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Overall power quality correction in distribution networks by active power filters. Optimization of location and strategy

***Abstract**. Power quality correction in distribution networks is usually performed locally, with a corrective device in each polluted bus. An overall correction system could provide acceptable results with reduction of costs. This paper presents a method for optimizing location and operation strategy of active power filters (APFs) in a distribution network, using a harmonic power flow algorithm. The proposed operation strategy for the APFs is inspired by perfect harmonic cancellation (PHC) and it is compared to other inspired by droop control.*

Streszczenie.** Poprawa jakości energii w sieci dystrybucyjnej zazwyczaj jest wykonywana lokalnie, przez zastosowanie urządzeń korekcyjnych w każdej linii, gdzie występują odkształcenia. Ogólny system poprawy mógłby zapewnić lepsze wyniki redukcji kosztów. W artykule przedstawiono metodę optymalizacji miejsca lokalizacji i opis działania energetycznych filtrów aktywnych (APF) w sieci dystrybucyjnej, stosując algorytm harmonicznych przepływu mocy. Proponowana strategia sterowania APF jest argumentowana doskonałą eliminacją harmonicznych (PHC) i jest porównywana z innymi metodami sterowania typu „droop control". (**Ogólna poprawa jakości energii w sieci dystrybucyjnej energetycznymi filtrami aktywnymi. Optymalizacja rozmieszczenia i strategii)

Keywords: Active power filters, power quality, harmonic power flow, pollutant loads.
Słowa kluczowe: Energetyczny filtr aktywny, jakość energii, przepływ mocy odkształcenia,

Introduction

The presence of harmonics in power systems is nowadays an expected situation in most distribution networks, due to the proliferation of pollutant loads as computers or other electronic devices. Power quality and electromagnetic compatibility standards [1-3] limit their presence locally in generation and consumption facilities, but the integration of multiple pollutant loads and even pollutant generation systems can lead to a poor power quality in voltage of network buses, mainly in radially operated networks, the most commonly used structure for distribution systems.

Many devices, as passive, active or hybrid power filters, and operation strategies have been developed for locally correction of power quality problems [4-7]. However, the contribution of these devices to the power quality improvement of the whole grid is nowadays under study [8-10] and new tools must be developed to facilitate and automate this task. On the other hand, harmonic power flow has been widely studied in time and frequency domain for power systems, with the aim of knowing the influence of pollutant loads in other buses of the network they are connected to [11-12].

This paper presents a simple method for integrating active power filters (APFs) in a harmonic load flow algorithm, with the aim of developing a tool for studying and optimizing their location and the strategy they must follow to reduce the Total Harmonic Distortion (THD) in the voltage of the network buses. Although the presented algorithm is prepared for radial networks, it can be easily extended to meshed networks.

The paper is structured as follows: firstly, a simple method for analyzing the harmonic load flow in terms of frequency with the possibility of integration of active power filters for power quality improvement is presented; secondly, different models for lines, linear and nonlinear loads and active power filters with two different operation strategies are proposed; thereafter a simulation of a distribution network is done and results for different locations and strategies of the active power filters are shown; finally, conclusions are presented.

Frequency domain harmonic load flow

In this paper, a simple method for a harmonic load flow analysis is proposed for radial networks. In this situation, we can suppose that the voltage in the supplying bus is known and the current there injected has a good quality (without harmonics). This algorithm uses the Norton equivalent circuits of elements connected to the different nodes [11], and currents are considered positive when enter the node.

For considering the different harmonics, the algorithm is repeated for each one, modifying in each case the current injected by active elements and the values of passive elements, as it is explained in Sections III and IV.

Finally, once calculated the voltage harmonics in each bus, up to the maximum order of harmonic determined, the Total Harmonic Distortion (THD) of each bus and power losses of the whole grid are calculated. THD in the bus *i* is defined in (1).

(1) $$THD_i(\%) = 100\frac{\sqrt{\sum_{h=2}^{H}\left(V_{i,h}\right)^2}}{V_{i,1}}$$

where: $V_{i,h}$ – h-harmonic voltage component in bus i, $V_{i,1}$ – fundamental voltage component in bus i, H – maximum order of harmonic considered.

Power losses are calculated from the resistance of the lines and the current that pass through them, considering every harmonic. Fig. 1 shows the proposed harmonic power flow algorithm.

Models for sources, power lines and loads

Before applying the algorithm, the different elements of the network must be modeled to be considered in the analysis. As it can be seen from Fig. 1, the proposed harmonic load flow algorithm works with Norton equivalent circuits for active elements, as it calculates currents and then obtains resulting voltages.

For our simulation, power sources and loads have been considered active elements of the network and their Norton equivalent circuits have been obtained and considered in the algorithm.

Fig. 2 shows a radial three-phase balanced network used as an example to illustrate the usefulness of the proposed algorithm.

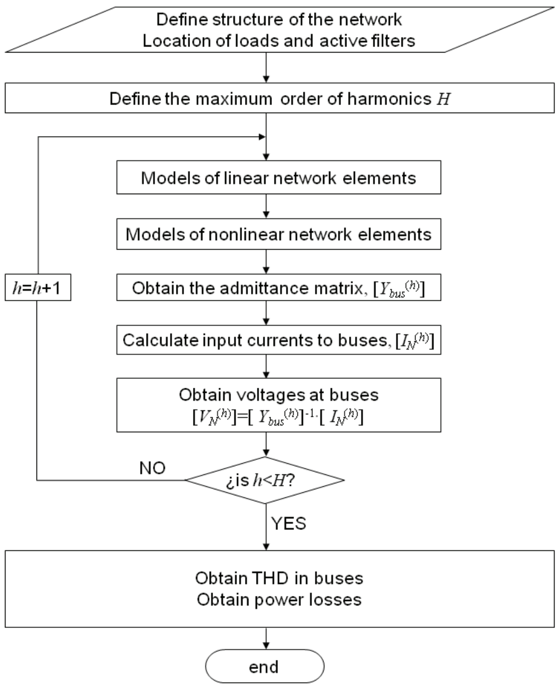

Fig.1. General algorithm for harmonic load flow analysis in radial networks

Model for the source

As this work deals with a radial network, only one power source has been used for simulation. It is located in the node number 1 and it presents a pu impedance of 0.017j (every pu magnitudes in this paper are referred to 6 kVA and 220 V base). For calculating the Norton current, a voltage of 1 pu has been considered in this node. This element only acts as a source for the first harmonic (fundamental component), as we consider that the power quality of the supply grid is good. For the other harmonics, this element is considered as passive shunt impedance.

Model for power lines

Power lines are usually modelled by a combination of series impedance and shunt capacitance. The length of the pieces of line in distribution network is not high enough to encourage to the use of distributed parameters for a steady state analysis, thus concentrated series resistance and reactance and shunt capacitance have been considered in this work. Capacitors are located in the network nodes for simulation. Although a line resistance is only influenced for the frequency due to the skin effect, it can be considered negligible for the purpose of this paper. However, both reactance and susceptance are proportional to the frequency. Therefore, values of these parameters must be adapted to the harmonic order. For each harmonic, the fundamental value of reactance and susceptance of lines are multiplied by the order of the harmonic, as it determines the proportionality with frequency.

For the example presented in this paper, two different types of lines have been used (Fig.2). Their parameter values, for 50 Hz fundamental frequency, are shown in Table 1.

Table 1. Data of lines (pu), referred to 6000 VA and 220 V base

Type of line	line 1	line 2
Resistance (pu)	0.0062	0.0123
Reactante (pu)	0.0093	0.0186
Susceptance (pu)	0.0913	0.0913

Model for linear loads

In linear loads, the current demanded can be calculated from the voltage in the node where it is connected and its impedance. For this work, one linear load has been used. It acts as a passive element with a shunt resistive impedance of 0.4 pu.

Model for nonlinear loads

A non-controlled rectifier is a source of harmonics in a power system. An idealized three-phase non-controlled 6-pulse rectifier, with constant dc current is used for simulation (Fig. 3), an acceptable approximation for rectifiers connected to R-L loads. For modelling these loads it is necessary to take into account the waveform distortion in order to achieve a better description of the interaction with the network. The current wave can be decomposed in Fourier series and each harmonic component can be injected into the system as a power source; thus, it is possible to determine harmonic voltages of the system nodes if a frequency sweep is made on the network.

Therefore, nonlinear loads can be modelled as constant current sources for each harmonic frequency and are calculated regarding to the fundamental frequency current. It is well known that an idealized three-phase 6-pulse rectifier, as describes above, demands a current composed by a fundamental component, $I_{R,1}$ and a combination of harmonics calculated as

$$I_{R,h}=\frac{I_{R,1}}{h} \tag{2}$$

where: $I_{R,h}$ is the h-harmonic current component demanded by the rectifier. In this case even and triple harmonics are zero [13],

$I_{R,1}$ is the current drawn by the rectifier at the fundamental component, whose expression is obtained from (3):

$$I_{R,1}=\frac{4}{\pi}\int_{\pi/6}^{\pi/2} I_0\cdot\sin(\theta)\cdot d\theta \tag{3}$$

where: I_0 – dc current provided by the rectifier, assumed to be constant.

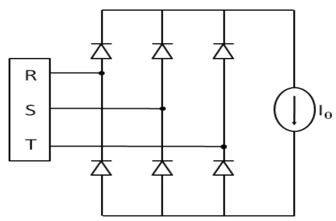

Fig.3. Three-phase non-controlled 6-pulse rectifier

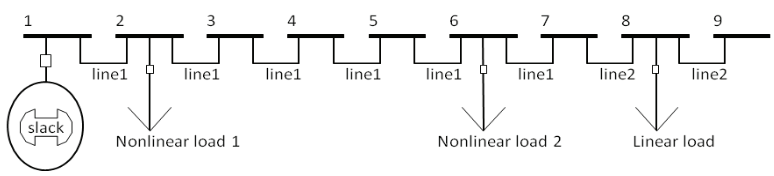

Fig.2. Network used for simulation

By solving the previous integral, the next expression is obtained:

$$I_{R,1} = \frac{4}{\pi} I_0 [\cos\theta]_{\pi/2}^{\pi/6} = \frac{4}{\pi} I_0 \frac{\sqrt{3}}{2} = \frac{2\sqrt{3}}{\pi} I_0 \quad (4)$$

If V_0 is the average dc voltage provided by the rectifier, R is the dc equivalent resistance, provided by the known rated capacity of the rectifier ($S_{RECTIF.}$) and V_{LL} is the line-to line ac voltage:

$$I_0 = \frac{V_0}{R} = \frac{1.35 \cdot V_{LL}}{R} \quad (5)$$

with:

$$R = \frac{(1.35 \cdot V_{LL})^2}{S_{RECTIF.}} \quad (6)$$

On the other hand, the equivalent star resistance of rectifier for the purposes of modelling its behaviour for the fundamental component can be expressed by:

$$R_{eq} = \frac{V_{LL}}{\sqrt{3} \cdot I_{R,1}} \quad (7)$$

Consequently, the equivalent resistance results:

$$R_{eq} = \frac{1.35 \cdot \pi \cdot V_{LL}^{\ 2}}{6 \cdot S_{RECTIF.}} \quad (8)$$

For the first harmonic, rectifiers are considered to behave as passive resistances, with values shown in (8). For the remaining harmonics, the Norton equivalent circuit for the rectifier is a current source calculated from (2). In this calculation, $I_{R,1}$ is obtained from the resistance in (8) and the obtained fundamental voltage in its node (7).

For the example presented in this paper, two ideal three-phase 6-pulse non-controlled rectifiers have been used (Fig.2). Their parameter values are shown in Table 2.

Table 2. Data of rectifiers (pu), referred to 6000 VA and 220 V base

Parameters:	Rectifier 1	Rectifier 2
Rated capacity, $S_{RECTIF.}$ (pu)	0.46	0.554
Equivalent resistance, R_{eq} (pu)	1.5356	1.2759

Models and strategies for active power filters

Active power filters (APFs) are being investigated and developed as a solution for power quality problems in nodes of networks where pollutant loads are connected. Several topologies and control strategies have been proposed for their performance. In [4], four control strategies for shunt active power filters are discussed and compared in different conditions of power quality of the current demanded by the pollutant load. In [4], the control strategy named perfect harmonic cancellation (PHC) is proved to be the most complete correction method, in presence of harmonics, unbalance and reactive power. The term “perfect harmonic cancellation” was introduced in [7] by the authors who proposed the strategy. Its philosophy consists on defining a reference current synchronized with the fundamental positive-sequence voltage in the connection bus, which is calculated with the aim of cancelling all the harmonic currents demanded by the load.

In the present paper, we introduce a distribution network with several linear and nonlinear loads connected in different buses. In this situation, the possibility of power quality correction in the case that location of pollutant loads is not exactly known must be considered. Therefore, the objective of the APFs must not be to correct power quality only in the bus where the pollutant load is connected, but in every nodes of the main grid.

In this section a performance strategy inspired by PHC [4] is proposed to reduce the voltage distortion in every node of a radial distribution network. Then, its performance is compared with a method based on droop control, proposed by [8].

In both cases, the action of the APFs is introduced in the harmonic power flow algorithm described in Section II, and the Total Harmonic Distortion (THD) of the bus voltages, as defined in (1) is used to evaluate results.

Strategy inspired by perfect harmonic cancellation (PHC)

As it has been commented before, the objective of the APFs in this paper is to correct power quality in every nodes of the distribution grid, not only in the node where the pollutant loads are connected. Therefore, the strategy of the APFs must be different than the conventional ones, consisting of cancelling harmonics due to the load connected to the same bus.

In this case, the control strategy of each APF is to cancel, if possible, every harmonic current present in the piece of the line located immediately upwards the APF node (Fig. 4). As the line is radial, this strategy pursues to reduce and even to totally cancel every harmonic in nodes located upwards of the APF.

With this strategy, THD is expected to be zero in every node if an APF is located in each node in which a pollutant load is connected. In other cases, the total cancellation of harmonics is not guaranteed. An obvious disadvantage of this strategy is that APFs located downwards of the pollutant loads are not useful and cannot contribute to harmonic cancellation.

The integration of this strategy for APFs in the harmonic power flow algorithm is made in two steps:

1) First, the harmonic power flow is done without considering APFs. Thus, harmonic components of voltage in different nodes are calculated.

2) In the second step, the target current needed from the APFs to cancel each harmonic current in the upwards piece of line is calculated. For this purpose, the harmonic currents in that piece of line are calculated from the voltages of the node where APF is connected and the previous one and the known impedance if the piece of line, adapted to each harmonic. Once obtained the target current for the APF, the harmonic power flow is repeated adding the contribution of the APFs, calculated as described.

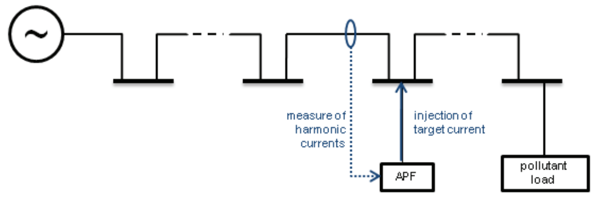

Fig.4. Strategy inspired by perfect harmonic cancellation (PHC)

Strategy inspired by Droop Control [8]

For comparison purposes, the strategy proposed in [8] for the APF performance, based on droop control, is adapted and applied to the example under study in this paper.

In this case, each APF acts as a shunt conductance. For each harmonic, this conductance (G_{APF}) is multiplied by the calculated voltage in the node where the APF is connected ($V_{APF,h}$) to obtain the target current ($I_{APF,h}$) the APF must inject to the grid (9).

(9) $$I_{APF,h} = G_{APF} \cdot V_{APF,h}$$

In [8], a droop relationship between the modeled conductance and the VA consumption of the APF is proposed (10).

(10) $$G_{APF} = G_0 + b \cdot (S - S_0)$$

where: G_0 – rated conductance of the APF (pu, original magnitude measured in Ω^{-1}), b – slope of the droop equation (pu, original magnitude measured in V^{-2}), S_0 – rated capacity of the APF (pu, original magnitude measured in VA), S – consumption of the APF (pu, original magnitude measured in VA).

On the other hand, the APF consumption, for the harmonic *h*, can be determined multiplying RMS values of voltage and current in the node where APF is located (when pu magnitudes are used, and three-phase criterion is applied, this equation is valid for three-phase pu systems). Assuming that the APF suppress the harmonics significantly, thus the voltage at buses with APF is dominated by the fundamental voltage component and the equation for calculating the APF consumption can be approximated to (11).

(11) $$S = \left|V_{APF,1}\right| \cdot \sqrt{\sum_{h=1}^{H} I_{APF,h}^2}$$

Combining (9) and (11) and considering that $I_{APF,1}$ is equal to zero, as the APF is not expected to inject any fundamental current component, we obtain (12).

(12) $$S = \left|V_{APF,1}\right| \cdot G_{APF} \cdot \sqrt{\sum_{h=2}^{H} V_{APF,h}^2}$$

Finally, combining (10) and (12), we can obtain G_{APF}.

(13) $$G_{APF} = \frac{G_0 - b \cdot S_0}{1 - b \cdot \left|V_{APF,1}\right| \cdot \sqrt{\sum_{h=2}^{H} V_{APF,h}^2}}$$

An iterative process is needed to obtain G_{APF} from the different calculated voltage components. Then, the APF is modeled as a current source, whose value is calculated from (9) and (13).

Thus, in this second strategy for the APF control, the harmonic power flow algorithm shown in Fig. 1 must be iteratively repeated towards convergence.

The parameters for two APFs applying this strategy in the example presented in this paper are shown in Table 3.

Table 3. Data of APFs (pu), referred to 6000 VA and 220 V base

Parameters:	APF 1	APF 2
Rated capacity, S_0 (pu)	0.083	0.083
Rated conductance, G_0 (pu)	0	0
Slope, b (pu)	-38.72	-38.72

Simulation of a radial distribution network

Once described the models employed for the different elements of the network under study (Fig. 2), this section shows the results obtained applying the algorithm shown in Fig.1 with MATLAB™. The proposed strategy for APFs, presented in the previous section, is first applied. One APF is located in bus 2, where the first pollutant load is connected, with the aim of verifying that it can absolutely suppress the THD in previous nodes. Another APF is used, varying its location from bus 3 to 6, where the second pollutant load is connected. A location downwards of both rectifiers is not tested, as APFs cannot be useful in this situation with the proposed strategy, as commented above.

Fig. 5 shows the resulting voltage THD in each node of the network when varying the location of the second APF. In every case, the original THD, obtained without APFs, is presented in grey for comparison. It can be easily observed that the THD in nodes upwards of both APFs are always equal to zero. On the other hand, those nodes located downwards of both APFs present a reduced THD. This THD reduction is higher as closer to the second pollutant load the second APF is. The optimal situation is that in which both APFs are located in the same buses than both pollutant loads. In this case, THD is totally eliminated from every node of the network.

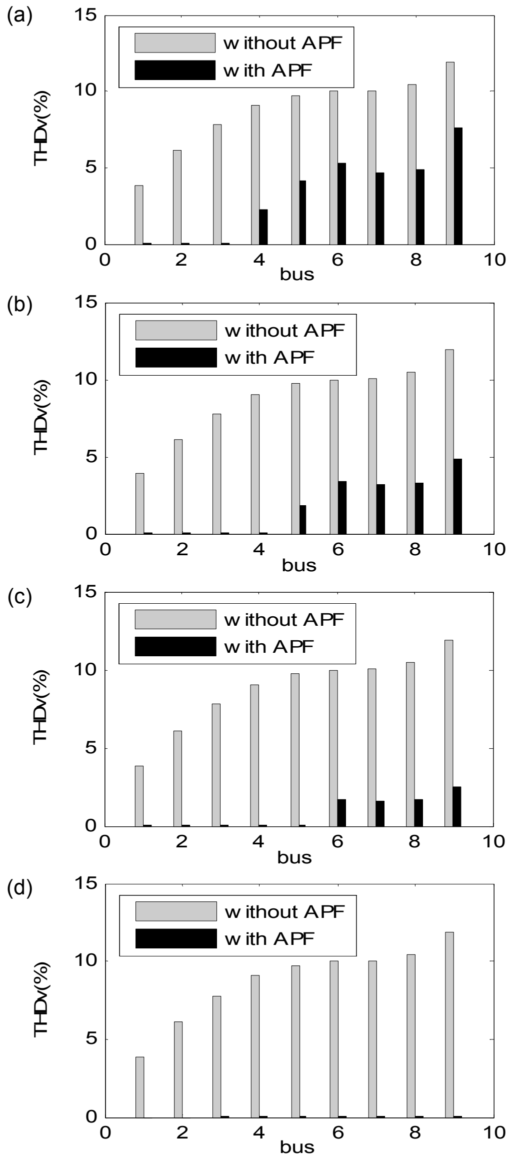

Fig. 5. THD (%) in bus voltages when varying the location of active power filters (APF) using the strategy inspired by PHC (Strategy A): (a) APF in buses 2 and 3; (b) APF in buses 2 and 4; (c) APF in buses 2 and 5; (d) APF in buses 2 and 6

The second strategy presented in the previous section is applied only in the optimal situation, with the aim of comparison with the proposed first strategy. Fig. 6 shows the resulting THD in every buses of the network. It can be observed that THD reduction is less effective than that obtained with the strategy inspired in PHC. This strategy, however, presents an advantage compared with the first one: as it pursues an overall reduction of THD in every node, its performance is not so dependant of the location of the pollutant loads.

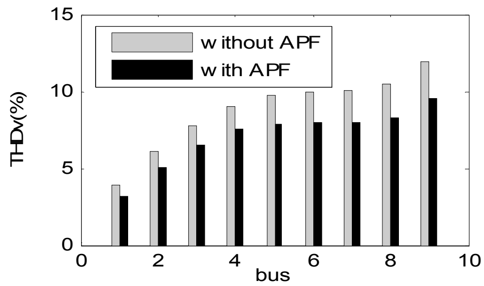

Fig. 6. THD (%) in bus voltages when droop control has been applied (Strategy B), locating APF in buses 2 and 6.

Table 4 shows reductions in power losses that APFs achieve in every simulated case. In this table, strategy A is referred to that inspired by perfect harmonic cancellation and strategy B corresponds to that inspired by droop control. This table evidences another great advantage of the use of APFs in distribution networks. They not only improve power quality in network buses, but also contribute to the system efficiency, reducing losses produced by the harmonic currents circulating through the lines. The reduction of power losses is very important when the proposed strategy (A) is used, even eliminating losses due to harmonics when APFs are located in the same buses than pollutant loads.

Table 4. Reduction in power losses with different locations and strategies for active power filters

APF Strategy	A	A	A	A	B
Location of APF (buses)	2,3	2,4	2,5	2,6	2,6
∇ losses by harmonics	60%	70%	90%	100%	30%
∇ total losses	0.47%	0.55%	0.71%	0.78%	0.24%

It is obvious that the use of less corrective devices than pollutant loads presents an economical advantage comparing to local correction, which needs as many corrective devices as pollutant loads. Thus, once concluded that the strategy inspired by perfect harmonic cancellation outperforms that inspired by droop control in the network simulated, the ability of this strategy for providing an overall power quality correction in the network is proved. For this purpose, only one active power filter has been used to correct power quality in a radial network with pollutant loads in two buses. In this simulation, nonlinear loads are located in buses 6 and 7 and the active power filter is located in bus 6. The simulation result is shown in Fig. 7.

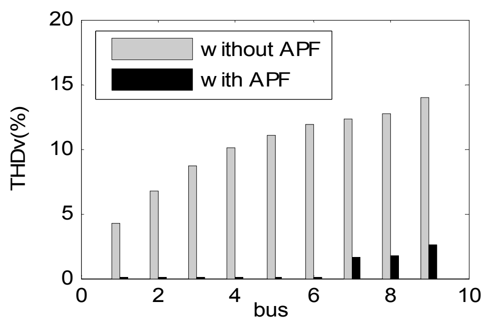

Fig. 7. THD (%) in bus voltages with Strategy A, with two pollutant loads in buses 6 and 7 and one active power filter located in bus 6.

Conclusions

This paper proposes an algorithm for harmonic load flow analysis of distribution networks with the presence of pollutant loads and active power filters (APFs). The strategy proposed for the APFs is inspired by perfect harmonic cancellation (PHC) presented in [4], and compared with other strategy adapted from that proposed in [8] and inspired by droop control.

The presented algorithm is simple to implement and permits the comparison of different strategies and locations of APFs with the aim of optimization.

A radial distribution network with linear and nonlinear loads and APFs is used as an example for simulation. The proposed strategy for APFs proves to be absolutely effective for voltage THD reduction in every node when the location of APFs is the same of the pollutant loads. In other cases, APFs significantly reduce THD in nodes and power losses due to current harmonics. The proposed strategy presents a better performance than that inspired by droop control in the cases simulated, although it presents a higher dependency of the location of the APFs.

The simulation also shows an economical advantage of overall power quality correction with an acceptable performance, due to the use of less corrective devices than pollutant loads, compared to the traditional local correction

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