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Research Paper Engineering

Active Filters for Power Quality Improvement

* Dipak t. Vaghela ** Dilip m. Bhankhodiya

*, ** Student of dept. of Electrical Engg, L.D. College of Engg, Ahmedabad, India

ABSTRACT

This paper deals with problems related with harmonics in power system networks. Several international standards issued to control power quality problems are briefly described and some important methods to analyse electrical circuits with non-sinusoidal waveforms are introduced and evaluated. One of these methods - the p-q theory - was used to implement the control algorithm of a shunt active filter, which is also described in this paper as an application example. The filter can compensate for harmonic currents, power factor and load unbalance. Both simulation and experimental results are presented, showing that good dynamic and steady-state response can be achieved with this approach.

Keywords : Active Filters, Harmonics Compensation, Power Factor Correction, Power Quality.

I. Introduction

Due to the intensive use of power converters and other non-linear loads in industry and by consumers in general, it can be observed an increasing deterioration of the power systems voltage and current waveforms.

The presence of harmonics in power lines results in greater power losses in the distribution system, interference problems in communication systems and, sometimes, in operation failures of electronic equipments, which are more and more sensitive since they include microelectronic control systems, which work with very low energy levels. Because of these problems, the issue of the power quality delivered to the end consumers is, more than ever, an object of great concern.

International standards concerning electrical power quality (IEEE-519, IEC 61000, EN 50160, among others) impose that electrical equipments and facilities should not produce harmonic contents greater than specified values, and also specify distortion limits to the supply voltage. Meanwhile, it is mandatory to solve the harmonic problems caused by those equipments already installed.

These problems can be classified into two kinds: instantaneous effects and long-term effects.

The instantaneous effects problems are associated with interferences, malfunction or performance degradation of equipments and devices.

Long-term effects are of thermal nature and are related, to additional losses and overheating, causing a reduction of the mean lifetime of capacitors, rotating machines and transformers.

II. MODELING

A. ACTIVE FILTERS

Active filters are special equipments that use power electronic converters to compensate for current and/or voltage harmonics originated by non-linear loads, or to avoid that harmonic voltages might be applied to sensitive loads.

There are basically two types of active filters: the shunt type and the series type. It is possible to have active filters combined with passive filters as well as active filters of both types acting together [6].

Figure 1 presents the electrical scheme of a shunt active filter for a three-phase power system with neutral wire, which, can both compensate for current harmonics and perform power factor correction. Furthermore, it allows load balancing, eliminating the current in the neutral wire. The power stage is, basically, a voltage-source inverter with only a single capacitor in the DC side (the active filter does not require any internal power supply), controlled in a way that it acts like a current-source. From the measured values of phase voltages (va, vb, vc) and load currents (ia, ib, ic), the controller calculates the reference currents (ica*, icb*, icc*, icn*) used by the inverter to produce the compensation currents (ica, icb, icc, icn). This solution requires 6 current sensors and 4 voltage sensors, and the inverter has 4 legs (8 power semiconductor switches). For balanced loads without 3rd order current harmonics (three-phase motors, three-phase adjustable speed drives, three-phase controlled or non-controlled rectifiers, etc) there is no need to compensate for the current in neutral wire. These allow the use of a simpler inverter (with only three legs) and only 4 current sensors. It also eases the controller calculations.

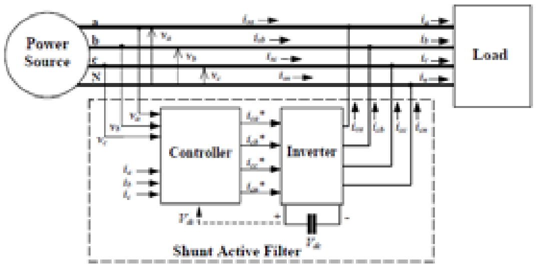


Fig. 1- Shunt active filter in a three-phase power system

Figure 2 shows the scheme of a series active filter for a three-phase power system. It is the dual of the shunt active filter, and is able to compensate for distortion in the power line voltages, making the voltages applied to the load sinusoidal (compensating for voltage harmonics). The filter consists of a voltage-source inverter (behaving as a controlled voltage source) and requires 3 single-phase transformers to interface with the power system. The series active filter does not compensate for load current harmonics but it acts as high-impedance to the current harmonics coming from the power source side. Therefore, it guarantees that passive filters eventually placed at the load input will not drain harmonic currents from the rest of the power system.

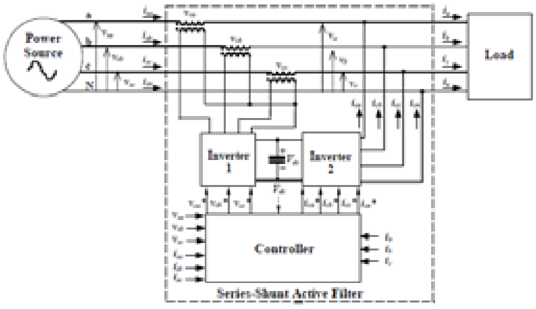


Fig. 3 – Series-shunt active filter in a three-phase power system.

Another solution to solve the load current harmonics is to use a shunt active filter together with the series active filter (Fig. 3), so that both load voltages and the supplied currents become sinusoidal waveforms.

Shunt active filters are already commercially available, although much research is being done, yet. The series and series-shunt types of active filters are yet at prototype level.

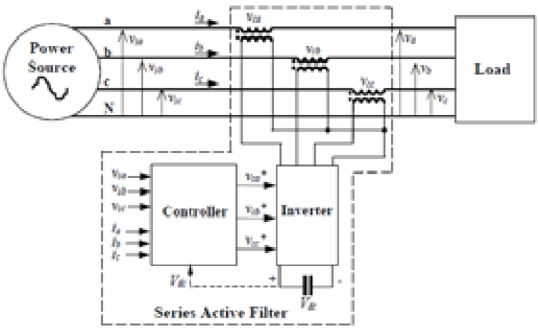


Fig. 2 - Series active filter in a three-phase power system

B. Control Strategy of FBD Method

The FBD (Frize-Buchholz-Depenbrock) method, proposed by Depenbrock et al. [7] decomposes the load currents into power components and powerless components. The goal is to compensate all the terms that do not produce power, but have the drawback of making the power factor less than one. With this purpose the method calculates an equivalent conductance for the load, given by the ratio between the consumed average power and the squared RMS collective voltage value :

$$G = \frac{\overline{P}_3}{V_\Sigma^{\ 2}}$$

where VΣ is the collective rms voltage defined as follows:

$$V_\Sigma = \sqrt{V_a^{\ 2} + V_b^{\ 2} + V_c^{\ 2}}$$

and Va, Vb, Vc, are the RMS voltage values of phase a, b and c, respectively. P3 is the mean value of the instantaneous three-phase power, which corresponds to the active power.

The reference compensation currents for the shunt active filter are given by the following equation, from theinstantaneous values of load voltages and currents:

$$i_{ca}(t) = G \cdot v_a(t) - i_a(t)$$
$$i_{cb}(t) = G \cdot v_b(t) - i_b(t)$$
$$i_{cc}(t) = G \cdot v_c(t) - i_c(t)$$

C. Control Strategy of Synchronous Reference Method

This method [8] uses the Park transform. The Park current components of a three-phase system can be found hrough the application of a Clarke transform, which causes the phase currents ia, ib e ic to be represented by two coordinates iα and iβ, and later, by rotation of the reference system of an angle θ, into the Park coordinates id and iq. In cases where exists zero sequence component (homopolar components), it will be represented by a third axis normal to the d-q plane. The values of the currents in 0-d-q coordinates, obtained from the load phase currents are:

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

With this transformation the current fundamental order part will be found in the DC component of the transformed d-q currents, thus making possible its extraction through the use of low-pass filters, for example.

The instantaneous power is given by the expression :

$$p(t) = v_0 \cdot i_0 + v_d \cdot i_d + v_q \cdot i_q$$

In order to minimize line power loss a reactiveinstantaneous power that must be compensated is defined:

$$\vec{q}(t) = \begin{bmatrix} v_q \cdot i_0 - v_0 \cdot i_q \\ v_0 \cdot i_d - v_d \cdot i_0 \\ v_d \cdot i_q - v_q \cdot i_d \end{bmatrix}$$

The vectorial nature of implies that all the threeterms must become zero in order to compensate all reactive instantaneous power:

$$\vec{q}(t) = \vec{0} \quad \Rightarrow \quad \begin{matrix} v_q \cdot i_0 - v_0 \cdot i_q = 0 \\ v_0 \cdot i_d - v_d \cdot i_0 = 0 \\ v_d \cdot i_q - v_q \cdot i_d = 0 \end{matrix}$$

D. Control Strategy of p-q Theory

This theory, also known as “instantaneous power theory” was proposed to control active filters. It is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operation, as well as for generic voltage and current waveforms. The p-q theory consists of an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in the a-b-c coordinates to the α-β-0 coordinates, followed by the calculation of the p-q theory instantaneous power components:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$p_0 = v_0 \cdot i_0$ instantaneous zero-sequence power

$p = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta$ instantaneous real power

$q = v_\alpha \cdot i_\beta - v_\beta \cdot i_\alpha$ instantaneous imaginary power

The power components p and q are related to the sam α-β voltages and currents, and can be written together:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

These quantities are illustrated in Fig 6 for an electrical system represented in a-b-c coordinates and have the following physical meaning:

$\bar{p}_0$ = mean value of the instantaneous zero-sequence power – corresponds to the energy per time unity which is transferred from the power supply to the load through the zero-sequence components of voltage and current.

$\tilde{p}_0$ = alternated value of the instantaneous zerosequence power – it means the energy per time unity that is exchanged between the power supply and the load through the zero-sequence components. The zero-sequence power only exists in three-phase systems with neutral wire. Furthermore, the systems must have unbalanced voltages and currents and/or 3rd harmonics in both voltage and current of at least one phase.

$\bar{p}$ = mean value of the instantaneous real power – corresponds to the energy per time unity which is transferred from the power supply to the load, through the a-b-c coordinates, in a balanced way (it is the desired power component).

$\tilde{p}$ = alternated value of the instantaneous real power – it is the energy per time unity that is exchanged between the power supply and the load, through the a-b-c coordinates.

q = instantaneous imaginary power – corresponds to the power that is exchanged between the phases of the load. This component does not imply any transference or exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases. In the case of a balanced sinusoidal voltage supply and a balanced load, with or without harmonics, $\bar{q}$ (the mean value of the instantaneous imaginary power) is equal to the conventional reactive power ($\bar{q}$ = 3·V · I1 · sinφ1).

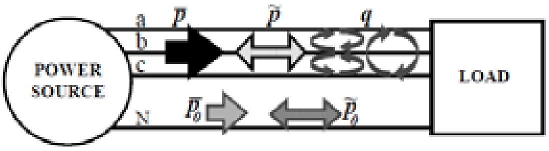


Fig. 4- Power components of the p-q theory.

The p-q theory presents some interesting features when applied to the control of active filters, namely:

- It is inherently a three-phase system theory.
- It can be applied to any three-phase system (balanced or unbalanced, with or without harmonics in both voltages and currents).
- It is based in instantaneous values, allowing excellent dynamic response.
- Its calculations are relatively simple (it only includes algebraic expressions that can be implemented using standard processors);
- It allows two control strategies: constant instantaneous supply power and sinusoidal supply current.

As seen before, $\bar{p}$ is usually the only desirable p-q theory power component. The other quantities can be compensated using a shunt active filter (Fig. 7). As shown by Watanabe et al. [11, 12], $\bar{p}_0$ can be compensated without the need of any power supply in the shunt active filter. This quantity is delivered from the power supply to the load, through the active filter (see Fig. 5). This means that the energy previously transferred from the source to the load through the zero-sequence components of voltage and current, is now delivered in a balanced way from the source phases.

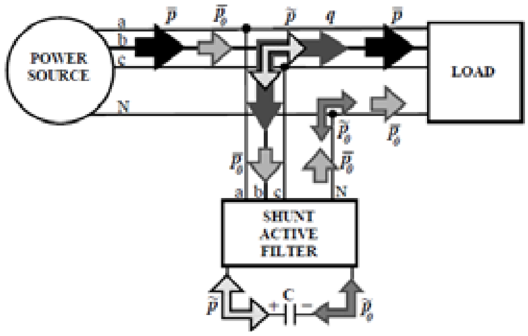


Fig. 5

Compensation of power components $\tilde{p}, q, \tilde{p}_0$ and $\bar{p}_0$.

It is also possible to conclude from Fig. 5 that the active filter capacitor is only necessary to compensate $\tilde{p}$ and $\tilde{p}_0$, since these quantities must be stored in this component at one moment to be later delivered to the load. The instantaneous imaginary power (q), which includes the conventional reactive power, is compensated without the contribution of the capacitor. This means that, the size of the capacitor does not depend on the amount of reactive power to be compensated.

To calculate the reference compensation currents in the α-β coordinates, and the powers to be compensated ($\tilde{p} - \bar{p}_0$ and q) are used:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \cdot \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} \tilde{p} - \bar{p}_0 \\ q \end{bmatrix}$$

Since the zero-sequence current must be compensated, the reference compensation current in the 0 coordinate is i0 itself: ic0* = i0

In order to obtain the reference compensation currents in the a-b-c coordinates the inverse of the transformation given is applied:

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{c0}^* \\ i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix}$$

$$i_{cn}^* = -(i_{ca}^* + i_{cb}^* + i_{cc}^*)$$

The calculations of the p-q theory are synthesized in Fig.6and correspond to a shunt active filter control strategy for constant instantaneous supply power. This approach, when applied to a three-phase system with balanced sinusoidal voltages, produces de following results:

- The phase supply currents become sinusoidal, balanced, and in phase with the voltages. (in other words, the power supply "sees" the load as a purely resistive symmetrical load);

- The neutral current is made equal to zero (even 3rd order current harmonics are compensated);

- The total instantaneous power supplied, is made constant.

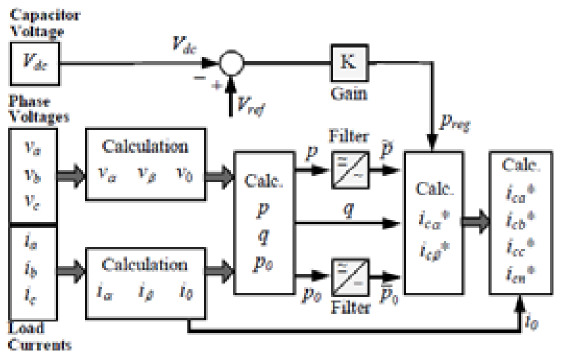
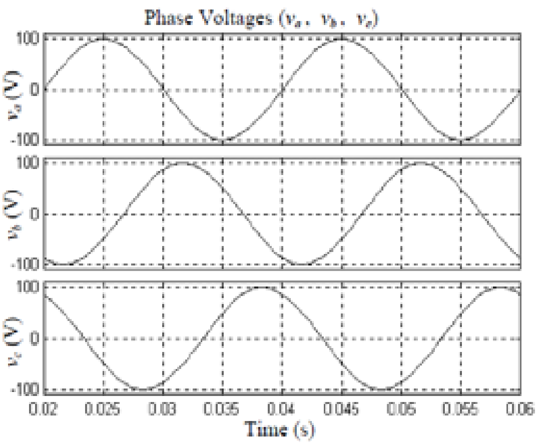


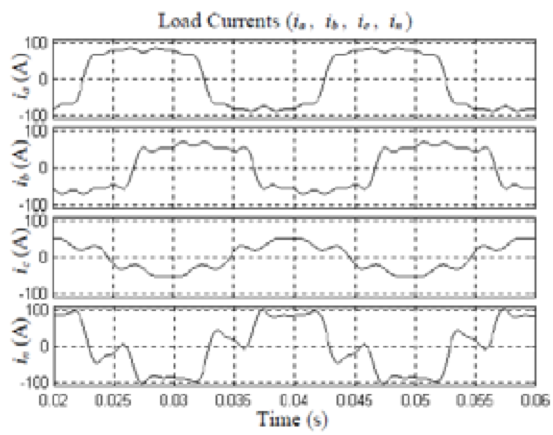
Fig. 6 - Calculations of the p-q theory.

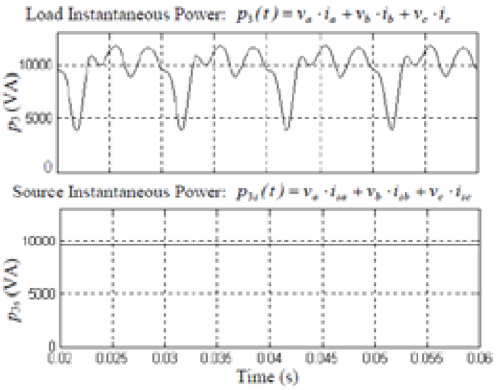
The p-q theory also permits a control strategy for the shunt active filter to be used when voltages are distorted and/or unbalanced and sinusoidal supply currents are desired [13]. However with this strategy the total instantaneous power supplied will not be constant, since it is not physically possible to achieve both sinusoidal currents and constant power in a system with unbalanced and/or distorted voltages.

III. SIMULATION RESULTS OF ACTIVE FILTER

Figure 7, presents simulation results using Matlab/Simulink [14, 15] for a three-phase power system with a shunt active filter with control based on the p-q theory. It includes the following waveforms, corresponding to two-cycles of steady-state operation: phase voltages (va, vb, vc); load phase and neutral currents (ia, ib, ic, in); total instantaneous power at load (p3) and source (p3s); and source phase and neutral currents (isa, isb, isc, isn).







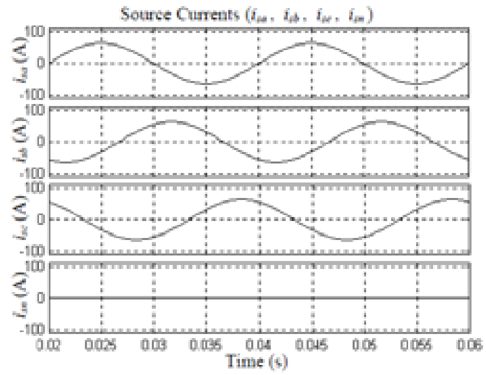


Fig. 7 - Simulations results for a shunt active filter.

TABLE I.

Nominal Voltage at PCC Un	Individual voltage distortion (%)	Total harmonic distortion (%)
Un ≤ 69 kV	3.0	5.0
69 kV < Un ≤ 161 kV	1.5	2.5
Un > 161 kV	1.0	1.5

In the first case (Fig. 8) the power system operates with a linear and almost "pure" L load, (the phase supply current, isa , is almost 90º delayed regarding to the same phase voltage, va). The active filter controller calculates the reference compensation current (ica*), and as soon as its inverter is turned-on the compensation current (ica) produced by the inverter makes isa in phase with va. In other words, the shunt active filter compensates the load power factor and it does so almost instantaneously.

The second operating condition shows (Fig.9) the power system operating both with a non-linear load (three-phase rectifier) and a linear load (RL load). The source current is distorted, and delayed in relation to the voltage. After the active filter inverter is turned-on, isa becomes sinusoidal and in phase with va Once again, the compensation is immediate.

In the third case (Fig. 10). the power system operates with only a non-linear load (three-phase rectifier with RL load at DC side). After turning-on the active filter inverter isa becomes sinusoidal.

Figure 11 shows, for this same case, the waveforms of phase voltage and supply current separately, for operation with active filter off and on. It is possible to see that the abrupt changes in load current produce notches in the system voltage. When the active filter compensates the currents these notches disappear.

Figure 12 illustrates the response of the system to a load change. At the beginning it operates with a linear RL load and then a non-linear load (three-phase rectifier) is connected. When the active filter is on, the load changing is fully compensated in a half cycle. The current increases in amplitude because the demanded energy becomes larger with the new load, but the source current remains sinusoidal and in phase with the voltage. The figure also shows the compensation current (ica) when the active filter is on.

It is important that, the ripple observed in the supply current waveform when the shunt active filter in operating occurs due to the inverter commutation. However, it only seems to be relevant because the loads used to obtain the experimental results were relatively small. Operating with larger loads the current ripple would be negligible. Besides, this is a high-frequency ripple, which is easily filtered by the power system.

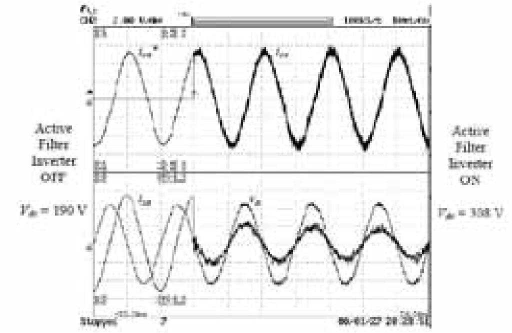


Fig. 8 - Operation with almost pure L load.

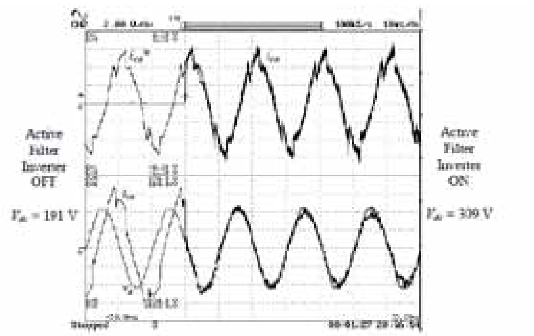


Fig. 9 - Operation with RL load and three-phase rectifier.

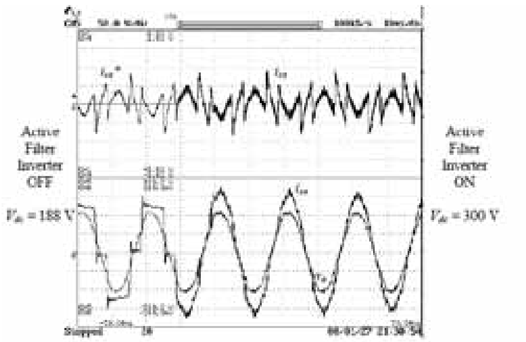


Fig. 10 - Operation with three-phase rectifier.

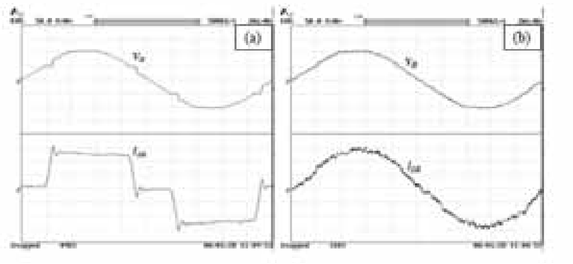


Fig. 11 - Operation with three-phase rectifier:
(a) Active filter off; (b) Active filter on.

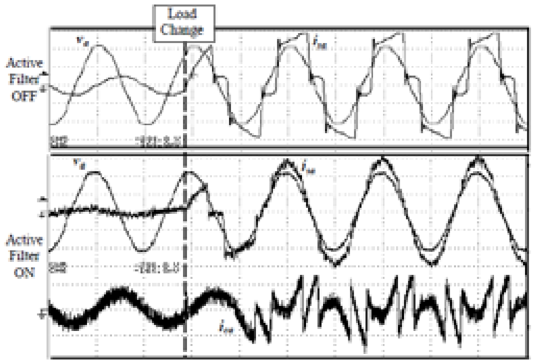


Fig. 12 - Response to load change, with shunt active filter off and on.

IV. CONCLUSIONS

This paper deals with problems related with harmonics in power system networks. Several international standards issued to control power quality problems are briefly described and some important tools to analyse electrical circuits with non-sinusoidal waveforms are introduced and evaluated. Among other application, these tools are useful in the implementationof control algorithms for active filters .

Active filters are an up-to-date solution to power quality problems.Shunt active filters allow the compensation of current harmonics and unbalance, together with power factor correction, and can be a much better solution than the conventional approach.

Simulations result show that the shuntactive filter presents good dynamic and steady-state response. It can perform harmonic currents compensation, together with power factor correction. It can also compensate for load current unbalances, eliminating the current in the neutral wire. Therefore, it allows the power source to see an unbalanced reactive non-linear load, as a symmetrical resistive load.

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