Power Factor Correction of Linear and Non-linear Loads Employing a Single Phase Active Power Filter Based on a Full-Bridge Current Source Inverter Controlled Through the Sensor of the AC Mains Current

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Abstract - This paper introduces a new technique to control a single phase active power filter based on a full-bridge current source inverter. The active power filter is controlled through the sensor of the input current, allowing the compensation for current harmonics and phase displacement of any linear, non-linear and multiple loads. Theoretical analysis, design procedure, simulation and experimental results are provided.

I. INTRODUCTION

In the last years the number of non-linear loads has been increasing rapidly. This non-linear loads drawn a current form the AC Mains with harmonic components, leading to low power factor, low efficiency, interference by the EMI, among others. A classic solutions is the use of passive filters, which have resonance problems, large size and fixed compensation characteristics. The most common single phase non-linear load is the uncontrolled rectifier followed by a capacitive filter. For this specific non-linear load the use of a Boost pre-regulator provides a reduction in the harmonic contents and an improvement in the power factor. However, the Boost pre-regulator can not be used in equipment already in service, and it is applied only to one kind of non-linear load.

The active power filter connected in parallel to the non-linear loads is a more interesting solution because it compensates the reactive power of any load and it may be installed in equipment already in service. The single phase active power filter more widely used is the full-bridge voltage source inverter. Many techniques to control the voltage source inverter have been proposed. Some calculating the reactive power of the load or even the load harmonic contents, and more lately through the sensor of the AC Mains current [1], [2]. However, the voltage source inverter needs a large capacitive bank and in order to be connected in parallel to the loads an inductance is necessary, and this inductance limits the active filter performance. The full-bridge current source inverter may be connected directly to the load and it is naturally a current amplifier, so a better performance may be expected. Some works have been made involving the full-bridge current source inverter [3], that is usually controlled through the calculation of the reactive power of the load or even the load current harmonic components. This techniques limits the active filter usage to harmonic cancellation and the active filter is not able to compensate for the load current phase displacement. In this work a full bridge current source inverter controlled through the sensor of the input current is proposed, allowing the compensation for current harmonics and phase displacement of any linear, non-linear and multiple loads.

II. CONTROL STRATEGY

The full-bridge current source inverter used as the active filter is presented in Fig. 1.

The active filter is connected in parallel to the load. A high frequency filter (composed by L_1 and C_1) shall be used, so that the harmonics due to the switching frequency will not flown in the AC Mains.

The average value of current I_{Lf} must be kept constant in order to ensure that in the active filter flows the necessary reactive power that cancels the reactive power generated by the load, emulating a resistive load for the AC Mains. However some active power shall flow in the active filter in order to compensate for the commutation and conduction losses in the switches and other parasitic components. Compared to the full-bridge voltage source inverter, the current source inverter presents more losses. Not only because a diode is placed in series with the switches (due to the bidirecional voltage applied to them), increasing the conduction losses, but also because the inductor L_f presents more losses than the capacitor bank used in the DC side of the voltage source inverter. However the current source inverter is more robust.

The control strategy, also shown on Fig. 1, is based on the sensor of the current I_{Lf} and its comparison with a reference current $I_{Lf_{ref}}$. The resulting error goes through an appropriate current controller. The output signal of the controller is multiplied by a sinusoidal signal proportional and in phase with the AC Mains, resulting in a sinusoidal reference which is compared to the input current. The resulting error is compared to the triangular signals, generating the drive signals to the switches. The employed modulation technique is a three level one, with two triangular signals with a phase displacement of 180°, as shown in Fig. 2.

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The advantage of using the three level modulation technique is that the current i_f' has a frequency which is twice the switching frequency, as can be noticed is Fig. 2, optimizing the high frequency filter (L_1 and C_1), and improving the performance as an active filter.

The proposed control strategy allows the compensation for current harmonics and phase displacement of any linear, non-linear and multiple loads.

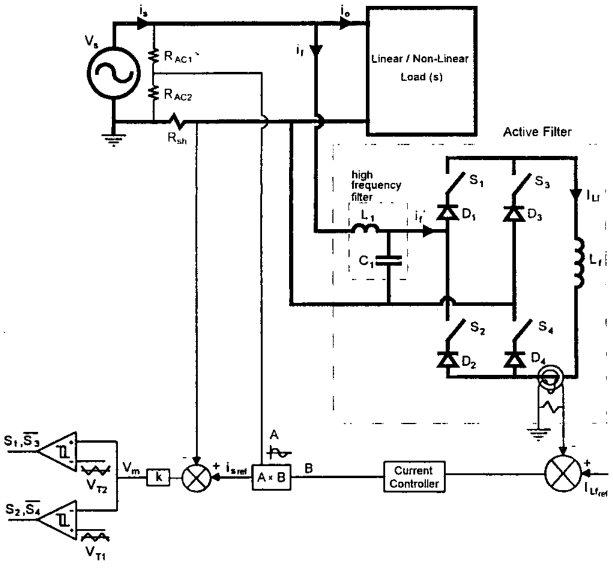

Fig. 1 – Diagram of the active filter and the proposed control strategy.

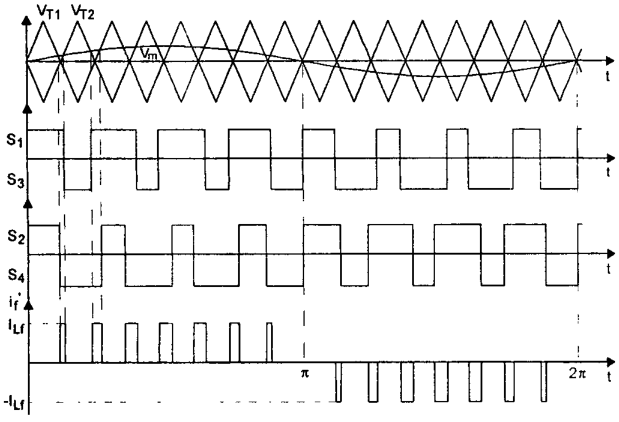

Fig. 2 – Three level modulation technique.

III. THEORETICAL ANALYSIS

In order to guaranty the proper operation of the full-bridge current source inverter as an active filter, the inductance L_f must be designed to ensure that its current average value be bigger than the input current peak value, as well as its instantaneous value. Otherwise the reactive power generated by the active filter will not compensate properly the loads. The relation between the input current peak value and the current I_{Lf} average value defines the modulation index as shown in (1). The smaller the modulation index, the bigger the ability of the active filter to compensate the loads.

$$M_i = \frac{i_{s\,peak}}{I_{Lf\,avg}} = \frac{V_{m\,peak}}{V_{T\,peak}} \tag{1}$$

Where: M_i→modulation index; i_{speak}→input current peak value; I_{Lfavg}→current I_{Lf} average value, V_{mpeak}→modulation signal peak value; V_{Tpeak}→triangular signal peak value.

The chosen current controller along with its Bode diagram is shown in Fig. 3 and its transfer function is presented in (2). The proportional integral controller ensures a null static error. Besides it must be a slow controller, presenting a crossover frequency bellow the line frequency, otherwise the sinusoidal reference signal will be distorted as well as the input current.

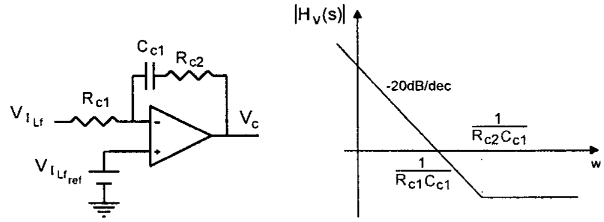

Fig. 3 – Proportional integral current controller (a) and its Bode diagram (b).

$$H_v(s) = \frac{V_c(s)}{V_{I_{Lf}}(s)} = \frac{-\left(1 + s\,C_{c1}\,R_{c2}\right)}{s\,C_{c1}\,R_{c1}} \tag{2}$$

IV. DESIGN METHODOLOGY AND EXAMPLE

A simplified design procedure and example is described in this Section. The specifications are presented as follows:

$V_{s\,peak} = 311\text{V}$

$f_{line} = 60\text{Hz}$

$P_0 = 1600\text{W}$

$I_{Lf} = 40\text{A}$

$f_s = 30\text{kHz}$

The input current for the load nominal power, and the modulation index are calculated as follows:

$$i_{s\,peak} = \frac{2\,P_0}{V_{s\,peak}} = \frac{2\times1600}{311} = 10.3\text{A}$$

$$M_i = \frac{i_{s\,peak}}{I_{Lf}} = \frac{10.3}{40} = 0.2575$$

Defining the triangular signals peak value, the modulation signal peak value is obtained.

$V_{T\,peak} = 5\text{V}$

$$V_{m\,peak} = V_{T\,peak}\, M_i = 5 \times 0.2575 = 1.288\text{V}$$

The high frequency input filter (L_I and C_I) is calculated according to the following procedure.

$$f_c = \frac{f_s}{10} = 3\text{kHz} \Rightarrow w_c = 18850\,\text{rad/s}$$

$$\zeta = 1.0$$

$$R_{eq} = \frac{V_{s\,peak}}{i_{s\,peak}} = \frac{311}{10.3} = 30.2\Omega$$

$$C_I = \frac{1}{R_{eq}\; 2\, \zeta\, w_c} = \frac{1}{30.2 \times 2 \times 1 \times 18850} \cong 0.9\mu\text{F}$$

$$L_I = \frac{1}{w_c^{\,2}\, C_f} = \frac{1}{18850^2 \times 0.9\mu} \cong 3.13\text{mH}$$

$$\text{Adjusting the filter by simulation:} \begin{cases} C_I = 2\mu\text{F} \\ L_I = 1.4\text{mH} \end{cases}$$

The current controller crossover frequency is 15Hz. Choosing $R_{cI} = 47\text{k}\Omega$, the capacitor C_{cI} is calculated.

$$C_{cI} = \frac{1}{R_{cI}\; 2\,\pi\; 15\text{Hz}} = \frac{1}{47 \times 10^3 \times 2 \times \pi \times 15\text{Hz}} \cong 220\text{nF}$$

The current controller zero is placed in 80Hz. The resistor R_{c2} is calculated as shown bellow.

$$R_{c2} = \frac{1}{C_{cI}\; 2\,\pi\; 80\text{Hz}} = \frac{1}{220 \times 10^{-9} \times 2 \times \pi \times 80\text{Hz}} \cong 10\text{k}\Omega$$

The inductance L_f is choosen to be 10mH.

V. SIMULATION RESULTS

In order to verify the principle of operation and the proposed control strategy the active power filter was simulated, according to the design example presented in Section IV. A 5Ω resistor was placed in series with the inductor L_I (high frequency filter) in order to avoid simulation oscillations.

In Fig. 5 are presented the simulation results of a resistive-inductive linear load, as shown in Fig. 4 (a). The input voltage and current, the linear load current and the active filter currents are presented. The resulting power factor is 0.999. Without the active filter the load power factor would be 0.87.

In Fig. 6 are presented the simulation results of a non-linear load consisting of a 1600W uncontrolled rectifier followed by a capacitive filter as shown in Fig. 4 (b). In Fig. 6 (a) and (c) are presented the input voltage and current and the input current and non-linear load current harmonic spectrum. The total input current harmonic distortion, considering up to the 60° component, is 5.88% and the current phase displacement is 0.1°, resulting in a power factor of 0.998. The total non-linear load current. harmonic distortion is 116%, which without the active filter would result in a power factor of 0.65. In Fig. 6 (b) are presented the load current and the active filter currents.

In Fig. 7 are presented the simulation results of a non-linear load consisting of a 1600W AC chopper, as shown in Fig. 4 (c). In Fig. 7 (a) and (c) are presented the input voltage and current and the input current and non-linear load current harmonic spectrum. The total input current harmonic distortion is 3.88% and the current phase displacement is 0.54°, resulting in a power factor of 0.999. The total non-linear load current harmonic distortion is 62.18%, which without the active filter would result in a power factor of 0.72. In Fig. 7 (b) are presented the load current and the active filter currents.

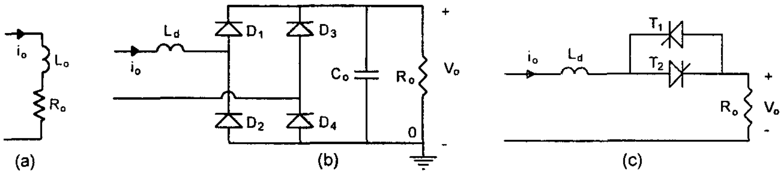

Fig. 4 – Linear load (a) and non-linear loads (b), (c).

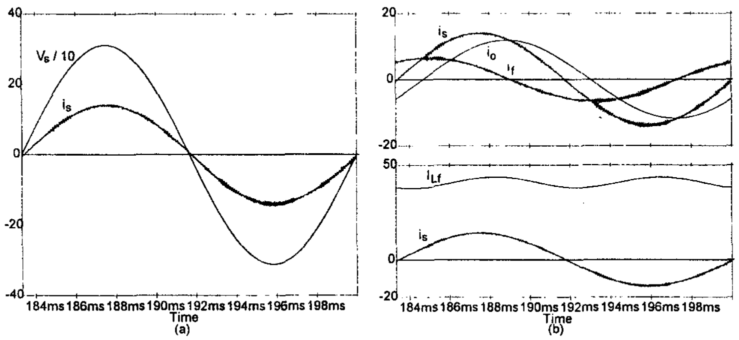

Fig. 5 – Input voltage and current (a), linear load current and active filter currents (b).

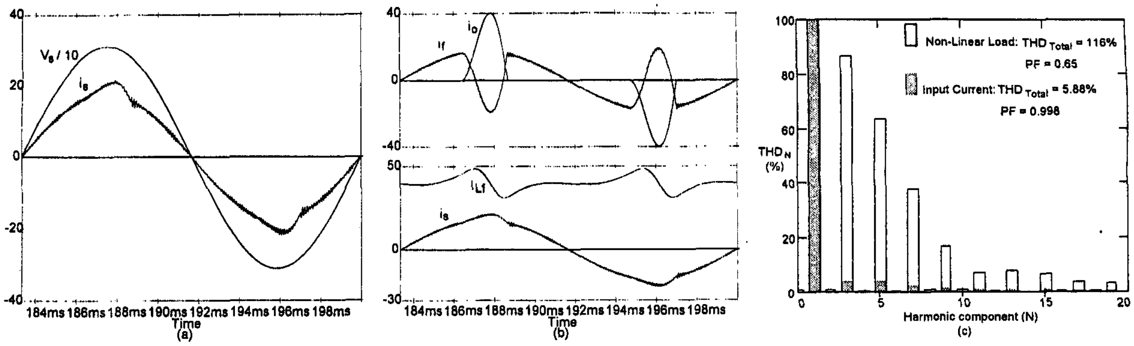

Fig. 6 – Input voltage and current (a), non-linear load current and active filter currents (b), input current and non-linear load current harmonic spectrum (c).

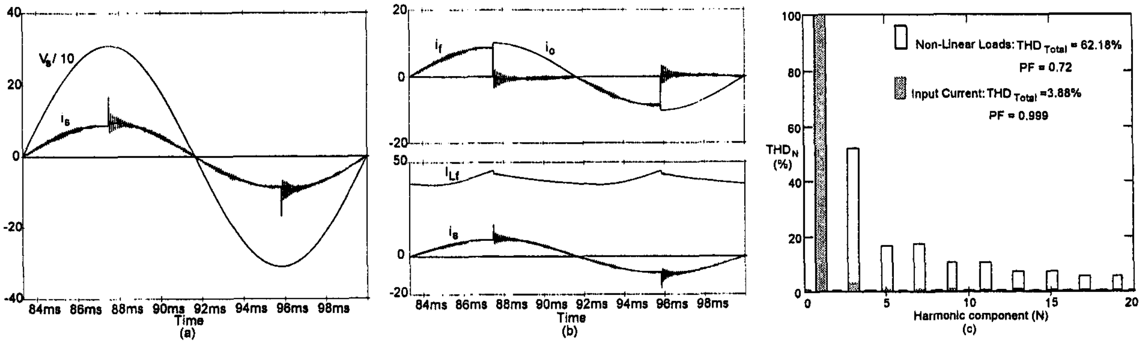

Fig. 7 – Input voltage and current (a), non-linear load current and active filter currents (b), input current and non-linear load current harmonic spectrum (c).

VI. EXPERIMENTAL RESULTS

In order to verify the principle of operation and the control strategy, a 1600W, 30kHz prototype was built.

The specifications are as follows:

$V_{Speak} = 311V$

$f_{line} = 60Hz$

$P_o = 1600W$

$I_{Lf} = 40A$

$f_s = 30kHz$

$L_1 = 1.4mH\ (3.9cm\ Fe\ Si\ core, 30\ turns, 5 \times 14AWG, gap = 0.8mm)$

$C_1 = 2\mu F / 280V\ (polypropylen)$

$L_f = 10mH\ (6cm\ Fe\ Si\ core, 48\ turns, 25 \times 18AWG, gap = 0.2cm)$

$S_{1,2,3,4}$:IRG4PC50W , $D_{1,2,3,4}$:HFA50PA60C

In Fig. 8 it is presented the prototype control diagram.

A dual monostable multivibrator MC14528 was used to provide the switches drive signals overlapping, and two M5792L opto-couplers were used to provide the drive signals isolation.

In Fig. 9 it is presented the experimental results of the active filter compensating a 510W resistive-inductive linear load. The input current is practically in phase with the input voltage, resulting in a power factor of 0.998. The linear load current presents a phase displacement of 42°, which without the active filter would result in a power factor of 0.743. Theoretically in the active filter flows only a reactive power. It means that for a linear load the active filter current should be with a 90° phase displacement in relation to the input voltage. In Fig. 9 (c) it can be noticed that the current i_f does not presents a 90° phase displacement because of the active filter losses.

In Fig. 10 it is presented the experimental results of the active filter compensating a non-linear load consisting of a 490W uncontrolled rectifier followed by a capacitive filter. The input current is practically sinusoidal and in phase with the input voltage. The total harmonic distortion, considering up to the 60° component, is 6.18% and the current phase displacement is 0.53°, resulting in a power factor of 0.998. The non-linear load current presents a total harmonic distortion of 119.11% and a phase displacement of 13.3°, which without the active filter would result in a power factor of 0.62.

In Fig. 11 it is presented the experimental results of the active filter compensating a non-linear load consisting of a 240W AC Chopper. The input current is practically sinusoidal and in phase with the input voltage. The total harmonic distortion is 4.79% and the current phase displacement is 1.76°, resulting in a power factor of 0.998. The non-linear load current presents a total harmonic distortion of 58% and a phase displacement of 29.42°, which without the active filter would result in a power factor of 0.75.

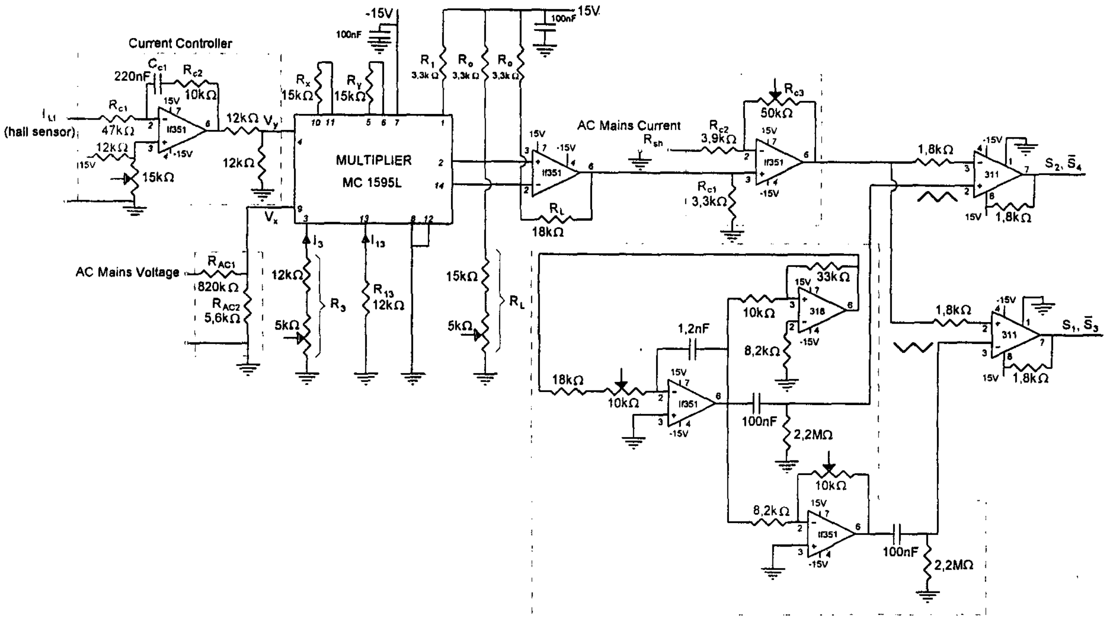

Fig. 8 – Control Diagram of the implemented prototype.

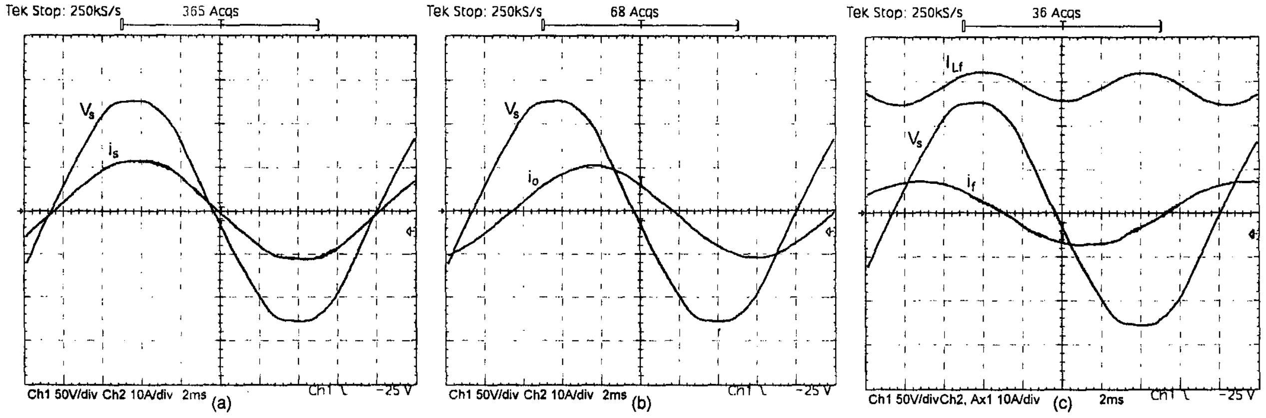

Fig. 9 – Input voltage and current (a), input voltage and linear load current (b), input voltage and active filter currents (c).

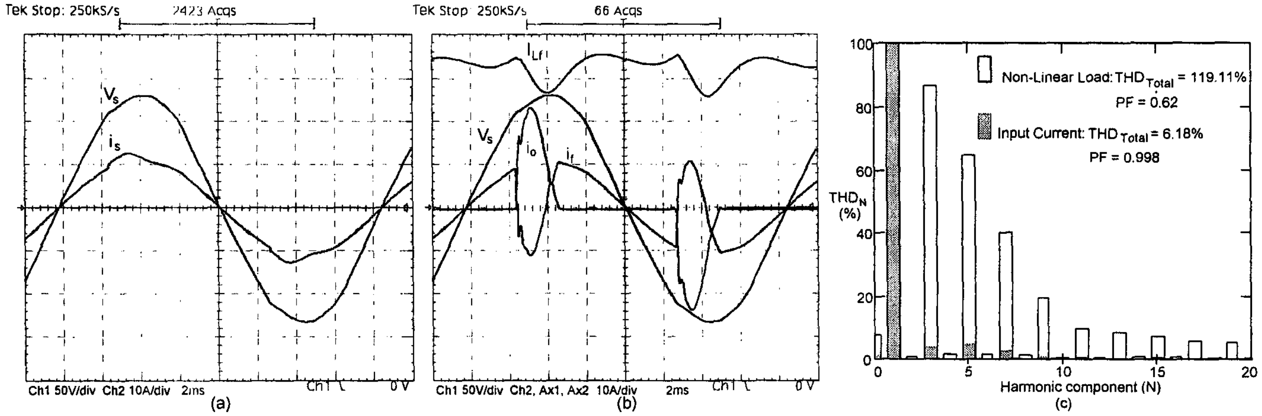

Fig. 10 – Input voltage and current (a), non-linear load current and active filter currents (b), input current and non-linear load current harmonic spectrum (c).

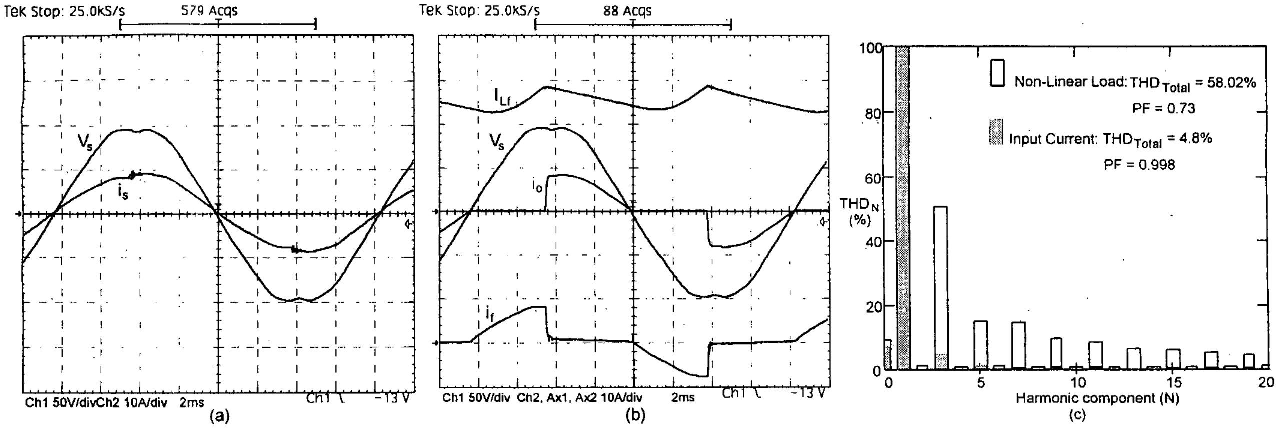

Fig. 11 – Input voltage and current (a), non-linear load current and active filter currents (b), input current and non-linear load current harmonic spectrum (c).

VII. CONCLUSION

In this paper a new control strategy to the full-bridge current source inverter operating as an active power filter was proposed. The control strategy, based on the sensor of the input current, is very simple and allows the compensation for current harmonics and phase displacement of any linear and non-linear-loads.

Simulation and experimental results of an active filter compensating linear and non-linear loads were presented, validating the theoretical analysis.

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