F. G. Communication & IOT 1(3): 39-49, 2022

Future Generation of Communication and Internet of Things (FGCIOT)

Journal homepage: http://fgciot.semnaniau.ac.ir/

PAPER TYPE (Research paper)

Optimal Determination of Location and Size of Active Harmonic Filters in Electric Energy Distribution Networks

M. Maddah, S. Firozbakht

Department of Electrical Engineering, Semnan Branch, Islamic Azad University Semnan, Iran

Article Info

Article History:

Received: October 10, 2022
Revised: November 6, 2022
Accepted: November 22, 2022

Keywords:

Improved Harmonic Search Algorithm, Power Quality Indicators, Electricity Distribution Networks, Active Harmonic Power Filters

*Corresponding Author's Email Address: madah.m@yahoo.com

Abstract

In this paper, the optimal determination of the location and the size of the active power harmonic filters in the distribution of electric energy distribution networks is studied in through a comprehensive approach. The main purpose of this approach is to improve the power quality indices in electric power distribution network. Total voltage harmonic distortion, loss of function of electric motors, harmonic loss of power transmission lines and sum of the currents injected by active harmonic power filters using appropriate weighted coefficients are considered as the objective function of the problem. Whereas individual and total harmonic distortion and maximum permissible capacity of active power filters are considered as limitations of the problem. Optimal determining of problem and size of active harmonic power filters is essentially a non-convex optimization problem that has a nonlinear character and is mixed with integers. Thus, an improved harmony search algorithm has been used to determine the optimal solution. The harmonic search algorithm is an optimization algorithm that mimics the music playing process by musicians. The problem of optimizing the location and size of active harmonic power filters is implemented on a 69-bus test system. Also, the performance of the proposed algorithm is compared with genetic algorithm and particle swarm optimization. The results indicate the usefulness of the proposed approach as well as the proposed algorithm in improving the power quality indices in the electricity distribution networks.

Introduction

Background and motivation

Nowadays, the widespread development and application of power electronics facts and nonlinear loads, such as electric arc furnaces, have made the voltage and harmonic currents in power systems more noticeable. Harmonic currents caused by these nonlinear loads can lead to severe distortion of the voltage waveform at the point of common coupling, torque oscillations, increases loss, shortening of the useful life of the facts and more [1]. Therefore, companies involved in the distribution of electrical energy have a serious challenge in evaluating harmonics and providing appropriate strategies to reduce or eliminate them. Traditionally, the solution to reduce or eliminate harmonic-related problems is to use passive R-L-C power filters [2].

The defects of PPFs are the large size, the series and parallel resonance, and the application of only specific harmonics. Therefore, active power filters have been developed to solve the above problems. Generally, AHPFs

Doi:

can play an effective role in eliminating current and voltage harmonics, power factor correction, reducing imbalances, and more [3]. Generally, AHPFs inject equal-sized, but opposite-current currents into PCCs from electrical energy distribution networks, which collect nonlinear loads with nonlinear components to eliminate non-sinusoidal components [6-4]. The purpose of utilizing AHPFs in power systems in particular power distribution networks, harmonics compensation, reactive power, flicker, negative sequence and more. Due to the capability and abilities of AHPFs, in particular the elimination of harmonics, many studies have focused on AHPFs in recent decades [4-12].

Research background

There are many mathematical models to solve the optimal location and size of AHPFs in power system sources. The proposed models can be classified as two types of objective functions and two types of constraints [7-12]. The first type of target functions tries to minimize the voltage distortions in order to reduce the adverse effects of harmonic distortion in electric power distribution networks. The other type of objective functions is to use harmonic standards on voltage harmonic distortions and THD levels to minimize the AHPFs capacity.

The optimal allocation problem and the size of AHPFs in electric power distribution networks are basically a complex optimization problem that can be studied in different target functions such as total harmonic distortion, total current harmonic distortion, harmonic transmission line losses, and total power filter currents, the losses of electric motors and so on [7-12]. The constraints are divided into two categories. First, the constraints associated with the harmonic standards applied on the harmonic-voltage levels of the IEEE - 519 standard and the second is the constraints associated with the maximum current of AHPFs [7-12].

On the other hand, optimization of optimal location and particle size in electric energy distribution networks is a very complicated optimization problem that has been used in the recent decade, many evolutionary optimization techniques to solve AHPFs planning problem such as algorithm Genetics9 [8], discrete particle swarm algorithm10 [7-10-13], modified discrete particle swarm algorithm11 [9], improved discrete firewall algorithm12 [12] and others have been used. These studies show that there are some weaknesses in the modeling front-such as the use of inadequate objective functions, disregard for technical and economic constraints, and the frontier of evolutionary optimization techniques-such as inadequate precision, premature convergence, and inflexibility.

This paper focuses on presenting an efficient approach to solve the problem of optimally determining the location and size of AHPFs in power distribution networks with the aim of improving power quality indices. In the proposed approach, THDV, MLLF, HTLL, and IAHPFs as indicators of the problem of optimizing the location and size of AHPFs in the electric energy distribution network as well as individual and total voltage harmonic distortions as well as the maximum permitted AHPFs are considered as limitations of this problem. In order to increase the flexibility of the proposed approach to solve the optimal scheduling problem and AHPFs size, four different types of AHPFs are considered with different nominal current rates. The improved harmonic search algorithm is used to obtain an optimal solution. The remainder of this paper is organized into seven sections. Section 2 describes the modeling of electrical energy distribution networks and AHPFs. The objective functions and constraints of the problem of optimizing the location and size of AHPFs are presented in Section 3. In addition, the proposed solution algorithm is reported in Section 4. The simulation results are presented in Section 5. Finally, Section 6 is devoted to the conclusion.

Modeling of electric power distribution networks and active power filters

Modeling of electric power distribution networks

In order to model the entire system, consider a EPDNs network with B bus, which, each bus can consist of one or more non-linear loads, and can also be a candidate bus to install one or more AHPFs. In addition, nonlinear loads are modeled as harmonic generating sources and electrical energy distribution network as admittance elements. The voltage in the B-bus electrical energy distribution network for h-rank harmonics in the presence of nonlinear loads and AHPFs can be calculated using equations (4)-(1).

$$V^{(h)} = \left[Y^{(h)} \right]^{-1} . \left[I_{\mathrm{nl}}^{(h)} - I_{\mathrm{af}}^{(h)} \right]; \forall h = 1, \ldots, H \tag{1}$$

$$\begin{aligned} V^{(h)} &= \left[V_{(1),r}^{(h)} + jV_{(1),i}^{(h)}, \ldots., V_{(B),r}^{(h)} + jV_{(B),i}^{(h)} \right]^{\mathrm{T}} ; \\ &\quad \forall h = 1, 2, \ldots, H; \forall b = 1, 2, \ldots, B \end{aligned} \tag{2}$$

$$\begin{aligned} I_{\mathrm{nl}}^{(h)} &= \left[I_{\mathrm{nl},(1),r}^{(h)} + jI_{\mathrm{nl},(1),i}^{(h)}, \ldots, I_{\mathrm{nl},(B),r}^{(h)} + jI_{\mathrm{nl},(B),i}^{(h)} \right]^{\mathrm{T}} ; \\ &\quad \forall h = 1, 2, \ldots, H, \forall b = 1, 2, \ldots, B \end{aligned} \tag{3}$$

$$\begin{aligned} I_{\mathrm{af}}^{(h)} &= \left[I_{\mathrm{af},(1),r}^{(h)} + jI_{\mathrm{af},(1),i}^{(h)}, \ldots, I_{\mathrm{af},(B),r}^{(h)} + jI_{\mathrm{af},(B),i}^{(h)} \right]^{\mathrm{T}} ; \\ &\quad \forall h = 1, 2, \ldots, H, \forall b = 1, 2, \ldots, B \end{aligned} \tag{4}$$

In equations (1) to (4) we have:

H	An indicator for the order harmonic.
H	A set of harmonics of the intended order.
B	Indicator for bus number.

B	A set of buses of the intended candidate.
$V^{(h)}$	The network voltage matrix for h-order harmonic.
$Y^{(h)}$	The network admittance matrix for h-order harmonic
$I_{\text{nl}}^{(h)}$	Nonlinear load current matrix for h-Order harmonic.
$I_{\text{af}}^{(h)}$	APFs current matrix for h-order harmonics.
$V_{(b),r}^{(h)}$	Real voltage part in b-bus for h-order harmonics.
$V_{(b),i}^{(h)}$	The imaginary part of the voltage in b-bus for h-order harmonics.
$I_{\text{nl},(b),r}^{(h)}$	The real part of the nonlinear load current in b-bus for h-order harmonics.
$I_{\text{nl},(b),i}^{(h)}$	The imaginary part of the nonlinear load current at b-bus for h-order harmonics.
$I_{\text{af},(b),r}^{(h)}$	The real part of the APF current in b-bus for h-order harmonics.
$I_{\text{af},(b),i}^{(h)}$	Imaginary part of APF current in b-bus for h-order harmonics.

Modeling Active Power Filters

In this paper, the model considered for AHPFs is a current source that injects harmonic current into the PCC from the electrical energy distribution network [7-12]. The phasor model from AHPFs is presented using Equation (5).

$$I_{\text{af},(b)}^{(h)} = I_{\text{af},(b),r}^{(h)} + jI_{\text{af},(b),i}^{(h)}; \quad \forall h = 2,3,\dots,H, \forall b = 1,2,\dots,B \tag{5}$$

In equation (5) we have:

AHPF current in b-bus for h-order harmonics.	$I_{\text{af},(b)}^{(h)}$
The real part of the AHPF current in b-bus for h-order harmonics.	$I_{\text{af},(b),r}^{(h)}$
The imaginary part of the AHPF current in b-bus for h-order harmonics.	$I_{\text{af},(b),i}^{(h)}$

The RMS current rate of AHPF can be defined by equation (6):

$$I_{\text{af},(b)} = \sqrt{\sum_{h=1}^{H}\left(I_{\text{af},(b),r}^{(h)}\right)^2 + \left(I_{\text{af},(b),i}^{(h)}\right)^2}; \quad \forall h = 2,3,\dots,H, \forall b = 1,2,\dots,B \tag{6}$$

Modeling the Problem of Determining the Optimal Location and Size of Active Harmonic Power Filters

In the proposed approach for optimal determining problem and AHPFs size to improve power quality indices in electric power distribution networks, four different objective functions including THDV, MLLF, and HTLL and I_{af} are considered. The objective functions are collected using appropriate weighting coefficients and are considered as the objective function of the optimal determination of location and size of AHPFs. Thus, the objective function of the problem is to determine the optimal location and size of the AHPFs using Eq. (7).

$$\begin{aligned}\text{OF} = {} & \text{W}_{\text{THDV}}.\text{OF}_{\text{THDV}} + \text{W}_{\text{MLLF}}.\text{OF}_{\text{MLLF}} + \\ & \text{W}_{\text{HTLL}}.\text{OF}_{\text{HTLL}} + \text{W}_{\text{I}_{\text{af}}}.\text{OF}_{\text{I}_{\text{af}}}\end{aligned} \tag{7}$$

The different objective functions are described in the optimal determining problem and the AHPFs size is explained below.

Harmonic distortion of the total voltage

Basically, the THDV adjoin function is a common formula used by many in the field [7–12]. Therefore, the THDV index is defined using Eq. (7):

$$\text{OF}_{\text{THDV}} = \sum_{b=1}^{B} THDV_{(b)}; \forall b = 1,2,\dots,B \tag{8}$$

where:

$$THDV_{(b)} = \sqrt{\sum_{h=2}^{H}\left|V_{(b)}^{(h)}\right|^2} \Big/ V_{(b)}^{(1)}; \quad \forall h = 2,3,\dots,H, \forall b = 1,2,\dots,B \tag{9}$$

In relations (7) and (8) we have:

Total voltage harmonic distortion.	THDV
Total voltage harmonic distortion in the b-bus.	$THDV_{(b)}$
Voltage amplitude in b-bus for h-order harmonics.	$\left\|V_{(b)}^{(h)}\right\|$
Voltage amplitude in b-bus for main frequency.	$\left\|V_{(b)}^{(1)}\right\|$

Loss function of electric motors

Voltage harmonics have adverse effects on induction motors such as increased losses, increased operating temperatures, reduced lifetimes and others [7]. From the predicted and measured results, the relationship between engine losses and voltage harmonics can be summarized as follows:

1) The losses are almost proportional to the harmonic order contrary.

2) The losses are approximately proportional to the

square of the harmonic domain.
Thus, in order to investigate the above effects, the MLLF index is described using Eq. (9).

$$\mathrm{OF}_{\mathrm{MLLF}} = \sum_{b=1}^{B} MLLF_{(b)}; \forall b = 1,2,...,B \tag{10}$$

where:

$$MLLF_{(b)} = \sqrt{\sum_{h=2}^{H} \left(\left| V_{(b)}^{(h)} \right|^2 \Big/ h \right)} \Big/ \left| V_{(b)}^{(1)} \right|; \quad \forall h = 2,3,...,H, \forall b = 1,2,...,B \tag{11}$$

In Equation (9) and (10) we have:

Loss function of electric motors.	MLLF
Loss function of electric motors in b-bus.	$MLLF_{(b)}$

Harmonic losses of transmission lines Harmonics also have detrimental effects, such as occupying transmission capacity, increasing casualties and more on power systems [7]. Thus, in this section, in order to investigate these effects, HTLL index is defined based on Eq. (11):

$$\mathrm{OF}_{\mathrm{HTLL}} = \sum_{h=2}^{H} \mathrm{HTLL}_{(h)}; \forall h = 1,2,...,H \tag{12}$$

where:

$$HTLL_{(h)} = \sum_{h=2}^{H} \left(\sum_{b=1}^{B} \sum_{\substack{b'=1 \\ b'>b}}^{B} \frac{R_{(b),(b')}^{(h)}}{\left(Z_{(b),(b')}^{(h)} \right)^2} \left| V_{(b)}^{(h)} - V_{(b')}^{(h)} \right|^2 \right); \quad \forall b, b' = 1,2,...,B, \forall h = 2,3,...,H \tag{13}$$

In Equation (11) and (12) we have:

Harmonic losss transmission lines.	HTLL
Harmonic losses Transmission lines for h-Harmonic	$HTLL_{(h)}$
An indicator of the bus number.	b'
Ohmic resistance between bus b and for h-order harmonics.	$R_{(b),(b')}^{(h)}$
Impedance between b-bus and for h-order harmonics.	$Z_{(b),(b')}^{(h)}$

Total currents of active power filters

In the problem of optimally determining the location and size of AHPFs, one of the main objectives is to respond to standard harmonic levels, while the sum of the injection currents is minimized by AHPFs. Therefore, the IAHPFs index is defined using Eq. (13) [7-12]. It is worth noting that the cost of an AHPF is proportional to the injection flows. Therefore, the above indices will minimize the cost of AHPFs installed on the electric power distribution network.

$$\mathrm{OF}_{\mathrm{I_{af}}} = \sum_{b=1}^{B} (I_{\mathrm{af}})_{(b)}; \forall b = 1,2,...,B \tag{14}$$

where:

$$\left(I_{\mathrm{af}} \right)_{(b)} = \sum_{b=1}^{B} \sqrt{\sum_{h=2}^{H} \left| (I_{\mathrm{af}})_{(b)}^{(h)} \right|^2}; \quad \forall h = 2,3,...,H, \forall b = 1,2,...,B \tag{15}$$

In Equation (13) and (14) we have:

The sum of AHPFs flows.	Iaf
The sum of AHPFs flows in the b-bus.	$\left(I_{\mathrm{af}} \right)_{(b)}$

Constraint with programming the problem of active power filters

The proposed approach for optimal determine problem and AHPFs size in order to improve the power quality indices in electrical energy distribution networks are as follows by constraints such as total and individual harmonic distortions of voltage and maximum permitted APFs.

$$I_{\mathrm{af},(b)}^{(a)} \le \overline{I_{\mathrm{af},(b)}}; \forall b = 1,2,...,B, \forall a = 1,2,...,A \tag{16}$$

$$I_{\mathrm{af},(b)}^{(a)} \in D; \forall b = 1,2,...,B, \forall a = 1,2,...,A \tag{17}$$

$$\left| V_{(b)}^{(h)} \right| \le \overline{V_{(b)}^{(h)}}; \forall b = 1,2,...,B, \forall h = 2,3,...,H \tag{18}$$

$$THDV_{(b)} \le \overline{THDV_{(b)}}; \forall b = 1,2,...,B \tag{19}$$

In Equation (18)- (15) we have:

An indicator of AHPFs.	A
A set of AHPFs.	A
AHPF current in b-bus.	$I_{\mathrm{af},(b)}^{(a)}$
Maximum AHPF current in b-bus.	$\overline{I_{\mathrm{af},(b)}}$
a set of different types of AHPFs considered.	D
Maximum allowed voltage in b-bus for h order harmonics.	$\overline{V_{(b)}^{(h)}}$
Maximum permissible amount of total harmonic distortion at b-bus.	$\overline{THDV_{(b)}}$

Equation (15) shows the maximum permissible a AHPF in b-bus of the power distribution network. The size of AHPFs can be continuous or discrete. Given that the DC source in the AHPFs structure is implemented by inductors and / or capacitors that are discrete devices, ignoring this limitation leads to impractical results. The value of AHPFs measures the smallest value of set D, according to Equation (16) is equal, D is a set of discrete values of zero and permitted, whenever AHPFs are discrete, and also D is a set of The values are true and non-negative, provided the AHPFs are continuous. Equations (17) and (18), describe the constraints associated with single harmonic and total voltage distortions in the b-bus of the electric power distribution network, respectively.

Solution algorithm

Harmony search algorithm (HSA)

The harmonic search algorithm is a meta-heuristic algorithm inspired by musical phenomena, first introduced in 2001 [14]. The HSA algorithm is based on the process of music improvisation, in which musicians play stage by stage to gain more harmony and better sound. The above process is similar to the optimization process in which the optimal solution can be searched by evaluating the objective function. This algorithm is called the harmonic solver vector. In other words, every harmony is a vector whose components are the values assigned to the decision variables of a problem. If the optimization problem has variable I, then the harmonic vector will also have component I.

The main stages of the HSA algorithm are as follows.

1) The initial determination of the problem and the parameters of the algorithm.

2) The initial determination of the harmony with the random resolution vectors.

3) Improvisation or the production of a New Harmony vector.

4) To update the memory of harmony.

5) Check the stopping criterion of the algorithm and the iteration of steps 3 and 4.

First Step:

In this stage, the optimization problem and parameters of HSA algorithm are determined. These parameters include size of the harmonic memory16, the number of improvisations17 (stop criterion), the bandwidth interval18, the harmonic memory reflection rate19, and the volume adjustment rate20.

Second step:

At this stage, the HM matrix is filled with a large number of randomly generated response vectors considering to HMS according to Equations (33) and (43).

$$x_i^j = x_{iL} + rand\left(0,1\right)\times\left(x_{iU} - x_{iL}\right); \qquad (20)$$
$$\forall i = 1,2,...,I, \forall j = 1,2,...,HMS$$

$$\text{HM} = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{I-1}^1 & x_I^1 \\ x_1^2 & x_2^2 & \cdots & x_{I-1}^2 & x_I^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{I-1}^{HMS-1} & x_I^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{I-1}^{HMS} & x_I^{HMS} \end{bmatrix}; \qquad (21)$$
$$\forall i = 1,2,...,I, \forall j = 1,2,...,HMS$$

In Equation (33) and (34) we have:

Index of decision variables considered.	i
The set of all decision variables considered.	I
Index of harmonic vectors stored in HM.	j
A set of all harmonic vectors stored in HM.	HMS
The i entries of the harmonic vector j stored in HM.	x_i^j
Lower limit of decision variable i.	x_{iL}
Upper limit of decision variable i.	x_{iU}
A random number between zero and one.	$rand\left(0,1\right)$

Third step:

The new harmonic vector is generated on the basis of three rules called improvisation: 1) memory considerations; 2) sound regulation, and 3) random selection. In memory considerations, new harmonic vector values are randomly selected from the HM vectors with the probability of HMCR. In other words, the value of the first decision variable for the new vector is chosen from any value in the HM $\left(x_1^1 - x_1^{\text{HMS}}\right)$ range. Other values of the decision variables are also selected in a similar way. It should be noted that the HMCR, which values between zero and one, is the rate of selection of a previously calculated value stored in the HM.

Where (1-HMCR) the random selection rate is a value of the possible range of values. This process is expressed using the relation (35):

$$x_i^{new}:\begin{cases} \text{with } \Pr\left(HMCR\right) \Rightarrow x_i^{new} \in \left\{x_i^j\right\}; \\ \forall i = 1,2,...,I, \forall j = rand\,\{1,2,...,HMS\} \\ \text{with } \Pr\left(1-HMCR\right) \Rightarrow x_i^{new} \in \left[x_{iL}, x_{iU}\right]; \\ \forall i = 1,2,...,I \end{cases} \qquad (22)$$

Each component is tested by memory considerations to determine whether proper sound is suitable. This operation is done using PAR parameter based on relation (36).

$$x_i^{new}:\begin{cases}\text{with }\Pr\left(PAR\right)\Rightarrow x_i^{new}=x_i^{old}\pm BW\times\varepsilon;\\ \forall i=1,2,\ldots,I\\ \text{with }\Pr\left(1-PAR\right)\Rightarrow x_i^{new}=x_i^{old};\\ \forall i=1,2,\ldots,I\end{cases}\tag{23}$$

In relation (36) we have:

The i entries of the HM vector selected from HM.	x_i^{old}
A random number between 1 and -1.	ε

In the stage of improvising or producing a new harmonic vector, memory considerations, sound adjustment, and random selection are applied to each new harmonic vector decision variable. The process of improvising or producing a new harmonic vector is as follows.

```
For each $i = 1, 2, ..., I$ Do
  If $rand1(0,1) \le HMCR$ Do
    $x_i^{new} = x_i^j$
    If $rand2(0,1) \le PAR$ Do
      $x_i^{new} = x_i^{old} \pm BW \times \varepsilon$
    End If
  Else
    $x_i^{new} = x_i^L \pm rand2() \times (x_{iU} - x_{iL})$
  End If
Done
```

Four step:

If the new harmonic vector of x^{new} is better than the worst harmonic vector in HM, i.e. x^{worst} based on the selected objective function, the new harmonic vector is inserted into the HM and the worst harmonic vector is excluded from the HM set. This process is expressed by Relation (37):

$$x^{worst}=x^{new}\ if\ f\left(x^{new}\right)<f\left(x^{worst}\right)\tag{24}$$

Step Five:

If the stop region of the algorithm (the maximum number of improvisations) is satisfied, the computations are completed and steps 3 and 4 are repeated.

Improved harmonic search algorithm

In order to improve the performance of the HSA algorithm, the IHSA algorithm was introduced in 2007 [15]. PAR and BW parameters in the HSA algorithm are important parameters in fine tuning the optimal response vectors, and can potentially be useful in adjusting the convergence rate of the algorithm to the optimal solution. Therefore, accurate and proper tuning of these parameters is very important. In the HSA algorithm, the PAR and BW values are set in the initial stage and cannot be changed over the next generations. The main disadvantage of this method is in the number of iterations required for the algorithm to find the optimal solution. In the IHSA algorithm, the PAR and BW values will be dynamically changed in terms of the number of generations. This process is applied to the IHSA algorithm using Equations (38) and (39):

$$PAR_{gn}=PAR_{\min}+\frac{\left(PAR_{\max}-PAR_{\min}\right)}{NI}\times gn\tag{25}$$

$$BW_{gn}=BW_{\max}.\exp\left(\frac{Ln\left(BW_{\min}/BW_{\max}\right)}{NI}.gn\right)\tag{26}$$

In relations (38) and (39) we have:

Rate of sound tuning in the gn generation.	PAR_{gn}
Minimum sound tuning rate.	$PAR_{\min}$
Maximum sound tuning rate.	$PAR_{\max}$
The bandwidth distance in the gn generation.	BW_{gn}
Minimum bandwidth distance.	$BW_{\min}$
Maximum bandwidth distance.	$BW_{\max}$

Simulation

The proposed approach for the problem of optimal location determination and size of AHPFs is implemented on the 69-bus test network shown in Figure (2). The full information associated with the above network is available in [16]. This network has multiple linear and thirteen nonlinear loads as 6 pulse of MW2/5 converters in bits 6, 19, 24, 29, 33, 40, 45, 48, 51, 55, 61 and 69, which are harmonic order of 5, 7, 11, 13, 17, 19, 23 and 25 create in network.

The harmonic contents of nonlinear loads (sources of harmonic currents) in terms of peritonitis are given in Table (1). It is also illustrated in Figure (3) for further explanation.

The THDV, MLLF, and HTLL indices are calculated before solving the proposed approach for the optimal location and size problem of AHPFs by performing the harmonic power distribution program in the test network under study, these values are obtained for each indicator in accordance with Table (2). It should be noted that all the values given in the table above are rounded to 4 decimal places.

Table 1: Harmonic content of nonlinear loads

Currentv(p.u)	Harmonic order	NUMBER
0.0551	5	1
0.0450	9	2
0.0388	11	3
0.0380	13	4
0.0251	17	5
0.0210	19	6
0.0100	23	7
0.0051	25	8

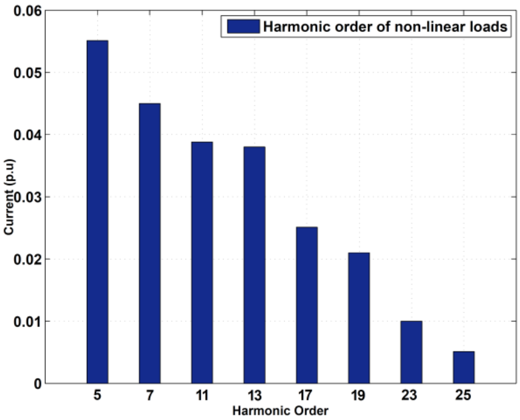

Fig. 2: Harmonic contents of nonlinear loads

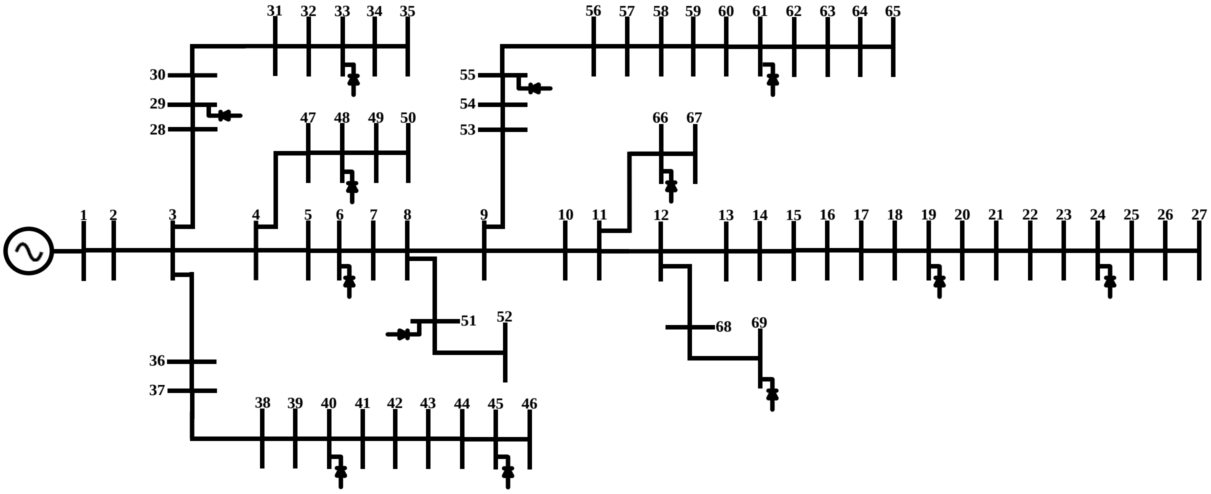

Fig. 1: The 69-bus test network under study

The proposed approach for optimal determining problem and AHPFs size in order to improve the power quality indices in electrical energy distribution networks in two studies will be investigated with the following assumptions:

1) Case Study 1: The algorithm does not consider the AHPF current limit.

2) Case Study 2: The algorithm considers the AHPF current constraint.

The proposed approach is implemented for optimal location determination and AHPFs size using IHSA algorithm. The regulatory parameters of the IHSA algorithm are presented in Table 4. The above parameters are the best values obtained after several performances.

Table 2: IHSA algorithm tuning parameters

Value	Parameters	No.
0.4	BWmin	1
0.9	BWmax	2
0.01	PARmin	3
0.99	PARmax	4
200	HMS	5
0.98	HMCR	6
800	NII	7

The first case study

In the case of a first study, the current limitation of the AHPF is not considered. In other words, the size of an AHPF is constantly considered. This assumption is impractical and non-economic because the size of the AHPFs has a discrete nature due to the discrete nature of inductor and capacitors.

Table 3: Proposed approach indicators for the problem of optimal location and size of AHPFs (before problem solving)

Value	Index	No.
18.2562	THDV (%)	1
3.4125	MLLF (%)	2
0.3564	HTLL (p.u)	3

The results obtained in Table 2 indicate the excessive harmonic pollution in the test network under study. In other words, the levels of harmonic distortion obtained are beyond the limits provided by IEEE 519. In order to increase the flexibility of the proposed approach to the optimal determining problem and the size of the power harmonic filters, four types of AHPF are used in accordance with the table (3).

Table 4: Types of AHPFs (current rates based on MVA10 and kV12)

Max current AHPFs(%)	AHPFs	No.
7	Type1	1
6	Type2	2
5	Type3	3
4	Type4	4

Also, optimal determination problem indicators of location and size of AHPFs in the 69-bus network for the first case study are presented in Table (6).

Table 5: Problem indicators of optimal location determination and size of AHPFs before and after problem solving based on the first study case

IAHPFs (p.u)	HTLL (p.u)	MLLF (%)	THDV (%)	Indices
0	0.347	3.927	18.344	Before
0.686308	0.0242	0.1628	0.6483	After

The results presented in Table 6 indicate the fact that the THDV, MLLF and HTLL are included in the first study within the allowable limits set by the standard of 519 IEEE. Consequently, after implementing the proposed approach for the problem of optimally determining the location and size of AHPFs in the 69-bus network, the network is at an optimal level of harmonic contamination.

The second case study

In this section, the algorithm considers constraints on the current of AHPFs (size of AHPFs). The size of an AHPF is considered as a discrete variable. The problem of determining the optimal location and size of AHPFs is a practical one, given the constraints on AHPF current. In this case, the algorithm uses integers of the size of AHPFs which are limited to the values presented in Table 6. In order to apply these assumptions, the real and imaginary portions of the harmonic currents in the harmonic vectors are modified using equations (25) and (26).

$$\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r = \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r \times \eta_{(b)}; \quad \forall h = 2,3,\ldots,H, \forall b = 1,2,\ldots,B \tag{27}$$

$$\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_i = \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_i \times \eta_{(b)}; \quad \forall h = 2,3,\ldots,H, \forall b = 1,2,\ldots,B \tag{28}$$

In equations (25) and (26), $\eta_{(b)}$ is the correction factor for correcting the real and imaginary parts of the AHPF current located at b-bus. This coefficient is defined as an integer multiple of the AHPF current located at b-bus. The correction factor considered is expressed by using (27) [5]. Consequently, in order to maximize the AHPF current located at b-bus, modifications to the harmonic vectors in accordance with (28) and (29) have to be made [5]. In relationships (28) and (29) we have:

Maximum permitted AHPF current at bus b-bus h order.	$\max\left(I_{\text{af}}\right)$

$$\eta_{(b)} = \frac{round\left(100\times\left(\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r^2 + \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2}\right)}{100\times\left(\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r^2 + \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2}}; \tag{29}$$

$$\forall h = 2,3,\ldots,H, \forall b = 1,2,\ldots,B$$

$$\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r = \begin{cases} \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r ; & \left(\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r^2 + \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2} \le \max\left(I_{\text{af}}\right) \\ \dfrac{\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r \times \max\left(I_{\text{af}}\right)}{\left(\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r^2 + \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2}} ; & \left(\left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_r^2 + \left[\left(I_{\text{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2} > \max\left(I_{\text{af}}\right) \end{cases} \tag{30}$$

$$; \forall h = 2,3,\ldots,H, \forall b = 1,2,\ldots,B$$

$$\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_i=\begin{cases}\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_i; & \left(\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_r^2+\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2}\leq\max\left(I_{\mathrm{af}}\right)\\ \dfrac{\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_i\times\max\left(I_{\mathrm{af}}\right)}{\left(\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_r^2+\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2}}; & \left(\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_r^2+\left[\left(I_{\mathrm{af}}\right)_{(b)}^{(h)}\right]_i^2\right)^{1/2}>\max\left(I_{\mathrm{af}}\right)\end{cases}\tag{31}$$
$$;\forall h=2,3,\ldots,H,\forall b=1,2,\ldots,B$$

The optimal results related to the location and size of the designed AHPFs in the problem of determining the optimal location and size of the AHPFs in the 69-bus network under second study are presented in Table 7.

Table 6: Optimal results related to location and size of AHPFs designed in the problem of optimal location and size of AHPFs based on the second study case

Injected Current {Bus}	AHPFs	No.
{29}:0/066412,{24}:0/068754 {61}:0/070000	Type1	1
{48}:0/056852 {66}:0/060000, ‘{6}:0/057840 {69}:0/059880	Type2	2
{51}:0/042650	Type3	3
{55}:0/035325	Type4	4

Also, problem indices for determining the optimal location and size of AHPFs in the 69-bus network for the first case study are presented in Table 9. It is worth noting that the problem of optimal location and size determination of AHPFs in electricity distribution networks is more realistic, practical and economical in view of the limitations of AHPFs.

Also, problem indices for determining the optimal location and size of AHPFs in the 69-bus network for the first case study are presented in Table (8). It is worth noting that the problem of optimizing the location and size of AHPFs in electricity distribution networks is a practical and economical problem considering the limitations of AHPFs.

Table 7: AHPFs programming problem indicators, before and after problem solving in all scenarios based on the first study case

IAHPFs (p.u)	HTLL (p.u)	MLLF (%)	THDV (%)	Indices
0	0/347	3/927	1/3448	Before
/5858670	/02530	/17450	/87230	After

The results presented in Table (8) indicate the fact that the THDV, MLLF and HTLL indices are in the second study within the permissible limit set by IEEE 519. Consequently, after implementing the proposed approach for the problem of optimal location determination and size of AHPFs in the 69-bus network under study, this network is in a very desirable state in the presence of AHPFs in terms of harmonic pollution. The flow of APFs with and without current constraints in both cases is shown in Fig. (4).

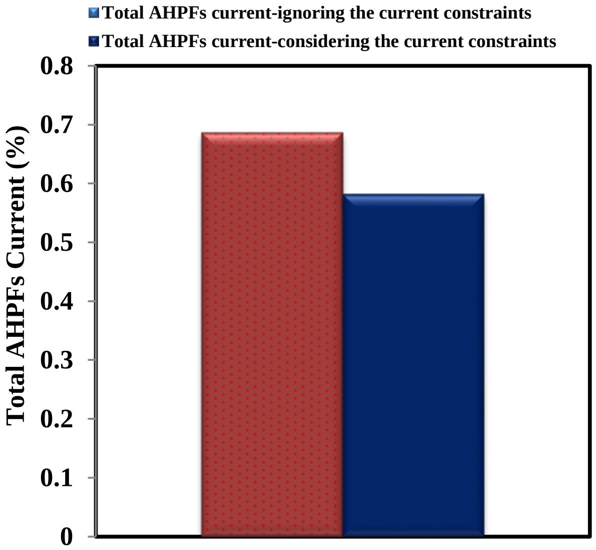

Figure (4): AHPFs current with and without current limitation

The results plotted in Fig. 4 illustrate the fact that, for the second study that considers the limitation associated with the current of AHPFs, the value obtained for the current of APFs is far less than the value obtained in AHPFs. This is the first case study. This means that the second case study, in which the problem of optimizing the location and size of AHPFs is implemented considering the current constraints of AHPFs, is a fully economical, cost-effective and practical approach.

Improved harmony search algorithm performance

In this section, the performance of the IHSA algorithm is compared to the genetic algorithm and the particle swarm optimization algorithm based on the second case study considering the current constraint of AHPFs. The regulatory parameters of GA and PSO algorithms are presented in Tables (9) and (10), respectively.

Table 8: GA Algorithm tuning Parameters

No.	Parameter GA	Value
1	Mutation probability	0/9
2	Probability of intersection	0/1
3	Selection rate	0/95
4	Population	100
5	generation	500

Table 9: tuning Parameters of PSO Algorithm

No.	Parameter PSO	Value
1	Inertia coefficient	0/9-0/1
2	Learning coefficient	2
3	Population	100
4	generation	500

The values of the objective functions considered in the problem of optimizing the location and size of AHPFs including THDV, MLLF, HTLL, and IAHPFs based on the second case study (taking into account AHPFs current constraint) and IHSA, GA and PSO algorithms are presented in Table (11). The optimal results presented in Table 11 indicate that the implementation of the proposed approach using IHSA algorithm has achieved far more desirable results than its implementation using GA and PSO algorithms. Thus, the proposed approach based on the IHSA algorithm may be an appropriate and well-designed method to optimally determine the location and size of AHPFs to improve power quality indices in electric power distribution networks. Also, in order to examine more accurately the performance of IHSA, GA and PSO algorithms, the convergence diagram of these algorithms is plotted in Fig. (5).

Table 10: Comparison of IHSA, GA and PSO algorithms based on the second case study

Problem Indicators	Iaf (p.u)	HTLL (p.u)	MLLF (%)	THDV (%)
Before solving	0	0.347	3.927	18.344
After settling with IHSA	0.585867	0.0253	0.1745	0.8723
After settling with PSO	0.609581	0.0272	0.1828	0.9438
After settling with GA	0.634512	0.0301	0.2065	1.0495

By analyzing Fig. 5, it can be seen that the IHSA algorithm has much faster speed and convergence rate than the PSO and GA algorithms. In other words, this algorithm performs better than PSO and GA algorithms.

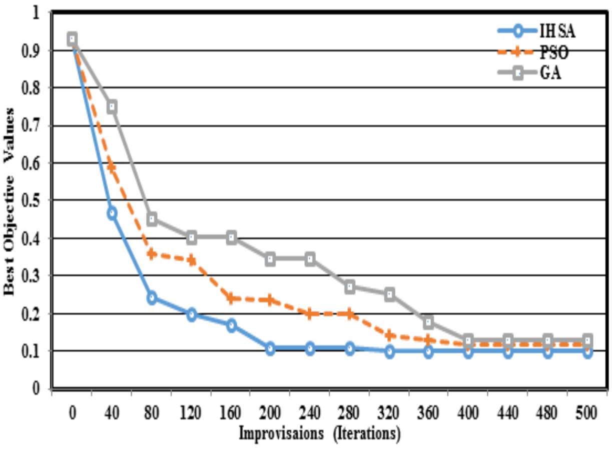

Figure 5: Convergence diagram of IHSA, PSO and GA algorithms

Conclusion

This paper focuses on presenting an approach to optimally determine the location and size of AHPFs in order to improve power quality indices in electric power distribution networks. The THDV, MLLF, HTLL and IAHPFs functions are collected by appropriate weighting coefficients and are considered as predominant problem function. Also, total and individual harmonic distortions of voltage and maximum permitted AHPFs are also considered as problem constraints. In addition, the flexibility of the proposed approach is enhanced by utilizing four different types of active filters. Replacement and measurement of active harmonic power filters were performed and implemented on two 69-bus network under two different case studies. The difference between the first and second case studies is in ignoring or considering the limitations associated with harmonic currents injected by AHPFs.

The proposed approach has been successfully implemented on the 69-bus network. According to the results, it can be seen that the power quality indices considered after solving the problem and in the presence of AHPFs are within the permissible range and the target network is in optimum condition for harmonic pollution. It is also observed that the results obtained from the proposed approach using IHSA algorithm are more desirable and effective than the results of GA and PSO algorithms. In the other word, the proposed approach based on IHSA algorithm achieves lower values for THDV, MLLF, HTLL and IAHPFs compared to GA and PSO algorithms.

References

[1] Fuchs E.F., Masoum M.A.S, Power quality in power systems and electrical machines, Elsevier Academic Press: Burlington, USA, 2008, ISBN: 978-0-12-369536-9.

[2] Arif M.R., Mahmood F., Hashmi M., Hanninen S. "Application of passive filters to mitigate power quality problems caused by induction furnaces", 2012 International Conference on Condition Monitoring and Diagnosis (CMD), Bali, Indonesia, 23–27 September 2012: 1227–1230.

[3] Das J.C. "Passive filters–potentialities and limitations", IEEE Transactions on Industrial Applications, 2004, Vol. 40, pp. 232-241.

[4] Kumar A., Singh J. "Harmonic mitigation and power quality improvement using shunt active power filter", International Journal of Electrical, Electronics and Mechanicals Controls (IJEEMC) 2013, Vol. 2, pp. 1–13.

[5] Mulla M.A., Chudamani R., Chowdhury A. "Series hybrid active power filter for mitigating voltage unbalance and harmonics under unbalanced non–sinusoidal supply conditions", 2012 IEEE International Conference on Power and Energy (PECON), Kota Kinabalu, Malaysia, 2–5 December 2012, pp. 671–676.

[6] Angulo M., Ruiz–Caballero D.A., Lago J., Heldwein M.L. "Active power filter control strategy with implicit closed–loop current control and resonant controller", IEEE Transactions on Industrial Electronics, 2013, Vol. 60, pp. 2721-2730.

[7] Ziari I., Jalilian A. "A new approach for allocation and sizing of multiple active power–line conditioners", IEEE Transactions on Power Delivery, 2010, Vol. 25, pp. 1026-1035.

[8] Keypour R., Seifi H., Yazdian-Varjani A. "Genetic based algorithm for active powerfilter allocation and sizing", Electric Power Systems Research, 2004, vol. 71, pp. 41–49.

[9] Ziari I., Jalilian A. "Optimal placement and sizing of multiple APLCs using a modified discrete PSO", International Journal of Electrical Power and Energy Systems, 2012, Vol. 43, pp. 630–639.

[10] Ziari I., Jalilian A. "Optimal allocation and sizing of active power line conditioners using a new particle swarm optimization–based approach", Electric Power Components and Systems, 2012, Vol. 40, pp. 273–291.

[11] Moradifar A., Soleymanpour H.R. "A fuzzy based solution for allocation and sizing of multiple active power filters", Journal of Power Electronics, 2012, Vol. 12, pp. 830–841.

[12] Farhoodnea M., Mohamed A., Shareef H., Zayanderodi H. "Optimum placement of active power conditioner in distribution systems using improved discrete firefly algorithm for power quality enhancement", Applied soft computing, 2014, Vol. 23, pp. 249–258.

[13] He N., Xu D., Huang L. "The application of particle swarm optimization to passive and hybrid active power filter design", IEEE Transactions on Industrial Electronics, 2009, Vol. 56, pp. 2841–2851.

[14] Geem Z.W, Kim J.H, Loganathan G.V. "Harmony search optimization: applica-tion to pipe network design, Int. J. Model " Simul. 22 (2002) 125–133.

[15] M. Mahdavi, M. Fesanghary, E. Damangir, “An improve harmony search algorithm for solving optimization problems” Applied Mathematics and Computing Vol. 188, pp. 1567-1579, 2007.

[16] M.E. Baran, F.F. Wu, “Optimal capacitor placement on radial distribution systems,” IEEE Transactions on Power Delivery, Vol. 4, No. 1, pp. 725–734, 1989.