Control Strategies of Selective Harmonic Current Shunt Active Filter

Gonzalo Casaravilla, Adriana Salvia, Cesar Briozzo and Edson Watanabe

Abstract— **This paper presents the possible calculation methodologies in order to design a selective shunt active filter. For realizing the selective extraction of harmonic sequences the modulation - filter - demodulation technique is used. The fundamental equations of this method are established in the case of pq theory showing its equivalence with the SRF (Synchronous Reference Frame) method. In order to prove the proposed ways of calculation real non-periodic currents data with a great harmonic distortion of an arc furnace are used; with the good results achieved shows the ability of filtering in a selective and controlled way the undesired current harmonics**

I. Introduction

In the last decades, the evolution of two aspects concerning power systems has created conditions for a more extended use of active filters. The first aspect is related to power semiconductor device development. Converters capable of synthesizing voltages and currents with an adequate bandwidth for harmonic current compensation at MVA - level are now available at competitive prices. The other aspect is the gradual application of regulations limiting the generation of harmonic currents by the customers.

Active filters are ideally suitable for filtering localized harmonic currents in a guided way. This allows to apply the concept "you dirty, you clean". This concept cannot be applied using conventional passive filters. In the same way, active filters allows to eliminate some of the problems of passive filters such as poor tuning due to dispersion of their characteristic parameters and resonances with the impedance of the surrounding electrical network which may appear.

Among the different methods for controlling active filters, the use of pq theory (active and imaginary power) [1], has demonstrated to be specially suitable. In particular, it has been used for separating the residual harmonics and thus eliminating (as theory indicates) or reducing (as it results in practice) the harmonic distortion. For the control of selective active filters several works use the SRF method (Synchronous Reference Frame) [2] [3] [4] [5] [6] which is definitively a particular case of applying the pq method with harmonic voltages as references. In this work, the contribution to this topic done in [7] is generalized.

The question of why canceling the harmonic distortion if the regulations does not require that; is presented and answered in [8]. The results obtained might be accepted by the applicable regulation, except for some harmonics that are difficult to reduce with this strategy. The question if better results could be achieved if each one of the harmonics is reduced in a controlled way in order to adjust exactly to the regulation arises naturally. One answer to this question is the use of selective filters.

G. Casaravilla - IIE-UDELAR-Uruguay, gcp@iie.edu.uy
A. Salvia - IIE-UDELAR-Uruguay, adriana@iie.edu.uy
C. Briozzo - IIE-UDELAR-Uruguay, cesar@iie.edu.uy
E. Watanabe - COPPE-UFRJ-Brasil, watanabe@coe.ufrj.br

II. Pq Theory, harmonic and sequence contributions to P and Q spectrum

Pq theory [1] is basically a time domain analysis tool. In a stationary periodic process it is possible to do a frequency domain analysis and current and voltage harmonic and sequences appear explicitly. The equations that are summarized here are explained in detail in [7] [9] [10].

$$\begin{aligned} v_k(t) &= \sum_{n=1}^{\infty} \sqrt{2} V_{kn} \sin(w_n t + \phi_{kn}) \\ i_k(t) &= \sum_{n=1}^{\infty} \sqrt{2} I_{kn} \sin(w_n t + \delta_{kn}) \end{aligned} \tag{1}$$

$$\begin{bmatrix} I_{on} \\ I_{+n} \\ I_{-n} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_{an} \\ I_{bn} \\ I_{cn} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} I_{an} \\ I_{bn} \\ I_{cn} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{on} \\ I_{+n} \\ I_{-n} \end{bmatrix} \tag{3}$$

$$\begin{aligned} i_{an} &= \sqrt{2} I_{0n} \sin(w_n t + \delta_{0n}) + \\ &\quad \sqrt{2} I_{+n} \sin(w_n t + \delta_{+n}) + \\ &\quad \sqrt{2} I_{-n} \sin(w_n t + \delta_{-n}) \\ i_{bn} &= \sqrt{2} I_{0n} \sin(w_n t + \delta_{0n}) + \\ &\quad \sqrt{2} I_{+n} \sin(w_n t + \delta_{+n} - \frac{2\pi}{3}) + \\ &\quad \sqrt{2} I_{-n} \sin(w_n t + \delta_{-n} + \frac{2\pi}{3}) \\ i_{cn} &= \sqrt{2} I_{0n} \sin(w_n t + \delta_{0n}) + \\ &\quad \sqrt{2} I_{+n} \sin(w_n t + \delta_{+n} + \frac{2\pi}{3}) + \\ &\quad \sqrt{2} I_{-n} \sin(w_n t + \delta_{-n} - \frac{2\pi}{3}) \end{aligned} \tag{4}$$

Current and voltage of a, b and c phases are given in (1), (2) and (3) are the direct and inverse calculation of these harmonics in positive, negative and zero sequences. Hence, results (4) where harmonics and sequences are present. Equation (5) represents the passage from three to two coordinates (Clarke transform) resulting in (6) in where those components are expressed in the reference axes α and β in terms of all the harmonic sequence components. Similar expressions can be obtained for the voltages, but they are not reproduced here.

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

$$\begin{aligned} i\alpha(t) &= + \sum_{n=1}^{\infty} \sqrt{3} I_{+n} \sin(w_n t + \delta_{+n}) + \\ & \sum_{n=1}^{\infty} \sqrt{3} I_{-n} \sin(w_n t + \delta_{-n}) \\ i\beta(t) &= - \sum_{n=1}^{\infty} \sqrt{3} I_{+n} \cos(w_n t + \delta_{+n}) + \\ & \sum_{n=1}^{\infty} \sqrt{3} I_{-n} \cos(w_n t + \delta_{-n}) \end{aligned} \tag{6}$$

Then the definition of instantaneous real powers p and imaginary power q [1], is the one shown in (7) with its decomposition in $\overline{p}$ and $\widetilde{p}$ as shown in (9) and (10). The table in Fig. 1 shows how these sequences are finally placed in p and q frequency spectrum.

$$\begin{aligned} \begin{bmatrix} p \\ q \end{bmatrix} &= \begin{bmatrix} v\alpha & v\beta \\ v\beta & -v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \Leftrightarrow \\ \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} &= \frac{1}{v\alpha^2 + v\beta^2} \begin{bmatrix} v\alpha & v\beta \\ v\beta & -v\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \end{aligned} \tag{7}$$

$$p = \bar{p} + \tilde{p} \qquad q = \bar{q} + \tilde{q} \tag{8}$$

$$\begin{aligned} \bar{p}(t) &= \sum_{n=1}^{\infty} +3V_{+n} I_{+n} \cos(\phi_{+n} - \delta_{+n}) + \\ & \sum_{n=1}^{\infty} +3V_{-n} I_{-n} \cos(\phi_{-n} - \delta_{-n}) \end{aligned} \tag{9}$$

$$\begin{aligned} \tilde{p}(t) &= \\ & + \sum_{\substack{m=1 \\ m \neq n}}^{\infty} \{ \sum_{n=1}^{\infty} +3V_{+m} I_{+n} \cos[(w_m - w_n)t + \phi_{+m} - \delta_{+n}] \} \\ & + \sum_{\substack{m=1 \\ m \neq n}}^{\infty} \{ \sum_{n=1}^{\infty} +3V_{-m} I_{-n} \cos[(w_m - w_n)t + \phi_{-m} - \delta_{-n}] \} \\ & + \sum_{m=1}^{\infty} \{ \sum_{n=1}^{\infty} -3V_{+m} I_{-n} \cos[(w_m + w_n)t + \phi_{+m} + \delta_{-n}] \} \\ & + \sum_{m=1}^{\infty} \{ \sum_{n=1}^{\infty} -3V_{-m} I_{+n} \cos[(w_m + w_n)t + \phi_{-m} + \delta_{+n}] \} \end{aligned} \tag{10}$$

	I+1	I+2	I+3	I+4	.....	I+n
V+1	0	1	2	3		n-1
V+2	1	0	1	2		n-2
V+3	2	1	0	1		n-3
V+4	3	2	1	0		n-4
.....					0	
V+n	n-1	n-2	n-3	n-4		0

	I-1	I-2	I-3	I-4	.....	I-n
V+1	2	3	4	5		n+1
V+2	3	4	5	6		n+2
V+3	4	5	6	7		n+3
V+4	5	6	7	8		n+4
.....						
V+n	n+1	n+2	n+3	n+4		2n

	I+1	I+2	I+3	I+4	.....	I+n
V-1	2	3	4	5		n+1
V-2	3	4	5	6		n+2
V-3	4	5	6	7		n+3
V-4	5	6	7	8		n+4
.....						
V-n	n+1	n+2	n+3	n+4		2n

	I-1	I-2	I-3	I-4	.....	I-n
V-1	0	1	2	3		n-1
V-2	1	0	1	2		n-2
V-3	2	1	0	1		n-3
V-4	3	2	1	0		n-4
.....					0	
V-n	n-1	n-2	n-3	n-4		0

Fig. 1. Harmonic sequences in p and q spectrum. For example, due to of I_{-2} and $V{+}1$ we have third harmonic on p or q

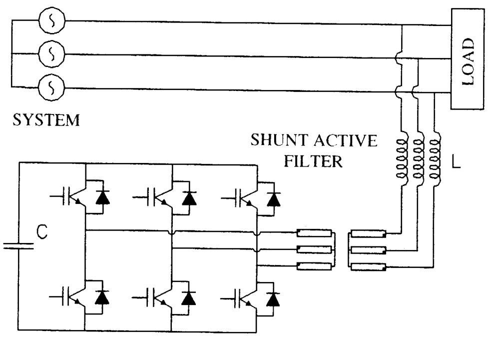

Fig. 2. Shunt active filter

III. Shunt selective active filter

The goal of a shunt selective filter connected as in Fig. 2, is to be able to determine in real time, the current to be taken by the active filter in order to eliminate from the sources system a certain harmonic sequence. The voltage used for doing the calculations is supposed to be only a positive sequence voltage of frequency $+w_c$. Thus, in this case, the voltage analogous expression for (6) indicates that the voltage is (11) where the respective amplitude and phase were eliminated. The purpose of using + sign is to remember that a positive sequence is used. Then, taking the definition of p and q from (7), (12) is obtained.

$$\begin{bmatrix} v\alpha(t) \\ v\beta(t) \end{bmatrix}_+ = \begin{bmatrix} +sin(w_c t) \\ -cos(w_c t) \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix}_+ = \begin{bmatrix} +sin(w_c t) & -cos(w_c t) \\ -cos(w_c t) & -sin(w_c t) \end{bmatrix} \begin{bmatrix} i\alpha(t) \\ i\beta(t) \end{bmatrix} \tag{12}$$

At this point the similarity that this calculation method has with the one named SRF (Synchronous Reference Frame) [2] [4] [11] [4] will be remarked. In SRF method the currents $i\alpha$ and $i\beta$ are decomposed in the synchronous reference frame d and q of the voltage sequence associated with $+w_c$.

That transformation (rotation) of the axes α and β to d and q is the transformation shown in (13). This expression can also be written as (14), then, comparing the expressions (12) and (14) it could be established that not being for the change in the sign of q, SRF

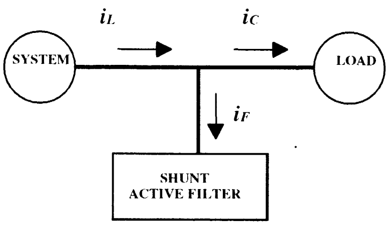

Fig. 3. Sign convention

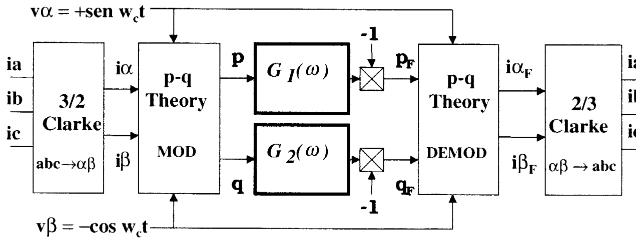

Fig. 4. Modulation - selective filtering - demodulation

method and the one based on pq theory that will be developed here are analogous [4]. In the same way, if the amplitude and phase restrictions imposed in (11) were eliminated, the meaning of p and q change from the conventional one, and could be interchanged in the case that the real phase differs from the calculated one in 90.

$$\begin{bmatrix} id(t) \\ iq(t) \end{bmatrix} = \begin{bmatrix} +cos(w_c t]) & -sin(w_c t) \\ +sin(w_c t) & +cos(w_c t) \end{bmatrix} \begin{bmatrix} i\alpha(t) \\ i\beta(t) \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} id(t) \\ iq(t) \end{bmatrix} = \begin{bmatrix} +sin(\frac{\pi}{2} - w_c t) & -cos(\frac{\pi}{2} - w_c t) \\ +cos(\frac{\pi}{2} - w_c t) & +sin(\frac{\pi}{2} - w_c t) \end{bmatrix} \begin{bmatrix} i\alpha(t) \\ i\beta(t) \end{bmatrix} \quad (14)$$

Looking at Fig. 1, it can be noticed that the p and q spectrum that results from the calculations in (12) presents at 0 frequency (DC), only the current sequence which is wanted to be identified and separated. If this DC portion of the spectrum is separated with a low pass filter and then and apply the inverse calculation (7) using the same reference voltage arrive to compensation currents $i\alpha_F$ and $i\beta_F$. This operations is represented in the diagram of Fig. 4, where the first stage is a MODULATION, the intermediate stage is a FILTER and the last stage a DEMODULATION [7] [4] . The multiplication of both channels by -1 after the filters $G_1(w)$ and $G_2(w)$ is associated with the current sense convention shown in Fig. 3. Basically the idea is that the active filter hands the powers p and q given by calculations so the line current will not supply them [1].

The expression shown in (15), is the same in (12), but in frequency domain, where * denotes convolution and the notation S_{wc} and C_{wc} are defined in (16). S_{wc} and C_{wc} are the sine and cosine Fourier transforms respectively.

$$\begin{bmatrix} P(w) \\ Q(w) \end{bmatrix}_+ = \frac{1}{2\pi} \begin{bmatrix} +S_{wc}(w) & -C_{wc}(w) \\ -C_{wc}(w) & -S_{wc}(w) \end{bmatrix} * \begin{bmatrix} I\alpha(w) \\ I\beta(w) \end{bmatrix} \quad (15)$$

$$\begin{aligned} sin(w_c t) &\Rightarrow S_{wc}(w) = \frac{\pi}{j}[\delta(w - w_c) - \delta(w + w_c)] \\ cos(w_c t) &\Rightarrow C_{wc}(w) = \pi[\delta(w - w_c) + \delta(w + w_c)] \quad (16) \end{aligned}$$

Afterwards, in order to obtain the powers p_F and q_F that will be demodulated, looking at Fig. 4, (17) can be written, where the multiplier -1 was also included. From the second expression of (7), (18) can be written; and this equation when passed to the frequency domain is transformed in (19). Replacing (15) and (17) in (19), the expression (20) is obtained after several calculations. The notation is defined in (21).

$$\begin{bmatrix} P_F(w) \\ Q_F(w) \end{bmatrix} = -\begin{bmatrix} G_1(w) & 0 \\ 0 & G_2(w) \end{bmatrix} * \begin{bmatrix} P(w) \\ Q(w) \end{bmatrix} \quad (17)$$

$$\begin{bmatrix} i\alpha_F(t) \\ i\beta_F(t) \end{bmatrix}_+ = \frac{1}{sin^2 + cos^2} \begin{bmatrix} +sin(w_c t) & -cos(w_c t) \\ -cos(w_c t) & -sin(w_c t) \end{bmatrix} \begin{bmatrix} p_F(t) \\ q_F(t) \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} I\alpha_F(w) \\ I\beta_F(w) \end{bmatrix}_+ = \frac{1}{2\pi} \begin{bmatrix} +S_{wc}(w) & -C_{wc}(w) \\ -C_{wc}(w) & -S_{wc}(w) \end{bmatrix} * \begin{bmatrix} P_F(w) \\ Q_F(w) \end{bmatrix} \quad (19)$$

$$\begin{bmatrix} I\alpha_F(w) \\ I\beta_F(w) \end{bmatrix}_+ = -\frac{1}{4} \left\{ \begin{aligned} &\begin{bmatrix} H^{-1} + H^{+1} & j(H^{-1} - H^{+1}) \\ -j(H^{-1} - H^{+1}) & H^{-1} + H^{+1} \end{bmatrix} \begin{bmatrix} I\alpha(w) \\ I\beta(w) \end{bmatrix} \\ &+ \begin{bmatrix} D^{+1} & jD^{+1}) \\ jD^{+1} & -D^{+1} \end{bmatrix} \begin{bmatrix} I\alpha(w + 2w_c) \\ I\beta(w + 2w_c) \end{bmatrix} \\ &+ \begin{bmatrix} D^{-1} & -jD^{-1}) \\ -jD^{-1} & -D^{-1} \end{bmatrix} \begin{bmatrix} I\alpha(w - 2w_c) \\ I\beta(w - 2w_c) \end{bmatrix} \end{aligned} \right\} \quad (20)$$

$$\begin{aligned} H^{+1} &= G_1(w + w_c) + G_2(w + w_c) \\ D^{+1} &= G_2(w + w_c) - G_1(w + w_c) \\ H^{-1} &= G_1(w - w_c) + G_2(w - w_c) \quad (21) \\ D^{-1} &= G_2(w - w_c) - G_1(w - w_c) \end{aligned}$$

$G_1(w)$ and $G_2(w)$ are supposed to be ideal low pass filters. In this case $H = 2G$ and $D = 0$, so (20) reduces to (22) or (23) in function of G that developed results in (24). Looking to the multipliers of $I\alpha$ and $I\beta$ in Fig. 5, it could be noticed that the possible results are placed in the frequencies $+wc$ and $-wc$. Hence, only will be taken in consideration the positive and negative sequences associated to frequency wc showed in (25). Any other frequency will not appear in the output $I\alpha_F$ and $I\beta_F$.

$$\begin{bmatrix} I\alpha_F(w) \\ I\beta_F(w) \end{bmatrix}_+ = -\frac{1}{4} \begin{bmatrix} H^{-1} + H^{+1} & j(H^{-1} - H^{+1}) \\ -j(H^{-1} - H^{+1}) & H^{-1} + H^{+1} \end{bmatrix} \begin{bmatrix} I\alpha(w) \\ I\beta(w) \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} I\alpha_F(w) \\ I\beta_F(w) \end{bmatrix}_+ = -\frac{1}{2} \begin{bmatrix} G^{-1} + G^{+1} & j(G^{-1} - G^{+1}) \\ -j(G^{-1} - G^{+1}) & G^{-1} + G^{+1} \end{bmatrix} \begin{bmatrix} I\alpha(w) \\ I\beta(w) \end{bmatrix} \quad (23)$$

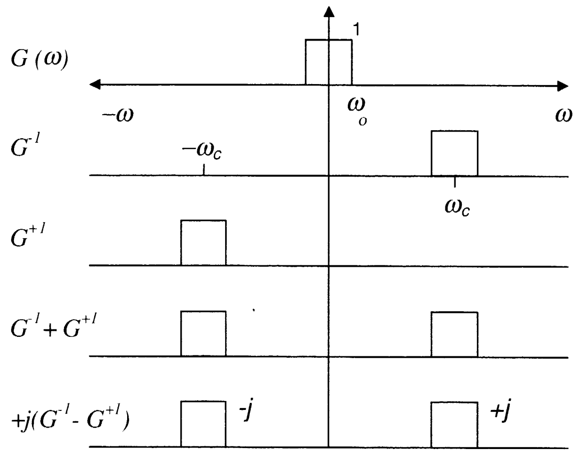

Fig. 5. G, G^{-1} and G^{+1} ideal filters

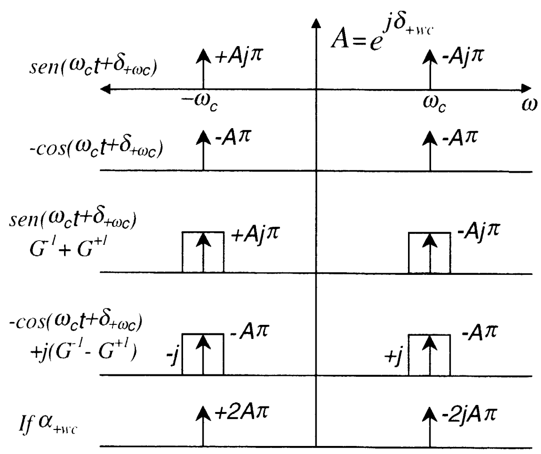

Fig. 6. Graphic operation of (24)

$$I\alpha_F(w)_+ = -\frac{1}{2}[(G^{-1}+G^{+1})I\alpha + j(G^{-1}-G^{+1})I\beta]$$
$$I\beta_F(w)_+ = -\frac{1}{2}[-j(G^{-1}-G^{+1})I\alpha + (G^{-1}+G^{+1})I\beta] \quad (24)$$

At first it will be seen what happens to the positive sequence shown in (25). Using the Fourier Transform property of a delayed - time signal (26), the interest terms can be located in the diagram of Fig. 5, and Fig. 6 is obtained where all the addends and multipliers of compensation current $I\alpha_F$ (24) for the positive sequence associated with wc are showed. Doing the same operative for $I\beta_F$ the final result is the one indicated in (27).

$$\begin{aligned} i\alpha(t)_{+wc} &= +\sqrt{3}I_{+wc}sin(w_c t + \delta_{+wc}) \\ i\beta(t)_{+wc} &= -\sqrt{3}I_{+wc}cos(w_c t + \delta_{+wc}) \end{aligned} \quad (25)$$

$$x(t-t_0) \Rightarrow e^{-jwt_0}X(w) \quad (26)$$

$$\begin{aligned} i\alpha_F(t)_{+wc} &= i\alpha(t)_{+wc} \\ i\beta_F(t)_{+wc} &= i\beta(t)_{+wc} \end{aligned} \quad (27)$$

The result in (28) is obtained doing the same reasoning and calculations for the negative sequence associated

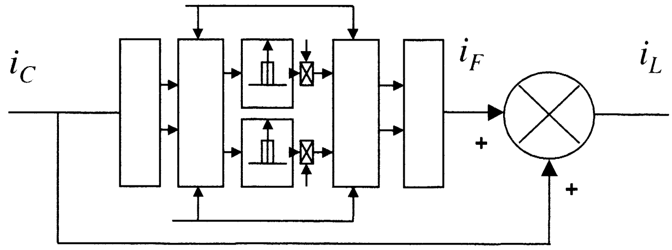

Fig. 7. Control system block diagram

with wc.

$$\begin{aligned} i\alpha_F(t)_{-wc} &= 0 \\ i\beta_F(t)_{-wc} &= 0 \end{aligned} \quad (28)$$

As a partial conclusion it can be said that the operative of modulating - low pass filter - demodulating of Fig. 4 with a positive sequence $+wc$ has as consequence that the obtained output current only has the positive sequence current associated with wc. With a similar reasoning it can be demonstrated that the same thing happens if a negative sequence of frequency $-wc$ is used for modulating and demodulating (it is enough to substitute wc for $-wc$). This important result, showed partially in [7] is the same one obtained with the SRF methodology as it has already been mentioned.

IV. Control strategies

As exposed in [12] there are three ways of controlling a shunt active filter: measuring the load current, measuring the line current or measuring the voltage in the point of common connection (PCC) of the load. A study for the second case will be done in this work, but the generalization for the other two cases does not present major problems.

With sign convention of Fig. 3, the system transference between line current i_L and load current i_C is shown in Fig. 7. That scheme can also be outlined as the drawing of Fig. 8 named here as Selective Filter Basic Cell (SFBC) where it is assumed that the input is the load current i_C and the outputs are the filter current i_F and the line current i_L. The parameter λ introduced in Fig.8, indicates the continuous (DC) gain of the low pass filter $G(w)$. Notice that if λ varies in the interval [1..0] the load current can be filtered from all the harmonic content associated with wc to not filtering anything, being a very useful aspect when designing a minimum size filter that satisfies certain harmonic distortion requirements [8]. We will define the transference $i_F(w)/i_C(w) = -G(w)$ so the final transference of the basic cell of Fig. 8 is $i_L(w)/i_C(w) = [1 - G(w)]$.

A. Series and parallel connection selective shunt filter

It has been established that by means of the calculations established in Fig. 7 and outlined in Fig. 8, with a SFBC it is possible to identify and separate a certain harmonic sequence. As a consequence at least two primary ways in which the calculations can be done to the effects of establishing the current associated with several harmonic sequences that are wanted to be eliminated from the line current i_L arises. Fig. 9 and Fig. 10 calculation methods will be referred as series (S) and parallel (P). Both calculation ways would arrive to the same result if the modulation - demodulation low pass filters $G(w)$ were ideal.

In practice, this does not happen and in spite of at first impression P method seems at least faster because of the possibility of making calculations in parallel, is S method the one which gives better practical results. Analyzing the calculation methods with ideal low pass filter G_k both methods arrive to the same transference

$$i_L = i_1 + \sum(1 - \lambda_k).i_k + i_\infty \tag{29}$$

On the other hand with real low pass filters G_k, in the series S case the transference is

$$\frac{i_L}{i_C} = \prod(1 - G_k) \tag{30}$$

and in the parallel P method is

$$\frac{i_L}{i_C} = (1 - \sum G_k) \tag{31}$$

This last method P have a great interference between the different selective filters so it becomes inapplicable. On the other hand, if the line feeder i_L is measured the results are symmetric: P method is better than S.

V. Results

To the effects of seeing the scope and the real possibilities of filtering several harmonic sequences simultaneously, a real application in an arc furnace [8] was taken as an example. In this case the difficulties increases because the current to be filtered is not at steady state. The goal was to design a selective filter that could attenuate in a pre-calculated value definite harmonic sequences in order to obtain in the line current a given harmonic distortion and individually for each harmonic in such a way of not exceeding the penalization regulation [13]. The filtered sequences components were 18 $(+2, -2, +3, -3, \ldots +10, -10)$. As low pass filters $G(w)$ digital Butterworth filters were used. To the effects of filtering each harmonic in an optimum way, the order and the cut-off frequency of the filter were calculated for each one. Fig. 12 shows the current harmonic distortion in the case of an S filter, when making equal to 1 all the gains λ (the filter tries to filter everything).

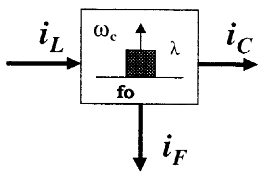

Fig. 8. Selective Filter Basic Cell (SFBC)

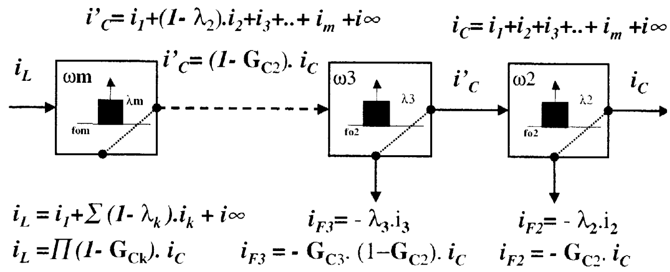

Fig. 9. S Method

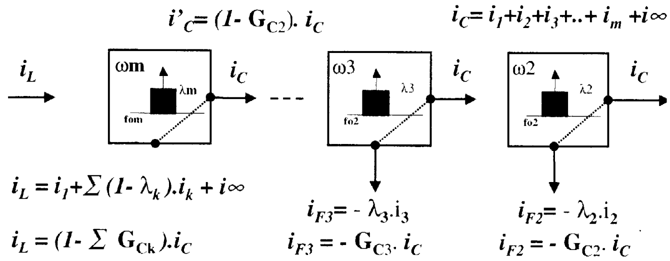

Fig. 10. P Method

One consequence of doing the calculation harmonic by harmonic is that each basic cell takes little portions of the fundamental current; hence the first harmonic current taken by the filter after 18 calculations is unacceptable. For solving this problem, the first harmonic current must be eliminated from the filter current by means of a filtering cell as shown in Fig. 11. Notice the change in this last filtering cell in which the filter $G(w)$ is now a high pass filter, in what some authors call as direct method harmonic elimination [11] [7] [4],and presented in [1] as a way of removing sequence +1 and only filter the harmonic residue. These simula-

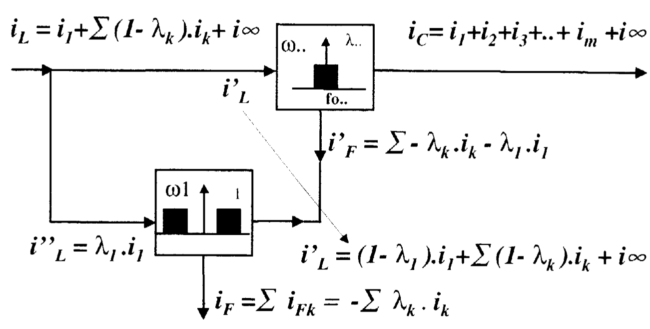

Fig. 11. SS method and +1 sequence post filter

tion results are worst than the one reported in [8], but the searched selectivity gives certain benefits. Then, the result shown in Fig. 13 is obtained if the values λi are calculated in order to attenuate the harmonics in a individual controlled way, following the criterion of respecting the regulations added to the criterion of having the minimum total current in the active filter (these calculations will be reported in a future work). This figure shows the ability of the realized calculations for synthesizing individually the harmonic currents to be synthesized by the active filter for controlling the total and individual distortion.

Fig. 14 shows the original load current, the actual

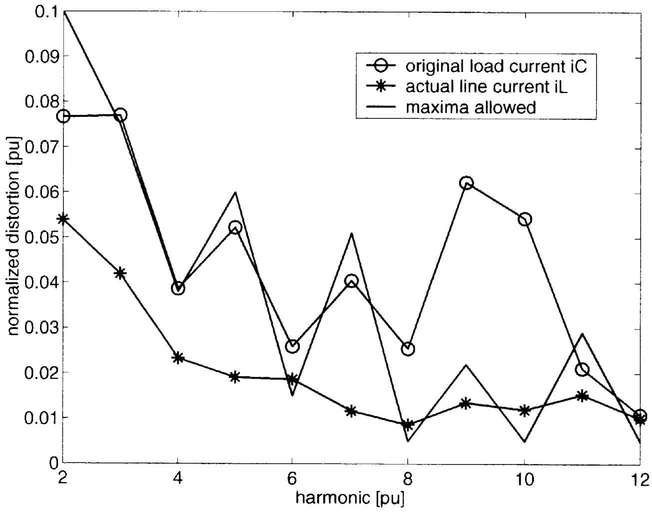

Fig. 12. Method S with all $\lambda_i = 1$

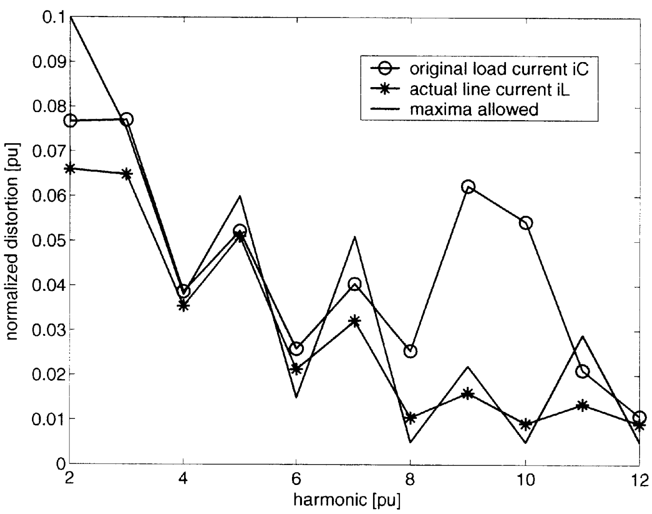

Fig. 13. Method S with optimism λ_i

obtained line current and the active filter current for the optimum λi where the 12% desired final total distortion is achieved.

VI. Conclusion

The theory associated with the way of calculating the selective shunt active filter current using pq theory and its equivalence with SRF method, has been presented. Two calculation alternatives named series (S) or parallel (P) were presented. If we compensate measuring the load current i_C, better performance of S method were reported because it has less interference between the filters of different harmonic sequences. If we feedback the line current i_L, symmetric results were introduced so P is better than S method.

As a way of proving the methodology real non-periodic waveform currents with a great harmonic distortion were used, and the results shown the ability of filtering in a selective way.

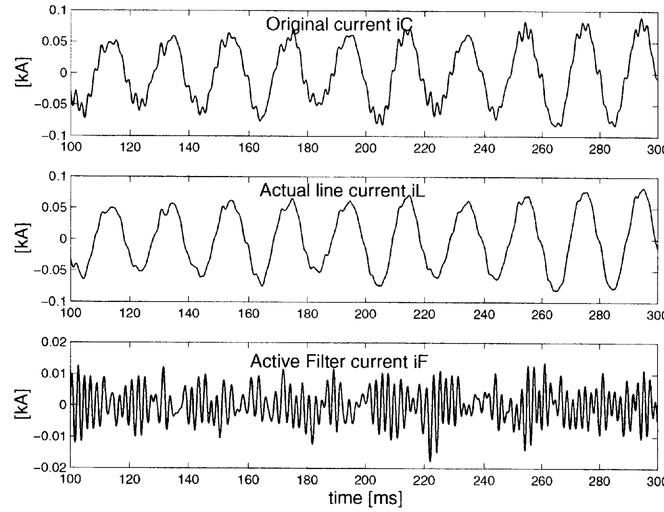

Fig. 14. Original load current, actual obtained line current and active filter current with optimum λ_i

References

[1] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive power compensator comprising switching devices without energy storage components," *IEEE Trans. Ind. Appl.*, vol. Vol. 20, no. 3, pp. 625–630, 1984.

[2] S. Bhattacharya, P. Cheng, and M. D. Divan, "Hybrid solutions for improving passive filter perfomance in high power applications," *IEEE Transactions on Industry Applications*, vol. 33, no. 3, pp. 732–747, 1997.

[3] S. Bhattacharya and D. Divan, "Design and implementation of a hybrid series active filter system," *IEEE*, pp. 189–195, June 1995.

[4] V.S. Ramsden D. Basic and P. Muttik, "Hybrid filter control system with adaptive filters for selective elimination of harmonics and interharmonics," *IEE Proc.-Electr. Power Appl.*, vol. 147, no. 3, pp. 295–303, May 2000.

[5] S.Park J.H.Shung and K.Nam, "New hybrid parallel active filter configuration minimising active filter size," *IEE Proc. Electr. Power Appl.*, vol. 147, no. 2, pp. 93–98, Mar. 2000.

[6] P. Mattavelli, "A closed-loop selective harmonic compensation for active filters," *IEEE Transactions on Industry Applications*, vol. 37, no. 1, pp. 81–89, 2001.

[7] J. Monteiro, "Filtros híbridos Ativo/Passivo de potência: Modelagem no domínio da freqüência," M.S. thesis, COPPE - UFRJ, 1997.

[8] G. Casaravilla, C. Briozzo, and E. Watanabe, "Filtro activo de mínimo costo ajustado a la carga de un horno de arco y a las regalamentaciones sobre emisión armónica aplicables," *XIII CBA-Congresso Brasileiro de Automática*, pp. 1108–1113, 2000.

[9] Mauricio Aredes and Edson H. Watanabe, "New control algorithms for series and shunt three-phase four-wire active power filters," *IEEE Trns. on Power Delivery*, vol. Vol. 10(3), pp. 1649–1656, 1995.

[10] Mauricio Aredes, *Active power line conditioners*, Ph.D. thesis, Technical University of Berlin, 1996.

[11] K. Al-Haddad B. Singh and A. Chandra, "A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960–971, Oct. 1999.

[12] H. Akagi, "Control strategy and site selection of a shunt active filter for damping of harmonic propagation in power distribution systems," *IEEE Transactions on Power Delivery*, vol. 12, no. 1, pp. 354–362, 1997.

[13] Ente Nacional Regulador de la Electricidad Argentina, "Decreto 99/97," 1997.

[14] Hirofumi Akagi, "New trends in active filters for power conditioning," *IEEE Trans. on Ind. Applications*, vol. Vol. 32(6), pp. 1312–1322, 1996.