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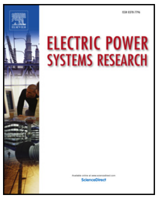

NSGAII optimization for single phase passive filter allocation in distribution systems

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ABSTRACT

This work presents a methodology for passive filter allocation within an electrical distribution system aiming to minimize the number of nodes that exceed harmonic distortion limits and investment costs. Harmonic distortions are usually mitigated by filters, but their allocation in the system requires attention. Depending on the filters location, harmonic distortion could increase at other nodes. The methodology of this study is based on harmonic flow simulation in the Alternative Transient Program (ATP/EMTP) as well as the NSGA II optimization algorithm simulated on Matrix Laboratory (MATLAB). The filters are located using single-phase units, in order to obtain solutions for unbalanced distribution systems with single-phase and two-phase circuits, while also attending features of single-phase inverter connected Distributed Generation (DG). Different scenarios are generated by MATLAB and simulated on ATP. The optimization problem is non-linear and multi-objective. One objective is to minimize the number of nodes exceeding distortion limits and the other is to minimize filter costs. The results show that the optimal installation of single-phase filters gives better results than the installation of three-phase filters at the critical nodes. The proposed methodology allows the user to choose the best option between the number of nodes exceeding limits and the investment cost.

1. Introduction

In distribution systems, harmonic distortion causes problems such as reduction of lifespan of devices and malfunction of protection systems. To reduce or mitigate harmonic distortion, the use of active or passive filters is common. Active filters work well, but they are more costly than passive filters, which are efficient to mitigate selected harmonics in addition to providing reactive power to the system at the fundamental frequency [1].

For a successful outcome in the whole distribution system, the installation of the filters must be preceded by a study. It is possible that harmonic distortion increases when filters are located at certain nodes due to changes in harmonic current flow [2].

The approach chosen for filter topology and allocation is justified both for the unbalanced three-phase configuration of distribution systems and the increase of single-phase inverter connected distributed generation by residential consumers. Often distributed generation such as small PV is single phase connected. Therefore, system voltages and harmonics are unbalanced.

Nowadays the challenge is to implement the suggested methodologies to improve power quality, because there is a strong opposition from utility companies and industries due to several factors, such as complex planning studies, high cost and unpredictable long-term performance. The proposal presented in this paper is focused on the filters` location, rather than on their design, since quite a lot of research on filter design [3] already has been conducted.

2. Background of the study

Previous research related to this subject proposed methods to

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Abbreviations: ATP, Alternative Transient Program; GA, Genetic Algorithm; IEEE, Institute of Electrical and Electronics Engineers; IHD, individual harmonic distortion of voltage; MATLAB, Matrix Laboratory; NSGA II, Non-Dominated Sorting Genetic Algorithm II; PQ, power quality; THD, total harmonic distortion of voltage

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allocate filters in electrical systems. An optimization algorithm based on the golden-section search method for allocating three-phase passive filters, with the objective to minimize the Total Harmonic Distortion (THD) verified in a certain node while THD at other nodes of the system was kept below standard limits was proposed [2].

A harmonic distortion anticipation methodology was proposed in Ref. [4]. The objective functions are several combinations of the sum of THD and when the largest value is found, each node of this case is analyzed and the filter is allocated in the node that produces the largest THD in the system. In this study, only the 5th and 7th harmonics are assumed to be generated in the system. The authors used the Genetic Algorithm (GA) to search for the location of three-phase passive filters in a distribution system. Just a few harmonic orders were considered in the case study.

In Ref. [5], only some nodes were selected for three-phase passive filter allocation. The aim is to find the optimum value of each filter component in order to minimize the THD of each node of the distribution system, considering limits of total and individual harmonic distortion in each node. This study is quite complete, since each individual harmonic distortion is considered.

Two location criteria were suggested for the three-phase passive filters in Ref. [6]: the node with the maximum THD and the node where the largest reduction of the average THD of the system can occur. The nonlinear loads are modeled as sources of harmonic currents in each node of the system and by simulation the THD is obtained in each of the nodes. A study that includes two suggestions to solve the problem is valuable, since a utility or a consumer can also have two paths to follow. Thus, through testing and comparing each possibility, the best solution can be chosen.

A GA was used to determine parameters and locations of three-phase passive filter in a distribution system for residential consumers in Ref. [7]. The objective function of the optimization model was the cost of the filter and the constraints are based on the limits for THD introduced by the IEEE Std. 519.

In Ref. [8] the objective was to minimize simultaneously the cost of the three-phase passive filter, power loss and the total harmonic distortion of currents and voltages in each node. Weights were assigned for each objective and a GA is used to find the optimal solution. By adjusting the weights adequately, different solutions are achieved and can be adapted depending on the priority. The same objective function can be used regardless of market changes or even when considering a different scenario during the filter planning, as long as the weights are adjusted adequately. An industrial system was analyzed, and passive filters were allocated.

According to Ref. [9], an analysis of the entire system with the allocated filters is necessary, simulating all possibilities of filter allocation. However, for large systems with a high number of filters, this alternative is not viable and consequently a GA was proposed. The objective was to minimize the average THD of the system. Although the minimum average THD is obtained, the THD may exceed the limits in some nodes. A 14-node test feeder was used, where several three-phase passive filters were located.

The installation of three-phase passive filters was suggested to improve the system PQ in Ref. [10]. The filters were supposed to reduce the THD in a node and to produce the largest impact on the overall system. Therefore, it was possible to verify the system sensitivity according to the location. The methodology of this study is called Harmonic Similarity (HS), which establishes a relationship between the distortions in the nodes. The case study is a balanced IEEE 13-node test feeder. The 5th, 7th, 11th, 13th and 17th harmonics were simulated by using PSCAD software. This research considered the total harmonic distortion limit in each node, but not the individual harmonic distortion limits.

An algorithm for three-phase passive filter allocation to minimize the maximum THD in the nodes was proposed in Ref. [11]. Type of filter, quality factor and filter tuning frequency were considered. Two types of filters were implemented: the tuning filter for the 5th and 7th harmonics and the high pass filter. The case study was conducted with IEEE 18-node and IEEE 33-node test feeders. The method used is the Particle Swarm Optimization (PSO), a method rarely used, since most studies in this area use the GA.

An optimization of the design and allocation of passive filters in distribution systems by using a multi-objective function is shown in Ref. [12]. The objective is to reduce power losses and harmonic distortions, according to European standard EN50160. The simulation requires the interaction of OpenDSS, Distributed Evolutionary Algorithms in Python and Python Parallel Global Multi-objective Optimizer. The simulation uses packages available in both software and the NSGA II and SPEA 2 algorithms. A 69-node test feeder with 5th and 7th harmonics is simulated. The co-simulation for designing and allocating filters was carried out using the Evolutionary Algorithms (EA). The Pareto frontier considering a set of possible solutions was presented. NSGA II showed better results in all cases to reduce THD and power losses.

A multi-objective model was presented in Ref. [13] aiming at maximizing annual savings and QEE improvement by allocating capacitors or passive filters in a distribution system. The methodology uses NSGA II and the objective functions are to maximize cost savings, minimize maximum voltage deviation, as well as to minimize maximum THD and maximum IHD respecting the limits of IEEE Std. 519/2014. According to the authors, during the optimization process to reduce only the maximum of each quality index causes the whole system to improve concomitantly. Two cases were used to test the methodology, a 69 nodes system and a 85 nodes system, the first case with 15 and the other with 25 types of compensators predefined to be allocated. Passive filters for harmonic mitigation are the 5th, 7th, 11th and 13th order. The results show the type, size, filter order and node to be allocated. The solutions are presented at the Pareto frontier and extra criteria are needed for the final decision among the options presented at the border.

The multi-objective grasshopper optimization algorithm (MOGOA) was applied in Ref. [14] where the goal is decreasing the THD by passive filters installation at minimizing the cost of filters. The optimization algorithm considers the parameters of tuned filters for 11th and 13th harmonic orders.

2.1. Research contributions

It is important to emphasize that the simulation of electrical power systems improves when more detailed and realistic the input data of the systems' models are. However, previous research [15] draws attention to the fact that harmonic mitigation has not been fully verified in a detailed distribution system model due to the complex structure and interaction among harmonic sources.

It is observed from the state-of-the-art review that often the solution is to simulate each filter allocation scenario, verifying the result. This approach is feasible in small electrical systems, but when the system is large, the complexity of the search space grows.

Compared to previous papers, the methodology presented in this paper proposes:

1 Detailed system representation: ATPDraw allows for a more detailed model of the system components. On ATPDraw, many models for each type of component are available. Besides that, a three-phase model of the system was used instead of a single-phase equivalent system. This choice is more appropriate for representing unbalanced distribution systems. More harmonics are included and harmonic components commonly found in distribution power systems are simulated. Moreover, harmonics generated by adjustable speed drives and fluorescent lights are considered. Harmonic orders from the 3rd to the 15th are simulated.

2 New approach to filter topology: single-phase passive filters are proposed. Single-phase passive filters in unbalanced three-phase systems are a novelty introduced in this paper. The examples of

allocation of single-phase filters found in literature review are restricted to active filters, most of which are limited to low-voltage systems.

3 Approach optimization: Although some previous papers propose multi-objective optimization, this paper includes an approach using the NSGA II, which considers improvements in the original GA and its successor NSGA. The NSGA II improves the complexity of non-dominated sorting, includes the elitism and excludes the requirement of shared parameters [20,21].

Approach for multi-objective formulation: the objective functions are developed to solve the harmonic problem considering the intrinsic characteristics in distribution networks. Other than shown in previous papers, in the present study the first objective function does not try to minimize THD, but rather minimizes the number of nodes that violate THD limits, because it is not always possible to maintain all nodes within limits with a feasible cost.

3. Harmonic distortion

Harmonic distortion estimation is the process of calculating the magnitudes and phases of each harmonic frequency. The Fourier Transform is one of the most used tools to obtain the harmonics of a non-sinusoidal periodic function [16].

3.1. Harmonic distortion indices

Individual Harmonic Distortion (IHD) is calculated by (1). The total harmonic distortion is calculated by (2), from IEEE Std. 519/1992 [17].

$$IHD = \frac{V_h}{V_1}.\ 100\% \tag{1}$$

$$THD_V = \frac{\sqrt{\sum_{h=2}^{h_{máx}=50} V_h^2}}{V_1}.\ 100\% \tag{2}$$

where V_h is the h-th harmonic voltage, V_1 is the fundamental frequency voltage and $h_{máx}$ the maximum harmonic order considered in the calculation.

3.2. Harmonic distortion limits

IEEE 519/2014 [18] and PRODIST Module 8/2016 [19] in Brazil established recommended and legal limits to IHD and THD. Tables 1 and 2 show the IHD and THD limits for different voltage levels [18,19].

Comparing the THD limits shown in both tables, it is possible to conclude that IEEE standard is stricter than PRODIST. On the other hand, IEEE standard is just a recommendation of limits whereas PRODIST has legal and financial consequences to the utility that violates the limits.

4. Proposed methodology

4.1. Modelling and simulation

The methodology begins with the modeling and simulation of a base case by using ATPDraw. Then the MATLAB is used to obtain the IHD and THD of each node, and the heuristic optimization with NSGA II is initialized. The NSGA II considers improvements in the original GA and its successor NSGA. The NSGA II improves the complexity of non-dominated sorting, includes elitism and excludes the requirement of shared parameters [20,21].

Table 1
IHD and THD limits (IEEE 519) [18].

Voltage	IHD (%)	THD (%)
V ≤ 1 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Table 2
THD limits (PRODIST) [19].

Voltage	THD (%)
V ≤ 1 kV	10.0
1 kV < V ≤ 13.8 kV	8.0
13.8 kV < V ≤ 69 kV	6.0
69 kV < V ≤ 230 kV	3.0

Modeling is a simplified way to represent the electrical characteristics of components, after which the behavior of the real systems is predicted by simulation and virtual modifications of their models [16,22,23].

For the system simulation, the ATPDraw program was used. This program performs time domain simulation, delivering current and voltage waveforms. Three-phase and single-phase circuits, transformers, nonlinear loads, motors and power sources were modeled for time domain simulation on ATPDraw as shown in Table 3, according to Refs. [16,23,24].

The harmonic flow is executed on ATPDraw. In this method, the nonlinear loads are represented as current sources connected to the system nodes. The current sources inject sinusoidal currents with harmonic frequencies. The harmonic voltages of the system nodes can be calculated by direct solution of the linear Eq. (3) [16].

$$[I_h] = [Y_h][V_h] \tag{3}$$

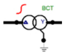
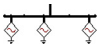
where $[I_h]$ is the vector of the node current injection of h-th harmonic, $[Y_h]$ is the system admittance matrix for the h-th harmonic and $[V_h]$ is the vector of the node voltages of h-th harmonic.

The equivalent circuit of the power transmission system connected at the substation is modeled as a three-phase connected as a wye-grounded AC voltage source. The short circuit impedance is modeled by series impedance. The transformer model used is the BCTRAN that accurately represents the transformer for harmonic frequency response. The feeder sections are modeled as series RL impedance and a shunt capacitance. All R, L and C parameters are considered lumped and constant due to the relative short length of distribution feeders. Passive linear loads are modeled as constant impedances. According to Ref. [24], constant impedance load model ensures accuracy equal to constant power load model. On the other hand, the nonlinear loads are modeled as current sources. Capacitors for reactive power compensation are modeled as a constant capacitor with the total value of the capacitance. Filters are modeled as constant RLC series impedance [26].

4.2. NSGA II optimization

NSGA II starts with the creation of an initial population, based on

Table 3
ATPDraw models.

Component	Model of ATPDraw
Source	
Transformer	
Feeder circuits	
Linear loads	
Nonlinear loads	
Capacitor bank	
Filters	

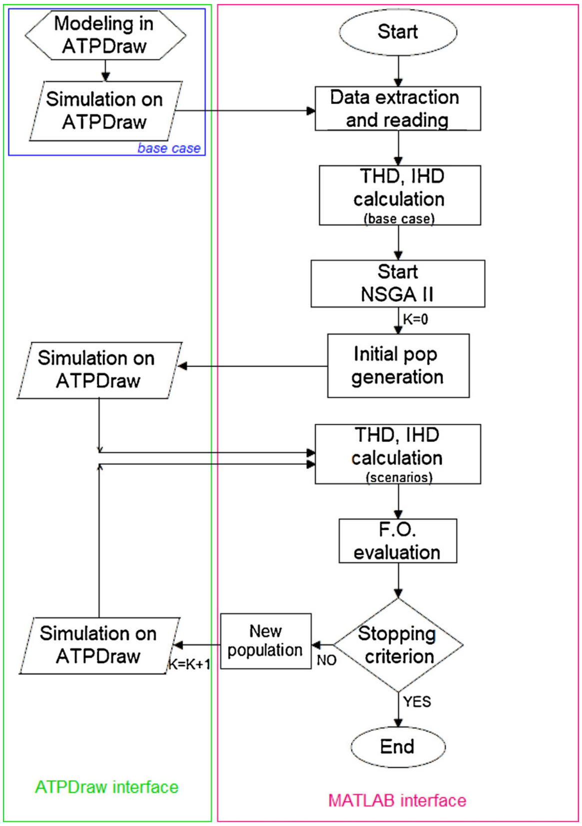


Fig. 1. Methodology flowchart.

the searching space. The greater the individual diversity, the better, because the algorithm will search for solutions through elitism, mutation and crossover [20]. Even so, for the initial population, a filter for the harmonic with the highest IHD is included. The initial IHD is calculated by the simulation of the base case.

Each individual corresponds to the scenarios of filters allocated in the system. That is, each individual is a chromosome composed by x genes, where x is three times the number of nodes due to the three possible phases for single-phase filter location.

ATPDraw simulates each individual and the node voltages are analyzed by MATLAB. So, during the search for the optimal result, the NSGA II will change the genes of the individuals in order to reduce the number of nodes whose THD violates the limits and to reduce the cost of the filters. The algorithm will stop when it reaches the maximum number of generations.

The flowchart of Fig. 1 shows the steps of this methodology. The two software interfaces are defined. A MATLAB program runs the optimization algorithm and a slave-simulator that modifies the ATPDraw reading card and brings the current and voltage signals to MATLAB environment. The way each software acts in the methodology will be explained in detail in the next sections.

4.3. Optimization model

It is well known that this optimization problem is not trivial, and that the complexity increases with the size of the distribution system and the number of filters. Keeping all nodes within the THD limits with minimum filter investment is a difficult task. It involves analysis of the harmonics flow, study of the feasible installation scenarios and analysis of the best solutions presented on the Pareto frontier.

The optimization method chosen is the NSGA II (Non-dominated Sorting Genetic Algorithm II), which presents good results when applied to multi-objective problems, where objectives are usually conflicting. The optimization model proposed in this work for filter allocation is given by (4)–(9). The objective function is (4). The objective F_1 representing the number of nodes/phases that violate the THD limits is given by (5). The objective F_2 represents filter costs, given by (6). The fact that both objectives are conflicting justifies the use of a multi-objective optimization algorithm. The optimization is subject to the maximum number of filters to be installed (8) and to the maximum investment of filters allocated in the system (9), according to the value of each filter. The total of filters allocated, c_n, is calculated with (10), each c_{hi} filter being a binary variable.

$$\min F = \{F_1, F_2\} \tag{4}$$

$$F_1 = \sum_{n=1}^{n_{máx}} b_n \tag{5}$$

$$F_2 = \sum_{n=1}^{n_{máx}} \varphi_n \tag{6}$$

$$b_n = \begin{cases} 1 \; if \; IHD_{h,n} > IHD_{h,lim} \; or \; THD_n > THD_{lim} \\ 0 \; otherwhise \end{cases} \tag{7}$$

Subject to:

$$\sum_{n=1}^{n_{máx}} c_n \leq n_f \tag{8}$$

$$\sum_{n=1}^{n_{máx}} C_{cn} \leq C_f \tag{9}$$

$$c_n = \{c_{h1} + c_{h2} + c_{h3} + c_{h4} + c_{h5}\} \tag{10}$$

where φ_n is the cost of the allocated filters in each node/phase, n is each possible node/phase for filter installation, n_f is the maximum number of filters available to install, h is the harmonic order, b_n is a binary variable to count the node/phase that violate distortion limit, c_n is the total of filters allocated in each node/phase n, C_{cn} is the investment at each node/phase n, C_f is the maximum investment permitted, THD_n is the total harmonic distortion of voltage at node/phase n, $IHD_{h,n}$ is the individual harmonic distortion of h-th harmonic voltage at node/phase n, THD_{lim} is the limit for the THD and $IHD_{h,lim}$ is the limit for the IHD for h-th harmonic.

In order to improve the search for the optimal solution, the algorithm ensures that the largest harmonic is filtered. Therefore, the initial population includes a filter for this harmonic.

4.4. Single-phase filters

Previous studies aiming to optimize the allocation of passive filters have used three-phase filters. The optimization of the allocation of single-phase filters found in the literature review is restricted to active filters. Therefore, the installation of tuned single-phase passive filters in unbalanced distribution systems is a novelty introduced in this paper.

The new approach intends to increase the flexibility of filter allocation and therefore improve the mitigation of the harmonic distortion in all system nodes. With this approach it is possible to consider some characteristics of unbalanced systems, such as single-phase and two-phase feeders.

In the methodology, the proposed passive filters are single-phase modules with resistance, inductance and capacitance, tuned for a certain harmonic order. In distribution power systems the most relevant harmonic orders are the 3rd, 5th, 7th, 11th and 13th according to Refs. [5,6,27]. However, the proposed methodology could be implemented to mitigate any other harmonic order. It is assumed that predesigned filters are available to be installed in the system. The filters have been designed in order to be installed in any node of the system, considering the need for reactive power compensation. Fig. 2 shows the ATPDraw model for single-phase filters. It is possible to see that the filter is a RLC

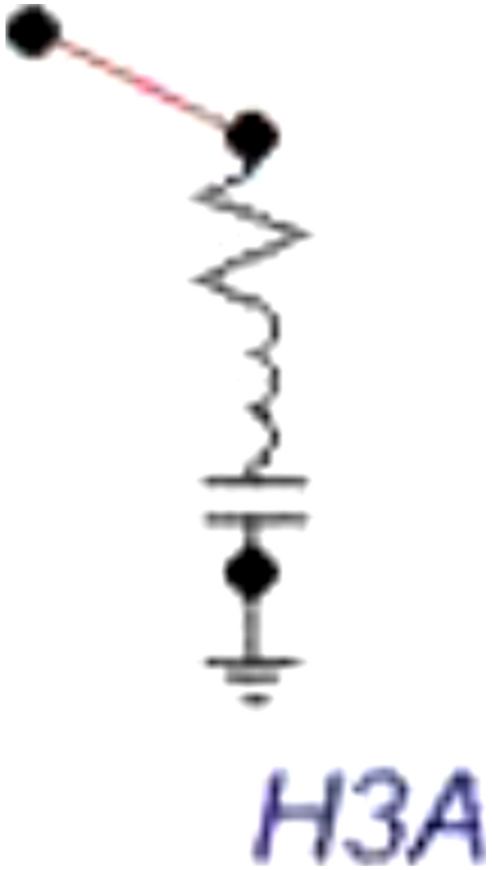


Fig. 2. Single-phase filter for 3rd harmonic.

series arrange.

4.5. Algorithm codification

To have a generic codification that could be used for any electric power system, a codification of the possible cases for filter allocation has been made. The codification handles up to five harmonic orders. The actual harmonic orders must be chosen by the user, based on his prior knowledge or analysis of the system.

The optimization algorithm will show a set of solutions that will be composed by the node, the phase and the filters. The set of solutions *p* is a population with *N* individuals, as shown in (11). Each individual i_i is a vector with the nodes/phases and filters as shown in (12).

$$p = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_N \end{bmatrix} \tag{11}$$

$$i_1 = [n_1, f_1\ n_2, f_2 \cdots n_i, f_i] \tag{12}$$

where f_i is a combination of filters installed at the node/phase n_i.

The set of locations of the tuned filters allocated for the respective harmonic orders to be mitigated represents a possible solution. The *p* solution is a population with *N* individuals, as shown in (10). Each individual is a vector with the node/phase and filters as shown in (11).

The methodology considers the possibility of asymmetric feeders, such as single-phase and two-phase circuits. Therefore, code 0 represents the absence of phase and code 32 represents that no filter is allocated. The other codes identify the possible combination of filters to be allocated in a gene. Table 4 shows the codes that represent the combinations of possible filters.

Table 4
Generic codes.

Code	**0**	**1**	**2**	**3**	**4**	**5**
Filter	No phase	h_{n1}	h_{n2}	h_{n3}	h_{n4}	h_{n5}
Code	**6**	**7**	**8**	**9**	**10**	**11**
Filters	h_{n1}/h_{n2}	h_{n1}/h_{n3}	h_{n1}/h_{n4}	h_{n1}/h_{n5}	h_{n2}/h_{n3}	h_{n2}/h_{n4}
Code	**12**	**13**	**14**	**15**	**16**	**17**
Filters	h_{n2}/h_{n5}	h_{n3}/h_{n4}	h_{n3}/h_{n5}	h_{n4}/h_{n5}	$h_{n1}/h_{n2}/h_{n3}$	$h_{n1}/h_{n2}/h_{n4}$
Code	**18**	**19**	**20**	**21**	**22**	**23**
Filters	$h_{n1}/h_{n2}/h_{n5}$	$h_{n1}/h_{n3}/h_{n4}$	$h_{n1}/h_{n3}/h_{n5}$	$h_{n1}/h_{n4}/h_{n5}$	$h_{n2}/h_{n3}/h_{n4}$	$h_{n2}/h_{n3}/h_{n5}$
Code	**24**	**25**	**26**	**27**	**28**	**29**
Filters	$h_{n2}/h_{n4}/h_{n5}$	$h_{n3}/h_{n4}/h_{n5}$	$h_{n1}/h_{n2}/h_{n3}/h_{n4}$	$h_{n1}/h_{n2}/h_{n3}/h_{n5}$	$h_{n1}/h_{n2}/h_{n4}/h_{n5}$	$h_{n1}/h_{n3}/h_{n4}/h_{n5}$
Code	**30**		**31**		**32**	
Filters	$h_{n2}/h_{n3}/h_{n4}/h_{n5}$		$h_{n1}/h_{n2}/h_{n3}/h_{n4}/h_{n5}$		No filter allocated	

The harmonic orders are represented as h_{n1}, h_{n2}, h_{n3}, h_{n4} and h_{n5}.

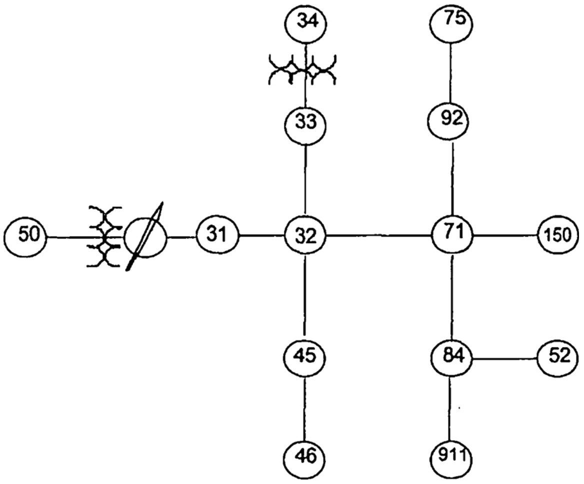


Fig. 3. IEEE 13-node test feeder.

5. Case study

5.1. Case 1

The proposed methodology is applied to the IEEE 13-node test feeder illustrated in Fig. 3. This test feeder is proposed by the Task Force on Harmonics Modeling and Simulation [28], which incorporates non-linear loads. The test feeder was modified by increasing the harmonic currents in order to obtain more distorted voltages.

The THD obtained for the base case, before filters are installed, are on Table 5. It is observed that some nodes are single-phase or two-

Table 5
Voltage THD — base case IEEE 13-node feeder.

Node	THD %		
	Phase A	Phase B	Phase C
32	8.87%	8.52%	8.35%
33	8.90%	8.54%	8.37%
34	4.23%	–	–
45	–	8.77%	9.02%
46	–	8.82%	9.05%
71	14.50%	13.51%	14.04%
84	14.55%	–	14.32%
911	–	–	14.60%
52	14.57%	–	–
92	14.51%	–	14.05%
75	14.97%	13.82%	14.34%
150	14.50%	13.52%	14.04%

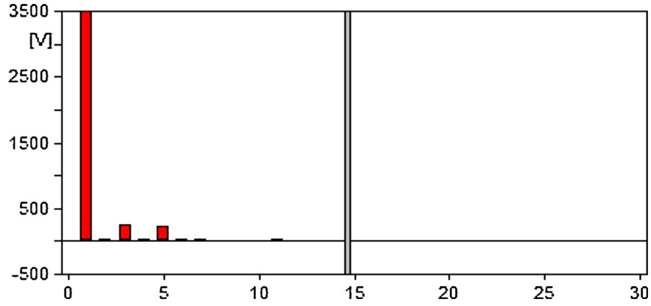


Fig. 4. Harmonic magnitude node 45.

phase.

It is possible to see that most of the nodes exceed the limit for the voltage THD, according to the IEEE Std. 519, the THD_{lim} is 5% and according to PRODIST, the THD_{lim} is 8%.

As shown in Fig. 4, the largest harmonic is the 3rd order in node 45 and the other nodes show a similar histogram. Therefore, this information is utilized by the optimization algorithm to improve the search for the optimum solution.

5.2. Codification and settings of NSGA II

In this 13-node test system there are 26 possible places for single-phase filter allocation and 32 possibilities of filter combinations, which gives a search space of 1.9×10^{45} possibilities.

Each node/phase is named according to Table 6. For instance, the node/phase 31A is called N001A, the node/phase 31B is called N001B, the node/phase 31C is called N001C and so on.

In the codification, 0 was used to identify the lack of phase; therefore, inside the chromosome that represents the system, the gene that refers to a missing phase will receive the number 0, to avoid attempts at inserting a filter there. To exemplify, bus 646 is single-phase, only phase B exists there, hence the genes that represent phases A and C are 0. Phase B could receive any of the filter combinations, 1–32, to complete its gene.

In this way, the possibilities of filter combinations are shown in Table 7. For instance:

- case one, a single-tuned filter for the 3rd harmonic is installed;
- case two, a single-tuned filter for the 5th harmonic is installed;
- case three, a single-tuned filter for the 7th harmonic is installed.
- and so on, mixing the harmonic orders.

Through this codification, the algorithm chooses the filters and orders to be installed in a node while it executes the search for the best solution to improve the THD in all nodes. The algorithm ensures that the 3rd and 5th harmonics filters are installed, because these harmonic orders are the worst as shown in Fig. 4.

Table 6
System nodes.

Node	Name	Phases
31	N001	N001A, N001B, N001C
32	N002	N002A, N002B, N002C
33	N003	N003A, N003B, N003C
34	N004	N004A, N004B, N004C
45	N005	N005A, N005B, N005C
46	N006	N006A, N006B, N006C
71	N007	N007A, N007B, N007C
84	N008	N008A, N008B, N008C
911	N009	N009A, N009B, N009C
52	N010	N010A, N010B, N010C
92	N011	N011A, N011B, N011C
75	N012	N012A, N012B, N012C
150	N013	N013A, N013B, N013C

Table 7
Case codes.

Code	**0**	**1**	**2**	**3**	**4**	**5**
Filter	No phase	3^{rd}	5^{th}	7^{th}	11^{th}	13^{th}
Code	**6**	**7**	**8**	**9**	**10**	**11**
Filters	3/5	3/7	3/11	3/13	5/7	5/11
Code	**12**	**13**	**14**	**15**	**16**	**17**
Filters	5/13	7/11	7/13	11/13	3/5/7	3/5/11
Code	**18**	**19**	**20**	**21**	**22**	**23**
Filters	3/5/13	3/7/11	3/7/13	3/11/13	5/7/11	5/7/13
Code	**24**	**25**	**26**	**27**	**28**	**29**
Filters	5/11/13	7/11/13	3/5/7/11	3/5/7/13	3/5/11/13	3/7/11/13
Code	**30**		**31**		**32**	
Filters	5/7/11/13		3/5/7/11/13		No filter allocated	

First, the size of the population and the number of generations must be defined. The chosen values were 100 for the population and 100 for the generation. The mutation probability and crossover probability were set as 0.03 and 0.9 respectively.

5.3. Results case 1

The methodology was applied to the test feeder shown in the Fig. 3. The filters are: 3rd harmonic on node 32, 3rd harmonic on node 150 and 5th harmonic on node 33. The proposed methodology considered a maximum of 9 single-phase filters installed. Thus, the THD and the IHD were compared.

The stop criterion of the NSGA2 is the number of generations; the more generations the greater the possibility of achieving ideal solution. The NSGA2 gives a Pareto frontier composed of individuals; each one gives the same value to the objective function. An extra criterion is required to choose between the individuals in the set of optimal solutions. The decision maker is responsible for this task; the decision may be based on previous experience or other needs according to the condition of the system. Sometimes a methodology is applied to search for the most suitable individual, for example technique for order preference by similarity to ideal solution (TOPSIS) [14].

The set solution given for the NSGA2 that composes the Pareto frontier is shown in (13).

$$p = \begin{bmatrix} N007A,\ 2N008C,\ 29N009C,\ 1N012B,\ 1 \\ N008A,\ 24N008C,\ 2N009C,\ 1N012B,\ 1 \\ N007A,\ 2N008C,\ 6N012B,\ 1 \\ N008C,\ 5N009C,\ 2N012A,\ 2N012B,\ 14 \\ N003B,\ 5N008C,\ 5N012A,\ 2N012B,\ 14 \\ N003B,\ 5N008C,\ 5N012A,\ 5N012B,\ 14 \end{bmatrix} \tag{13}$$

For this study, the individual with the least number of nodes violating THD/IHD limits was chosen to comparison. Seven single-phase filters were installed in the test feeder. These are the 5th on 71A, the 3rd, 7th, 11th, 13th on 84C, the 3rd on 911C and the 3rd on 75B. The choice was made to approximate the most ideal solution according to the PQ standards.

5.4. Comparing results

To compare the proposed approach with a common solution, three-phase filters were installed in the system considering a typical filter allocation: nodes with the largest distortion.

Table 8 presents the results for allocation of three-phase filters at the nodes with the largest THD. Table 9 shows the results for the proposed methodology.

According to Tables 5, 8 and 9, it is possible to see that the THD decreases with the filter allocation. The allocation of three-phase filters improved IHD and THD at many nodes, nevertheless the situation regarding harmonic distortion remains poor. There are 15 nodes

Table 8
Results for three-phase filters located at critical nodes.

Node	Phase A	Phase B	Phase C
32	4.92%	2.88%	4.36%
33	4.90%	2.89%	4.37%
34	1.84%	–	–
45	–	3.00%	5.12%
46	–	3.02%	5.18%
71	7.71%	4.85%	6.84%
84	7.75%	–	7.07%
911	–	–	7.30%
52	7.76%	–	–
92	7.72%	–	6.85%
75	8.00%	5.07%	7.07%
150	7.19%	4.18%	6.07%

Table 9
Results for the proposed methodology for single-phase filter allocation.

Node	Phase A	Phase B	Phase C
32	3.09%	2.01%	4.58%
33	3.10%	2.02%	4.69%
34	2.56%	–	–
45	–	1,97%	3.32%
46	–	1.98%	3.34%
71	4.77%	4.34%	5.13%
84	4.82%	–	3.67%
911	–	–	4.31%
52	4.67%	–	–
92	4.72%	–	5.26%
75	4.79%	4.62%	4.78%
150	4.81%	4.88%	5.65%

exceeding the limits according to IEEE 519 Std. On the other hand, all nodes are within the limits according to PRODIST. The results of the proposed methodology, using single-phase filters, as shown in Table 9, are better than the ones using three-phase filters. After the optimization of the single-phase filter allocation there are still 3 nodes exceeding THD limits according to IEEE Std. Table 10 summarizes the results.

Fig. 5 shows the Pareto frontier for NSGA II optimization. It is possible to see many individuals in the frontier, each of them is considered equally good. The individual that best balances both objective functions F1 and F2 is located in the middle of the plot. The individual with the minimum cost (F2 = US$700) leaves 22 nodes/phases exceeding THD/IHD limits (F1 = 22). On the other hand, the individual with the minimum number of nodes exceeding the limits (F1 = 3) presents more expensive filter costs (F2 = US$2700).

5.5. Case 2

A larger test feeder was simulated in order to test the proposed methodology. The IEEE 34-nodes were chosen, it is a 24.9 kV unbalanced distribution system including a 24.9/4.16 kV transformer, shunt capacitors and nonlinear loads.

Banks of capacitors in an electrical system do not consider the presence of harmonic distortions and nonlinear loads, that can generate erroneous results and problems with the resonance conditions in the system [30]. So, a systemic view of the electrical system is required, observing the behavior with the filters, it is possible with a proposed methodology.

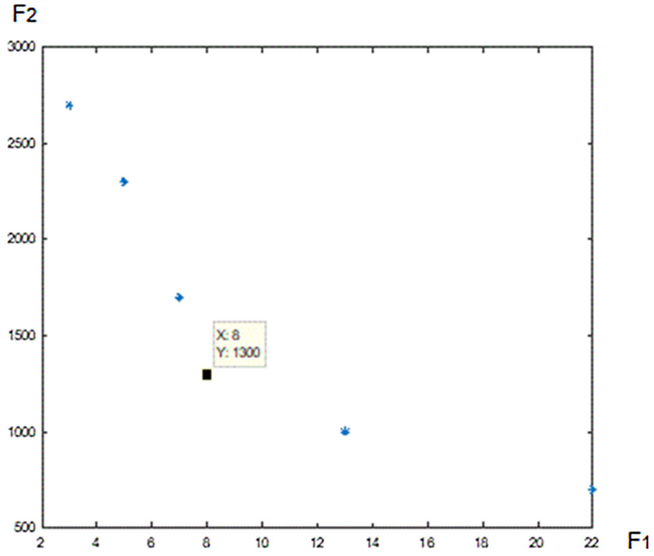


Fig. 5. Pareto frontier of NSGA II for case 1.

Fig. 6 shows the test feeder, and Table 11 presents the THD obtained on ATPDraw for the base case, before filters are installed.

5.6. Results case 2

The same codification to filter allocation is used to this test feeder, the possibilities of filter combinations are shown in Table 7. NSGA II returns a Pareto frontier composed of individuals, the set of solutions that composes the Pareto frontier is shown in (14).

$$p = \begin{bmatrix} N005B,\ 2 & N012B,\ 29 & N021B,\ 2 & \\ N005B,\ 5 & N007A,\ 1 & N021A,\ 23 & N021B,\ 1 \\ N005B,\ 2 & N021A,\ 1 & N021B,\ 23 & N034A,\ 4 \\ N007A,\ 1 & N013B,\ 1 & N021B,\ 3 & N034C,\ 25 \\ N007B,\ 24 & N020A,\ 9 & N021A,\ 3 & \\ N007B,\ 24 & N020A,\ 8 & N021B,\ 4 & \\ N007A,\ 4 & N013B,\ 29 & N021B,\ 3 & \\ N017B,\ 5 & N028C,\ 5 & N029A,\ 25 & \\ N017B,\ 5 & N028C,\ 5 & N034C,\ 25 & \end{bmatrix} \tag{14}$$

In the set of solutions of this system we observe that all the nodes are within the limits for some individuals. The individuals that present zero nodes violating THD/IHD are the following two:

- six single-phase filters installed in the test feeder: the 3rd on 814A, the 3rd on 824B, the 7th on 888B and the 7th, 11th, 13th on 840C.
- six single-phase filters installed in the test feeder: the 13rd on 810B, the 3rd on 814A, the 5th, 11th, 13th on 888A and the 3rd on 888B.

Fig. 7 shows the Pareto frontier for the 34-node test feeder, that is the set solution of the NSGA II optimization. It is possible to see three points in the frontier, each of them is considered equally good. There are in minimum three individuals in the frontier, but not necessarily only three, it is because some individuals have the same F1 and F2 value, the difference is in which local and phase the same order filter is

Table 10
Results comparison.

	Base case	Traditional three-phase filters allocation	Optimum single-phase filter allocation
Number of filters	0	3 three-phase filters	7 single-phase filters
Nodes/phases exceeding limits IEEE Std. 519	25	15	3
Costs (US$)	0	4400	2700

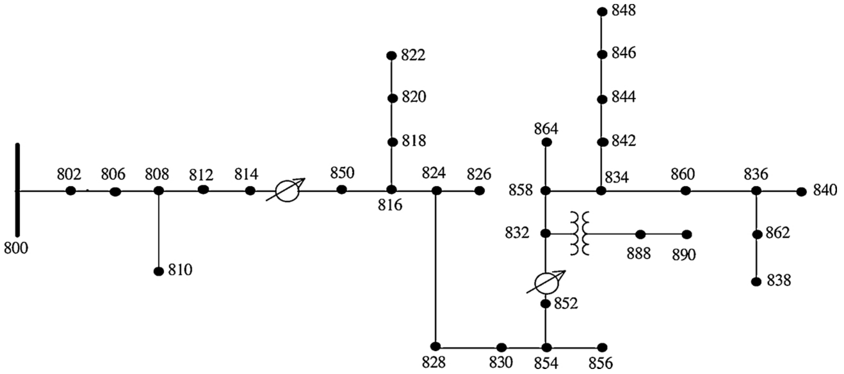


Fig. 6. IEEE 34-node test feeder.

Table 11
Voltage THD — base case for the IEEE 34-node feeder.

Node	Phase A	Phase B	Phase C
800	5.73%	4.63%	1.32%
802	5.81%	4.02%	1.40%
806	5.98%	4.22%	1.59%
808	8.86%	7.53%	2.40%
810	–	7.82%	–
812	7.21%	8.76%	2.56%
814	7.63%	10.16%	4.84%
850	7.78%	10.59%	4.62%
816	7.82%	10.78%	4.68%
818	4.79%	–	–
820	4.83%	–	–
822	4.84%	–	–
824	8.32%	13.78%	4.89%
826	Ø	12.96%	–
828	8.33%	13.38%	5.01%
830	7.83%	10.85%	4.63%
854	7.58%	10.67%	4.59%
856	9.35%	–	–
852	6.89%	9.68%	4.58%
832	6.91%	9.70%	4.60%
888	6.83%	9.56%	4.66%
890	6.78%	9.28%	4.84%
858	6.89%	9.69%	4.57%
864	9.53%	–	–
834	6.79%	9.30%	4.84%
842	6.78%	9.29%	4.83%
844	6.80%	9.30%	4.82%
846	6.80%	9.27%	4.81%
848	6.79%	9.26%	4.80%
860	6.79%	9.26%	4.81%
836	6.79%	9.25%	4.80%
862	6.78%	9.24%	4.79%
838	9.23%	–	–
840	6.80%	9.26%	4.79%

being allocated in another individual. The individual that best balances both objective functions F1 and F2 is located in the middle of the plot. The individual with the minimum cost (F2 = US$17,000) leaves 18 nodes/phases exceeding THD/IHD limits (F1 = 18). On the other hand, the individual with the minimum number of nodes exceeding the limits (F1 = 0) presents more expensive filter costs (F2 = US$14,200).

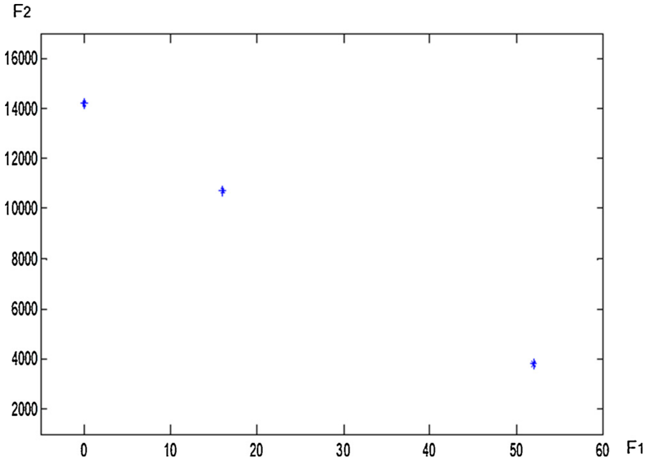


Fig. 7. Pareto frontier of NSGA II for case 2.

5.7. Computation time

The total time to complete the optimization process depends of some characteristics: the complexity and size of the feeder, the population and generation numbers, integration step of the ATP simulation, memory and processor of the machine that runs the optimization.

Each case of this research took a different time to finish the optimization process. The feeder of Case 1 is smaller than the feeder of Case 2, but includes more nonlinear and linear loads than Case 2. The population and generation numbers are 100 in both cases, integration step is equivalent to 12 cycles. The PC that runs the simulation and the optimization uses a core i5 processor with 8GB of RAM (Windows 10 operating system). Because of these characteristics the computation time for the Case 1 was 10 h and for Case 2 was 8 h.

6. Conclusion

A NSGA II based approach has been proposed in this paper for optimizing the problem of allocation of single-phase passive filters in distribution systems in order to minimize the number of nodes exceeding distortion limits and the cost of the filters.

The problem was characterized as a non-linear problem. To verify the validity of the proposed method, two test feeders have been chosen, the IEEE 13-node and the IEEE 34-node test feeders. The test feeders include single-phase, two-phase and three-phase unbalanced circuits, with unbalanced loads and nonlinear loads injecting harmonic currents in the system.

A new approach was presented, based on the installation of single-phase passive filters instead of the more usual approach of using three-phase filters. The case 1 results show that this methodology is better for finding a solution for filter allocation. Furthermore, the installation of single-phase filters shows better results than the three-phase filters concerning mitigation of harmonic distortion in unbalanced distribution systems with single-phase and two-phase branches. The case 2 shows that it is possible to mitigate all the harmonic distortion with the methodology, using single-phase filters in single-phase and two-phase circuits.

Some improvements have already been proposed, such as the selection of the most relevant harmonic orders for the passive filter initial selection and the limitation of the maximum number of filters. The IHD and THD limits were considered implicitly in the objective function.

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