Selective Active Filter Comparison: Shunt or Shunt Hybrid with Remote Harmonic Distortion Control

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Abstract— **This paper analyzes and compares some of the harmonic current selective filtering possibilities that can be applied to an existing industrial arc furnace installation. In the studied case, the customer is connected to a 150kV busbar point. The verification of the coustomer compliance with the harmonic emission regulation must be done in that point of common coupling (PCC). With that purpose, the alternatives of installing a Selective Shunt Active Filter in the PCC or a Selective Shunt Hybrid Active Filter in a intermediate voltage level of 31.5kV, are designed and compared. In this last case, the verification of the harmonic emission regulation compliance must be done in a remote point (PCC), different from the one where the filter is connected. This fact, requires to consider the harmonic propagation between those points in the network, caused by the resonances between the short-circuit impedance and the capacitors used for reactive power compensation. In both cases, the calculation methodologies that must be used to obtain the wished selectivity for complying with the regulation and to minimize the size of the active filter VSI, are shown and discussed.**

I. Introduction

The classic way of solving some harmonic problems is by installing a tuned LC shunt passive filter as close as possible to the harmonic source. Passive filters are economical and efficient. Although they help to solve the problem, they have many drawbacks. For instance, the passive filter can be overloaded if the voltage supply has harmonics. Another problem could arise from the resonance produced between the passive filter and the line impedance.

If a resonance between a reactive power compensation and the line impedance existed before the installation of the passive filter, then, when using the capacitor in the shunt tuned filter, the resonance frequency could be dangerously reduced in respect to the previous resonance frequency.

Active Filters are one of the solutions to harmonic problems given by Power Electronics. An active filter is only a controlled alternating voltage source (VSI) which, if commanded in a proper way (PWM), could handle power quality problems. The active filter basic configurations are: Shunt, Series and their Hybrid derivatives (shunt or series).

Nowadays is growing the awareness associated with the principle *"you dirty, you clean"*. Passive filters are not appropriate for using that principle. The shunt passive filter will take the harmonics that are emitted near it, no matter who generates them. The filter will take the harmonics which are generated by its owner and the harmonics generated by its neighbors. The passive filters are examples of solidarity.

The device which adapts better to the principle *"you dirty, you clean"* is the shunt active filter. Even more if it is controlled in order to compensate only the consumed harmonics. If the supply voltage quality is bad and causes a rise in the consumed harmonics, they must not be filtered by the consumer. In this paper, the control method that will be used compensates (filters) only what is needed of the load current.

All the harmonic currents can be filtered using the PQ Theory [1]. Some problems which may appear when using this Theory for harmonic elimination can be solved. For instance, when the voltages are not sinusoidal, Akagi et all [2] concludes that the solution is to use a PLL. The basic idea of applying this Theory is to separate the fundamental frequency contributions from the instantaneous powers $\tilde{p}$ and imaginary power $\tilde{q}$. Some authors call this method as *direct* [3]. In this work the propose is to call it as *residual* because all the harmonic residue is treated in the same way. This method is deeply analyzed for a particular case in [4]. Conceptual tools useful for it analysis are given in [5] and [6].

On the other hand, [6] concludes that although THD requirements are met when using *residual* filtering, certain problems persist in some individual harmonics. The reason why several individual limits of the harmonic regulation are not met is the non selective characteristic of *residual* filtering.

Many works [3][7][8] and [9], have studied selective active filters within the last years. Although there is experience in their usage, implementation and limitations, they have been applied mostly in particular cases where it was not always necessary to filter in a selective way many frequencies. In several cases, when the goal was to completely eliminate a certain frequency, stability problems became critical, and they were investigated. In other cases no distinction between different sequences was made and both were filtered equally.

Selective filter basic cells $SFBC$ [10][11][12] are used as calculation units to obtain the VSI references when selective filtering is the goal. $SFBC$ can discriminate the harmonics sequences of unbalanced three-phase currents. The current transference obtained is $\frac{i(w)}{i_c(w)} = -G_c(w \mp wc)$ where the minus sign is applied when filtering a positive sequence in a selective way, the plus sign is used for a negative sequence, wc is the filtered harmonic sequence and $G_c(w)$ is a low pass filter with a λ gain and a wo bandwidth.

The differences between the calculation method of VSI control references in the case where the control uses the load current (i_C) measure and in the case where it feeds back the line current (i_L) [13] were never reported. These differences are shown in [11]. This work concludes that when load current (i_C) compensation is performed, the references of the VSI for doing a selective filtering must be calculated by using a *Series* method, and the transference is $\frac{i_L(w)}{i_C(w)} = \Pi(1-G_{ck})$. On the other hand, a *Parallel* calculation method must be used when the line current is fed back and the transference is $\frac{i_L(w)}{i_C(w)} = (1-\sum G_{ck})$ where $G_{ck} = G_{ck}(w \mp w_{ck})$ are the low pass filters of each SFBC.

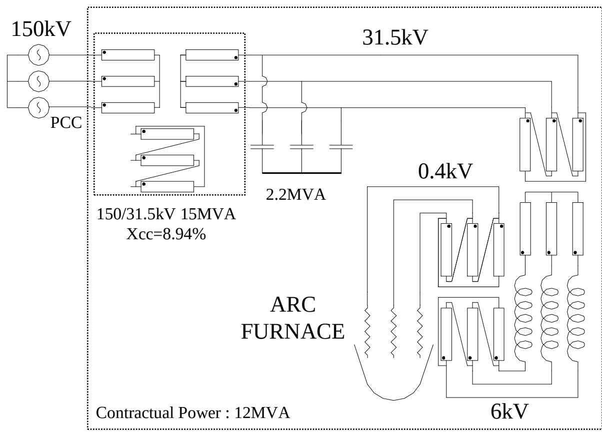

Fig. 1. Three-pase circuit of the arc furnace installations.

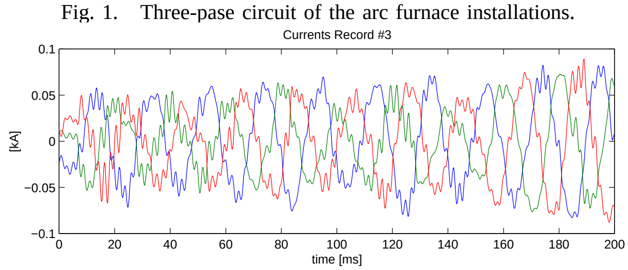

Fig. 2. Actual current oscilogram at the PCC without filtering.

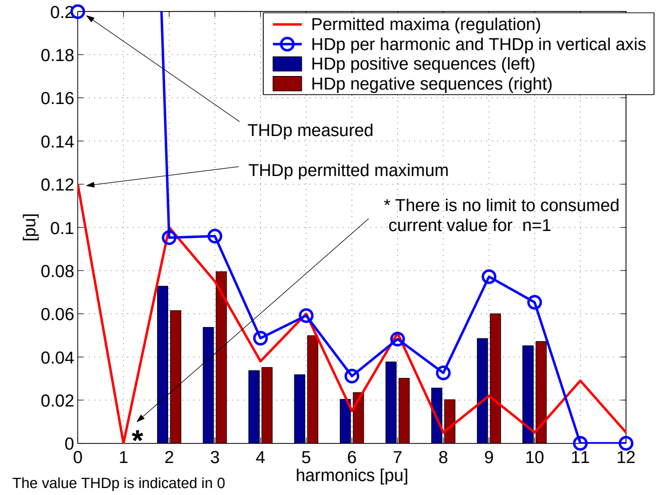

Fig. 3. Fifteen net cycles average harmonic content $THDp$ for each harmonic sequence and permitted maxima.

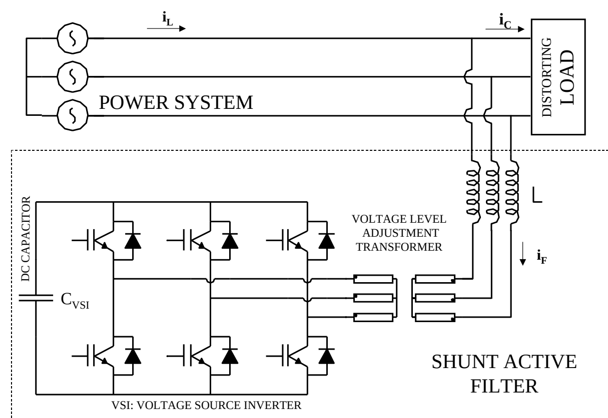

Fig. 4. Shunt active filter connected at 150kV.

II. Studied Industrial Example

The diagram of Fig. 1 shows the electric circuit of an industrial arc furnace. Its rated power is 12MVA and it is connected to the 150kV busbar (PCC). Fig. 2 shows a real current register in the PCC. This current is the one used in the simulations of the designed active filter. Fig. 3 shows the frequency content (normalized harmonic distortions[1]) of the records plotted in Fig. 2 for each harmonic sequence ($HD_{\pm k}$). It also shows the harmonic distortion weighted for the three phases and for each harmonic (HDp_k), the maxima permitted by the regulation for each harmonic and the total weigted harmonic distortion (TDH_p) [15].

III. Shunt Active Filter in the 150kV Busbar

One option is to design the shunt active filter connected to the 150kV busbar as shown in Fig. 4.

A. Selective filter design

A selective filtering will be done by compensating the measured load current i_C with the *Series* calculation method. At first, the harmonic sequences that are going to be filtered are chosen. Then, low pass digital filter G_{ck} must be determined for each one of the $SFBC$ associated to each harmonic sequence k.

Second order low pass filters implemented digitally as the complement of a high pass Butterworth IIR filter will be used. Higher orders produce such a delay in the signals that makes selective filtering impossible. This circumstance becomes worse in this case where the currents that are going to be filtered are non-periodic.

Regulations about harmonic emission establish two requirements: not to exceed a determined value of THD and not to exceed a certain value of harmonic distortion HD for each individual harmonic.

In order to comply with the regulations and also minimize the active filter VSI, the optimum method presented in [15] is used for calculating the attenuation that must be imposed to each harmonic sequence and the gains λ_i. This method makes $THDp = THD$ required and $HD_p = HD$ required for the individual harmonics up to certain frequency.

Fig. 5 shows the obtained optimum values for the gains λ_i. As it can be noticed in this figure, selective filtering will be performed up to the 10 harmonic inclusive, and 16 $SFBCs$ will be required. Then, only the bandwidths wo and the *leads* [8] applied in the demodulation of each $SFBC$ must be determined.

The value wo that will be chosen for each selective filter is the one which best filters each harmonic sequence. This election is done individually for each selective filter. In the same process, the most appropriate *lead* is also chosen.

Afterward, a local optimization which takes the individual optima as starting values must be done. The optimization objective is to minimize $Imax_{95}$[2] current. The optimum wo values for a determined current arise from this last calculation process. In this

[1]Distortion definitions used in the regulations are relative to the aparent nominal current I_N. This value represents the current that corresponds to the contracted active current with a certain power factor. In the Argentinean case the power factor is equal to 0.85 [14]

[2]$Imax_{95}$ is the 95th percentile of the instantaneous currents that the active filter must take. Therefore, if the active filter inverter can supply that current value, the calculated requirements can be met up to 95% of the time.

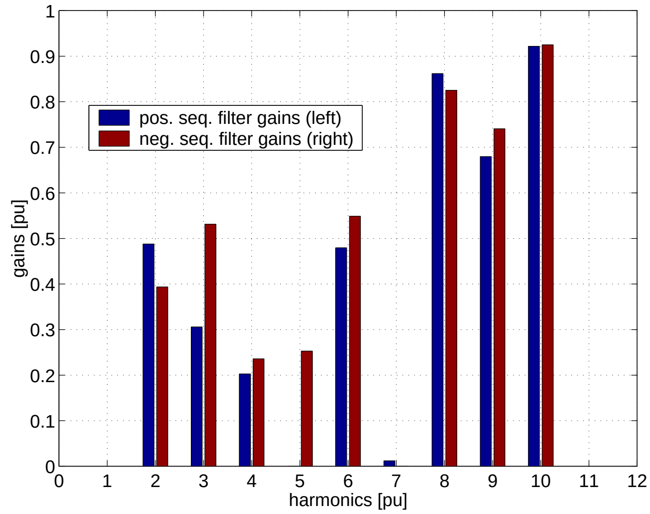

Fig. 5. Optimum gains λ_i. Shunt active filter located in the 150kV bus bar.

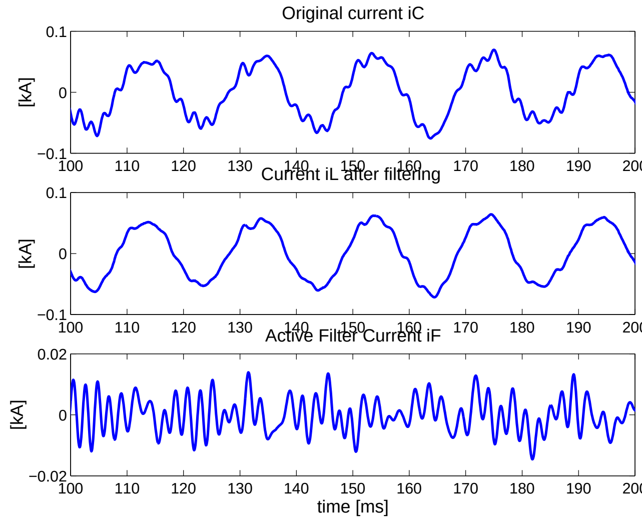

Fig. 6. Currents i_C, i_L and i_F. Optimum selective active filtering that meets the regulations.

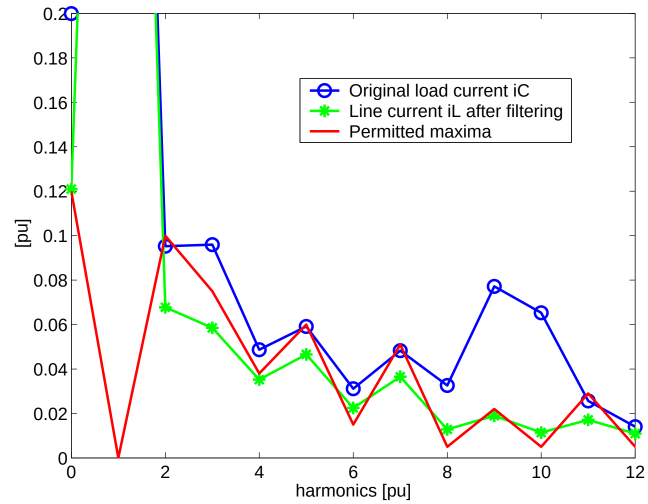

Fig. 7. Current i_C, i_L spectrums and permitted maxima. Optimum selective active filtering that meets the regulations.

example, the search of the local optimum instead of keeping the initial values, reduces 2% the size of the required active filter.

On the other hand, the search of the optimum *leads* can reduce 4% the size of the active filter. When unavoidable *real* delays (as the one that can be caused by the VSI control) are considered, these *leads* must be calculated again. For example, [8] presents a criteria for the theoretic determination of the *leads*, taking into account the VSI control delay. Fig. 6 shows real current i_C, the final current i_L obtained after filtering and active filter current i_F. Fig 7 shows the harmonic distortions of these currents together with the permitted maxima. Current $Imax_{95}$ of current i_F is 10.2A[3] and RMS current 5.7A.

Another value that must be chosen is the working voltage V_{DC} of the VSI capacitor C_{VSI}. This value strongly depends on the reference current that will be imposed to the active filter inverter. One criteria is to take a value greater than the maximum phase voltage, for example $\frac{V_{DC}}{2} = [150\sqrt{2}/\sqrt{3}] * 1.4 = 170kV$. The 1.4 factor is considerably conservative to the effects of assuring a good inverter performance and achieving to impose the desired current.

IV. Shunt Active Filter in the 31.5kV Busbar

The other option is to design a shunt hybrid active filter in the 31.5kV bus bar as shown in Fig. 8.

A. Hybrid filter generic model

The diagram of Fig. 9 models the elements of the system that is going be analyzed. Z_{PF} is the series impedance of a capacitor C_{PF}, an inductance L_{PF} and a resistance R_{PF}. The impedance Z_L is the series of an inductance L_L with a resistance R_L. Z_L is the shortcircuit impedance of the installation site where the active filter will be placed (PCC). In the studied example this impedance is reduced to the shortcircuit impedance of the 150/31.5kV transformer.

Fig. 10 results from replacing the Norton equivalent of the hybrid filter. Equations (1), (2) and (3) represent the dynamic of the circuit.

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

$$i_L = \frac{U_L}{Z_L + Z_{PF}} + i_C\frac{Z_{PF}}{Z_L + Z_{PF}} - U_{AF}\frac{1}{Z_L + Z_{PF}} \quad (2)$$

[3]All values referred to 150kV busbar.

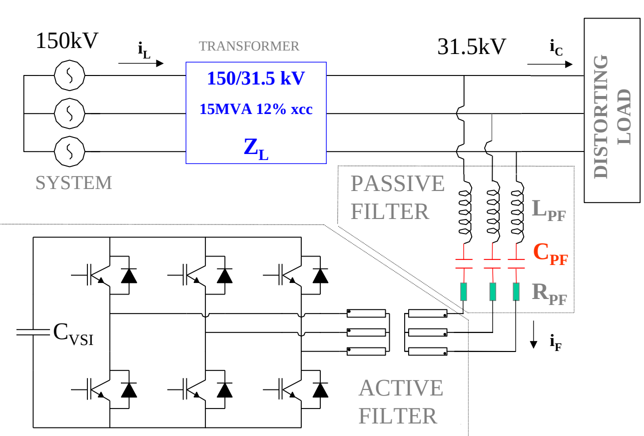

Fig. 8. Hybrid active filter connected at 31.5kV

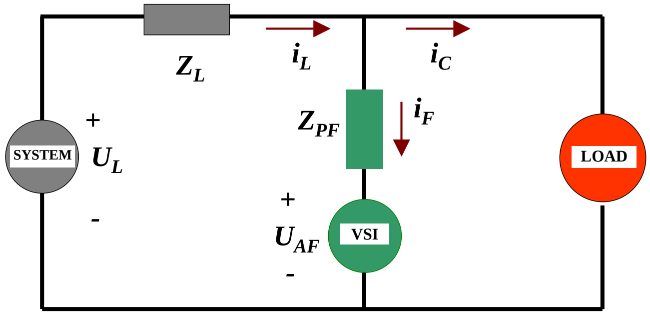

Fig. 9. Generic system model with an hybrid shunt filter.

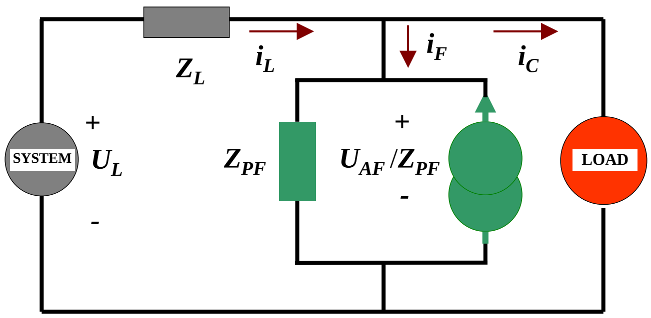

Fig. 10. Norton equivalent model.

$$i_L = i_C + i_F \tag{3}$$

The system control takes the reference current i_C and must determine the voltage U_{AF}. This transference is defined as Z_{eq}[4]

$$U_{AF} = i_C Z_{eq} \tag{4}$$

Replacing these definitions in (1) and (2), (5) and (6) are obtained.

$$i_F = \frac{U_L}{Z_L + Z_{PF}} - i_C \frac{Z_L + Z_{eq}}{Z_L + Z_{PF}} \tag{5}$$

$$i_L = \frac{U_L}{Z_L + Z_{PF}} - i_C \frac{Z_{eq} - Z_{PF}}{Z_L + Z_{PF}} \tag{6}$$

Assuming that $U_L = 0$ for all the harmonics greater than one (pure sinusoidal system voltage) (6) can be written as

$$\frac{i_L}{i_C} = \frac{1 - \frac{Z_{eq}}{Z_{PF}}}{1 + \frac{Z_L}{Z_{PF}}} \tag{7}$$

B. U_{AF} calculation method

Again, the *Series* calculation method must be used. In [11] it is demonstrated that in this case the transference is

$$\frac{i_L(w)}{i_C(w)} = \frac{\prod(1 - \frac{Z_{eqi}}{Z_{PF}})}{1 + \frac{Z_L}{Z_{PF}}} \tag{8}$$

If the requirement is to eliminate a given harmonic from the current, a term of the numerator must be equal to zero. This is equivalent to impose to that harmonic sequence

$$\frac{Z_{eqi}}{Z_{PF}} = 1 \tag{9}$$

thus, $\frac{Z_{eqi}}{Z_{PF}}$ is a band pass filter which only allows the selected harmonic to pass. This is the duty of each $SFBC$.

[4]It is defined as Z due to the transference having the same dimension than impedance

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

From *Series* calculation, which transference is stated in (8), the intermediate current i_C^* is obtained

$$i_C^* = i_C \prod(1 - \frac{Z_{eqi}}{Z_{PF}}) \tag{10}$$

This current, when filtered by the passive filter, determines the final line current

$$i_L = \frac{i_C^*}{1 + \frac{Z_L}{Z_{PF}}} \tag{11}$$

The passive transference has a zero at the resonance frequency of the impedance Z_{PF}

$$f_{PF} = \frac{1}{2\pi}\sqrt{\frac{1}{C_{PF}L_{PF}}} \tag{12}$$

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

$$f_R = \frac{1}{2\pi}\sqrt{\frac{1}{C_{PF}(L_{PF} + L_L)}} \tag{13}$$

A common circumstance is to meet systems like the one that is being studied where Z_L and C_{PF} already exists -being C_{PF} the system reactive filter- so the original system already has a transference that presents an undesirable resonance pole at a frequency f_Q.

$$f_Q = \frac{1}{2\pi}\sqrt{\frac{1}{C_{PF}L_L}} \tag{14}$$

Fig. 12 shows the original transference of the studied example. The resonance that can be noticed in this figure, explains the high harmonic content of the 8^{th}, 9^{th} and 10^{th} harmonics shown in Fig. 3 where the harmonic content of a real record of the current measured in the 150kV bus was plotted. This agrees with the fact that an arc furnace does not consume a particular frequency current due to the random of the process. From (12), (13) and (14) the relation between f_{PF}, f_R and f_Q can be calculated

$$f_{PF} = f_R\sqrt{\frac{1}{1 - (\frac{f_R}{f_Q})^2}} \tag{15}$$

If frequencies f_R and f_{PF} are normalized to the first harmonic system frequency f_1, equation (16) is obtained, which results in the graph of Fig. 11.

$$\frac{f_{PF}}{f_1} = \frac{f_R}{f_1}\sqrt{\frac{1}{1 - (\frac{f_R/f_1}{f_Q/f_1})^2}} \tag{16}$$

Fig. 12 shows the behavior of the passive transference for several values of f_R, where it was chosen a given quality factor Q_{PF}[5] equal to 40 for the Z_{PF} filter.

Then it can be concluded that:

- Frequency f_R will always be smaller than f_Q.
- As f_R gets closer to f_Q, frequency f_{PF} tends to infinite.
- Frequency f_R will always be smaller than f_{PF}.
- As f_R gets lower, f_{PF} gets closer to f_R and the transference tends to compensate the pole with the zero.
- It is convenient to choose f_R in interharmonics values in order to minimize its resonance effects, and try that the value of f_{PF} belongs to the spectrum zone where the content of undesirable frequencies is high for reducing them with the passive filter.
- If f_R is lower than $f_Q/\sqrt{2}$, then f_{PF} is lower than f_Q.
- If f_R is greater than $f_Q/\sqrt{2}$, then f_{PF} is greater than f_Q.

[5]$R_{PF} = \frac{2\Pi f_{PF} L_{PF}}{Q_{PF}}$

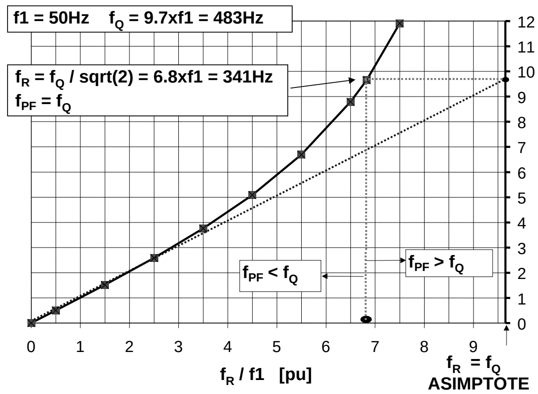

Fig. 11. Relation between f_{PF}, f_R, f_Q y f_1

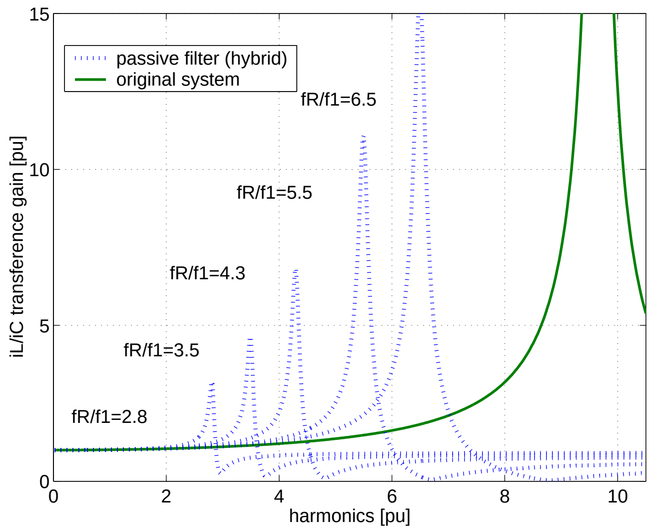

Fig. 12. Original and final passive transference i_L/i_C^* for several f_R values

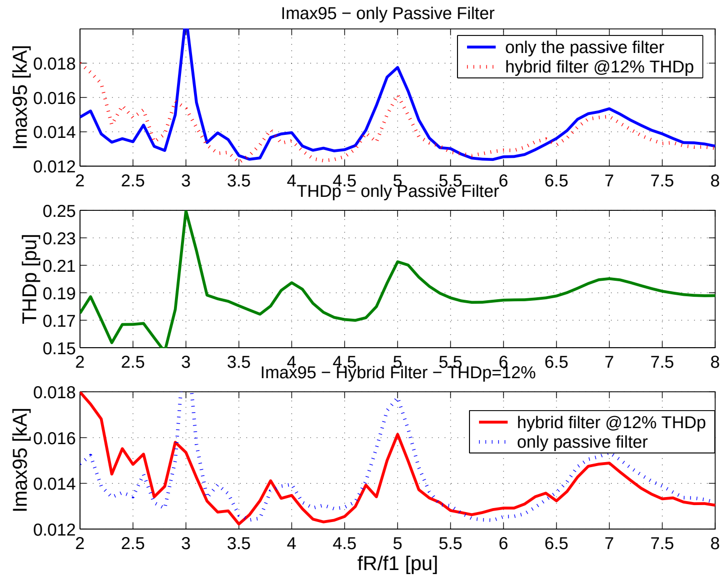

Fig. 13. Up and middle: Imax95 and THDp with the passive filter only. Down: Imax95 of the optimum selective which are obtained meeting with the regulation. Y-axis: f_R/f_1

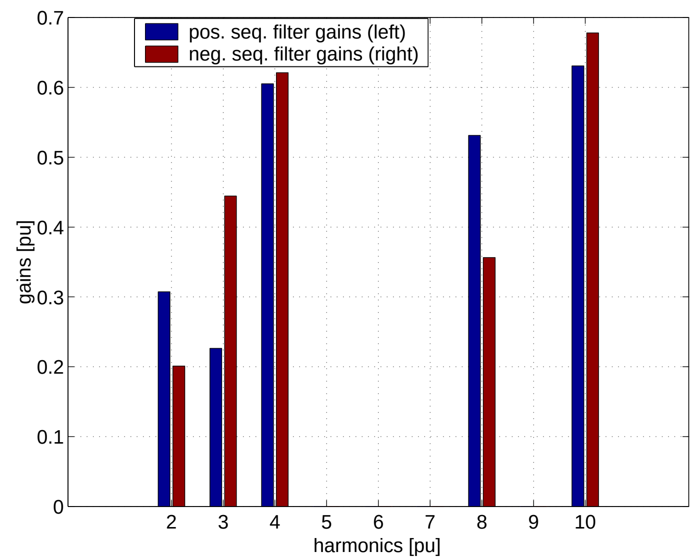

Fig. 14. Gains λ_i: Optimum selective filtering with $f_R = 4.3 f_1$

D. Selective filter and passive filter design

This passive system current transference has a zero at f_{PF} resonance frequency and a pole at the resonance frequency f_R of the system formed by the impedance of the passive filter Z_{PF} and the line short circuit impedance Z_L. In the case that the active filter is out of service, being its output shortcircuited, the passive filter can help to decrease the THD and must not amplify the harmonic frequencies of the load with its pole. On the other hand, the selective filtering must be optimized with the aim of having minimum current in the active filter. Therefore, the optimization of the passive and active elements must be done together and considering the current that will be filtered.

From Fig.12 it can be seen that low values of f_R as $3.5f_1$, are more adequate than higher values as $6.5f_1$. However, if the value of f_R gets lower, f_{PF} will be even lower and the value of the passive filter inductance L_{PF} will increase. On the other hand, as f_R (f_{PF}) increases, the resistance of the passive filter will be bigger, therefore its losses will also increase.

The first and second graphs shown in Fig. 13 where plotted by changing the frequency f_R and using the values of $Imax_{95}$ and THD_p obtained with only the passive filter Z_{PF}.

If the criterion used for designing the passive filter is that it alone must filter as much as possible, and must be of minimum current, from the first and the second plot of Fig. 13 the value $f_R = 2.8f_1$ can be selected. However the close presence of the resonance at 150Hz would recommend to choose a value far from that zone. On the other hand, this would result in a relatively big value of L_{PF}.

Finally, if the criterion used is that after the hybrid filter is design, its inverter must take minimum current ($Imax_{95}$) $f_R = 3.5f_1$ must be selected from the third plot of Fig.13. This graph was obtained by calculating the selective remote optimum filter that minimizes $Imax_{95}$ and also meets the regulations for each value f_R [15].

Similar results are obtained also with $f_R = 4.3f_1$, but the value of L_{PF} (and R_{PF}) will be reduced.

In some cases, the optimum selective hybrid active filter can meet the regulation ($THDp = 12\%$) using less current $Imax_{95}$ than if only the passive filter is connected (where the regulations are not verified). This aspect becomes clearer when the selected

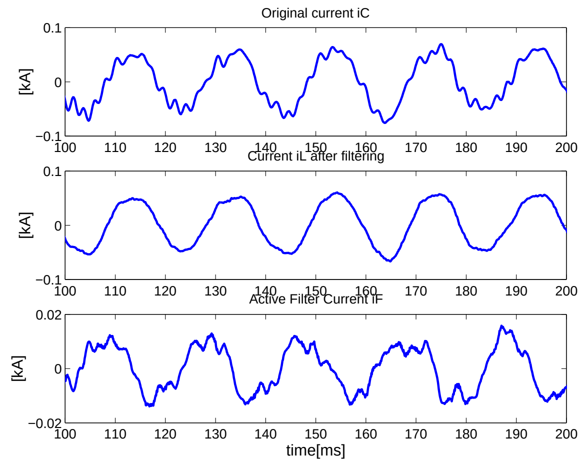

Fig. 15. Hybrid Residual Series Calculation: i_C, i_L and i_F currents for some network cycles

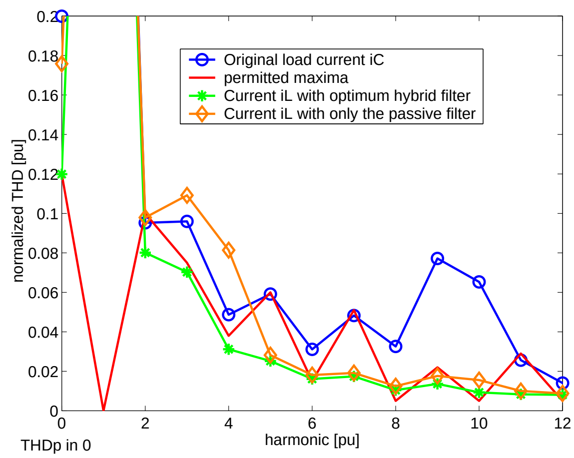

Fig. 16. Hybrid Residual Series Calculation: $THDp$ of the permitted maxima, original i_C currents, i_L currents after the selective hybrid filtering and i_L currents with only the passive filter

f_R is equal to an harmonic frequency of the network. In these cases the optimum hybrid filter tries to selectively counteract the resonance effect by filtering the load current. As it is demonstrated in the Appendix, when the phase delay of the passive filter is greater than a certain value, less selective filtered current i_F will be consumed, and at the same time better results are obtained in the $THDp$ of i_L current.

In the example that is being studied, Fig. 14 shows the λ_i gains when selective optimum remote [15] filtering for the value $f_R = 4.3f_1$. Fig. 15 and 16 show the involved currents and their spectrums. The current $Imax_{95}$ for current i_F turns out in a value 12.3A and a RMS value of 8A[6].

In the i_F current waveform it can be seen that in addition to current harmonics, it has current of the fundamental frequency (reactive current).

Finally, Fig. 17 shows the voltage U_{AF} that active filter VSI must impose in its R phase. It was verified by means of simulations that this voltage can be synthesized using a PWM of a 4.8kHz carrier frequency and a continuous voltage V_{DC} equal to 160kV.

[6]Although the hybrid filter is connected at 31.5kV all the values are normalized to 150kV

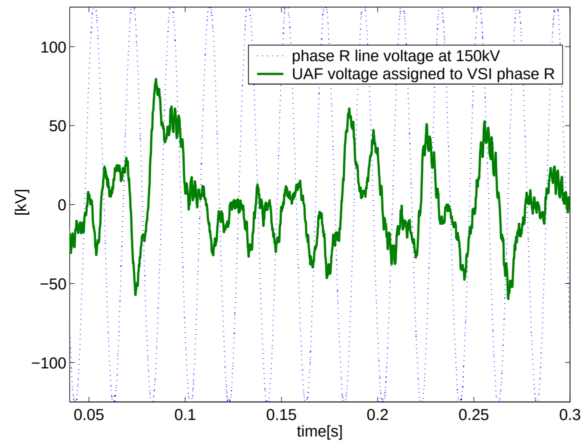

Fig. 17. U_{AF} voltage that the VSI must impose in its phase R.

E. ¿Active filter in 150kV or hybrid filter in 31.5kV?

Fig. 18 shows current i_F in the case that has been seen when installing the active filter in the 150kV busbar or in the case when the hybrid active filter is installed in the 31.5kV busbar. Fig. 19 shows the final spectrums of currents i_L. Both cases meet the regulation. When the active filter is connected at 150kV current $Imax_{95}$ is equal to 10.2A and the RMS value is 5.7A. In the hybrid case they are equal to 12.3A and 8A respectively. Therefore, in the hybrid case the current capacity of the inverter switches will be 20% (12.3/10.2) higher. The inverter must also have a grater dissipation capacity because it must handle more RMS current.

Having the hybrid filter option, operation with the VSI out of order is possible. The passive filter will still be working and attenuating the harmonic distortion from 20% to 17.5%. Also in Fig. 15 it can be seen that there are no remarkable resonances when the passive filter is connected alone.

In the example of the active filter connected at 150kV, the needed voltage V_{DC} that would allow the VSI to impose the wished current is 340kV. On the other hand, in the hybrid case, V_{DC} can be substantially lower and 160kV would be enough. As the value V_{DC} is lower for hybrid active filters, the capacitor C_{VSI} from the DC bus will be less costly. However, as the VSI is connected to the network by impedance Z_{PF}, VSI switches must be selected according to the same network voltage than in the case where the active filter is connected to 150kV.

Another solution is to design a protection system which that acts immediately if the VSI control gets out of service.

In this work it will be assumed that this protection is performed in the hybrid case and it will be not necessary to oversize the switches and the C_{VSI} capacitor of the VSI. In this conditions it is posible to calculate, for both cases, the VSI apparent power. The apparent power definition that will be used is

$$S = \sqrt{3} U_A^{max} I_{phase}^{max} \tag{17}$$

Assuming that phase RMS current I_{phase}^{max} is the maximum value of the phase current divided by $\sqrt{2}$ results

$$I_{phase}^{max} = \frac{Imax_{95}}{\sqrt{2}} \tag{18}$$

and if the maximum RMS voltage that a VSI can give at its output

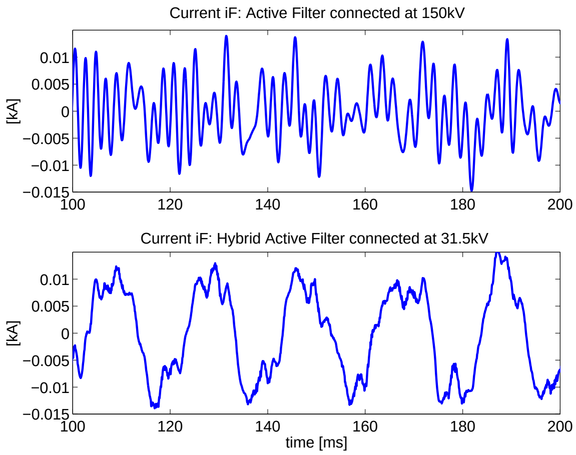

Fig. 18. Currents i_F for the optimum selective in 150kV or 31.5KV.

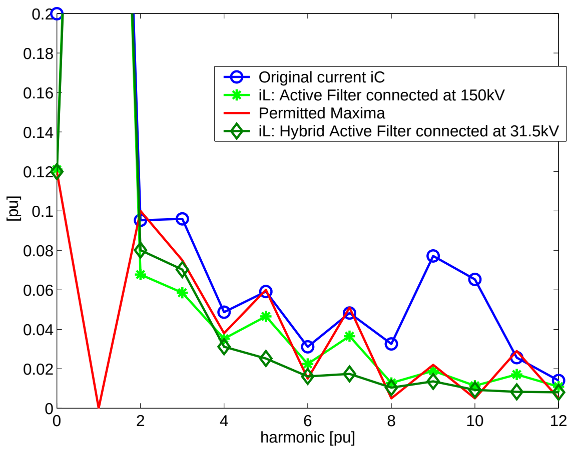

Fig. 19. Current i_F spectrums for optimum selective filtering at 150kV or at 31.5KV busbar.

when feeded with a voltage V_{CC} is

$$U_A^{max} = \sqrt{\frac{2}{3}} V_{CC} \tag{19}$$

it can be obtained

$$S = V_{CC} Imax_{95} \tag{20}$$

Using this definition in both studied cases, the calculated apparent power for the shunt active filter located in the 150kV bus is 3.5MVA, and for the hybrid filter case is 2MVA.

Another aspect that can be considered in order to low the relative cost of the hybrid filter, is the case when the zero located at frequency f_{PF} filters high harmonics, then the selective filter would only deal with low harmonics. As the synthesized currents will be of low frequencies, the VSI output voltage will be also of low frequencies, therefore the carrier frequency of the PWM will be lower reducing the commutation losses.

V. Conclusions

The need of taking into account the compensatory leading angles in each $SFBC$ has been stated. The advantage in trying to find the optimization of all the $SFBC$ bandwidths has also been stated. The need of studying hybrid active filters emerged from the example proposed. In fact, this is a common situation where there are reactive compensation capacitors and certain short circuit impedances in the point of connection. This situation determines the appearance of inevitable harmonic resonances which must be regarded in the design of the active filter. The placing of the zero and pole of the passive filter transference has to be done jointly with the optimization of the active selective filtering.

A simulated result complying with the harmonic regulation is obtained by optimizing with the objective of getting the minimal current in the VSI for the studied example of the arc furnace.

In this example, the hybrid shunt active filter connected to the 31.5kV busbar is 20% bigger with respect to its current than a shunt active filter connected to the 150kV busbar. This rise in the VSI current capacity is basically due to the fact that the reactive current must circulate in it. On the other hand, the V_{DC} voltage of the supply capacitor of the VSI in the hybrid case could be half the value of the pure active filter case, resulting in an active filter whose apparent power is 57% the apparent power which results in the 150 kV case. Besides, if for any reason the VSI becomes out of service, in the hybrid filter case, the system will still count with the help of the passive filter. The fact of having the passive filter decreases the total harmonic distortion and attenuates the original resonances. Even in some cases, installing the active filter closer to the load and overtaking the unavoidable resonances, could cause that the selective active filter will have to compensate lower frequencies which will allow to lower the PWM frequency with the consequence of reducing the commutation losses. This comparison agrees with the general idea that the best filtering is achieved when the filter is located close to the distorting load.

It is worth to point out the aspect analyzed in the annex: selectively filtering between the pole and zero frequencies of the passive transference has the double effect of reducing the harmonic distortion while diminishing the current of the active filter with respect to the situation of having only a passive filter installed.

Appendix

Fig. 20 shows the Norton equivalent circuit used when compensating a determined harmonic sequence k when load current compensation (i_C) is performed. In the case of having $G(w)$ ideal filters the selective current source is

$$\lambda_k I_{Ck} \tag{21}$$

then the load current of the passive filter is

$$I_{Ck}^* = (1 - \lambda_k) I_{Ck} \tag{22}$$

If the filter current transference has a modulus equal to q_k and an argument equal to θ_k at the frequency associated with k, the line current can be written as

$$I_{Lk} = (1 - \lambda_k) q_k e^{j\theta_k} I_{Ck} \tag{23}$$

Finally, the current taken by active filter is

$$I_{Fk} = I_{Lk} + I_{Ck} \tag{24}$$

Supposing that selective filtering is performed for frequencies between f_R and f_{PF}; the passive transference has high negative phases as shown in Fig. 21. For this case, the upper phasor diagram of Fig. 22 shows the filter current when the filtering is only done by the passive filter. The lower phasor diagram shows the filter current when a selective filtering is performed. *When filtering in a selective way, two effects can be achieved: to lower the harmonic distortion of the line current and to make less current circulate through the hybrid filter than in the case when only the passive part of the filter is operative.* If, on the contrary, the phase θ_k is low, Fig. 23 shows, in its upper part, the

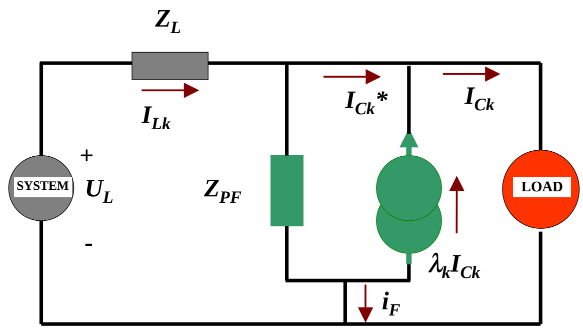

Fig. 20. Compensation scheme Norton equivalent for an harmonic sequence k

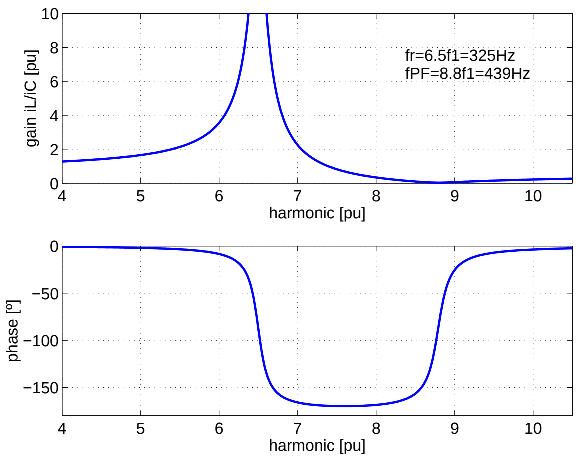

Fig. 21. Current transference of the passive filter $Z_L - Z_{PF}$ when $f_R = 6.5f_1$ and $f_{PF} = 8.8f_1$

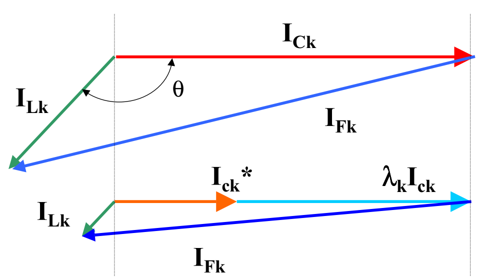

Fig. 22. Compensation phasor diagram for a high θ_k

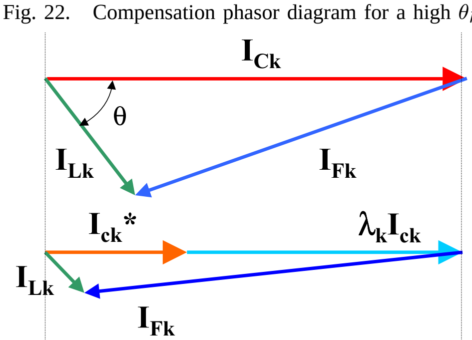

Fig. 23. Compensation phasor diagram in the case that θ_k is relatively small

filter current when having only the passive filter. Then, the lower part shows the filter current when selective filtering is performed. In this case, for lowering the current I_{Lk}, the current I_{Fk} must be increased. Generally, this situation happens for frequencies that are outside the zone $[f_R..f_{PF}]$ where the phase of the transference is zero.

It is also possible to show that the same results are obtained when the control uses the measure of the line current (i_L) as input.

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