Low Cost High Power Factor Electronic Ballast to Supply Two Independent Lamps

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***Abstract*- This paper presents an alternative high power factor electronic ballast to supply two fluorescent lamps. A modified valley-fill filter provides power factor correction, which is efficient and cheap. A new arrangement of the lamps in the half bridge topology is done, putting one lamp in each switch of the converter. An analysis between typical ballasts and this is done. The advantages of this ballast are: if one lamp is damaged, the other keeps working; there is an efficiency improvement when compared to the ballasts that supply only one lamp; and the voltage supported by the switches is the half when compared to the conventional ballasts that supply two lamps.**

I. INTRODUCTION

With the proliferation of power devices in the market, regulatory agencies and power utilities are establishing stringent requirements on power quality of such devices. One such device that is flooding the consumer and commercial market is the electronic ballast to supply fluorescent lamps.

The use of electromagnetic ballasts to supply fluorescent lamps reduces the consumption of electrical energy when compared to incandescent lamps, because the former presents higher efficacy (lm/W), although they require large fixtures and ballasts [1].

The performance of fluorescent lamps is improved when they are supplied by electronic ballasts instead of electromagnetic ballasts, due to their merits, as high efficiency, low audible noise, longer lamp useful life, small size, light weight, and flicker absence. Fluorescent lamp operating with electromagnetic ballasts presents higher losses and flicker at a rate of 120 Hz [2] and [3].

Conventional electronic ballasts present low power factor because of the large capacitor after the rectifier bridge (C_B), to filter the voltage ripple. There are many methods to make the power factor correction, as to use the valley-fill filter instead the large capacitor.

II. CONVENTIONAL ELECTRONIC BALLAST

Conventional electronic ballasts are usually utilized to supply one fluorescent lamp. This circuit is composed of a rectifier bridge, and a filter capacitor, that can be represented by a V_{CC} source; high frequency driver, power switches, load filter, and lamp. This circuit is shown in Fig. 1 (a) [4].

III. TWO LAMPS CONVENTIONAL ELECTRONIC BALLAST

Fig. 1. (b) shows conventional electronic ballast circuit to supply two fluorescent lamps in series. It brings the disadvantages of electronic ballast operation dependent on the two lamps, decreasing the reliability, although the LCC filter is the same to supply both lamps.

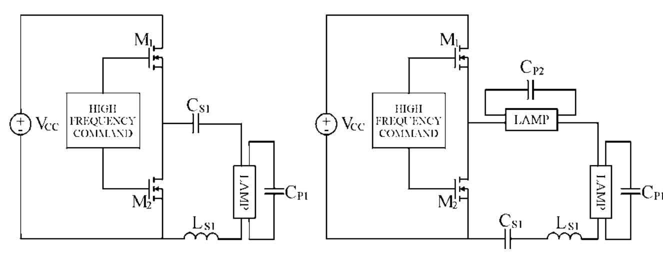
This circuit, compared to the circuit that supplies only one lamp, has to increase the voltage in the V_{CC} source to keep the same lamp power. So, the switches have to support higher voltage, demanding switches more robust and increasing the conduction losses in these elements. Also, if one lamp is out of order, other lamp does not work.

But, if the high frequency driver losses remain the same than the circuit of the Fig. 1 (a), the efficiency of this ballast increases.

IV. WORK PURPOSE

The purpose of this work is to ally the advantages of the two former ballasts: lower V_{CC} voltage applied over the circuit switches of the Fig. 1 (a), and the better ballast efficiency of the Fig. 1(b).

The idea for this new arrangement of the lamps in the circuit was born by the followed question: Why do not use one lamp in each switch of the ballast? Thus, the efficiency is similar to Fig 1 (b), lamp power and voltage in the V_{CC} source is the same than Fig. 1 (a), and the lamps are independent. This circuit is shown in Fig. 2.



(a) (b)

Fig. 1. Conventional lamp arrangements

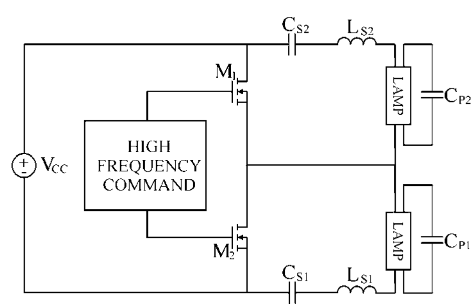


Fig 2 – New arrangement of two independent lamps

V. LCC Filter Design

The LCC filter design is based on [5]. This method consists on choosing the correct phase angle (ϕ) of the LCC filter that concerns the lamp starting and the correct lamp power in steady state.

This analysis is done to one of the lamps, and the other uses the same values.

The phase angle is determined by (1):

$$\phi = \tan^{-1}\left[\omega R^{-1}\left(L - C_S^{-1}\omega^{-2}\right)\left(1 + C_P^2 R^2 \omega^2\right) - R^2 C_P\right] , \qquad (1)$$

where R is the lamp resistance, $\omega = 2\pi f_S$, and ϕ is the filter impedance phase angle.

In this approach the fundamental approximation is employed. The components are linear and the load (lamp) is modeled as a resistor.

Based on LCC filter phase angle (1), it is possible to solve L_S, C_S, and C_P values. Therefore, the design methodology of the resonant filter components is made by the following procedures:

A. Calculation of C_P Value:

Parallel capacitor value can be found by (2):

$$C_P(\phi) = \frac{1}{\omega R V_{rms}^2}\sqrt{\frac{P}{R}\left(R^2 + \left(R \cdot \tan(\phi)\right)^2\right) - 1} \qquad (2)$$

B. Calculation of L_S Value:

By choosing an usual C_S value, series inductor value can be found by (3):

$$L(\phi) = \frac{R\tan(\phi)\omega^{-1} + C_P(\phi)R^2}{1 + \omega^2 C_P^2(\phi)R^2} + \frac{1}{C_S \omega^2} \qquad (3)$$

C. Phase Angle ϕ:

To provide the lamp starting voltage, nominal power in steady-state, operation with zero-voltage switching (ZVS), and to obtain lower switching losses as ϕ decreases to zero degree [6], ϕ can be graphically obtained, by plotting P versus ϕ, considering the power in the lamp starting and steady state by:

$$P(\phi) = \frac{V_{rms}^2 R\left(1 + \omega^2 C_P^2(\phi) R^2\right)}{R^2 + \omega^2\left[\left(L(\phi) - \frac{1}{C_S \omega^2}\right)\left(1 + \omega^2 C_P^2(\phi) R^2\right) - R^2 C_P(\phi)\right]} \qquad (4)$$

Procedures above allow the requirements to correct lamp operation, guaranteeing a sinusoidal waveform with low harmonic distortion and low crest factor, what is necessary to increase the lamp useful life.

VI. Power Factor Correction

Conventional electronic ballast presents great results in terms of efficiency and crest factor. But, it presents poor results of input current THD, and low ballast power factor. Using an active power factor correction method (e.g.: boost converter) is not the best solution, because it depends on the load (without feedback) and this ballast is being designed to supply one or two lamps. So, the solution is to use a passive power factor correction method as the modified valley-fill filter, which is independent of the load [7].

Typical electronic ballasts have a rectifier bridge followed by an electrolytic energy storage capacitor to provide a smooth DC voltage to the subsequent high frequency resonant driving the lamp. A circuit, referred to as valley-fill, attempts to address high power-factor, low THD and high efficiency. Fig. 3 is the basic diagram and waveforms of the modified valley-fill circuit.

This circuit is composed of two electrolytic capacitors (C_{B1}, C_{B2}), three rectifying diodes ($D_5 \sim D_7$). Around the line peak, C_{B1} and C_{B2} are charged through D_6 to half the peak line voltage. As long as the line voltage remains above each capacitor voltage, the line supplies the ballast directly. When the line voltage falls bellow each capacitor voltage, i.e., valley voltage, bridge rectifier diodes are reverse-biased, and D_5 and D_7 conduct to feed the ballast. Resistor R improves the ballast power factor.

VII. EMI Filter

Modified valley fill filter provides a high power factor, improving the line current waveform decreasing its THD. But, this circuit does not have EMI filter to filter EMI generated by the switches switching.

So, it’s necessary to use an EMI filter to solve this problem. There are many EMI filters in the literature, as: π filter, T filter, R-C shunt filter, L filter, and others [8].

We choose L type; it is the most often used filter. Both, π and T are composed of three element, or more if multiples are used, and should give 18 dB loss per octave. The L, because it has only two elements, provides 12 dB per octave. All these loss figures refer to the loss starting above the cutoff frequency. A single L often works better in the dc mode if the load has switchers, because a large L would face the dc supply and the large capacitor would provide low impedance for the switcher frequency.

This cutoff frequency should be at least 50 times bigger than the line frequency. We choose 10 kHz, four times smaller than switching frequency (40 kHz). Component values of LC filter are calculated by (5) and the circuit is shown in Fig. 4.

$$f_{cutoff} = \frac{1}{2\pi\sqrt{L_F C_F}} , \qquad (5)$$

where L_F is the filter inductor, and C_F is the filter capacitor.

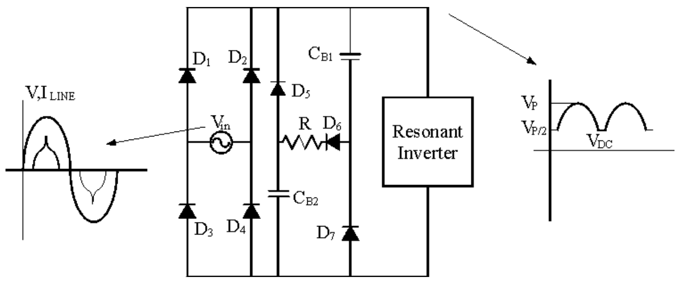


Fig. 3. Modified Valley-Fill Topology

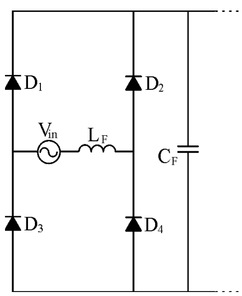


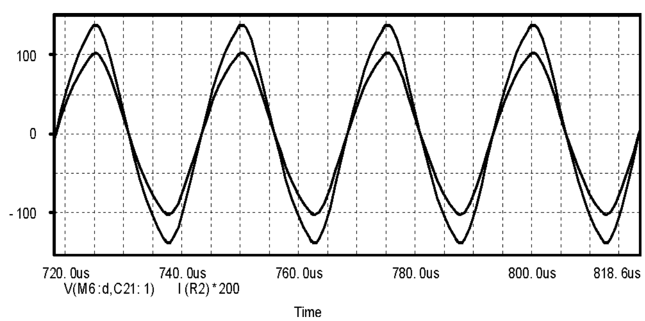
Fig. 4. EMI filter

VIII. Simulation Results

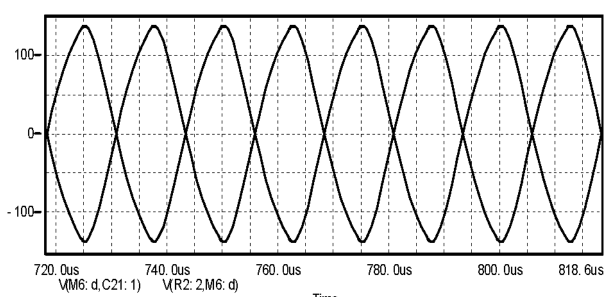
Some simulations were carried out in order to verify the ballast behavior under steady state operation and lamp starting, power factor correction, and EMI filter results.

Fig. 5 (a) shows sinusoidal voltage and current in one of the lamps, (b) voltage in each lamp of the ballast, (c) voltage and current in one of the switches, and (d) lamp starting with the other lamp already in steady state.

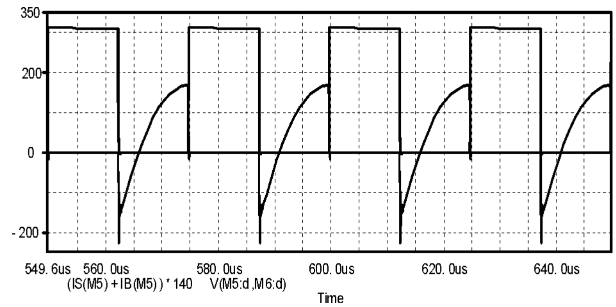
Fig. 6 shows the power factor correction using valley fill filter (a) without EMI filter, and (b) using EMI filter.



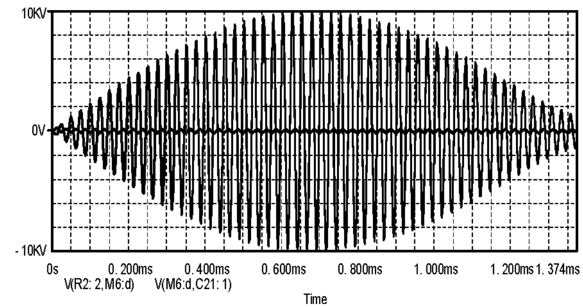
(a) Voltage and current in one of the lamps



(b) Voltage in each lamp of the ballast

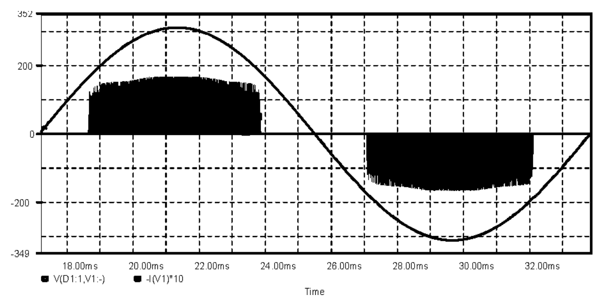


(b) Voltage and Current in one of the switches

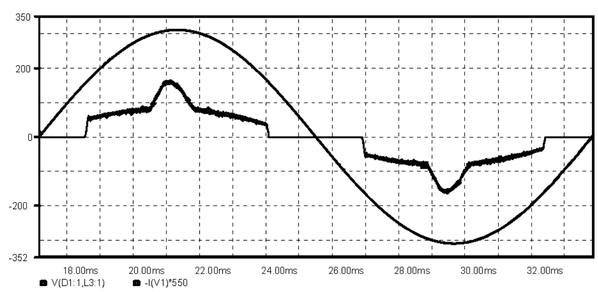


(d) Lamp starting

Fig. 5. Simulation results



(a) Line voltage and current without EMI filter



(b) Line voltage and current using input L filter

Fig. 6. Power factor correction simulation results

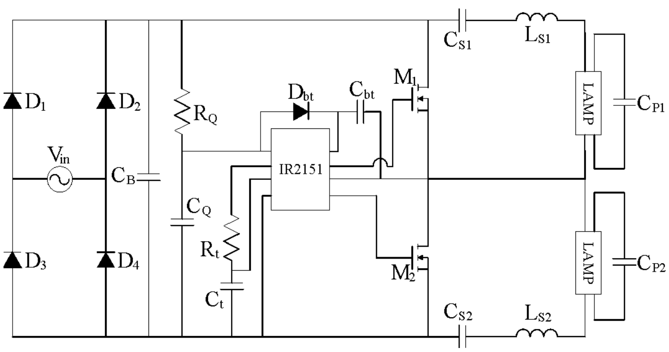
IX. Design Procedure

Three prototypes were carried out in order to verify the new arrangement of the lamps behavior, power factor correction and EMI filter. At first, a prototype without power factor correction was done, to verify if the new arrangement of the lamps, this circuit is shown in the Fig. 7 (a).

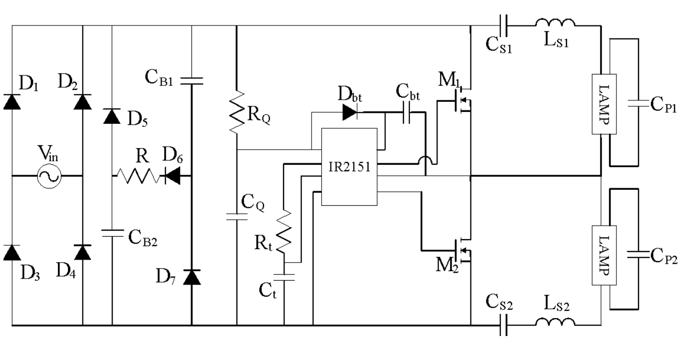
Fig. 7. (a) shows prototype without power factor correction, which brings good results in lamp supply, but has a poor power factor. So, a prototype with power factor correction by the valley fill filter was carried out, this circuit is shown in the Fig. 7 (b).

The prototype with power factor correction showed good results on the lamp supply and high power factor, but it doesn't have EMI filter. The prototype with power factor correction and EMI filter is shown in the Fig. 7 (c).

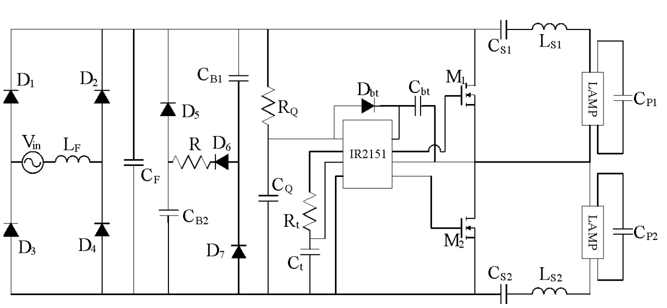
To define the component values were used (1), (2), (3), (4) and (5). We choose the driver IR 2151 to do the high frequency command, and the switching frequency (f_s) is 40 KHz. All the prototype circuit values are summonsed in table 1. In this table the prototypes are named as (a), (b) and (c), referring to Fig. 7.



(a) Prototype without power factor correction



(b) Prototype with power factor correction using valley fill filter and without EMI filter



(c) Prototype with power factor correction using valley fill filter and EMI filter using L filter type

Fig. 7. Prototypes built

TABLE I
PROTOTYPE CIRCUIT VALUES

Parameters	(a)	(b)	(c)
V_{in}	220 V_{ac} @ 60 Hz	220 V_{ac} @ 60 Hz	220 V_{ac} @ 60 Hz
$D_1 - D_7$	1N4007	1N4007	1N4007
D_{bt}	UF4007	UF4007	UF4007
C_B	22 μF / 350 V	-	-
$C_{B1} - C_{B2}$	-	22 μF / 200 V	22 μF / 200 V
C_F	-	-	68 nF / 400 V
C_Q	33 μF / 25 V	33 μF / 25 V	33 μF / 25 V
C_t	10 nF / 25 V	10 nF / 25 V	10 nF / 25 V
$C_{S1} - C_{S2}$	150 nF / 250 V	150 nF / 250 V	150 nF / 250 V
$C_{P1} - C_{P2}$	10 nF / 600 V	10 nF / 600 V	10 nF / 600 V
C_{bt}	100 nF / 30 V	100 nF / 30 V	100 nF / 30 V
R_Q	56 kΩ / 2 W	56 kΩ / 2 W	56 kΩ / 2 W
R_t	2.5 kΩ / 0.25 W	2.5 kΩ / 0.25 W	2.5 kΩ / 0.25 W
R	-	22 Ω / 1 W	22 Ω / 1 W
$L_{S1} - L_{S2}$	1.6 mH	1.3 mH	1.3 mH
L_F	-	-	2 mH
Driver	IR2151	IR2151	IR2151
M_1, M_2	IRF 730	IRF 730	IRF 730
f_s	40 kHz	40 kHz	40 kHz

X. EXPERIMENTAL RESULTS

Some experimental results were done in order to verify the prototypes of the Fig. 7 behavior. Fig. 8 presents the experimental results from the prototype of the Fig. 7 (a), were: (a) High frequency voltage and current in each lamp (50 V/div; 200 mA/div), (b) Voltage and current envelopment in each lamp (100 V/div; 200 mA/div), (c) Line voltage and current (100 V/div; 1 A/div), and (d) lamp starting (250 V/div).

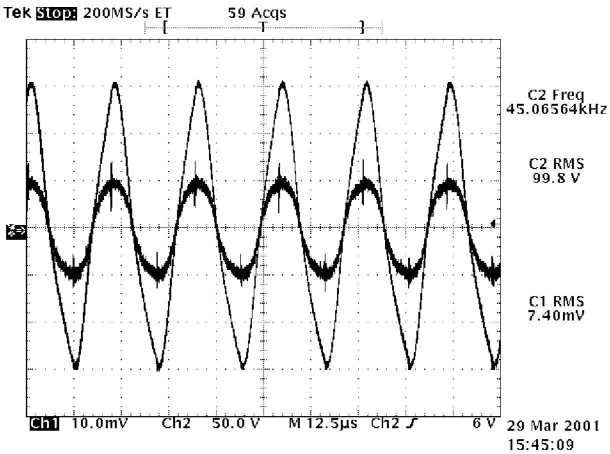
Fig. 9 presents the experimental results from the prototype of the Fig. 7 (b), were: (a) High frequency voltage and current in each lamp (50 V/div; 200 mA/div), (b) Voltage and current envelopment in each lamp (100 V/div; 200 mA/div), (c) Line voltage and current (100 V/div; 500 mA/div), and (d) lamp starting (250 V/div).

Fig. 10 presents the experimental results from the prototype of the Fig. 7 (c), were: (a) High frequency voltage and current in each lamp (50 V/div; 200 mA/div), (b) Voltage and current envelopment in each lamp (100 V/div; 200 mA/div), (c) Line voltage and current (100 V/div; 200 mA/div), and (d) lamp starting (250 V/div).

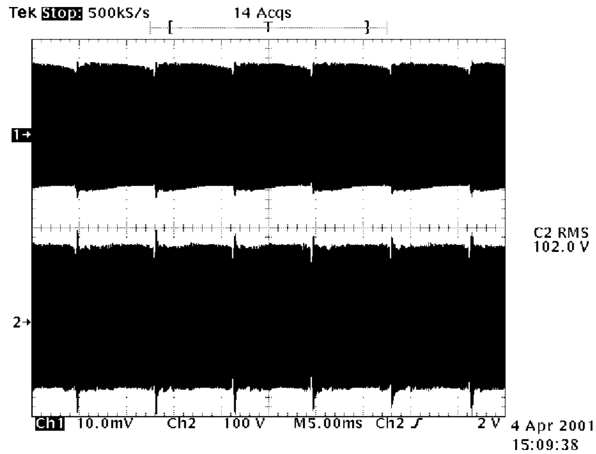
High frequency voltage and current in each lamp shows that the LCC filter have a correct design, because of the sinusoidal waveform of both. Voltage and current envelopment were verified to show the low crest factor in the lamps. Line voltage and current shows the power factor correction and EMI filter behavior.

Table 2 shows the measurement results of input power, lamp power, ballast efficiency, input current THD, power factor and crest factor to the ballasts of the Fig. 7. (a), (b) and (c); supplying one or two lamps.

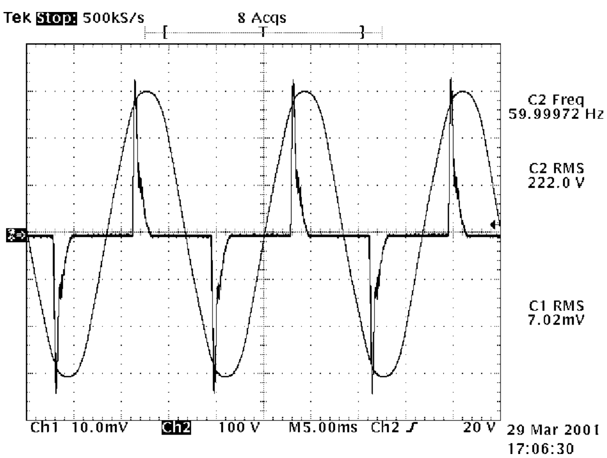
Measures with only one lamp were done to compare the ballast efficiency of the proposed work to the conventional electronic ballasts that supply only one lamp.



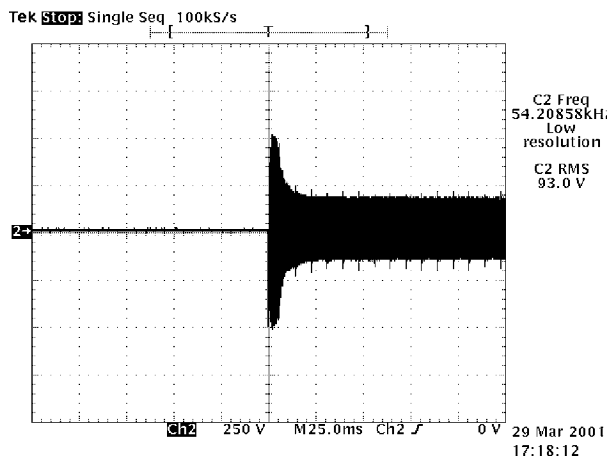
(a) Voltage and current in each lamp (50 V/div; 200 mA/div)



(b) Voltage and current envelopment in each lamp (100 V/div; 200 mA/div)

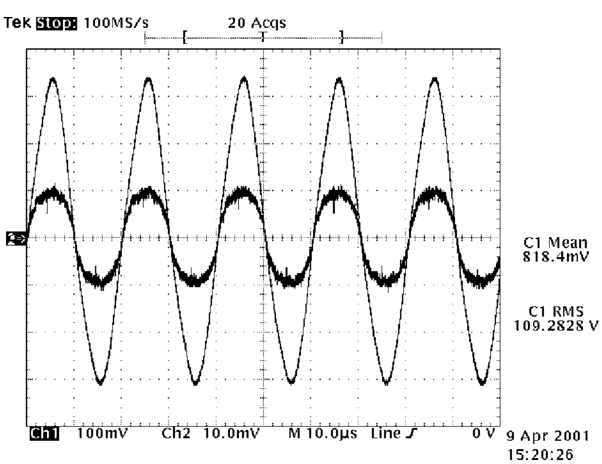


(c) Input voltage and current (100 V/div; 1 A/div)

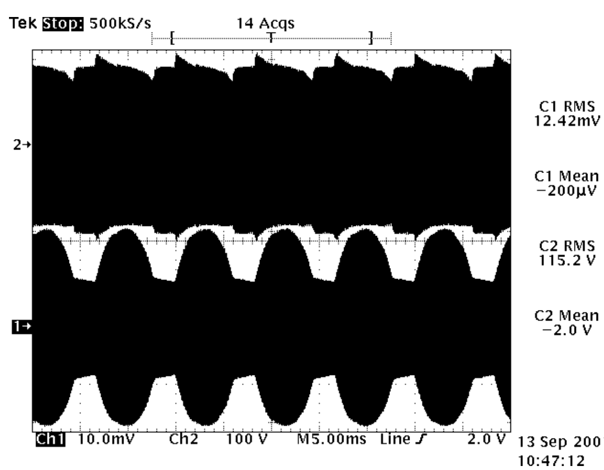


(d) lamp starting (250 V/div)

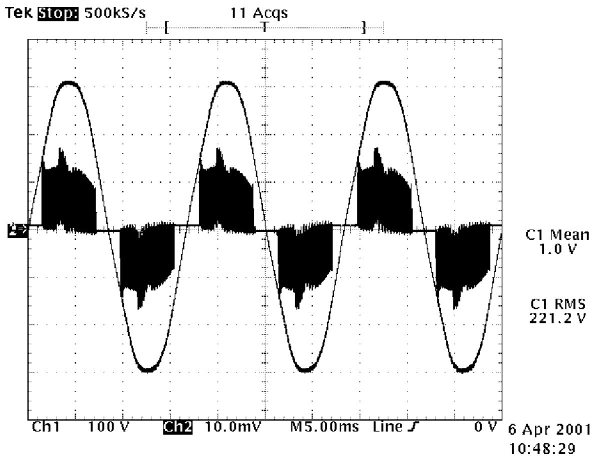
Fig. 8. Obtained waveforms from the prototype of the Fig. 7 (a)



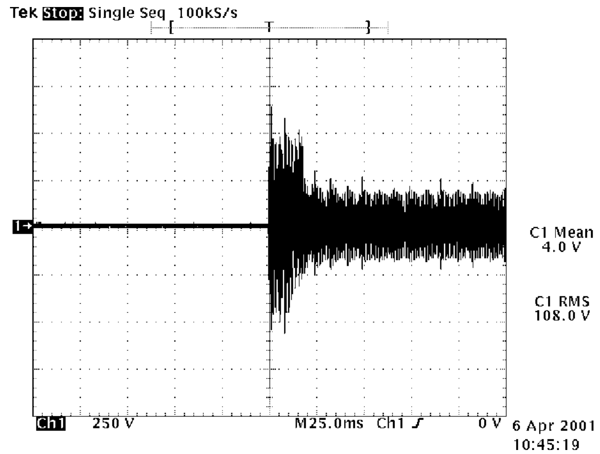
(a) Voltage and current in each lamp (50 V/div; 200 mA/div)



(b) Voltage and current envelopment in each lamp (100 V/div; 200 mA/div)

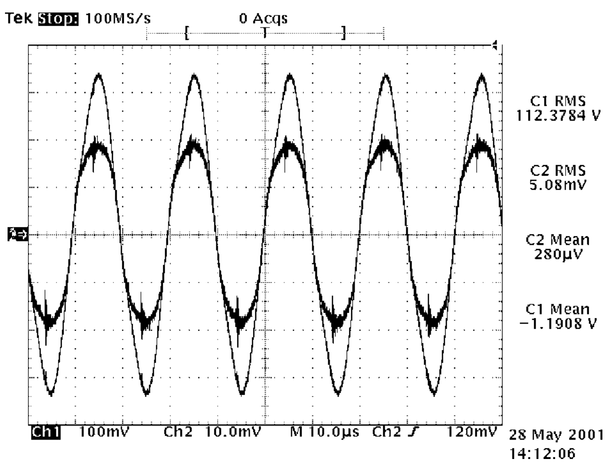


(c) Input voltage and current (100 V/div; 500 mA/div)

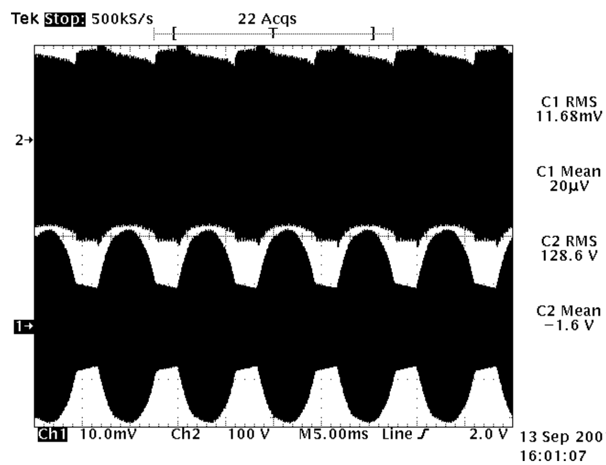


(d) lamp starting (250 V/div)

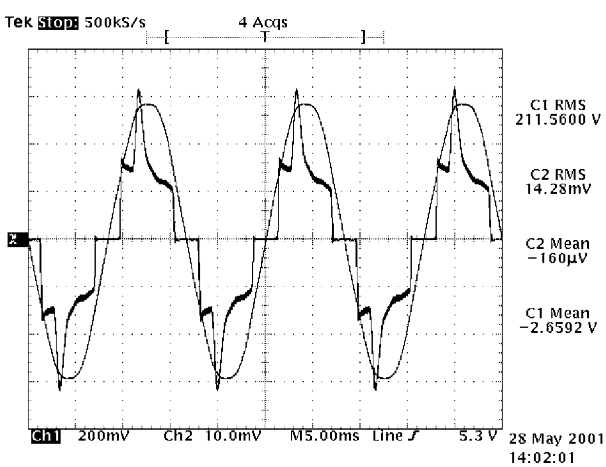
Fig. 9. Obtained waveforms from the prototype of the Fig. 7 (b)



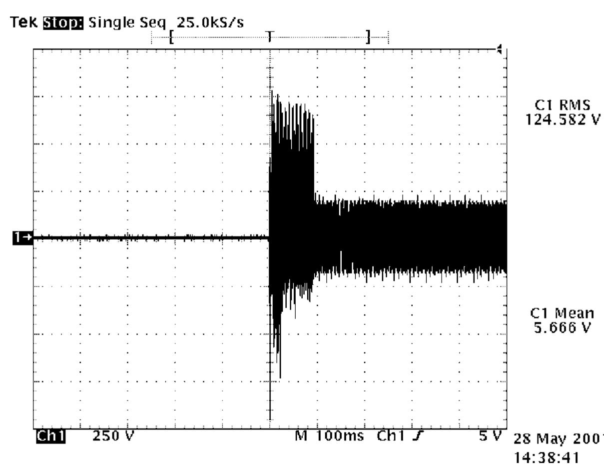
(a) Voltage and current in each lamp (50 V/div; 200 mA/div)



(b) Voltage and current envelopment in each lamp (100 V/div; 200 mA/div)



(c) Input voltage and current (100 V/div; 200 mA/div)



(d) lamp starting (250 V/div)

Fig. 10. Obtained waveforms from the prototype of the Fig. 7 (c)

TABLE II
COMPARATIVE EXPERIMENTAL VALUES

Prototypes:	(a) 2 lamps	(a) 1 lamp	(b) 2 lamps	(b) 1 lamp	(c) 2 lamps	(c) 1 lamp
input power (W)	67.92	35.93	65.18	39.62	65.26	35.5
lamp power (W)	32.63+32.19=64.82	33.27	30.05+29.76=59.81	35.7	29.67+29.71=59.34	31.87
efficiency (%)	95.4	92.6	91.76	90.1	91	89.7
THD (%)	179	200	34	33.5	29	27
power factor	0.46	0.43	0.934	0.937	0.95	0.953
crest factor	1.6 and 1.59	1.46	1.75 and 1.78	1.72	1.85 and 1.83	1.79

XI. DISCUSSION

The improved arrangement of the lamps in the half-bridge topology, power factor correction by the valley fill filter, and EMI filter presented several vantages:

- It's a low cost ballast to supply a great lamp power ($\approx$ 60 W), with a high power factor ($\approx$ 0.95) and a low crest factor ($\approx$ 1.6);

- Comparing to conventional electronic ballast (supplying 1 lamp), it has an efficiency increase (92.6 % $\Rightarrow$ 95.4 %, 90.1 % $\Rightarrow$ 91.76 %, and 89.7 % $\Rightarrow$ 91 %);

- It's not necessary to increase the V_{CC} voltage (V_{CB}) to keep the same power on the two lamps. So, it is not necessary to use switches with higher nominal rates (higher voltage), and the conduction losses in these elements are decreased.

- When one of the lamps is out of order, other lamp remains in operation. It is a better characteristic than the conventional electronic and electromagnetic ballasts, because if one lamp is damaged is easier to see which lamp is damaged and to change only one of the lamps.

- As we can see on Figs. 8 (c), 9 (c), and 10(c), when the power factor correction is done, the bridge diode peak current decreases from 3.2 A to 800 mA. And when the EMI filter is used, the bridge diode peak current decreases from 800 mA to 600 mA.

XII. CONCLUSION

We analyzed an improved arrangement of the lamps in the half-bridge topology, power factor correction by the valley fill filter, and EMI filter by L filter type. This arrangement concerns several vantages mentioned in the anterior item, these facts were observed in laboratory. These results show that it is a good alternative to replace the conventional electromagnetic ballasts.

LCC filter design is similar to one lamp filter design, it is just to repeat the found values to the other lamp. So, this ballast works as two independent ballasts, but increasing only the LCC filter components than the ballasts that supply only one lamp.

ACKNOWLEDGMENT

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