Powereng'2007 – International Conference on Power Engineering, Energy and Electrical Drives
Setúbal, Portugal, 12-14 Abril de 2007.

A Combined Series Active Filter and Passive Filters for Harmonics, Unbalances and Flicker Compensation

J. G. Pinto, R. Pregitzer, Luís. F. C. Monteiro, Carlos Couto, João. L. Afonso,
University of Minho – Industrial Electronics Dept.
gpinto@dei.uminho.pt, rpregitzer@dei.uminho.pt, lmonteiro@dei.uminho, ccouto@dei.uminho.pt, jla@dei.uminho.pt

Abstract- **This paper describes a combined operation involving a series active filter and shunt passive filters for three-phase three-wire systems. The series active filter is able to minimize Power Quality problems like unbalances, harmonics and flicker observed at the system voltages. Another task for the series active filter is to damp possible resonances involving the passive filters and the system impedance. The shunt passive filters are designed to drain harmonic current-components generated by the load. The control strategy of the series active conditioner is based on the instantaneous power theory on *α-β-0* reference frame, together with a robust synchronizing circuit PLL (Phase-Locked-Loop). A dc-link voltage controller, applied to the series conditioner, is also introduced due to the fact that there is only a single capacitor at the inverter dc-side. Simulation results on PSCAD®/EMTDC™ are presented in order to verify the performance involving a combined operation of passive and active filters.**

Index Terms **— Custom Power, Power Quality, System Stability, Instantaneous Power Theory.**

I. Introduction

POWER QUALITY is a key concern for the Industry nowadays. The intensive use of power converters and non-linear loads has contributed for the deterioration of the power quality, and this factor affects critical processes, resulting in substantial economical losses. Therefore the development of equipment that can mitigate problems that affect electrical installations is of great interest. The devices based on power electronics directed to improve power quality are denominated as "Custom-Power".

One Custom-Power device can be obtained from the combined operation of an active filter with a passive filter, which results in a hybrid filter. The hybrid filter used in this work consists of shunt passive filters operating with a series active filter [1] [2].

Nowadays it is very common to observe the use of passive elements designed to correct power factor or to drain some harmonic components from the load currents. However, in sensitive power systems, resonances involving the system impedance with these passive filters may occur, which results in an inadequate operation of the passive filters. Such a problem may be overcome by means of a series active conditioner designed to damp the aforementioned resonance, improving the system stability [3]-[6].

Besides, in power systems where the voltages delivered to the load are distorted, the shunt passive filters may also have their performance compromised. Thus, by using series active conditioner, to improve the load voltages, the performance of the passive filters will also get better.

In the system analyzed in this paper, the shunt passive filters are designed to drain harmonic currents generated by the load, and they may also be used to regulate power factor. On the other hand, the series active filter presents functionalities to improve the system stability and to suppress distortions at the system voltages. In this case the distortions on the system voltages are represented by unbalance and flicker. Another important aspect is that the dc-link of the series active filter is composed only by one capacitor. Therefore one of the tasks of the controller is to force a constant value for the dc-link voltage, by exchanging energy between the dc-link and the electric grid.

The control strategy applied in this work is based on the definitions for instantaneous power in the *α-β-0* reference frame (*pq theory*), proposed by Akagi et al. [7]. In literature, several works can be found on control strategies for active filters and active power line conditioners based on instantaneous power theory [8]-[10].

A summary involving the major topics of this paper is described as follows. Aspects related to the system configuration of the proposed power line conditioner are illustrated in Section II. A set of equations describing the control system based on the instantaneous power theory for three-phase three-wire systems are presented in Section III. In Section IV the proposed system is analyzed by means of simulation results on PSCAD®/EMTDC™. Finally, conclusions and suggestions for further works are presented in Section V.

II. System Configuration

Fig. 1 shows the complete test system that was analyzed through computer simulations. The passive filters were designed to compensate harmonic currents produced by a 6-pulse thyristor rectifier. A series RL circuit with a 1.5 Ω resistor and a 35 mH inductor are connected to the dc side of the rectifier, and the thyristors operate with a firing angle of 30º.

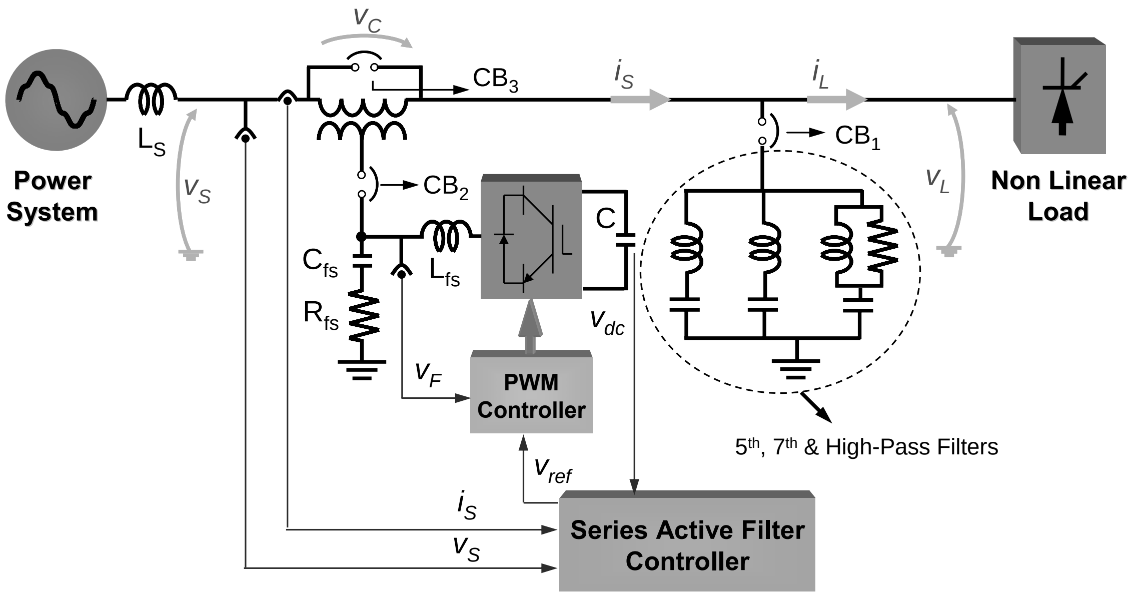

Fig. 1 – Electric diagram of the analyzed system

The series active filter consists of a three-phase voltage-fed PWM inverter connected in series with the power grid through three single phase transformers. The power converter is a standard 2-level 3-leg voltage controlled Voltage Source Inverter (VSI) with a capacitor on the dc-side. The dc-link capacitor has a value of 9 mF, with a dc-voltage reference of 400 V.

A passive circuit (RLC filter) is applied to the output of the series active filter inverter in order to smooth the ripple on the generated compensation voltages. This passive filter is represented by L_{fs}, R_{fs}, and C_{fs}. These components are a 1 mH inductor, a 5 μF capacitor, and a 2.5 Ω resistor, respectively. Single-phase transformers, with a turn ratio of 1:2.5, are used to connect the series active filter to the power system.

According to Fig. 1, i_L represents the load currents, i_S the supply currents, v_S the system voltages, v_L the load voltages, v_{dc} the inverter dc-link voltage, and v_F the measured voltages on the secondary side of the single-phase transformers.

The control block "Series Active Filter Controller" uses as input signals v_S and i_S, and determines, in real time, the control signals v_{ref} that will be synthesized by the power inverter.

The control block "PWM Controller" determines and sends the firing pulses to the IGBTs of the power inverter, based on information related to v_{ref} and v_F.

The shunt passive filters connected to the electric grid after the series active conditioner have the characteristics shown in Table I.

Finally, circuit breakers are employed to connect the shunt passive filters and the series active filter. These circuit breakers are represented in Fig. 1 as CB_1, CB_2 and CB_3

TABLE I
PASSIVE FILTERS CHARACTERISTICS

5th order passive filter	L = 1.2 mH C = 340 uF	F = 250 Hz Q = 6.26
7th order passive filter	L = 1.2 mH C = 170 uF	F = 350 Hz Q = 8.86
High-pass filter	L = 260 uH C = 300 uF R = 3 Ω	F = 1.8kHz Q = 3.22

III. CONTROL SYSTEM

The series active filter controller works in the *α-β-0* reference frame and therefore the source voltages, v_{Sa}, v_{Sb}, v_{Sc}, and the source currents, i_{Sa}, i_{Sb}, i_{Sc}, must be converted to this reference frame by applying the Clarke matrices, illustrated on equations (1) and (2). Fig. 2 shows a simplified diagram of the applied control system.

$$\begin{bmatrix} v_{S0} \\ v_{S\alpha} \\ v_{S\beta} \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_{S0} \\ i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \tag{2}$$

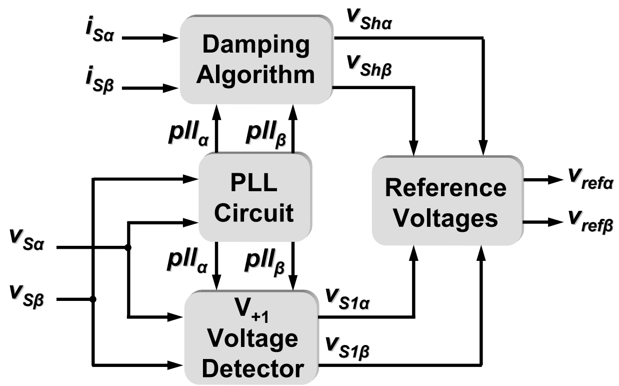

Fig.2 – Control system block diagram

As illustrated in Fig. 2, the control system is composed by an algorithm that extracts the fundamental positive-sequence component of the system voltages, followed by a control block that determines control voltages with the objective to damp resonance phenomena, denominated as "Damping Algorithm" block, and a control algorithm that determines $v_{ref\alpha}$ and $v_{ref\beta}$.

Still observing Fig. 2, a synchronizing circuit (PLL) that detects the positive-sequence phase-angle of the system voltages at the fundamental frequency is applied. In this control system, there is a necessity to apply a synchronizing circuit, since the detection of the fundamental positive-sequence system voltages is required. More details involving the PLL circuit can be found in [4].

A. Fundamental Positive-Sequence Voltage Detector

The inputs of the PLL are the system voltages $v_{S\alpha}$, and $v_{S\beta}$, resulting in the output signals, pll_α and pll_β, which correspond to unitary, sinusoidal signals, in phase with the fundamental positive-sequence components of the system voltages in the *α-β-0* reference frame. Fig. 3 shows a detailed diagram of the fundamental positive-sequence detector

It is also necessary to determine the amplitude of the fundamental positive-sequence component in the source voltages. Since the PLL calculates, in real-time, the phase-angle and the fundamental frequency of this component, it is possible to use the PLL output signals, together with the source voltages, as a first stage to determine the amplitude.

This first step consists in calculating a fictitious instantaneous real power, p.

$$p = v_{S\alpha} \cdot pll_\alpha + v_{S\beta} \cdot pll_\beta \tag{3}$$

Due to the possible distortions at the system voltages, a low-pass filter is used to extract the average value of p. The average value of p, denominated in Fig. 3 as $\bar{p}$, is directly related to the magnitude of the fundamental positive-sequence component in the source voltages. The instantaneous value of these components is obtained by applying the following expression:

$$\begin{bmatrix} v_{S1\alpha} \\ v_{S1\beta} \end{bmatrix} = \frac{1}{pll_\alpha^2 + pll_\beta^2} \begin{bmatrix} pll_\alpha & pll_\beta \\ pll_\beta & -pll_\alpha \end{bmatrix} \cdot \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix}. \tag{4}$$

It is important to emphasize that, because the signals pll_α and pll_β are unitary sine waves, their quadratic sum will be a constant value of 1.5. Therefore it is possible to reduce the computational effort of the controller, since the division observed in (4) can be eliminated.

B. Damping Algorithm

As already mentioned in this work, in a hybrid filter configuration, instability problems due to the resonance phenomena, involving the passive filters and the system impedance, may occur. In order to enhance the overall system stability, an auxiliary algorithm can be added to the controller of the series active conditioner [4].

The basic idea consists in increasing harmonic damping, by using each transformer as a series resistance, which is effective only for harmonic frequencies, and is a short-circuit for the fundamental component of the currents. This damping principle was first proposed by Peng [3], in terms of components defined in the *pq theory* and used by Aredes [4] and Fujita [5]. The damping algorithm is illustrated in Fig. 4.

The damping controller uses as inputs the control signals obtained by the PLL circuit, pll_α and pll_β, together with the source currents, $i_{S\alpha}$ and $i_{S\beta}$.

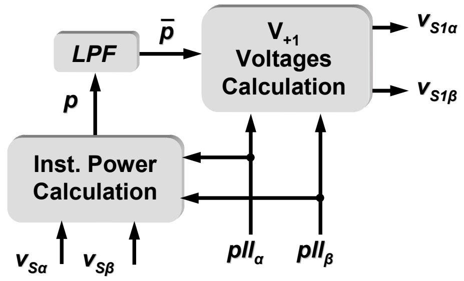

Fig. 3 – Block diagram of the Fundamental Positive-Sequence Detector

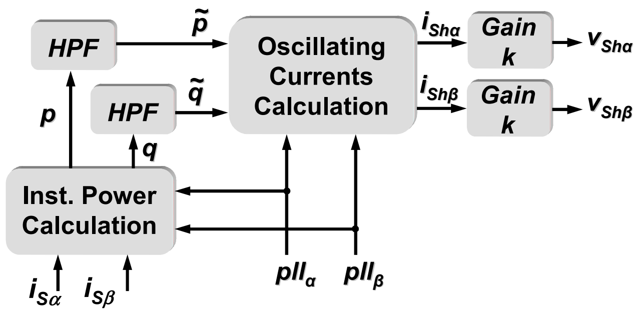

Fig. 4 – Damping Algorithm block diagram

The oscillating components of these source currents should be determined according to equation 5, together with high-pass filters.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} pll_\alpha & pll_\beta \\ pll_\beta & -pll_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} \quad (5)$$

High-pass filters are used to extract the oscillating components from real (p) and imaginary (q) fictitious powers, denominated as $\tilde{p}$ and $\tilde{q}$, respectively. Such signals are proportional to the oscillating components of the source currents. In order to determine the real value of these current components, denominated as $i_{Sh\alpha}$ and $i_{Sh\beta}$, a matrix equation is applied, as seen in (6).

$$\begin{bmatrix} i_{Sh\alpha} \\ i_{Sh\beta} \end{bmatrix} = \frac{1}{pll_\alpha + pll_\beta} \begin{bmatrix} pll_\alpha & pll_\beta \\ pll_\beta & -pll_\alpha \end{bmatrix} \cdot \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (6)$$

Finally, the control voltages $v_{Sh\alpha}$ and $v_{Sh\beta}$, are calculated by means of a proportional controller, just as illustrated on equation (7). It is important to emphasize that the proportional gain k should be designed to damp the oscillating components only. Some algorithms to determine the gain k are proposed in [5].

$$\begin{bmatrix} v_{Sh\alpha} \\ v_{Sh\beta} \end{bmatrix} = k. \begin{bmatrix} i_{Sh\alpha} \\ i_{Sh\beta} \end{bmatrix} \quad (7)$$

C. DC-Voltage Regulation

Since there are no power sources on the dc side of the inverter, a controller that keeps the dc-link voltage regulated has to be implemented. The basic idea consists in forcing an exchange of energy between the dc-link capacitor with the electric grid. The control diagram is shown in Fig. 5. It may also be implemented by applying a proportional controller only. Nevertheless, if zero error in steady-state is required, a PI controller is necessary.

It is important to comment that the output signal of this controller may be understood as a demand of average real power to the power converter due to the switching losses. This aspect results in a reduction on the magnitude of the voltages delivered to the load. In a real application this reduction has to be taken into account, and it is necessary to determine if the sensitive loads are affected by it.

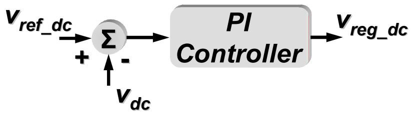

Fig.5 – Block diagram of the dc voltage controller

D. Reference Voltages Calculation

The reference voltages that will be synthesized by the power inverter are determined by applying (8). The signals adopted in expression (8) should be in accordance to the standard used in Fig. 1.

$$\begin{bmatrix} v_{ref\alpha} \\ v_{ref\beta} \end{bmatrix} = \begin{bmatrix} v_{S1\alpha} - (v_{S\alpha} + v_{Sh\alpha} + v_{reg\_dc}) \\ v_{S1\beta} - (v_{S\beta} + v_{Sh\beta} + v_{reg\_dc}) \end{bmatrix} \quad (8)$$

IV. SIMULATION RESULTS

A test case was conceived to analyze the performance of the proposed system through digital simulations, with PSCAD®/EMTDC™ 4.2. The simulation time is of 2 s, with a fixed time step of 5 µs, which enables the observation of phenomena up to 200 kHz.

The system line voltages present a RMS value of about 230 V, including 4.4 % of negative-sequence unbalance, 6.5 % of 5th harmonic (negative-sequence), and 5.2 % of 10 Hz flicker (positive-sequence). These conditions, together with the harmonic content of the load currents, that also contributes to increase the voltage distortion, result in a source voltage THD equal to 14 %.

As can be seen in Fig. 1, the electric diagram of the test system presents three circuit breakers (CB_1, CB_2 and CB_3). Initially the load is connected, CB_3 is closed, and CB_1 and CB_2 are open. At 0.3 s CB_1 is closed and the passive filters start compensating the harmonic components. After stabilization, the series active filter is also connected, but the controller is only regulating the dc-link voltage. The activation of the series active filter is done in two stages: the first stage occurs at 0.45 s and consists of connecting the secondary of the transformer to the inverter by closing CB_2, and the second stage involves connecting the primary side of the transformer to the electric grid by opening CB_3 at 0.47 s. The damping algorithm is activated at 0.6 s, and the series active filter starts acting as high impedance for the current harmonics and as a short circuit for the fundamental component of the source currents. Finally, at 0.9 s the series active filter starts compensating the voltage flicker, the voltage harmonics and the voltage unbalance, increasing global power quality for the loads and suppressing the harmonics still remaining in the source currents.

In Fig. 6 it is possible to see the source currents before and after the passive filters being connected at 0.3 seconds. After a small transient period, the source currents present their harmonic distortion reduced from 15% to 11%. The passive filters have their performance compromised due to the resonance phenomenon.

When the damping controller starts, the resonance phenomenon is suppressed, and the harmonic distortion observed at the source currents is reduced from 11% to 6.5%. Such aspect can be observed in Fig. 7.

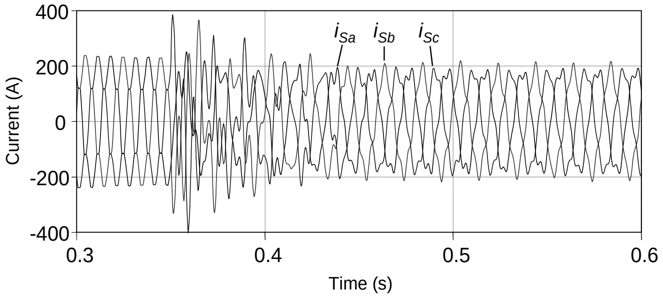

Fig. 6 – Source Currents before and after the passive filters connection

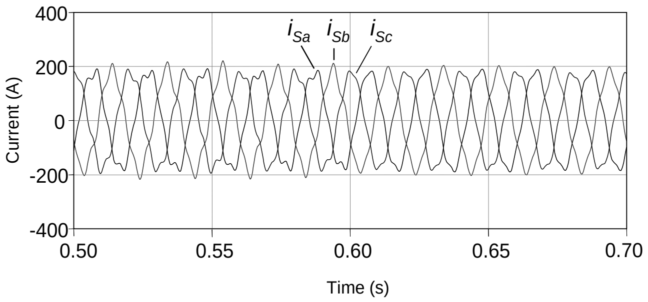

Fig. 7 – Source Currents before and after damping controller starts.

However a small harmonic distortion still remains at the source currents due to the presence of distorted components at the system voltages. Such a drawback is overcome when the active filter starts compensating the distorted components presented at the system voltages, which occurs at 0.9 s. At this time, the harmonic distortion of the source currents is reduced from 6.5% to 3.0%. In Fig. 8 it is possible to see the source currents before and after the series active filter starts compensating the voltages.

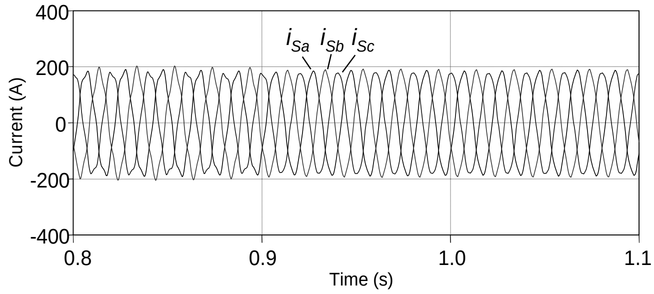

Fig. 8 – Source Currents before and after series active filter starts compensating distorted voltages

Fig. 9 and Fig. 10 illustrate the load voltages respectively before and after the active filter starts compensating distortions present in the system voltages. When the active filter starts compensating distortions, the THD of the load voltages is reduced from 12.5% to 1.0%. In Fig. 9, the system voltages present notches in their waveform due to the fact that the load consists of a 6-pulse thyristor rectifier. Once the passive filters are operating, these notches are no more observed in the system voltages as illustrated in Fig. 10.

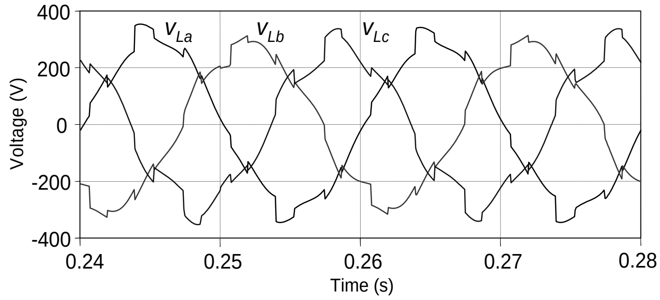

Fig. 9 – Load voltages before hybrid filter connection

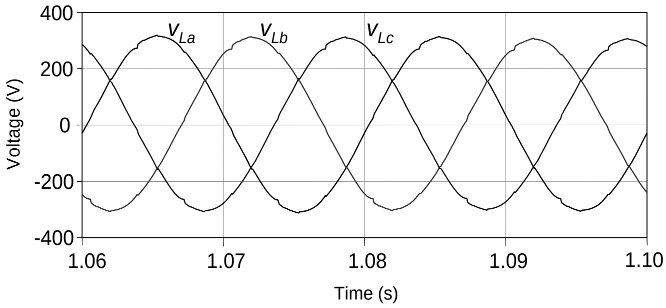

Fig. 10 – Load voltages after hybrid filter connection

Fig. 11 shows the dc-link voltage during the different stages of the simulation. At first, the dc-link capacitor is charged to 400 V. At 0.45 s, when the series active filter is connected to the electric grid, there are no oscillations At 0.9 s, the active filter starts compensating distortions presented in the source voltages, and the dc-link voltage starts having an oscillating value in the 10 Hz frequency. Such a behavior was expected due to the presence of a flicker of 10 Hz frequency at the system voltages.

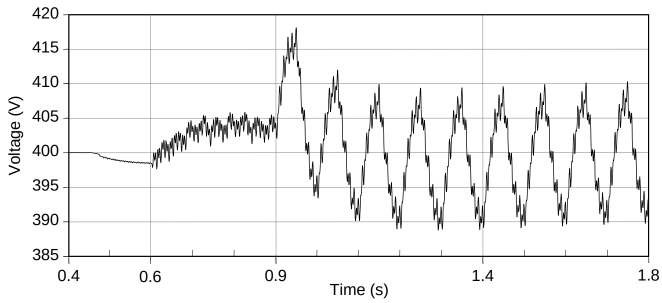

Fig. 11 – dc-link voltage

If the series active filter is connected before the shunt passive filters, then the transient period that occurs during the connection of these devices will be less critical due to the damping algorithm. Fig. 12 shows the result of a simulation, where the active filter is initialized at 0.3 s and the passive filters are connected at 0.4 s. In this case, the transient period related to the connection of the passive filters lasts only one cycle, while this transient lasted more than 3 cycles in the case previously presented (Fig. 6), in which the shunt passive filters were connected before than the series active filter.

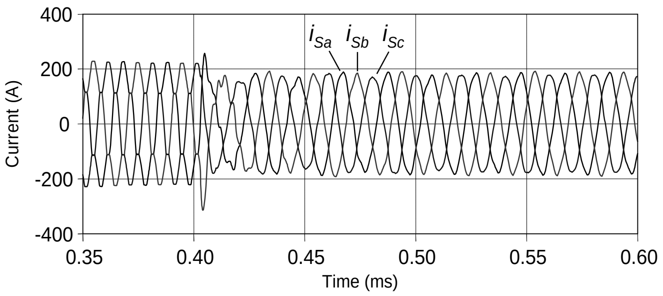

Fig. 12 – Source currents before and after the passive filters connection with the series active filter already connected

The peak currents are also much smaller when the series active filter is already connected; in this case only phase *b* had a peak of approximately 300 A. When the passive filters were connected before the active filter all currents had peaks of almost 400 A.

V. Conclusions and Suggestions for Further Works

A Hybrid Active Filter involving shunt passive filters together with a series active filter was analyzed. Through simulation results it was possible to see a better performance of the passive filters when the series active filter provides system stability and suppresses possible distortions presented in the source voltages.

However, active conditioners connected in series with electric grid through transformers may have its performance compromised. Such aspect occurs due to the fact that transformers are not designed to deal with distorted voltages. Thus researches involving design of transformers or development of conditioners capable to be connected with the system without using power transformers, may constitute solutions to improve the drawbacks aforementioned.

It is important to clarify that the introduced series active filter, without energy sources on the inverter dc-side, does not have the capability to keep regulated the voltage delivered to the load, in case of voltage sags. This drawback can be overcome by means of energy store elements on the dc-side as flywheels, SMES (Superconducting Magnetic Energy Storer), batteries, and many others.

Another important aspect commented in this work concerns to the fact that, in order to suppress the switching losses of the power converter, an amount of energy is drained from the electric system to the series active filter, which results in a reduction in the magnitude of the delivered voltages to the load. Therefore, in a real application, these switching losses must be taken into account in order to avoid unsatisfactory operation of sensitive equipments presented in the load.

Acknowledgment

This work was supported by the FCT (Fundação para a Ciência e a Tecnologia), project funding POCTI/ESE/41170/2001 and POCTI/ESE/48242/2002. The authors are also grateful to PRIME (Programa de Incentivos à Modernização da Economia) for funding the Project SINUS.

Luís F. C. Monteiro is supported by the Programme Alβan, the European Union Programme of High Level Scholarships for Latin America, scholarship no. E06D103177BR.

References

[1] B. Singh, V. Verma, A. Chandra, K. Al-Haddad, "Hybrid filters for power quality improvement," IEE Proceedings-Generation, Transmission and Distribution, Volume 152, Issue 3, 6 May 2005 pp. 365 – 378.

[2] F.Z. Peng, H. Akagi and A.Nabe, "A New Approach to Harmonic Compensation in Power Systems - A Combined System of Shunt Passive and Series Active Filters", IEEE Transactions on Industry Applications, vol.26, No.6, Nov/Dec 1990, pp. 983-990.

[3] F. Z. Peng, H. Akagi, A. Nabae, "A novel harmonic power filter," Power Electronics Specialists Conference, PESC '88 Record., 19th Annual IEEE, 11-14 Abril 1988, vol. 2, pp. 1151 -1159.

[4] M. Aredes, J. Häffner and K. Heumman, "A combined series and shunt active power filters," IEEE / KTH– Stockholm Power Tech. Conf., SPT PE 07-05-0643, vol. Power Elect., Sweden, June 1995, pp. 237–242.

[5] H. Fujita, H. Akagi, "The Unified Power Quality Conditioner: The Integration of Series and Shunt Active Filters," IEEE Trans. On Power Electronics, vol.13, No.2, March 1998, pp. 315-322.

[6] R. Li, A.R. Johns, M.M. Elkateb, F.V.P. Robinson, "Comparative study of parallel hybrid filters in resonance damping," Electric Power International Conference on Engineering, 1999. PowerTech Budapest 99. 29 Aug.-2 Sept. 1999 pp. 230.

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

[8] E.H. Watanabe, R.M. Stephan and M. Aredes, "New Concepts of Instantaneous Active and Reactive Powers in Electrical Systems with Generic Loads," IEEE Trans. on Power Delivery, vol. 8, no. 2, pp. 697-703, April 1993.

[9] M. Aredes, E.H. Watanabe, "New Control Algorithms for Series and Shunt Three-Phase Four-Wire Active Power Filters," IEEE Trans. on Power Delivery, vol. 10, no. 3, pp. 1649-1656, July 1995.

[10] Ricardo Pregitzer, J. C. Costa, Júlio S. Martins, and João L. Afonso, "Simulation and Implementation Results of a 3 Phase 4 Wire Shunt Active Power Filter", Proceedings (CD-ROM) ICHQP'2006 - International Conference on Harmonics and Quality of Power, 1-5 Oct. 2006, Cascais, Portugal.