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Optimum placement of active power conditioner in distribution systems using improved discrete firefly algorithm for power quality enhancement

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ABSTRACT

This paper presents an improved solution for optimal placement and sizing of active power conditioner (APC) to enhance power quality in distribution systems using the improved discrete firefly algorithm (IDFA). A multi-objective optimization problem is formulated to improve voltage profile, minimize voltage total harmonic distortion and minimize total investment cost. The performance of the proposed algorithm is validated on the IEEE 16- and 69-bus test systems using the Matlab software. The obtained results are compared with the conventional discrete firefly algorithm, genetic algorithm and discrete particle swarm optimization. The comparison of results showed that the proposed IDFA is the most effective method among others in determining optimum location and size of APC in distribution systems.

Introduction

Over the past few decades, the occurrence of power quality disturbances such as harmonic distortion and voltage sag in distribution systems is increasing and is becoming of great concern. These disturbances may cause interruption in processing plants, resulting in hours of downtime and high turnover losses for utilities and customers. Therefore, the delivered power should be constantly monitored and improved to ensure that power quality is within pre-specified baseline [1,2]. The traditional solutions for power quality improvement are by applying passive harmonic filters and zig-zag reactors, nonetheless the best and most effective solution to mitigate power quality disturbances and protect sensitive equipment is to install proper types of custom power devices (CPDs) such as active power conditioner (APC), dynamic voltage restorer, static compensator and unified power quality conditioner [3]. The placement and sizing of the CPDs should be determined based on economic feasibility, in which optimization is usually considered in the procedure.

In the last two decades, various types of population based optimization algorithms such as bee colony-based approach [4], particle swarm optimization algorithm [5,6], cuckoo search algorithm [7,8], firefly algorithm [9,10] have been widely developed and applied in many industrial applications such as structural designs, milling operations and power systems [11]. In addition, hybrid evolutionary optimization algorithms such as hybrid Taguchi-differential evolution algorithm [12], hybrid differential evolution algorithm [13], hybrid immune algorithm [14], hybrid immune-hill climbing optimization approach [15], hybrid artificial bee colony algorithm [16] can be applied to increase the convergence speed and robustness in finding the global minimum [17].

From power systems point of view, many heuristic optimization techniques have been applied to address the optimal placement and sizing problems of CPDs by introducing different objective functions and constraints to minimize cost and disturbances such as voltage sag and harmonic distortion. A fuzzy system was applied to optimally locate APCs by minimizing harmonic distortion in active power systems [18]. Genetic Algorithm (GA) was applied to optimally place a dynamic voltage restorer and thyristor voltage regulator by minimizing the imposed costs due to the occurrence of voltage sags [19]. Genetic Algorithm was also used to solve the optimal placement problem of several types of flexible alternating current transmission system for improving the overall network sag performance of a power system [20]. An improvement to the conventional GA was then developed using the niching genetic algorithm which has the capability of exploring a wider search space to decrease the probability of convergence in local optima [21]. A solution to the problem of optimal placement of D-STATCOM

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was suggested by using the binary gravitational search algorithm to improve reliability of distribution systems [22]. The optimal placement and sizing of unified power quality conditioner for improving voltage and current profiles and reducing power was considered by using differential evolution algorithm [23].

In addition to the CPDs, many research works have also focused on the optimal placement of other devices such as capacitor banks and distributed generations (DG) for improving power quality by applying heuristic optimization techniques such as particle swarm optimization (PSO) [24,25], GA [26,27], combined GA and neural network [28], combined GA and PSO [29], sensitivity-based heuristic solution [30] and shuffled frog leaping algorithm [31]. Due to the discrete nature of the optimal placement and sizing problem of DG and CPD, discrete optimization techniques such as discrete nonlinear programming [32], GA [33] and discrete PSO (DPSO) [34,35] are also applied for minimizing harmonic distortion and improving system reliability.

In this paper, a new heuristic optimization technique is proposed using the improved discrete firefly algorithm (IDFA) for determining the optimal size and location of APCs. A multi-objective problem is formulated by minimizing the average voltage total harmonic distortion (THD_V), voltage deviation, and total investment cost including installation and incremental costs to improve overall power quality of the system. The voltage limits, APC capacity limits, power flow limits and THD_V for each individual bus are considered as constraints in the optimization problem. The performance of the proposed IDFA is then evaluated on the radial IEEE 16- and 69-bus test systems. To evaluate the effectiveness of the proposed IDFA, the results are also compared with the obtained results using other optimization techniques such as the conventional Discrete Firefly Algorithm (DFA), GA and DPSO.

Modeling of active power conditioner

APC is a parallel multi-function compensating device, which, depending on the available controller design, is able to mitigate voltage sag and harmonic distortion, performs power factor correction, and improves the overall power quality. The voltage–source converter is the main part of the APC, which converts the dc-link voltage into three-phase ac voltages with controllable amplitude, frequency and phase. Considering the steady-state APC losses such as transformer and inverter losses, an accurate load flow model of the APC should be obtained. Fig. 1 shows the schematic diagram of an APC and its Thevenin equivalent circuit with respect to bus N. From the figure, the injected current I_{APC} at bus N in fundamental and harmonic frequencies can be expressed as

$$I^h_{APC} = I^h_L - I^h_S = I^h_L - \frac{(V^h_S - V^h_N)}{Z^h_S} = \frac{(I^h_{con} Z^h_{APC} - V^h_N)}{Z^h_{APC}} \tag{1}$$

where, I_{APC} is the injected current by APC with phase angle δ_i; I_{con} is the Norton current with phase angle δ_{con}; I_S is the utility side current with phase angle θ_i; V_S is the utility side voltage with phase angle θ_v; V_N is the voltage at bus N with phase angle $\theta_{v\text{-}N}$; I_L is the load side current with phase angle λ_i; Z_S is the utility impedance; Z_{APC} is APC Norton impedance ($1/Y_{APC}$); h is harmonic orders, like $1, 2, 3, \ldots, H$.

Eq. (1) shows that the injected APC current I^h_{APC} can correct voltage sag, voltage variation and harmonic distortion at bus N by adjusting the voltage drop across the impedance Z_{APC} in the fundamental and harmonic frequencies.

To compute the bus voltage variations in fundamental and harmonic frequencies in the presence of APC, it is assumed that APC is added to the system as a PQ bus (the bus with the specified real power $|P|$ and reactive power $|Q|$) with impedance Z^h_{APC} between the existing bus N and the newly added virtual bus K in a M-bus system. Therefore, the new impedance matrix of the system should be modified based on Z^h_{APC} as [36]

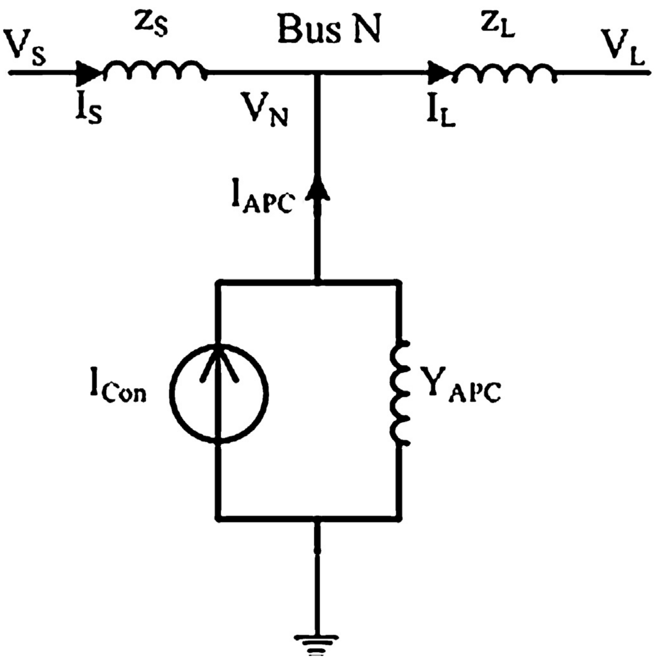

Fig. 1. APC single line Norton equivalent circuit.

$$Z^h_{bus\text{-}new} = \begin{bmatrix} & & & Z^h_{1N} \\ & & & Z^h_{2N} \\ & Z^h_{old} & & \vdots \\ & & & Z^h_{MN} \\ Z^h_{N1} & Z^h_{N2} & \cdots \; Z^h_{NM} & Z^h_{NN} + Z^h_{APC} \end{bmatrix} \tag{2}$$

The new column accounts for the increase of all bus voltages due to Z^h_{APC}. Considering virtual bus K is short circuited to the reference node, the virtual bus K can be eliminated using the Kron reduction method on (2) as

$$Z^h_{hi\text{-}new} = Z^h_{hi} - \frac{Z^h_{h(M+1)} Z^h_{(M+1)i}}{Z^h_{NN} + Z^h_{APC}} \tag{3}$$

Hence, the bus voltages calculated at the fundamental and harmonic frequencies due to the presence of APC can be obtained using the modified impedance matrix (2) and (3) as

$$I^k_i = I^{rel}_i(V^k_i) + jI^{Img}_i(V^k_i) = \left(\frac{P_i + jQ_i}{V^k_i}\right)^* \tag{4}$$

$$V^h = Z^h I^h \tag{5}$$

where, $V_i{}^k$, $I_i{}^k$, I^{rel}_i and I^{Img}_i are the node voltage at the kth iteration, equivalent current injection at the kth iteration, and the real and imaginary parts of the equivalent current injection at the kth iteration, respectively. In addition, [V], [Z] and [I] are the bus voltage vector, system impedance matrix, and nodal injected current vector in fundamental and harmonic frequency.

Eqs. (4) and (5) can be solved using the backward/forward sweep method [37,38]. Note that the values of P and Q in (4) are positive for conventional PQ (load) buses and negative for bus with APC. The bus voltage at bus i in the fundamental and harmonic frequencies, and the voltage THD can be changed by altering the rating of the installed APC during the optimization process.

Multi-objective problem formulation

The optimal APC placement and sizing problem in this paper is essentially a multi-objective optimization problem, which aims to simultaneously enhance power quality and minimize the total investment costs of the located APCs in the system. Therefore, the problem is designed in terms of a single objective function which comprises of three sub-functions and three constraints representing the control variables as follows.

Objective functions

Minimization of normalized-average voltage deviation

The voltage deviation index is expressed as the deviation of the voltage magnitudes of all buses from the reference voltage. Thus, for a given M-bus system, the voltage deviation index is expressed as

$$V_{\text{dev}} = \sqrt{\sum_{i=1}^{M} \left(\frac{V_{i\text{-ref}} - V_i}{V_{i\text{-ref}}} \right)^2} \tag{6}$$

where, $V_{i\text{-ref}}$ is the ith bus reference voltage which is usually considered as 1 pu, and V_i is the measured voltage at bus i. Using (6), the normalized-average voltage deviation index of a M-bus system can be expressed as

$$V_{\text{dev-avr}} = \frac{V_{\text{dev}}}{\sqrt{M}} \tag{7}$$

where M is the total number of system buses. Eq. (7) can be used to measure the deviation in the bus voltages from the reference voltage because of the unregulated voltage or the voltage sag that occurs because of motor starting in the system.

Minimization of average THD_V

To control the THD_V level of the whole system, the average of normalized THD_V of system buses is considered as

$$THD_{V\text{-avr}} = \frac{\sum_{i=1}^{M} THD_{V\text{-}i}^{\text{norm}}}{M} \tag{8}$$

where $THD_{V\text{-}i}^{\text{norm}}$ is the normalized THD_V at bus i.

Minimization of the total investment cost

The total cost of an APC, which is composed of the installation and incremental costs [39], can be expressed in terms of a normalized-polynomial function as

$$C_{\text{APC}} = \frac{\sum_{i=1}^{k} (\alpha S_{\text{APC-}i}^2 - \beta S_{\text{APC-}i} + C_{0\text{-}i})}{Cost_{\max}} \tag{9}$$

where, C_{APC}, C_0, $Cost_{\max}$, and S_{APC} are the normalized total cost, fixed installation cost, maximum total cost and capacity of the APC, respectively. In addition, α and β are fixed coefficients, which are assumed in this work as 0.0002466 and 0.2243, respectively.

Problem constraints

Bus voltage limits

With respect to power quality and system stability considerations, each bus voltage V_i must be maintained around its nominal value $V_{i\text{-nom}}$ within a permissible voltage band, specified as $[V_{i\text{-min}}, V_{i\text{-max}}]$, where $V_{i\text{-min}}$ and $V_{i\text{-max}}$ are the minimum and maximum permissible voltages at bus i, respectively. These limits can be expressed in terms of an inequality function as

$$V_{i\text{- min}} \leq V_i \leq V_{i\text{- max}}. \tag{10}$$

APC capacity limits

Considering that the APC capacity is inherently limited by the energy resources at any given location, the capacity has to be constrained within a permissible band, specified as $[S_{\text{APC-min}}, S_{\text{APC-max}}]$, where $S_{\text{APC-min}}$ and $S_{\text{APC-max}}$ are the minimum and maximum permissible values of each APC capacity, respectively. These limits can be expressed in terms of an inequality function as

$$S_{\text{APC-min}} \leq S_{\text{APC}} \leq S_{\text{APC-max}}. \tag{11}$$

Power flow limits

The apparent power S_l transmitted through branch l must not exceed its maximum thermal limit $S_{l\text{-max}}$ in the steady state operation as

$$S_l \leq S_{l\text{-max}}. \tag{12}$$

THD limits

The THD value at each bus i should be maintained less than its maximum value to meet the limits defined in IEEE Standard 519 [40] as

$$THD_i \leq THD_{\max}. \tag{13}$$

Overall objective function

To solve the above-mentioned constrained multi-objective optimization problem, the weighted sum method is considered to combine all the individual objective functions (7)–(9) in terms of a single objective function. Furthermore, the constraint violations (10)–(13) are applied in the overall objective function using the penalty function approach. Hence, the final single objective function to be minimized is expressed as

$$\begin{aligned} F &= f(\text{Location,Size}) \\ &= w_1 \frac{V_{\text{dev}}}{\sqrt{M}} + w_2 \frac{\sum_{i=1}^{M} THD_{V\text{-}i}^{\text{norm}}}{M} + w_3 C_{\text{APC}} \\ &\quad + \lambda_V \sum_{i \in M} [\max(V_i - V_{i\text{-max}}, 0) + \max(V_{i\text{-min}} - V_i, 0)] \\ &\quad + \lambda_l \sum_{l \in L} \max(|S_l| - |S_{l\text{-max}}|, 0) \\ &\quad + \lambda_{\text{APC}} \sum_{i \in P} [\max(S_{\text{APC}} - S_{\text{APC-max}}, 0) \\ &\quad + \max(S_{\text{APC-min}} - S_{\text{APC}}, 0)] \\ &\quad + \lambda_{THD} \sum_{i \in M} \max(THD_i - THD_{\max}, 0) \end{aligned} \tag{14}$$

where, w_i is the relative fixed weight factors assigned to the individual objectives in which $\sum w_i = 1$ and $0 < w_i < 1$. In addition λ, L, P and M are the penalty multipliers for the violated constraints which are large fixed scalar number, total line number, total APC number and total bus number, respectively.

The assigned weight factors to the individual objective functions in (14) are based on their importance, and may vary according to the preferences of the operators. Here, the assumed weighting factors used are $w_1 = w_2 = 0.4$ and $w_3 = 0.2$, in which the voltage deviation and harmonic distortion are considered to be more important than the total investment cost. In addition, all the individual objective functions have been scalarized in (7)–(9) by normalizing each component to keep the average values between 0 and 1 [23].

Improved Discrete Firefly Algorithm and its application

Discrete firefly algorithm

Firefly Algorithm (FA) which is based on the social behavior of fireflies, is first introduced as a novel nature-inspired

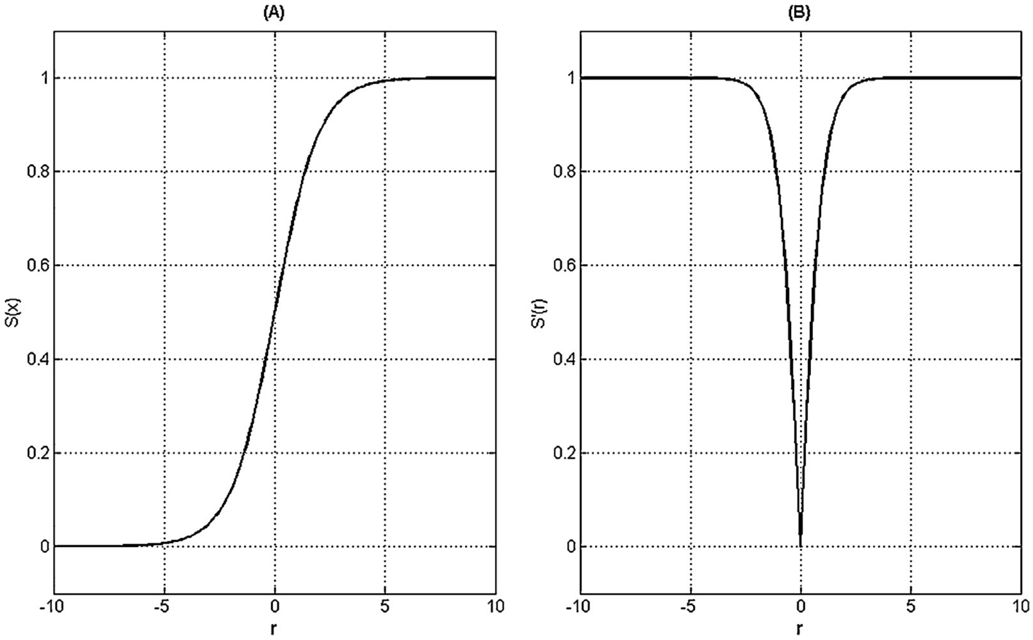

Fig. 2. Graph of sigmoid functions, (A) logistic sigmoid function, (B) tangent hyperbolic sigmoid function.

metaheuristic algorithm to solve the continuous multi-objective optimization problems with superior success rates and efficiency compared to PSO and GA [41,42]. There are two important issues arise in the standard FA, namely, the variation in light intensity I and formulation of the attractiveness β. In the simplest form and considering a fixed light absorption coefficient γ and light intensity I, the firefly's attractiveness β which varies with distance r, can be expressed as

$$\beta(r) = \beta_0 \exp(-\gamma r^2) \tag{15}$$

where, β_0 is the attractiveness at $r = 0$.

The distance between any two fireflies i and j at locations x_i and x_j, can be obtained using the Euclidean distance as

$$r_{ij} = \left\|x_i - x_j\right\| = \sqrt{\sum_{d \in D}(x_{i,d} - x_{j,d})^2} \tag{16}$$

where $x_{i,d}$ is the dth component of the spatial coordinate x_i of the ith firefly and D is the dimension of the problem.

The movement of a firefly i to another more attractive firefly j can be expressed as

$$x_i^{k+1} = x_i^k + \beta_0 e^{-\gamma r_{ij}^{k2}}(x_j^k - x_i^k) + \alpha \xi_i \tag{17}$$

where, α is the randomization parameter and ξ_i is a vector of random numbers with Gaussian or uniform distributions.

In the DFA, when a firefly i moves toward firefly j, the position of firefly i changes from a binary number to a real number. To replace the produced real number with a binary digit (bit), the logistic sigmoid function is used to constrain the position value in the interval of [0,1] as [43,44]

$$S(x_i^k) = \frac{1}{1 + e^{-x_i^k}} \tag{18}$$

where, $S(x_i{}^k)$ is the probability of bit $x_i{}^k$ considered as 1, and k is the iteration number.

In practice, the Pareto optimal solution can be reached by changing the positions of fireflies to a more attractive position and decreasing the distance between them to zero at further iterations. Resultantly in DFA, the probability of changing the positions between fireflies should tend to zero as their distance decrease. Nonetheless, by applying (18), the distance between fireflies may increase when the algorithm proceeds to further iterations. Thus, (18) is not able to accurately estimate the probability of fireflies' movements positions toward each other.

Improved Discrete Firefly Algorithm

The above-mentioned problem related to DFA can easily be solved by applying a tangent hyperbolic sigmoid function on distance r and updating the movement x as

$$S'(r_{ij}^k) = \left|\tanh(\lambda r_{ij}^k)\right| \tag{19}$$

```
Insert the objective function $f(x)$, $x = (x_1, x_2, \ldots, x_d)^T$
Initialize the fireflies population $x_i$, $i = 1, 2, \ldots, n$)
Determine the light intensity $I_i$ at $x_i$ using $f(x_i)$
Set light absorption coefficient $\gamma$, randomize coefficient $\alpha$
while ($t < MaxGeneration$)
    for $i = 1 : n$    all $n$ fireflies
        for $j = 1 : n$
            if ($I_i < I_j$), Move firefly $i$ towards $j$ ; end if
            Vary attractiveness with distance $r$ via exp[$-\gamma r^2$]
            Discrete the distance between Fireflies using (19) and (20)
            Evaluate new solutions and update light intensity
        end for $j$
    end for $i$
    Rank the fireflies and find the current global best
end while
Print Results
```

Fig. 3. Implementation procedure of IDFA.

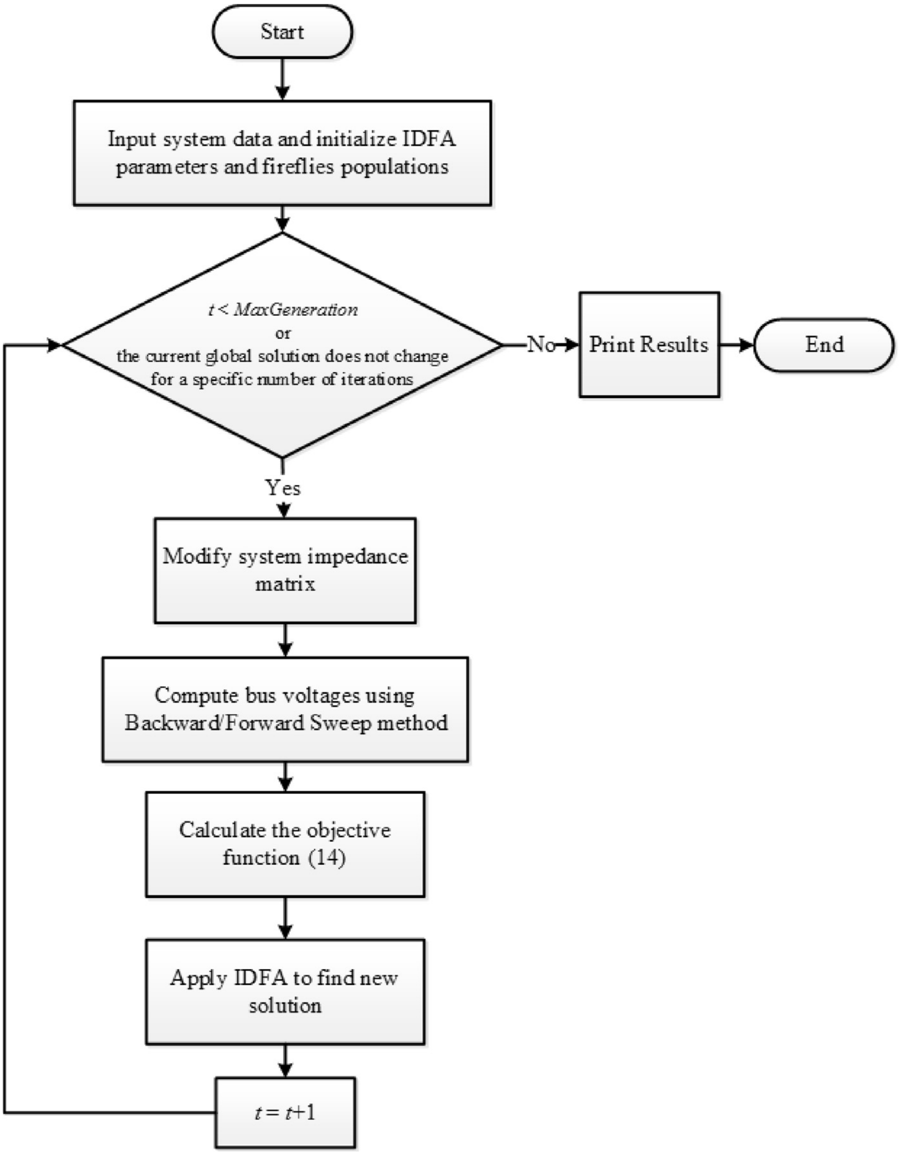

Fig. 4. IDFA implementation to solve the APC placement and sizing problem.

$$x_i^{k+1} = \begin{cases} x_i^k + \beta_0 e^{-\gamma r_{ij}^{k2}} (x_j^k - x_i^k) + \alpha\xi_i & \text{if } rand < S'(r_{ij}^k) \\ x_i^k & \text{else} \end{cases} \quad (20)$$

where, λ is a constant coefficient close to 1, and *rand* is a random number in the interval [0,1].

In comparison with (18), by changing the positions of fireflies to a more attractive position and decreasing the distance, the probability of S' in (19) tends to zero. In other words, when the distance of fireflies are too far at a specific position, the probability of moving $x_i{}^k$ in (20) to a new location $x_i{}^{k+1}$ is too high, while by decreasing the distance at further iterations, the probability of moving $x_i{}^k$ is decreased and finally when the distance is zero, the position $x_i{}^k$ remains unchanged as new location $x_i{}^{k+1}$. Fig. 2 shows the graph of (18) and (19) and their variations when r tends to zero. The figure clearly shows that Eq. (19) has a better performance to keep the probability $S'(x)$ close to zero when r tends to zero. The procedure in implementing the IDFA is described in terms of a pseudo code as shown in Fig. 3.

Application of IDFA in solving the optimal location and sizing of APC in radial distribution systems

To determine the optimal location and size of the APC in radial distribution systems, IDFA is applied to minimize the objective function (14). Initially, the number of APCs and the system specifications, including the bus and line data, should be considered as inputs of the IDFA. The real and imaginary parts of the APC power at fundamental and harmonic frequencies and system buses are considered as the optimization variables. After initializing the locations and sizes of APCs as the fireflies populations described in Fig. 3, the bus voltages of the system in fundamental and harmonic frequencies in (4) and (5) are calculated using Fig. 1. The voltage variation index, THD_V, and total device cost of the system are then obtained using the calculated bus voltages and initialized APC sizes in order to compute the objective function (14). Hence, using the obtained result from (14), the fireflies can be ranked to find the current global solution and proceed to the next iteration. The convergence criteria are set to $t = MaxGeneration$ or when the current global solution does not change for a specific number of iterations. If convergence is not achieved, the algorithm continues

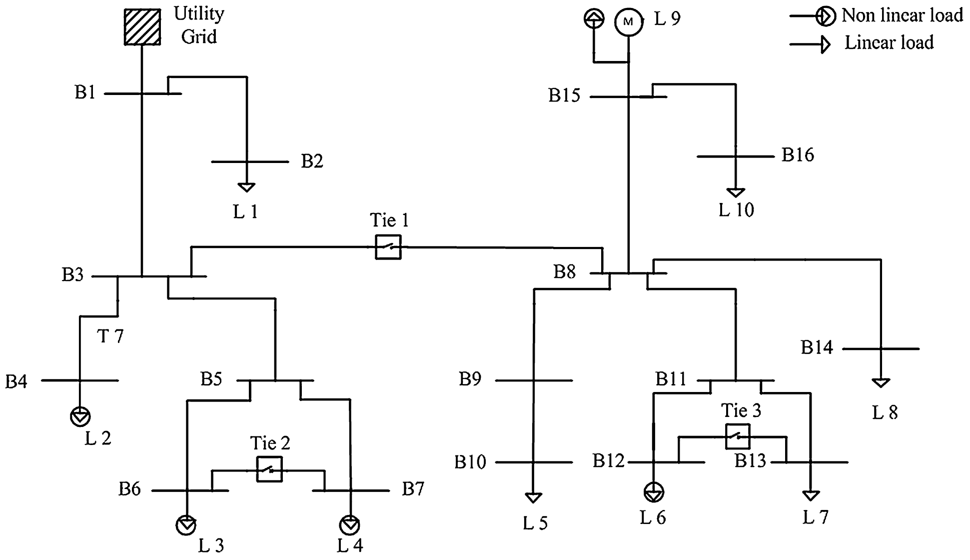

Fig. 5. Single line diagram of IEEE 16-bus test system.

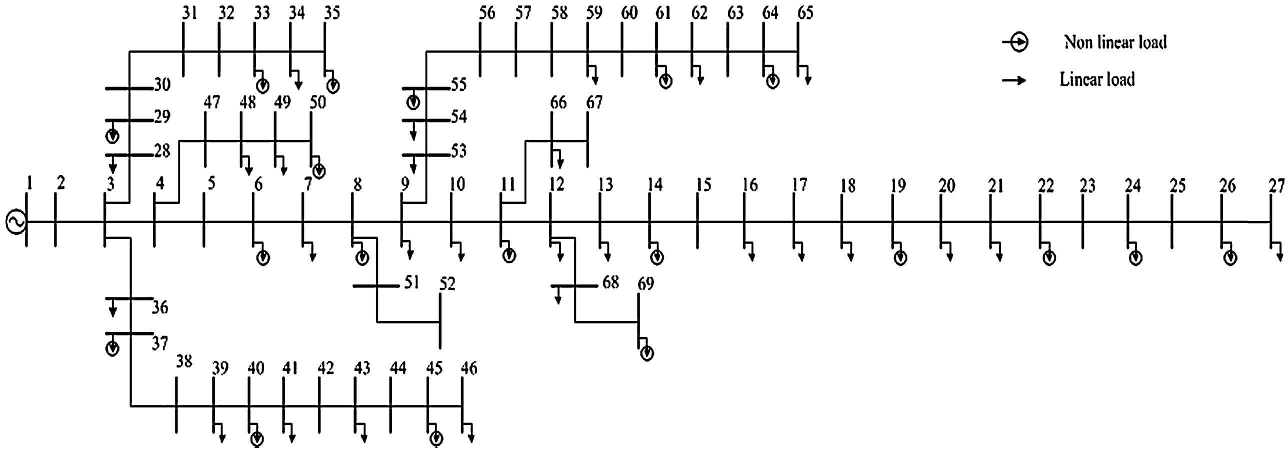

Fig. 6. Single line diagram of IEEE 69-bus test system.

with the next generation. Fig. 4 shows the schematic diagram of the procedures used in solving the optimal APC placement and sizing problem using the IDFA.

Simulation and test results

To verify the effectiveness and applicability of the proposed IDFA on radial distribution systems, the IEEE 16- and IEEE 69-bus test systems shown in Figs. 5 and 6 are modified and used [45,46]. Both systems are designed to feed the distributed linear and non-linear loads with a total power of 2.73 and 4.66 MVA, respectively. The non-linear loads which distort system voltage and current waveforms are modeled as harmonic current sources with the harmonic components shown in Table 1 to represent different and more realistic harmonic sources [46]. In addition, a heavy induction motor is placed in the16-bus system so as to create a voltage sag condition due to motor starting, while the 69-bus system has an inherently severe voltage profile problem due to its unmanaged distributed heavy loads.

In order to validate the developed optimization problem and improve power quality of the system, three sets of APCs, comprising of 3, 5 and 7 APCs for the 16-bus system and 7, 10 and 13 APCs for the 69-bus system, are considered to be placed in the systems. For each APC, its power rating limits of [0,1.5] p.u with base power of 100 kVA are considered. The optimization results of IDFA are then compared with the results using the standard DFA, GA, and DPSO [35]. Tables 3 and 4 show the simulation results for the 16- and 69-bus test systems, respectively. Note that the applied optimization methods in this work have several parameters that govern their behavior and efficiency in optimization process. To make a fair comparison between the proposed method and previous ones, no Meta-optimization method is applied in this paper for tuning the optimization parameters and the applied parameters for the

Table 1
Harmonic spectrums.

Harmonic order	Delta connected TCR		ASD	
	Mag. (p.u)	Angle (deg)	Mag. (p.u)	Angle (deg)
1	1.0000	46.92	1.0000	0.00
5	0.0702	−124.40	0.1824	−55.68
7	0.0250	−29.87	0.1190	−84.11
11	0.0136	−23.75	0.0573	−143.56
13	0.0075	71.50	0.0401	−175.58
17	0.0062	77.12	0.0193	111.39
19	0.0032	173.43	0.0139	68.30
23	0.0043	178.02	0.0094	−24.61
25	0.0013	−83.45	0.0086	−67.64
29	0.0040	−80.45	0.0071	−145.46

Table 2
Optimization parameters.

Solver	Parameter
IDFA	$\alpha = 0.6$, $\beta_0 = 0.5$, $\gamma = 6$
DFA	$\alpha = 0.6$, $\beta_0 = 0.5$, $\gamma = 6$
DPSO	$w = 0.7$, $C_1 = 0.7$, $C_2 = 0.4$
GA	Crossover rate = 0.6, mutation rate = 0.001, population size = 50

DFA and proposed IDFA are considered to be the same as reported in [41]. In addition, the applied parameters for DPSO and GA are taken from relevant researches in [35,47], as shown in Table 2.

From the tables, it is obvious that the IDFA gives a superior performance over other optimization techniques in terms of minimizing the objective function *F*. In addition, the effectiveness of IDFA is more visible when the system size and the required search space are increased. For the results of the 16-bus test system shown in Table 3, the minimized values of *F* in almost all the methods are very close. However, for the results of the 69-bus test system shown in Table 4, the significant difference between the objective function values of *F* and the superiority of the IDFA are more obvious compared to other methods especially DPSO and GA. In addition, the total number of evaluated functions indicates that IDFA need to evaluate fewer functions for finding the global optimum with less computational burden compared to other methods.

Another important fact from the results shown in Tables 2 and 3 is that in small system like the 16-bus system, increasing the number of placed APCs may reduce the required size of each device and the total cost due to the polynomial nature of the cost function (9) as shown in Table 3. Nevertheless due to the presence of fix cost C_0 in (9) and variation of the curve slope of (9) depending the number of APCs, rigorous increment of the number of APCs may increase the total cost of installed APCs, as shown in Table 4 in the case of the 69-bus system. Therefore, the required number of APCs to be installed in the system should be wisely chosen by utility at the time of system planning to justify both technical and economy aspect of the system.

To investigate the sensitivity of the proposed IDFA to the randomness of the initial values, the Relative Standard Deviation (RSD) and mean value are calculated for 50 run times of the algorithm with the optimization parameters being kept constant when 4 and 10 APCs are considered to be placed in the 16- and 69-bus systems, respectively. Table 5 shows the obtained RSD and the mean value and the comparison with the DFA, DPSO and GA methods. In addition, the average computation times of each algorithm are reported

Table 3
Optimization results of the 16-bus test system.

Solver	Number of APC	Location (Bus)	APC power rating (p.u)	APC total cost (US $)	Total function evaluation	Objective function, *F*
IDFA	3	15, 10, 9	1.025, 1.014, 0.730	6,377,757	12,500	0.2956
	4	4, 15, 10, 13	0.547, 0.937, 0.960, 0.346	5,393,875	21,700	0.2758
	5	15, 10, 2, 11, 4	0.633, 0.743, 0.018, 0.386, 0.518	3,327,905	27,400	0.2645
DFA	3	9, 10, 15	0.730, 1.043, 1.013	6,465,165	17,200	0.2956
	4	10, 4, 12, 15	0.966, 0.575, 0.336, 0.920	5,418,839	28,200	0.2763
	5	15, 4, 10, 12, 9	0.644, 0.575, 0.649, 0.415, 0.568	4,038,254	33,500	0.2656
DPSO	3	10, 9, 15	1.018, 0.731, 1.037	6,465,255	43,200	0.2956
	4	4, 15, 10, 9	0.521, 0.971, 1.041, 0.594	6,469,310	35,700	0.2783
	5	11, 10, 9, 15, 4	0.445, 0.274, 0.704, 0.989, 0.473	4,796,951	41,900	0.2665
GA	3	10, 9, 15	1.086, 0.966, 0.752	6,539,977	24,600	0.2964
	4	14, 15, 10, 9	0.448, 0.891, 1.154, 0.375	6,019,246	41,500	0.2777
	5	13, 15, 10, 4, 11	0.399, 0.702, 0.458, 0.542, 0.778	4,277,600	45,900	0.2735

Table 4
Optimization results of the 69-bus test system.

Solver	Number of APC	Location (Bus)	APC power rating (p.u)	APC total cost (US $)	Total function evaluation	Objective function, *F*
IDFA	7	6, 66, 7, 50, 22, 40, 11	0.741, 0.937, 0.835, 0.479, 0.495, 0.441, 0.953	9,020,443	34,900	0.1282
	10	52, 64, 40, 2, 47, 54, 68, 12, 10, 17	1.007, 0.947, 0.703, 0.522, 0.097, 0.241, 0.486, 0.539, 0.438, 0.448	8,920,219	29,700	0.0958
	13	5, 6, 23, 4, 51, 8, 9, 40, 68, 26, 67,47, 7	0.539, 0.835, 0.225, 1.012, 0.620, 0.648, 0.717, 0.956, 0.385, 0.203, 0.827, 0.387, 0.906	14,949,431	37,600	0.1139
DFA	7	2, 68, 10, 49, 20, 60,40	0.893, 1.260, 0.262, 0.713, 0.464, 0.034, 1.376	12,396,030	48,100	0.1289
	10	57, 55, 67,40, 63, 52, 5, 13, 6, 51	0.652, 1.311, 0.437, 0.708, 0.040, 0.590, 0.248, 0.415, 1.005, 0.453	11,302,234	38,700	0.1124
	13	50, 20, 3, 4, 68, 6, 12, 61, 62, 51, 55, 48, 5	0.838, 0.384, 0.551, 0.989, 0.546, 0.719, 0.773, 0.996, 0.823, 0.888, 0.221, 0.434, 1.326	19,508,789	42,700	0.1976
DPSO	7	28, 15, 68, 53, 4, 51, 40	1.112, 1.050, 1.051, 1.229, 0.847, 0.405, 0.770	15,705,067	45,100	0.2157
	10	48, 40, 8, 13, 68, 18, 49, 11, 33, 55	0.939, 0.567, 0.705, 0.882, 0.802, 0.689, 0.779, 0.476, 0.546, 0.571	12,312,500	50,300	0.1289
	13	49, 45, 26, 11, 28, 29, 37, 27, 54, 17, 31, 68, 10	0.999, 0.757, 0.706, 0.684, 0.981, 0.934, 0.402, 0.639, 0.591, 0.748, 0.250, 0.916, 1.230	20,163,660	44,700	0.2708
GA	7	56, 2, 3,67, 5, 49, 29	1.247, 0.801, 0.689, 1.174, 0.812, 0.750, 0.863	14,696,712	51,500	0.2218
	10	2, 29, 58, 53, 19, 28, 30, 5, 50, 49	0.438, 0.739, 0.501, 0.561, 0.966, 0.549, 0.901, 1.115, 0.186, 0.903	13,273,902	34,500	0.2354
	13	49, 4, 18, 54, 21, 3, 40, 62, 53, 34, 2, 39, 65	0.671, 0.688, 0.640, 0.713, 0.954, 0.911, 1.036, 0.644, 1.022, 0.998, 0.098, 0.505, 0.767	19,423,302	51,700	0.2307

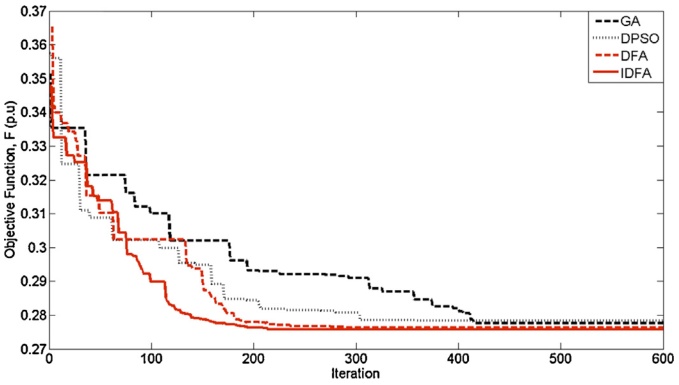

Fig. 7. Convergence characteristic of IDFA in the 16-bus test system.

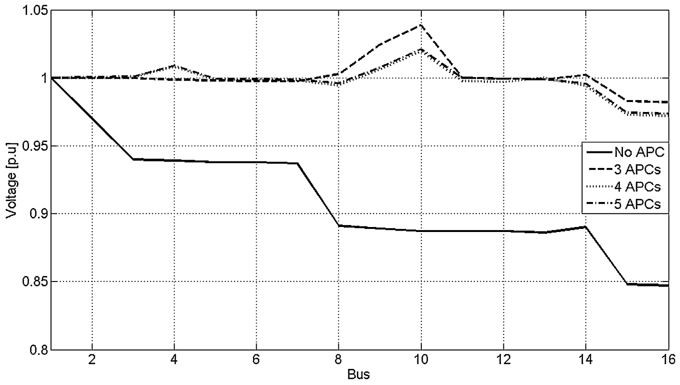

Fig. 9. Voltage profile of the 16-bus test system.

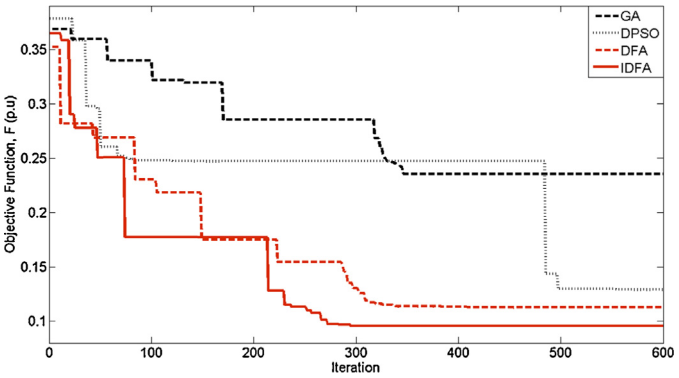

Fig. 8. Convergence characteristic of IDFA in the 69-bus test system.

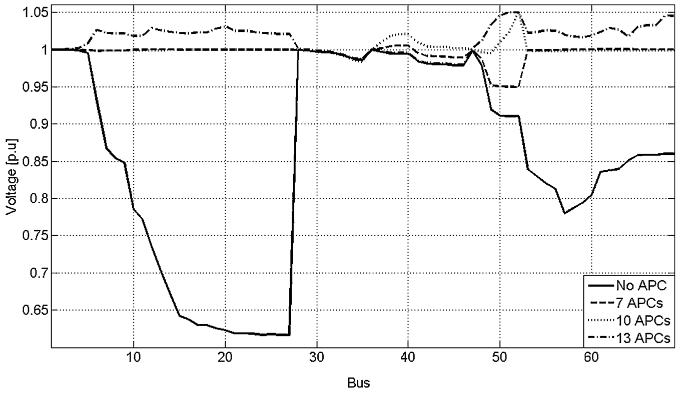

Fig. 10. Voltage profile of the 69-bus test system.

in the table. Note that in Table 5, $F_{\min}$ and $F_{\max}$ show the maximum and minimum valves of objective function F during the run times.

Comparing the RSD and the mean values shown in Table 5, it is shown that the IDFA is the fastest algorithm and has the smallest RSD and mean value among other optimization methods, and this proves the higher accuracy and robustness of IDFA in solving the optimal placement and sizing of APCs.

To illustrate further the IDFA performance, the convergence characteristic of the IDFA for the 16- and 69-bus systems in case of 4 and 10 APCs, respectively, are compared with the DFA, DPSO and GA for 600 iterations as shown in Figs. 7 and 8, respectively. From the figures, it is shown that the IDFA gives better performance for both cases in finding the global solution in fewer iteration steps, where other methods especially DPSO and GA need more iteration steps to converge when the size of system and search space increases (Fig. 8).

The voltage profile of the 16- and 69-bus systems before and after placement of different numbers of APCs using the proposed IDFA are shown in Figs. 9 and 10. As illustrated, the voltage profiles are not of interest before installing APC sets due to occurrence of visible voltage drop caused by motor starting in 16-bus system and unmanaged loading in 69-bus systems. The figures clearly show that the placed APCs in all cases can accurately regulate the voltage profile and even compensate the occurred under voltage in both test systems.

The THD_V and voltage deviation levels in the 16- and 69-bus test systems before and after the optimal placement of APCs are measured and shown in Tables 6 and 7. Note that due to the space limitation, only the THD_V and voltage deviation of some selected buses are reported in Table 7. From the tables, after optimal placement of APCs, the general voltage profiles of both systems are significantly improved and voltage harmonic distortion is also reduced below 5% to meet IEEE Standard 519 [40]. Note that the small THD_V and voltage deviation index values for bus 32, 44 and 50 in Table 7 are due to the presence of weak harmonic sources in vicinity of these buses, and almost negligible voltage drop at these buses as shown in Fig. 10. Nonetheless, increasing the number of installed APCs in the 16-bus system does not have significant effect on the value of $THD_{V.}$ However, this value considerably increases as the number of APC is increased in the 69-bus system due to the interaction of network and APC impedances at harmonic frequencies. From the results shown in Tables 2–6, increasing the number of APCs may not have technical and economic justifications even by using optimization techniques and therefore careful selection for the number of APC is required at the time of system planning.

Table 5
RSD and mean for different initial values.

	16-Bus test system					69-Bus test system				
	RSD (%)	Mean	$F_{\min}$	$F_{\max}$	Comp. time (s)	RSD (%)	Mean	$F_{\min}$	$F_{\max}$	Comp. time (s)
IDFA	0.1280	0.2759	0.2752	0.2765	2540	0.4514	0.1122	0.1114	0.1132	9883
DFA	0.1327	0.2763	0.2758	0.2771	2680	0.5033	0.1158	0.0951	0.0965	10,558
DPSO	0.2463	0.2776	0.2765	0.2789	2967	0.5432	0.1287	0.1273	0.1298	11,210
GA	0.2613	0.2776	0.2761	0.2785	3701	0.5451	0.2349	0.2326	0.2370	13,821

Table 6
System performance before and after APC installation in 16-bus test system.

Bus no.	THD_V (%)				Voltage dev. (%)			
	No APC	3 APCs	4 APCs	5 APCs	No APC	3 APCs	4 APCs	5 APCs
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	2.969	0.136	0.125	0.125	3.028	0.029	0.000	0.039
3	6.128	0.272	0.250	0.251	6.029	0.032	0.026	0.098
4	6.157	0.280	0.207	0.210	6.141	0.137	0.826	0.896
5	6.139	0.272	0.250	0.251	6.200	0.193	0.135	0.063
6	6.142	0.272	0.250	0.251	6.237	0.228	0.170	0.098
7	6.144	0.272	0.251	0.251	6.270	0.259	0.201	0.129
8	9.598	0.396	0.436	0.436	10.944	0.270	0.543	0.392
9	13.178	0.527	0.639	0.637	11.109	2.437	0.588	0.737
10	16.252	1.081	1.308	1.306	11.308	3.839	1.951	2.095
11	9.633	0.397	0.435	0.434	11.261	0.012	0.229	0.000
12	9.641	0.398	0.435	0.434	11.330	0.073	0.290	0.061
13	9.646	0.398	0.434	0.434	11.376	0.114	0.000	0.102
14	9.605	0.396	0.437	0.436	11.006	0.215	0.599	0.448
15	10.086	0.404	0.446	0.445	15.245	1.710	2.727	2.569
16	10.095	0.404	0.446	0.446	15.323	1.778	2.795	2.637

Table 7
System performance before and after APC installation in the 69-bus test system.

Bus no.	THD_V (%)				Voltage dev. (%)			
	No APC	7 APCs	10 APCs	13 APCs	No APC	7 APCs	10 APCs	13 APCs
6	6.86	0.10	0.15	0.21	6.99	0.18	0.14	2.65
7	13.82	0.19	0.25	0.41	13.21	0.14	0.14	2.23
8	15.46	0.19	0.28	0.43	14.55	0.13	0.14	2.17
9	16.35	0.19	0.29	0.45	15.21	0.12	0.14	2.19
10	18.99	0.29	0.46	0.35	21.50	0.02	0.11	1.86
11	19.63	0.31	0.50	0.34	22.84	0.00	0.11	1.86
12	21.76	0.42	0.65	0.36	26.56	0.02	0.10	2.93
13	24.52	0.58	0.86	0.54	29.91	0.02	0.10	2.62
14	25.87	0.77	1.09	0.27	32.99	0.02	0.06	2.39
15	27.22	0.97	1.32	0.12	35.77	0.02	0.03	2.23
20	28.28	1.17	1.56	0.35	37.71	0.01	0.00	3.11
27	28.79	1.42	1.85	0.82	38.34	0.01	0.01	2.09
32	0.29	0.06	0.07	0.06	0.47	0.48	0.53	0.35
44	0.18	0.13	0.11	0.12	1.97	0.91	0.36	1.84
50	1.72	0.11	0.35	0.46	8.88	4.93	1.03	4.63
53	18.89	0.17	0.28	0.54	16.09	0.11	0.15	2.27
54	21.90	0.15	0.28	0.65	17.00	0.09	0.16	2.37
55	26.15	0.12	0.27	0.80	18.01	0.08	0.17	2.61
56	30.36	0.09	0.26	0.96	18.71	0.06	0.17	2.53
57	47.62	0.06	0.23	1.57	22.03	0.00	0.15	2.01
58	55.01	0.11	0.21	1.87	21.27	0.03	0.13	1.75
59	57.51	0.13	0.20	1.99	20.57	0.04	0.13	1.66
60	60.17	0.16	0.20	2.12	19.54	0.05	0.12	1.91
61	64.80	0.22	0.18	2.40	16.39	0.07	0.11	2.35
62	64.90	0.22	0.18	2.41	16.23	0.07	0.11	2.89
63	65.05	0.22	0.18	2.43	16.00	0.07	0.11	2.69
64	65.75	0.23	0.18	2.49	14.86	0.07	0.11	1.72
69	65.48	0.23	0.18	2.51	13.98	0.05	0.11	4.57

Finally in terms of computation time, it is observed that IDFA, DFA and DPSO have almost the same computation times for 600 iterations, and they are more time-efficient than GA. These same computation times is due to the fact that the standard PSO is known as the simplified version of standard FA.

Conclusion

In this paper, an IDFA has been presented for determining the optimal location and size of APCs in distribution systems. The DFA is improved to solve the problem using a multi-objective function which considers enhancing the system voltage profile, and minimizing the THD_V and total investment cost. The effectiveness of the proposed IDFA is validated on the radial IEEE 16- and 69-bus test systems. The results are also compared with the DFA, DPSO and GA to verify the superior performance of the proposed IDFA. The simulation and comparison results approved the superiority of the proposed IDFA over other optimization techniques in minimizing the objective function, F and improving general power quality of the both test systems.

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