

# Power Factor Correction of Non-Linear Loads Employing a Single Phase Active Power Filter: Control Strategy, Design Methodology and Experimentation

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**Abstract** - This paper presents a technique for single phase power factor correction of non-linear loads employing an active power filter. The current control strategy is the same used in the boost pre-regulator, which is the average current mode technique. The paper will focus on the design methodology and the analysis of the control strategy which allows the compensation of harmonics and phase displacement of the input current, for single and multiple non-linear and linear loads. Simulation results of an active filter controlling a single load, which consists of a 1600W rectifier with a capacitive filter, and a multiple load, which consists of a 800W rectifier with a capacitive filter and a 800W AC chopper, are provided. Experimental results of an active filter controlling a 400W rectifier with a capacitive filter, a 800W AC chopper and a 580W multiple load, which consists of a rectifier with a capacitive filter and an AC chopper, are presented.

## I. INTRODUCTION

In the last years the use of electronic equipment has been increasing rapidly. This equipment draws a different current from the AC mains when compared to traditional loads such as motors and resistive heating elements. The current drawn from the AC mains has harmonic components, which leads to low power factor, low efficiency, interference in some instruments and communication equipment by the EMI, overloaded electrical-distribution systems, overheated transformers and electromagnetic fields. A classical solution is the use of passive filters to suppress harmonics in power systems. However, passive filters have many disadvantages, such as large size, resonance, and fixed compensation characteristics. Therefore, it does not provide a complete solution.

The most usual single phase non-linear load is the front-end rectifier followed by a bulk capacitor, which draws current from the input during its charging. The boost pre-regulator, shown in Fig. 1 [1] [2], is a well-established technique that is used to reduce the harmonic contents and improves the power factor. The current control loop consists in the average current mode technique. The boost pre-regulator has some disadvantage because it can not be used in equipment already in service, and it is applied only to one kind of non-linear load which is the front end rectifier followed by a bulk capacitor.

A very interesting solution is the use of a single-phase active power filter, which is connected in parallel with the

non-linear loads as shown in Fig. 2, allowing its use in existing plants. The active power filter concept uses power electronics to produce harmonic components which cancel the harmonic components from the non-linear loads. It can limit harmonics to acceptable levels and can adapt itself in case of harmonic component alteration or even changes in the non-linear loads types. Usually the technique used to control the single-phase active filter senses the non-linear load current and calculates its harmonics components. This technique is not suitable in small power (up to 3kW). Reference [3] presented an easier way to control the active filter, sensing the input current and comparing it with a sinusoidal reference in phase with the AC mains voltage. The current control loop is based in a slide mode control technique.

This paper will focus on the design and the control strategy for a shunt single-phase active power filter. The active filter is able to compensate the displacement of the input current in relation to the AC mains voltage and the harmonics components of single and multiple non-linear loads, through the sensing of the input current. The current control loop is the same employed in the boost pre-regulator, which is the average current control technique.

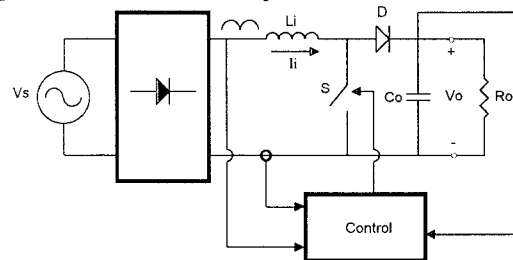


Fig. 1 - Boost pre-regulator.

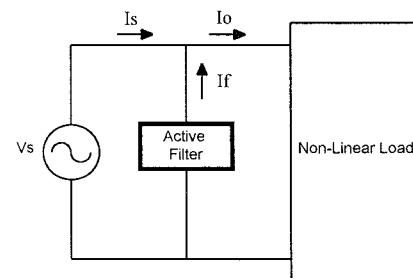


Fig. 2 - Single-phase active filter.

## II. ACTIVE POWER FILTER TOPOLOGY AND PROPOSED CONTROL STRATEGY

The converter, which is used as the active filter, is a full-bridge voltage source inverter, due to its current reversibility characteristics. The full-bridge inverter is connected in parallel with the AC mains through a filter inductance  $L_f$ , and the DC side of the inverter is connected to a filter capacitor  $C_f$ , as shown in Fig. 3.

Thanks to the appropriate control of the full bridge switches, the current  $I_f$  cancels the harmonics components of the non-linear loads, resulting in a sinusoidal input current in phase with the AC mains voltage. The switching frequency is constant and the  $S_1$  and  $S_2$  gate signals are complementary to  $S_3$  and  $S_4$  ones.

If the output voltage of the active filter ( $V_f$ ) is kept constant, then the active power flowing in the active filter is zero. Thus, in the active filter flows a reactive power that cancels the reactive power generated by the non-linear loads, emulating a resistive load for the AC mains.

The outer voltage loop consists in the comparison of the voltage  $V_f$  with a reference voltage. The resulting error is injected in an appropriate voltage controller. The output of the voltage controller is then multiplied by a sinusoidal signal proportional and in phase with the input voltage. The result of this multiplication is a reference current  $I_{ref}$ .

The inner current loop consists of the comparison of the reference current with the input current. The resulting error is injected in an appropriate current controller that in this case uses the average current mode technique. The output of the current controller is then compared with a triangular signal, generating the drive signals to the switches. The control strategy of the active filter allows the compensation of harmonics and phase displacement of the input current for any non-linear and linear loads.

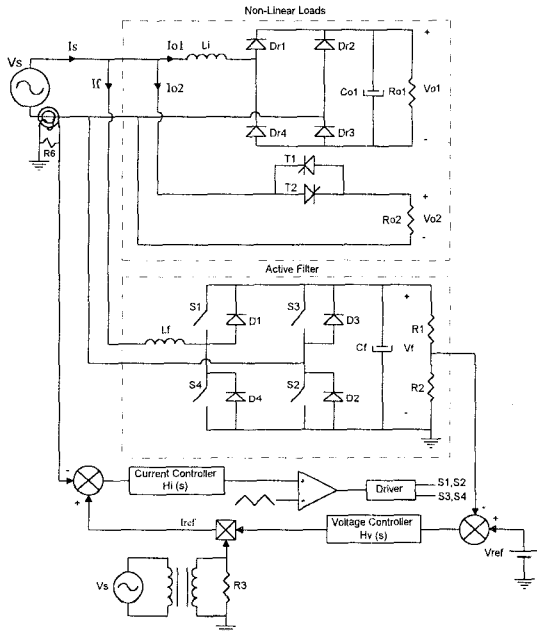


Fig. 3 - Active power filter and the proposed control strategy diagram.

## III. RELEVANT ANALYSIS RESULTS

The relevant equations used to design the active filter, its outer voltage control loop and the inner current loop are presented below.

The active filter capacitor  $C_f$  is calculated using (1). The voltage ripple is defined about 10%  $V_f$ ,  $P_o$  is the active power of the non-linear load(s), and  $f_{line}$  is the frequency of the AC mains. The active filter inductance  $L_f$  is calculated using (2).  $\Delta I_{max}$  is the maximum current ripple and  $f_s$  is the switching frequency. The smaller the inductance  $L_f$ , the better the ability to track the desired input current. However, the maximum ripple increases. The choice of the maximum current ripple depends on the harmonics components of the non-linear loads. The bigger the harmonic distortion of the load, the bigger should be the tolerated ripple, otherwise the inductor will not track properly the input current.

$$C_f \geq \frac{P_o}{2 \cdot f_{line} \cdot (V_{fmax}^2 - V_{fmin}^2)} \quad (1)$$

$$L_f = \frac{0,5 \cdot V_f}{\Delta I_{max} \cdot f_s} \quad (2)$$

The DC voltage-to-inductor current transfer function is presented in (3). The controller is an one pole one zero configuration. The zero must be located at a small frequency (around 1Hz), and the pole must be located at about two decades above the zero. The voltage controller transfer function is presented in (4).

$$G_v(s) = \frac{\Delta V_f(s)}{\Delta I_f(s)} = \frac{V_{s,rms}}{V_f} \cdot \frac{1}{C_f \cdot s^2} \quad (3)$$

$$H_v(s) = k_v \cdot \frac{(1 + s/w_{zv})}{(1 + s/w_{pv})} \quad (4)$$

The inductor current-to-duty-cycle (D) transfer function is presented in (5). As can be noticed the difference between this transfer function and the one obtained in the boost pre-regulator is the gain. Thus the controller is the same used for the boost pre-regulator, which is an one zero two poles configuration. However, due to the different gain, the position of the poles and zero are different. The zero must be located about two decades above the switching frequency, one pole is located at 0 Hz and the other pole must be located around the switching frequency. The current controller transfer function is presented in (6). The transfer function of the ac line current sampling effect is shown in (7) and must be taken in consideration in the current controller design.

$$G_i(s) = \frac{\Delta I_f(s)}{\Delta D(s)} = \frac{-2 \cdot V_f}{L_f} \cdot \frac{1}{s} \quad (5)$$

$$H_i(s) = k_i \cdot \frac{-(1 + s/w_{zi})}{s \cdot (1 + s/w_{pi})} \quad (6)$$

$$H_c(s) = 1 - \frac{s}{2 \cdot f_s} + \left( \frac{s}{\pi \cdot f_s} \right)^2 \quad (7)$$

#### IV. SIMULATION RESULTS

According to the equations presented in section 3, and according to the specifications, an active filter was designed and the results are presented as follow:

Specifications:	Calculated Parameters:
$P_o = 1600W$	$C_f = 900\mu F$
$V_{sp} = 311V$	$L_f = 800\mu H$
$f_{line} = 60Hz$	$\omega_{iz} = 1256.64 \text{ rad/s}$
$V_f = 400V$	$\omega_{ip} = 251328 \text{ rad/s}$
$\Delta V_f = 10\% V_f$	$k_i = 0.1 \quad k_v = 2$
$f_s = 40kHz$	$\omega_{vz} = 0.63 \text{ rad/s}$
$\Delta I_{max} = 60\% I_{sp}$	$\omega_{vp} = 314.16 \text{ rad/s}$

The active filter was simulated in the Pspice program. Only the inner current loop was simulated due to slow dynamics of the voltage control loop, that would result in large simulation time. As shown in Fig. 4, one simulation was performed with a single load, which consists of a 1600W rectifier with a capacitive filter ( $R_o = 49\Omega$ ;  $C_o = 900\mu F$ ). The other simulation, shown in Fig. 5, was performed with a multiple load, which consists of a 800W rectifier with a capacitive filter ( $R_{o1} = 89\Omega$ ;  $C_{o1} = 900\mu F$ ), and an 800W AC chopper ( $R_{o2} = 60.5\Omega$ ).

In Fig. 6 it is presented the simulation results of the active filter compensating the single non-linear load shown in Fig. 4. The voltage and the current in the AC mains can be observed. The harmonic analysis was performed in the Pspice program and an harmonic distortion of 1.896% in the input current, considering up to the 9<sup>th</sup> harmonics, and a current displacement of 4.4° in relation to the AC mains voltage, were obtained, resulting in a power factor of 0.9969. It is also presented the current in the non-linear load and the current in the active filter. It is important to notice the ability of the active filter to generate the necessary harmonic components to cancel the reactive power generated by the non-linear load.

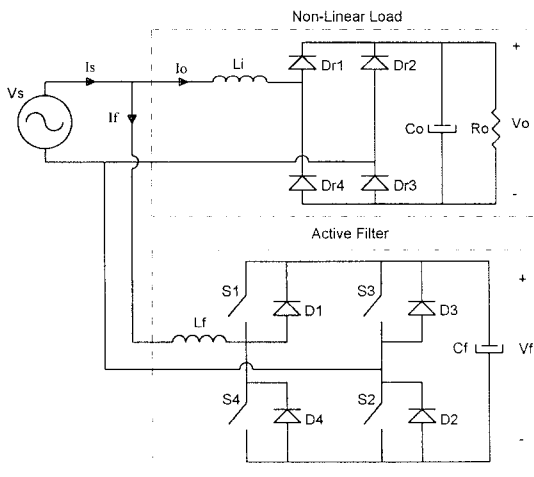


Fig. 4 - Simulated circuit:  
single load - uncontrolled rectifier with RC filter.

In Fig. 7 it is presented the simulation results of the active filter compensating the multiple non-linear load shown in Fig. 5. The voltage and the current in the AC mains can be observed. The input current harmonic distortion is 2.274% and the current displacement is 4.3° resulting in a power factor of 0.99693. It is also presented the currents in the non-linear loads and the current in the active filter.

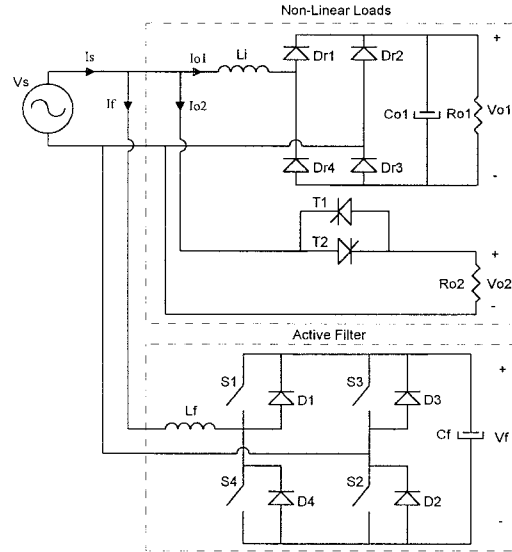


Fig. 5 - Simulated circuit:  
multiple load - uncontrolled rectifier with RC filter and AC chopper.

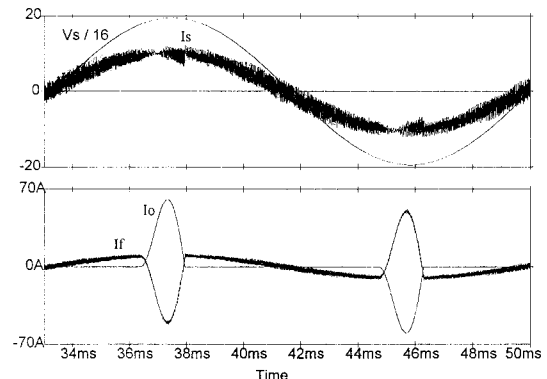


Fig. 6 - Simulation results:  
single load - uncontrolled rectifier with RC filter.

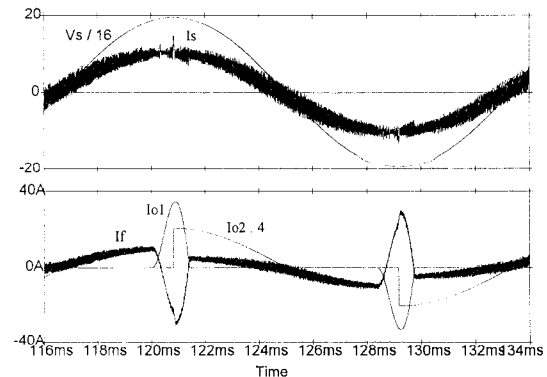


Fig. 7 - Simulation results:  
multiple load - uncontrolled rectifier with RC filter and AC chopper.

## V. EXPERIMENTAL RESULTS

In order to verify the principle of operation and the control strategy, a 800W, 30kHz, active power filter has been implemented.

The power stage diagram of the prototype is shown in Fig. 10, whose parameter and component specifications are the following:

$$V_s = 220V_{rms} \quad V_o = 400V$$

MOSFETs M1 - M4 – IRFP460  
 D1 – D4 – APT15D60K  
 $L_f = 1.4mH$        $C_f = 1.5mF$

The MOSFETs drive diagram is presented in Fig. 11, and the control diagram is presented in Fig. 12. As it can be noticed a proportional controller was used in the voltage controller, instead of the proposed one pole one zero configuration.

In Fig. 13 to 16 it is presented the experimental results of the active filter compensating a 400W uncontrolled rectifier with RC filter. The voltage in the AC mains and the current in the non-linear load are presented in Fig. 13. In Fig. 16 the harmonic spectrum of the load current considering up to the 40<sup>th</sup> component is presented. The total harmonic distortion considering up to the switching frequency is 127% and the current displacement is 2.53° resulting in a power factor of 0.613. In Fig. 14 the current in the active filter can be observed and in Fig. 15 the resulting current in the AC mains. In Fig. 17 it is shown the harmonic spectrum of this current. The total harmonic distortion is 29% and the current displacement is 2.53°, resulting in a power factor of 0.96.

In Fig. 18 to 22 it is presented the experimental results of the active filter compensating a 800W AC chopper. The voltage in the AC mains and the current in the non-linear load are presented in Fig. 18. In Fig. 21 the harmonic spectrum of the load current is presented. The total harmonic distortion is

14% and the current displacement is 3.32°, resulting in a power factor of 0.988. In Fig. 19 the current in the active filter can be observed and in Fig. 20 the resulting current in the AC mains. In Fig. 22 it is shown the harmonic spectrum of this current. The total harmonic distortion is 9% and the current displacement is 2.67°, resulting in a power factor of 0.995.

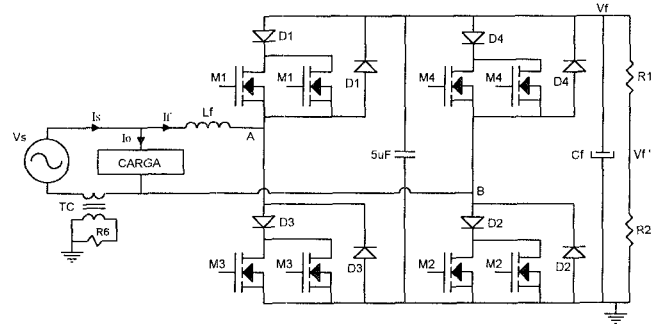


Fig. 10 – Power stage diagram.

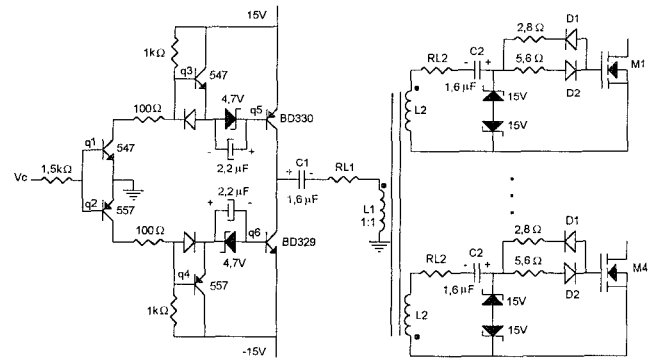


Fig. 11 – MOSFETs drive diagram.

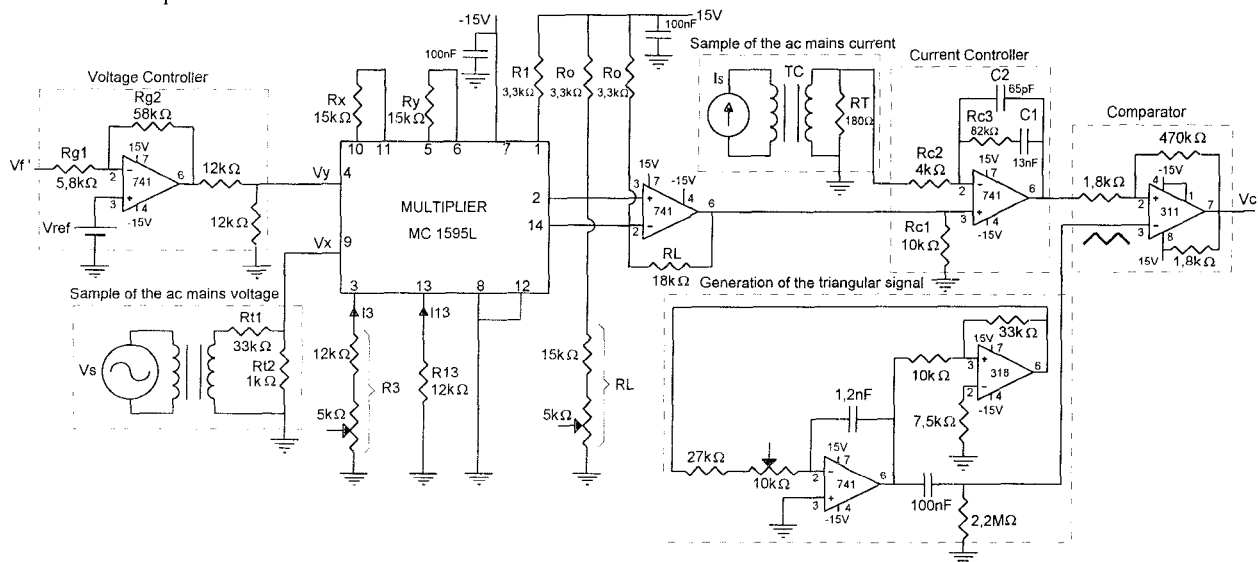


Fig. 12 – Control diagram.

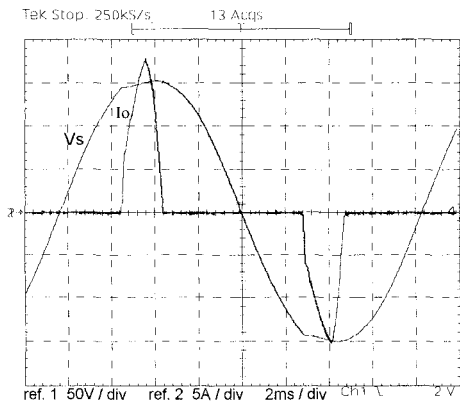


Fig. 13 – Voltage in the AC mains and current in the non-linear load.

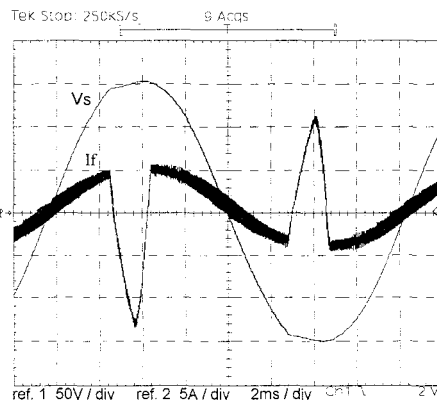


Fig. 14 – Voltage in the AC mains and current in the active filter.

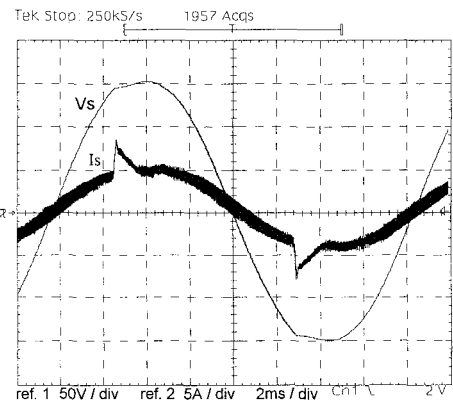


Fig. 15 – Voltage and current in the AC mains.

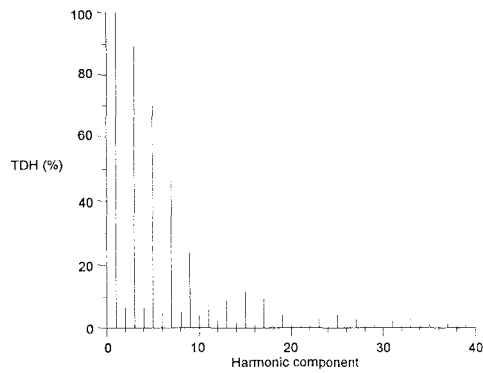


Fig. 16 – Non-linear current harmonic spectrum.

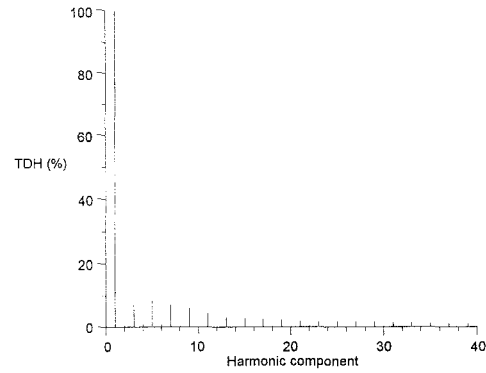


Fig. 17 – Input current harmonic spectrum.

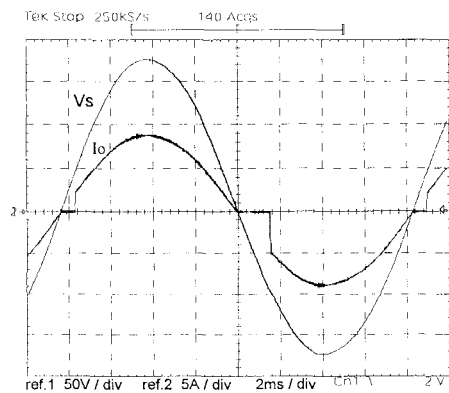


Fig. 18 – Voltage in the AC mains and current in the non-linear load.

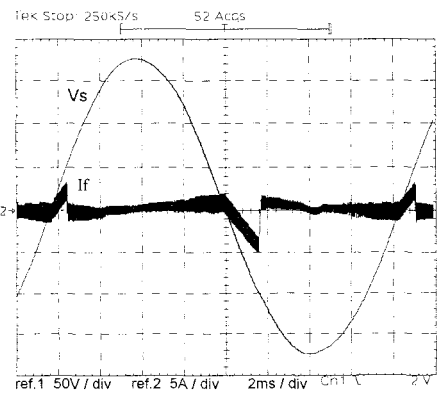


Fig. 19 – Voltage in the AC mains and current in the active filter.

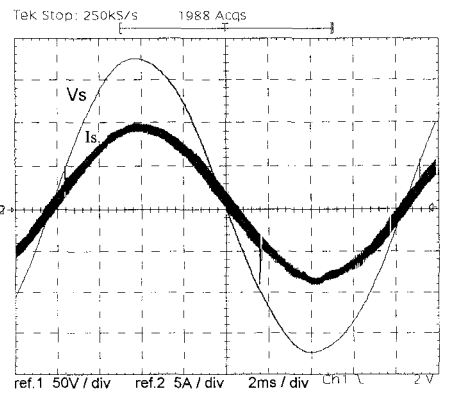


Fig. 20 – Voltage and current in the AC mains.

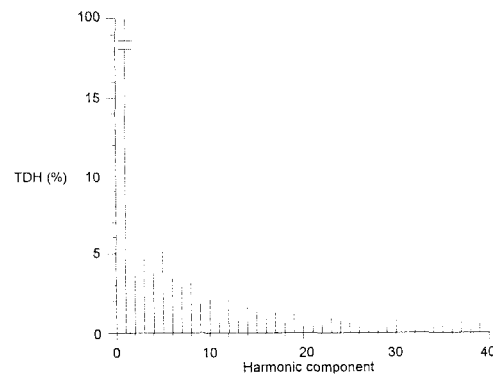


Fig. 21 – Non-linear current harmonic spectrum.

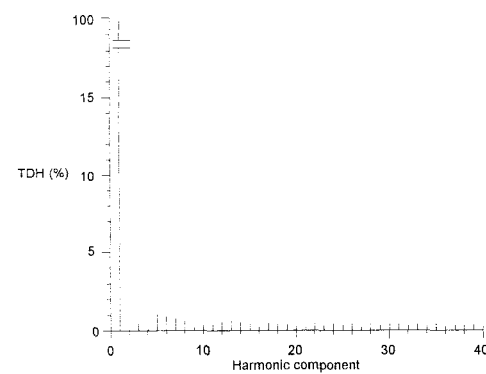


Fig. 22 – Input current harmonic spectrum.

In Fig. 23 to 27 it is presented the experimental results of the active filter compensating a 585W multiple load, which consist of an uncontrolled rectifier with RC filter and an AC chopper in parallel. The voltage in the AC mains and the total load current are presented in Fig. 23. In Fig. 26 the harmonic spectrum of the load current is presented. The total harmonic distortion is 87% and the current displacement is  $9.47^\circ$  resulting in a power factor of 0.744. In Fig. 24 the current in the active filter can be observed and in Fig. 25 the resulting current in the AC mains. In Fig. 27 it is shown the harmonic spectrum of this current. The total harmonic distortion is 14% and the current displacement is  $3.05^\circ$ , resulting in a power factor of 0.98.

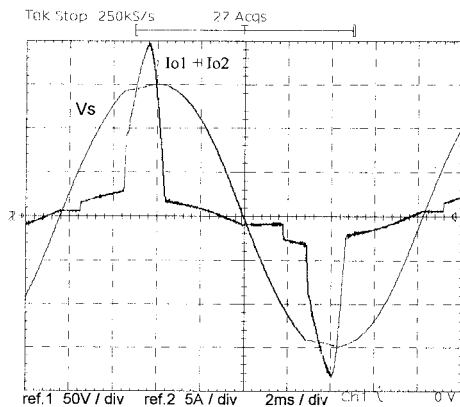


Fig. 23 – Voltage in the AC mains and current in the non-linear load.

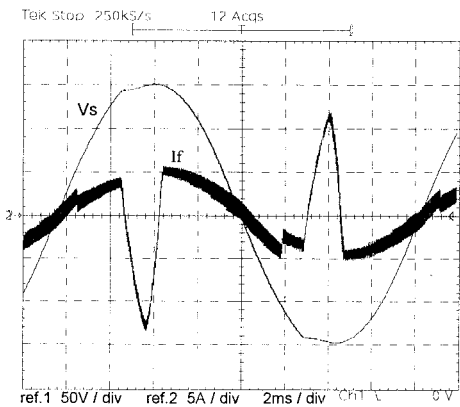


Fig. 24 – Voltage in the AC mains and current in the active filter.

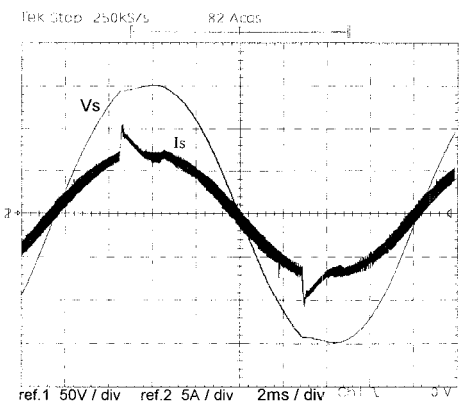


Fig. 25 – Voltage and current in the AC mains.

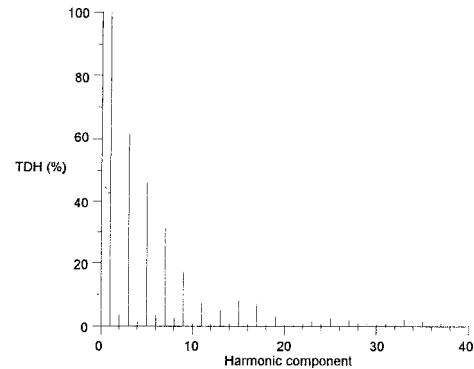


Fig. 26 – Non-linear current harmonic spectrum.

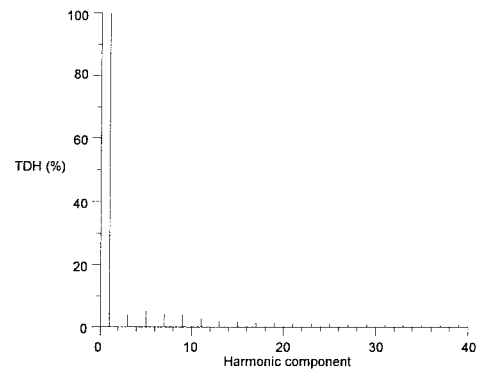


Fig. 27 – Input current harmonic spectrum.

## VI. CONCLUSION

In this paper it was presented a design methodology of an active filter and its new control loops strategy. Simulation results were provided in section 4 for single and multiple non-linear loads. Experimental results of an active filter compensating an uncontrolled rectifier with RC filter and an AC chopper were presented in section 5, validating the theoretical analysis. In despite of a simple control strategy, a high power factor is obtained.

The active power filter combined with the control strategy is a very attractive solution, because a high power factor can be achieved to any type of non-linear load, including equipment already in service.

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- [3] D. A. Torrey, A. Al-Zamel., "Single-phase active power filters for multiple nonlinear loads," IEEE Transactions on Power Electronics, Vol. 10, pp. 263-271, may 1995.