OPTIMUM SELECTIVE ACTIVE FILTERING FOR FOUR-WIRE LOADS: DIMMING OF HIGH PRESSURE Na HID LAMPS

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***Abstract*— This paper presents an extension of the methodology to calculate the referential currents of a Shunt Active Filter in order to selectively filter harmonic sequences including homopolar ones. In the same direction, the optimum calculating method to determinate the active filter of minimum size associated to the fulfillment of some harmonic regulation, is extended to the selective homopolar filtering case. To illustrate both extents of the theory, an application where High-Pressure Sodium HID Lamps for public lighting are dimmed using thyristors is analyzed.**

***Keywords*- Active Filtering, Four-Wire VSI, Power Quality, Selective, Dimming $Na-HID$.**

I. INTRODUCTION

The present century is associated with the constant concern about trying to reduce power consumption while improving people's quality of life at the same time. In this scenery, public lighting systems play a particular role. On the one hand, the growing demand for night lighting requires increasing amount of energy. On the other hand, technology advance has determined the present popularity of High-Pressure Sodium High-Intensity Discharge ($NaHID$) Lamps, that are gradually replacing Mercury High-Pressure HID Lamps.

Although there are other technologies beginning to be considered, like the use of high efficiency LEDs or the monochromatic Low-Pressure $NaHID$ Lamps, High-Pressure $NaHID$ Lamps still have a long life ahead. One of the alternatives to reduce power consumption is the public lighting system dimming while the traffic is low. There are several technologies in order to obtain this. In particular, some dimming systems are installed in line head, while others are distributed in each luminary.

Voltage regulators are remarkable examples of line head alternatives, whereas electronic or bi-tension ballast are remarkable examples of distributed ones. Commonly, line head regulators are devices based on thyristor or contactor conmuted autotransformers, which are relatively big and heavy. As alternative to this, we will discuss dimming lamp power supply using a simple thyristor dimmer, as shown in Figure 1. Nevertheless, it is important to analyze harmonic impact on power system; consequently, consumed currents must be filtered (just in the necessary level) in order to fulfill the applicable regulation about harmonic current emission.

As it will be shown in V, dimming of High-Pressure $NaHID$ lamps is possible within all the applicable range (until 50% of the nominal flux). However, in some cases (depending on the regulation used as reference) some limits are exceeded by individual harmonics and by the THD as well. In particular, it will be shown that the worst case is the homopolar third harmonic.

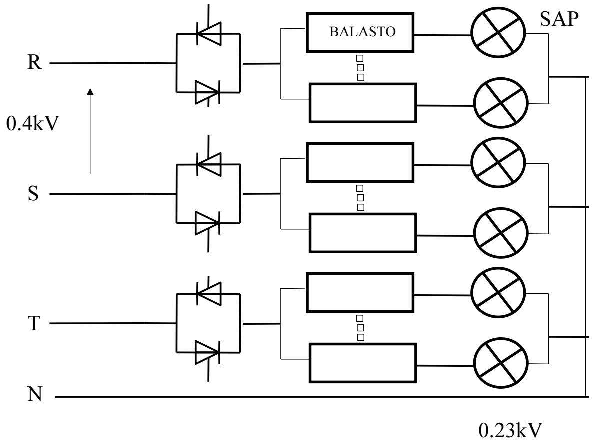

Fig. 1. Four-Wire Three-Phase dimmer.

In this context, the use of Selective Shunt Active Filters is an option to be analyzed, because it permits to filter just what the regulation specifies, and therefore minimizing the active filter size. In section IV the way to perform an optimum filtering with minimum-size inverter is analyzed. Since the active filter must take homopolar currents, a four-wire topology must be used.

II. EXTENSION OF THE SELECTIVE ACTIVE FILTERS THEORY IN PRESENCE OF HOMOPOLAR SEQUENCES

Previous works have shown ways to control shunt active selective filters [1] [2] (SERIES and PARALLEL methods) depending on the selected control type [3] (one of them is based on compensated load current feedforward, while the other is based on line current or voltage at the PCC point feedbacking).

These works are typically about three-wire circuits, where homopolar is not considered. From the expression of homopolar currents as a sequences function [4] shown in (1), it is evident that channels $i_\alpha(t)$ and $i_\beta(t)$ are completely decoupled from $i_o(t)$. In particular, homopolar channel $i_o(t)$ only depends on homopolar harmonic components Io_n.

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

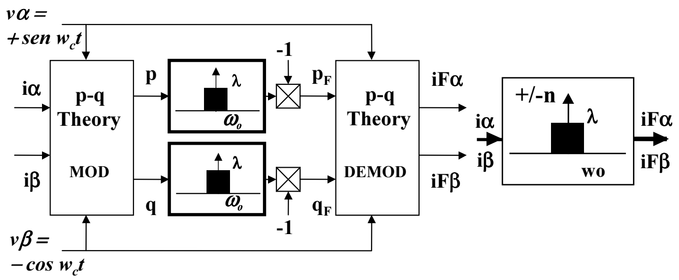

Fig. 2. Selective Filtering Basic Cell.

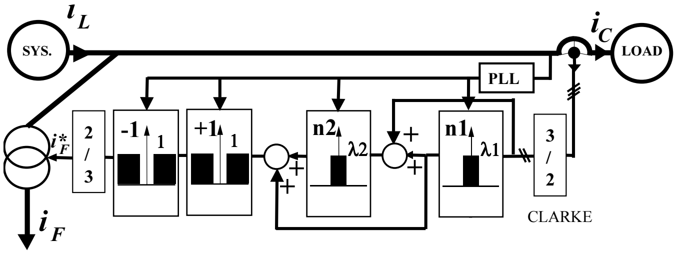

Fig. 3. Filtering of two sequences, positive or negative

$$\begin{aligned} & \sum_{n=1}^{\infty} \sqrt{3} I_{-n} \cos(w_n t + \delta_{-n}) \\ i_o(t) \quad = & \sum_{n=1}^{\infty} \sqrt{6} Io_n \sin(w_n t + \delta_{on}) \qquad (1) \end{aligned}$$

Figure 2 shows schematically the calculations made within a Selective Filter Basic Cell ($SFBC$) [5] [6] that can isolate a certain harmonic sequence characterized by n (n is positive for positive sequences and negative for negative ones). Figure 2 at the right also show the compact representation of a $SFBC$

Figure 3 shows, for example, what a selective filtering (feedforward control) of two positive or negative harmonic sequences would be. This case used SERIES methods in order to obtain the referential current for the active filter VSI (considered here as a current source). The blocks marked with $+1$ and -1 are needed in order to filter from the active filter current the positive and negative fundamental current that the previous blocks allowed to pass through [6] [7]. In those two blocks the p and q channels filters are pass band instead of low pass filters. Therefore, what is needed is the calculation of the referential current associated with the homopolar currents that are desired to be filtrated.

Given that $i_o(t)$ is a simple time domain signal, it is filtered with a classic selective filter with adequate bandpass filters. In combination, the whole control circuit is shown in Figure 4 for the same example of two harmonic sequence filtering with SERIES method. The multiple bandpass filter in the homopolar channel takes the same practical considerations reported in [1] [2], where it is proven that SERIES method produce better results when controlling the interference between the several bandpass filters with capability of dynamic reconfigurations. This inevitable interference is produced by the frequency closeness of the bands and the need of a relatively fast dynamic response (orders grater than 2 begin to be a problem).

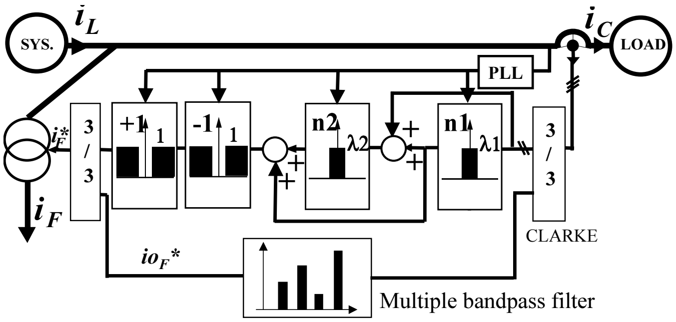

Fig. 4. Complete system scheme of selective filtering.

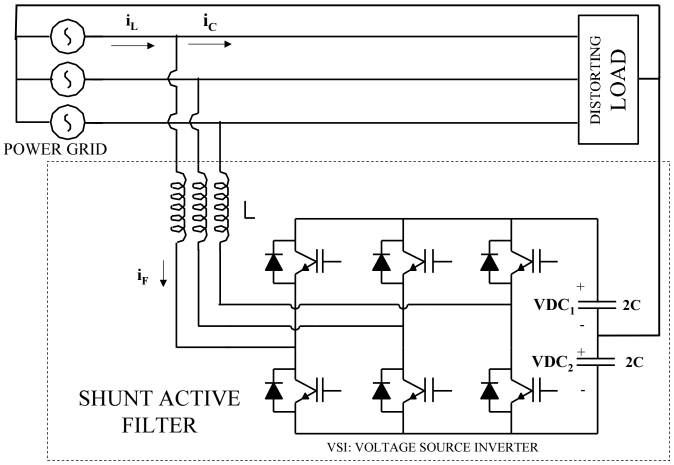

Fig. 5. Four wire VSI with split DC bus.

III. CONTROL OF THE DC VOLTAGE OF THE VSI

Figure 5 shows the four wire VSI used. In order to control the VDC voltage and the balance of VDC_1 and VDC_2 voltages, a new decoupled strategy is proposed as shown in Figure 6. Then p^* and $i_o{}^*$ compensation signals are utilized as shown in Figure 7.

So, on the one hand, in order to control the VDC voltage, active power (in fact $\overline{p}$ means instantaneous active power) is subtracted or added to the busbar. This is made by p^* control signal injected in the p channel of the $SFBC$ $+1$. On the other hand, in order to balance VDC_1 and VDC_2, i_o^* (in fact $\overline{i_o}$) is injected in the middle point of the capacitors. For example if the difference between VDC_1 and VDC_2 (related to VDC) increases, the control injects i_o^* current that tends to increase VDC_2 and reduce VDC_1.

IV. OPTIMUM FOUR-WIRE SELECTIVE ACTIVE FILTER

In [8] it is explained how to optimize the size of the shunt active filter to be used. The key of the optimization is to minimize the current of the active filter inverter (VSI) while harmonic current emission regulation is fulfilled. The main objective of the optimization process is complying with the requirement of each individual harmonic and the THD. This work extends the theory presented in [8] to include the optimization process of homopolar sequences.

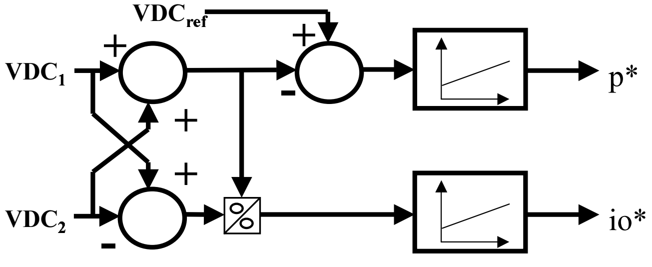

Fig. 6. VDC and balance control strategy.

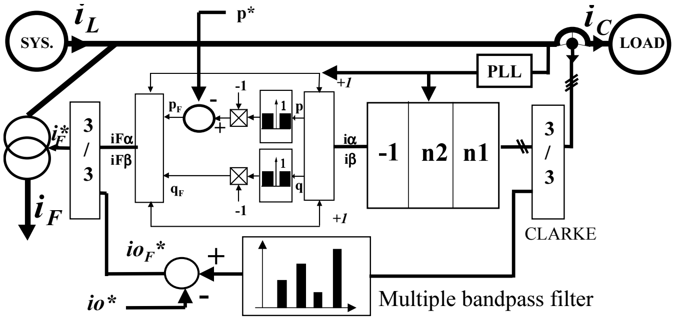

Fig. 7. Complete four wire selective filtering control strategy.

On the one hand, to calculate the average quadratic harmonic distortion in the three phases ($THDp$), the homopolar sequence must be added in the calculation expression as it is shown in (2)

$$THDp = \frac{\sqrt{\sum_D IL_d^2}}{I_N} \tag{2}$$

$$\begin{aligned} D = [&+2\ -2\ \ o2\ +3\ -3\ \ o3 + \cdots \\ &+40\ -40\ \ o40] \end{aligned} \tag{3}$$

where IL is the final line current, I_N is the nominal current contracted by the consumer (associated with the customer contract power at a power factor of 0.92), and '+', '-' and 'o' corresponds to positive, negative and homopolar sequences respectively.

On the other hand, active filter must be optimized in order to fulfill the requirements for each frequency. In this part it is enough to consider the three sequences involved with each harmonic current (see (4)).

$$I_j^2 = IL_{+j}^2 + IL_{-j}^2 + IL_{0j}^2 \tag{4}$$

where I_j is the objective value who specify the regulation for harmonic j. Then, in order to calculate the optimum values which the sequences must be reduced to, a value of M=3 (instead the $M = 2$ value for the non homopolar case) is used because in this case all three positive, negative and homopolar sequences are present.

Finally, the general method remains without any modifications. First, each harmonic is filtered until the value specified by the regulation is fulfilled. Then, the optimization method that forces to fulfill the $THDp$ value is applied, taking harmonic sequences from the NOT-CHOSEN group to the CHOSEN group until the convergence of the method is achieved. The CHOSEN sequences are the ones that will finally be filtrated, while the NOT-CHOSEN sequences are the rest of them.

V. DIMMING OF NAHID LAMPS USING THYRISTORS

The public lighting system to be installed is composed of 66 lamps of 250W ($NaHID$ lamps), each one with their own ballast, connected to the $0.4kV$ four-wire three-phase system in a balanced way (22 lamps per phase). The whole system, without compensation, consume $20.4kW$ and $40.2kVAr$ which represent an uncompensated line current of $44.7A$. A bank of capacitors that contribute $31.5kVAr$ is installed to achieve a power factor of 0.92, causing the line current to be $32A$ (then, this is the contracted current I_N). A point to be remarked, is that the reactive energy compensation capacitor of each lamp must be taken off (the voltage supply will be thyristor-dimmed), and this capacitors will be connected to the PCC. The implications of this in the pre-existent installation must be analyzed, because the current without compensation is up to 40% greater than the compensated current. In the table of Figure 8 it can be seen that the first row shows the values specified (for each harmonic and for THD) by the regulation that is under study of approval in Uruguay for this types of load. In the first column, the resultant luminous flux for different thyristor triggering angles are shown. These angles, which appear in the last column, are measured form the ballast/lamp input voltage zero-crossing. Finally, the measured distortion values are shown in the table. All current distortion values are relative to I_N, in agreement with the regulation. Measures were made with new lamps, using a $230V$ supply voltage.

These values are plotted in Figure 9 where it is clear that the third harmonic is the largest problem to solve. It is also shown that when power supply is $230V$ (nominal) it is enough to thyristor dimm up to 81^o of triggering angle in order to regulate the lamp flux down to 50% of the nominal value.

Considering the lamp capacity to be thyristor dimmed, the worst case is when the input voltage is higher than $230V$. In this situation, the triggering angle increases, and so does the period of time in which current is zero. As a consequence, it can make the lamp electric arc to extinguish. Moreover, with 81^o of triggering angle relevant emitted harmonic are maximum and also the THD. Another aspect to keep in mind is that arc voltage increases when the lamp gets older, thus making the control circuit to be modified in order to keep flux within desired range during dimming. These subjects will be reported opportunely.

VI. SIMULATIONS AND EXPERIMENTAL RESULTS

In this section simulated results made with $Simulink$ and an experimental validation of the implementation of the control in the $DSP\ TMDSEZD2812$ (kit $TMSF2812eZdsp$) are shown. To validate the DSP program a Hardware-in-the-loop strategy was used. The communication between the $Simulink$ and the DSP kit was made using serial communication. The VSI current control is a simple hysteresis one at regular sampling. The DSP samples the data by the serial port from Simulink, makes its task (spending some overlay

			HARMONICS							
		THD	**3**	**5**	**7**	**9**	**11**	**13**	**15**	
	REG	**8,0**	**16,6**	**12,0**	**8,5**	**2,2**	**4,3**	**3,0**	**0,6**	
FLUX [%]	**100**	21,2	20,5	2,7	3,4	0,7	0,7	0,7	0,0	**angle [%]**
	96	20,7	20,5	2,1	3,4	0,7	0,7	0,7	0,0	**61**
	87	20,8	20,5	1,4	3,4	0,7	0,7	0,7	0,7	**67**
	79	21,4	20,5	1,4	3,4	1,4	1,4	1,4	0,7	**68**
	72	21,8	21,2	2,1	4,1	2,1	1,4	1,4	1,4	**72**
	64	22,7	21,9	3,4	4,8	2,1	2,1	1,4	1,4	**76**
	55	23,7	22,6	4,8	4,8	2,7	2,1	1,4	0,7	**79**
	47	24,8	23,3	6,2	5,5	2,7	2,1	1,4	0,7	**83**

Fig. 8. Current and THD consumed by thyristor dimmer.

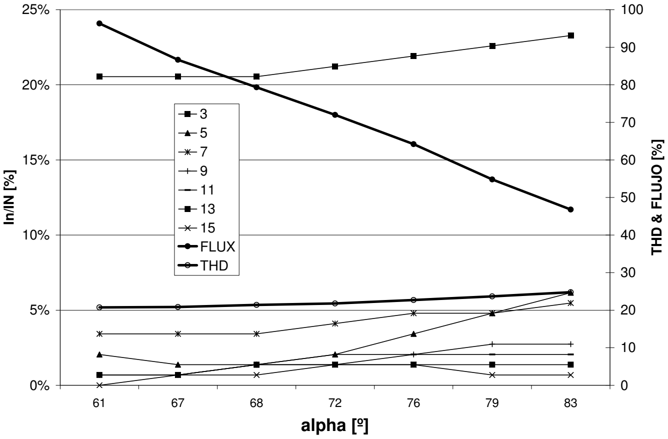

Fig. 9. Current and THD consumed by a thyristor dimmer.

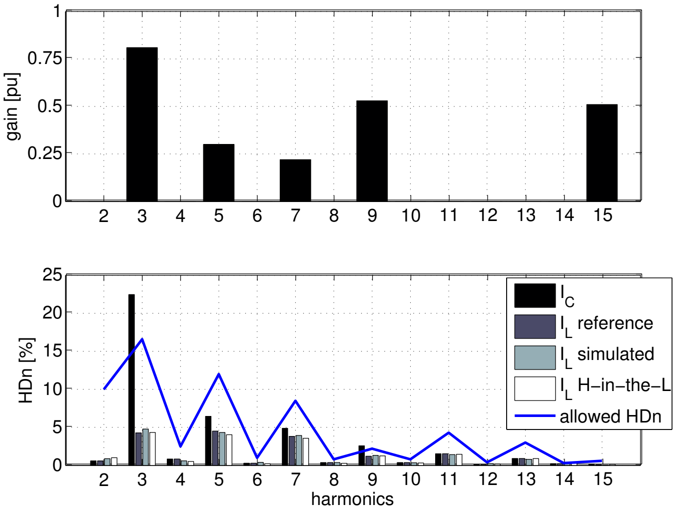

Fig. 10. Selective filtering objective and results. THD of 8%.

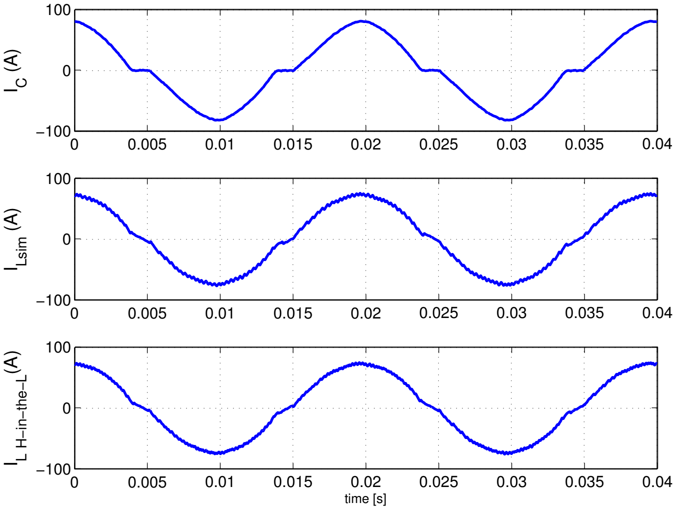

Fig. 11. Line currents after and before filtering.

time) and after it, sends the commutation order for the VSI back to Simulink by the serial port, and so on.

Data: $VDC_{ref} = 600V$, $C = 1000\mu F$, grid voltaje $U = 230V$, grid frequency $f = 50Hz$, $L = 10mHy$, sample and control frequency $f_m = 25.6kHz$ (512 samples for each grid cycle) so $T_m = 39\mu s$, dead time delay introduced by the DSP $19.5\mu s$. Having in mind the commutation losses, this sampling and control frequency is equivalent to a $f_m = 25.6/2kHz$ averaging PWM current control.

Figure 10 shows at the upper part the selective filtering gains of each sequences to be filtered obtained by the optimum calculating method discussed in section IV in order to selectively filter the current consumed by lamps emitting 50% of the nominal luminous flux. The lower part of the figure shows the harmonic content before filtering, the final line current calculated (objective) and the final line current from the Hardware-in-the-loop procedure. In addition it is shown the maximum values (for each harmonic) allowed by regulation. In this particular case, where three-phase current is balanced, 5th and 11th harmonics are exclusively negative sequences, 7th and 13th harmonics are exclusively positive sequences and multiple of 3 are exclusively homopolar ones. Therefore, the optimum selective filtering that fulfills regulation for individual harmonics and THD of 8% consists of filtering sequences 3rd, 5th, 7th, 9th and 15th by the amount shown in the upper part of Figure 10.

Figure 11 shows the line current before and after filtering for the simulation and Hardware-in-the-loop case.

Figure 12 shows the comparison between simulations and the Hardware-in-the-loop results of the active filter current.

Figure 13 shows line current before and after filtering and the active filter current for the Hardware-in-the-loop case.

Notice that active filter currents seem to have a fundamental component. This is not desirable since it would mean the filter would be taking currents different from the aimed ones, in particular from the harmonic content point of view. In spite of that, shown currents do not have a fundamental one. For example, what can be seen in Figure 13 is mostly an optical effect produced by 5th and 7th harmonics. The problem here is the maximum common divider between 5 and 7 is just unity, which causes that the resultant wave repeats in each fundamental period (but not in a higher rate).

Figure 14 shows the transient of going from 20% of the load to full load of the I_F current of one phase and the mean value of the instantaneous active power p for the Hardware-in-the-loop case (filtered with a 10Hz low pass filter).

Figure 15 shows for the same transient the VDC_1, VDC_2 and VDC voltages for the Hardware-in-the-loop case. The ripple of VDC_1 and VDC_2 have a frequency of $150Hz$ as a

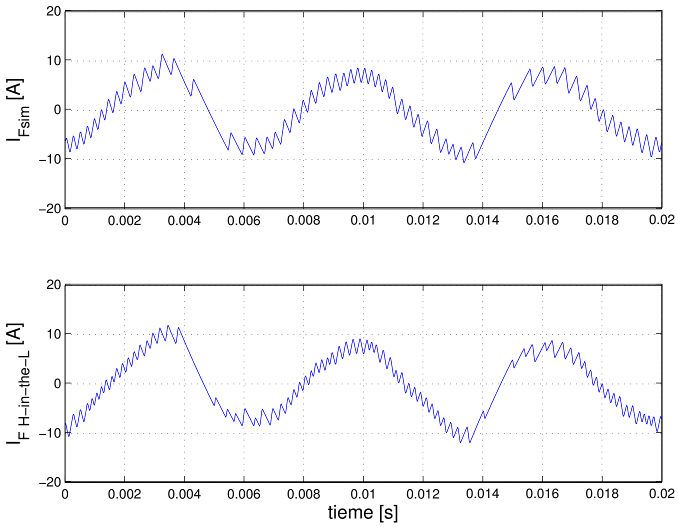

Fig. 12. Comparison of the active filter currents.

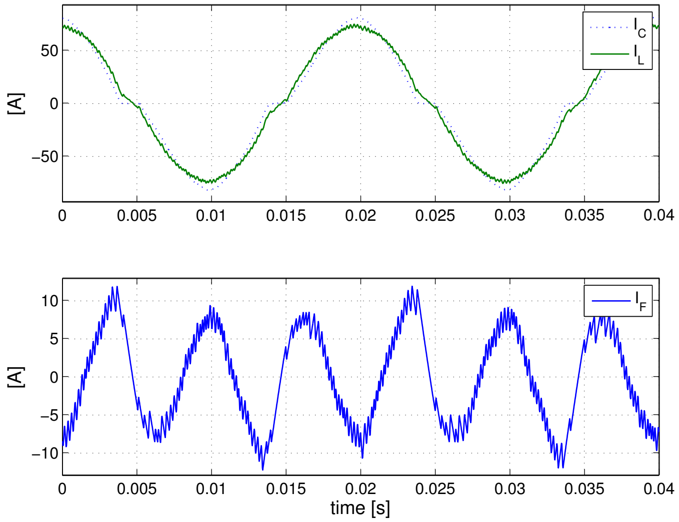

Fig. 13. Line current before and after filtering and the active filter current for the Hardware-in-the-loop case.

consequence of the homopolar third harmonic an the shapes are in quadrature.

VII. CONCLUSIONS

This paper presented the extended Selective Filter Theory to the case of currents with homopolar sequences. In the same way, the optimum gain-calculating method for each selective filter was extended, in order to obtain an active filter capable of complying with a certain harmonic regulation.

Experimental results on a thyristor-dimmed High Pressure Sodium Lamps circuit have been presented. In order to validate the implementation of the whole control in a DSP, Hardware-in-the-loop results are reported with great coincidence with the simulations.

It was presented a new control strategy was presented in order to stabilize and balance VDC_1 and VDC_2 voltages of the input capacitors of the Active Filter. The simulation and Hardware-in-the-loop results show that the proposed strategy works fine.

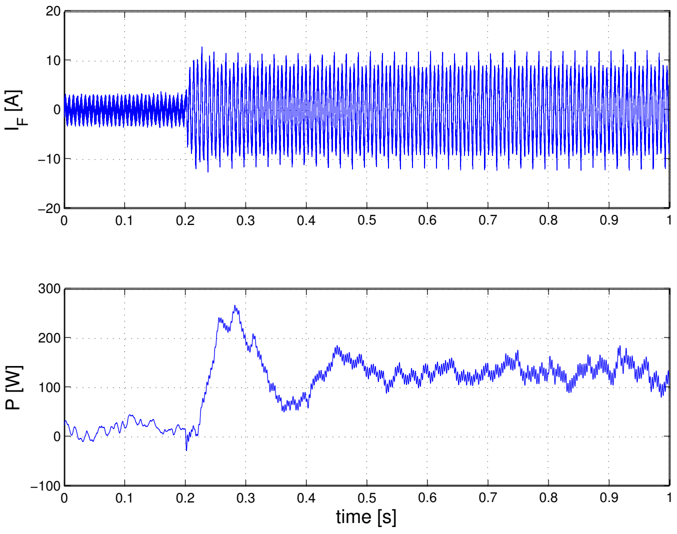

Fig. 14. Transient of the active filter current and $\overline{p}$.

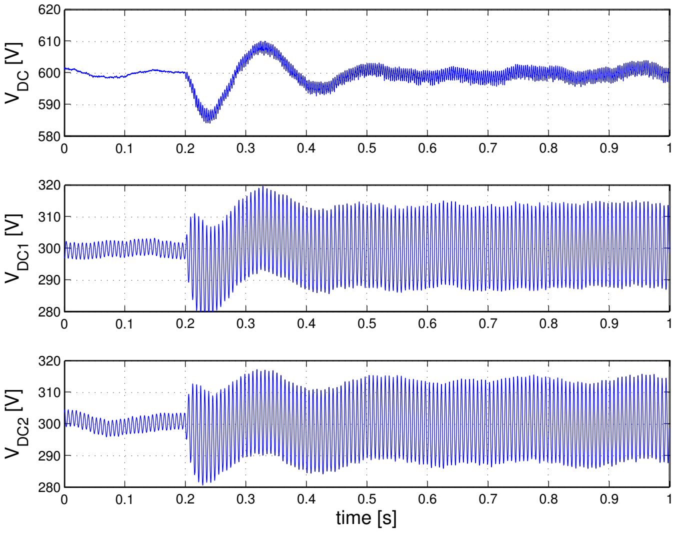

Fig. 15. Transient of the $VDC1$, $VDC2$ and VDC voltages.

As a general conclusion, in the case of non-linear loads including homopolar harmonics, while it is important to take notice of harmonics regulation, the application of selective active filters controlled with the proposed optimization is an interesting option since they allow the minimization of inverter currents.

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