost and THD index as well as more reduction in real power losses. For instance, the percentile variation of real power losses in scenario 6 is computed thorough following formulation:

$$\text{Real power losses reduction in senario 6} = \left| \frac{\text{Ploss}^{\text{senario 1}} - \text{Ploss}^{\text{senario 6}}}{\text{Ploss}^{\text{senario 1}}} \right| \times 100$$

(21)

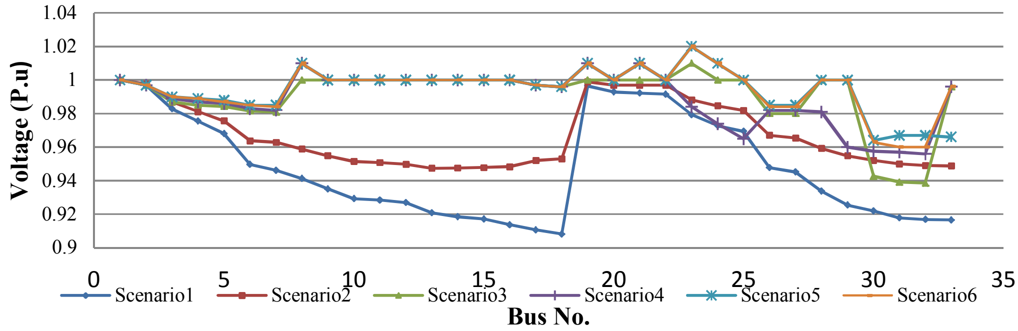

Fig. 6 The magnitude of bus voltages in different scenarios of case study I

Table 5 Comparison of different case study results for multi-objective problem (Case study I)

	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Real power losses reduction (%)	32.37	33	34	42.7	50
Minimum bus voltage increment (%)	3.28	3.28	3.98	4.14	4.79
Maximum THD improvement (%)	26.47	28.7	27.8	35.1	35.37
SATHD improvement (%)	15.6	14.34	51.1	53.54	55.5
NEB reduction (%)	63.63	72.72	77.27	77.27	81.81
Total cost reduction (%)	31.93	30.88	45.68	45.83	45.83

Other variations of parameters are calculated in a similar way to real power losses reduction. As it is shown in Table 5, in this case study, the network reconfiguration and capacitor placement have approximately comparable performance in reducing real power losses and improving harmonic parameters. However, the best results are obtained as soon as the network reconfiguration and capacitor placement are performed at the same time.

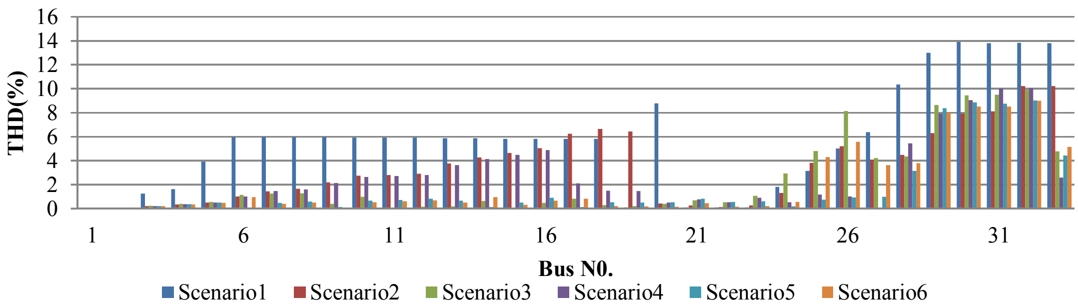

Fig. 7 Harmonic profile in different scenarios of case study I

Fig. 6 and 7 show voltages at all buses and harmonic profile of network in various scenarios. According to Fig. 6, the magnitude of voltage at all buses is within the permissible range which is defined as 10% of nominal voltage. In scenario 6, the THD parameter in most of the buses has less magnitude compared to other scenarios. Figure 8represents the convergence characteristics of original and proposed P-PSO algorithms obtained for scenario 6. As it is shown, proposed P-PSO algorithm has a better convergence property. The optimal cost function in this scenario has been calculated 19.978$ for PSO and 18.023$ for P-PSO, respectively, which implies that original PSO algorithm is trapped in local minimum points.

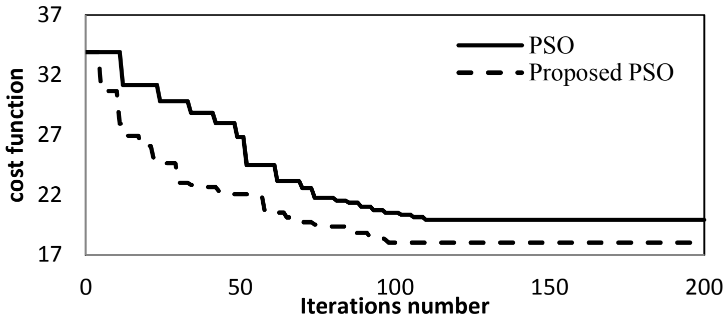

Fig. 8 *The convergence characteristics of proposed P-PSO algorithm, and original PSO* for scenario 6 (case study I)

For examining the effectiveness of proposed P-PSO algorithm, the results obtained from Harmony Search (HS), fuzzy-HS, ACO and PSO methods for scenario 6 with the same cost function and constraints are compared in Table 6. (In the fuzzy-HS case fuzzification process is done [16]). It can be seen from Table 6 that the best total cost (Eq. 5) is obtained 18.023 $, 19.395 $, 19.929$, 19.929$ and19.978$ from proposed P-PSO, Fuzzy-HS, HS, ACO and PSO methods, respectively, which means that these algorithms are trapped in local minima and the best profit in the system is achieved using proposed P-PSO algorithm. Due to the stochastic nature of PSO algorithms, the results of the proposed algorithm is reported in average terms with 150 number of simulation runs with different values of the control parameters in Table 1 in the last columns of Table 6. As a result, the proposed method in changing the parameters is more robust than conventional PSO method.

Table 6 *Results obtained from proposed P-PSO, fuzzy-HS, HS, ACO and PSO methods (case study I, scenario 6)*

	Proposed P-PSO (best)	Fuzzy-HS [16]	HS [16]	ACO [16]	PSO (best)	Proposed P-PSO (averaged)	PSO (averaged)
Real power losses (kW)	100.9007	111.429	114.914	114.914	115.045	104.653	121.231
Fitness Function f	0.1002	0.1062	0.118	0.118	0.129	0.1168	0.1345
Minimum bus voltage (pu)	0.9561	0.9429	0.9579	0.9579	0.9645	0.9474	0.9585
Maximum THD (%)	8.9947	9.1185	7.6524	7.6524	7.7084	9.375	9.025
SATHD (%)	3.0314	3.1637	3.0151	3.0151	3.4846	3.327	3.419
NEB	4	4	4	4	5	4.634	5.302
Total cost ($)	18.023	19.359	19.929	19.929	19.978	18.821	20.804
Tie switches	7,8,17,31,34	6, 8, 9, 28, 32	6, 8, 9, 28, 32	6, 8, 9, 28, 32	7, 9, 13, 16, 26	-	-
Capacitor Location (Bus no.)	11, 18,20, 24, 29	31, 30, 15, 22, 20	25, 20, 12, 18	25, 20, 12, 18	32, 25, 15, 31	-	-
Size of capacitors (×150 kVAr)	1,4,1,3,5	2, 9, 1, 1, 2	8, 4, 1, 2	8, 4, 1, 2	5, 6, 8, 1	-	-

5.2 Case study II

This example is a real distribution network from Sirjan which is shown in Fig. 9. This system consists of 114 sectionalizing switches as well as 10 tie switches [13]. This practical distribution system has 11 supply feeders and the lines include both overhead lines and underground cables. The system voltage is 20 kV and its total load (for peak load level) is 10.344 MW and 8.1 MVAr. Percentage of nonlinear load to the total load is 20% for each bus. Power flow calculation is carried out in per unit based on Sbase = 100 MVA and Vbase = 20 kV. This system consists of non-linear loads as indicated in table 7 with six pulse converter type 1, six pulse variable frequency drive (six pulse VFD) and PWM adjustable speed drives (ASD) harmonic spectrum [16]. Load levels and time percentages are taken to account as Table 8 for linear and nonlinear loads.

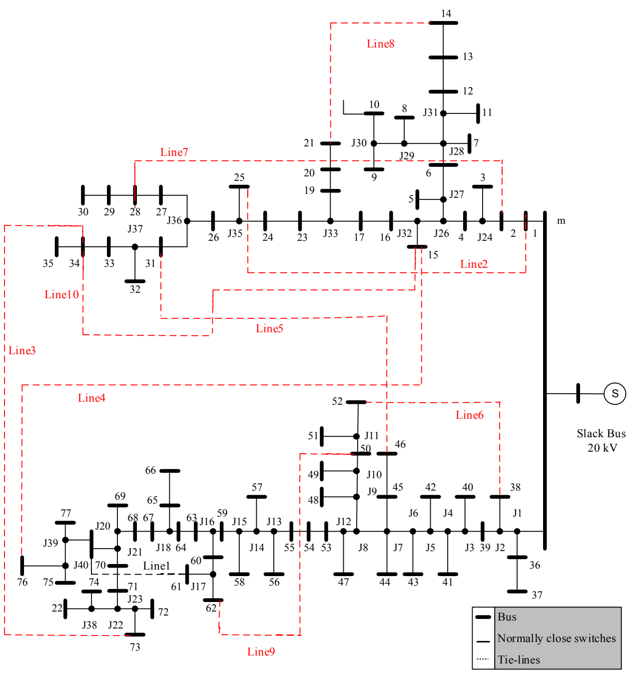

Fig. 9*. Real-life 77-bus distribution system (case study II)*

Table 7 *Non-linear load type for the 77-bus system*

Non-linear load type	Bus number
six pulse converter type 1	7,8,15,21,24,3,5,11,12,19,27,28,30, 31,38,39,41,45,46,48,49,54,56,58,59, 60,64,65,68,69,72,73,76,77
six pulse VFD	1,2,14,17,18,25,33,34,36,37,43,44,51 ,52,57,62,63,67,75,74
PWM ASD	4,6,9,10,13,16,22,23,26,29,32,35,40, 42,50,53,55,57,61,66,70,71,74,75

Table8*: Load levels and percentage of hours of the year*

Load level No.	Load level	α_l
1 (peak)	1	0.25
2 (medium)	0.8	0.5
3 (low)	0.5	0.25

1) Single-objective solution: In a similar way as case study I, first, the single-objective solution is considered for solving optimization problem. The results obtained for aforementioned scenarios are the same as those obtained for IEEE 33-bus system which was described in the last section. Since the focus is on the cost reduction in single-objective solution, the total cost and real power losses are well minimized in scenarios 2, 3, 4, 5 and 6. The most reduction in real power losses and total cost is occurred in scenario 6, where the network reconfiguration and capacitor placement are performed simultaneously. The real power losses in this scenario are relatively reduced to 42.7% of those obtained for scenario 1.

Table 9 *Simulation results for single-objective problem (Case study II)*

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Real power losses (kW)	74.6	52.78	51.61	47.15	46.9	42.74
Minimum bus voltage (pu)	0.9492	0.97035	0.9816	0.9512	0.9602	0.9802
Maximum THD (%)	5.9117	6.9637	6.3529	6.798	6.8436	6.9993
SATHD (%)	2.247	2.3215	2.4198	2.3098	2.349	2.2336
NEB	13	14	13	13	14	14
Total cost ($)	20.367	17.423	16.7658	15.5698	15.419	14.0285
Tie switches	Line1,2,3,4,5, 6,7,8,9,10	Line1,2,3,4,5 6,7,8,9,10	13-14,15-j32,17-j33,26-j35,j36-33,j4-j7,54-55,60-j17,j17-61,j21-18	12-13,15-J32,17-J33,18-J39,J35-26,31-J36,J7-J8,J9-J10,J18-67,J21-70	12-13,24-J35 26-J35,31-J36 J3-J4 J8-J12 J16-63,71-J22,Line4, Line10	12-13,24-J35,26-J35,31-J36,J3-J4,J8-J12,J16-63,71-J22,Line4, Line10
Capacitor Location (Bus no.)	-	77,76,43,40,39, 12,10	-	77,76,43,40,39, 12,10	77,60,43,42,60,2 5,12,10	60,43,42,39,25,12
Size of capacitors (×150 kVAr)	-	1,9,1,5,3,5,2,1	-	1,13,1,2,3,4,1,1	3,2,2,4,2,10,1	2,1,2,7,3,11

2) *Multi-objective solution:* Similar to case study I, The obtained results for six scenarios are shown in Table 10. As it can be seen, in scenario 2, the optimal cost is decreased from 20.367 in scenario 1 to 17.219 by shunt capacitor placement. In scenario 3, where the network reconfiguration is performed, the optimal cost is 16.3084$ while in scenario 6 the simultaneous performing network reconfiguration and capacitor placement, decreases the optimal fitness to 13.8193$. It can be inferred that in scenario 6, we have been getting closer to our optimization goals in compared to other scenarios.

The obtained results for scenario 6 show that, as it is expected, the simultaneous study of network reconfiguration and capacitor placement leads to more reduction in cost, and more improvement in THD index. It should also be noted that as case study I, the magnitudes of voltages are kept in desired range.

Table 10 *Simulation results for multi-objective problem (Case study II)*

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Real power losses (kW)	74.6	55.73	54.78	49.92	48.94	44.98
Fitness Function f	0.1864	0.14268	0.14271	0.1305	0.1291	0.1112
Minimum bus voltage (pu)	0.9492	0.9712	0.9744	0.9767	0.9796	0.9897
Maximum THD (%)	5.9117	5.2944	5.3287	5.3028	5.2854	5.13
SATHD (%)	2.247	2.2152	2.2408	2.2087	2.1857	2.1207
NEB	13	7	9	6	5	2
Total cost ($)	20.367	17.219	16.3084	15.1886	15.0285	13.8193
Tie switches	Line1,2,3,4,5, 6,7,8,9,10	Line1,2,3,4,5, 6,7,8,9,10	15-j32,16-17,j35-26,J36-31,j7-J8,J9-j10,J18-67,70-71,18-61,14-21	4-j26,12-13,26-j36,31-j36,33-34,j6-j7,50-j10,j17-61,63-j16,j21-18	15-j32,16-17,j35-26,J36-31,j7-J8,J9-j10,J18-67,70-71,18-61,14-21	J21-70, 15-J32,17-J33,J35-26,31-J36,J7-J8,J18-67,12-13, 18-J39,J9-J10
Capacitor Location (Bus no.)	-	77,60,43,42,3 9,10,2	-	77,60,43,42,39,1 0,2	77,43,60,40,39 38,12	77,76,42,39, 25,2
Size of capacitors (×150 kVAr)	-	2,2,3,6,11,2,1	-	2,3,2,8,10,1,1	1,4,8,1,5,3,3	3,2,13,3,4,1

Fig. 10 and 11 respectively show the minimum voltages at all buses and the maximum harmonic profile of network in various scenarios. According to Fig. 10, the magnitude of voltage at all buses is laid within the permissible range which is defined as 5% of nominal voltage. As shown in Fig. 11, in scenario 6, the THD parameter in most of the buses has less magnitude compared to other scenarios.

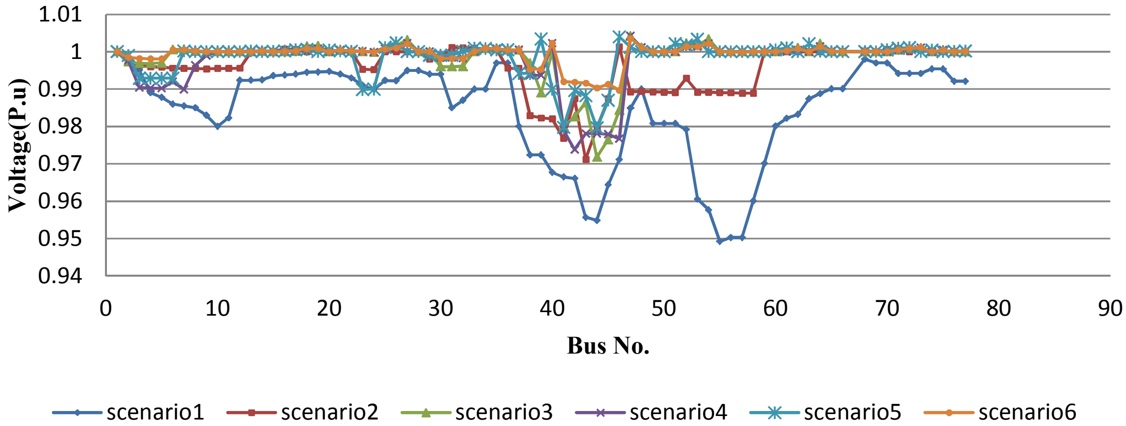

Fig. 10 The magnitude of bus voltages in different scenarios of case study II

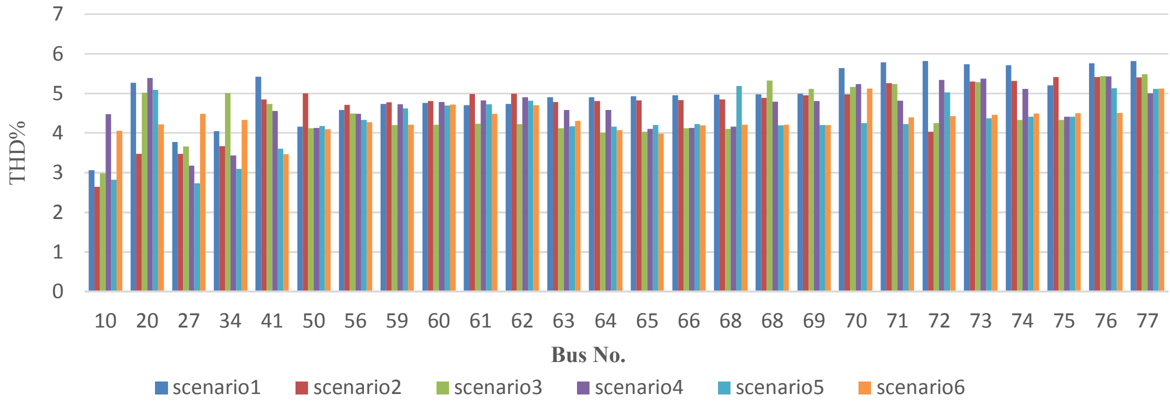

Fig. 11 Harmonic profile in different scenarios of case study II

For examining the effectiveness of proposed P-PSO algorithm, the results obtained from proposed P-PSO and PSO methods for scenario 6 are compared in Table 11. As it can be seen, the total cost is obtained 13.81$ and 14.71$ from proposed P-PSO and PSO methods respectively. It means that more significant profit is achieved using proposed P-PSO algorithm.

***Table 11** Results obtained from proposed P-PSO and PSO methods (case study II, scenario 6)*

	Proposed P-PSO	PSO
Real power losses (kW)	49.9791	52.671
Fitness Function f	0.1112	0.1235
Minimum bus voltage (pu)	0.9897	0.9898
Maximum THD (%)	5.13	5.42
SATHD (%)	2.1207	2.2448
NEB	2	4
Total cost ($)	13.8193	14.7191
Tie switches	J21-70, 15-J32,17-J33,J35-26,31-J36,J7-J8,J18-67,12-13, 18-J39,J9-J10	13-14,15-J32,16-17,J35-26, J36-31,J4-J5,J8-J12,J18-67, J21-70,J40-76
Capacitor Location	77,76,42,39,	77,76,42,38,25, 10,2

(Bus no.)	25,2	
Size of capacitors (×150 kVAr)	3,5,13,3,5,1	3,5,11,7,2,2,3

6. Conclusion

In this paper, an innovative PSO algorithm was proposed to combine the capacitor placement and the network reconfiguration in the presence of non-linear loads. Minimizing the cost of real power losses and capacitor installation and improving the power quality criteria have been pursued as the goals of optimization problem. Superiority of the proposed optimization method was also demonstrated through six scenarios based on two case studies including 33-bus IEEE standard network and a 77-bus radial distribution system of Sirjan, Iran. Capacitor placement and network reconfiguration have an inherent coupling relationship, and therefore, simultaneous implementation of them is more effective than the case in which they are considered separately. Simulation results verified that the effectiveness of the method proposed (with application of multi-objective or single objective functions), and also its solution manner. In addition, considering harmonic distortion of the network as a term of multi-objective function provided a suitable criterion for network designer to improve the power quality of the network during the reconfiguration and capacitor placement. The results of those simulations which were compared with other methods showed that the proposed method converge into optimal solution faster and more accurate.

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