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Passive filters allocation in unbalanced distribution network with high penetration of distributed generation

Alocação de filtros passivos em rede de distribuição desequilibrada com alta penetração de geração distribuída

Marcelo Semensato[1*], Jaqueline Oliveira Rezende[2], José Antônio Lambert[3]

[1,2,3] Doctor in electrical engineering, Teacher and Researcher, Instituto Federal de Goiás, campus Jataí, GO, Brazil

* Corresponding author, E-mail: marcelo.semensato@ifg.edu.br

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Abstract: The purpose of this paper is the allocation of passive filters in an unbalanced power network with high penetration of distributed generation to minimize the costs of power losses in the distribution lines, including power losses caused by harmonic components and neutral conductor power losses due to unbalanced loads. The harmonic components and the fundamental current generated by the distributed generation cause a voltage increase in the generation bus, and the voltages in the network above the limit allowed by standard are reduced by allocating passive filters without cutting the active power in the distributed generation. The unbalance and reactive power compensation is performed by the ideal compensation method applied to the distribution network. The tests are for the IEEE 34 bus network, with the fourth wire in the simulation being the isolated neutral. The scatter search metaheuristic applied in the simulation tends to minimize the costs of power losses in the lines and the costs of the passive filters allocated in the medium voltage distribution network, meeting the operational constraints of the network.
Keywords: Allocation of passive filters, unbalanced distribution network, ideal compensation method, harmonic components, distributed generation.

1 Introduction

In the distribution network, unbalanced loads and distributed generation (DG) are connected. The electrical currents of unbalanced three-phase and single-phase loads generate current and voltage unbalance along the network. Unbalanced currents generate additional losses power in the power network due to negative-sequence and zero-sequence components, which are undesirable in networks with symmetrical generation and balanced line impedance. The IEEE 34-bus medium voltage distribution network tested in this paper is a network with unbalanced loads (three-phase and single-phase), high penetration of photovoltaic distributed generation and with the presence of the neutral conductor.

Unbalanced three-phase loads in the power network consume positive-sequence, negative-sequence, and zero-sequence currents. Negative-sequence, zero-sequence currents, and the reactive part of the positive-sequence current not perform work and can be compensated (Emanuel, 2011). The compensation of these portions in distribution networks with unbalanced loads is performed by the ideal compensation method (Semensato, 2019). The ideal compensation method is commonly used in the literature to compensate isolated loads (Lee; Wu, 1993; Oliveira; Neto; Souza, 2000), allowing the supply voltages to be symmetrical and the power factor to be unity. The ideal compensation method applied in distribution networks to reduce losses due to unbalance and reactive power is proposed in Semensato (2019), without the use of passive filters, only with capacitors. In Semensato (2022) the author compares the ideal compensation method with the capacitor allocation method by phase and with the capacitor allocation method by balanced bank, the latter two being traditional methods for allocation in unbalanced distribution networks. The author proves the effectiveness of the ideal compensation method in relation to the others by tests performed on the unbalanced distribution network. Therefore, the objective of this paper is not the comparison of methods, but the application of passive filters in the ideal compensation (unbalance compensation and reactive power). The passive filter, in addition to ideal compensation, is useful in reducing the voltage in the DG bus, in cases of high penetration, and in filtering the harmonic components caused by the DG inverters.

Frequency inverters, which are electronically switched devices, present in photovoltaic systems, inject harmonic currents into the network (Oliva and Balda, 2003; Jannesar et al., 2019). These harmonic currents cause losses power in the lines, increase in photovoltaic generation bus voltage in relation to the zero Volt reference in the substation for harmonic frequencies and can cause resonance in the network between inductors (loads and lines) and installed capacitors.

The harmonic currents injected by photovoltaic systems do not produce active power and can be compensated through passive filters that establish low impedance paths for the harmonic current at a specific frequency, that is, each filter is specified for a current harmonic frequency. This low impedance path prevents the harmonic current from causing additional losses in the network, resonance, high harmonic distortion and voltage increase in the generation bus due to this current injected into the network.

In this paper, passive filters (series combination of capacitor and inductor) can be modeled as predominantly inductive or capacitive at the fundamental frequency of the network. The filter modeled as an inductive load in the fundamental is used to reduce the voltage in the network, allowing the voltages in the buses to meet the standard, without cutting the active power of the DG. This method is used so that the power distribution company bills with the power of the installed generators themselves in view of the costs and losses power in the network due to the installed inductive load.

The high penetration of DG in the network increases the voltages in the buses, which can reach voltages above the standard. The DG inverters can be adjusted to consume or supply reactive power, that is, they can operate with capacitive or inductive power factor, but for that they must be designed for this amount of reactive power (Flota et al., 2016). Depending on the amount of active power generated by the DG, the power factor control by the inverter is not effective in reducing the voltages in the network, requiring the use of the inductive load allocation method (predominantly inductive filter). The inductive load allocation method is used when batteries have already been allocated or are costly compared to the inductor, not including these devices in the paper.

The objective of the paper is to minimize losses power in the unbalanced medium voltage distribution network with high penetration of DG and harmonic components, meeting operational restrictions such as the voltage level on the buses, the unbalance factor and the total harmonic distortion, without cut of the active power of the DGs. The minimization of losses power and operational restrictions are met by the allocation of passive filters in the network with capacitive or inductive predominance in the network frequency and by controlling the power factor in the DG. Passive filters can have different values per phase and be connected in wye or delta to ensure unbalance compensation. The compensation of the unbalance will be visible by the reduction of losses in the neutral conductor.

The contributions of the paper are in the allocation of passive filters for ideal compensation and in the reduction of voltages in the network buses with allocation of inductive loads without cutting the generation.

The scattered search metaheuristic (Martí, Laguna and Glover, 2006) is applied to minimize the costs of losses power in the network and the costs of installed passive filters. The costs are seen from the side of the power distribution company, which owns distributed generators. These costs justify the importance of inductive compensators allocation by the company, without cutting the active power of the DGs. The optimization algorithm is implemented in MatLab software and the four-wire power flow is performed in OpenDSS software.

The authors in León (2022) review the solutions adopted for the high penetration of photovoltaic distributed generation. The authors cite as solutions reinforcing conductors, voltage regulators, static distribution controllers, cutting active power from DG, reactive power control using frequency inverters, demand side management and batteries with charge and discharge control. In comparison with the techniques in León (2022), control of reactive by the inverter is used in this paper in addition to inductive load allocation to find solutions related to high DG penetration, but other methods are not used due to the high cost.

The authors in Hong and Chiu (2010) allocate passive filters in the 18-bus network using the Simultaneous Perturbation Stochastic Approximation algorithm in order to minimize the costs of passive filters and meet restrictions on harmonic distortion, power factor and tuning frequency. The results are compared with the genetic algorithm.

In Au and Milanovic (2007) the authors propose the allocation of passive filters using a sensitivity index and injection of harmonic currents with different modules. The authors show that the location and magnitude of the injected harmonic current influence the bus sensitivity. The objective is to reduce the total harmonic distortion in the buses and the maximum distortion in an 11 kV distribution network.

Passive filter allocation is performed to reduce harmonic distortion and minimize losses power (Jannesar, 2019). The harmonic components injected into the network are due to non-linear loads and the high penetration of photovoltaic generation. In addition to reducing losses power, mitigating harmonics increases the capacity of the photovoltaic generator. The author takes a probabilistic approach to loads and generation, considering the phase angle of harmonic currents.

In Melo (2020) the author allocates passive filters in unbalanced power networks, connected in wye or delta, to minimize the total harmonic distortion in the buses and improve some indices of power quality. Phases can have filters of different capacitive values. The genetic algorithm is used for optimization. The networks do not have a neutral conductor for the simulations.

The paper is divided into six sections. The second section describes the compensation methods, the third section discusses the optimization algorithm, the fourth is the problem formulation, the fifth section is the paper results and the last section the conclusion.

2 Compensation methods

The ideal compensation method is the compensation of unbalance power and reactive power in unbalanced three-phase loads. The unbalance power of unbalanced loads, which is calculated by the symmetrical component of the zero- and negative-sequence current, does no work and can be compensated for by using passive elements, even in purely resistive loads. An error occurs when the unbalance compensation in three-phase loads is carried out by compensating only the calculated reactive power per phase and when the connection of the compensators (delta or wye) is disregarded.

The ideal compensation of a three-phase power load connected in wye with wye-center connected to the neutral conductor is obtained by passive components (capacitor and/or inductor) connected in delta and wye, as shown in Figure 1. Wye-connected compensators inject the symmetrical component of the zero-sequence current (unbalance power) and the imaginary part of the positive-sequence current (reactive power) into the network. Delta-connected compensators inject negative-sequence current (unbalance power) and an imaginary part of positive-sequence current into the network. Both connections, delta and wye, can share the reactive power compensation or only one connection can fully compensate the reactive power (Lee; Wu, 1993). Only the delta connection compensates the portion of the unbalance power corresponding to the negative-sequence current and the wye connection compensates the portion of the unbalance power corresponding to the zero-sequence current.

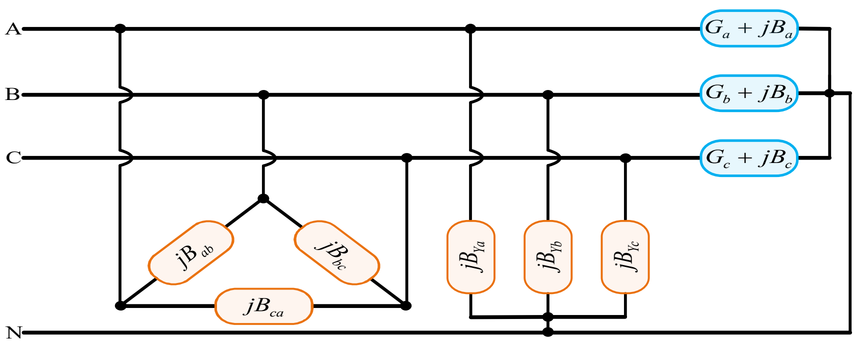

Figure 1. Ideal compensation.

The passive components for ideal compensation of the wye-connected three-phase load, Figure 1, are calculated according to Eq. (1). In this case, the wye-connected compensator compensates the reactive power of the load. Ideal compensation raises the power factor seen by the source to unity. Where G is conductance and B is susceptance, in Siemens.

$$B_{Ya} = \frac{G_b}{\sqrt{3}} - \frac{G_c}{\sqrt{3}} - B_a;\ B_{Yb} = \frac{G_c}{\sqrt{3}} - \frac{G_a}{\sqrt{3}} - B_b;\ B_{Yc} = \frac{G_a}{\sqrt{3}} - \frac{G_b}{\sqrt{3}} - B_c;\ B_{ab} = \frac{2\sqrt{3}(G_a - G_b)}{9};\ B_{bc} = \frac{2\sqrt{3}(G_b - G_c)}{9};\ B_{ca} = \frac{2\sqrt{3}(G_c - G_a)}{9} \quad (1)$$

A new approach to compensation in Eq. (1) results in compensation of unbalance power and increase in load reactive power. This new method compensates for the unbalance and contributes to reducing the voltage in the network, including the distributed generation bus, as long as the load susceptances per phase ($B_a, B_b\ e\ B_c$) are not compensated, but increased to a value that is equal to at all phases. In this case, the power factor seen by the source is inductive, assuming the load is inductive.

The ideal compensation and its new approach previously described can be performed by means of passive filters, since the passive filter at the fundamental frequency has inductive or capacitive predominance, and can be connected in wye or delta. In this paper, the passive filter, in addition to ideal compensation, is used to filter harmonics and reduce the distributed generation voltage. Therefore, the passive filter at the fundamental is used for ideal compensation or as an inductive load, and at harmonic frequencies it is useful as a filter.

Figure 2 exemplifies the compensation characteristics in which a passive filter is inserted in bus 2 (L_2 in series with C_1) of an electrical system. A passive filter, in its simple topology, is the series connection of an inductor and a capacitor, connected in parallel to the system (Shakeri; Esmaeili; Koochi, 2022). In this paper, the tuning frequency of the passive filter varies according to the value of the inductor and the capacitor, randomly selected by the meta-heuristic.

The predominantly capacitive filter at fundamental frequency at bus 2 in Figure 2 is inserted to attenuate the penetration of the specific harmonic component of current I_h in the network, this component being the sum $I_{h1} + I_{h2}$, therefore, the current I_{h2} is much smaller than I_{h1}. Being I_h injected by distributed generation (DG). This filtering reduces the active losses in the network, since the harmonic losses are $R_2 I_h^2 + R_1 I_{h2}^2$. This attenuation also allows the reduction of the harmonic voltage on bus 3 (V_{h3}), corresponding to the DG bus, as$V_{h3} = R_2 I_h + (R_1 + j\omega_h L_1) I_{h2}$, being ω_h the harmonic frequency. The advantage of the predominantly capacitive filter is that at the fundamental frequency it injects reactive current into the network (I_{qr}) to compensate the inductive power factor of the load (R_3+j$\omega_1 L_3$), reducing the reactive current in the line (I_{qs}) and increasing the voltage in bus 2, according to the equations $I_{qc} = I_{qs} + I_{qr}$ and $V_2 = V_1 - (R_1 + j\omega_1 L_1)(I_{ps} + jI_{qs})$, where ω_1 is the fundamental frequency and $V_1$is the constant voltage on bus 1 of the substation (Subs).

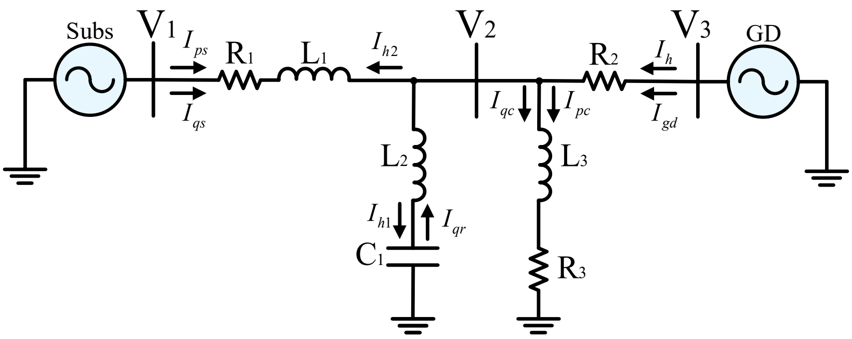

Figure 2. Electrical system with the presence of passive filter.

The disadvantage for the system with high DG penetration is the voltage increase at the fundamental frequency on the DG bus (which may reach levels above the standard), since $V_3 = V_2 + R_2 I_{gd}$, Where I_{gd} is the current supplied by the DG operating with unit power factor. The predominantly inductive filter at the fundamental frequency inserted in bus 2 of Figure 2 consumes a reactive current from the network ($-I_{qr}$) at the fundamental frequency, where $I_{qs} = -I_{qr} + I_{qc}$, therefore causes a reduction in the DG voltage at the fundamental frequency, as $V_3 = V_1 - (R_1 + j\omega_1 L_1)(I_{ps} + jI_{qs}) + R_2 I_{gd}$, increasing line losses power. This filter does not contribute to the filtering of the harmonic component, I_h, as it establishes a high reactance path, increasing the losses power in the line at harmonic frequency. In both types of passive filters, the active load current is $I_{pc} = I_{ps} + I_{gd}$.

The scheme in Figure 2 is per phase, considering the same logic for unbalanced three-phase systems in which it is possible to allocate three single-phase passive filters with different values, connected in wye or delta. It is possible to adjust the filters to Eq. (1) to, including filtering, compensate or add reactive power and unbalance power compensation.

3 Meta-heuristics scatter search

The scatter search (SS) is a meta-heuristic based on diversification and intensification in the search for solutions (Martí; Laguna; Glover, 2006). The population consists of 100 randomly generated individuals, being classified as feasible and unfeasible. The first stage of SS consists of an improvement of this population. In this paper, the improvement steps are acquired from the Chu-Beasley genetic algorithm (Huanca; Gallego, 2021), through tournament selection, recombination, mutation and local improvement. The individual with the best fitness in each generation is replaced in the population in the position of the lowest fitness individual, if applicable. The quality of the solution (fitness) is evaluated by the objective function.

In the second stage, 20 individuals are selected for the quality solutions set (QSS). These 20 individuals are selected among the feasible individuals based on quality and diversification, with the first ten being the highest quality and the last ten having the worst quality. The QSS receives the improvement of the first stage and the best individual is the solution to the problem. The individual's coding is presented in Table 1.

Table 1. Coding of the individual.

B	X	C_a	C_b	C_c	L_a	L_b	L_c	...	f_1	f_2	f_3	f_4	f_5

An individual represents the allocation of five passive filters in the network, thus allowing filters to be allocated in a maximum of 15% of the bus in the network. Being B and X, the allocation bus and the filter connection type (wye or delta), respectively. The columns C_a and L_a, C_b and L_b, C_c and L_c represent the values of capacitors (C) and inductors (L) connected in series allocated in phases *a, b* and *c,* respectively. If connection X is wye, the filters are connected between phase and neutral, if connected in delta, the filters are connected between phases, following the order *a-b, b-c* and *c-a*. The first eight columns correspond to the allocation of one passive filter, thus moving on to the other four allocated filters. In the optimization algorithm, it is possible to zero any inductor or capacitor, or both, with the possibility that purely capacitive, inductive or no filters are allocated in the network. The five final columns of the individual represent the power factor of the five generators distributed in the network, which can be capacitive, inductive or unity power factor.

The nominal values of the capacitors for allocation in the network are 50, 75, 100, 133 and 150, in kVAr, at the fundamental frequency (60 Hz). The nominal values are specified both for capacitors connected between phase and neutral (single-phase nominal network voltage) and for capacitors connected between phase and phase (nominal line voltage). Inducers for allocation are 3.6547, 1.3157, 0.6713, 2.4365, 0.8771, 0.4475, 1.8274, 0.6578, 0.3356, 1.3740, 0.4946, 0.2524, 1.2183, 0.4386 and 0.223, in H, values for passive filters connected between phase and phase. The inductor values for passive filters connected between phase and neutral are these divided by three. The values of the inductors are calculated for the resonance in series with the capacitors at the three harmonic frequencies of the currents injected by the distributed generation. For example, the first three inductor values (3.6547, 1.3157 and 0.6713) are resonant with the 50 kVAr capacitor, at frequencies of 180 Hz, 300 Hz and 420 Hz, respectively. However, the composition of the individual can contain any passive filter configuration among the values of the presented capacitors and inductors, randomly selected by the meta-heuristic. The power factors of the distributed generators can be selected randomly among the values from 0.92 to 0.99, for the generation to supply reactive power and from -0.99 to -0.92, for the generation to consume reactive power. Both with a step of 0.01. Unity power factor is also included in the algorithm.

4 Problem formulation

The problem is to minimize the objective function and meet the operational constraints of the network.

The objective function given in Eq. (2) is the cost of power losses in the power network added to the cost of allocated capacitors and inductors. The costs of power losses are accounted for over a period of 20 years, corresponding to the useful life of the allocated equipment (Jannesar, 2019). The cost of electrical energy and power loads are considered constant during this period.

$$fo = C_E(Perdf + 10Perdn) + C_c Cap + C_L L, \quad (2)$$

where:
C_E: Cost of electrical energy (54 US$/MWh) (CCEE, 2023);
$Perdf$: Power losses in the phases of the power network during the period of 20 years (MWh);
$Perdn$: Power losses in the neutral conductor during the period of 20 years (MWh);
C_c: Cost of capacitors ($5{,}10\ US\$/kVAr$);
C_L: Cost of inductors ($12000\ US\$/H$);
Cap: Sum of allocated capacitors (kVAr); and
L: Sum of allocated inductors (H).

Power losses are calculated for the fundamental frequency and harmonic components present in the power network. The power losses in the neutral are multiplied by 10 and this value is adopted for a better compensation of losses in the conductor, considering that in symmetrical and balanced three-phase systems these losses are zero.

Operational constraints are given in Eqs. (3), (4) and (5).

$$0.93 \leq V_{fn} \leq 1.05, \quad (3)$$

$$fd \leq 2\ \%, \quad (4)$$

$$THD \leq 5\ \%. \quad (5)$$

The V_{fn} index is the effective voltage between phase and neutral on the network bus, in *pu*, calculated for all network frequencies, according to Eq. (6), where h is the order of the harmonic frequency. The neutral voltage must be minimized, as this directly influences the calculation of the restriction in Eq. (3) (ANEEL, 2021). The index fd is the unbalance factor, calculated for the fundamental frequency (ANEEL, 2021). The THD index is the total harmonic distortion of voltage in the network bus (IEEE, 2014).

$$V_{rms} = \sqrt{\sum_{h=1}^{\infty} V_h^2}. \quad (6)$$

5 Results

The simulated power network is the IEEE 34-bus (Ciric, Feltrin and Ochoa, 2003). The power network in (Ciric, Feltrin and Ochoa, 2003) has unbalanced loads and the neutral conductor is present throughout the network. The neutral is isolated, that is, it is not grounded. Power loads are connected between phase and neutral, modeled as constant power type at fundamental frequency. The voltage at the substation, bus zero, is symmetrical and has a value of 1 pu. The substation is solidly grounded. The nominal voltage of the network is 24.9 kV (phase-phase), with the adopted bases equal to 24.9 kV and 1 MVA.

Five photovoltaic generators are allocated in the power network with constant active power at the fundamental frequency in the values of 600, 500, 600, 500 and 600, in kW, inserted in buses 12, 18, 22, 24, and 30, respectively. Generators can operate with positive, negative or unity power factor, as described in section 3.

The DGs inject harmonic currents into the network at frequencies of 180, 300, and 420, in Hz, corresponding to the third, fifth and seventh harmonics, respectively. The value of each harmonic component (third, fifth and seventh) is 0.5 A per phase, on all generators. These harmonic components are chosen because they present the most significant values in photovoltaic generation (Oliva; Balda, 2003). Current harmonic components are modeled as constant current source (Yang; Adinda, 2021).

Passive filters are allocated in network bus, in shunt. In the simulations, a resistance of 10 ohms is inserted in the allocated passive filters, in series, representing the power losses.

Four cases are simulated for the IEEE 34-bus network:

- **Case 1** – Nominal load. The values of the DGs are 600, 500, 600, 500 and 600, in kW, and the harmonic currents are 0.5 A, as already specified;
- **Case 2** – The third and fifth harmonics are raised to 0.7 A and 0.6 A per phase, respectively. The remaining data are the same as case 1;
- **Case 3** – The power loads in phases a and c are increased and decreased by 5 %, respectively. The values of the DGs are 200, 150, 200, 150, and 200, in order and in kW. Third, fifth and seventh order harmonics are reduced to 0.1 A per phase, each component;
- **Case 4** – The weighting of the value of losses in the neutral conductor in Eq. (2) is increased from 10 to 50. The remaining data are the same as case 3.

The power flow is simulated in OpenDSS software and the SS algorithm is implemented in MatLab software. MatLab and OpenDSS software are programmed to share common data. The power flow data are essential for the SS algorithm, as well as the location of the filters is fundamental for the power flow.

The passive filters allocated in the network and the power factor of the DGs is shown in Table 6 and Table 7, respectively, for each simulated case (results for the simulated cases). The indices a, b and c represent the connection to the phases and the index *n* represents the connection to the neutral (Table 6).

5.1 Results for the case 1

Costs are the objective function value in Eq. (2). The expression $Perdf + Perdn$ represents the total power losses in the network during the 20 year period. The base value (Base) is the simulation results when filters are not allocated. The adopted power factor for the DGs is unitary, before the allocation of the passive filters. The *fd* and *THD* indices represent their maximum values obtained in the simulation.

The voltages in phases a, b and c for the base value are shown in Figure 3. The voltages obtained by the passive filter allocation method (PFA), described in sections 2 and 3, are shown in Figure 4. The results for the simulated case are shown in Table 2.

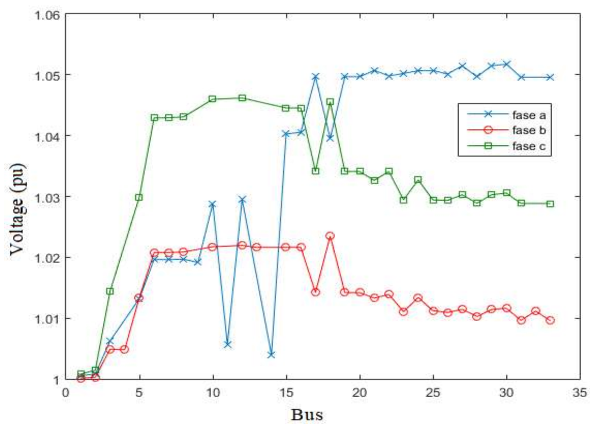

Figure 3. Voltage in the network phases to base value (case 1).

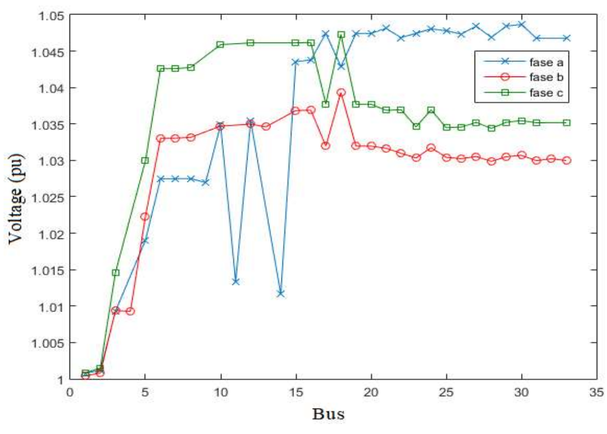

Figure 4. Voltage in the network phases for the PFA (case 1).

Table 2. Results for the case 1.

	Base	PFA
Costs (US$)	2,069,956	1,790,888
$Perdn$ (MWh)	604.88	373.02
$Perdf + Perdn$ (MWh)	32888.57	28773.54
fd (%)	0.6	1.22
THD (%)	3.86	2.18

5.2 Results for the case 2

The voltages for the base value are shown in Figure 5 and the voltages for the PFA are shown in Figure 6. The results for the simulated case are shown in Table 3.

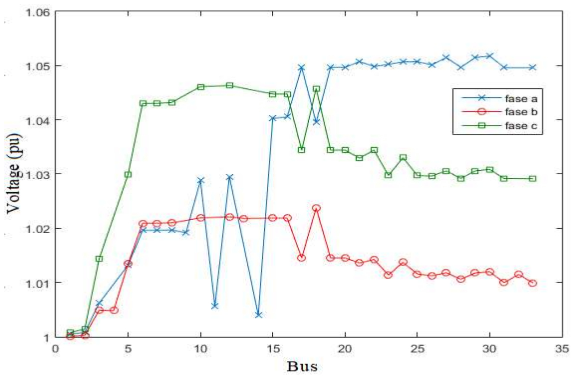

Figure 5. Voltage in the network phases to base value (case 2).

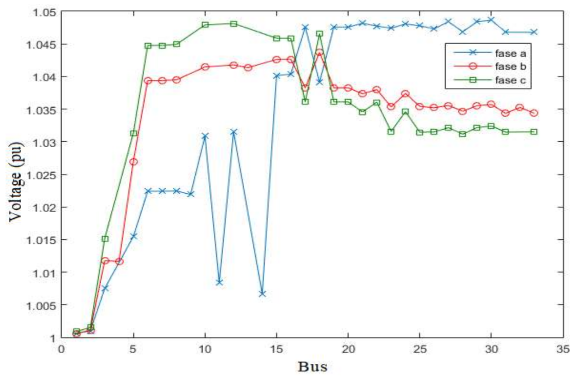

Figure 6. Voltage in the network phases for the PFA (case 2).

Table 3. Results for the case 2.

	Base	PFA
Costs (US$)	2,098,304	1,898,181
$Perdn$ (MWh)	646.06	623.62
$Perdf + Perdn$ (MWh)	33042.91	28608.02
fd (%)	0.6	1.38
THD (%)	4.69	3.79

5.3 Results for the case 3

The voltages for base value and PFA are shown in Figure 7 and Figure 8, respectively. The voltage profile in the neutral conductor is shown in Figure 9. The results for the simulated case are shown in Table 4.

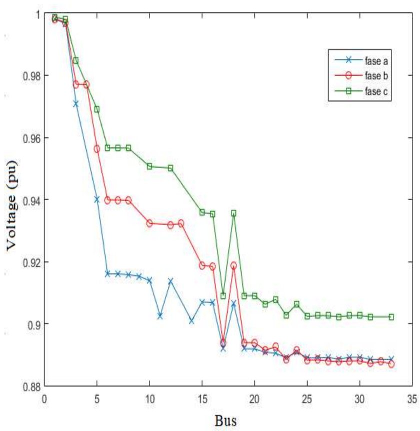

Figure 7. Voltage in the network phases to base value (case 3).

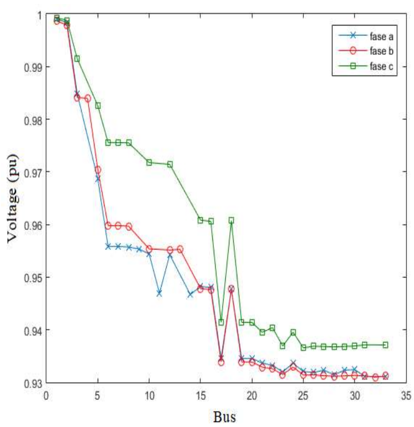

Figure 8. Voltage in the network phases for the PFA (case 3).

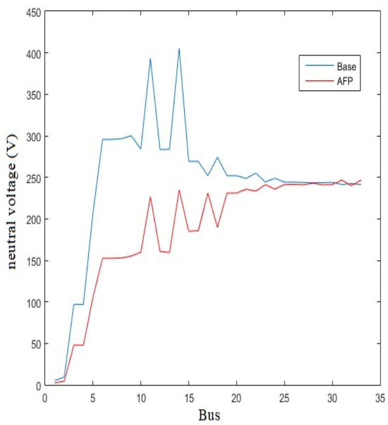

Figure 9. Voltage in the neutral conductor (case 3).

Table 4. Results for the case 3.

	Base	PFA
Costs (US$)	1,429,282	715,001
$Perdn$ (MWh)	566.34	208.20
$Perdf + Perdn$ (MWh)	21371.13	10339.61
fd (%)	0.88	0.91
THD (%)	1.42	1.64

5.4 Results for the case 4

The voltages for the base value are shown in Figure 10 and the voltages for the PFA are shown in Figure 11. The voltage profile in the neutral conductor is shown in Figure 12. The results for the simulated case are shown in Table 5.

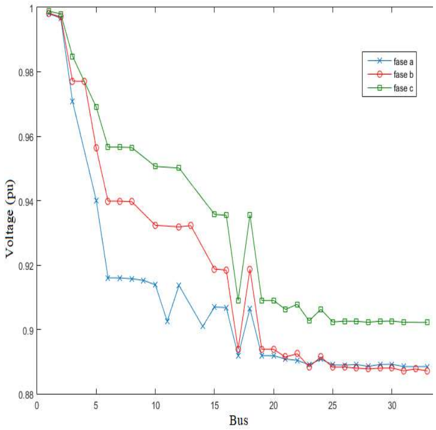

Figure 10. Voltage in the network phases to base value (case 4).

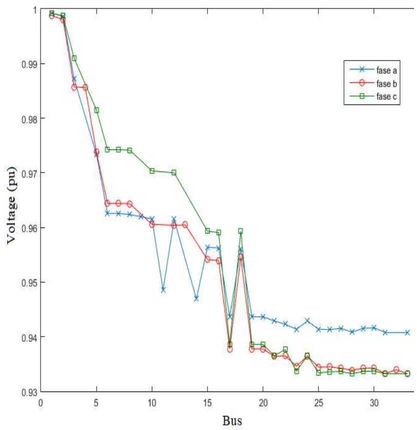

Figure 11. Voltage in the network phases for the PFA (case 4).

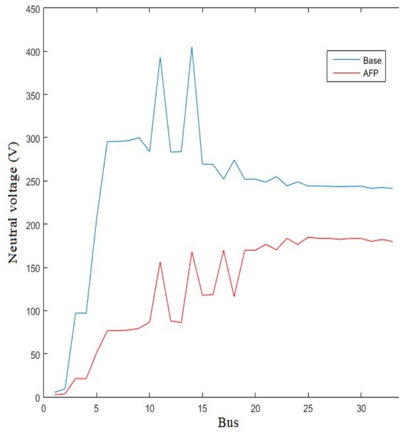

Figure 12. Voltage in the neutral conductor (case 4).

Table 5. Results for the case 4.

	Base	PFA
Costs (US$)	2,652,576	1,138,869
$Perdn$ (MWh)	566.34	191.09
$Perdf + Perdn$ (MWh)	21371.13	10863.99
fd (%)	0.88	0.97
THD (%)	1.42	1.30

The phase *a* presents voltages above the maximum limit in Eq. (3) for case 1 and case 2, as shown in Figure 3 and Figure 5, respectively, before the allocation of passive filters (Base). The power network has voltages below the minimum limit in Eq. (3) for case 3 and case 4, as shown in Figure 7 and Figure 10, respectively, without the allocation of filters. The results of the four cases by the PFA method show that the voltages meet the standard in Eq. (3), as shown in Figure 4, Figure 6, Figure 8 and Figure 11. The costs of case 1, 2, 3, and 4 show a reduction of 13.48%, 9.54%, 49.97% and 57.07%, respectively. Costs are reduced by the PFA method, even in cases where the voltages in the network bus are high (case 1 and 2).

The losses in the neutral conductor for cases 1, 2, 3, and 4 present a reduction of 38.33%, 3.47%, 63.24% and 66.26%, respectively, therefore, the unbalance in the neutral is reduced by the PFA method. Passive filter is useful for filtering harmonic components, compensation or increase of reactive power and according to Eq. (1) compensation of unbalance (zero- and negative-sequence fundamental current component). The algorithm, however, prioritizes the costs of losses in the phases and in the neutral conductor, with the reduction of losses in the neutral due to the compensation of the zero-sequence current component of the fundamental and the third harmonic. Figure 12 shows the lowest neutral voltage level for the PFA method, as a higher value is attributed in the objective function to neutral losses for case 4 compared to case 3.

Unlike neutral losses, the unbalance factor does not reduce, as it only accounts for the negative-sequence in its equation in Eq. (4), not being present in the objective function in Eq. (2). Harmonic distortion presents a greater reduction in cases with greater harmonic penetration, case 1 (43.52% reduction) and case 2 (19.19% reduction), as they are more harmful to the system. The reduction in total losses is greater in case 3 (51.62%), because in this case the voltage level is not high as in cases 1 and 2, allowing the insertion of predominantly capacitive or purely capacitive passive filters at the fundamental frequency. The active power cut method of distributed generation is not viable in relation to the PFA method, as it will be necessary to contract more energy electrical from centralized generation, buying energy at the price of the PLD (Firmes et al., 2018).

Table 6. Allocated passive filters.

	Bus, Phase, Filter Value (Capacitor in kVAr in fundamental; Inductor in H; Resistor in Ohm)
Case 1	7a-n(133; 0.4061; 10); 7b-n(50; 0.4061; 10); 7c-n(100; 0.2238; 10); 23a-b(50; 0; 10); 31a-n(75; 0.1462; 10); 31b-n(133; 0.0841; 10); 31c-n(100; 0.2924; 10); 33a-b(0; 0.6713; 10); 33b-c(133; 1.8274; 10); 33c-a(100; 0.2238; 10).
Case 2	6a-b(150; 0.6713; 10); 6b-c(100; 0.2238; 10); 6c-a(0; 0.4386; 0); 17a-b(100; 0.2238; 10); 17b-c(133; 0.4946; 10); 17c-a(75; 0.2238; 10); 33b-c(150; 0.6713; 10); 33c-a(150; 0.8771; 10).
Case 3	8a-n(75; 0; 10); 8c-n(133; 0.2238; 10); 14a-n(75; 0.1119; 10); 28a-b(100; 0.2238; 10); 28b-c(150; 0.2238; 10); 28c-a(100; 0.8771; 10); 30a-b(133; 0.2524; 10); 30b-c(133; 0; 10); 30c-a(50; 0.6578; 10); 31a-n(75; 1.2182; 10); 31b-n(150; 0.2193; 10); 31c-n(75; 0.0841; 10).
Case 4	6a-n(100; 0.2924; 10); 6b-n(0; 0.0746; 10); 6c-n(133; 0.4061; 10); 9a-n(50; 0; 10); 16a-b(0; 0.4475; 10); 16b-c(150; 0.8771; 10); 16c-a(0; 0.2238; 10); 23a-n(100; 0.4386; 10); 23b-n(150; 0.1462; 10); 23c-n(100; 0; 10); 26a-n(75; 0; 10); 26b-n(50; 0.458; 10); 26c-n(50; 0.1119; 10).

Table 7. Power factor of DGs.

	DG1	DG2	DG3	DG4	DG5
Case 1	-0.96	0.98	-0.92	-0.97	-0.96
Case 2	0.97	-0.95	1	-0.93	-0.96
Case 3	0.93	-0.95	0.94	0.94	-0.96
Case 4	0.93	0.92	0.92	0.95	0.94

6 Conclusion

The tested cases prove the validity of the method of passive filters allocation to maintain the voltage in the network within the established limit, reducing the losses in the phases and in the neutral conductor. The method can be used by power distribution company in order to filter harmonics and minimize power losses in the network without active power cuts in distributed generation. The results, obtained from an original proposal, although complex simulation, are practicable and simple to install in the power network. The reduction of power losses and the insertion of renewable energy sources in the network are linked to sustainable development, both in terms of economics, social and environmental responsibility.

References

ANEEL - AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional – PRODIST (2021). Available: https://www2.aneel.gov.br/cedoc/aren2021956_2_7.pdf (Accessed May 2023).

Au, MT and Milanovic, JV (2007) 'Planning Approaches for the Strategic Placement of Passive Harmonic Filters in Radial Distribution Networks', *IEEE Trans. Power Delivery*, vol. 22, no. 1, pp. 347-353.

CCEE - Câmera de Comercialização de Energia Elétrica. [Online]. Available: https://www.ccee.org.br/ (Accessed May 2023).

Ciric, RM, Feltrin, AP and Ochoa, LF (2003) 'Power Flow in Four-Wire Distribution Networks-General Approach', *IEEE Trans. Power Syst.,* vol. 18, no. 4, pp. 1283–1290.

Emanuel, AE (2011) *Power Definitions and the Physical Mechanism of Power Flow*. Ed. WILEY-IEEE PRESS.

Firmes, VP, Silva, A, Chaves, GLD, Celeste, WC (2018) 'Uma análise do consumo de energia elétrica na UFES - campus São Mateus', *Latin American Journal of Energy Research – Lajer*, v.5, n.2, pp. 1-11.

Flota, M, Ali, B, Villanueva, C and Pérez, M (2016) 'Passivity-Based Control for a Photovoltaic Inverter with Power Factor Correction and Night Operation', *IEEE Latin America Transactions*, vol. 14, no. 8, pp. 3569-3574.

Hong, Y and Chiu, C (2010) 'Passive Filter Planning Using Simultaneous Perturbation Stochastic Approximation', *IEEE Trans. Power Delivery*, vol. 25, no. 2, pp. 939-946.

Huanca, DH and Gallego, LA (2021) 'Chu and Beasley Genetic Algorithm to Solve the Transmission Network Expansion Planning Problem Considering Active Power Losses', *IEEE Latin America Transactions*, vol. 19, no. 11, pp. 1967-1975.

IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems (*IEEE STD 519-2014)*, (2014), New York.

Jannesar, MR, Sedighi, A, Savaghebi, M and Anvari-Moghaddam, A (2019) 'Optimal probabilistic planning of passive harmonic filters in distribution networks with high penetration of photovoltaic generation', *Electrical Power and Energy Systems*, vol. 110, pp. 332-348.

Lee, S and Wu, C (1993) 'On-line Reactive Power Compensation Schemes for Unbalanced three Phase Four Wire Distribution Feeders', *IEEE Trans. Power Deliv.*, vol. 8, no. 4, pp. 1958–1965.

León, L, Martinez, M, Ontiveros, LJ and Mercado, PE (2022) 'Devices and Control Strategies for Voltage Regulation Under Influence of Photovoltaic Distributed Generation. A review', *IEEE Latin America Transactions*, vol. 20, no. 5, pp. 731-745.

Martí, R, Laguna, M and Glover, F (2006) 'Principles of scatter search', *European Journal of Operational Research*, vol. 169, pp. 359-372

Melo, ID, Pereira, JLR, Variz, AM and Ribeiro, PF (2020) 'Allocation and sizing of single tuned passive filters in three-phase distribution systems for power quality improvement', *Electric Power Systems Research*, vol. 180, pp. 1-12.

Oliva, AR and Balda, JCA (2003) 'A PV dispersed generator: A power quality analysis within the IEEE 519', *IEEE Trans. Power Delivery*, vol. 18, no. 2, pp. 525–530.

Oliveira, LCO, Neto, MCB and Souza, JB (2000) 'Load Compensationin Four-Wire Electrical Power Systems', *IEEE 2000 International Conference on Power System Technology*, pp. 1575-1580.

Semensato, M. (2019) 'Application of the Ideal Compensation Method in Unbalanced Distribution Network Considering Harmonics', *IEEE PES Innovative Smart Grid Technologies Conference Latin America*, pp. 1-6.

Semensato, M (2022) 'Capacitor placement in unbalanced distribution networks to minimize reactive and unbalance power losses', *Congresso Brasileiro de Automática*, vol. 2, no.1, pp. 1-8.

Shakeri, S, Esmaeili, S and Koochi, MHR (2022) "Passive Harmonic Filter Design Considering Voltage Sag Performance - Applicable to Large Industries", *IEEE Trans. Power Delivery*, vol. 37, no. 3, pp. 1714-1722.

Yang, N and Adinda, EW (2021) 'MATPOWER-Based Harmonic Power Flow Analysis for Power Systems With Passive Power Filters', *IEEE Access*, vol. 9, pp. 167322-167331.