ELECTONIC BALLASTS WITH INTEGRATED STAGES AND HIGH POWER FACTOR APPLIED TO 250-WATT HIGH PRESSURE SODIUM LAMPS

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***Abstract* – This work shows the study of electronic ballast for 250W high pressure sodium lamps (HPS), where the power factor correction stage is integrated to the DC-AC converter. To provide more than one solution, it was developed a study of three different topologies. The main characteristic of the first structure (VS-CPPFC) is that it has almost unity power factor, with low crest factor and the power in the lamp is almost constant even with it's aging. For the second structure, (CIC-CPPFC) is the high efficiency, that occurs because the current in the load is the same of the power factor correction stage current. For the third structure is a combination of a double charge-pump and a half-bridge inverter which share the same switches operating in a complementary way. All the presented ballasts have high power factor and energy efficiency, which is improved by the zero-voltage switching technique. Experimental results obtained for the three structures are discussed.**

***Keywords* - Electronic ballast, High-Pressure Sodium Lamp, Power Factor Correction – PFC, Single Stage Charge Pump.**

I. INTRODUCTION

The majority of the AC sourced electronic equipment has an electronic converter to process energy. These converters have electronic switches that, during operation, distort the source current waveform increasing its harmonic content and decreasing the equipment power factor [1, 2].

Actually, around 30% of the electrical energy used worldwide is spent in the form of artificial illumination. In this context, the illumination based on HPS lamps corresponds to almost 20% of all available artificial light sources.

Due to its efficiency, the low correlated color temperature and the low color rendering index, these lamps have been widely employed in public illumination. This kind of lamp requires a high voltage to initiate the discharge and a ballast to limit the current given to the lamp, after the startup.

Electromagnetic ballasts operating at the AC power supply are been widely employed in limiting that current, as well the current flow through fluorescent lamps. Its main attractiveness refers to being simple and reliable structures. Nevertheless, several inconveniencies are present, such that the heaviness and high volume, the low power factor, low efficiency, poor power regulation, source voltage droppings sensitiveness and need an external igniter to generate the high voltage pulse.

To overcome these drawbacks, several researches [3, 7-14] have been conducted towards developing more effective electronic ballasts, mainly directed to fluorescent lamps purposes. Following this research topic, the unique-stage with high power factor electronic ballasts comes into spotlight.

There are much works that relate integration techniques between the input stage and the inverter stage of electronic ballast. Among the employed techniques, those who use the charge pump concept assume great importance [4, 5], with can be defined as: Charge Pumps are circuits that use charge storage elements that, operating at high frequencies or not, share the function of elevate the output voltage levels in some structures.

In electronic ballasts, charge-pump techniques are used to correct the power factor. Although widely spread at final 90'ies and beginning 2000, there are few works that use such technique in HPS lamps.

In this sense, this work has the objective of presenting a study related to the main electronic ballast structures that use the charge-pump technique applied to 250W HPS lamps.

In this work, three structures will be presented. Two of them are already totally dominated through the works, applied in fluorescent lamps, of QIAN and LEE [4, 5] known as "Voltage Source – Charge Pump Power Factor Correction" (VS – CPPFC) [11] and "Continuous Input Current – Charge Pump Power Factor Correction" (CIC-CPPFC) [8-10]. The third structure refers to the proposed structure in this work regarding the defined power level with a double charge-pump ballast [6-7].

II. VS-CPPFC TOPOLOGY

Fig. 1 presents the VS-CPPFC ballast [5].

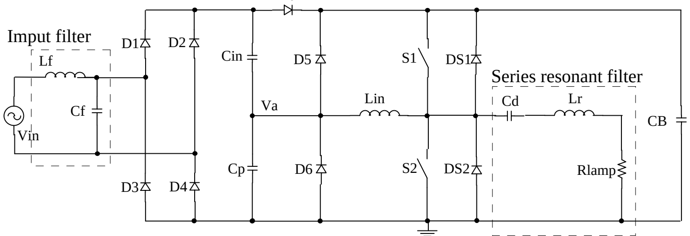

Fig. 1 – Power structure of the VS-CPPFC ballast.

The elements C_{in} and L_{in}, together with the input LC filter are responsible for the structure power factor correction, whilst C_d and L_r are responsible for blocking the continuous component and for limiting the current over the lamp. Diodes D_5 and D_6 are used for clamping the voltage V_a to the bus voltage and at zero, respectively. Capacitor C_p has the function of smoothing the high frequency voltage source Va. Considering the impedance of C_p much higher than that of C_{in}, the current through C_p can be neglected.

In this structure, the power factor correction stage do not rely on the resonant series filter current, only the power switches are shared by both stages. In this sense, the switches will be exposed to higher current effort and the ballast will be submitted to very high bus voltage variations, in contrast to the lamp equivalent-resistance parametric variations.

By means of an analysis of the structure one can obtain the equations that describe the values of the ballast main charge-pump parameters, i.e., C_{in} and L_{in}. In this sense, result:

$$C_{in} = \frac{2.P_{out}}{\eta.f_S.V_{inpk}^2} \quad (1) \qquad L_{in} = \frac{\eta.V_{inpk}^2}{32.f_S.P_{out}} \quad (2)$$

The equations that represent the input filter parameters and the output resonant series filter parameters will not be presented in this work. The design of such parameters are entirely dominated and spread into the references.

A. Experimental results of the VS-CPPFC ballast

The design data for the implementation of the ballast follows:

$P_{out} = 250W$ Lamp power;
$V_{in} = 220V$ RMS source voltage;
$V_{lampi} = 90.8V$ Lamp voltage at its beginning lifetime;
$V_{lampf} = 130V$ Lamp voltage at its ending lifetime;
$fs = 40kHz$ Switching frequency;
$fr = 60Hz$ AC source frequency;
$\eta = 0.8$ Estimated efficiency of the ballast;
$\Delta V_B = 15\%$ Bus voltage ripple;
$V_B = 420V$ DC bus voltage.

The calculated parameters of the ballast are:

C_{in} = 162nF and L_{in} = 242μH

C_B = 47μF; C_d=68nF; L_r = 472.14μH;

C_f = 100nF; L_f = 4.31mH; C_p= 1nF.

In this work, although implemented, the auxiliary circuits needed to guarantee the lamps to work properly will not be presented, such as: the lamp ignition circuit, the bus over voltage protection circuits (software and hardware protection), the design of the bootstrap circuit used as driver to the switches and the auxiliary supply that sources all these circuits.

In this work also, all acquisitions were done with new lamps and the obtained experimental results for the VS-CPPFC ballast are:

Pin (W)	Pout (W)	η(%)	Vout (V)	Iout (A)
300	258	86	87.6	2.992

Crest Factor	THD_I(%)	THD_V(%)	Power Factor
1.55	4.95	3.79	0.997

The measured ac input current and its harmonic spectrum are shown in Fig. 2 and Fig. 3, respectively. The line harmonic components, with a THD (Total Harmonic Distortion) of 4.95% and a 0.997 PF (Power Factor), complies IEC 61000-3-2 for Class C lighting applications.

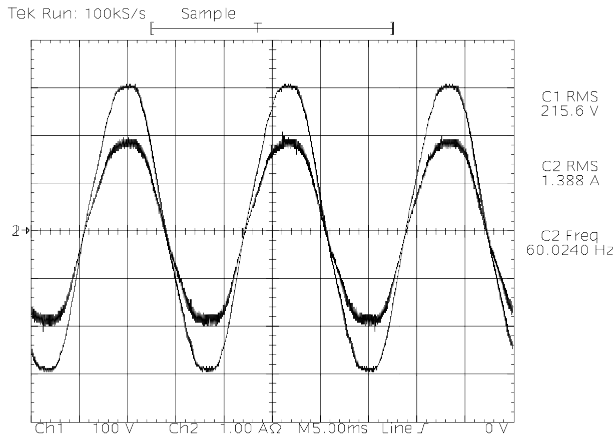

Fig. 2 – Ballast input voltage and current.

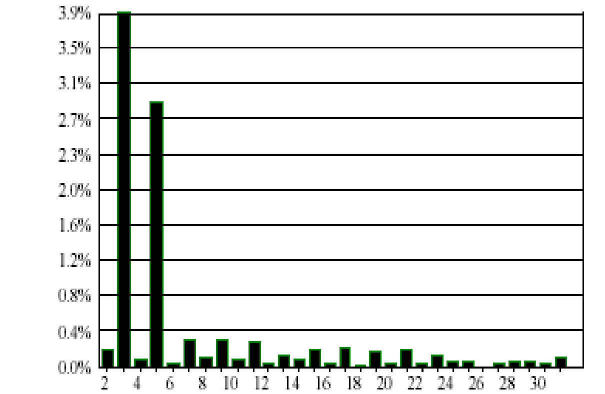

Fig. 3 – Harmonic components of the ac input current.

Fig. 4 shows the measured low frequency voltage and current in the lamp. The measured crest factor (CF) is 1.55.

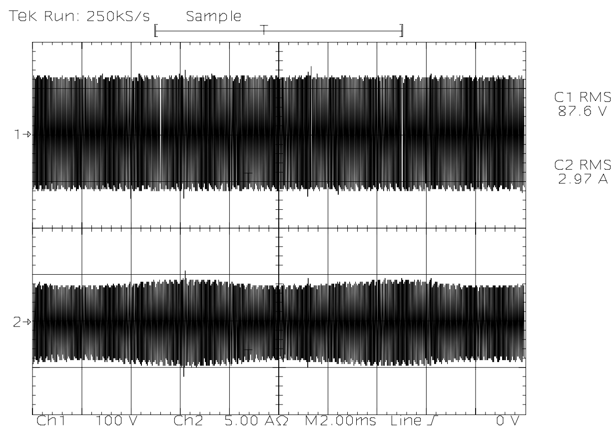

Fig. 4 – Low frequency voltage and current of the lamp.

Fig. 5 presents the high frequency voltage and current waveforms in the lamp. This show that the lamp operates like a resistance at high frequency.

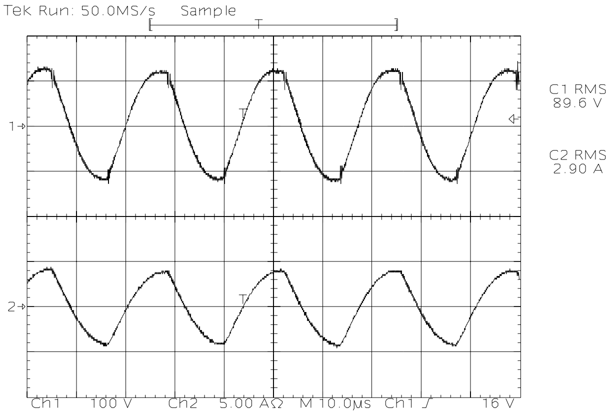

Fig. 5 – Voltage and current of the lamp at high frequency.

Fig. 6 shows the bus voltage ripple in steady-state.

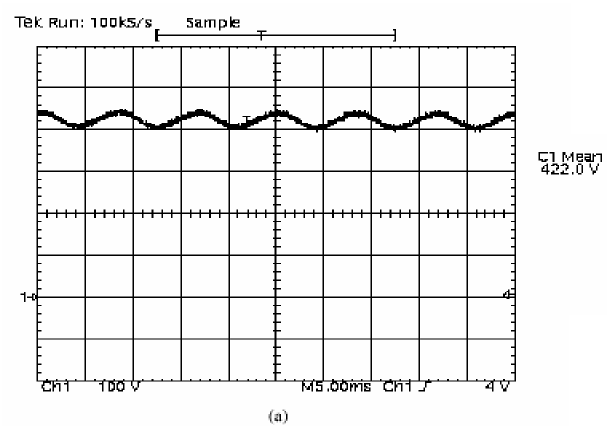

Fig. 6 – DC bus voltage.

III. CIC-CPPFC TOPOLOGY

The schematic diagram of the charge-pump CIC-CPPFC ballast is presented in Fig. 7 [5]. The ballast is formed by the integration of a half-bridge inverter, switches S_1 and S_2, diodes D_{S1} and D_{S2} and a PFC stage that, in turn, is formed by the capacitor C_{in} (charge pump) and the inductor L_{in}. In the inverter, both switches operate with a D=0.5 duty cycle, characterizing a symmetric operation. The inverter sources energy from the resonant LC series-filter, taking into account that the resonant inductor L_r is responsible to limit the lamp current and the capacitor C_d is responsible to block the continuous component.

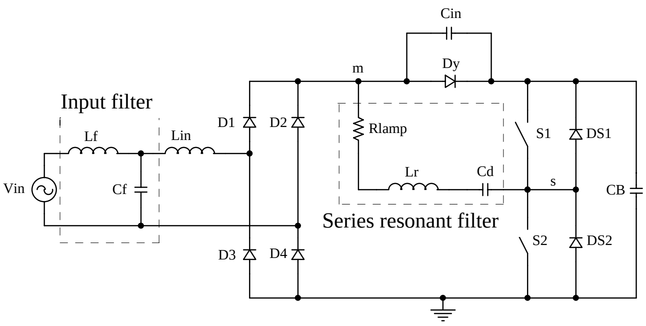

Fig. 7 – Power stage structure of the CIC-CPPFC.

In this topology, the loop capacitor C_{in} deviate part of the current from the resonant stage towards the input. This way, the nonlinear characteristics of the current in the rectifier diodes (D_1 up to D_4) are reduced resulting, as a consequence, a significant power factor increase. The inductor L_{in} decreases the input current ripple.

Analyzing the structure one can derive the equations that define the main parameters of the ballast, i. e.:

$$C_{in} = \frac{P_{out}}{\eta . f_S . V_{inpk}^{\ 2}} \quad (3) \qquad L_{in} = \frac{9.\eta . V_{inpk}^{\ 2}}{16.\pi^2 . f_S . P_{out}} \quad (4)$$

A. *Experimental Results of the CIC-CPPFC ballast*

For the ballast implementation the following design specifications were used:

$P_{out} = 250W$ Lamp power;
$V_{in} = 220V$ Supply voltage RMS;
$V_{lampi} = 90.8V$ Lamp voltage at its beginning lifetime;
$V_{lampf} = 130V$ Lamp voltage at its ending lifetime;
$fs = 30kHz$ Switching frequency;
$fr = 60Hz$ AC source frequency;
$\eta = 0.9$ Estimated ballast efficiency;
$\Delta V_B = 15\%$ Bus voltage ripple;

This way, the calculated parameters are:

C_{in} = 95.65μF and L_{in} = 662.04μH

C_B = 47μF; C_d = 200nF; L_r = 437.27μH;

V_B = 400V C_f = 120nF; L_f = 6.47mH.

The following experimental results were obtained:

Pin (W)	Pout (W)	η(%)	Vout (V)	Iout (A)
275	247	89.8	89.2	2.98

Crest Factor	THD_I(%)	THD_V(%)	Power Factor
1.963	8.92	3.44	0.995

Fig. 8 shows input voltage and input current. The measured power factor is 0.995.

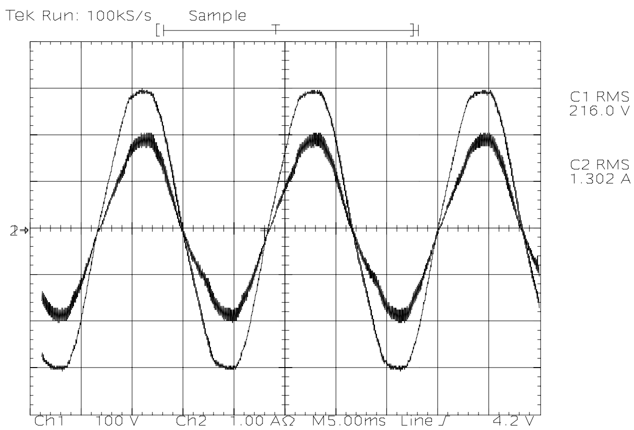

Fig. 8 – Input source voltage and current.

The measured line current harmonics are presented in Fig. 9. Each measured harmonic component meets the IEC 61000-3-2 Class C requirements.

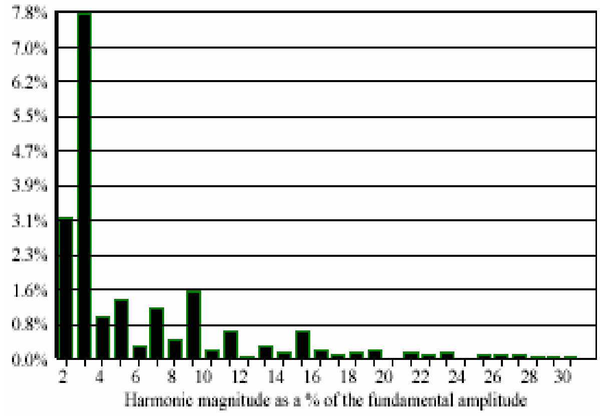

Fig. 9 – Measured line current harmonics.

Fig. 10 shows the measured voltage and current in the lamp where the measured crest factor (CF) is 1.963. Fig. 11 presents the voltage and current waveforms in the lamp.

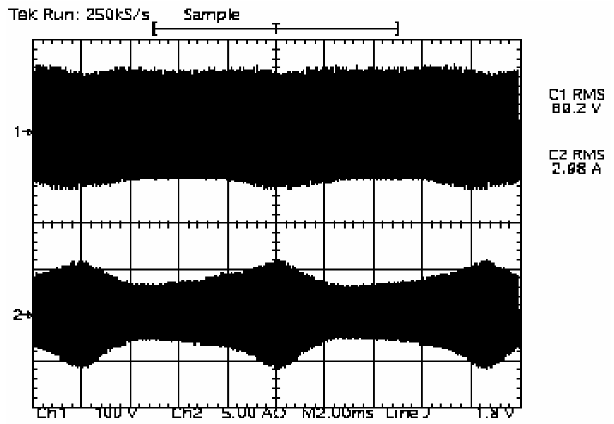

Fig. 10 – Low frequency voltage and current in the lamp.

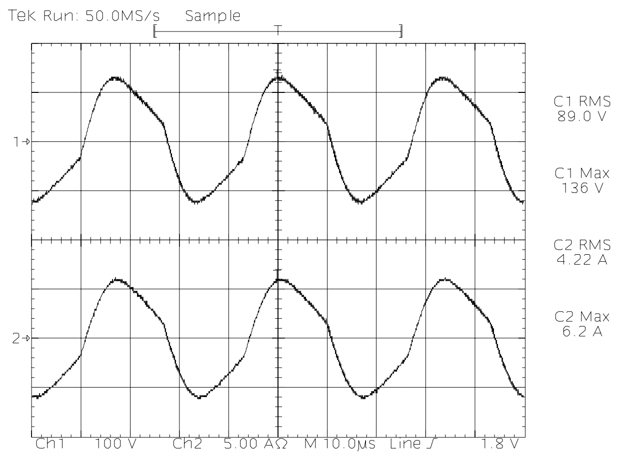

Fig. 11 - Hight frequency voltage and current in the lamp.

Fig. 12 shows the bus voltage ripple in steady-state.

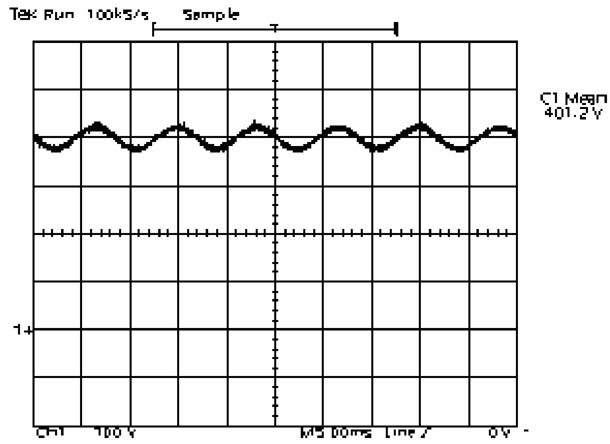

Fig. 12 – DC bus voltage.

IV. DOUBLE CHARGE-PUMP TOPOLOGY

The third ballast presented in this work is shown in Fig. 13 [6-7]. The main difference between this topology and the VS-CPPC and CIC-CPPFC ballasts is related to the direct connection of the stage that corrects the power factor, i. e., the capacitors C_{f1} and C_{f2} and the inductors L_{in1} and L_{in2} to the inverter stage. This direct connection, in addition to eliminating the input LC filter, makes the AC supply provide an instantaneous current to the ballast with double the switching frequency in the inverter stage, providing, this way, a considerable reduction in the input inductor L_f wich, in some applications, can be eliminated.

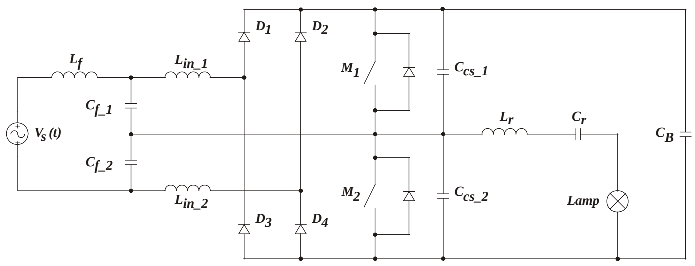

Fig. 13 - Power stage structure of the double charge-pump ballast.

Regardless the structure presented in Fig. 13 have a distinct configuration from that presented in Fig. 1 (VS-CPPFC), its operational characteristics are similar. This fact includes this topology in the VS-CPPFC ballasts group. However, due to the behavior of the power factor correction stage, it can be defined as being a double charge-pump ballast.

This configuration has also been used in some works directed to switched single stage high power factor power supplies [11]. Nevertheless, due to the need of a 0.5 duty cycle operation, its application is limited. For electronic ballasts, the 0.5 duty cycle operation is necessary for achieving a symmetric waveform over the lamp.

A. Experimental results of the proposed ballast

Through an analysis of the ballast presented in Fig. 13 [9], the parameters related to power factor correction (C_{in1}, C_{in2}, L_{in1} e L_{in2}) can be obtained:

$$L_{in1} = L_{in2} = \frac{V_p^{\,2} \cdot \eta}{16 \cdot f_s \cdot P_0} \quad (5) \qquad C_{f1} = C_{f2} = \frac{4 \cdot P_{out}}{\pi^2 \cdot f_s \cdot \alpha^2 \cdot V_p^{\,2} \cdot \eta} \quad (6)$$

For the ballast implementation, the following design specifications were used:

$P_{out} = 250W$ Lamp power;
$V_{in} = 220V$ RMS supply voltage;
$V_{lampi} = 90.8V$ Lamp voltage at its beginning lifetime;
$V_{lampf} = 130V$ Lamp voltage at its ending lifetime;
fs = 50khz Switching frequency;
$fr = 60Hz$ AC source frequency;
$\eta = 0.9$ Estimated ballast efficiency;
$\Delta V_B = 15\%$ Bus voltage ripple;
$\alpha = 0.3$ Switching and resonant frequencies relation.

This manner, the used parameters are:

$L_{in1} = L_{in2} = 440\mu H$ and $C_{f1} = C_{f2} = 220nF$

$C_B = 220\mu F$; $C_r = 47nF$; $L_r = 395\mu H$;

$V_B = 400V$; $L_f = 700\mu H$.

The soft-switching capacitors used in this experiment were the internal drain-source capacitors of the MOSFETs.

The following experimental results were obtained:

Pin (W)	Pout (W)	η(%)	Vout (V)	Iout (A)
285.8	259.6	90.8	96.8	2.7

Crest Factor	THD_I(%)	THD_V(%)	Power Factor
1.47	8.72	3.17	0.996

In Fig. 14 the ballast voltage and the input current are shown. The total THD of the input current is 8.72%, with no individual harmonics outside the bounds of IEC 61000-3-2 standard, in accordance to Fig. 15.

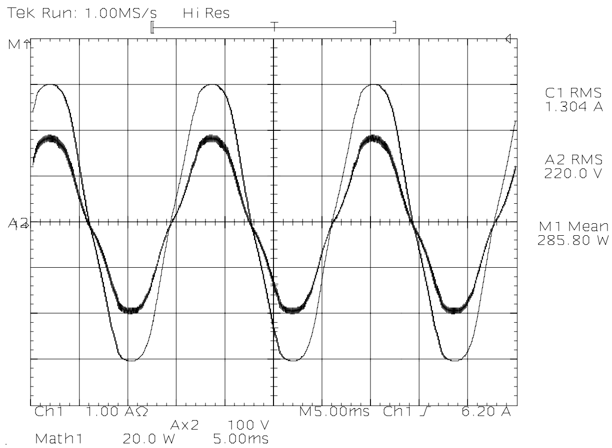

Fig. 14 – AC input source voltage and current.

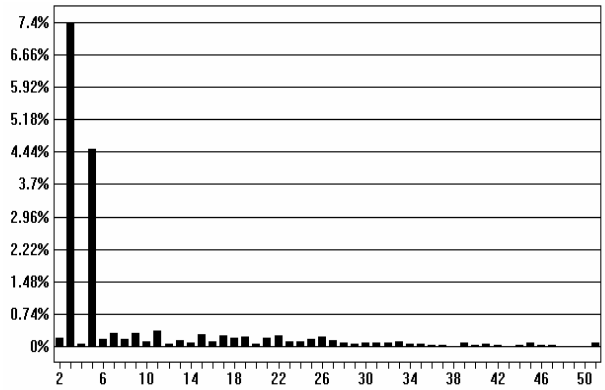

Fig. 15 – Harmonic spectrum of the ballast input current.

Fig. 16 shows the measured current in the lamp and the measured crest factor is 1.48.

Fig. 17 presents the lamp voltage and current at the switching frequency.

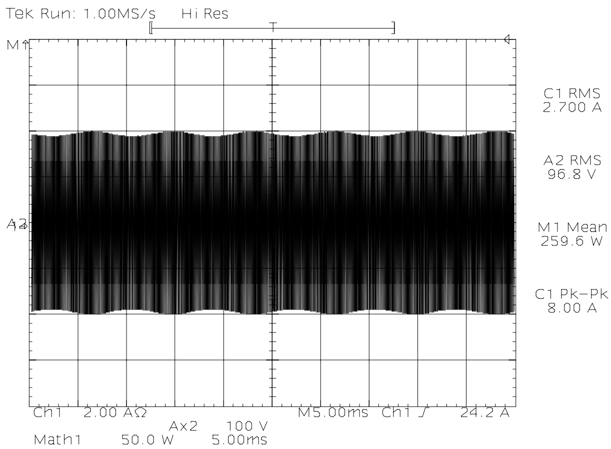

Fig. 16 – Low frequency Lamp's current waveform.

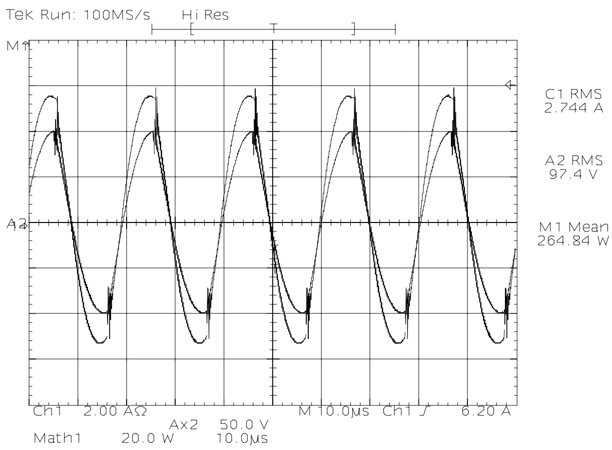

Fig. 17 – Lamp voltage and current at the switching frequency.

Fig. 18 presents the DC bus voltage at steady-state. No matter the voltage has been stabilized at 460V, during the start process its necessary that the switching frequency as well as the duty cycle of the switching driving pulses be low, to avoid this voltage to reach very high levels (typical VS-CPPFC ballasts characteristics) hindering the switches destruction.

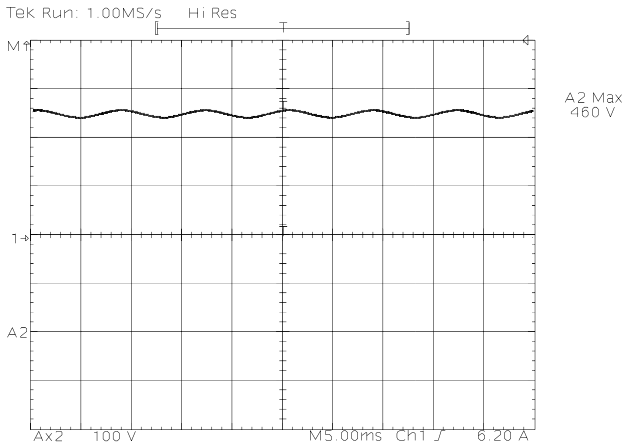

Fig. 18 – DC Bus voltage at steady-state.

V. RESULTS ANALYSIS

By means of studying and implementing the three mentioned structures in this work, some conclusions follow:

VS-CPPFC ballast - The VS-CPPFC ballast presented as main advantages the practically unity power factor together with the low THD, low crest factor and almost constant power over the lamp, faced to its aging. As drawback, we present the efficiency and the replication cost, compared against the results obtained in the other two structures.

CIC-CPPFC ballast - The main advantages presented by this structure are the high power factor, low THD (except its second harmonics), high efficiency and low replication cost. As drawback, there's a variation of the lamp power faced to its aging, presence of a second harmonics and high crest factor.

Double charge pump ballast - The proposed ballast demonstrated to aggregate the good characteristics of the CIC-CPPFC and VS-CPPFC ballasts, i.e., it is notable that, at an exception of THD, the proposed ballast presented the best characteristics related to the classic charge-pump ballasts, i.e., the efficiency is similar to the CIC-CPPFC ballast and the crest factor is similar to a typical VS-CPPFC.

With a efficiency over 90% together with the possibility control of the lamp power during all its lifetime (characteristic that only the VS-CPPFC ballasts can provide), it have a very attractive structure directed to a possible commercial application, not only to 250W lamps, but to 400W lamps too, because the MOSFETs (IRFP27N60K, used in this work) still withstand the inverter stage output current levels.

VI. CONCLUSIONS

This work realization has been extremely important in the sense of demonstrate that the employed techniques for the power factor correction of the studied ballasts, that since then were only applied to fluorescent lamps, can be successfully applied to other kinds of lamps, for example, the HPSs lamps.

The use of optimized topologies (few components, with weight and volume reduction), with high power factors, low crest factors and very high efficiency, show that such ballasts are extremely attractive to possible commercial applications. In this way, the analyzed ballasts represent a viable and low cost solution in a natural or maybe irreversible change in the electromagnetic ballasts that source the HPSs.

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