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

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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 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 a large amount of contaminant sources or harmonic producers, where the nonlinear loads used in industry, commercial and residential installations stand out [1][2][3].

As fontes contaminantes de média e alta potência geralmente se concentram nos sistemas elétricos industriais. Entre estas se incluem conversores estáticos de potência e fornos de arco elétrico [4][5][6][7].

. In commercial and residential installations, a large number of nonlinear loads of small power are employed, which due to their large number can not be neglected as a source of distortion. This is the case of home and office equipment, discharge lamps, among others.

The harmonics injected into the electrical system by nonlinear loads produce effects on the electrical power systems themselves and on the electrical loads connected to them, as well as on communications systems. [8][9][10][11].

All the effects of harmonics in power systems are harmful and among them we can mention [12][13][14][15]:

1) The possible existence of series and parallel resoncances, which contribute to the amplification of harmonis and their effects;
2) Reduction of system efficiency, increasing losses in power generation, transmission and distribution systems;
3) The premature aging of the insulation of the components of the electrical network and, consequently, reduction of its useful life.
4) The malfunction of the system or any of its components.

One of the most damaging phenomena associated with the presence of harmonics is the possibility of **resonance** occurring in the electric circuit. Like most elements in power systems such as transformers, rotary machines, etc. have the inductive character, the presence of capacitor banks to compensate for the power factor or the own capacitive effect of the power lines can interact with the inductive elements of

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the circuit so that at certain frequencies are equal to the equivalent inductive and capacitive reactances causing a condition of resonance in which high values of voltage and current, which affect the correct functioning of the system and can cause equipment failure [16][17][18].

Harmonic filters are active or passive devices, whose mission is to avoid harmonic circulation by the electrical power system to prevent the occurrence of harmful resonances and avoid other undesirable effects that may occur [19][20][21].

Although active filters have better performance characteristics than passive, the latter are still more used than the former. Figure 1 shows the pre-definition of filters types according to [29].

II. PASSIVE FILTERS

Passive filters use passive components, such as inductors, capacitors, and resistors. These cannot increase the signal energy; the frequency range for harmonic filters is limited to approximately 3000 Hz. It is common to characterize the frequency-selective filters with respect to their passbands [22].

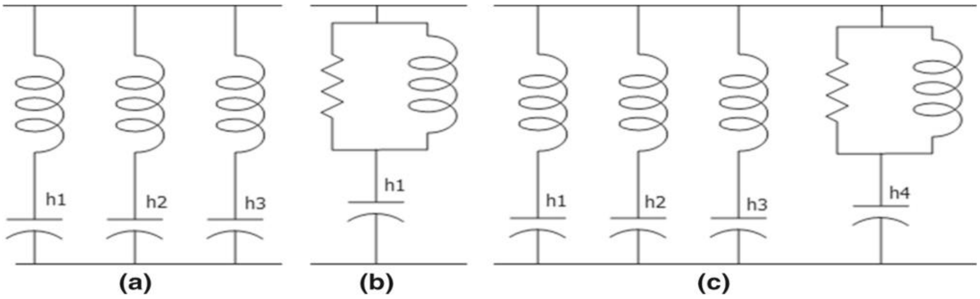

Fig.1: Predefined configurations of the filters.

Source: [23].

2.1 FILTER TYPES

A low-pass (LP) filter passes the low-frequency components and suppresses the high-frequency components. Their loss characteristic is given by

$$A(\omega) = 0,\ 0 \le \omega < \omega c \qquad (1)$$
$$= \infty,\ \omega c < \omega < \infty$$

The frequency from 0 to ωc is the passband and from ωc to ∞ is stopband. The boundary between passband and stopband = ωc is the cutoff frequency. However, there cannot be a sudden transition from passband to stopband. Practically, passband loss is not zero, and the stopband loss in not infinite. There is a gradual transition between passband and stopband. Then, for the LP filter, the loss characteristic is [22]:

$$A(\omega) \le Ap,\ 0 \le \omega \le \omega p \qquad (2)$$
$$\ge Aa,\ \omega a \le \omega \le \infty$$

A high-pass filter acts in the reverse manner, suppresses the low frequency, and passes the high frequency. For an ideal filter

$$A(\omega) = \infty,\ 0 \le \omega < \omega c \qquad (3)$$
$$= 0,\ \omega c < \omega < \infty$$

For a practical filter, the loss characteristic is

$$A(\omega) \ge Aa,\ 0 \le \omega \le \omega a \qquad (4)$$
$$\le Ap,\ \omega p \le \omega \le \infty$$

The bandpass filter passes frequencies within a certain band and blocks the low and high frequencies. Ideally,

$$A(\omega) = \infty,\ 0 \le \omega < \omega c1$$
$$= 0,\ \omega c1 < \omega < \omega c2 \qquad (5)$$
$$= \infty,\ \omega c2 \le \omega < \infty$$

For a practical filter, the loss characteristic is

$$A(\omega) \ge Aa,\ 0 \le \omega \le \omega a1$$
$$\le Ap,\ \omega p1 \le \omega \le \omega p2 \qquad (6)$$
$$\ge Aa,\ \omega a2 \le \omega \le \infty$$

The loss function referred earlier can be determined as follows: A filter represented by voltage transfer function:

$$\frac{V_o(s)}{V_i(s)} = H(s) = \frac{N(s)}{D(s)} \qquad (7)$$

where $Vi(s)$ and $Vo(s$ ... ns of the input and output voltages and $N(s)$ and $D(s)$ are polynomials in s.

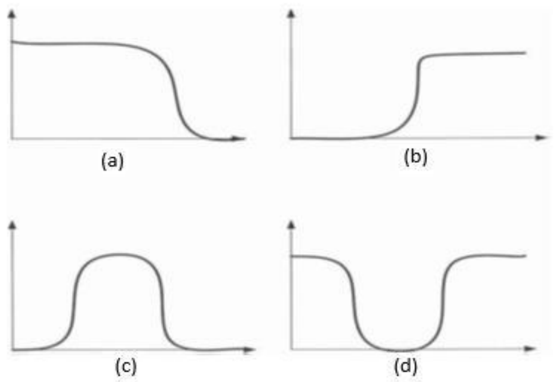

Fig.2: Frequency response of low-pass (a), high-pass 9b0, bandpass (c), and stopband (d) (notch) filters.
Source: [22].

The loss or attenuation is in decibels:

$$A(\omega) = 20\log\left|\frac{V_i(j\omega)}{V_o(j\omega)}\right| = 20\log\frac{1}{|H(j\omega)|} \quad (8)$$

The filters for harmonic mitigation are generally of shunt type to offer a low-impedance path to a certain harmonic or harmonics so that these are bypassed into the filter and their flow is minimized into the system, as discussed in the following section [22][24][25].

These may use resonance in the filter components to offer minimum impedance to a particular harmonic or a band of harmonics. This does not mean that we do not use series filters, that is, filters connected in series with the converter to impede the flow of a certain harmonic [26].

2.3 LOCATION OF HARMONIC FILTERS

Passive filters at suitable locations, preferably close to the source of harmonic generation, can be provided so that much of the harmonic currents are trapped at the source and the harmonics propagated to the point of common coupling (PCC) are reduced. Active filters, hybrid combination of active and passive filters, and phase multiplication to reduce harmonic emission. By reduction of harmonics at the source, the electrical equipment need not be oversized, losses are minimized, voltage distortions are reduced, the filters can be [22].Conversely, when filters are located away from the harmonic producing loads, the harmonics must flow to the filter through system impedances with the resultant derating of electrical equipment. Yet, it may not be practical or economical to provide filters at each source of harmonic emission.

The key considerations are the following:

• Harmonic limitations at PCC must meet IEEE 519 requirements, but it is desirable to limit harmonic distortions throughout the power systems [22].

- Reactive power compensationmay be simultaneously required.

• Normal and contingency conditions of the plant operation, along with ambient harmonics, must be considered.

- Normal and contingency filter conditions must be considered.

• Harmonic emission must be estimated correctly under various operating conditions.
• System interaction with harmonic emissions must be considered.
• A three-phase modeling may be necessary where large unbalances exist.

II.4 SINGLE-TUNED FILTERS

The single-tuned (ST) filters are efficient filters and will bypass a certain harmonic to which these are tuned. These are most widely used filters in all applications of harmonicmitigation. However, care is required in their design, so that the components are not overloaded, and overvoltages due to their applications are controlled. Many times a group of ST filters are applied, each tuned to a specific frequency [22].

The operation of an ST shunt filter is explained with reference to Fig. 3. (Any other type of filter connected in the shunt can be termed a shunt filter.) Figure (a) shows a system configuration with nonlinear load, and Fig. 3(b) shows the equivalent circuit. Harmonic current injected from the source through impedance *Zc* divides into filter and system equivalent impedance *Z*eq. This system impedance can be found by circuit reduction – this is in fact the short-circuit equivalent impedance at bus 1.

The current *Is* divides into three parallel paths: the current at PCC is the current flowing through utility source, and utility transformer is series:

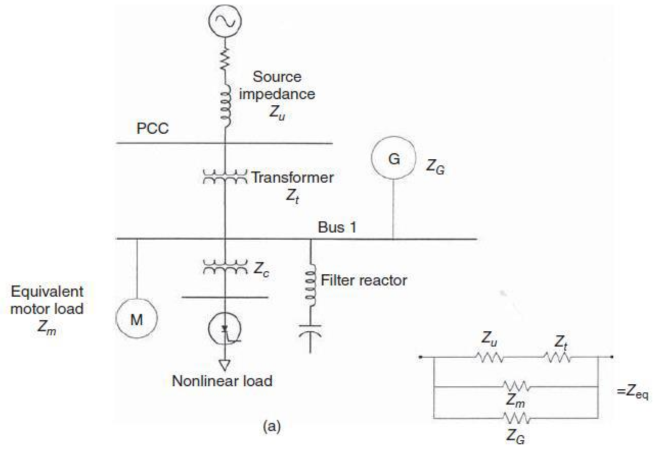

Fig.3(a): Connections of an ST filter, harmonic source in a distribution system.

Source: [22].

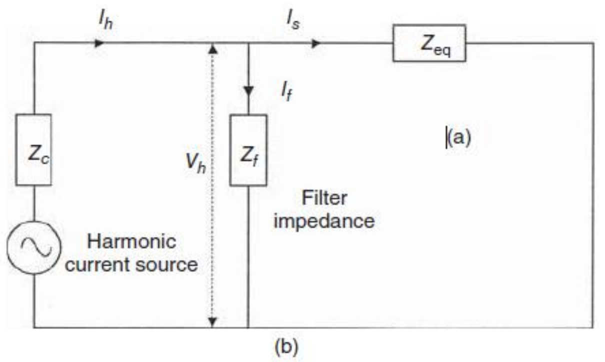

Fig.3(b): Equivalent circuit looking from harmonic injection as the source.

Source: [22].

We alluded to this concept in Chapter 6 in connection with active filters, the IEEE harmonic limits of TDD [27] are based on this concept. The higher is the short-circuit power of the source, the higher is the permissible TDD.

In an ST filter, as the inductive and capacitive impedances are equal at the resonant frequency, the impedance is given by the resistance *R*:

$$Z = R + j\omega_n L + \frac{1}{j\omega_n C} \quad (9)$$

At resonant frequency ωn, $Z = R$.

The following parameters can be defined:

ωn is the tuned angular frequency in radians and is given by

$$\omega_n = \frac{1}{\sqrt{LC}} \quad (10)$$

$X0$ is the reactance of the inductor or capacitor at the tuned angular frequency. Here, $n = fn/f$, where fn is the filter-tuned frequency and f is the power system frequency.

$$X_0 = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} \text{ and } \omega_n = \sqrt{\frac{1}{LC}} \quad (11)$$

The quality factor of the tuning reactor is defined as

$$Q = \frac{X_0}{R} = \frac{\sqrt{L/C}}{R} \quad (12)$$

It determines the sharpness of tuning, see Chapter 3. The pass band is bounded by frequencies at which

$$|Z_f| = \sqrt{2}R \quad (13)$$

$$\delta = \frac{\omega - \omega_n}{\omega_n} \quad (14)$$

$$\omega = \omega_n(1 + \delta)$$

At these frequencies, the net reactance equals resistance, capacitive on one side, and inductive on the other side. If it is defined as the deviation per unit from the tuned frequency, then for small frequency deviations, the impedance is approximately given by

$$|Z_f| = R\sqrt{1 + 4\delta^2 Q^2} = X_0\sqrt{Q^{-2} + 4\delta^2} \quad (15)$$

To minimize the harmonic voltage, *Zf* should be reduced or the filter admittance should be high as compared to the system admittance.

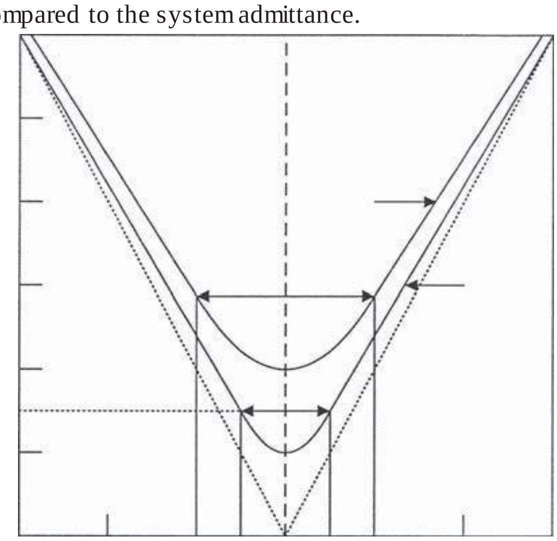

Fig.4: Response of an ST shunt filter showing pass band and asymptotes.

Source [28].

The plot of the impedance is shown in Fig. 4 [28]. The sharpness of tuning is dependent on *R* as well as on *X*0, and the impedance of the filter at its resonant frequency can be reduced by reducing these. The asymptotes are at

$$|X_f| = \pm 2X_0|\delta| \quad (16)$$

The edges of the pass band are at $\delta = \pm 1/2Q$ and width = $1/Q$. In Fig. 15.4, curve A is for R = 5 ohms, $X0$ = 500 ohms, and Q = 100, with asymptotes and pass band, as shown. Curve B is for R = 10 ohms, $X0$ = 500 ohms, and Q = 50. These two curves have the same asymptotes. The resistance, therefore, affects sharpness of tuning.

In terms of admittances

$$Y_f = G_f + jB_f$$
$$= \frac{Q}{X_0(1+4\delta^2Q^2)} - \frac{2\delta Q^2}{X(1+4\delta^2Q^2)} \quad (17)$$

The harmonic voltage at filter bus is

$$V_h = \frac{I_h}{Y_h} \quad (18)$$

For minimum voltage distortion, the overall admittance of filter should be increased. The impedance loci indicate that generally the harmonic impedances can be defined in a region of *R*, *jX*, determined by two straight lines and a circle passing through the origin.

The other types of filters that were used in article [29] have the same characteristics of the search:

a) *Filters tuned*
b) *Damped Filter (High pass)*
c) *d) Third-order filter*
d) *C type filter*

III. MATERIAL AND METHODS

The research follows the same methodology of Article [29]:

A. Formulation of the problem
B. *Problem variables*

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.

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, …, Fd_{w+1}	Factors for the distribution of reactive power among all branches
Fq_1, …, Fq_{w+3}	Tuning frequencies of all branches
Q_1, …, Q_{w+3}	Quality factors of all branches

Source: [29].

IV. RESULTS AND DISCUSSIONS

The results of the research follows the same methodology of article [29] using case 2.

NPV of filters design [29] and equations (8), (9), (10), (11), (12), (13), (14), (15), (16), (17), (18), (19), (20), (21), (22), (23), (24), (25), (26) and (27).

4.1 OTIMIZATION 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 (*f1*, *f2* and *f3*). In multiobjective optimization, the notion of optimal solution is replaced by the notion of Pareto unpaired or optimal solution [29][31].

4.2 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 [32]. The industrial plant is described according to the singleline diagram shown in Figure 5.

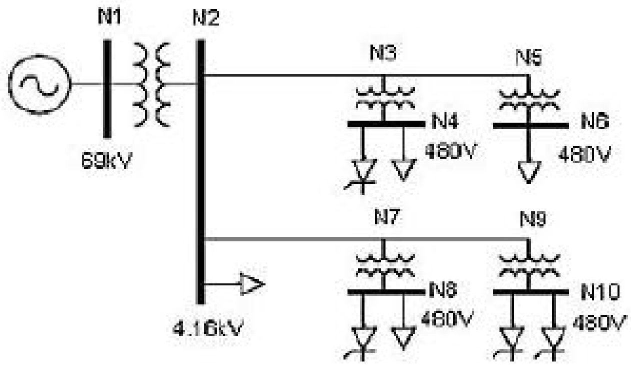

Fig.5: Industrial plant single line diagram.
Source: [29].

Os dados que descrevem a instalação industrial estão apresentados e para o processo de otimização, são considerados cinco cenários de operação possíveis, os quais são apresentados na Tabela 2.

Tabela 2: Cenários para as análises.

Parâmetro	Cenários				
	1	2	3	4	5
Duração diária do cenário (h/día)	6	10	8	0	0
Depreciação da capacitância dos filtros ΔC(%)	0	0	0	0	10
Depreciação da indutância dos filtros ΔL(%)	0	0	0	-5	5
MVA de curto-circuito no PCC (MVA)	250	250	250	125	125

Source: Authors, (2019).

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 [29]. 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 nonlinear loads [29]. 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 [30]:

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 [32] were used as energy quality constraints.

In addition, 100 generations of the algorithm were performed, with a population of 500 individuals.

4.3 DESIGN OF THE FILTERS FOR THE THREE CHARACTERISTIC SCENARIOS

In this case, by adding two non-characteristic scenarios that complicate the problem, they may have a modern scenario for all scenarios. As the voltage distortion rates increased, as in the previous case, there were no violations of the PRODIST Module 8 standard, which can be seen in Table 3.

Table 3: Initial results (case 2).

Parâmetro	Valor
Custo anual da energia ($/ano)	840124
Máximo TDD (%)	7.412
Máximo IDD (%)	6.498
Máximo THD (%)	9.090
Máximo IHD (%)	6.818
Fator de potencia	0.797

Source: Authors, (2019).

According to [29][31], 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 6.

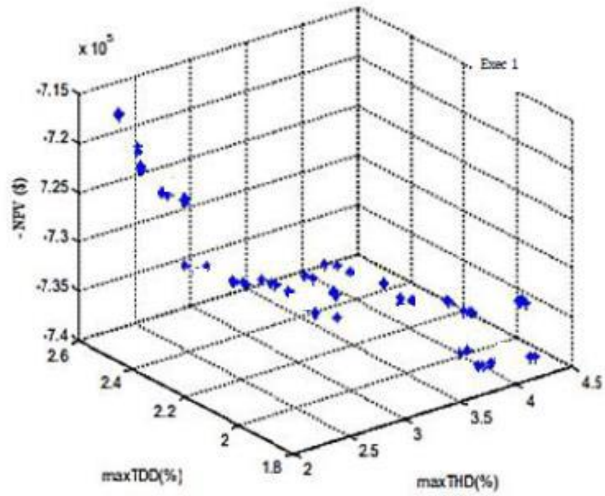

Fig.6: Pareto frontier.
Source: Authors, (2019).

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 [29][30].

A Figura 7 mostra as soluções ordenadas para o novo caso, onde se repete o comportamento observado previamente.

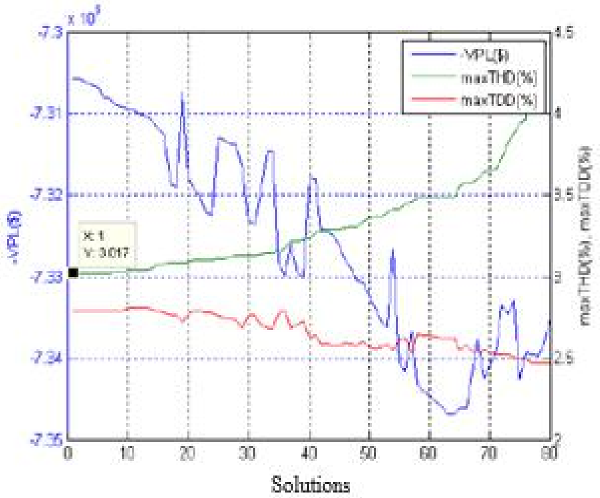

Fig.7: Ordered solutions (case 2).
Source: Authors, (2019).

The solution chosen, shown in Figure 7, is composed of the filters whose parameters are shown in Table 4.

Table 4: Parameters of selected filters (case 2).

Barra	Parâmetro	Ramo 1	Ramo 2
N4	Tipo	2ª ordem	
	Capacitor	8x50 kvar	
	Freqüência	5.6	
	Fator de qualidade	5.8	
N8	Tipo	2ª ordem	
	Capacitor	4x50 kvar	
	Freqüência	5.5	
	Fator de qualidade	5.8	
N10	Tipo	sintonizado	sintonizado
	Capacitor	4x50 kvar	2x50 kvar
	Freqüência	4.7	6.6
	Fator de qualidade	41.3	22.7

Source: Authors, (2019).

For these filters, the results of Table 5 are obtained, which demonstrate an appreciable reduction of the distortion limits, and a good NPV of the design is expected.

Table 5: Final results (case 2).

Parameters	Value	%
Annual energy cost ($/year)	637442	75.875
Max TDD (%)	2.795	37.711
Max IDD (%)	2.481	38.177
Max THD (%)	3.017	33.191
Max IHD (%)	2.594	38.040
Power Factor	0,982	123.218
Cost of filter investments ($)	37751	
Project NPV	739857	

Source: Authors, (2019).

As can be seen, in Figure 8, these filters have a very stable performance against the variations of their parameters L and C.

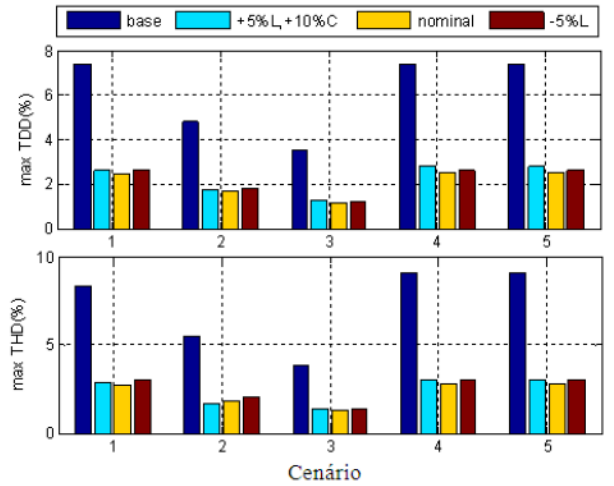

Fig.8: Results with filter depreciation (case 2).
Source: Authors, (2019).

Thus, the frequency sweep results in Figure 9 show that the impedance peaks do not match the present harmonics and therefore the selected filters can operate without problems.

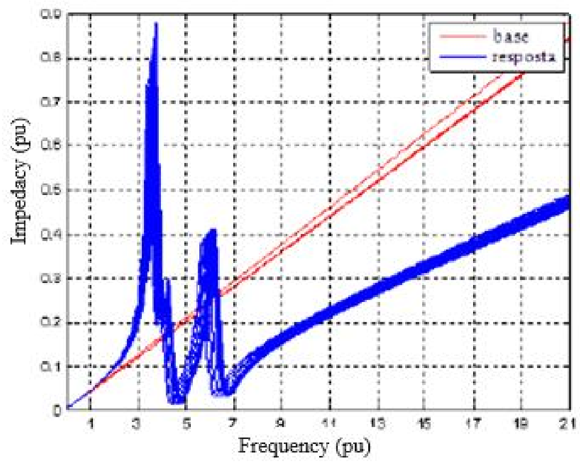

Fig.9: Frequency scanning on bar N10.
Source: Authors, (2019).

As cases 1 [29] and 2 are very similar, the results were compared for the TDD and THD distortion rates of the solution variants applied in case 2, hoping that the variant found in this case is better, especially for the scenarios 4 and 5. The results are shown in Table 6.

Table 6: Comparison between solutions 1 and 2 for case 2.

Index	Solution	Scenario					Max
		1	2	3	4	5	
maxTDD	1	2.596	1.699	1.234	2.445	4.450	4.450
	2	2.469	1.655	1.139	2.617	2.795	2.795
maxTHD	1	2.346	1.564	1.100	2.369	4.134	4.134
	2	2.742	1.834	1.280	3.017	3.017	3.017

Source: Authors, (2019).

As expected, the solution of case 2 behaves better than the solution obtained for case 1.

V. CONCLUSION

From the results obtained, the following conclusions can be drawn:

1) In order to obtain good results, it is necessary to use populations that exceed several times the number of variables of the problem. The cases considered with three filters were applied with populations of 500 elements (individuals per variable).

2) The responses obtained usually use capacitors of different powers for the different branches of a filter. This is different from the proposals of several authors, who use the same capacitors for the different branches.

3) Due to the characteristics of the genetic algorithms, there is no guarantee that the type of filter configuration chosen by the algorithm is the best. It is noticed that the algorithm will produce a set of good solutions to the problem. Therefore, the program (NSGA II) has the option to restrict the possible solutions to choose and prefix the desired configuration in each case.

4) It is necessary to improve the tools for the selection of the final variant, from the set of viable solutions, determined by NSGA II.

5) The solutions obtained with the algorithm should be analyzed for different conditions of capacitance depreciation and inductance of the filters and, in this way, correctly judge the performance of the selected filters.

6) The optimization algorithm (NSGA II) developed can adapt significantly to the parallel programming with which it would drastically reduce the execution time of the algorithm.

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