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Approach of Passive Filters using NSGA II in industrial installations: Part I

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Abstract**—***The optimization of passive filters in industrial systems has been presented by different computational methods. The objective of this paper is to develop a computational algorithm with NSGA II to select the configuration and design parameters of a set of passive filters for industrial installations. As a methodology, the optimization problem was addressed using three independent objective functions of innovative character for compensation of harmonics through passive filters as a multiobjective problem. The results were the computational solution to this problem that determines a set of Pareto optimal solutions (Frontier). In addition, the computational tool has several new features such as: calculates the parameters that characterize the filters, but also selects the type of configuration and the number of branches of the filter in each candidate bar according to a set of pre-established configurations according to PRODIST-M8 (Brazilian Standard) and IEEE 519-2014. Also determine solutions with good power quality indicators (THD, TDD and NPV) for several characteristic and non-characteristic scenarios of the system that allow to represent: daily variations of the load, and variations of system parameters and filters. It evaluates the cost of energy bills in an industrial power grid that has different operating conditions (characteristic scenarios) and evaluates the economic effect of harmonic filters as reactive power compensators.*
Keywords—Quality Power, NSGA II, Passive Filters, multiobjective optimization.

I. INTRODUCTION

Modern electrical systems contain the quantities of sources capable of contaminating or producing various harmonic impacts in the distribution network where the non-linear loads found in industrial sectors, commercial and residential installations stand out. The optimization of passive filters in distribution systems has been approached through different approaches. In general, these can be classified as single goal formulations (Ghiasi, Rashtchi, & Hoseini, 2008; J. C. A. Leite, I.P.; Azevedo, M.S.S., Nascimento, M.H.R.; Moraes, N. M., Reis, A.M. , 2015; Mahaboob, Ajithan, & Jayaraman, 2018; A. Zobaa, Vaccaro, Zeineldin, Lecci, & Monem, 2010) and multiobjective optimization (J. C. Leite, Abril, de Lima Tostes, & De Oliveira, 2017; C. f. Yang, Lai, & Su, 2013).

Medium and high-power contaminant sources generally focus on industrial electrical systems. These include static power converters and electric arc furnaces. For this purpose single goal formulations usually attempt to determine the least costly filters that ensure compliance with relevant standards of power quality standards. In multiobjective approaches, other objectives are added to achieve the following: minimum total current distortion (Acuna et al., 2015; Ji, Liu, Zeng, & Zhang, 2012), minimum total demand ratio(Beres, Wang, Liserre, Blaabjerg, & Bak, 2016), minimum total voltage distortion(A. F. Zobaa, 2014), minimum investment cost of filters(Busarello, Pomilio, & Simões, 2016), minimum cost losses(Hu, He, & Gao, 2015; N.-C. Yang & Le, 2015), etc.

In commercial and residential installations, a large number of nonlinear loads of small power are employed, which due to their large numbers cannot be neglected as a source of distortion. This is the case of home and office equipment, discharge lamps as shown by the standards (Association, 2014; Maciel, Lins, & Cunha, 1996), among others.

The harmonics injected into the electrical system by the non-linear loads produce effects: in the electric

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power systems themselves and in the electric charges connected to them, as well as in the communications systems (Std.153L, 2003).

II. PASSIVE FILTERS

a. Introdution of Passive Filters

When designing an industrial installation containing large non-linear loads, the limits recommended by harmonic distortion standard are generally violated. Given this premise, measures must be taken to ensure compliance with these limits and, in this way, reduce the undesirable effects of the harmonics in the industrial electrical system, thus avoiding the extension of power quality problems to the external supply system

The means of compensation of the harmonic distortion by excellence are the filters of harmonics that aim essentially to restrict the circulation of the harmonic currents by the network, in order to avoid the distortion of the tension in the bars (Arrillaga & Watson, 2004).

For the operating principle, the harmonic filters can be: passive, active or hybrid (when using a mixture of the first two). Although active filters have shown advantages in low voltage systems, passive filters are still the most attractive in medium and high voltage systems (Nassif & Xu, 2007). There are several types of parallel passive filters that can be classified into tuned filters and damped filters (Nassif, Xu, & Freitas, 2009).

A. Filtertypes

a) Filterstuned

In the tuned filters or bandpass filters, the passive circuit consists of a capacitor and a series inductance to a low value resistor (Dehini & Sefiane, 2011). Figure 1 shows the tuned filter

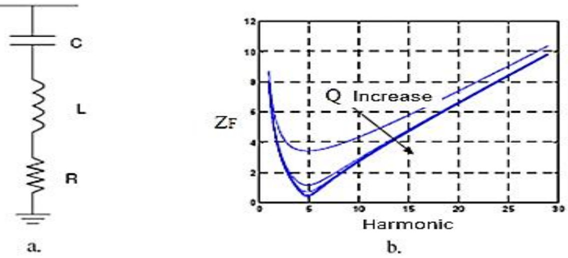

Fig.1: Filter tuned. a) Topology, b) Impedance versus frequency.

Source: Adapted from (Kahar & Zobaa, 2018).

b) Damped Filter (High pass)

The damped filters shown in Figure 2 are characterized by having an impedance characteristic versus smoother frequency, which allows the passage of high frequencies and therefore their elimination.

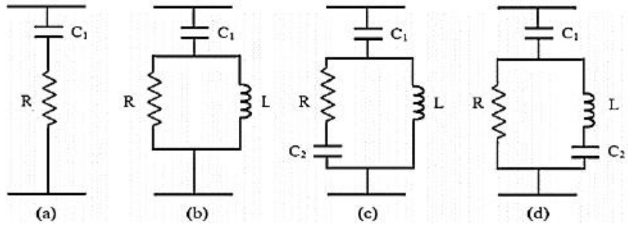

Fig.2: Damped filters. (a) 1st order, (b) 2nd order, (c) 3rd order, (d) type C. Source: (Abdel Aleem, Zobaa, & Balci, 2017).

c) Second order filter

The most used damping filter in practice is the second order filter as shown in Figure 3 whose behavior depends on the quality factor used in its design. A high quality factor implies a more selective bandwidth, while a low quality factor reduces the impedance of the filter for high frequencies

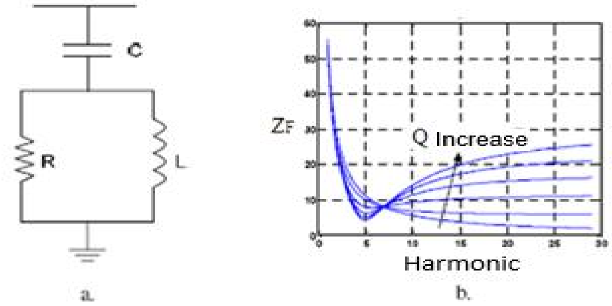

Fig.3: Filter of second order: a) Topology, b) Impedance versus frequency. Source: Adapted from (Maundy & Elwakil, 2015).

d) Third-order filter

The third-order filter incorporates a new capacitor C_2 in the circuit (Figure 4).

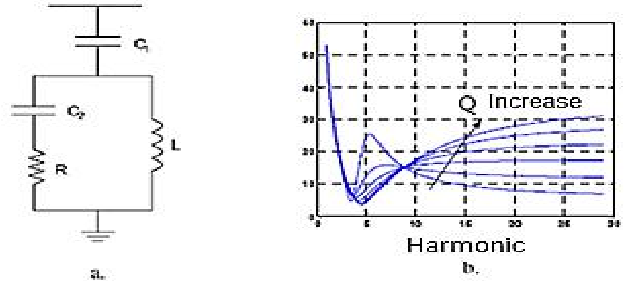

Fig.4: Third order filter. a) Topology, b) Impedance x frequency.

Source: Adapted from (Zhang, Wang, Xu, & Sitther, 2018).

e) C type filter

The design of this filter shown in Figure 5 is based on the fact that X_l is equal to Xc_2 and therefore produces a series resonance therebetween at the fundamental frequency so that the resistance is short-

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circuited at this frequency and the filter operate as a capacitor (Zhang et al., 2018).

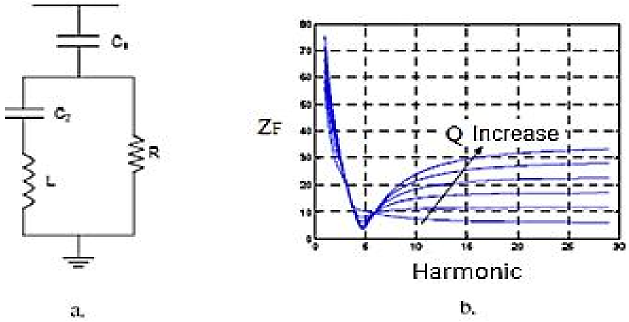

Fig.5: Filter type C. a) Topology, b) Impedance versus frequency. Source: Adapted from (Zhang et al., 2018).

The impedance of the type C filter for the frequency *n* in (1) is:

$$Z = \frac{jR(Xl \cdot n - Xc_2 / n)}{R + j(Xl \cdot n - Xc_2 \cdot n)} - jXc_1 / n \tag{1}$$

Following the described procedure, the resistance is obtained from (Abril, 2012) according to (2):

$$R = \frac{Xc_1}{n^3(n^4-1)Q}\Big(\big(n^2(Q^2+2) - n^4 - 1\big) + \cdots + \sqrt{n^{12}(Q^4+2Q^2+2) - 2n^{10}(3Q^2+4) + n^8(4Q^2+11) + 2n^6(Q^2-2) - 2n^4(Q^2+2) + 4n^2 - 1}\Big) \tag{2}$$

C. Saturation of components

The standard ("IEEE Standard for Shunt Power Capacitors," 2013) states that the power capacitors of the harmonic filters must be able to operate on a continuous basis under any condition of the system provided that the following conditions are met:

1) The *rms* voltage applied to the capacitor does not exceed 110% of its rated voltage *rms* (V_{cnom}).

2) The peak voltage applied to the capacitor (including harmonics but not transients) does not exceed 120% of its rated peak voltage.

3) The *rms* current flowing through the capacitor does not exceed 135% of its nominal current rms (I_{cnom}).

4) The reactive power generated by the capacitor does not exceed 135% of its nominal reactive power (Q_{cnom}).

Thus, if *h* is the set of harmonics to which the capacitor is subjected, one can establish the following relations (3), (4), (5) e (6):

$$\sqrt{\sum_{h \in H} V_h^{\,2}} \le 1.1 \cdot Vc_{nom} \tag{3}$$

where V_h represents the harmonic voltage*h* applied to the capacitor.

$$V_{peak} \le 1.2 \cdot \sqrt{2} \cdot Vc_{nom} \tag{4}$$

where V_{peak} is the peak voltage applied to the capacitor.

$$\sqrt{\sum_{h \in H} I_h^{\,2}} \le 1.35 \cdot Ic_{nom} \tag{5}$$

where I_h represents the current of the harmonic *h* that circulates through the capacitor

$$\sum_{h \in H} Qc_h \le 1.35 \cdot Qc_{nom} \tag{6}$$

where Q_{ch} is the reactive power of the harmonic *h* generated by the capacitor.

In the saturation of reactors and resistors, although there is no specific norm (Std.153L, 2003), it is considered that the values of *rms* voltage, *rms* current and the nominal power of these elements, cannot surpass any condition of stable operation of the filter.

D. Filter costs

The investment cost of a filter is the sum of the costs of its component elements (Std.153L, 2003):

1) Capacitors, reactors and resistors;

2) Protection (fuses, switches, etc.), and;

3) Housing (Chassis, etc.)

With respect to the cost of the other elements, this can be considered as 1% of the total cost of the filter (Std.153L, 2003).

III. MATERIAL AND METHODS

A. Formulation of the problem

Given the issues raised, this thesis formulates the problem of optimizing the design of passive filters in industrial electrical systems as a multiobjective problem that seeks the selection and design of passive filters necessary to meet the following objectives: Maximize Net Present Value (NPV) installation filters design; Minimize total distortion of current in the CCP, and; Minimize the total distortion of the voltage in the bars of the industrial electrical system. Subject to the restrictions of: 1) Meeting the current energy quality standards; 2) Compliance with technical specifications.

A.1. Problem variables

The independent variables of the optimization problem, represented by the X arrangement, are the types of passive filters to install and their respective design parameters. In a genetic algorithm the problem variables are somehow encoded on a chromosome representing the data corresponding to a solution or individual. The computational implementation of the NSGA-II used in this work uses a direct coding in real numbers, facilitating the interpretation of the data stored in this chromosome.

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To represent a set of data on a chromosome that can be of variable size (the type of filter and the number of branches chosen may differ from one solution to another), this chromosome must be able to represent the maximum number of data it defines a filter.

For the location of the passive filters in the industrial installation, a set of *K*-bars should be determined where such filters are to be installed. These bars are usually those in which there are significant nonlinear loads or distribution centers which have a set of such loads (Nassif et al., 2009).

The chromosome representing an individual's data consists of an arrangement of the *K* elements, where each *Sk* element as shown in Table 1 is an arrangement of integer and real data representing the various parameters of the harmonic filter to be located on bar *k*.

Table.1: Variables that describe a filter represented on the chromosome (J. C. LEITE, 2013).

Variable	Description
Cfg	ConfigurationType (1, 2, 3, 4)
m	Number of branches tuned (if it is type 1 filter)
Qc	Total reactive power in capacitors
$Fd_1, \ldots, Fd_{w+1}$	Factors for the distribution of reactive power among all branches
$Fq_1, \ldots, Fq_{w+3}$	Tuning frequencies of all branches
$Q_1, \ldots, Q_{w+3}$	Quality factors of all branches

IV. RESULTS AND DISCUSSIONS

NPV offilters design

The installation of the harmonic filters in the system has two fundamental effects: the reduction of the harmonic distortion of the voltages and currents; and the compensation of the reactive power of the load. The reduction of the harmonic distortion of the voltage in the system bars improves the quality of energy supplied to the loads supplied from the electrical system of the industrial installation as well as from other consumers that are fed from the PCC or the bar under consideration. Although it is known that increasing the quality of energy means reducing the operating costs of electrical equipment, it is difficult to economically evaluate this result.

In addition, when the filters are installed, the currents circulating in the network are reduced at the fundamental frequency, due to the large increase in the power factor, and the harmonic frequencies due to the filtering effect of the filters. Reducing harmonic currents through the network reduces the loading of generators, transformers, cables, and other elements of the system, reducing system losses. The impact of reducing filter losses is easier to assess economically when the required network and load data are known. In an industrial company, the cost components of the electric energy bill is a convenient way to measure the annual cost of the electrical energy consumption of the facilities (*Costs*). To determine the economic effect of filter installation, we choose (*L*) scenarios typical of the daily load variation to calculate the power consumption and the power factor of the installation. These characteristic scenarios correspond to the different load levels that are repeated daily for a given time.

For each daily load scenario, the total active power (P_T) and the total reactive power (Q_T) supplied by the network, as well as the active and reactive power losses in each element of the installation (including the filters) can be calculated by a power flow program at fundamental frequency and with a harmonic penetration program. Using the calculated values of P_T and Q_T, the maximum demand for active and reactive power as well as the active and reactive power consumption of the installation can be estimated for a typical working day. Therefore, the monthly and annual electricity bill can be estimated when considering a number of typical working days per year. This method of aggregation can be more or less exact, insofar as the load of the installation is better characterized. The Electric Energy Billing Manual defines various types of tariffs to be used in electric energy billing and defines the concepts of DREX Excess Reactive Demand and EREX Excess Reactive Energy, magnitudes that are calculated as the demand and the reactive energy that exceeds the reactive energy and demand values corresponding to a power factor of 0.92. As the circuit load varies in different *L* characteristic load states, the billed energy is the sum of the active power and the reactive power consumed in each state *k* of the annual duration Δ_{tk}:

$$E_F = \sum_{k=1}^{L}(P_{Tk}\cdot\Delta t_k + EREX_k) = \sum_{k=1}^{L}(P_{Tk} + DREX_k)\cdot\Delta t_k \quad (8)$$

In the same way, the demand billed D_F is composed of the sum of the active demand and the surplus reactive demand of the scenario *k* of maximum load

$$D_F = \max_{k\in L}\{P_{Tk} + DREX_k\} \quad (9)$$

Thus, the annual costs of electricity billing are calculated by:

$$Cost(x) = c_D \cdot D_F(x) + c_E \cdot E_F(x) \quad (10)$$

Where c_D($/kW) and c_E($/kWh) are coefficients of the

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corresponding electric charge cost.

Thus, the benefits of installing the filters for the characteristic *L* scenarios are determined as the difference between the annual cost of electricity bill before *Cost(0)* and after the installation of the *Cost(x)* harmonic filters. The investment cost of *I(x)* filters is composed of the costs of capacitor, reactor, resistor and other elements. The cost of the capacitor, reactor and resistor depends linearly on its power for each voltage level, while the other components of the cost can be assumed proportional to the reactive power of the filter (Std.153L, 2003). Thus, the investment cost of the filter is:

$$I(x) = \sum_{i \in C_C} K_{Ci} Q_{Ci} + \sum_{i \in C_L} K_{Li} Q_{Li} + \sum_{i \in C_R} K_{Ri} P_{Ri} \qquad (11)$$

where $Kc(\$/kvar)$, $K_L(\$/kvar)$ and $K_R(\$/kW)$ are the power cost coefficients of capacitors Q_C, inductors Q_L and resistors P_R respectively, and C_C, C_L and C_R represent the sets of each one of these types of elements.

Considering a period of evaluation of *N* years with an interest rate *i*, the *NPV* of the installation project of the filters is calculated as shown by the relation (12):

$$NPV(x) = -I(x) + \sum_{k=1}^{N} (Cost(0) - Cost(x)) / (1+i)^k \qquad (12)$$

...roject, the *NPV(x)* must be maximized. However, genetic algorithms usually work by minimizing the objective functions. In this way, the first objective function to be minimized is defined as (13):

$$f_1(x) = -NPV(x) \qquad (13)$$

a) Harmoniccontrolobjectives

Passive harmonic filters are primarily harmonic control devices whose function is to avoid the circulation of distorted currents through the elements of the system, reducing the harmonic distortions of voltage in the bars. To evaluate the effect of filters on distortion rates, all possible operating scenarios of the system should be evaluated, including the *L* characteristic scenarios considered and another set of special system and load conditions. These special conditions may include variations in network impedance, different modes of operation of harmonic producing loads, tuning of filters, etc. They are non-characteristic operating states for which a daily operating time is not allocated, with impacts on energy calculations, power factor, etc., but with influence on the determination of harmonic distortion rates.

For each scenario k considered, the total distortion of the current in the PCC (TDD_k) and the total distortion of the voltage in each bar *i* (THD_k, *i*) can be calculated by a harmonic flow program. Both rates, the total distortion of current in the PCC and the total distortions of voltage in the bars should be minimized by the optimization process (ANEEL, 2018; Association, 2014).

To minimize *TDD* in all possible scenarios it would be necessary to define an objective function for each scenario. However, considering that all harmonic control standards limit only the maximum value (95% or 99% probability) of harmonic distortion, it is only easier to minimize only the maximum *TDD* value of all the operating scenarios of the system as shows (14) (ANEEL, 2018; Association, 2014):

$$f_2(x) = \max_{k \in W} \{TDD_k(x)\} \qquad (14)$$

Following the same reasoning, the maximum *THD* value between all operating scenarios and all system buses using the function f_3 according to (15) is minimized.

$$f_3(x) = \max_{\substack{k \in W \\ i \in U}} \{THD_{k,i}(x)\} \qquad (15)$$

b) Restrictions

The body of constraints of the filter optimization problem consider:

1. The stress quality constraints on the system bars;
2. The quality constraints of the currents in the PCC, and;
3. Saturation constraints on the filter components.

The way of evaluating the quality restrictions of the voltage and current depends on the standard adopted to formulate the problem. If the standards of (ANEEL, 2018) or (Std.153L, 2003) are used, there are no limits for current distortion in the CCP, so this set of constraints is not taken into account. Therefore, the formulation used here considers all possible restrictions according to the adopted norms.

In addition, to ensure that the optimization program obtains feasible solutions to the problem, a fourth objective function to be minimized, which represents the quadratic sum of all constraint violations of the problem is defined as (16):

$$f_4(x) = \sum_{v_i(x) > l_i} (v_i(x) - l_i)^2 \qquad (16)$$

Where v_i and l_i represent the calculated value and the limit value of parameter *i* bounded by the correspondingconstraints.

Para determinar o valor de f_4 para um conjunto de filtros x instalados, têm-se o seguinte procedimento (as sentenças estão escritas em pseudocódigo):

1) Initializewith $f_4 = 0$.
2) For each operating scenario k and each bar *i* of the system, the voltage quality constraints of the type are evaluated:

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a) Limit the value of the voltage modulus Vmk, i according to (17).

$$if\ Vm_{k,i} > Vlim_i,\ \ f_4 = f_4 + \left(Vm_{k,i} - Vlim_i\right)^2 \quad (17)$$

b) Limit the total voltage distortion THD_k, i. as shown (18).

$$if\ THD_{k,i} > THDlim_i,\ \ f_4 = f_4 + \left(THD_{k,i} - THDlim_i\right)^2 \quad (18)$$

For each harmonic *h*, the limiting of the individual distortion limit of the voltage $IHD_{k,i,h}$, is evaluated. as shown (19).

$$if\ IHD_{k,i,h} > IHDlim_{i,h},\ \ f_4 = f_4 + \left(IHD_{k,i,h} - IHDlim_{i,h}\right)^2 \quad (19)$$

3) For each system operating scenario *k* (only for standard (ANEEL, 2018), the current quality restrictions in the PCC of the type::

a) Limite a distorção total da demanda TDD_k.de acordo com (20).

$$if\ TDD_k > TDDlim,\ \ f_4 = f_4 + \left(TDD_k - TDDlim\right)^2 \quad (20)$$

For each harmonic h, the limit constraint of the individual distortion of the current demand $IDD_{k,h}$, is evaluated as shown (21):

$$if\ IDD_{k,h} > IDDlim_h,\ \ f_4 = f_4 + \left(IDD_{k,h} - IDDlim_h\right)^2 \quad (21)$$

4) For each system operating scenario k and each capacitor j of the filters installed, the saturation restrictions of capacitors of the type are evaluated:

a) Limit the voltage applied to the capacitor Vck, i. according to (22).

$$if\ Vc_{k,j} > 1.1Vcnom_j,\ \ f_4 = f_4 + \left(Vc_{k,j} - 1.1Vcnom_j\right)^2 \quad (22)$$

Limit the peak voltage applied to the capacitor $Vcpeak_{k,j}$. according to (23).

$$if\ Vcpeak_{k,j} > 1.2\sqrt{2}Vcnom_j,\ \ f_4 = f_4 + \left(Vcpeak_{k,j} - 1.2\sqrt{2}Vcnom_j\right)^2 \quad (23)$$

b) Limit the circulating current through the capacitor $I_{ck,i}$. according (24)

$$if\ Ic_{k,j} > 1.35Icnom_j,\ \ f_4 = f_4 + \left(Ic_{k,j} - 1.35Icnom_j\right)^2 \quad (24)$$

c) Limit the reactive power generated by the capacitor $Qc_{k,i}$. according (25).

$$if\ Qc_{k,j} > 1.35Qcnom_j,\ \ f_4 = f_4 + \left(Qc_{k,j} - 1.35Qcnom_j\right)^2 \quad (25)$$

Having evaluated all constraints of the problem, f_4 is the quadratic sum of all violations of such constraints. If f_4 is zero, solution *x* will be feasible, otherwise ($f_4 \neq 0$) the solution will not be efficient with the characteristics adopted for one or more constraints.

Then the global optimization problem is defined as shown in (26):

$$\min\left\{f_1(x), f_2(x), f_3(x)\right\} \text{sujeito a } \left\{f_4(x) = 0\right\} \quad (26)$$

There are different ways to manipulate constraints in an optimization problem. However, since zero is the smallest possible value of f_4 and there is a multiobjective optimization method, the problem can be formulated as shown in (27)

$$\min\left\{f_1(x), f_2(x), f_3(x), f_4(x)\right\} \quad (27)$$

By minimizing f_4, the algorithm tries to obtain the zero value of this function, in other words, it looks for the viable solutions of the problem. In this way, both feasible and quasi-viable solutions ($f_4 \approx 0$) are obtained, which may be advantageous in very difficult solution problems.

V. OPTIMIZATION ALGORITHM

For the problem formulated for the design of filters whose nonlinear features with real and integer variables whose solution requires an optimization algorithm using the NSGA II. The types of optimization problems present several objective functions, which are almost always in conflict, and if one wishes to optimize simultaneously in this case, in an innovative way, it presents three objective functions (f_1, f_2 and f_3). In multiobjective optimization, the notion of optimal solution is replaced by the notion of Pareto unpaired or optimal solution(Kawann & Emanuel, 1996).

5.1 APPLICATION EXAMPLES

This example corresponds to an industry that contains medium and low voltage loads. The electrical system uses a primary distribution network of 4160V that feeds the medium voltage loads and four substations that feed the loads of 480V. The nonlinear loads are concentrated in the low voltage part and are formed by three-phase six-pulse converters.

In this case it is considered that the voltage of all the nodes of the network must comply with the quality indicators as established in the standard (ANEEL, 2018). The industrial plant is described according to the single-line diagram shown in Figure 6.

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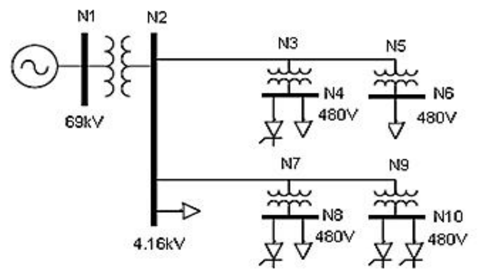

Fig.6: Industrial plant single line diagram.
Source: (Abril, 2012).

For the optimization process, five possible operating scenarios are considered, which are presented in Table 2.

Table.2: Scenarios for the analyzes.

Parameter	Scenarios				
	1	2	3	4	5
Daily scenario duration (h/day)	6	10	8	0	0
FilterCapacitanceDepreciationΔC(%)	0	0	0	0	10
FilterinductancedepreciationΔL(%)	0	0	0	-5	5
Short-circuit MVA in PCC (MVA)	250	250	250	125	125

The first three scenarios are load regimes characteristic of a normal industrial plant work day, considered to evaluate the 12-month energy bill with 30 days. These scenarios do not consider depreciation of the filters components, since they assume that they exactly maintain their design parameters. Scenarios four and five are pessimistic conditions of network operation with reduced short-circuit MVA in the PCC. In addition, these scenarios add a depreciation of capacitance (*ΔC*) and inductance (*ΔL*) for all filters that are installed. The bars (N4, N8 and N10) were selected for the installation of filters considering that they are the ones that feed non-linear loads. To evaluate the economic effectiveness (*NPV*) of the compensation project, it was considered a duration of five years, with a rate of return of 10% per year. The following cases were analyzed:

1) Design of filters for the three characteristic scenarios;

2) Design of filters for the five possible scenarios.

In both cases, the limits of voltage harmonics (ANEEL, 2018) were used as energy quality constraints. In addition, 100 generations of the algorithm were performed, with a population of 500 individuals.

5.2 Design of the filters for the three characteristic scenarios

The initial results of the problem (base case), considering only the three characteristic scenarios (1, 2 and 3) are presented in Table 3.

Table.3: Initialresults (case 1).

Parameter	Value
Annualenergycost ($ / year)	840124
Maximum TDD (%)	7.412
Maximum IDD (%)	6.498
Maximum THD (%)	8.349
Maximum IHD (%)	6.267
Power factor	0.797

According to (ANEEL, 2018), these levels of distortion are within the established limits. Finished 100 generations, the genetic algorithm produced a population of 500 solutions, for example. Extracting only viable solutions, the results obtained are shown in 9 for the Pareto frontier of the problem, as shown in figure 7.

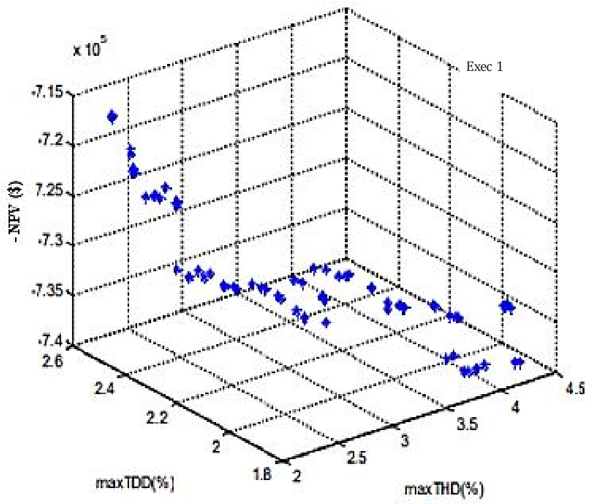

Fig.7: Pareto frontier.

In order to select the possible solution to the problem, considering that the PRODIST-Module 8 standard only restricts the voltage distortion, we can order the solutions in ascending order of *maxTHD*, *maxTDD* and *-NPV* respectively. Figure 8 shows the ordered solutions, where as*maxTHD* increases, *maxTDD* and *-NPV* decrease.

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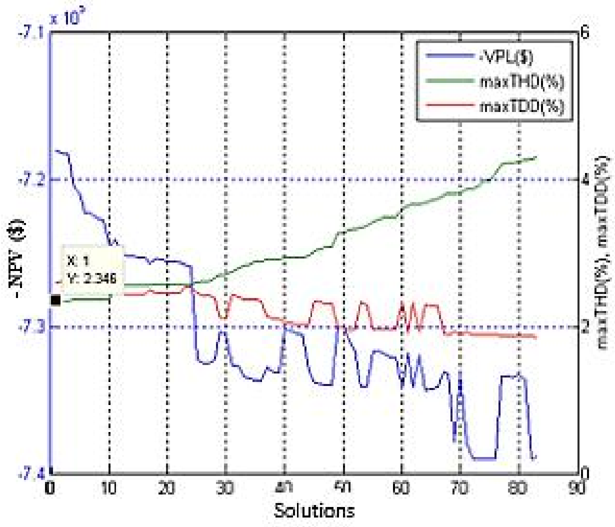

Fig.8: Possible ordered solutions (case 1).

Here, different criteria can be used to choose the solution and to be used. If the least voltage distortion solution is selected as shown in Figure 10, a variant is obtained whose parameters are shown in Table 4.

Table.4: Parameters of selected filters (case 1).

Bus	Parameter	Branch 1	Branch 2	Branch 3	Branch 4
N4	Type	tuning in	2ªorder		
	Capacitors	4x50 kvar	4x50 kvar		
	Frequency	4.7	7.6		
	Qualityfactor	21.6	10		
N8	Type	tuning in	tuning in	tuning in	tuning in
	Capacitors	4x50 kvar	1x50 kvar	2x50 kvar	1x50 kvar
	Frequency	4.7	6.6	10.4	13
	Qualityfactor	37.9	19.8	22.2	8
N10	Type	tuning in	tuning in		
	Capacitors	3x50 kvar	2x50 kvar		
	Frequency	4.7	6.6		
	Qualityfactor	28.1	34		

This solution is composed almost exclusively of tuned filters, since the selected second order branches have a high quality factor. Thus, it is possible to obtain a solution only with tuned filters, adopting the possible configurations of the variables are given to a single configuration of type 1. The developed program admits this possibility. The results obtained, when installing the selected filters, are shown in Table 5, where a great reduction of the harmonic distortion indicators and the annual cost of electric power is proven.

Table.5: Final results (case 1).

Parameters	Value	%
Annualenergycost ($ / year)	638400	75.989
Maximum TDD (%)	2.596	35.024
Maximum IDD (%)	2.064	31.763
Maximum THD (%)	2.346	28.097
Maximum IHD (%)	1.635	26.090
Power factor	0.992	124.582
Cost of investment of the filters ($)	46687	
NPVfromtheproject	718005	

To verify the effectiveness of the solution for variations of the filter parameters, the harmonic penetration program is executed for all scenarios with different depreciation of these parameters and the results are shown in Figure 9, where a reduction of the *maximum TDD* between 31 to 37% and the *maximum THD* between 27.2 and 47.1% compared to the base case values for all scenarios of the problem and considering the possible depreciation of the filters.

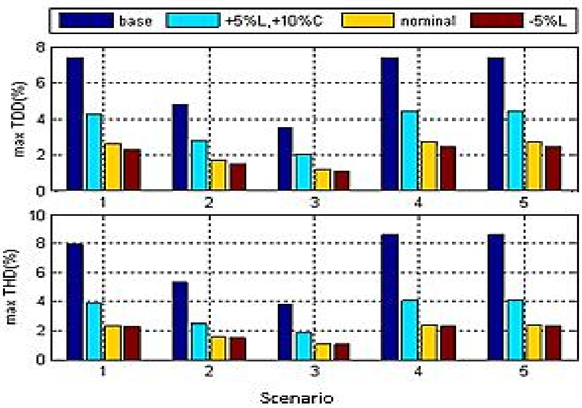

Fig.9: Results with depreciation of the filters (case 1).

As shown in Figure 9, the worst results are obtained when the components of the filters have a positive depreciation, which reduces the frequency of tuning, separating them from the harmonics to be eliminated. This same behavior is repeated for the individual harmonics, which is exemplified for the current distortion in the PCC shown in Figure 10 and the voltage distortion in the N10 bar shown in Figure 11 for scenario 1.

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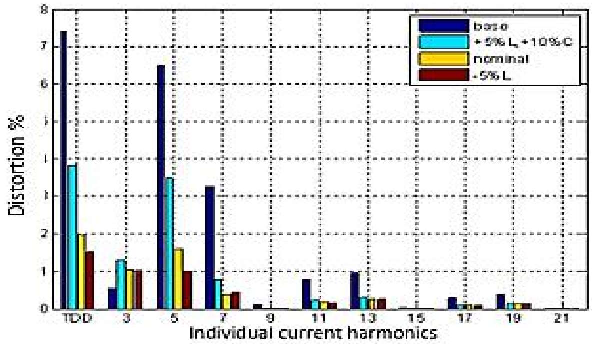

Fig.10: Current distortion in the PCC (case 1).

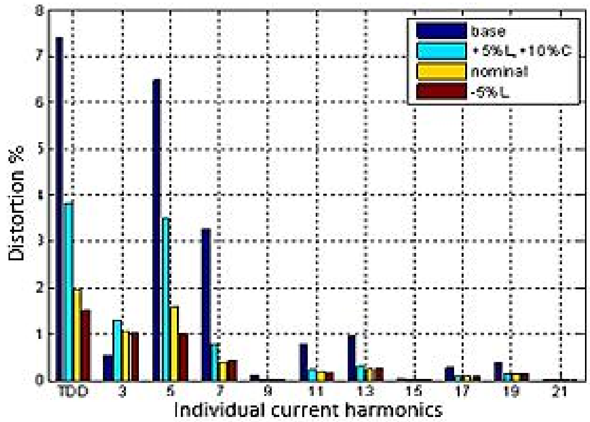

Fig.11: Distortion of the tension in the bar N10 (case 1).

However, a frequency sweep study in bar N10, shown in Figure 12, comparing the impedance characteristics vs base case frequency (without filters) and the response obtained for all scenarios and with capacitance depreciation (0 to + 10%) and the inductance (-5% to + 5%), shows that the impedance peaks occur in low order harmonics in the nonlinear loads in the problem. Thus, this behavior is repeated in the figures N8 and N4, and it can be concluded that the selected filters will perform satisfactorily.

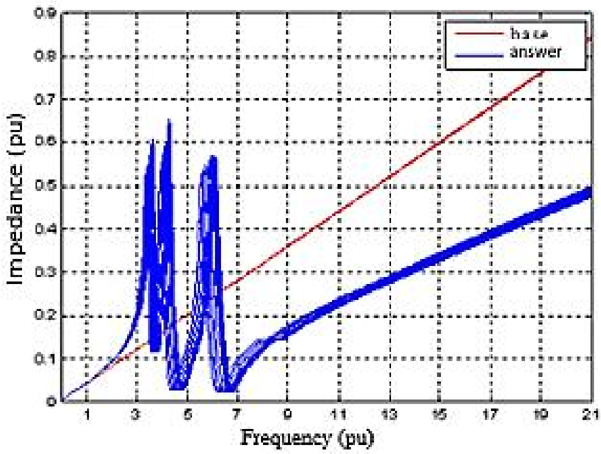

Fig.12: Frequency sweep in bar N10 (case 1).

VI. CONCLUSION

It is concluded that the computational solution to this problem was achieved using the genetic algorithm NSGA-II that determines a set of optimal solutions of Pareto (Frontier) that allow the designer to choose the most appropriate solutions to the problem. In addition, the computational tool developed has several novelties such as: The parameters that characterize the filters are calculated, but also the type of configuration and the number of branches of the filter in each candidate bar according to a set of configurations preestablished; Two standards have been programmed to evaluate the energy quality constraints that can be selected by the user; We determine solutions with good performance indicators for several characteristic and non-characteristic scenarios of the system that allow us to represent: the daily variations of the load, and the variations of the system parameters and the filters; It evaluates the cost of energy bills in an industrial power grid that has different operating conditions (characteristic scenarios) and evaluates the economic effect of harmonic filters as reactive power compensators. The positive results, from the analysis of several practical examples, show the advantages of the developed method.

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REFERENCES

[1] Abdel Aleem, S. H. E., Zobaa, A. F., & Balci, M. E. (2017). Optimal resonance-free third-order high-pass filters based on minimization of the total cost of the filters using Crow Search Algorithm. *Electric Power Systems Research, 151*, 381-394. doi:https://doi.org/10.1016/j.epsr.2017.06.009

[2] Abril, I. P. (2012). Cálculo de parámetros de filtros pasivos de armónicos; Calculation of the harmonics passive filters parameters. *Ingeniería Energética, 33*(2), 134-143.

[3] Acuna, P., Morán, L., Rivera, M., Aguilera, R., Burgos, R., & Agelidis, V. G. (2015). A single-objective predictive control method for a multivariable single-phase three-level NPC converter-based active power filter. *IEEE Transactions on Industrial Electronics, 62*(7), 4598-4607.

[4] ANEEL, P. d. D. d. E. (2018). Elétrica no Sistema Elétrico Nacional–PRODIST: Módulo 8-Qualidade de Energia Elétrica. *Revisão, 10*, 88.

[5] Arrillaga, J., & Watson, N. R. (2004). *Power system harmonics* (2nd ed.): John Wiley & Sons.

[6] Association, I. S. (2014). 519-2014-IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. *New York, IEEE*.

[7] Beres, R. N., Wang, X., Liserre, M., Blaabjerg, F., & Bak, C. L. (2016). A review of passive power filters for three-phase grid-connected voltage-source converters. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 4*(1), 54-69.

[8] Busarello, T. D. C., Pomilio, J. A., & Simões, M. G. (2016). Passive filter aided by shunt compensators based on the conservative power theory. *IEEE Transactions on Industry Applications, 52*(4), 3340-3347.

[9] Dehini, R., & Sefiane, S. (2011). POWER QUALITY AND COST IMPROVEMENT BY PASSIVE POWER FILTERS SYNTHESIS USING ANT COLONY ALGORITHM. *Journal of Theoretical & Applied Information Technology, 23*(2).

[10] Ghiasi, M., Rashtchi, V., & Hoseini, S. (2008). *Optimum location and sizing of passive filters in distribution networks using genetic algorithm.* Paper presented at the Emerging Technologies, 2008. ICET 2008. 4th International Conference on.

[11] Hu, H., He, Z., & Gao, S. (2015). Passive filter design for China high-speed railway with considering harmonic resonance and characteristic harmonics. *IEEE transactions on Power Delivery, 30*(1), 505-514.

[12] IEEE Standard for Shunt Power Capacitors. (2013). *IEEE Std 18-2012 (Revision of IEEE Std 18-2002)*, 1-39. doi:10.1109/IEEESTD.2013.6466331

[13] Ji, J., Liu, H., Zeng, G., & Zhang, J. (2012). *The multi-objective optimization design of passive power filter based on PSO.* Paper presented at the Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific.

[14] Kahar, N. H. A., & Zobaa, A. F. (2018). Application of mixed integer distributed ant colony optimization to the design of undamped single-tuned passive filters based harmonics mitigation. *Swarm and Evolutionary Computation*.

[15] Kawann, C., & Emanuel, A. E. (1996). Passive shunt harmonic filters for low and medium voltage: A cost comparison study. *IEEE Transactions on Power Systems, 11*(4), 1825-1831.

[16] LEITE, J. C. (2013). *Projeto multicritério de filtros harmônicos passivos para instalações industriais utilizando técnicas de inteligência computacional.* (DOCTOR IN ELECTRICAL ENGINEERING), UFPA, BELÉM. Retrieved from http://repositorio.ufpa.br/jspui/bitstream/2011/4599/6/Tese_ProjetoMulticriterioFiltros.pdf

[17] Leite, J. C., Abril, I. P., de Lima Tostes, M. E., & De Oliveira, R. C. L. (2017). Multi-objective optimization of passive filters in industrial power systems. *Electrical Engineering, 99*(1), 387-395.

[18] Leite, J. C. A., I.P.; Azevedo, M.S.S., Nascimento, M.H.R.; Moraes, N. M., Reis, A.M. . (2015). Multicriteria design of passive harmonic filters for industrial installations using evolutionary computation techniques. *Journal of Engineering and Technology for Industrial Applications (JETIA), 01*(03), 52-60.

[19] Maciel, P. R., Lins, R. D., & Cunha, P. R. (1996). *Introdução às redes de Petri e aplicações*: UNICAMP-Instituto de Computacao.

[20] Mahaboob, S., Ajithan, S. K., & Jayaraman, S. (2018). Optimal design of shunt active power filter for power quality enhancement using predator-prey based firefly optimization. *Swarm and Evolutionary Computation*.

[21] Maundy, B. J., & Elwakil, A. S. (2015). Second order bandstop and bandpass filters using transformers. *Microelectronics Journal, 46*(8), 690-697. doi:https://doi.org/10.1016/j.mejo.2015.05.004

[22] Nassif, A. B., & Xu, W. (2007). *Passive harmonic filters for medium-voltage industrial systems: Practical considerations and topology analysis.* Paper presented at the Power Symposium, 2007. NAPS'07. 39th North American.

[23] Nassif, A. B., Xu, W., & Freitas, W. (2009). An investigation on the selection of filter topologies for passive filter applications. *IEEE transactions on Power Delivery, 24*(3), 1710-1718.

[24] Std.153L, I. (2003). IEEE Guide for Application and Specification for Harmonic Filters.

[25] Yang, C. f., Lai, G. G., & Su, C. T. (2013). Optimal planning of passive harmonic filters using hybrid differential evolution considering variation of system parameters. *International Transactions on Electrical Energy Systems, 23*(8), 1317-1334.

[26] Yang, N.-C., & Le, M.-D. (2015). Multi-objective bat algorithm with time-varying inertia weights for optimal design of passive power filters set. *IET Generation, Transmission & Distribution, 9*(7), 644-654.

[27] Zhang, G., Wang, Y., Xu, W., & Sitther, E. (2018). Characteristic Parameter-Based Detuned C-Type Filter Design. *IEEE Power and Energy Technology Systems Journal, 5*(2), 65-72. doi:10.1109/JPETS.2018.2825279

[28] Zobaa, A., Vaccaro, A., Zeineldin, H., Lecci, A., & Monem, A. A. (2010). *Sizing of passive filters in time-varying nonsinusoidal environments.* Paper presented at the Harmonics and Quality of Power (ICHQP), 2010 14th International Conference on.

[29] Zobaa, A. F. (2014). Optimal multiobjective design of hybrid active power filters considering a distorted environment. *IEEE Transactions on Industrial Electronics*, *61*(1), 107-114.