Harmonic Distortion Mitigation in Unbalanced Distribution Systems by NSGAII optimization

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***Abstract*—This paper presents a methodology for passive filter allocation within an electrical unbalanced distribution system aiming to reduce system harmonic distortion. Harmonic distortions are usually eliminated using filters, however, their allocation in the system requires attention. An inadequate allocation of filters might harm Power Quality (PQ) and could increasing harmonic distortion at other buses by harmonic flow changes. We consider that filters are single-phase. The methodology is based on modeling and simulation on Alternative Transient Program (ATP/EMTP) and Matrix Laboratory (MATLAB) where the indices of harmonic distortions are verified. Different scenarios are generated through the Non-Dominated Sorting Genetic Algorithm II (NSGAII), then using an automatic simulator, all them run on ATP while MATLAB evaluates each one through multiobjective function. The problem is composed by two objectives, they are conflicting, one aims to decrease the harmonic distortion and the other to reduce the filters cost. The results show that the use of single-phase passive filters is a viable solution when the system is unbalanced and polluted by harmonic distortion.**

***Index Terms*—ATPDraw, harmonic distortion, multiobjective optimization, NSGAII, unbalanced system.**

I. INTRODUCTION

This paper provides a study in Electric Power Systems with focus in Power Quality (PQ). In distribution systems, harmonic distortion causes problems such as reduction of devices lifespan and malfunction of protection systems.

In order to reduce or mitigate harmonic distortion, it is common the use of active or passives filters. Although the active filters works well they are more expensive than passive filters in high voltages. Furthermore passive filters are efficient fulfill the function of mitigating selected harmonics in addition to providing reactive power to the system at fundamental frequency [1].

For a successful outcome considering the whole distribution system, the installation of the filters must be done with a previous study, because depending on the chosen locations there may be increase of harmonic distortion at other nodes due to changes in current flow in the system.

There is research related to this subject, which propose methods of choosing location for filters in electrical systems. In [2] the objective was to minimize the Total Harmonic Distortion (THD) verified in a certain node, at the same time that each node of the system tried to maintain the level of THD below the limit values. The optimization is done with the golden-section search method for allocating passive filters in distribution systems.

In [3] a harmonic distortion anticipation methodology was proposed. The objective functions are different combinations of the sum of THD and when the worst value is found, each node of this case is analyzed, being allocated the filter in the worst-case node. In the study, only the 5th and 7th harmonics are assumed to be generated in the system. The authors use the Genetic Algorithm (GA) to search for the location of the passive filters in a distribution system. It is important to emphasize that in studies that involves simulation of an electrical system, the more detailed and realistic the input data of the components of the modeling system, the better the simulations results will be. Therefore, assuming that only a few harmonic components will be present in the system often does not refer to reality.

In [4], only some nodes are elected to be candidate to allocate the filter, the problem is formulated 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 distortion is taken into account.

In [5] the filter allocation is given with two possibilities: the node with the maximum THD of the system or 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 bus of the system and with simulation the THD is measured in each of the nodes. A study that brings two suggestions to solve the problem is interesting from the point of view that, often a utility or a consumer can also have two paths to follow. So, by testing virtually each possibility, by comparing them, the best can be chosen.

In [6] Genetic Algorithm (GA) is used to determine parameters and location of passive filter installation in a distribution system, with its installation being in residential consumers. The minimization function is composed of the values of the filter components, and the constraints are based on the IEEE Std. 519 THD and IHD limits, so the goal is to minimize the cost of the filters and at the same time meet the THD limits in the bus of the electrical system.

In [7] the objective is to minimize the cost of the passive filter, power loss and the total harmonic distortion of currents and voltages in each node, simultaneously. Weights (w) are assigned for each part that composes the formulation, GA is used to find the solution. By adjusting the weights adequately, different solutions are achieved and can be adapted depending on the priority, i.e., the same objective function can be used regardless of market changes or even when considering a different scenario during the filter planning period, just given that adequate adjustments on the weights are done.

According to [8] an analysis of the entire system with the allocated filter is necessary, simulating all possibilities of filter allocation. However, for larger systems with a high number of filters available, this alternative is not viable, therefore, the GA is used. The objective is to minimize the average THD of the system and, according to the authors, although a good result for the average THD in the studied system is possible, the THD may exceed the maximum limits in some nodes.

In [9] it is suggested the filter installation in nodes that best preserve the PQ. It reduces the THD to an acceptable level in a node, in order to get the biggest impact on the overall system. The methodology used is called Harmonic Similarity (HS), which establishes a relationship between the disturbances in the system buses. In the case study, the 5^{th}, 7^{th}, 11^{th}, 13^{th} and 17^{th} order harmonics are assumed for modeling and simulation, which is done in PSCAD software. This research brings the concern of the total distortion limit in each node, but not with each individual distortion. The harmonic orders considered in the study are traditional in electrical systems, being truer to reality.

In [10] an algorithm for filter allocation is designed to minimize the maximum THD in the nodes of the system. The type of filter, quality factor and the tuned harmonic order of the filter are considered. There are two possibilities of filters to be implemented in the analyzed system: the tuning filters of 5^{th} and 7^{th} harmonics or high pass. The method used is the Particle Swarm Optimization (PSO), a method that is rarely used, since most studies in this area use GA.

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, in small size electrical systems, is possible, but when the system increases, the solution search complexity grows as well.

Comparing with the previous papers, the present methodology proposes:

- New approach to filter allocation: single-phase filters are proposed. To the best of our knowledge, researches that approach allocation of single-phase passive filters in three-phase systems are a novelty introduced in this paper. The examples of allocation of single-phase filters found in the literature are restricted to the active filters, most of which are limited to low-voltage.
- Detailed system representation: ATPDraw lets a detailed model of the system components. On ATPDraw there are available a lot of representation models to each type of component. Besides that, a three-phase model of the system was used instead of a single-phase equivalent system. This choice is more appropriate to represent distribution systems that are normally unbalanced. There are more harmonic order represented, others order of harmonics generated by devices presents in distribution networks are considered, typical harmonic orders from 3^{rd} to 15^{th} are simulated.
- Differentiated approach multiobjective formulation: the objective functions are developed to solve the harmonic problem considering the intrinsic characteristics in distribution networks. On a different way, comparing with the most of the research, in this present study the objective function F_1 does not try to reduce the max. THD or a sum of the THD, but it minimizes the number of buses that violate THD standards, because it is not always possible to maintain all nodes within limits with a coherent or practicable cost, which on the other hand is the conflicting function, F_2. This paper brings the approach using the NSGA II, that improves the complexity of non-dominated sorting, includes the elitism and excludes the requirement of shared parameters [11].
- New codification to represents the individual on the NSGAII, where each code represents a set of single-phase passive filters. Each gene is a possible local of filter installation, counting per phase: A, B and C.

II. Harmonic Distortion

The harmonic analysis is the process of calculating the magnitudes and phases of each frequency of a periodic waveform. The Fourier Transform establishes a relationship between the function in time domain and frequencies [12].

A. Calculation of Harmonic Distortion

The formulations to quantify the total harmonic distortion is given by (1), (2) and (3), from IEEE Std. 519/1992 [13].

$$THD_V = \frac{\sqrt{\sum_{h=2}^{h_{máx}=50} V_h^2}}{V_1}.100\% \qquad (1)$$

$$THD_I = \frac{\sqrt{\sum_{h=2}^{h_{máx}=50} I_h^2}}{I_1}.100\% \quad (2)$$

Where V_h is the harmonic voltage of order h, V_1 the nominal system voltage at the fundamental frequency and h_{max} the maximum harmonic being considered in the calculation. Similarly, I_h is the harmonic current of order h and I_1 is the fundamental current.

Individual Harmonic Distortion (IHD) is calculated by (3).

$$IHD = \frac{V_h}{V_1}.100\% \quad (3)$$

B. Limits of Harmonic Distortion

Some limits were stipulated to improve the PQ in electric systems, both THD and IHD.

The limits of this indexes are in the standards IEEE 519/2014 [14], that is the upgrade of IEEE 519/1992 and PRODIST Module 8 /2016 [15] in Brazil.

The table I and II show the THD limits for different voltage levels [14]-[15].

TABLE I.
HARMONICS DISTORTION LIMITS VOLTAGE (IEEE 519)

Voltage in the node (PCC)	Individual distortion of voltage (%)	Total distortion of voltage (%) - *THD*
V ≤ 1.0 kV	5.0	8.0
1001V < V ≤ 69 kV	3.0	5.0
69 kV < V < 161 kV	1.5	2.5
161 kV < V	1.0	1.5

TABLE II.
HARMONICS DISTORTION LIMITS –VOLTAGE (PRODIST)

Voltage in the node	Total distortion of voltage (%)
$V_n \leq$ 1kV	10
1kV < $V_n \leq$ 13.8 kV	8.0
13.8 kV < $V_n \leq$ 69 kV	6.0
69 kV < V_n < 230 kV	3.0

V_n = nominal voltage

The limits of THD of voltage were the only PQ metric considered in this research since they occur in both standards and are considered the most important index in those standards.

Besides, the IHD decreases together with the decreasing the THD, both are related [16].

III. PROPOSED METHODOLOGY

A. Single-phase filters solution

The proposed filter are single-phase modules with predetermined resistance, inductance and capacitance values, corresponding to tuning filters to harmonic orders usually presents in distribution power systems: 3rd, 5th, 7th, 11th and 13th according to [3] and [4].

Then, some predesigned filters are available to be installed in the system with harmonic distortion. Figure 1 shows the three-phase filter on modeling of ATPDraw. It is possible see that the filter is a RLC series to each phase, and could be decoupled, and used the single-phase filter.

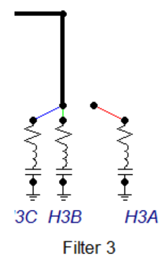


Figure 1. Single-phase filter decoupling

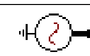
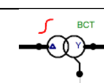
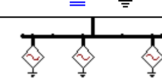
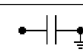
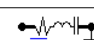
B. Modeling and Simulation

The modeling aims at components representation while the simulation is made to study the behavior of real systems, through virtual modifications of their models [12],[17],[18].

For system simulation, ATPDraw program was used. This program works well in time domain and frequency domain, obtain the harmonic power flow, with easy and intuitive use, reliable and free.

Three-phase and single-phase circuits, transformers, nonlinear loads, motors and source were modeled for time domain simulation on ATPDraw as show in Table III, according with [12],[19],[20].

TABLE III.
COMPONENTS OF ATPDRAW CHOSEN TO MODELING THE ELECTRIC POWER SYSTEM OF DISTRIBUTION

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

C. Formulation Problem

For the development of the filter allocation algorithm, the objective function (OF) was elaborated, given by (4).

$$\min \begin{Bmatrix} F_1 = n_{ol} \\ F_2 = C_f \end{Bmatrix} \quad (4)$$

s.t.

$$n_f \leq filter\ number \quad (5)$$

Where,
n_{ol}=n° of nodes out of limit
c_f= filters cost

One objective function, F_1, minimizes the number of buses that violate THD standards and the other, F_2, minimize the filters costs, both are conflicting, this justifies the uses of multiobjetive function.

THD and IHD indexes are used to check when the nodes are still above the limits even with the installation of filters and then, through the formulation it is possible to counts them.

Considering the possibility to allocate single-phase filters, the heuristic optimization method, based on the genetic algorithm, obtains the solution for which the objective function is minimized.

The optimization method chosen is the (Non-dominated Sorting Genetic Algorithm II) NSGA II, which presents good results when applied to multiobjective problems, in which normally the objectives are conflicting.

D. Block Diagram

The block diagram depicted in Figure 2 shows the methodology since the modeling and simulations on ATPDraw until the evaluation on MatLab with the NSGA II. The two interfaces are well delimited and their function in the methodology is further explain below.

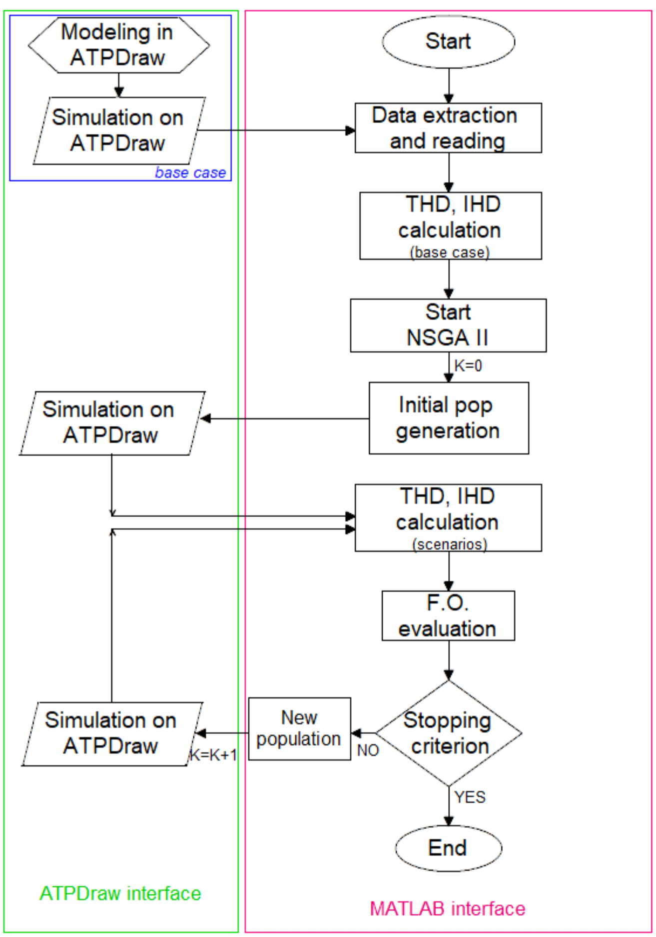


Figure 2. Block diagram

Methodology starts in the ATPDraw interface with the modeling and simulation of a base case. Then, the harmonic distortion information is used to obtain THD and IHD.

On MatLab interface, the NSGA II is initialized by creating an initial population, based on the searching space. The greater the individuals diversity, the better, because the algorithm will search for solutions through elitism, mutation and crossover [11]. Each individual corresponds to scenarios of filters allocated on the system. That is, the individual is a chromosome composed by x genes, where x is three times the number of buses due to the three possible phases, i.e., x is the vector showing all possible locations for a single phase tuned filter. The genes will be completed with a case, the cases are presented in Table V, from 0 until 32, where case 0 is used to inexistent local to insert filter, i.e., phase absent in single or two phase branches. The others cases corresponding the quantity and order of passive filters to be allocated in a gene. It is a general codification once there are five harmonics orders to be mitigated, 3rd, 5th, 7th, 11th, 13th, and the cases mixes them.

ATPDraw simulates each individual and the data go back to MatLab to evaluate the OF. So, during the search for the best result, the NSGA II will change the genes inside the individuals in order to reduce the number of buses whose voltage harmonic indices are out of the limits and the costs of the passive filters. The algorithm will stop when it reaches the pre-stablished number of generations.

IV. Case Study

To test the application of the proposed methodology, the IEEE 13 bus test feeder [20] of the Task Force on Harmonics Modeling and Simulation was used. This system incorporates non-linear loads, the single-line diagram is show in Figure 3.

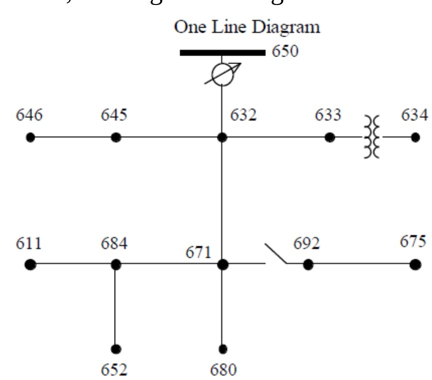


Figure 3. Single-line diagram

A. Codification of NSGA II

In this case study, with 13 buses, there are 39 possible places for single-phase filter allocations and there are 32 possibilities of filters combinations, which gives us a search space of $8.2x10^{50}$ possibilities. However, due to single-phase or two-phase buses, the space of search is somewhat smaller.

The code 0 were used to identify the absent phases, so, inside the chromosome that represents the system, the gene that refers a phase missing will receive the number 0, to avoid attempt to insert filter there. To exemplify, bus 646 is single-phase, only exists phase B, so, the genes that represents phases A and C are 0. The phase B could receive any of the filter combinations, 1 to 32, to complete it gene.

In this way, the possibilities of filters combinations are showed in table V. Code one, insert a filter single-tuned for 3rd harmonic. Code two, insert filter single-tuned for 5th harmonic. Which it codification the algorithm chose the filters and orders to be installing in a node while executes the search for the better solution to improve PQ in all the system. Due the constrains and large search space, rarely a lot of filters will be install on the same node, but the methodology is general, could be used in large systems where a lot of filters could be allocated in same node of system, depending of the number of filters chosen to allocated.

TABLE V. POSSIBILITIES OF CODES

Code	**0**	**1**	**2**	**3**	**4**	**5**
Filter	No phase	3rd	5th	7th	11th	13th
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			

B. Settings of NSGA II

The programing in MatLab [21] was used in this work.

First the number of population should be defined, for each case simulated, a different value has been stipulated. For the first case population number is 20 and generation number is 500; for the second population 100 and generation 10 and for the last, 100 and 100. The mutation probability and crossover probability, p_m and p_c, were p_m=0.05 or 0.01, depending the number of individuals, and p_c= 0.9; p_m is calculated with 1/n, where n is the number of the population.

The OFs (5) and (6) were considered and evaluated.

C. Results

Methodology validation was done with, three cases studies. The table VI presents settings and results in each of the cases studies.

TABLE VI. RESULTS NSGA II

	Population	Generation	F_1	F_2
Case 1	20	500	8	2200
Case 2	100	10	8	1800
Case 3	100	100	8	1300

To compares, we took the same number of F_1, eight. The results show that in this study case, the number of generations is not so impacting to give a result with less costs at the same time as maintaining the buses within the limits if the population number is poor.

If we compare case 1 and 2. The case 2, with 490 generations less than case 1, and with 80 individuals more in the algorithm search, find the same number of buses out of limits, with $500 less. If the number of individuals is the same and 90 generations more, comparing with case 1 yet, the solution is the best, because the cost is less, it is the case 3.

So, does not pay that number of generations, if isn't a good diversity of individuals. Otherwise, the number of individuals it is good to find a better solution.

The Figures 4, 5 and 6 shows the Pareto frontier, that is composed by a set of solutions.

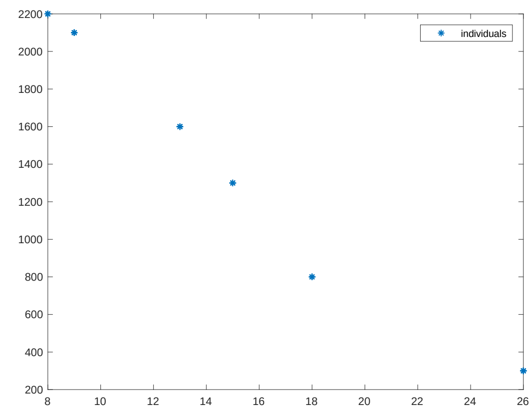


Figure 4. Case 1 (pop 20 gen 500)

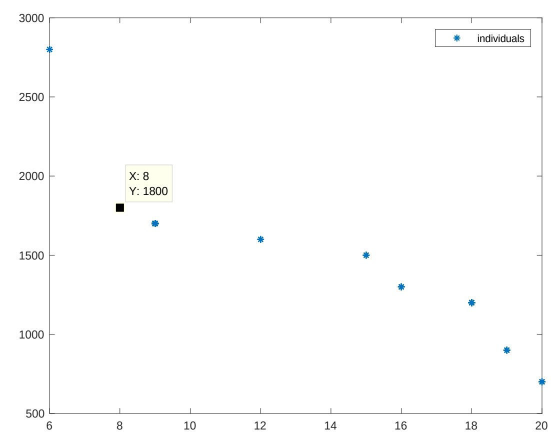


Figure 5. Case 2 (pop 100 gen 10)

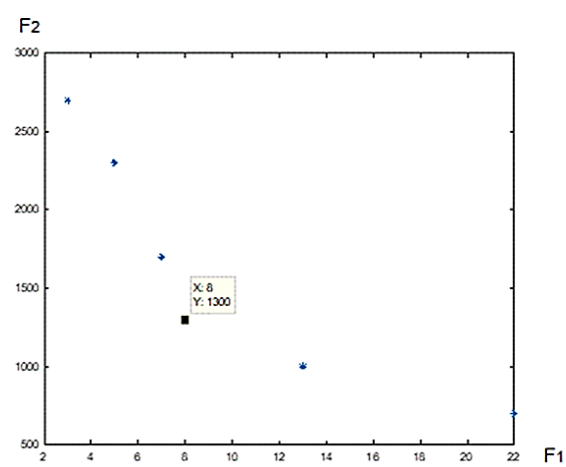


Figure 6. Case 2 (pop 100 gen 100)

The individuals of the solutions that are localized most close of zero on Pareto Frontier were analyzed to compare the cases. So, the best case was the case 3, with eight buses out of the limit, and $1300 of cost. The passive filters allocated in case 3 were: 5th on 671A, 3rd, 7th, 11th, 13th on 684C, 3rd on 611C and 3rd on 675B, total 7 single-phase single-tuned filters allocated.

It is possible to note that no one case obtained zero buses out of limits. But on the third case, a good individual has been found, only three bus out of the limits (F_1). So, we believe that improving the generation and population numbers it is possible to find a better solution. So, the single-phase methodology could be considered since now an useful and feasible methodology to solve the problem of PQ.

V. Conclusion

This paper presented a methodology for optimal allocation of passive filters within an electrical distribution system in order to reduce the number of buses that violate distortion limits and the filter cost.

The total number of filters was also considered into the constrains. The THD and IHD limits were considered implicit into the objective functions.

In the three case studies perform validation of the methodology, it was possible to determine the principal settings to obtain a good result. It was verified that the number of individuals of population is very important to find a good solution, but the number of generations is impacting if there are a medium number population.

The results show that methodology is a good way to find a solution of filters allocation in an unbalanced distribution power system.

There are some improvements already proposes to this methodology, such input preferential harmonic order of passive filters according the system, i.e., priories the main or most polluting order harmonic on the system analyzed.

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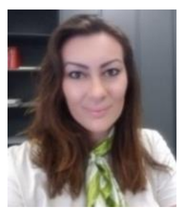
Biographies



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