Selective Active Filter Applied to an Arc Furnace Adjusted to Harmonic Emission Limitations

Gonzalo Casaravilla, Adriana Salvia, Cesar Briozzo, Edson Watanabe

Abstract— **This paper describes how to calculate the different harmonic sequences that should be filtered with a shunt selective active filter, for two control alternatives: load current measurement or line current measurement. These results are then generalized for shunt hybrid selective filters. Passive parameters are chosen considering the resonances with the electric system that appear. Design basis are defined in order to obtain a minimum cost filter which also meet the applicable regulations requirements. Finally, results showing the potentiality of the selective filter controlled for the proposed methods are reported.**

Keywords— **Hybrid selective active filter, arc furnace, pq theory**

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. A 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 systems 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 tunning 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.

The question of why canceling the harmonic distortion if the regulations does not require that; is presented and answered in [7]. The results of this first work [7], start from an active shunt filter, and a minimum cost active filter is should be compensated. 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. Another answer is related to how much each individual harmonic should be reduced in order to comply exactly with what the regulation demands, but minimizing the active filter cost. Previous works have indicated the convenience of using hybrid filters in several topologies in accordance with the searched requirements [8] [5]. From the economic point of view, it is convenient to reuse the existing reactive compensation capacitors. These capacitors are, in most of the cases, the cause of resonances with the electric system, and making the incidence of the harmonics injected into the electric system even worse.

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II. Control and calculation methods

As exposed in [9] there are three ways of controlling a shunt active filter: measuring the load current method, measuring the line feeder current method or measuring the voltage in the point of common connection (PCC) of the load. A comparative study of the first and the second methods will be done here. These two methods will be named C (load) and L (line) respectively. In fact, method C is a compensation (feedforward) so it should not present major stability difficulties. This is not true for the method L because being a feedback system the stability must be analyzed carefully. A fundamental element of control strategy is the basic filter selective cell (BFSC) [10] represented in Fig. 1. The BFSC is capable of identifying and separating in real time a certain individual harmonic sequence of a certain current. The calculations presented in [10] are based on pq theory [1], equivalent to SRF method as also demonstrated in that paper. As a main result, it can be concluded that BSFC presents for the positive harmonic sequences a transference between the input -i_C or i_L- and the output i_F that can be expressed as $-G(w-w_c)$, being $G(w)$ the transference of an ideal low pass filter and w_c the frequency of the positive sequence carrier signal used for modulate and demodulate. If a negative harmonic sequence is used as a modulating and demodulating signal, the result becomes $-G(w+w_c)$. Fig. 1 also establish the signs convention adopted. The aim of a selective filter is controlling at will, how much of the load current is injected in the line, taking the selective filter the difference. Fig. 2 shows the ideal transference $G_{LC}(w) = i_L(w)/i_C(w)$ that might be obtained from a generic selective filter, being f_1

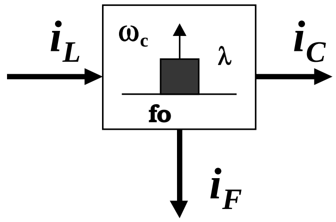


Fig. 1. Basic filter selective cell: BFSC

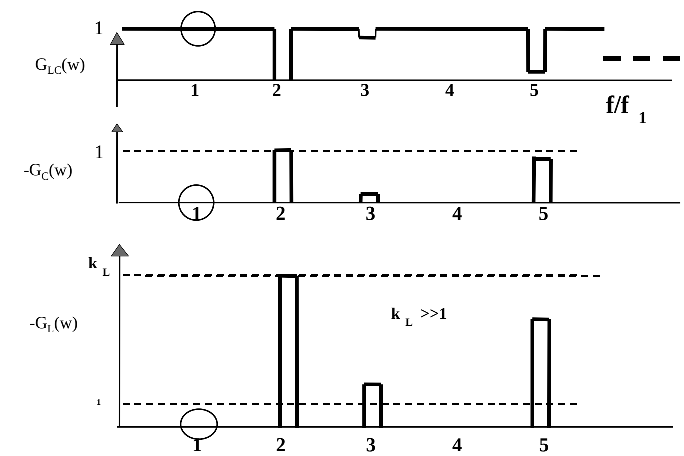


Fig. 2. Ideal transference $G = i_L/i_C$, $-G_C = i_F/i_C$ and $-G_L = i_F/i_L$

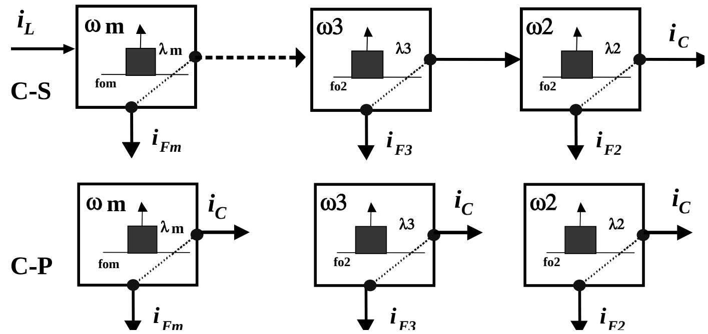
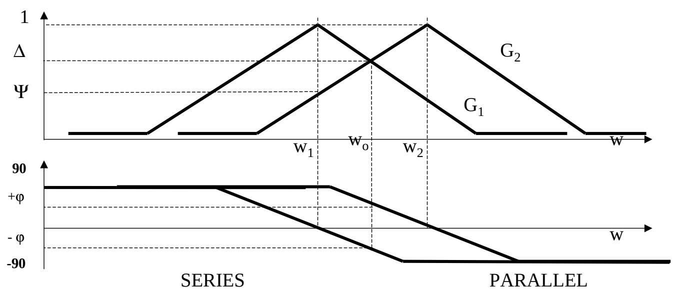


Fig. 3. $C-S$ and $C-P$ methods



	SERIES	PARALLEL
il / ic	$(1-G_1)(1-G_2) = 1-G_1-G_2-G_1G_2$	$1-G_1-G_2$
At w_1	$0.(1-\Psi_{90}) = 0$	$1-1-\Psi_{90} = -\Psi_{90}$
At w_2	$(1-\Psi_{-90}).0 = 0$	$1-\Psi_{-90}-1 = -\Psi_{-90}$
At w_0	$1-\Delta_{-\varphi}-\Delta_{\varphi}+\Delta^2 = 1-2\Delta\cos\varphi+\Delta^2$	$1-\Delta_{-\varphi}-\Delta_{\varphi} = 1-2\Delta\cos\varphi$

Fig. 4. $C-S$ and $C-P$ comparison

the frequency of the network (50 or 60 Hz). Notice that the active filter must not take anything of this frequency. In the example of Fig. 2 the purpose is to filter all the second harmonic, part of the third harmonic, nothing of the fourth harmonic an almost all the fifth harmonic, etc. Taking into account that $i_L = i_C + i_F$, we will define the transferences $i_F(w)/i_C(w) = -G_C$ (C control method) and $i_F(w)/i_L(w) = -G_L$ (L control method). For the example of Fig. 2 those transferences are shown in the same picture. Then the transferences $G_{LC}(w) = i_L(w)/i_C(w)$ become $1-G_C$ and $1/(1+G_L)$ for the C and L methods respectively.

Coming back to the BFSC, in [10] two possible methods of calculation are established, SERIES (S) and PARALLEL (P). Top of Fig. 3 shows the S calculation alternative for C control method. Starting from the right of the diagram, the first BFSC applied to the given load current i_C, extracts the harmonic sequence i_{F2} from i_C. The second BFSC is applied to the resulting current $i_C - i_{F2}$ and current i_{F3} is extracted and so on. The total transference of the C-S alternative is shown in (1) where $G_2, G_3, .., G_m$ are the low pass filters of each BFSC.

$$i_L(w)/i_C(w) = [1-G_2(w-w_2)]...[1-G_m(w-w_m)] \quad (1)$$

On the other hand, bottom of Fig. 3 shows the alternative P calculation using C control. The deduction of the transference in this case is trivial because all the BFSC have as input data the same given load current i_C. For the C-P alternative the transference is therefore:

$$i_L(w)/i_C(w) = 1-G_2(w-w_2)-...-G_m(w-w_m) \quad (2)$$

In the case that the low pass filters G_i are ideal, it is easy to conclude that both methods will give the same results.

Fig. 4 shows the reason for why the C-S alternative is better than the C-P alternative as the interference between the band pass filters is less in the S case than in the P case. In that diagram two equal band pass filters G_1 and G_2 have been taken. The fact that in the S case the value of the gain is 0 in w_1 and also in w_2 and Δ^2 closer to 1 in w_0, determines that method S is better than P. As it will be shown in the results ahead, the difference makes the P method inapplicable. With respect to the other control method which feeds back the line system current (L), a strategy of calculation S or P can also be established. For example, in Fig. 5 the scheme of S method is shown; this diagram must be analyzed starting from left to right. Again, the consecutive BFSCs receive as input the outputs of their predecessors. Hence the total transference of the L-S alternative is given by:

$$i_L(w)/i_C(w) = \frac{1}{1+G_2(w-w_2)}...\frac{1}{1+G_m(w-w_m)} \quad (3)$$

Similarly, it can be established that the transference for the

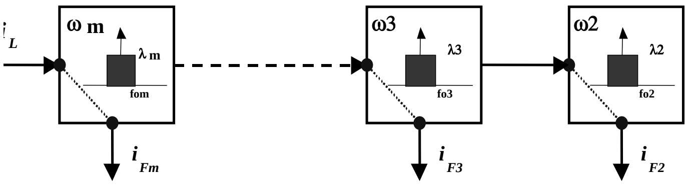


Fig. 5. $L-S$ method

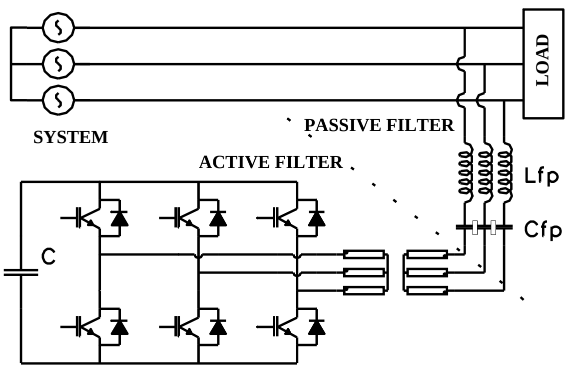


Fig. 6. Hybrid shunt active filter

L-P alternative is:

$$i_L(w)/i_C(w) = \frac{1}{1 + G_2(w - w_2) + ... + G_m(w - w_m)} \quad (4)$$

In the case of having an ideal G_i it can be seen that the transferences will be equal again, but if the L-S method is compared with the L-P method, a symmetric result is obtained: P method is significantly better than S when the line current is fed back.

III. Hybrid active filter

As it has already been said, the alternative of using active-passive hybrid filters should be considered. On one hand, in some cases, it is possible to reduce the size of the active filter in comparison with the utilization of a pure shunt active filter. But facing a real application in which a passive filter exists, or the reactive compensation capacitor is intended to be used in order to lower the invesment costs, an hybrid filter like the one shown in Fig. 6 is a natural option. In order to generalize the calculations, the shortcircuit impedance of the installation site where the active filter will be placed will be taken into account. This impedance, as it will be shown in the studied example, is reduced to the shortcircuit impedance of the HV power transformer connecting the service. The diagram of Fig. 7 models the elements of the system that is going to be analyzed. Z_{PF} is the series impedance of a capacitor C_{PF}, an inductance L_{PF} and a resistance R_{PF}. Z_L corresponds to an inductance L_L.

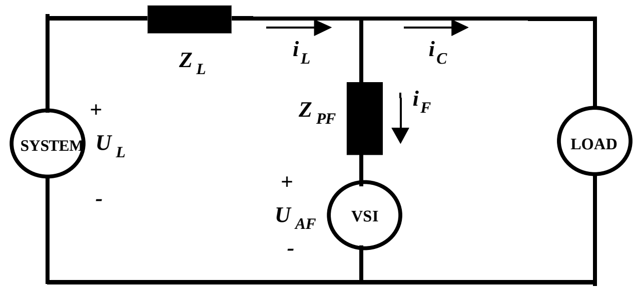


Fig. 7. Generic system model with an hybrid shunt filter

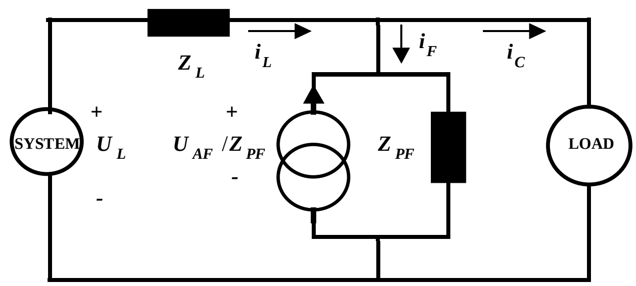


Fig. 8. Norton equivalent generic model

Fig. 8 results from replacing the Norton equivalent of the hybrid filter. Equations (5), (6) and (7) represent the dynamic of the circuit. The system control takes the reference current (i_C or i_L depending on the control method C or L) and must determine the voltage U_{AF}. This transference is defined as Z_{eq} shown in (8) or (9) if the control is C or L respectively.

$$i_F = \frac{U_L}{Z_L + Z_{PF}} - i_C \frac{Z_L}{Z_L + Z_{PF}} - U_{AF} \frac{1}{Z_L + Z_{PF}} \quad (5)$$

$$i_L = \frac{U_L}{Z_L + Z_{PF}} + i_C \frac{Z_{PF}}{Z_L + Z_{PF}} - U_{AF} \frac{1}{Z_L + Z_{PF}} \quad (6)$$

$$i_L = i_C + i_F \quad (7)$$

$$U_{AF} = Z_{eq} \times i_C \quad (8)$$

$$U_{AF} = Z_{eq} \times i_L \quad (9)$$

Hence, replacing these definitions, (10) and (11) are obtained for the C control method and (12) and (13) for the L control method. Considering that $U_L = 0$ for all the harmonics different from the first one (pure sinusoidal voltage); (11) and (13) can be written as (14) and (15) which represents the generic transferences of the C and L control methods respectively.

$$i_F = \frac{U_L}{Z_L + Z_{PF}} - i_C \frac{Z_L + Z_{eq}}{Z_L + Z_{PF}} \quad (10)$$

$$i_L = \frac{U_L}{Z_L + Z_{PF}} - i_C \frac{Z_{eq} - Z_{PF}}{Z_L + Z_{PF}} \quad (11)$$

$$i_F = \frac{U_L}{Z_{PF}} - i_L \frac{Z_L + Z_{eq}}{Z_{PF}} \quad (12)$$

$$i_L = \frac{U_L}{Z_L + Z_{PF} + Z_{eq}} + i_C \frac{Z_{PF}}{Z_L + Z_{PF} + Z_{eq}} \quad (13)$$

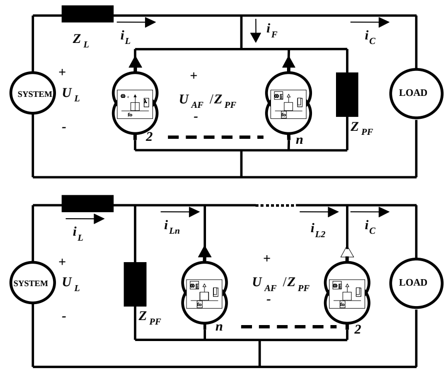


Fig. 9. C-P and C-S methods

$$\frac{i_L}{i_C} = \frac{1 - \frac{Z_{eq}}{Z_{PF}}}{1 + \frac{Z_L}{Z_{PF}}} \tag{14}$$

$$\frac{i_L}{i_C} = \frac{1}{1 + \frac{Z_L}{Z_{PF}} + \frac{Z_{eq}}{Z_{PF}}} \tag{15}$$

The possibility of making the S or P calculations arises here again. Top of Fig. 9 shows how, in the C-P case, the voltage U_{AF} can be considered as the sum of the voltages UAF_i calculated for each harmonic sequence by the BFSC modules. Then, it is possible to operate in accordance to (16), which determines the equality (17). This equation substituted in (14) determines that the transference for the C-P alternative is the one shown in (18).

$$U_{AF} = \sum U_{AFi} = \sum Z_{eqi} \cdot i_C = i_C \sum Z_{eqi} = i_C Z_{eq} \tag{16}$$

$$Z_{eq} = \sum Z_{eqi} \tag{17}$$

$$\frac{i_L}{i_C} = \frac{(1 - \frac{\sum Z_{eqi}}{Z_{PF}})}{1 + \frac{Z_L}{Z_{PF}}} \tag{18}$$

Then, for the of C-S method calculations it can be seen also on the bottom of Fig. 9 that the analysis must start from right to left. The first BFSC module calculates the current injected by the active filter for this first sequence (19); this current together with the initial current i_C determines the input current i_{L2} for the rest of the circuit at the left; and it will be the input current of the second BFSC. In this way it is possible to arrive to the expression for i_{Ln} in (20). Then the total current of the Norton model current sources is the one shown in (21). Finally, only Z_{eq} as defined in (8) remains to be identified. Operating (22) is obtained, which substituted in (14) results in the final transference for the C-S method as shown in (23).

$$i_{L2} = i_C - \frac{U_{AF2}}{Z_{PF}} = i_C(1 - \frac{Z_{eq2}}{Z_{PF}}) \tag{19}$$

$$i_{Ln} = i_C(1 - \frac{Z_{eq2}}{Z_{PF}})...(1 - \frac{Z_{eqn}}{Z_{PF}}) \tag{20}$$

$$\frac{U_{AF}}{Z_{PF}} = i_C - i_{Ln} \tag{21}$$

$$\frac{Z_{eq}}{Z_{PF}} = 1 - \prod(1 - \frac{Z_{eqi}}{Z_{PF}}) \tag{22}$$

$$\frac{i_L}{i_C} = \frac{\prod(1 - \frac{Z_{eqi}}{Z_{PF}})}{1 + \frac{Z_L}{Z_{PF}}} \tag{23}$$

Similar methodology analysis can be applied to the L-control alternatives for the P or for the S calculation methods showed in (24) and (25) respectively.

$$\frac{i_L}{i_C} = \frac{1}{\frac{Z_L}{Z_{PF}} + 1 + \sum \frac{Z_{eqi}}{Z_{PF}}} \tag{24}$$

$$\frac{i_L}{i_C} = \frac{1}{\frac{Z_L}{Z_{PF}} + \prod(1 + \frac{Z_{eqi}}{Z_{PF}})} \tag{25}$$

It is possible to conclude which are the benefits of C-S method in comparison with C-P method and the ones of L-P method in comparison with L-S method. The main difference between the study shown in section II and the last result, is the appearance of the passive system transference, consisting of Z_L and Z_{PF}. As it will be shown later, these passive elements play a fundamental role when deciding what is going to be filtered with the hybrid filter active element. If, for example, the transference of the C-S system is analyzed, it can be seen that if the requirement is to eliminate a given harmonic sequence from the line current, Z_{eqi}/Z_{PF} must be a band pass filter of unitary amplitude. The denominator Z_{PF} is associated with the real active filter real implementation with a voltage inverter (VSI). The VSI will have to cope with the impedance Z_{PF} to impose the active filter current which compensates the harmonic current that is desired to be eliminated from the line.

IV. Passive system $Z_L - Z_{PF}$ transference

As it has already been determined the passive system current transference is:

$$\frac{i_L}{i_C} = \frac{1}{1 + \frac{Z_L}{Z_{PF}}} \tag{26}$$

This transference has a zero at f_{PF} resonance frequency and a pole at the resonance frequency f_R of the system formed by the Z_{PF} filter and the line shortcircuit impedance Z_L. As it has been said, a common circumstance is to meet systems where C_{PF} already exists -being C_{PF} the system reactive filter- so the original system already has a transference that presents an undesirable resonance at a frequency we will call f_o. Then f_{PF}, f_R and f_o are expressed by:

$$f_{PF} = \frac{1}{2\pi}\sqrt{\frac{1}{C_{PF}L_{PF}}} \tag{27}$$

$$f_R = \frac{1}{2\pi}\sqrt{\frac{1}{C_{PF}(L_{PF} + L_L)}} \tag{28}$$

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1}{C_{PF}L_L}} \tag{29}$$

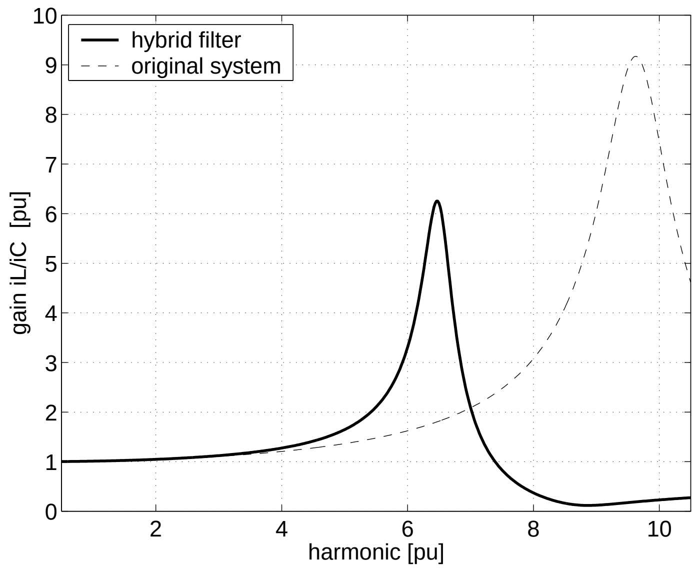


Fig. 10. Original and final passive transference i_L/i_C.

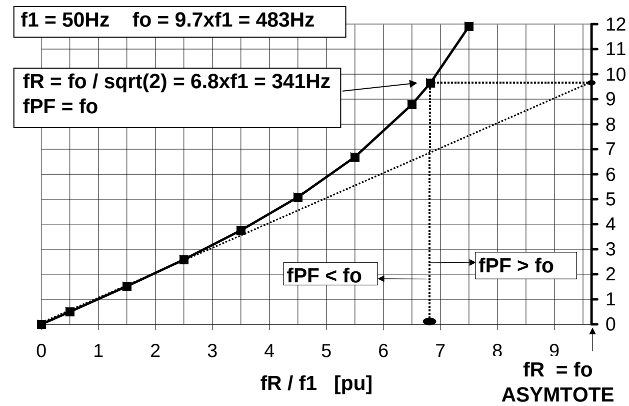


Fig. 11. Relations between f_{PF}, f_R, f_o and f_1

Fig. 10 shows the behavior of those transference where it was chosen a given quality factor Q_{PF} for the Z_{PF} filter, a final resonance at $f_R = 6.5f_1 = 325Hz$ and with a original resonance at $f_o = 9.7f_1 = 483Hz$. The dependence of f_{PF} from f_R and f_o is calculated using (27), (28) and (29). This dependence is expressed in (30). If the frequencies are normalized to the first harmonic system frequency f_1 then (31) is obtained, which results in the graph of Fig. 11. Then it can be concluded that:

- Frequency f_R will always be smaller than f_o
- As f_R gets closer to f_o, frequency f_{PF} tends to infinite
- f_R is always smaller than f_{PF}
- When f_R passes from being less than $f_R = f_o/\sqrt{2}$ to being larger, f_{PF} passes from being less than f_o to being larger than f_o.
- It is convenient to choose f_R in interharmonics values in order to minimize its resonance effects, and to try that the value of f_{PF} belongs to the spectrum zone where the content of undesirable frequencies is high in order to reduce them with the passive filter

$$f_{PF} = f_R\sqrt{\frac{1}{1-(\frac{f_R}{f_o})^2}} \tag{30}$$

$$\frac{f_{PF}}{f_1} = \frac{f_R}{f_1}\sqrt{\frac{1}{1-(\frac{f_1}{f_o}\frac{f_R}{f_1})^2}} \tag{31}$$

V. Studied case

The real case presented is a load consisting of an industrial arc furnace whose fundamental elements are shown in Fig. 12. In [7] a shunt active filter connected to the 150 kV bus bar was designed. In this work, an hybrid active shunt filter to be connected to the 31.5 kV bus bar is presented. The costs associated with a 150 kV design, and, as it will be seen later, the resonance between the 150/31.5 kV

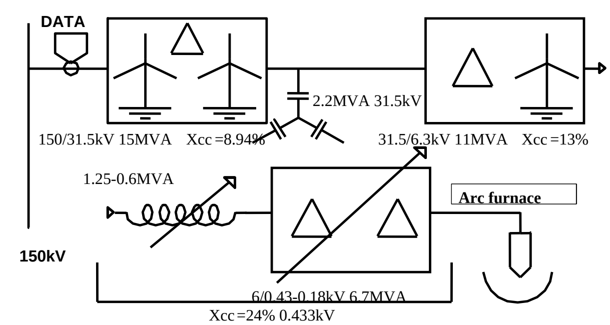


Fig. 12. Studied complete system

transformer shortcircuit impedance and the reactive compensation capacitor, suggest to attempt to attenuate this resonance with the low design hybrid filter. The graph of Fig. 10 was calculated with the values of the studied real system, so the resonance at $f_o = 9.7f_1 = 483Hz$ frequency is a problem to be solved.

In Fig. 13 a record of the original current i_L and i_C normalized to the 150 kV level is presented. Fig. 15 shows their respective harmonic distortions normalized to the contract nominal current, as the reference regulation [11] demands. The effect of the resonance mentioned above at f_o can be noticed. In the same graphic the maximum allowed values are included, so it can be said that if the arc furnace were connected directly to 31.5 kV it will almost comply with the regulation since total distortion will be 14% a little bit above the admitted 12%. The capacitor C_{PF} is at 31.5 kV, and is responsible with Z_L for the resonance problem.

The goal of this design is to obtain a minimum cost hybrid active filter which make the current i_L at 150 kV level to comply with the regulations which were taken as reference [11]. As it has been presented in [7], where statistical considerations and arc furnace weekly work regime are brought together, our problem reduces to the fact that with the current i_C of Fig. 13 the final current i_L must have a total harmonic distortion of 12% and the permitted limits for each individual harmonic are not exceeded.

A. Calculation and control strategy selection

With the minimum cost goal, the option C developed in this work is chosen because it is more simple and it is also quite representative of the concept "you dirty, you clean". Line current i_L feed back options are more interesting to eliminate given harmonics, but they make the active filter to work for compensating eventual deviations from the ideal waveform of the feeding voltage of the system. If the power mains is not ideal and therefore injects harmonics in the system, we would have a negotiation element in front of an eventual penalization of who offers the electric service. With respect to the calculation method, the alternative of series calculations (S) is used, since its advantages have been demonstrated above.

B. Passive filter selection

L_{PF} is determined by choosing the frequency f_R where the resonance will be, and which frequencies can be attenuated placing the zero at the frequency f_{PF} of the transference i_L/i_C. Looking at the graph in Fig. 11 and the distortion of i_C shown in Fig. 15 it is possible to arrive quickly to the choice of $f_R = 6.5 f_1 = 325Hz$ (interharmonic selection) making that $f_{PF} = 8.8 f_1 = 439Hz$. Concerning to the choice of R_{PF} a low resonant filter quality factor $Q_{PF} = w_1 L_{PF}/R_{PF}$ of 10 was used.

C. Optimum selectivity

The need of knowing which and how much each harmonic sequence has to be compensated arises. Initially, the choice was to act up to the 10th harmonic order, so there are 18 harmonic sequences as candidates (+2 -2 +3 -3 ..+10 -10). Remembering the aim of having a minimum cost active filter, it must be intended that its inverter takes the minimum possible instant current, so if it is assumed that every compensation current are in phase, it can be said that the aim is to minimize $\sum i_{Fi}$. The other restriction when searching the optimum is that the total harmonic distortion is 12% at 150 kV bus bar, so this expression must be evaluated including the passive filter transference. Because of space reasons, it is impossible to present here the development of this optimization and it will be presented in future works. The obtained result comprises 100% of compensation for the second sequences, 20% for the third, 50% for the fourth, 25% for the fifth, 100% for the sixth, 25% for the seventh and no compensation for the eighth, ninth and tenth.

VI. Results

Fig. 14 shows the result of the complete simulation obtained by applying the pre calculated compensation using C-S control and calculation strategy, whose transference was showed in (23). Fig. 15 shows relevant currents frequency spectrum. It can be noticed that the final current,

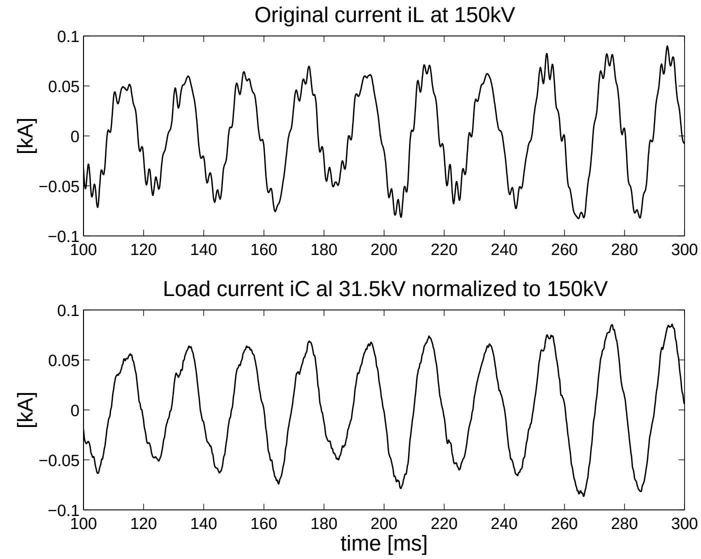


Fig. 13. Original records of line current i_L and load current i_C

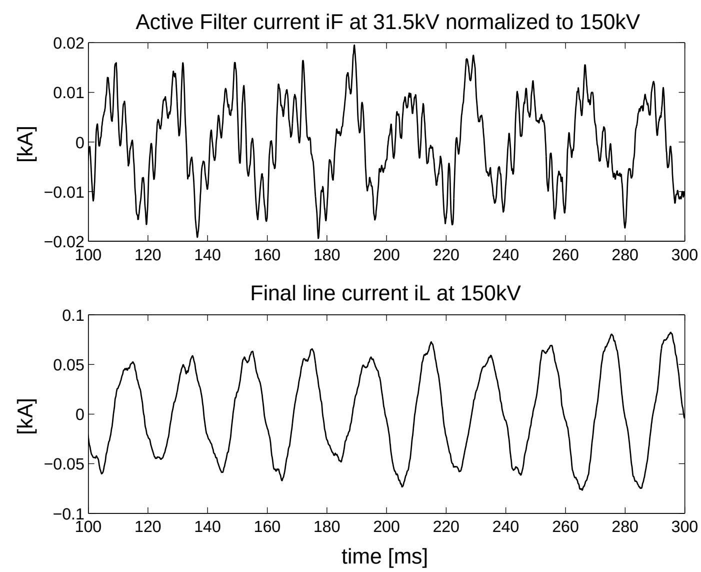


Fig. 14. Hybrid active filter current i_F and final line current i_L

after applying the filter, has all its individual harmonics below the accepted maximum and that the total distortion is 12% (distortions are measured values in the 15 net cycles of the record). Notice how the filter also takes the reactive compensation current.

In Fig. 16 is shown the transference in steady state of the control system and it can be appreciated how calculation method S is better than P. The results in real time simulations (Fig. 14) shows that the system responds to this transference, in spite of the absence of periodicity in the recorded real current used as system input.

VII. Conclusions

The theory associated with two of the possible control alternatives, which feeds back the load current -C- or the line current -L-, has been presented. Having the goal of accomplishing a selective filtering, it has been shown how

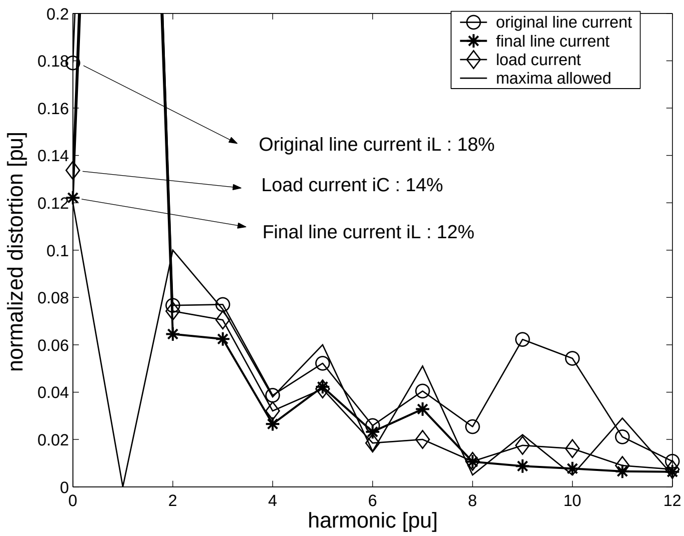


Fig. 15. Spectrum of the Fig. 13 and Fig. 14 currents and allowed maxima permitted by reference regulations. Total distortion shown at 0Hz

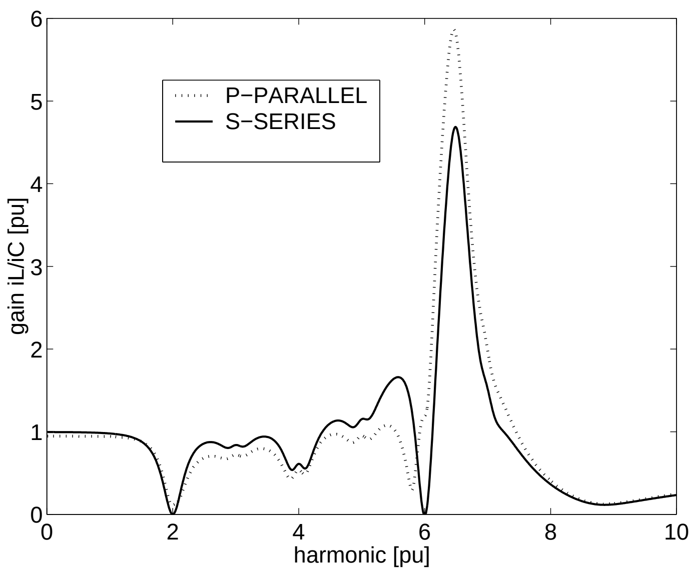


Fig. 16. Steady state transference i_L/i_C of C-S method and C-P method

the two calculation alternatives "series -S- and parallel -P-" arise, showing that S is better in C case meanwhile P is better in L case. The influence of the passive elements of the hybrid active filter and the line has been shown, establishing the selection criteria for the filter parameters in order to obtain selective filtering. There were established selection criteria for the control and calculation strategies, in the case of designing a minimum cost filter adapted to a load as an arc furnace which also fulfils the applicable regulations emphasizing that the concept "you dirty, you clean" must be followed. Finally, the simulation results that show the potentiality of the selective hybrid filtering are reported.

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] 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.

[8] 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.

[9] 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.

[10] G. Casaravilla, A. Salvia, C. Briozzo, and E. Watanabe, "Control strategies of selective harmonic current shunt active filter," *COBEP - Congresso Brasileiro de Electrónica de Potencia*, pp. 432–437, 2001.

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

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

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