HARMONIC MITIGATION BASED ON OPTIMAL ALLOCATION AND SIZING OF TUNED FILTERS USING GENETIC ALGORITHM

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Abstract— In this paper, an optimization problem is formulated for optimal allocation and sizing of harmonic passive single-tuned filters in a power distribution system with the objective of minimizing its THD (Total Harmonic Distortion). Voltage magnitude, tuned frequency, THD and power factor are treated as inequality constraints with upper and lower bounds. The problem is solved via genetic algorithm which determines the filters locations, their connection types and parameters values, including the tuned resonance frequency and quality factor. An IEEE 33-bus radial system is used for demonstrating results obtained by the proposed method.

Keywords— Harmonic filters, Power systems, Power quality, Genetic algorithm.

Resumo— Neste artigo, um problema de otimização é formulado para alocação e dimensionamento de filtros passivos sintonizados em sistemas de distribuição de energia elétrica com o objetivo de minimizar a taxa total de distorção harmônica, THD (Total Harmonic Distortion). Magnitude de tensão, frequência de sintonia, THD e fator de potência são tratados como restrições de desigualdade com limites inferiores e superiores. O problema é resolvido via Algoritmo Genético que determina a localização dos filtros, seus tipos de conexão e valores de parâmetros, incluindo a frequência de sintonia e fator de qualidade. Um sistema IEEE radial de 33 barras é usado para demonstrar os resultados obtidos pela metodologia proposta.

Palavras-chave— Filtros harmônicos, Sistemas de potência, Qualidade de energia, Algoritmo genético.

1 Introduction

The appearing and increasing of harmonic distortion in power distribution systems are consequences of the widespread usage of nonlinear loads and power-electronic-based equipments (Brunoro et al., 2017). They are associated to several problems including power losses, resonance effects, telecommunication conflicts, malfunction of electric machines and decreasing of equipments lifespan when existing harmonics exceed the IEEE 519 standard (Halpin, 2003). As a consequence, harmonic mitigation is essential for power quality improvement.

Within this context, the installation of harmonic single-tuned passive filters into power systems represents the most simple and commonly used solution for reducing harmonic distortion, since it is cheaper than other existing solutions, according to reference (Sakar et al., 2018). These equipments are basically shunt devices, which consist of the series-connection of inductors (L), capacitors (C) and resistors (R) that in a specified tuned frequency act as a resonant element with a low impedance, forcing the current at the tuned frequency to be absorbed by the filters, flowing to the earth. The parameters are determined based on the system requirements. It is also important to decide if the filter will be connected in Y or Δ when three-phase power distribution systems are considered.

In Figure 1, the basic principle of the filter is presented. While a harmonic source (e.g. nonlinear load, distributed generation or power electronic device) is injecting harmonic currents into the power grid, the filter absorbs the currents in a specified tuned resonance frequency, mitigating harmonic propagation and consequently, the system THD (Total Harmonic Distortion).

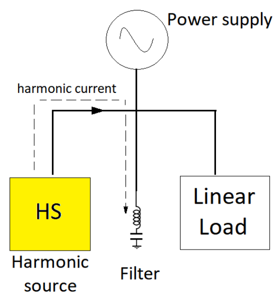


Figure 1: Basic principle of harmonic mitigation.

The tuned resonance frequency f_n in Hertz of the filter can be calculated by equation (1):

$$f_n = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The quality factor of the n^{th} filter is calculated accordingly to (2). It serves for characterizing a resonator's bandwidth relative to its tuned frequency, using a resistance value for this purpose, according to IEEE 519 standard.

$$Q_n = \frac{\sqrt{L/C}}{R} \tag{2}$$

The frequency response of a given filter is illustrated by Figure 2. It can be noted that it is tuned for 180 Hz once the lowest impedance is for this frequency, indicating that currents for that harmonic order will be absorbed by the filter.

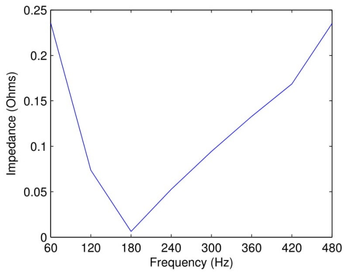


Figure 2: Filter Frequency Response.

Although harmonic filters are generally allocated at buses with large nonlinear loads and high distortion levels, the optimal allocation may not be a trivial task as it seems, because the whole system must be analyzed (Sakar et al., 2018). It means that their allocation must be decided based on global analysis and not simply just to mitigate the harmonic distortion in a single point of the network. In reference (Variz et al., 2012), three single tuned passive filters are allocated at buses without any harmonic source. However, it is proved that the optimal allocation benefits the whole system by minimizing its voltage THD.

The optimal allocation of harmonic filters can be formulated by an optimal harmonic power flow (OHPF), with an objective function to be minimized and inequality constraints to be satisfied. Once the problem is of mixed-integer non linear programming, heuristic/meta-heuristic methods are generally used for searching the optimal solutions. In reference (Rosyadi et al., 2017), an optimization problem is solved by the Whale Optimization Algorithm (WOA) for determining the optimal allocation of passive filters for reducing harmonic propagation. Ant colony algorithm is used in (Kahar and Zobaa, 2017) with the purpose of allocating harmonic single-tuned filters for reducing power losses. Particle swarm optimization is used in (Ramos and Franklin, 2016). All these references present practical solutions with satisfactory results for harmonic mitigation but they do not consider three phase radial systems.

This paper presents an optimization problem formulation for determining the optimal allocation and sizing of a given number of harmonic passive filters in power distribution networks based on the minimization of total harmonic distortion (THD) according to IEEE 519 standard. Inequality constraints are also considered for power factor, voltage magnitudes and THD. The objective is to define where the filters must be installed and also their connection type (Y or Δ connected), and their parameters optimally calculated. Genetic algorithm is used for searching the optimal solution. Simulations are carried out using a 33-bus radial system for presenting the obtained results.

2 Proposed method

2.1 The variables vector

In this paper, it is assumed that a given number N of filters will be installed into the power grid. Therefore, it must be decided where to allocate them, being their parameters and connection type also determined by the proposed method. In this paper, the number N of filters is user defined.

Their allocation are determined by a vector ALL which contains integer numbers, as presented in (3):

$$ALL = [a_1, a_2, a_3, ...a_N] \tag{3}$$

where N is the number of filters to be allocated and a represents the bus number in which the n^{th} filter is installed. Therefore, the number of integer elements within this vector is equal to the number of filters.

The connection type of each filter is also determined, as expressed by the vector CON, in (4):

$$CON = [c_1, c_2, c_3, ...c_N] \tag{4}$$

in which c represents an integer number which determines if the filter is Y or Δ- connected. Thus, in the mathematical model, the elements within the vector assumes binary encoding, being 0 associated to Y and 1 to Δ connection. It is important to decide the filters connection once they may influence on the harmonic propagation.

The capacitance parameters of the filters must be informed by the vector PAR, in (5):

$$PAR = [C_1, C_2, C_3, ...C_N] \tag{5}$$

where C_n is the capacitance value of the n^{th} filter. The total number of elements within the vector is equal to the number of filters to be allocated. The tuned frequency associated to each filter (f_n) are informed by the vector FIL, in(6):

$$FIL = [f_1, f_2, f_3, ...f_N] \tag{6}$$

Finally, the quality factors of the filters (Q_n) are informed by the vector QUA, in(7):

$$QUA = [Q_1, Q_2, Q_3, ...Q_N] \tag{7}$$

Based on the capacitance values, the tuned frequency and quality factor it is possible to calculate inductance and resistance of the filters by equations (1) and (2), respectively. In this paper, the values of the elements of each filter are assumed to be equal for each phase.

Thus, the solution is determined by the vector x, containing all the variables in ALL, CON, PAR, FIL and QUA as specified in (8):

$$x = [ALL, CON, PAR, FIL, QUA] \qquad (8)$$

Note that this is the variables vector which contains information about the location of filters, their parameters, connection types, tuned resonance frequencies and quality factors. This vector must be determined by the solution of the optimization problem presented in section 2.2.

2.2 Optimization problem formulation

The optimization problem is formulated based on the minimization of the summation of THD for all the buses of the system, for all harmonic orders and for all the three phases (A, B, C), as expressed by (9). The problem is subject to constraints from (10) to (20):

$$min \sum_{s \in \{A,B,C\}} \left(\sum_{k=1}^{Nb} THD_k^s(x) \right) \qquad (9)$$

subject to:

$$V_{k,min}^{s,1} \leq V_k^{s,1} \leq V_{k,max}^{s,1} \qquad (10)$$

$$THD_k^s \leq THD_{k,max}^s \qquad (11)$$

$$0.92 \leq pf_k \leq 1 \qquad (12)$$

$$F_1 < f_n \leq F_1 H_{max} \qquad (13)$$

$$Q_{n,min} \leq Q_n \leq Q_{n,max} \qquad (14)$$

$$C_{n,min} \leq C_n \leq C_{n,max} \qquad (15)$$

$$1 \leq a_n \leq N_b \qquad (16)$$

$$c_n \in \{0, 1\} \qquad (17)$$

$$L_n = \frac{1}{(2\pi f_n)^2 C_n} \qquad (18)$$

$$R_n = \frac{\sqrt{L_n / C_n}}{Q_n} \qquad (19)$$

$$THD_k^s = \frac{\sqrt{(\sum_{h \neq 1}^{H_{max}} V_k^{s,h})^2}}{V_k^{s,1}} \qquad (20)$$

where:

- N_b is the total number of buses of the system;
- F_1 is the fundamental frequency;
- $V_k^{s,h}$ is the voltage at bus k, on phase s, for harmonic order h;
- $V_{k,min}^{s,1}$ and $V_{k,max}^{s,1}$ are the upper and lower bounds of the voltage magnitude for fundamental frequency $(h = 1)$;
- pf_k is the power factor calculated for a given bus k in which the filter is installed;
- f_n is the n^{th} filter tuned frequency, which is an integer value different from F_1 with upper bound equal to $F_1 H_{max}$;
- Q_n, $Q_{n,min}$ and $Q_{n,max}$ is the quality factor of an n^{th} filter, minimum and maximum allowed values, respectively;
- $C_{n,min}$ and $C_{n,max}$ are the lower and upper bounds for the capacitance value of the n^{th} filter;
- L_n and R_n are the inductance and resistance value of an n^{th} filter;
- H_{max} is the maximum harmonic order considered by the study.

Note that the objective function minimizes the THD as function of the solution x, defined in equation (8). The optimization problem contains non linear inequality constraints and also integer ones, being a mixed-integer non linear programming problem. In this paper, the solution is obtained using genetic algorithm (GA).

3 Genetic Algorithm

3.1 Basic theory

The genetic algorithm technique simulates the processes of species evolution based on the natural selection theory proposed by Darwin. Evolutionary strategies algorithms, such GA aims to find the optimal solution of a given optimization problem by minimizing or maximizing a given objective (fitness) function (Whitley, 1994).

Basically, the solution is obtained iteratively, being the iterations of the algorithm named as generations. Each possible solution is known as individual (the variables vector) and each element within an individual is known as a chromosome gene. The search for the optimal solution is made through successive application of genetic operations on a set of individuals (Kothari, 2012).

The basic flowchart of the GA is presented in Figure 3.

Firstly, a given initial population is created randomly. The objective function is analyzed for each possible solution (individual). A stopping criteria must be pre-determined based on the maximum number of generations (g), stagnation, or maximum allowed computational time.

If the stopping criteria is not satisfied, a new population must be created based on the application of genetic operators, such selection of best individuals, crossover, mutation and elitism. They are briefly discussed below:

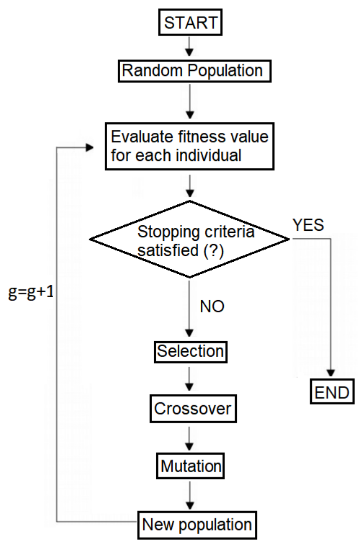


Figure 3: GA basic flowchart.

- Selection: This operator is used for determining the best candidates among a population. The best individuals are those who better minimize the objective function. They are called as parents, once they are more likely to reproduce, generating better individuals. One of the most common selection methods is roulette with rank, in which a given percentage of individuals are selected to be parents and reproduce;
- Crossover: Once the parents are selected, they must reproduce by the crossover operator, which is responsible for the combination of characteristics (parameters) of each individual in the reproduction of a new one with inherited characteristics. When a new individual is created by the crossover of their parents, the parents will no more exist in the next generation. In the crossover, chromosome genes are mutually exchanged in order to create a new individual;
- Mutation: This operator introduce a "disturbance" in the chromosome genes of some randomly selected individuals. The purpose is to ensure genetic diversity of the population during the evolution process;
- Elitism: With this operator, a percentage portion of best individuals in each population are kept in the next generation without crossover or mutation. This feature is used to prevent the disappearance of the best individuals during the genetic operations.

The new population is evaluated at the new generation ($g = g + 1$) and if the stopping criteria is satisfied, the algorithm stops.

3.2 Application into the proposed method

The solution vector in equation (8) comprises information about the optimal allocation and sizing of harmonic filters.

An initial population of possible candidates (individuals) is created randomly, being each one of them evaluated with respect to their capability of minimizing the objective function (6).

Genetic operators are applied to create a new population, searching for better solutions at each generation. The stopping criteria will be adopted as the maximum number of generations and response stagnation.

The optimization model has inequality constraints. Therefore, in order not to allow any constraint violation, a penalty factor equal to 100 is assigned to the objective function if any constraint is violated. This feature avoids the selection of worst solutions. Other parameters will be defined along the tests ans results section.

The GA toolbox of the MATLAB software is used for the computational time, using a computer Intel Core i5-4770 CPU @ 3.40 GHz and 16 GB (RAM), with the operational system Windows-8.

4 Tests and Results

4.1 Test System

The 33-bus radial distribution system is used for the computational simulations. The fundamental frequency is 60Hz and the system data are determined in (Melo et al., 2016), including unbalanced three phases and mutual impedances. Its single-line diagram is presented in Figure 4:

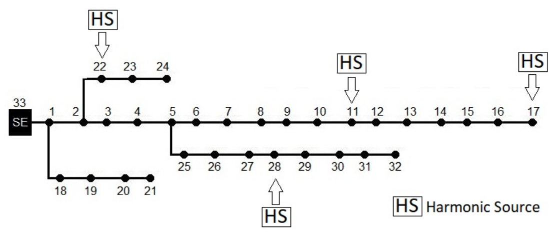


Figure 4: 33-bus distribution system.

Dominant harmonic sources are considered at buses number 11, 17, 22 and 28. Their data is presented in Appendix A. The linear loads for harmonic frequencies are according to CIGRE model (Corasaniti et al., 2001)

A harmonic power flow is used as reference (Variz et al., 2006) in order to analyze the harmonics propagations and flow into the system. It is executed for each possible solution candidate (individual) in order to assess the system state.

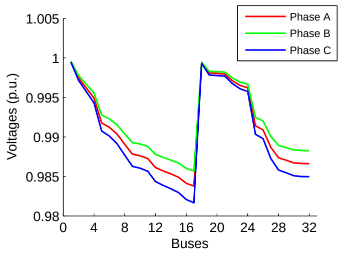
The minimum allowed capacitance value is 10^{-5} and maximum is 10^{-2} pu, based on reference (Variz et al., 2012).

The connection must be also determined by the system requirements. $Q_{n,min}$ and $Q_{n,max}$ are set equal to 20 and 100, as in (Kahar and Zobaa, 2017). Voltage magnitudes lower and upper bounds at fundamental frequency are respectively 0.95 and 1.05 pu as in (Bakirtzis et al., 2002). The maximum allowed voltage THD at each bus is 5%, according to the IEEE Standard 519/2014.

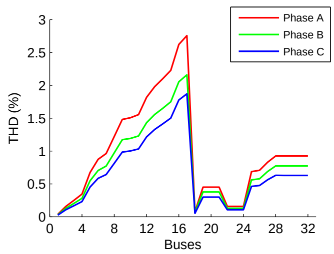
The first case study presents results for the voltage magnitudes and THD for the system without the instalation of the filters. The second case study presents results for the instalation of three filters and in the third one, sub-areas are predetermined for their installation. The fourth case presents results when only one filter is allocated into the system.

4.2 Case-1

Firstly, the system is evaluated without the allocation of harmonic passive tuned filters. The purpose is to show the actual state of the system before the filters installation. The harmonic load flow is executed, and gives as solution the voltage profiles for the three phases and the voltage THD, presented in Figure 5:



(a) Voltage profiles.



(b) THD profiles.

Figure 5: Results for Case-1.

It can be noted that there are buses with THD near to 3% and the voltage profile is between acceptable limits.

If the objective function would be calculated for this case, it would result in 78.45. The question that this paper seeks to answer is: How much the objective function can be minimized when the filters are installed into the system?

4.3 Case-2

Three harmonic passive filters must be installed into the 33-bus power system, with the purpose of mitigating harmonic distortion.

The individuals of the population are formed according to the vector (8). The population contains a total number of individuals equal to 2 times the number of variables to be calculated. The initial population is created randomly. The selection operator used the roulette method with rank as in (Variz et al., 2012). The elitism is set to 10% of the population. The crossover is done in two different points (chromosome genes) of the individuals chosen as parents. The mutation rate is set to 1% with uniform bit replacement defined randomly. The convergence criterion used is the response stagnation with tolerance of 10^{-6} pu and also the maximum number of 1000 generations. These values are adopted based on reference (Variz et al., 2012) and on previous sensitivity analysis of the method.

Results for the optimal allocation and sizing are presented in Table 1. The three filters are connected in Y, being their locations at buses 17, 27 and 20. The capacitance, tuned frequency and quality factors are also determined.

Table 1: Optimal solution for Case-2

Location	C_n (pu)	**Conn.**	f_n (Hz)	Q_n
Bus 17	0.0079	Y	300	25.80
Bus 27	0.0081	Y	420	36.45
Bus 20	0.0083	Y	180	51.82

The results of the solution are provided with a maximum number of 37 generations after 23.53 minutes of computational simulations. The minimized value of the objective function is 41.20, which is less than the base case value (78.45). There is an impressive reduction of 47%.

In Figure 6, the convergence process is presented for each generation of the algorithm. At each generation, each individual of the population was evaluated. The best individual is the one who better fits the objective function minimization. Mean values are also indicated for each created population.

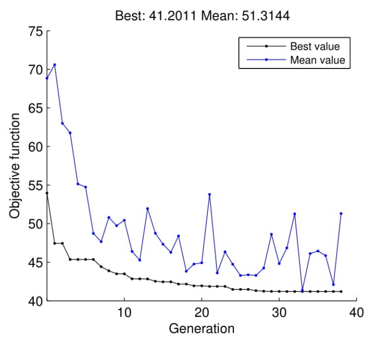
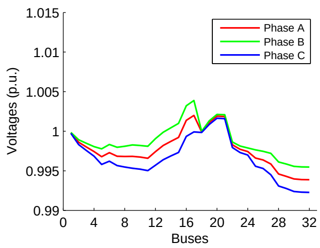


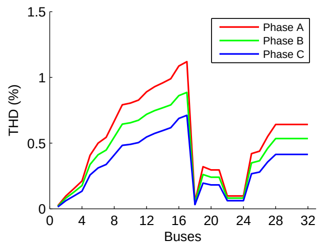
Figure 6: Mean and best results at each generation.

The algorithm has a good convergence process since the objective function decreases at each generation, until the stopping criteria is satisfied.

In Figure 7, the results for voltage profile and THD on each one of the three phases are presented. It can clearly be noted that the introduction of the capacitance values increases the voltage magnitudes. However, all calculated values are between the proposed upper/lower limits. The THD values are all decreased for the system buses. Note that in the base case, there were buses with THD near to 3%. In this case, the values are generally lower than 1%, except for buses 16 and 17 at phase A, slightly exceeding this threshold to 1.1%.



(a) Voltage profiles.



(b) THD profiles.

Figure 7: Results for Case-2.

With this case study, it can be proved the efficiency of the proposed methodology for harmonic mitigation by the adopted allocation procedure. The THD values are all reduced, meaning that the propagation of harmonics is controlled by the strategy and the voltage profiles are better than the previous situation once their magnitudes are very close to the unitary value.

4.4 Case-3

In this case study, three harmonic filters must be installed into the system. However, sub-areas are pre-selected in order to limit the number of possible solutions of the algorithm. The first filter must be allocated from bus number 5 to 15, the second from bus 18 to 23 and the third from bus 25 to 31. This case study presents a practical situation which can happen in real scenarios, when the utility have different areas of interest to mitigate harmonics or specific portions of the system which require enhancement due to poor power quality.

Results for the optimal allocation and sizing are presented in Table 2.

It can be noted the second filter are connected in Δ, differently from the others. The filters locations are at buses 14, 22 and 27. Results for quality factors associated to each filter are also presented, as well as the capacitance values.

Solution is found with a maximum number of 34 generations after 21.65 minutes of computational simulation. The minimized value of the objective function is 43.21, which is less than the base case value (78.45) but greater than case-2, in which there is no restriction for candidate buses for filters allocation. The reduction is of 44.9%.

Table 2: Optimal solution for Case-3

Location	C_n (pu)	**Conn.**	f_n (Hz)	Q_n
Bus 14	0.0087	Y	180	66.8258
Bus 22	0.0094	Δ	300	58.2107
Bus 27	0.0092	Y	300	37.1531

In Figure 8, the convergence process is presented during the generations of the algorithm:

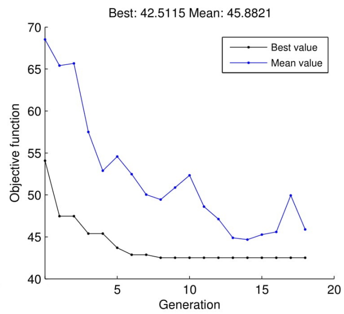
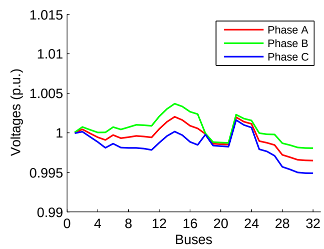
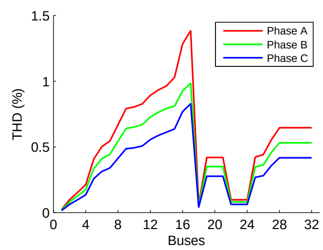


Figure 8: Mean and best results at each generation.

In Figure 9, the results for three-phase voltage profiles and THD are shown. All the calculated values are between proposed bounds. The maximum THD (1.4%) is for bus 17, phase A.



(a) Voltage profiles.



(b) THD profiles.

Figure 9: Results for Case-3.

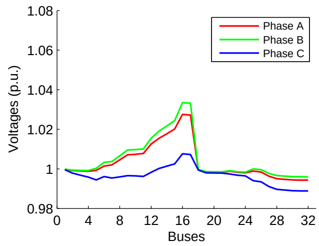
4.5 Case-4

One harmonic passive filter must be installed into the 33-bus power system. The GA parameters are equal to Case-1. According to Table 3, it would be installed at bus 16, Δ-connected, tuned to 180 Hz with quality factor of 35.0547.

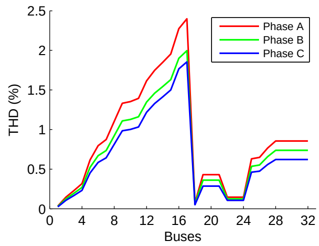
Table 3: Optimal solution for Case-4

Location	C_n (pu)	**Conn.**	f_n (Hz)	Q_n
Bus 16	0.0081	Δ	180	35.0547

The voltage profiles for the three phases and their THD are presented in Figure 10. The maximum THD is at bus 17 with 2.2%. The objective function is equal to 72.79. In comparison to the base case, the reduction is of 7.21%.



(a) Voltage profiles.



(b) THD profiles.

Figure 10: Results for Case-2.

In Figure 11, the convergence process is presented during the 23 generations of the algorithm:

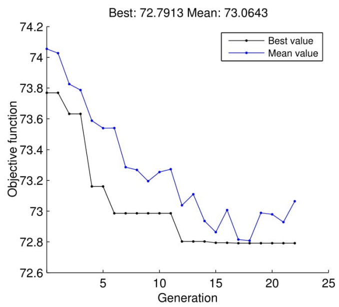


Figure 11: Mean and best results at each generation.

4.90 minutes is the computational time spent by the algorithm to provide the solution.

4.6 Comparative analysis

In this subsection, results are compared for the four case studies considered in this paper. The maximum THD, minimum and maximum voltage magnitudes are presented in Table 4:

The better solution is obviously for Case-2 once the voltage magnitudes are very close to 1 pu for all the buses of the system. The third case also presents better solution than base case. However, their results are less impressive than Case-2.

When only one filter is installed, the voltage profile and THD values are improved. However, it is not much effective as the other cases.

Table 4: Comparative analysis

Case	THD_{max} (%)	V_{min} (pu)	V_{max} (pu)
1	2.78	0.983	1.000
2	1.12	0.993	1.003
3	1.44	0.995	1.004
4	2.45	0.999	1.031

5 Conclusions

By the presented results, it can be affirmed that the installation of the harmonic filters really reduced the harmonic distortion of the system. The decision of the allocation of the filters is determined by the algorithm and it does not depend on other methods, representing a practical solution for power quality management in power distribution systems.

The three phase voltage profiles are improved as well as their total harmonic distortion index.

Not only the localization of the filters but also their parameters, connection types are calculated based on the tuned resonance frequency and quality factor of each one of the devices, according to the definitions in IEEE 519 standard.

The computational time spent by the algorithm is adequate since the allocation of filters can be faced as a medium-term planning strategy.

Future works include optimal allocation for power losses minimization, other evolutionary strategies for solving the proposed optimization problem, minimization of costs associated to the project, correction of unbalances by switched capacitor banks and other systems.

6 Acknowledgments

The authors thank INERGE, CNPq, FAPEMIG and CAPES for providing financial support for this work.

7 Appendix

From Table 5 to 8, the harmonic sources data are presented. Values are based on reference (Melo et al., 2016).

Table 5: Harmonic source at bus 11.

h	I^A (%)	θ^A (^{o})	I^B (%)	θ^B (^{o})	I^C (%)	θ^C (^{o})
1	100	0	100	0	100	0
3	35.87	-7.09	18.96	-19.74	35.23	-51.86
5	33.20	-10.70	14.01	93.38	21.25	-70.77
7	28.81	-14.42	10.18	-149.12	13.92	76.16
9	2.10	-14.42	1.18	-149.12	3.42	76.16

Table 6: Harmonic source at bus 17.

h	I^A (%)	θ^A (^{o})	I^B (%)	θ^B (^{o})	I^C (%)	θ^C (^{o})
1	100.00	0	100.00	0	100.00	0
3	22.76	-5.29	12.09	-25.50	22.48	-50.74
5	21.03	-8.22	8.93	87.86	13.53	-169.44
7	18.41	-11.02	6.45	-152.82	8.93	77.86
11	2.81	-14.42	1.18	-149.12	3.92	76.16

Table 7: Harmonic source at bus 22.

h	I^A (%)	θ^A (^{o})	I^B (%)	θ^B (^{o})	I^C (%)	θ^C (^{o})
1	100.00	0	100.00	0	100.00	0
3	47.82	-4.19	25.71	-19.74	55.36	-45.93
5	44.72	-6.38	20.33	93.38	34.29	-166.65
7	39.78	-8.70	15.33	-149.12	22.85	79.37
9	2.10	-14.42	1.18	-148.02	3.52	75.11

Table 8: Harmonic source at bus 28.

h	I^A (%)	θ^A (^{o})	I^B (%)	θ^B (^{o})	I^C (%)	θ^C (^{o})
1	100.00	0	100.00	0	100.00	0
3	35.87	-7.09	18.96	-19.74	35.23	-51.86
5	33.20	-10.70	14.01	93.38	21.25	-170.77
7	28.81	-14.42	10.18	-149.12	13.92	76.16
15	2.81	-14.42	1.18	-149.12	3.92	76.16

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