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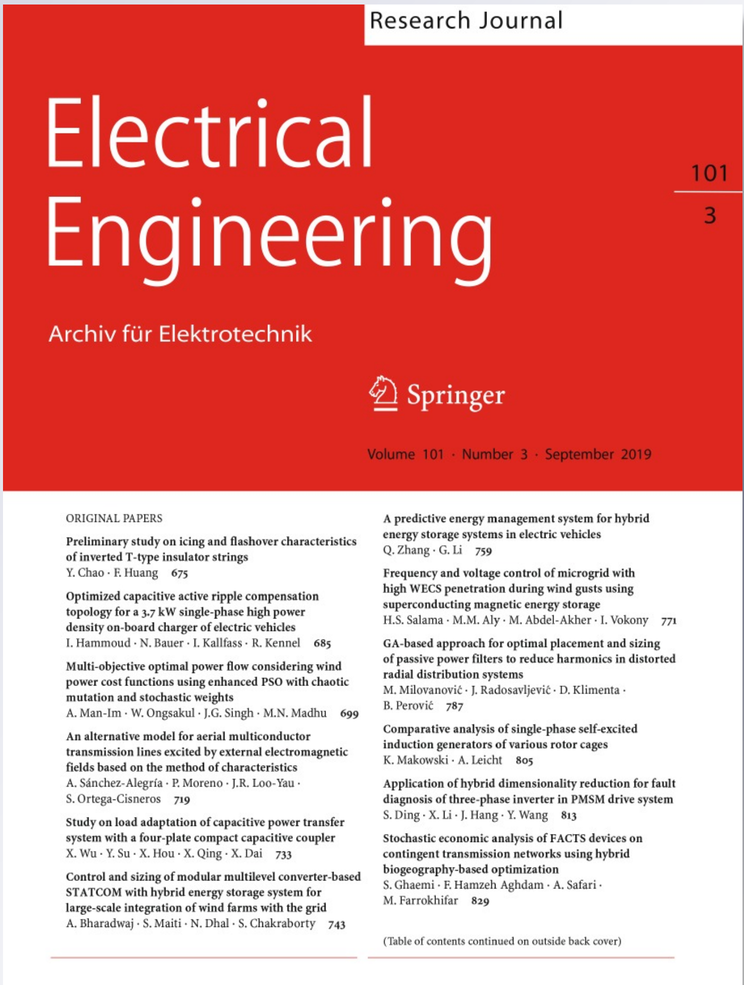

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ORIGINAL PAPER

GA-based approach for optimal placement and sizing of passive power filters to reduce harmonics in distorted radial distribution systems

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Abstract
This paper presents a Genetic Algorithm-based approach for optimal placement and sizing of passive power filters to mitigate harmonics in radial distribution systems with linear and nonlinear loads. The problem is formulated as a nonlinear multi-objective optimisation problem with equality and inequality constraints. For solving this problem, the Genetic Algorithm's performances are analysed and evaluated using the standard IEEE 18- and 33-bus test systems. The optimal solutions are obtained based on the following four optimisation criteria: (1) minimisation of the maximum level of the total harmonic distortion in voltage, (2) minimisation of the initial investment costs of the filters, (3) minimisation of total active power losses in distribution lines and (4) a simultaneous minimisation of the maximum total harmonic distortion in voltage, initial investment costs of filters and total active power losses. The system harmonic levels are estimated using the Decoupled Harmonic Power Flow algorithm. Simulation results, obtained using the proposed Genetic Algorithm-based approach, are compared with those obtained using other optimisation algorithms and verified using the Harmonic Analysis module of the Electrical Transient Analysis Program. It is shown that the Genetic Algorithm-based approach provides effective, robust and high-quality solutions.

Keywords Genetic Algorithm (GA) · Harmonics · Optimisation · Passive power filter (PPF) · Radial distribution system

1 Introduction

In recent years, the widespread use of nonlinear loads, such as adjustable speed drives and rectifiers within the electrical power distribution systems, leads to power quality problems. One of the most important aspects of the power quality is the presence of harmonics in the systems. Loads with a nonlinear current–voltage characteristic inject harmonic currents which have detrimental effects on the power quality, including the communication interference, loss of reliability, reduction of efficiency in power generation, transmission and utilisation, increased operating costs, equipment overheating, components of ageing and inaccurate power metering [1]. Among the several recommended solutions used to mitigate harmonic distortions and improve power quality, the passive power filters (PPFs) are the most frequently employed ones due to their simplicity, high reliability and efficiency, small construction and economical cost. Determining the location, size and harmonic tuning orders of PPFs, in order to achieve permissible/acceptable levels of the harmonic distortion defined in the IEEE-519 standard [2] along with an application of the minimum costs of filters, [3] represents a significant problem of using the PPFs.

In relevant scientific literature such as [3–14], a great attention is paid to addressing the problem of optimal placement and sizing of PPFs of different types and topologies using meta-heuristic optimisation methods [15]. In addition, different optimisation criteria were considered, i.e. different objective functions and constraints. In [3], the optimal planning of PPFs in radial distribution systems using the Bacterial Foraging Optimisation (BFO) algorithm was addressed. In this reference, the objective function included a reduction in power losses and investment costs of PPFs. In addition, Juan et al. [4] discussed an optimal design of PPFs of an asymmetrical system based on the Genetic Algorithm (GA) with the aim of minimisation of total harmonic distortion in current (THD_I) and reduction in costs for equipment. The problem analysed in [5] was focused on an optimal design of

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PPFs for reducing harmonic distortion and correcting power factor, and the Simulated Annealing (SA) algorithm was used to solve the problem. In [6], the multi-objective optimisation considering the costs of PPFs and THD_I was solved by using the Ant Colony Optimisation (ACO) algorithm. In [7], a practical technique based on the Graph Search (GS) algorithm, which determines the number, sizes and locations of PPFs, was proposed to minimise filter costs, power losses and total harmonic distortion in voltage (THD_V), as well as to enhance the voltage profile.

The Non-dominated Sorting Genetic Algorithm-II (NSGA-II) for solving the multi-objective filter planning problems was used in [8, 9]. Mazlumi et al. [10] presented an approach based on the Imperialist Competitive Algorithm (ICA) to find optimal parameters of PPFs for harmonic mitigation. In the study of Tosun et al. [11], an optimal design of single-tuned PPFs of an industrial power system based on the Gravitational Search Algorithm (GSA) was discussed. In [12], optimal planning problem of PPFs and distributed generations (DGs) in distribution systems with nonlinear loads using an adaptive BFO approach was addressed. At the same time, constraints of the problem included the voltage limits and the limit candidate buses for PPFs and DGs installation. In [13], an approach based on the GA and Monte Carlo Simulation (MCS) for the optimal probabilistic planning of single-tuned PPFs in unbalanced three-phase distribution systems with high penetration of photovoltaic generation was proposed. Moreover, Teng et at. [16] proposed a three-phase harmonic analysis method for unbalanced distribution systems that can be used for optimal harmonic filter design and harmonic resonance mitigation.

The optimal selection of the location, size, type, quality factor and tuned harmonic order together with constraints on bus voltage magnitudes, total and individual harmonic limits, design of components and operation limits for PPFs, in order to minimise the maximum level of the THD_V using the Particle Swarm Optimisation (PSO) algorithm and thereby reduce the effect of harmonics on electric power system, were recently carried out [14]. For the estimation of harmonic components, the Decoupled Harmonic Power Flow (DHPF) algorithm was used in [14]. In particular, this was attempt to suppress the 5th, 7th, 11th and higher-order harmonics in the IEEE 18- and 33-bus distribution systems, where in the corresponding bus admittance matrix, the slack bus of the IEEE 33-bus test system was represented in a manner, which is not in line with the IEC 60076-5 standard [17]. In the publications [4–13], the capacity and number of PPFs were used as control variables, while other essential parameters, such as the type of a PPF, quality factor and harmonic order that needs to be suppressed, were not considered. Potential locations for placement of PPFs, in some of the aforementioned publications, were determined through a harmonic power flow calculation which, as a result, gives the THD_V levels at all buses of each considered system. According to the calculations, potential locations for placement of PPFs are at buses with the maximum THD_V levels.

Compared with the paper [14] where the minimisation of the maximum THD_V was used as a single objective function, in this paper, together with this minimisation, the three other minimisations listed in Abstract are used as objective functions. This is the main novelty in relation to [3–14] and other relevant references.

The GA-based approach enables the determination of optimal solutions for different objective functions, taking into consideration constraints which include power balance constraints, total and individual harmonic limits in accordance with the IEEE-519 standard [2], tuned harmonic order variation constraints due to temperature changes and error tolerances in manufacturing process, constraints on bus voltage magnitudes, quality factor limits, limit on current of the filters' inductors, and limits on voltage, current and reactive power of the filters' capacitors in accordance with the IEEE-1531 standard [18]. The proposed approach is tested on two standard distribution systems with nonlinear loads, i.e. the distorted IEEE 18- and 33-bus test systems, so that the optimal solution is obtained for different objectives that reflect reduction in harmonic distortion, minimisation of the initial investment costs of PPFs and reduction in power losses. A linear load is represented by a parallel combination of a resistor and an inductor. Nonlinear loads are treated as harmonic current sources that inject harmonic currents into the considered systems. In order to calculate the higher-order harmonic components, the DHPF algorithm is applied. The results obtained by the proposed approach are compared with the PSO [14] and the eight following algorithms: Artificial Bee Colony (ABC) algorithm [19], Biogeography-Based Optimisation (BBO) algorithm [20], Backtracking Search Algorithm (BSA) [21], Gravitational Search Algorithm (GSA) [22], Grey Wolf Optimiser (GWO) algorithm [23], Imperialist Competitive Algorithm (ICA) [24], Wind Driven Optimisation (WDO) algorithm [25] and hybrid GA-PSO algorithm [26], taking the minimisation of the maximum THD_V into account for the objective function. These comparisons represent an additional contribution to the field of research. The effects of installing one PPF and two PPFs on the power quality parameters are considered. Also, in order to validate the accuracy of the DHPF algorithm, simulation results are compared to those generated by the Harmonic Analysis module of the ETAP programme [27].

2 Design of passive power filters

A passive shunt filter represents a suitable combination of inductors, capacitors and resistors. Commonly used types of passive harmonic filters are single-tuned and high-pass filters [28]. Neglecting the resistances in the reactors and the dielectric power losses in the capacitors, the total impedance of these two harmonic filters at any angular frequency ω can be expressed as follows:

- For single-tuned filter

$$\underline{Z}_f^{(h)} = R + j\omega L + \frac{1}{j\omega C} \tag{1}$$

- For second-order high-pass filter

$$\underline{Z}_f^{(h)} = \frac{1}{j\omega C} + \left(\frac{1}{R} + \frac{1}{j\omega L}\right)^{-1} \tag{2}$$

where R is the filter resistance in Ω, L is the filter inductance in H, C is the filter capacitance in F, $\omega = 2\pi h f_1$ is the angular frequency in rad/s, $f_1 = 50$ Hz is the fundamental frequency, $h = f_h/f_1$ is the harmonic frequency order number and f_h is the harmonic frequency in Hz.

In order to design a single-tuned passive filter, it is important to calculate appropriate values of the R, C and L parameters which enable engineers to reduce harmonics and to meet the acceptable distortion levels of the IEEE 519 standard. When the angular frequency ω equals the angular frequency of resonance $\omega_n = h_n\omega_1$ (where h_n is the tuned harmonic order, and ω_1 is the fundamental angular frequency), the inductive reactance magnitude equals the capacitive reactance magnitude, and the total impedance consists only of the resistive component R.

The inductor or capacitor reactance at the tuned frequency is defined as [1, 29]:

$$X_0 = \omega_n L = \frac{1}{\omega_n C} \tag{3}$$

If Q_f is the reactive power capacity at the fundamental frequency ($h = 1$) in MVAr, if h_n is the order for which the filter is tuned to suppress a single frequency, if V_L is the nominal line-to-line system voltage, and if Q is the quality factor, then the capacitor reactance X_C, inductor reactance X_L, filter capacitance C, filter inductance L, and filter resistance R, at the fundamental frequency, can be calculated as follows [14]:

$$X_C = \frac{V_L^2}{Q_f}\left(\frac{h_n^2}{h_n^2 - 1}\right) \tag{4}$$

$$X_L = \frac{X_C}{h_n^2} \tag{5}$$

$$C = \frac{1}{\omega_1 X_C} \tag{6}$$

$$L = \frac{X_L}{\omega_1} \tag{7}$$

$$R = \frac{h_n X_L}{Q} \tag{8}$$

The inductor's quality factor Q is a quantity that defines the bandwidth of the filter. For single-tuned filters, a typical range for Q is between 50 and 150 [1].

A high-pass filter absorbs all higher-order harmonics and provides damping due to the presence of a resistor in the circuit. In this case, the corresponding filter parameters X_C, X_L, C and L are, respectively, defined by Eqs. (4)–(7), while R can be obtained from the quality factor Q as [14]:

$$R = Q h_n X_L \tag{9}$$

For high-pass filters, the inductor's quality factor ranges between 0.5 and 2 [1].

3 Problem formulation

In this section, the problem of placement and sizing of the PPFs for mitigation of harmonics is modelled as an optimisation problem. The goal is to find the optimal settings of some control variables that will minimise a selected objective function while respecting various equality and inequality constraints. Generally, this problem can be described mathematically as follows:

$$\min F(\mathbf{x}, \mathbf{u}) \tag{10}$$

$$g(\mathbf{x}, \mathbf{u}) = 0 \tag{11}$$

$$h(\mathbf{x}, \mathbf{u}) \le 0 \tag{12}$$

$$\mathbf{u} \in \mathbf{U} \tag{13}$$

where $F(\mathbf{x},\mathbf{u})$ is a scalar-valued objective function, $g(\mathbf{x},\mathbf{u})$ is a vector composed of equality constraints, $h(\mathbf{x},\mathbf{u})$ is a vector composed of inequality constraints, $\mathbf{x}$ is a vector of dependent variables, $\mathbf{u}$ is a vector of control variables and $\mathbf{U}$ is a feasible space/region.

For a distribution system polluted by harmonics, having N buses and n PPFs, the vector of dependent variables x consists of the RMS bus voltages ($V_{\mathrm{RMS},1},\ldots,V_{\mathrm{RMS},N}$), total harmonic distortions in voltage ($\mathrm{THD}_{\mathrm{V},1},\ldots,\mathrm{THD}_{\mathrm{V},N}$), individual harmonic distortions in voltage ($\mathrm{IHD}_{\mathrm{V},1},\ldots,\mathrm{IHD}_{\mathrm{V},N}$), RMS currents flowing through the inductors ($I_{L,1}^{\mathrm{RMS}},\ldots,I_{L,n}^{\mathrm{RMS}}$), RMS voltages across the capacitors ($V_{C,1}^{\mathrm{RMS}},\ldots,V_{C,n}^{\mathrm{RMS}}$), peak voltages across the capacitors ($V_{C,1}^{\mathrm{peak}},\ldots,V_{C,n}^{\mathrm{peak}}$), RMS currents flowing through the capacitors ($I_{C,1}^{\mathrm{RMS}},\ldots,I_{C,n}^{\mathrm{RMS}}$) and reactive powers of the capacitors ($Q_{C,1},\ldots,Q_{C,n}$). Therefore, the vector $\mathbf{x}$ can be defined as:

$$\mathbf{x} = [V_{\text{RMS},1}, \dots, V_{\text{RMS},N}, \text{THD}_{\text{V},1}, \dots, \text{THD}_{\text{V},N}, \text{IHD}_{\text{V},1}, \dots, \text{IHD}_{\text{V},N}, I_{L,1}^{\text{RMS}}, \dots, I_{L,n}^{\text{RMS}}, V_{C,1}^{\text{RMS}}, \dots, V_{C,n}^{\text{RMS}}, V_{C,1}^{\text{peak}}, \dots, V_{C,n}^{\text{peak}}, I_{C,1}^{\text{RMS}}, \dots, I_{C,n}^{\text{RMS}}, Q_{C,1}, \dots, Q_{C,n}]^{\text{T}} \quad (14)$$

The vector of control variables $\mathbf{u}$, whose values will be optimised using the GA-based approach, consists of the locations ($\ell_1,\ldots,\ell_n$), sizes ($Q_{f,1},\ldots,Q_{f,n}$), types ($FT_1,\ldots,FT_n$), tuned harmonic orders ($h_{n,1},\ldots,h_{n,n}$) and quality factors ($Q_1,\ldots,Q_n$) of PPFs. Accordingly, the vector $\mathbf{u}$ can be given as:

$$\mathbf{u} = [\ell_1, \dots, \ell_n, Q_{f,1}, \dots, Q_{f,n}, FT_1, \dots, FT_n, h_{n,1}, \dots, h_{n,n}, Q_1, \dots, Q_n]^{\text{T}} \quad (15)$$

3.1 Objective functions

This paper considers the following four optimisation problems:

Problem 1 Minimisation of the maximum THD_V [14]:

$$F_1 = \max(\text{THD}_\text{V}) = \max_{i \in U_s} \left(\frac{1}{\left|V_i^{(1)}\right|} \sqrt{\sum_{h=2}^{h_{\max}} \left|V_i^{(h)}\right|^2} \right) \cdot 100 \quad (16)$$

where U_s is the set of bus numbers, $V_i^{(h)}$ is the voltage at bus i for the harmonic order h, and $h_{\max}$ is the maximum harmonic order under consideration.

Problem 2 Minimisation of the initial investment costs of PPFs [4]:

$$F_2 = \sum_{i=1}^{n} \left(k_R R_i + k_L L_i + k_C C_i\right) \quad (17)$$

where R_i, L_i, and C_i are the resistance in Ω, inductance in mH, and capacitance in μF of the ith PPF, respectively; k_R, k_L, and k_C are cost weighting coefficients corresponding to R, L, and C in p.u./Ω, p.u./mH, and p.u./μF, respectively. According to [29], the values of these coefficients are $k_R = 5$ p.u./Ω, $k_L = 3$ p.u./mH and $k_C = 2$ p.u./μF.

Problem 3 Minimisation of total active power losses in distribution lines [30]:

$$F_3 = P_{\text{loss}}^{(h)} = \sum_{h=1}^{h_{\max}} \left(\sum_{i=1}^{N-1} P_{\text{loss}(i,i+1)}^{(h)} \right) \quad (18)$$

where $P_{\text{loss}}^{(h)}$ and $P_{\text{loss}(i,i+1)}^{(h)}$ are the total active power losses in distribution lines and active power losses in a single line between buses i and $i+1$ for the harmonic order h, respectively.

Problem 4 Simultaneous minimisation of the maximum THD_V, initial investment costs of the PPFs and total active power losses:

$$F_4 = F_1 + w_{\text{cost}} F_2 + w_{\text{loss}} F_3 \quad (19)$$

where w_{cost} and w_{loss} are the weighting factors for the functions of filter costs and active power losses, respectively.

3.2 Equality and inequality constraints

At the fundamental frequency, the equality constraints (11) relating to the active and reactive powers at bus i can be expressed as:

$$P_{G,i} - P_{D,i} = \left|V_i^{(1)}\right| \sum_{j=1}^{N} \left|V_j^{(1)}\right| \left|Y_{i,j}^{(1)}\right| \cos\left(\Phi_{i,j}^{(1)} - \delta_i^{(1)} + \delta_j^{(1)}\right) \quad (20)$$

$$Q_{G,i} - Q_{D,i} = \left|V_i^{(1)}\right| \sum_{j=1}^{N} \left|V_j^{(1)}\right| \left|Y_{i,j}^{(1)}\right| \sin\left(\Phi_{i,j}^{(1)} - \delta_i^{(1)} + \delta_j^{(1)}\right) \quad (21)$$

where $i = 1,\ldots, N$ is the bus number, $P_{G,i}$ and $Q_{G,i}$ are the fundamental active and reactive power generations at bus i, $P_{D,i}$ and $Q_{D,i}$ are the fundamental active and reactive load demands at bus i, $Y_{i,j}^{(1)}$ is the (i,j)th element of the fundamental admittance matrix corresponding to the ith row and the jth column, $\Phi_{i,j}^{(1)}$ is the angle of the (i,j)th element of the fundamental admittance matrix, and $\delta_i^{(1)}$ and $\delta_j^{(1)}$ are the fundamental voltage angles at the buses i and j, respectively. The Backward–Forward Sweep (BFS) method was used to obtain and analyse the parameters of the considered distribution systems at the fundamental frequency. Power flow equations of the BFS method are given in [31, 32].

The equality constrains related to harmonic power flow are defined as:

$$\mathbf{V}^{(h)} = \left[\mathbf{Y}_{\mathbf{BUS}}^{(h)}\right]^{-1} \mathbf{I}^{(h)} \quad (22)$$

where $\mathbf{V}^{(h)} = [V_1^{(h)}, V_2^{(h)}, \dots, V_N^{(h)}]^{\text{T}}$ is the system bus voltage vector at the hth harmonic, $\mathbf{Y}_{\mathbf{BUS}}^{(h)}$ is the system bus admittance matrix at the hth harmonic, and $\mathbf{I}^{(h)} = [I_1^{(h)}, I_2^{(h)}, \dots, I_N^{(h)}]^{\text{T}}$ is the system bus injected current vector at the hth harmonic. The DHPF method was used to estimate harmonic components [1, 30].

The inequality constraints (12) represent the operation limits which include the bus voltage quality constraints of the system and limits of filter components design and operation. The values of bus voltage magnitudes are bounded by their lower (0.9 p.u.) and upper (1.1 p.u.) limits as follows:

$$V_{\mathrm{RMS}}^{\min} \leq \sqrt{\sum_{h=1}^{h_{\max}} \left|V_i^{(h)}\right|^2} \leq V_{\mathrm{RMS}}^{\max} \tag{23}$$

where $i = 1,\ldots, N$ is the bus number, while $V_{\mathrm{RMS}}^{\min}$ and $V_{\mathrm{RMS}}^{\max}$ are the minimum and maximum bus voltage limits, respectively.

Limits on the $\mathrm{THD_V}$ and $\mathrm{IHD_V}$ are defined by introducing the corresponding maximum acceptable levels. According to the IEEE-519 standard [2], at the point of common coupling in distribution systems below 69 kV, the levels of the $\mathrm{THD_V}$ and $\mathrm{IHD_V}$ must be lower than 5% and 3%, respectively; i.e.

$$\mathrm{THD}_{\mathrm{V},i}(\%) \leq \mathrm{THD}_{\mathrm{V}}^{\max} \tag{24}$$

$$\mathrm{IHD}_{\mathrm{V},i}^{(h)}(\%) \leq \mathrm{IHD}_{\mathrm{V}}^{\max,h} \tag{25}$$

where $i = 1,\ldots, N$ is the bus number, $\mathrm{THD}_{\mathrm{V}}^{\max} = 5\%$ is the maximum acceptable level of the $\mathrm{THD_V}$ at any bus i, and $\mathrm{IHD}_{\mathrm{V}}^{\max,h} = 3\%$ is the maximum acceptable level of the $\mathrm{IHD_V}$ at the hth harmonic.

The IEEE-1513 standard [18] recommends voltage and current limits/levels in components (capacitors and inductors) of PPFs operating under non-sinusoidal conditions. According to this standard, the RMS voltages across the filter capacitors and RMS currents flowing through the filter inductors are limited by 110% and 135%, respectively. The limit of 135% relating to the filter inductors is based on rated kVAr and rated voltage. In addition, the utilised capacitors must be able to withstand 120% of rated peak voltage including harmonics, but excluding transients; as well as 135% of rated kVAr.

The set of constraints (13) defines the feasible region of the problem control variables. The feasible region **U** is the set of values that the control variables can take and satisfy the problem constraints. In particular, in this case, the control variables are the locations ($\ell_1,\ldots,\ell_n$), sizes ($Q_{f,1},\ldots,Q_{f,n}$), types ($FT_1,\ldots,FT_n$), tuned harmonic orders ($h_{n,1},\ldots,h_{n,n}$) and quality factors ($Q_1,\ldots,Q_n$) of PPFs. Accordingly, it is clear that an optimal solution of the problem must satisfy the constraints, meaning it must belong to the feasible region.

Each bus in a distribution system represents a potential location for placement of a PPF. If the reactive power supplied by PPFs exceeds the system demand, an over-voltage occurs in the system [5]. In addition, incorrect installation of PPFs could lead to overcompensation, which is not allowed. For these reasons, the filter capacitors are selected such that the reactive power supplied by them does not exceed a specified value,

$$Q_{f,i}^{\min} \leq Q_{f,i} \leq Q_{f,i}^{\max} \tag{26}$$

$$\sum_{i=1}^{n} Q_{f,i} \leq Q_{\mathrm{total}}^{\max} \tag{27}$$

where $i = 1,\ldots, n$ is the filter number, $Q_{f,i}^{\min}$ and $Q_{f,i}^{\max}$ are the lower and upper limits of the fundamental reactive power provided by the ith filter, and $Q_{\mathrm{total}}^{\max}$ is the system's upper limit of the total fundamental reactive power.

In order to achieve an acceptable level of distortion at minimum costs for filters, reduce power losses and improve voltage profile, the authors considered several different types of PPFs. The value of the control variable FT can be 1, 2 and 3, which corresponds to the single-tuned filter for the fifth-order harmonic, single-tuned filter for the seventh-order harmonic and high-pass filter for the 11th-order harmonic, respectively. The harmonic filters are not usually tuned to the exact values of harmonic frequency. According to [14], the impact analysis of variations in frequency and reactances of inductors and capacitors due to temperature changes and error tolerances in manufacturing process on performance of PPFs shows the importance of including the filter detuning effect in the design. In this paper, taking into account the aforementioned variations, the considered filters are tuned to a frequency from the range of 0.92h to 1.036h. In addition to this, the single-tuned and high-pass filters are designed to have the quality factors of the inductors between 10 and 100, and between 0.5 and 2, respectively.

3.3 Expanded objective function

The inequality constraints described by expression (12) are taken into account through quadratic penalty factors by means of which the objective function F is expanded in the following manner:

$$F_e = F + \sum_{i=1}^{p} \lambda_i (x_i - x_i^{\lim})^2 \tag{28}$$

where F_e is the expanded objective function that will be minimised, F is the function representing the objective function F_1, F_2, F_3 or F_4, λ_i is the corresponding penalty factor, p is the number of inequality constraints, $x_i^{\lim}$ is an upper or lower bound on dependent variable x_i, which is defined by: $x_i^{\lim} = x_i^{\max}$ if $x_i > x_i^{\max}$, and $x_i^{\lim} = x_i^{\min}$ if $x_i < x_i^{\min}$. The penalty factor of 10^5 is selected for all the inequality constraints, which are defined in the considered optimisation Problems 1–4.

4 Decoupled harmonic power flow

At harmonic frequencies, a distribution system is modelled with a combination of passive elements and harmonic current sources. In order to determine the harmonic components in the system, the DHPF algorithm is applied. In this method, the interaction among the harmonic frequencies is assumed to be negligible and hence the admittance matrix is formulated individually for all harmonics of interest [30]. The advantages of this method are the following: the solution can be obtained directly, it is able to handle several harmonic sources simultaneously, and it is computationally efficient.

If the skin effect is neglected, admittance of the linear load at bus i ($y_{l,i}^{(h)}$), shunt capacitor at bus i ($y_{c,i}^{(h)}$), passive filter at bus i ($y_{f,i}^{(h)}$), and line between buses i and $i+1$ ($y_{i,i+1}^{(h)}$) are, respectively, defined by the following equations [1, 30]:

$$y_{l,i}^{(h)} = \frac{P_{l,i}}{\left|V_i^{(1)}\right|^2} - j\frac{Q_{l,i}}{h\left|V_i^{(1)}\right|^2} \tag{29}$$

$$y_{c,i}^{(h)} = hy_{c,i}^{(1)} \tag{30}$$

$$y_{f,i}^{(h)} = \frac{1}{Z_{f,i}^{(h)}} \tag{31}$$

$$y_{i,i+1}^{(h)} = \frac{1}{R_{i,i+1} + jhX_{i,i+1}} \tag{32}$$

where $P_{l,i}$ and $Q_{l,i}$ are the fundamental active and reactive linear load powers at bus i, $y_{c,i}^{(1)}$ is the fundamental admittance of the shunt capacitor at bus i, and $R_{i,i+1}$ and $X_{i,i+1}$ are the resistance and reactance of the line between busses i and $i+1$, respectively.

The fundamental and the hth harmonic currents of the nonlinear load at bus i with the fundamental active power $P_{nl,i}$ and the fundamental reactive power $Q_{nl,i}$ are [1, 30]:

$$I_{nl,i}^{(1)} = \left[\frac{P_{nl,i} + jQ_{nl,i}}{V_i^{(1)}}\right]^* \tag{33}$$

$$I_{nl,i}^{(h)} = C(h)I_{nl,i}^{(1)} \tag{34}$$

where $I_{nl,i}^{(1)}$ and $I_{nl,i}^{(h)}$ are the fundamental and harmonic currents of the nonlinear load at bus i, respectively, and $C(h)$ is the ratio of the hth harmonic current to its fundamental value.

After the formation of the bus admittance matrix and calculation of the current vector, the harmonic voltages can be found using Eq. (22). Once the harmonic voltages have been determined, the RMS bus voltages and THD_V levels can be calculated.

Active power losses in the line between buses i and $i+1$ for the harmonic order h are [30]:

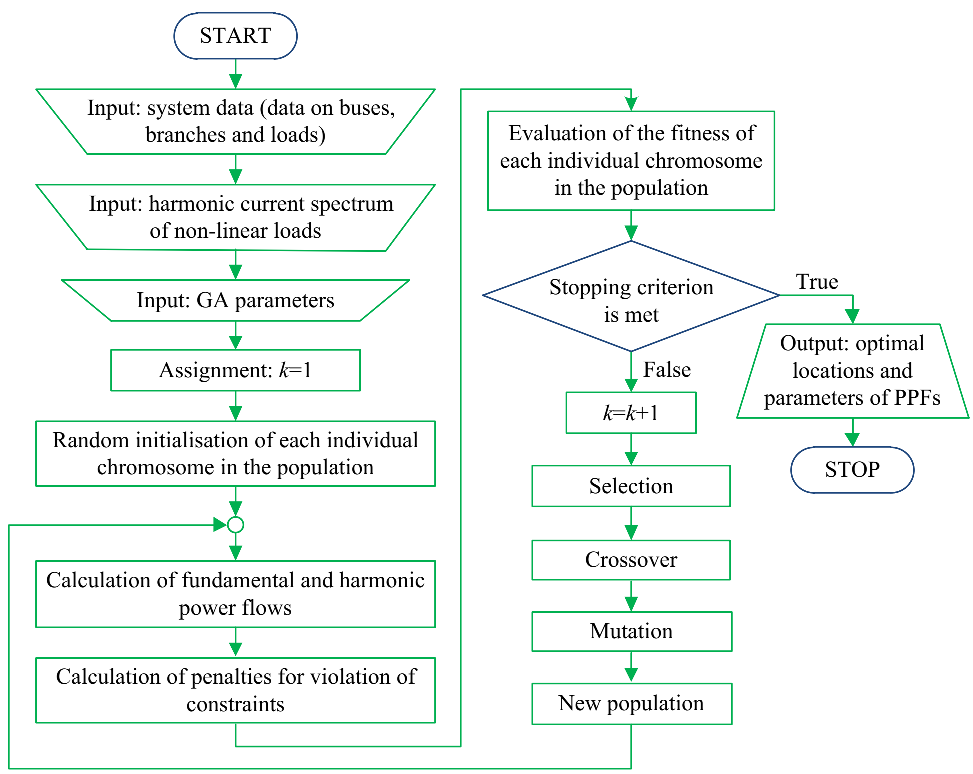

Fig. 1 Flowchart illustrating the GA-based approach to optimise the locations and parameters of PPFs

Table 1 Parameters of the GA

Number of generations	300	
Population size	200	
Tournament size	4	
Crossover ratio	1.4	
Mutation function	Adaptive feasible	
Ending conditions	Maximum number of iterations allowed	300
	Termination tolerance on the function value	10^{-6}

$$P^{(h)}_{\text{loss}(i,i+1)} = R_{i,i+1}\left(\left|V_i^{(h)} - V_{i+1}^{(h)}\right|\left|y_{i,i+1}^{(h)}\right|\right)^2 \tag{35}$$

At the end of the calculation, the total power losses of the system for all harmonics are determined using Eq. (18).

5 GA-based approach for the optimal design of PPFs

Finding the optimal parameters of PPFs using the GA for different objective functions was considered in [4]. The GA application begins with a random generation of the initial population representing the first set or group of chromosomes (i.e. individuals). As defined by Eq. (15), the chromosome used for the design of a PPF includes an array of real numbers which may represent its parameters. Each chromosome in the population represents a potential solution of the optimisation problem. The quality or fitness of a chromosome is usually calculated by means of an objective function, indicating how good the solution is for the optimisation problem. In this case, the calculation of the fitness is based on the power flow calculation at the fundamental frequency, as well as the harmonic power flow analysis performed using the DHPF algorithm. Therefore, the accuracy of the DHPF algorithm is necessary to ensure that the filter, which is being designed, will have the expected performance. If a solution violates any constraint, its fitness is penalised according to the importance of this constraint. Within each generation, new chromosomes are created using crossover and mutation genetic operators. Selection operator generates new population from the old population based on fitness values of the chromosomes, while tournament selection is used for selecting the chromosomes with best fitness values from the population. The selected chromosomes are then used to produce new population by the crossover operation. If stopping criterion is met, then the process ends, otherwise it is

Table 2 Optimal filter design for the IEEE 18-bus distorted radial distribution test system

Design parameters and objective function values	Optimisation problem								
	No filter	One filter				Two filters			
	Base case	Problem 1	Problem 2	Problem 3	Problem 4	Problem 1	Problem 2	Problem 3	Problem 4
Location, ℓ	–	7	8	7	7	5	8	5	3
						7	–	6	6
Size, Q_f (MVAr)	–	3.000	1.787	1.667	1.725	0.960	1.776	0.525	0.651
						2.039	–	0.289	0.899
Type, FT	–	2	2	2	2	1	2	1	2
						3	–	2	1
Tuned order, h_n	–	6.626	6.669	6.440	6.440	4.995	6.667	4.999	7.252
						10.120	–	7.041	5.064
Quality factor, Q	–	10.000	97.980	10.385	29.024	99.645	66.262	100.00	99.997
						0.987	–	99.845	99.975
Resistance, R (Ω)	–	0.804	0.137	1.436	0.497	0.341	0.204	0.620	0.337
						7.547	–	0.785	0.357
Inductance, L (mH)	–	3.864	6.402	7.372	7.124	21.632	6.445	39.489	14.808
						2.405	–	35.429	22.449
Capacitance, C (μF)	–	59.723	35.586	33.141	34.294	18.773	35.366	10.267	13.010
						41.133	–	5.769	17.600
Max. THD_V (%)	7.277	**2.912**	4.361	4.170	**4.228**	**2.132**	4.369	3.094	**2.991**
Max. IHD_V (%)	6.086	1.838	3.000	2.999	3.000	1.824	3.000	1.880	1.768
Max. V_{RMS} (p.u.)	1.055	1.093	1.071	1.070	1.070	1.090	1.071	1.062	1.069
Min. V_{RMS} (p.u.)	1.029	1.050	1.050	1.050	1.050	1.050	1.050	1.041	1.050
$P^{(h)}_{loss}$ (kW)	277.10	305.55	284.78	**274.74**	**275.21**	289.22	284.49	**259.89**	**261.93**
Costs (p.u.)	–	135.06	**91.07**	95.57	**92.45**	231.36	**91.08**	264.15	**176.50**

repeated. The stopping criterion may include the maximum number of iterations (generations), or a termination tolerance on the function value. The flowchart in Fig. 1 illustrates the proposed GA-based approach to optimising the locations and parameters of PPFs. The GA parameters used are listed in Table 1.

6 Results and discussion

The proposed GA-based approach to solve the passive filter design problem was evaluated using the IEEE 18- and 33-bus distorted radial distribution test systems. The approach was implemented in MATLAB 2017b computing environment. All simulation data were obtained using a PC

Table 3 A comparison of the results obtained by the proposed GA-based approach, ETAP programme, PSO algorithm and eight other algorithms for the optimisation Problem 1

Number of filters	Approach, algorithm or programme	ℓ	Q_f (MVAr)	FT	h_n	Q	Max. THD_V (%)	Max. IHD_V (%)	R (Ω)	L (mH)	C (μF)
No filter	PSO [14]	–	–	–	–	–	7.458	6.078	–	–	–
	GA-based	–	–	–	–	–	7.277	6.086	–	–	–
	ETAP	–	–	–	–	–	7.28	6.09	–	–	–
One filter	PSO [14]						3.138	2.835			
	GA-based*	8	3.073	3	10.12	2	3.077	2.767	10.147	1.596	61.997
	ETAP*						3.08	2.77			
	GA-based	7	3	2	6.626	10	**2.912**	1.838	0.804	3.864	59.723
	ETAP**						2.91	1.84			
	ABC	7	3	2	6.626	10	2.912	1.838	0.804	3.864	59.723
	BBO	7	2.714	2	6.448	10.782	3.067	1.861	0.849	4.516	53.959
	BSA	7	3	2	6.625	10	2.912	1.838	0.804	3.865	59.723
	GSA	7	2.906	2	6.443	17.353	2.969	1.86	0.493	4.225	57.77
	GWO	7	3	2	6.625	10	2.912	1.838	0.804	3.865	59.723
	ICA	7	3	2	6.626	10	2.912	1.838	0.804	3.864	59.723
	WDO	7	3	2	6.629	10.089	2.913	1.838	0.797	3.861	59.725
	GA-PSO	7	3	2	6.626	10	2.912	1.838	0.804	3.864	59.723
Two filters	PSO [14]						1.912	1.631			
	GA-based*	7	1.5	2	7.252	30	4.013	3.671	0.488	6.427	29.977
	ETAP*	6	1.047	3	11.396	2	4	3.68	26.388	3.685	21.17
	GA-based	5	0.96	1	4.995	99.645	**2.132**	1.824	0.341	21.632	18.773
	ETAP**	7	2.039	3	10.12	0.987	2.14	1.83	7.547	2.405	41.133
	ABC	7	1.674	2	6.687	11.737	2.662	2.36	1.216	6.796	33.34
		8	1.309	3	10.169	1.373			16.273	3.71	26.409
	BBO	6	1.299	1	5.104	89.252	2.814	1.85	0.275	15.284	25.447
		7	1.559	2	7.165	13.833			1.031	6.338	31.141
	BSA	5	0.702	1	4.998	100	2.137	1.779	0.464	29.56	13.72
		7	2.037	3	10.12	1.008			7.718	2.407	41.096
	GSA	7	1.572	2	6.763	14.752	2.706	2.464	1.019	7.072	31.324
		8	1.425	3	10.276	1.278			13.767	3.337	28.755
	GWO	5	0.93	1	4.998	36.564	2.14	1.789	0.958	22.302	18.187
		7	2.049	3	10.12	1.026			7.807	2.393	41.334
	ICA	5	0.964	1	4.993	100	2.133	1.825	0.338	21.56	18.851
		7	2.034	3	10.12	0.999			7.658	2.411	41.032
	WDO	7	2.402	2	6.577	31.896	2.504	2.024	0.317	4.9	47.802
		8	0.597	3	11.021	0.981			23.49	6.916	12.062
	GA-PSO	5	0.818	1	4.996	100	2.133	1.815	0.398	25.378	15.995
		7	2.001	3	10.12	1.029			8.022	2.452	40.355

*Results obtained using parameters from [14]

**Results obtained using parameters generated by the proposed GA-based approach with a CPU at 2.70 GHz and 8.0 GB RAM. In order to demonstrate the effectiveness, robustness and high quality of the proposed GA-based approach, the four different objective functions (Problems 1–4) were considered. For each problem under consideration, a sequence of ten consecutive tests was performed, and the results presented here represent the best values from each of the sequences. The calculations included harmonics up to the 49th order.

6.1 Simulations on the IEEE 18-bus test system

Sixteen of the busses from the IEEE 18-bus test system are located in the 12.5 kV distribution system and two busses (51 and 50) are located on the 138 kV side of the transformer substation. The base voltage and base power for this system are 12.5 kV and 10 MVA, respectively. It is assumed that the substation voltage magnitude is 1.05 p.u. and that the substation voltage does not contain any harmonic component. The slack bus is effectively earthed for harmonics with a "harmonics-only sub-transient impedance" that equals $j0.01\%$. The system contains a three-phase six-pulse rectifier at bus 5. Active and reactive powers of this rectifier are 0.3 p.u. (3 MW) and 0.226 p.u. (2.26 MVAr), respectively. This rectifier, as a nonlinear load, generates non-triplen odd-order harmonic currents, i.e. the 5th, 7th, 11th, 13th, 17th,… order harmonics. Current harmonic injections are calculated as fractions of the fundamental component, applying the rule of $1/h$, in the following manner: the fifth harmonic current injection is 20% of the fundamental component, the seventh 14%, the eleventh 9% and so on. At the fundamental frequency, all loads are modelled with constant powers, while capacitor banks are modelled with constant admittances (impedances). More details on the IEEE 18-bus test system can be found in [33].

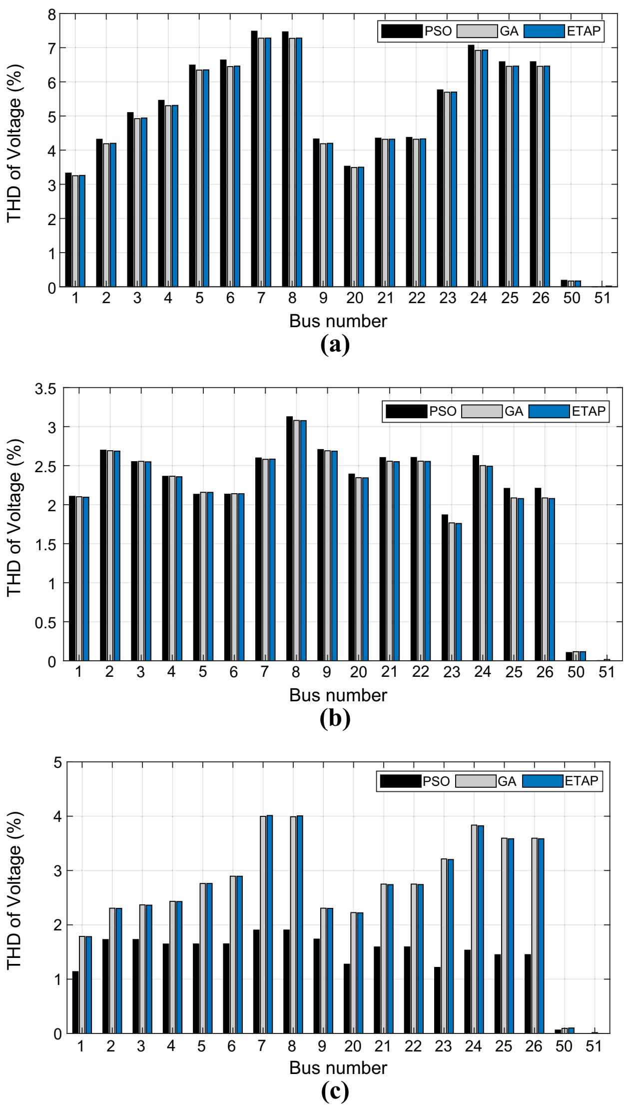

Fig. 2 Comparisons between the results obtained by the PSO algorithm, proposed GA-based approach and ETAP programme for **a** the base case, **b** Problem 1 with one filter that has parameters identical to the corresponding filter from [14], and **c** Problem 1 with two filters which have parameters identical to the corresponding filters from [14]

The problem of designing the filter parameters was considered on the IEEE 18-bus test system with one filter and with two filters, and the results obtained were then compared to those generated in case when there are no filters in the given test system. For each filter, the size is set between 0 and 3 MVAr. It is also assumed that the system's upper limit of the total fundamental reactive power supplied by filters equals 3 MVAr. Table 2 shows the optimal settings of the filter parameters and objective function values. In addition, Table 2 contains the maximum and minimum values of calculated bus voltage magnitudes (min. V_{RMS} and max. V_{RMS}) as well as maximum IHD_V. The best objective function values for the considered optimisation problems are highlighted in bold.

As can be seen from Table 2, in relation to the base case, the maximum THD_V level in Problem 1 can be reduced from 7.277 to 2.912% if one single-tuned filter is installed at bus 7 and if the tuned harmonic order is 6.626. This means, the maximum THD_V level is reduced by 59.98% and the total active power losses are increased by 10.27%. A further reduction in the THD_V is possible if two passive filters are installed instead of one, but this solution requires higher initial investment costs.

In Problem 2 with one filter, the optimal filter design has the lowest initial investment costs. Moreover, almost the same results are obtained for Problem 2 with two filters. The total active power losses in the distribution system without filters amount to 277.1 kW and can be reduced to a minimum of 259.89 kW if two filters are used, as in Problem 3. It is clear that the optimal design of passive harmonic filters, in addition to the suppression of harmonics, can lead to a significant reduction in losses in the whole distribution system. In Problem 4, the objective function maintains a balance

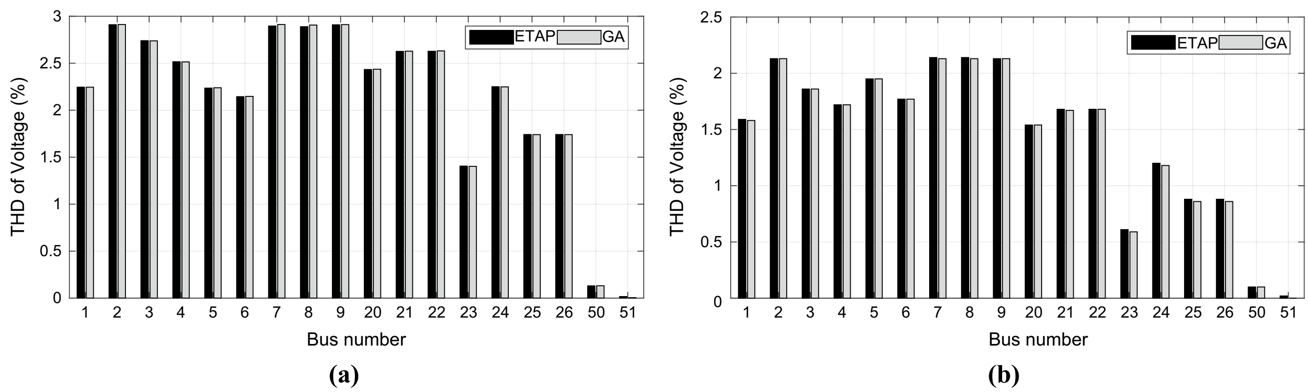

Fig. 3 Comparisons between the results obtained by the ETAP programme and proposed GA-based approach for **a** Problem 1 with one filter, and **b** Problem 1 with two filters, where the filters' parameters are generated by the GA-based approach

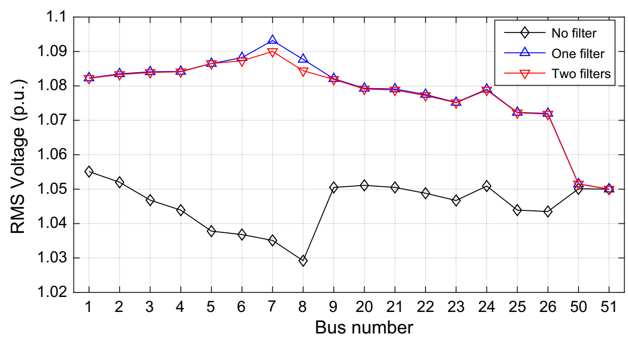

Fig. 4 Voltage profiles of the IEEE 18-bus test system with and without PPFs

between the three objectives such that one objective does not tend to dominate the others. The best compromise solution corresponds to Problem 4 with one filter (maximum THD_V level of 4.228%, total active power losses of 275.21 kW and initial investment costs of 92.45 p.u.). In comparison with the base case, the best compromise solution shows a reduction of 41.9% in the maximum THD_V level and a reduction of 0.68% in the total active power losses.

In this subsection, for almost all optimisation problems, it is assumed that the weighting factors w_{cost} and w_{loss} are equal to 0.05 and 0.1, respectively. These values are carefully selected after a number of simulation experiments. In Problem 4 with two filters, the total active power losses and maximum THD_V are reduced by 5.47% and 58.9%, respectively. However, only in this case, the values of w_{cost} and

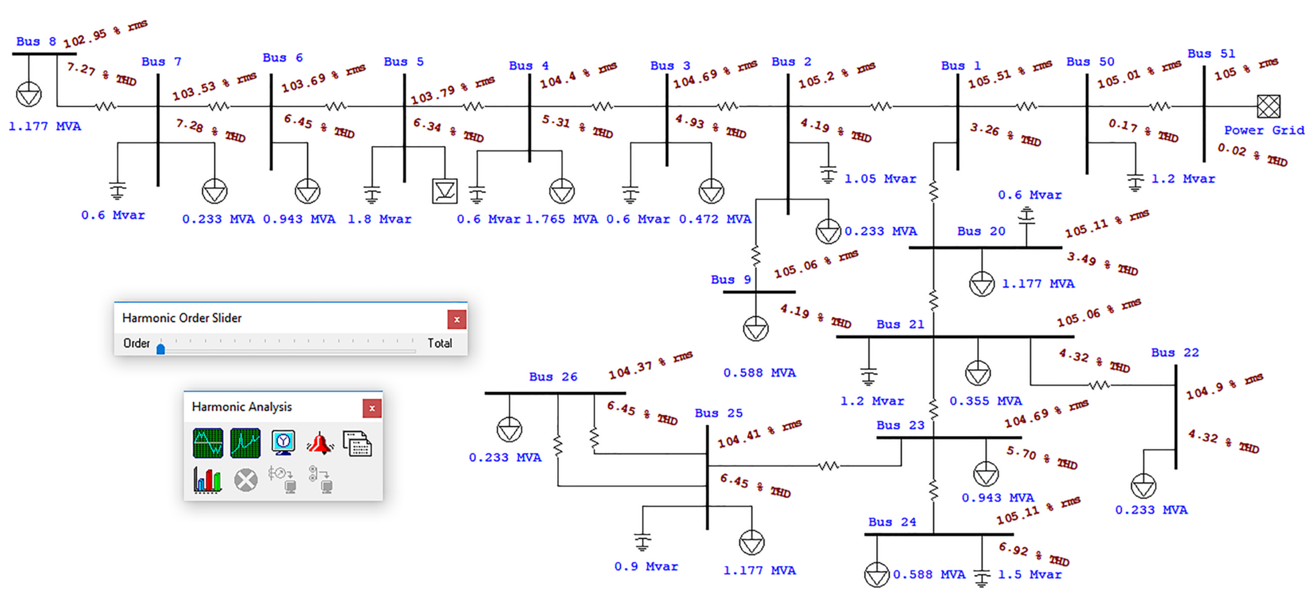

Fig. 5 ETAP simulation result obtained for the IEEE 18-bus test system in the case without filters (i.e. the base case)

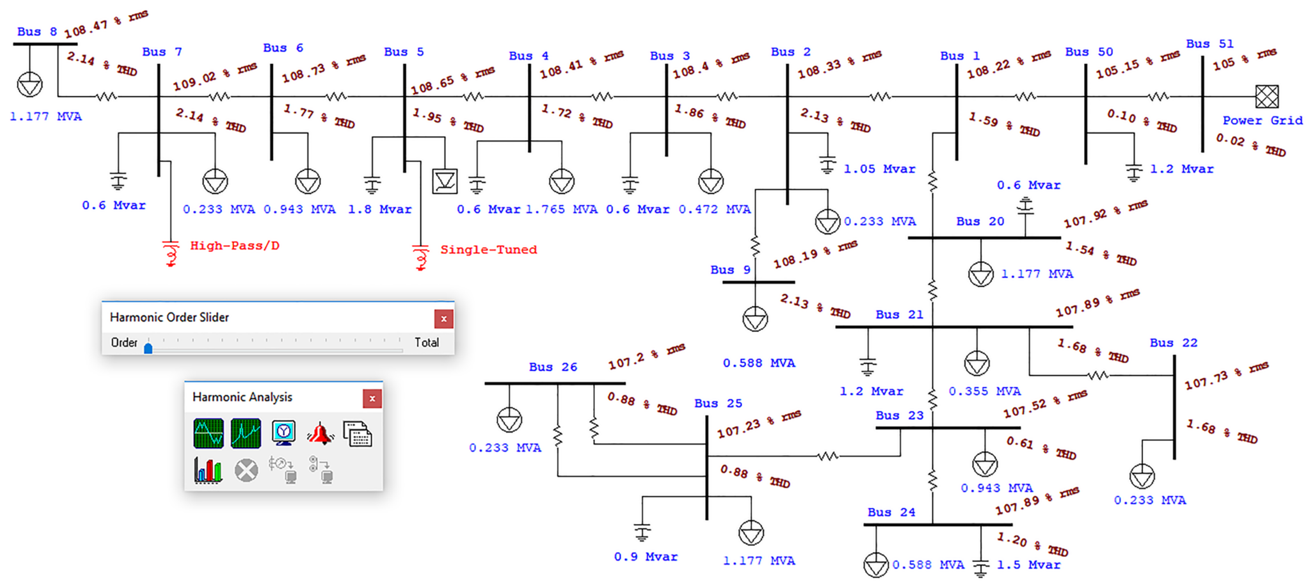

Fig. 6 ETAP simulation result obtained for the IEEE 18-bus test system in the case of Problem 1 with two filters

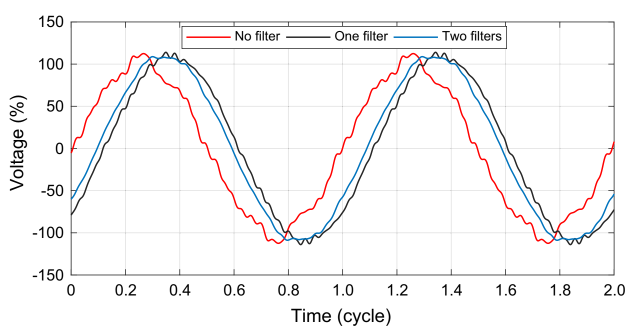

Fig. 7 Voltage waveforms at bus 7 before and after placement of filters

w_{loss} were 0.05 and 0.5, respectively. From Table 2, it can also be observed that the maximum and minimum values of calculated bus voltage magnitudes and maximum IHD_V meet the limits defined in the IEEE-519 standard.

In order to examine the validity and performance of the proposed approach for the optimisation Problem 1, the fitness values of the maximum THD_V, and the levels of the maximum IHD_V generated by the ETAP programme, PSO algorithm and eight other widely used optimisation algorithms (which are listed in Introduction) against the corresponding values generated by the GA-based approach are presented in Table 3.

Parameters of different algorithms used for the simulations are adopted as follows: for the ABC, the number of food sources, as well as the number of employed bees is equal to half of the colony population size, and the predetermined number of cycles called "limit" is set to 50; for the BBO, the migration probability is set to 1, the mutation probability is set to 0.04, the maximum immigration and emigration rates for each island are set to 1, and the elite number is set to 2; for the GSA, the initial value of the gravitational constant is set to 100, and the user-specified constant (α) is set to 20; for the ICA, the number of initial imperialists is set to 20, the revolution rate is set to 0.3, assimilation coefficient (β) is set to 2, the assimilation angle coefficient (θ) is set to 0.5, the ζ coefficient is set to 0.02, and the uniting threshold which enables the uniting process of two empires is set to 0.02; for the WDO, the *RT* coefficient is set to 1, the gravitational constant is set to 0.2, the maximum allowed speed is set to 0.3, and the Coriolis effect is set to 0.4; for the hybrid GA-PSO, the acceleration constants c_1 and c_2 are set to 2, the inertia weight factor w decreases linearly from 0.9 to 0.4, the crossover probability is set to 90%, and the mutation probability is set to 5%. The control parameters of the GWO algorithm are the maximum number of iterations/generations and number of search agents, while unlike other search algorithms used by the authors, the BSA has a single control parameter, the maximum number of cycles (iterations).

The same population size (200) and the same maximum number of iterations (300) are used for the ABC, BBO, BSA, GSA, GWO, ICA, WDO and GA-PSO algorithms. The results obtained by the algorithm ensuring the best performance are indicated in bold print. The eighth column of Table 3 shows that the results obtained by the GA-based approach are better than those obtained by the PSO and eight other optimisation algorithms. Figure 2 presents the results obtained by the PSO algorithm and ETAP programme against the results generated by the GA-based approach, while Fig. 3 presents the results obtained by the ETAP programme against the results generated by the GA-based approach.

The principal reason for making comparisons in Fig. 3 is to demonstrate the accuracy of the DHPF method which was used to estimate the fitness values for the considered optimisation problem. Figure 3a, b shows a very high degree of consistency between the results obtained by the ETAP programme and proposed GA-based approach. In addition, Fig. 2a, b, as well as Table 3, indicate that the results generated by the proposed GA-based approach and ETAP programme for the base case and Problem 1 with one filter are almost identical to those reported in [14].

For Problem 1 with two filters, from the eighth column of Table 3, it can be observed that the PSO algorithm generates a significantly lower level of the maximum THD_V than the GA-based approach or ETAP programme. In order to check this, the authors performed the calculation of the harmonic power flow with the filters' parameters identical to the ones used in [14]. The accurate simulation results for Problem 1 with two filters are shown in Fig. 2c, while the two corresponding maximum THD_V levels are given in Table 3. According to these simulation results, the corresponding result from [14] can be considered incorrect. The optimal solutions of Problem 1 with one filter and with two filters, obtained by the GA-based approach, are shown in Fig. 3a, b, respectively. From Figs. 2a and 3a, b, it is clear that the optimal choice of filter location, size and other filter parameters helps in improving the power quality in the whole IEEE 18-bus test system. The corresponding voltage profiles are shown in Fig. 4.

The results obtained by the Harmonic Analysis module of the ETAP programme for the base case and Problem 1 with two filters, in the case when the filters' parameters are generated by the GA-based approach, are shown in Figs. 5 and 6, respectively. In addition, Fig. 7 illustrates the voltage waveforms at the most distorted bus of the system (i.e. at bus 7) before and after installation of the filters. The results in Fig. 7 confirmed the expected improvement of the voltage waveforms after installation of one filter and two filters.

6.2 Simulations on the IEEE 33-bus test system

The IEEE 33-bus test system is a 12.66 kV radial distribution system having the three-phase short-circuit power of 500 MVA. According to the IEC 60076-5 standard [17], the

Table 4 Optimal filter design for the IEEE 33-bus distorted radial distribution test system

Design parameters and objective function values	Optimisation problem								
	No filter	One filter				Two filters			
	Base case	Problem 1	Problem 2	Problem 3	Problem 4	Problem 1	Problem 2	Problem 3	Problem 4
Location, ℓ	–	8	15	9	12	12	15	12	12
						23	–	29	29
Size, Q_f (MVAr)	–	3	0.889	1.582	1.254	2.072	0.888	0.954	1.061
						0.928	–	1.275	1.131
Type, FT	–	3	2	2	2	3	2	1	2
						3	–	3	2
Tuned order, h_n	–	10.12	7.252	6.44	7.252	10.406	7.252	5.18	7.252
						11.034	–	11.392	7.252
Quality factor, Q	–	0.684	100	100	100	1.465	99.98	100	99.814
						0.588	–	2	99.938
Resistance, R (Ω)	–	3.647	0.253	0.161	0.18	10.992	0.254	0.337	0.213
						9.28	–	22.241	0.199
Inductance, L (mH)	–	1.677	11.123	7.968	7.886	2.295	11.136	20.702	9.32
						4.553	–	3.107	8.743
Capacitance, C (μF)	–	58.999	17.32	30.661	24.431	40.77	17.3	18.24	20.671
						18.279	–	25.127	22.035
Max. THD_V (%)	8.802	**3.355**	4.606	4.621	**3.645**	**2.044**	4.606	4.317	**3.587**
Max. IHD_V (%)	2.817	1.555	2.741	1.293	2.415	1.905	2.741	1.192	2.29
Max. V_{RMS} (p.u.)	1	1	1	1	1	1	1	1	1
Min. V_{RMS} (p.u.)	0.874	0.928	0.906	0.908	0.91	0.921	0.906	0.913	0.915
$P_{loss}^{(h)}$ (kW)	371.24	334.63	310.39	**293.88**	**295.24**	309.81	310.39	**250.08**	**252.82**
Costs (p.u.)	–	141.26	**69.27**	86.03	**73.42**	240	**69.28**	271.05	**141.66**

power of 500 MVA represents a typical short-circuit power for rated voltages from 7.2 to 24 kV. If this power is not given, then the following applies: the short-circuit power is infinite, "harmonics-only sub-transient impedance" is zero, and there is no harmonic distortion of voltage at the slack bus (i.e. $THD_V = 0$). The base voltage is 12.66 kV, and the base power is 10 MVA. The ratio of reactance-to-resistance is 10, and the substation voltage magnitude is assumed to be 1.0 p.u. In addition, the system contains two three-phase six-pulse rectifiers at buses 12 and 24. Active and reactive powers of these rectifiers are 480 kW and 360 kVAr, respectively. More details on this test system are available in [34].

In this subsection, as in the previous one, four different objective functions were considered taking into account

Table 5 A comparison of the results obtained by the proposed GA-based approach, ETAP programme, PSO algorithm and eight other algorithms for the optimisation Problem 1

Number of filters	Approach, algorithm or programme	ℓ	Q_f (MVAr)	FT	h_n	Q	Max. THD_V (%)	Max. IHD_V (%)	R (Ω)	L (mH)	C (μF)
No filter	PSO [14]	–	–	–	–	–	9.676	5.397	–	–	–
	GA-based	–	–	–	–	–	8.802	2.817	–	–	–
	ETAP	–	–	–	–	–	8.79	2.82	–	–	–
One filter	PSO [14]						3.417	2.179			
	GA-based*	8	2.64	3	11.396	0.01	4.054	3.037	0.054	1.499	52.027
	ETAP*						4.07	3.02			
	GA-based	8	3	3	10.12	0.684	**3.355**	1.555	3.647	1.677	58.999
	ETAP**						3.4	1.54			
	ABC	8	3	3	10.12	0.684	3.355	1.555	3.647	1.677	58.999
	BBO	10	2.309	3	11.383	0.505	3.377	2.264	3.103	1.718	45.503
	BSA	8	3	3	10.12	0.684	3.355	1.555	3.647	1.677	58.999
	GSA	9	2.344	3	11.396	0.5	3.374	2.25	3.023	1.689	46.194
	GWO	8	3	3	10.12	0.684	3.355	1.555	3.647	1.677	58.999
	ICA	8	3	3	10.12	0.626	3.356	1.582	3.338	1.677	58.999
	WDO	9	2.337	3	11.394	0.5	3.374	2.261	3.033	1.695	46.056
	GA-PSO	8	3	3	10.12	0.684	3.355	1.555	3.647	1.677	58.999
Two filters	PSO [14]	10	1.5	2	6.605	78.499	0.593	0.471	0.211	7.979	29.107
	GA-based*	24	1.457	2	7.083	69.734	4.422	2.265	0.227	7.123	28.359
	ETAP*						4.41	2.22			
	GA-based	12	2.072	3	10.406	1.465	**2.044**	1.905	10.992	2.295	40.77
	ETAP**	23	0.928	3	11.034	0.588	2.05	1.9	9.28	4.553	18.279
	ABC	13	2.036	3	11.396	0.5	2.099	1.933	3.481	1.944	40.124
		23	0.961	3	10.974	0.572			8.766	4.445	18.927
	BBO	12	1.863	2	7.25	10.521	2.183	1.478	1.15	5.311	36.296
		24	1.132	3	10.129	1.195			16.868	4.436	22.263
	BSA	12	1.93	2	7.252	95.023	2.113	1.361	0.123	5.124	37.601
		23	1.065	3	10.747	0.5			7.063	4.184	20.968
	GSA	13	1.911	3	11.329	2	2.164	1.91	14.923	2.096	37.657
		23	0.85	3	10.283	0.533			9.867	5.73	16.721
	GWO	13	1.846	3	10.27	1.196	2.068	1.928	10.208	2.645	36.314
		23	1.153	3	10.12	0.553			7.671	4.363	22.675
	ICA	12	2.007	3	10.937	1.844	2.219	2.076	13.578	2.143	39.526
		24	0.43	3	11.396	1.655			54.551	9.207	8.474
	WDO	12	2.076	3	10.942	1.688	2.103	1.967	12.01	2.07	40.885
		23	0.924	3	10.766	0.935			15.197	4.805	18.192
	GA-PSO	12	2.075	3	10.594	1.663	2.055	1.917	12.234	2.211	40.835
		23	0.898	3	11.004	0.604			9.875	4.731	17.687

*Results obtained using parameters from [14]

**Results obtained using parameters generated by the proposed GA-based approach one filter design and two filters design. Similarly as in [14], each filter has a size between 0 and 3 MVAr. The system's upper limit of the total fundamental reactive power supplied by filters (Q_{total}^{max}) is set to 3 MVAr. The optimal settings of the filter parameters are listed in Table 4. It is clear from Table 4 compared to the base case that one passive filter design can reduce the maximum THD_V level from 8.802 to 3.355% if one high-pass filter is installed at bus 8 and if the tuned harmonic order is 10.12. This relates to the optimisation Problem 1. A further reduction in the THD_V from 3.355 to 2.044% is possible if two high-pass filters are installed at buses 12 and 23. This also reduces the total active power losses $P_{loss}^{(h)}$ from 334.63 to 309.81 kW.

In Problem 2 with one filter or with two filters, the optimal filter design has the lowest initial investment costs. The lowest value of the total active power losses $P_{loss}^{(h)}$ is obtained for Problem 3 with two filters. By comparison with the base case, it appears that the power losses $P_{loss}^{(h)}$ are significantly reduced in the case of Problems 3 and 4 with two filters. As in the case of Table 2, the best compromise solution corresponds to Problem 4 with one filter. Accordingly, the best compromise solution is the following: the maximum THD_V level of 3.645%, $P_{loss}^{(h)}$ of 295.24 kW and initial investment costs of 73.42 p.u. Compared to the base case, this solution provides reductions of 58.59% and 20.47% in the maximum THD_V and $P_{loss}^{(h)}$, respectively. In Problem 4 with two filters, the power losses $P_{loss}^{(h)}$ and maximum THD_V are reduced by about 32% and 59%, respectively. Also, it is assumed for all optimisation problems that the weighting factors w_{cost} and w_{loss} are equal to 0.05 and 0.1, respectively. From Table 4, it is evident that the maximum and minimum values of calculated bus voltage magnitudes and the maximum IHD_V level meet the limits of the IEEE-519 standard.

Table 5 shows the results obtained by the GA-based approach, ETAP programme, PSO algorithm and eight other algorithms for the optimisation Problem 1. These results are generated for the system data, constraints on control variables, and other constraints identical to those used for Problem 1 from Table 4. The best results in terms of performance are indicated in bold type.

As can be seen from Table 5, the results reported in [14] differ significantly from those obtained by the GA-based approach and ETAP programme. The main reason for such deviations from the results presented here could be modelling that was not in accordance with recommended rules, an error in data entry or an error due to neglecting the presence of a load. In addition, according to [14], the THD_V level at the slack bus is over 7%. This suggests that there is something wrong with the results from [14]. On the other hand, it is also evident from Table 5 that there is a high degree of compatibility between the results obtained by the GA-based approach, and the results generated by the ETAP programme. This observation is also illustrated by the bar chart in Fig. 8.

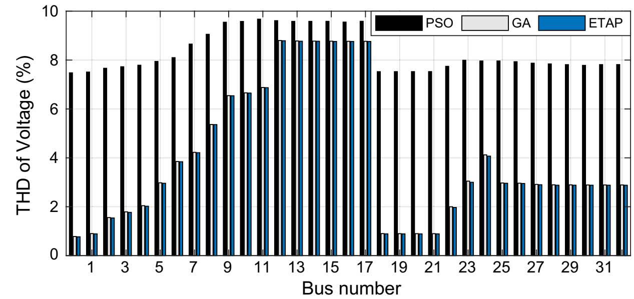

Fig. 8 Comparison of the THD_V levels obtained by the PSO algorithm, proposed GA-based approach and ETAP programme for the base case

Comparisons between the THD_V levels and between the corresponding voltage profiles at buses of the IEEE 33-bus test system (with no filter, with one filter and with two filters) are shown in Fig. 9a, b, respectively. The results obtained by the ETAP programme for Problem 1 with two filters, in the case when the filters' parameters are generated by the GA-based approach, are presented in Fig. 10.

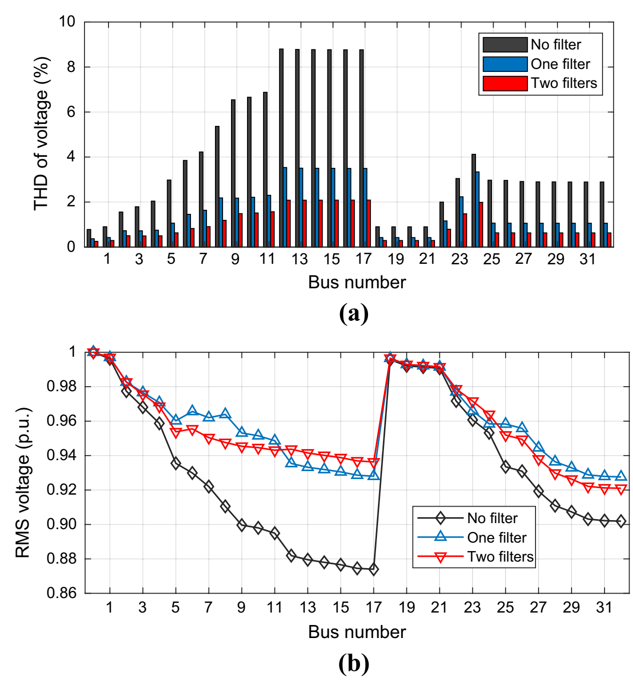

Fig. 9 Comparisons **a** between the THD_V levels and **b** between the voltage profiles of the IEEE 33-bus test system with and without PPFs

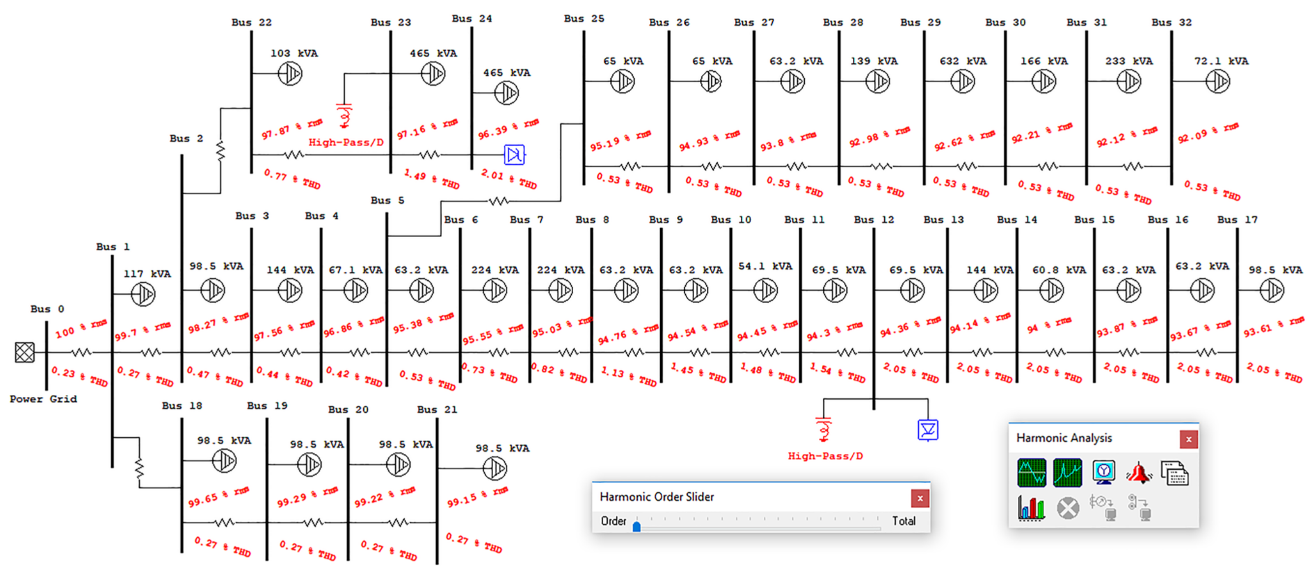

Fig. 10 ETAP simulation result obtained for the IEEE 33-bus test system in the case of Problem 1 with two filters

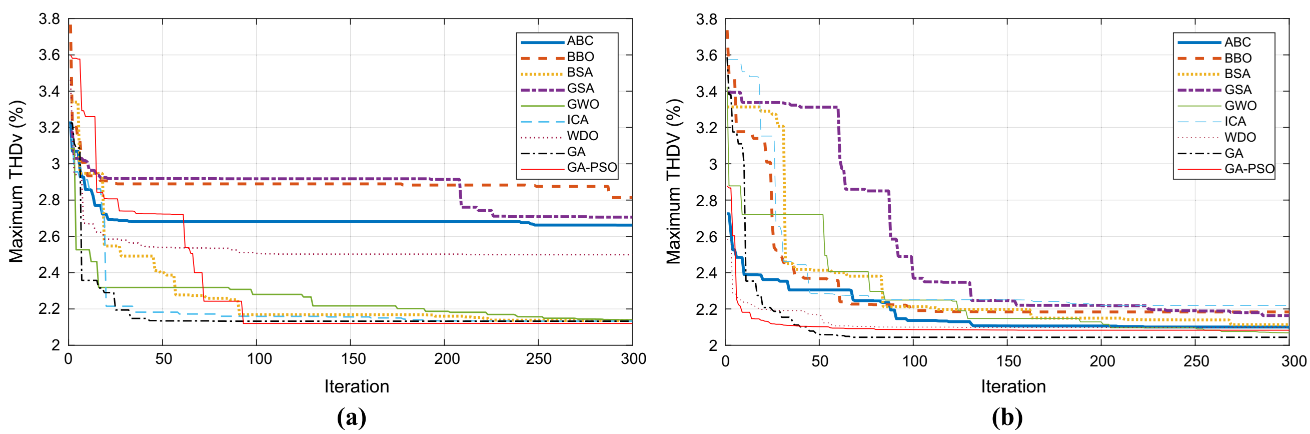

Fig. 11 Convergence profiles of different optimisation algorithms in the case of minimisation of the maximum THD_V for **a** the IEEE 18-bus test system, and **b** the IEEE 33-bus test system

6.3 Convergence profiles

Comparisons of convergence profiles of all the algorithms used to minimise the maximum THD_V for the IEEE 18- and 33-bus test systems with two filters are presented in Fig. 11a, b, respectively. It is clear that the proposed GA-based approach can converge to its global optimal solutions after lower numbers of iterations compared to other algorithms used by the authors. From the aspect of running, the running time of the GA-based approach is slightly longer. The average running time of the GA-based approach in the cases of the IEEE 18- and 33-bus test systems was about 8 and about 10 min in each run, respectively.

7 Conclusions

The main conclusions arising from the results and discussion are as follows:

- The results obtained using the proposed GA-based approach are in accordance with the considered objective functions, and all the specified constraints are met.
- By comparing the results obtained using the GA-based approach with those obtained using eight other optimisation algorithms (i.e. using the ABC, BBO, BSA, GSA, GWO, ICA, WDO and GA-PSO algorithms), it is found that the GA-based approach provides effective, robust and high-quality solutions.

- The accuracy and efficiency of the GA-based approach that employs the DHPF method are successfully verified using the ETAP programme, and well illustrated by its applications to the standard IEEE 18- and 33-bus test systems.
- The differences between the maximum THD_V levels obtained by the GA-based approach and those using the ETAP program are lower than 1.5%.
- It is found that some of the results reported in [14] do not comply with the relevant IEEE standard.
- Regardless of the form of the objective function, the proposed GA-based approach can be quickly and easily applied to any other distribution system with linear or/and nonlinear loads.
- The average running time of the GA-based approach that employs the DHPF method was lower than 10 min in each run.

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