ACTIVE POWER LINE CONDITIONER BASED ON TWO PARALLEL CONVERTERS TOPOLOGY

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Abstract: A new topology for active power line conditioners is presented in this paper. It is based on the association of two electronic converters with the main objective of minimising the volume of the filtering inductors, what become more significant in high power applications. A control strategy for the two collaborative converters is proposed.

power quality, active power line conditioner, power active filter.

1. INTRODUCTION

Active power line conditioners (APLC) are becoming actual solutions in order to improve the power quality in the points where it is needed.

In this paper the attention is paid to parallel APLCs [1,2] that compensate the current demanded by a non-linear load injecting a predetermined correction current.

These devices could operate not only doing active filtering [1,2], but also fundamental reactive power compensating and supplying the critical load in case of power faults [3,4].

The converters used in these APLCs need some inductors that are designed to perform a double function:

- to filter the harmonics associated to the switching frequency and
- to produce the desired reference current, being able to produce the necessary current variation (*di/dt*).

As the switching frequency is usually high (10 kHz-20 kHz) these devices use inductors with air core, so the volume of the inductors become high (as the energy storage density of air coils inductors are low). In addition the volume (and weight) of cooper needed to get the calculated autoinductance value is high too.

This paper presents a new APLC topology that is based on two parallel converters that operates as follow:

- one converter, called „slow", operates with a low switching frequency in order to allow the use of ferromagnetic core inductors. Due to the low switching frequency this converter only corrects the fundamental reactive power and the low order harmonics. As result, this converter produces the higher percentage of the RMS value of the correction current;
- the other converter, called „fast", operates with a usual switching frequency, so air core inductor have to be used, producing the rest of the correction current. The RMS value of this current results notably lower than the total current correction. So the cooper wire sections of the air core inductors are lower, resulting in a lower volume and weight.

Collaborative converters have been treated in other works [5,6], but never with the aim proposed in the present paper.

2. APLC DESCRIPTION

2.1. Previous Analysis of the Load

An analysis of the non-lineal load is necessary in order to evaluate the viability of the proposed APLC topology and collaborative strategy.

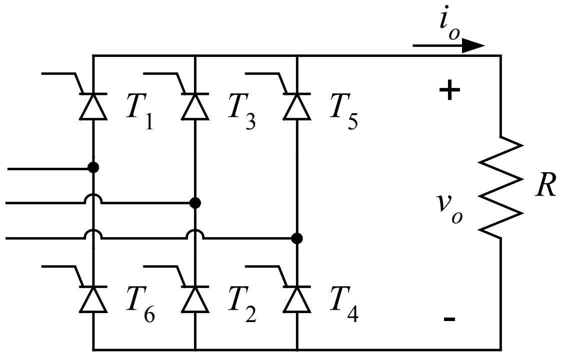


Fig.1. Three-phase-controlled rectifier with resistive load proposed as non-lineal load for APLC design.

In this paper a three-phase-controlled rectifier (Fig.1) with resistive load (R = 88 Ω) is adopted as non-lineal load. This load has been selected because produces high current variations and presents variable characteristics (depending on the firing angle) so the design of the APLC will be most exigent.

The total reference correction current must be divided into two reference currents: one for the slow converter of the APLC, and another one for the fast converter.

The criterion to separate the two parts of the total current is the harmonic order, so the low order harmonics will be selected to be corrected by the slow converter, and the high order harmonics by the fast one.

The limit order harmonic selected to separate the two parts is the 7^{th}. On the one hand, this selection allows the desired objective of reducing the RMS value of the fast converter correction current. On the other hand, its frequency (350 Hz) is low enough compared with the switching frequency of the slow converter (4 kHz), resulting in a correct value for the frequency modulation:

$$mf = \frac{4000}{350} > 11\,. \quad (1)$$

Fig.2 shows the different current waveforms obtained varying the firing angle between zero and sixty degrees. The slow converter corrects the harmonic components of the non-lineal load current up to the 7^{th} harmonic order and the fundamental reactive power. The fast converter corrects the rest of the harmonic components (from the 11^{th}).

The main parameters of the correction currents of the APLC when operating in this collaborative way are summarised in Fig.3 and in Tab.1.

It could be observed from Tab.1 that:

- fast correction current presents a RMS value (0,81) notably lower than the total correction current (2,49), so the cooper section will be lower.
- slow correction current presents instantaneous increments (0,09) much lower than the total correction current (6,09).

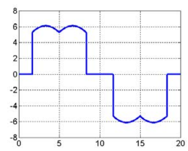
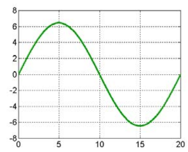
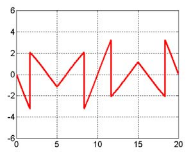
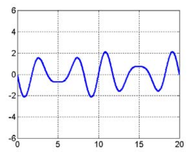
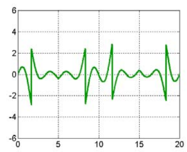
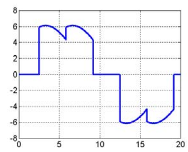
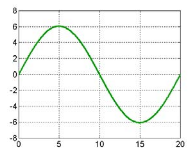
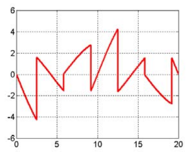
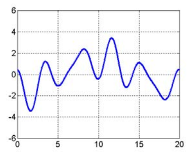
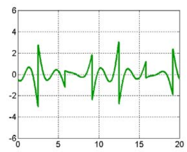
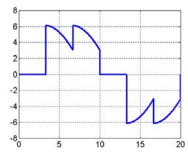
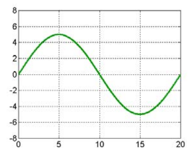
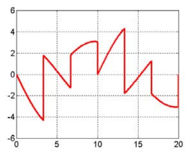
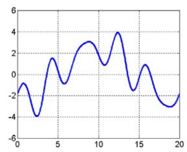
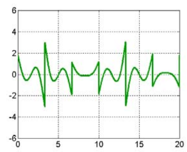
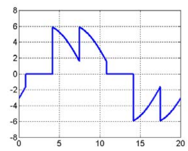
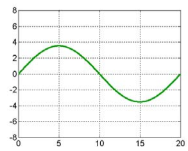
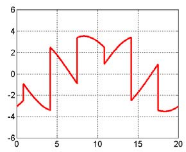
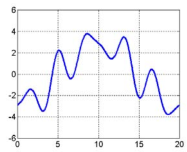
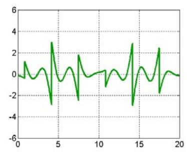
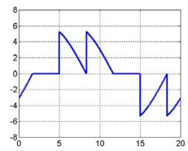
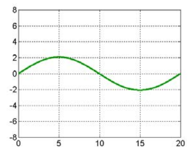
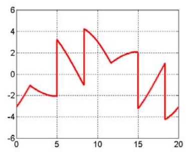
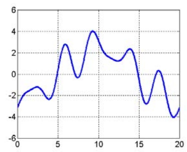
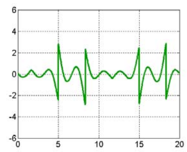
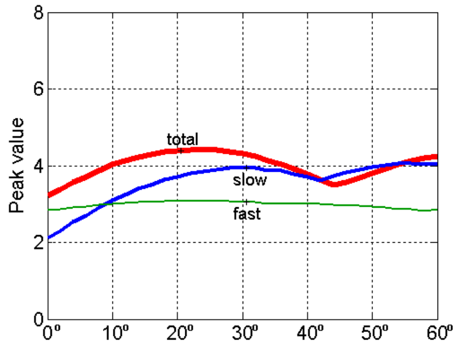
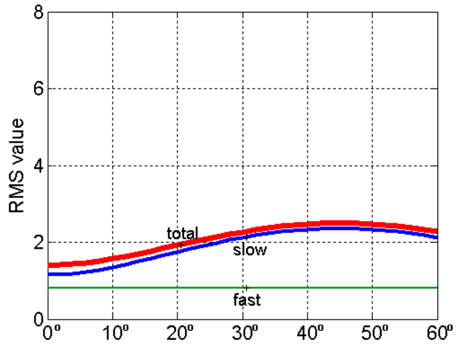
α	Corriente de carga	Corriente de alimentación	*Corriente de corrección*	*Corriente de corrección del corrector* lento	*Corriente de corrección del corrector* rápido
0º					
15º					
30º					
45º					
60º					

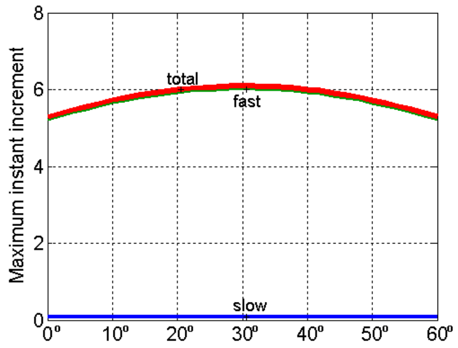
Fig.2. Changes producedvaying the firing angle: on the non-lineal current load, source current, total correction current, correction current of the slow converter, correction current of the fast converter.



(a)



(b)



(c)

Fig.3. Current parameters evolution when varying the firing angle of the three-phase-controlled rectifier: (a) peak current value (A), (b) RMS current value (A), and (c) maximum instantaneous increment (A) in the correction current.

Tab.1. Summary of absolute maximum values of correction current parameters (separated at the 7th harmonic).

Parameter / Value (A) / α (º)	Total correction current	Slow correction current	Fast correction current
Peak value	4,42 22	4,05 56	3,08 22
RMS value	2,49 46	2,36 46	0,81 30
Maximum instantaneous increment	6,09 30	0,09 42	6,00 30

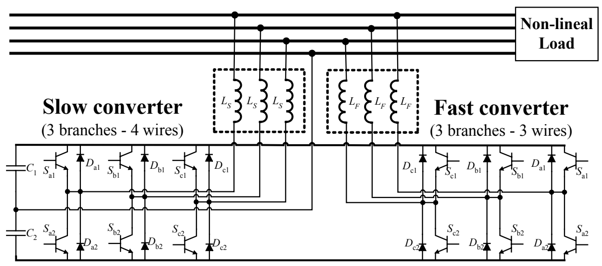


Fig.4. Proposed APLC based on two parallel converters topology.

2.2. APLC Topology

The topology of the proposed APLC is shown in Fig.4.

It consists in two parallel converters connected in parallel with the non-lineal load. Both converters present three branches and share a DC bus with middle point.

It could be assumed that the slow converter is a 3 branches – 4 wires and the fast converter is a 3 branches – 3 wires converter.

The three inductors of the slow converter could be of ferromagnetic core (because its low switching frequency, below 4 kHz) and the three inductors of the fast converter could not, because the switching frequency is high enough, so air core inductors might be used.

2.3. Simulation results

The simulation results produced by the system will be shown in this section. The parameters values used in the simulation are listed in Tab.2. Special attention has been put on the selection of the inductantes values [7].

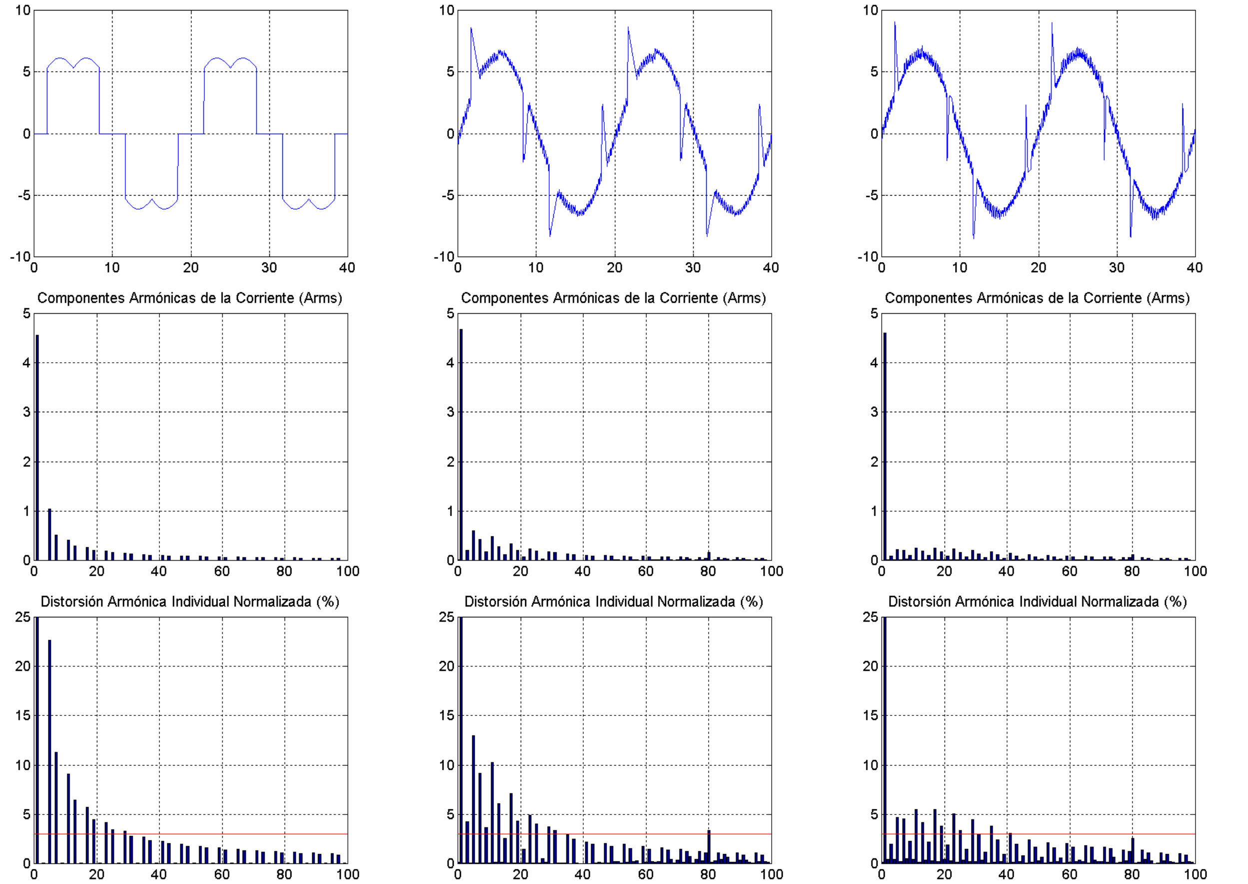
Tab.2. Values uses for the simulation of the APLC.

Parameter	Variable	Value
Phase-to-neutral supply voltage	V_S	230 V
Rectifier resistor load	R_L	88 Ω
DC bus voltage	V_{dc}	1000 V
DC bus capacitance	$C_1 = C_2$	3 mF
Slow converter inductance	L_{Slow}	70 mH
Fast converter inductance	L_{Fast}	40 mH

The control of the proposed APLC could be divided into three parts: control strategy (reference current determination), current control technique and switching signal generation.

The control or compensation strategy is voltage synchronisation [8,9]. This strategy determines the total correction current (slow plus fast). The collaboration strategy between the two converters is the following one: the slow one tries to correct the load current at the maximum of its possibilities. The fast converter helps the slow converter to comply with the correction that has not been done.

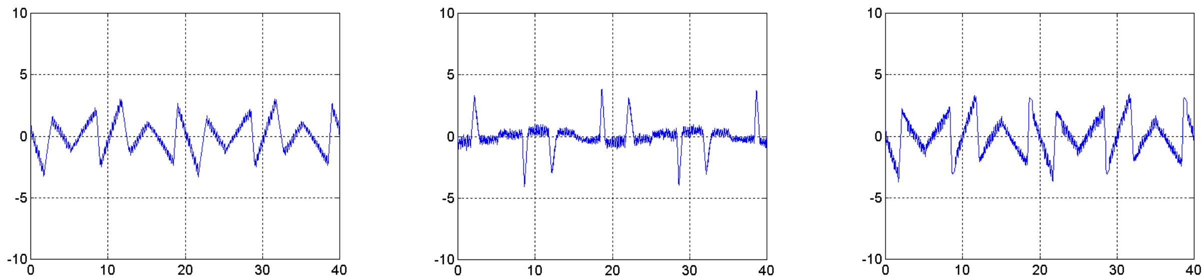
In this way, it is not necessary a filter to separate the low order harmonics from the high order ones and the



(a)		(b)		(c)	
DAT%	*30,80*	*DAT%*	*25,93*	*DAT%*	*18,66*
$DA_{hmax}\%$	*22,67*	$DA_{hmax}\%$	*12,96*	$DA_{hmax}\%$	*5,53*
h_{max}	*5*	h_{max}	*5*	h_{max}	*11*

(a) (b) (c)

Fig.5. Waveforms, frequency spectra (absolute and relative), and harmonic distortion indexes for α=0°: (a) load current, (b) supply current with the operation of the slow converters alone, (c) supply current with the operation of the two converters.



(a) (b) (c)

Fig.6: Simulated current waveforms for α=0°: (a) slow correction current, (b) fast correction current, (c) total correction current (adding both of them).

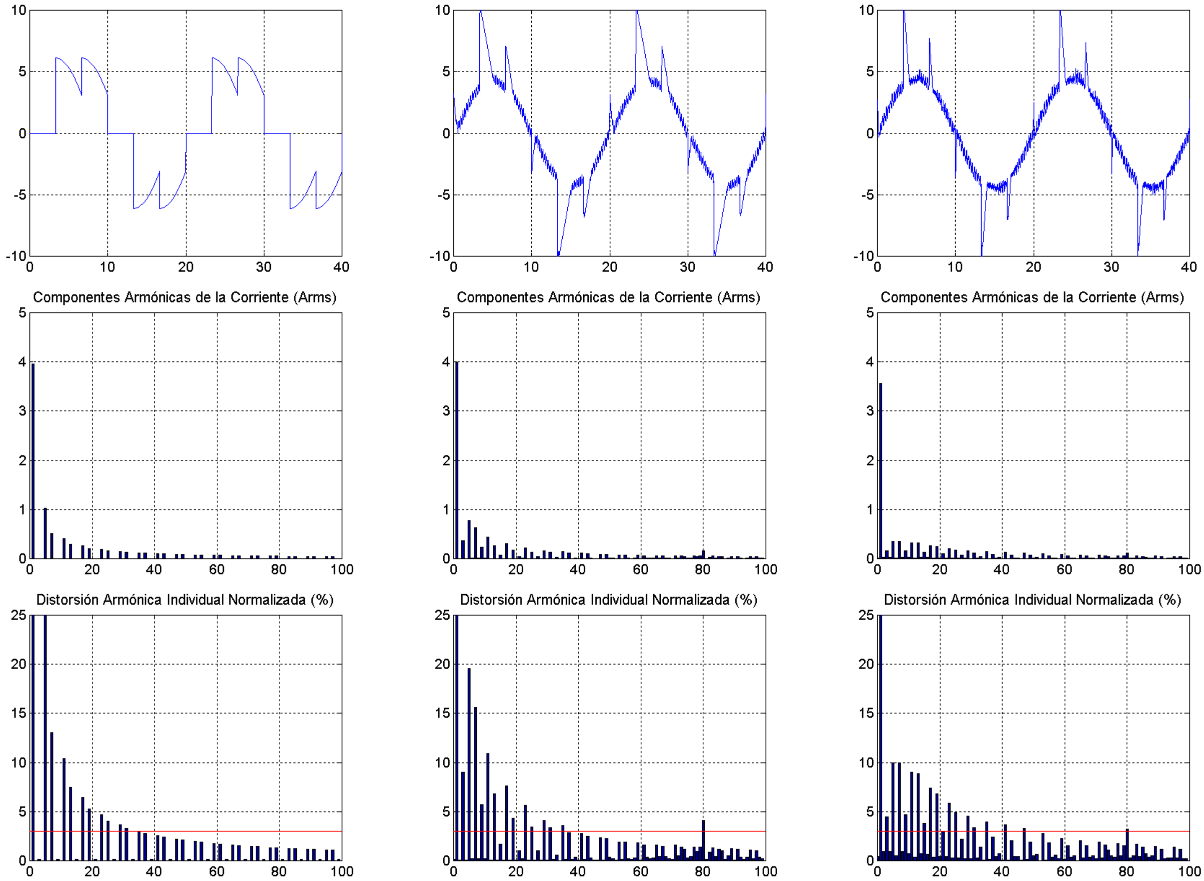
number of measurements is reduced because it is not necessary to measure the slow converter current.

The current control technique used in the APLC is based on a modified dead-beat control [10,11] for taking into accounts the collaborative operation of both converters.

The collaborative control algorithm of both converters is done in three steps.

The total duty cycle that must be applied in order to cancel the tracking current error in one slow sample period is calculated in the first step.

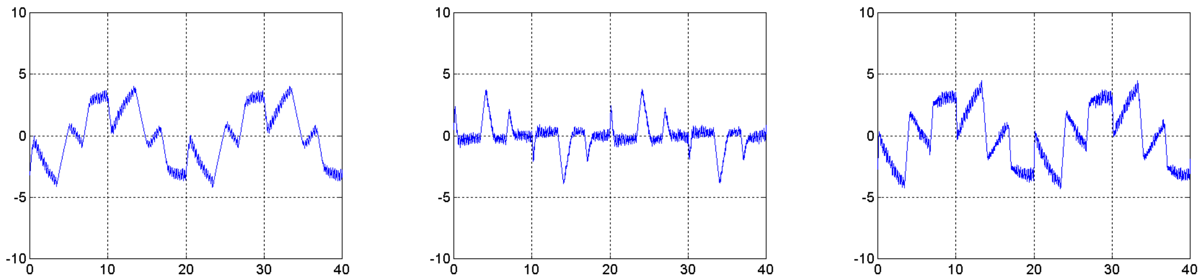
The duty cycle of the slow converter is determined in the second step. It will be taken into account that this converter uses a slow sample period and the saturation effect due to the fact that the duty cycles are limited to the interval (0,1).



DAT%	35,41	*DAT%*	34,67	*DAT%*	28,30
$DA_{hmax}\%$	26,03	$DA_{hmax}\%$	19,61	$DA_{hmax}\%$	9,98
h_{max}	5	h_{max}	5	h_{max}	7

(a) *(b)* *(c)*

Fig.7. Waveforms, frequency spectra (absolute and relative), and harmonic distortion indexes for α=30º: (a) load current, (b) supply current with the only operation of the slow converters, (c) supply current with the operation of the two converters.



(a) *(b)* *(c)*

Fig.8: Simulated current waveforms for α=30º: (a) slow correction current, (b) fast correction current, (c) total correction current (adding both of them).

Finally, the duty cycle of the fast converter is calculated in the third step, to compensate the difference between the total duty cycle (calculated at step one) and the one applied to the slow converter (step two).

With this collaborative operation the fast converter will produce the ramps that corresponds to the quick variations of the load current (that are over the slow converter capability).

The switching signal generation used in the APLC is a centre-aligned PWM at the corresponding switching frequency (slow or fast).

Simulation results are shown in Fig.5 and Fig.6 for a firing angle equals to 0 degree and in Fig.7 and Fig.8 for a firing angle equals to 30 degree.

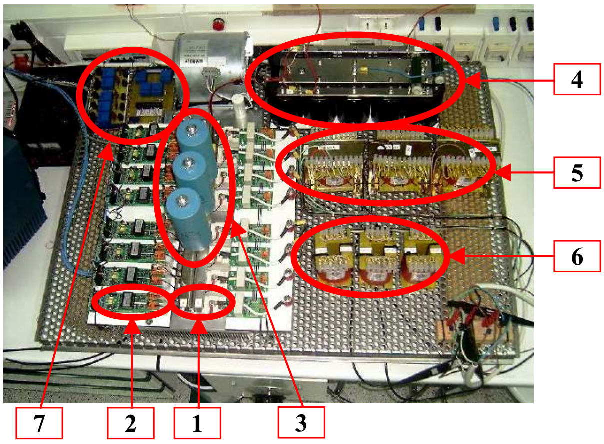


Fig.9. Proposed APLC based on two parallel converters topology: 1-IGBT modules, 2-drivers, 3-bipolar capacitors, 4-unipolar capacitors, 5-ferromagnetic coil inductances, 6-air coil inductances, 7-hall sensor based measurer boards.

Tab.3. Values uses for the prototype of the APLC.

Parameter	*Variable*	*Value*
Phase-to-neutral supply voltage	V_S	*230 V*
DC bus voltage	V_{dc}	*900 V*
DC bus capacitance	$C_1 = C_2$	*10 mF*
Slow converter inductance	L_S	*40 mH*
Fast converter inductance	L_F	*30 mH*
Slow switching frequency	$f_{s,slow}$	*4 kHz*
Fast switching frequency	$f_{s,slow}$	*20 kHz*

2.4. Experimental results

The proposed APLC topology is tested using a laboratory prototype (Fig.9) whose main characteristics are shown in Tab.3.

The control platform used in the prototype APLC is a dSPACE 1104, a standard real-time control platform.

The experimental results are shown in Fig.8.

2.5. Inductors analysis

Tab.4 is obtained from the analysis of the different current waveforms captured by an oscilloscope.

The most significant values of the filtering inductors used in the converters are summarised on Tab.5.

From this table it can be observed that the cooper wire section of the air core inductors is lower because the RMS current value has decreases from 0,47 A to 0,24 A, resulting in a reduction from 0,2 mm^2 to 0,1 mm^2, so it reduces the skin effect. In the same way the inductor volume decrease from 63,1 to 32,8 cm^3.

3. CONCLUSIONS

The proposed APLC is an alternative that allows to reduce the volume of the filtering inductors by the use of ferromagnetic cores and so the volume of the APLC. It has been shown how the collaborative topology could be controlled with a simple variation in the current control technique.

The reduction in filtering inductors will be more significant as much as the application power increase.

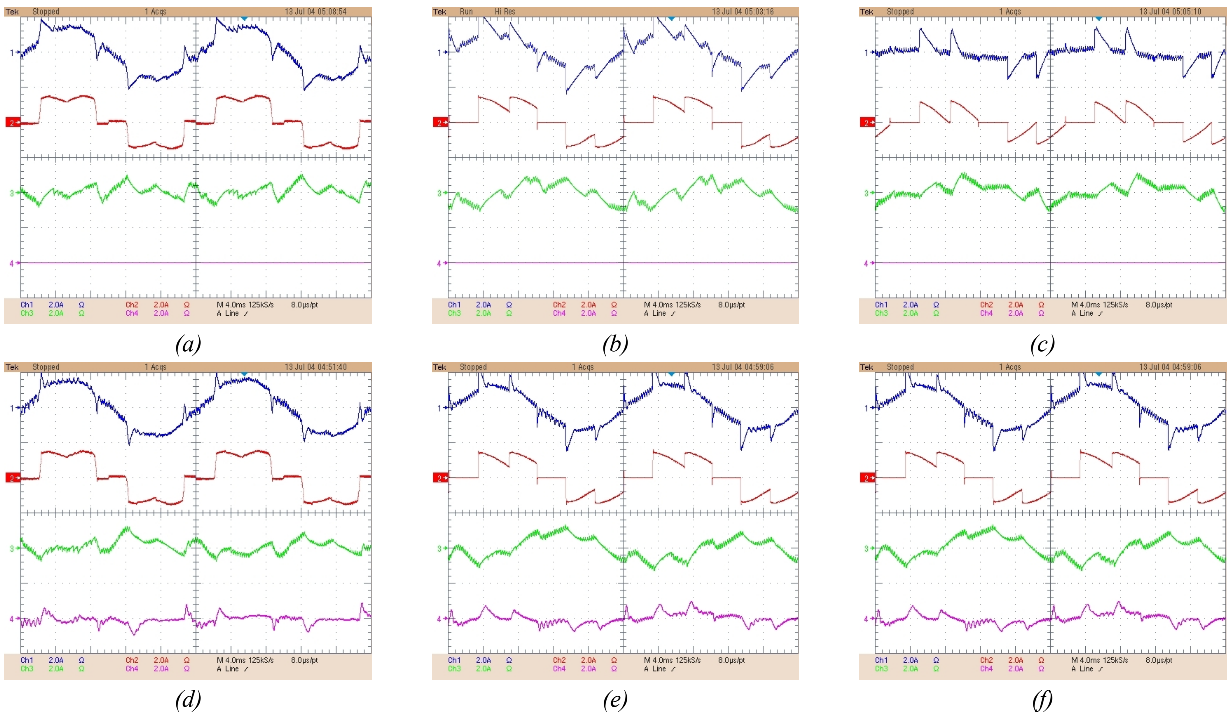


Fig.10: Experimental current waveforms showing from up to bottom: supply current, load current, slow correction current, fast correction current. (a) α=0º - fast corrector off, (b) α=30º - fast corrector off, (c) α=60º - fast corrector off, (d) α=0º - fast corrector on, (e) α=30º - fast corrector on, (f) α=60º - fast corrector on.

Tab.4. Resume of the most significant measures of the current waveforms.

	Current trough the filter inductor (A)	
Filter inductance of ...	*RMS value*	*Peak-peak value*
A conventional APLC operating with 20 kHz	*0,47*	*2,50*
Fast converter of the proposed APLC	*0,24*	*1,63*
Slow converter of the proposed APLC	*0,70*	*3,22*

Tab.5. Resume of the most significant dimensions of filter inductors: volume, cooper wire sections, total cooper weight and total iron weight.

Filter inductance of ...	V *(cm^3)*	S_{Cu} *(mm^2)*	P_{Cu} *(gr)*	P_{Fe} *(gr)*
A conventional APLC operating with 20 kHz	*63,1*	*0,2*	*264*	*0*
Fast converter of the proposed APLC	*32,8*	*0,1*	*118*	*0*
Slow converter of the proposed APLC	*33,9*	*0,3*	*50*	*140*

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