Abstract — In this paper is reported the study and implementation of a single stage, High Power Factor (HPF) electronic ballast for High Pressure Sodium (HPS) lamps using a LCC filter. In the recent years, many authors are working to obtain single stage HPF electronic ballast for fluorescent lamps [1] [2]. Normally, to obtain HPF in electronic ballast for high-pressure sodium lamps, a Power Factor Pre-regulator (PFP) is used between the mains and the electronic ballast [3]. The main idea of this work is to present a simple and low-cost electronic ballast with HPF for HPS lamps, which does not require an additional PFP converter. To get all this advantages the price to be paid is accepting a high crest factor on the lamp.

I. INTRODUCTION

Nowadays, an important topic of awareness is the importance of environment preservation. In this direction, significant efforts have been made in the diverse areas of knowledge. In electrical engineering field, this phenomenon has resulted in the search for alternative energy systems, higher efficiency on available resources utilization, reduction of losses in equipments and the increase of electric energy quality.

In the last few years, the market was flooded by a great number of electronic ballasts for fluorescent lamps operating in high frequency, especially for compact fluorescent lamps. Its utilization was widely stimulated by Brazilian media for energy economy, because luminous efficiency increases with the frequency for this kind of lamp. Brazil faced a serious energy crisis in 2001. Many corrective actions were taken to mitigate this serious problem. One of them was the energy rationing, which consisted in overtaxing or even cutting the energy supply from consumers that exceeded the prefixed energy quotes. In addition, many electric energy concessionaires gratuitously distributed compact fluorescent lamps for residential customers, depicting the importance of the illumination segment inside the global energy consumption, estimated to be about thirty percent of the total consumption of electrical energy in the country. Because of this, countless research groups around the world, like [1], [2], [3], [4], [5] and [6] for example, have dedicated their efforts to the development of new topologies and new control techniques for different kinds of discharge lamps.

Most magnetic ballasts manufacturers had to develop electronic ballasts for discharge lamps to guarantee their survival in the market, as the customers started to demand more and more this type of product. It also simplifies the production line, which had an expressive physical reduction and productivity increase in comparison to the line that produces the conventional low frequency ballasts. Now, the challenges for industry are the reduction of production costs, the reduction of converter size, to obtain high power factor and low harmonic distortion, which implies in a substantial improvement on the quality of the energy consumed by ballasts. In Brazil, the development of electronic ballasts for HID lamps is being made by a few groups of researchers. However, in a close future, these ballasts will be at the production lines of main national manufacturers.

The purpose of this paper is to report the development of a low cost, single stage HPF electronic ballast for HPS lamps. A design criteria will be presented in this work for the proposed circuit. There are many kind of high-pressure lamps; however, this work will focus only the high-pressure sodium lamps (HPS), widely used in public illumination. The HPS lamps radiate energy on a great part of the visible spectrum [6]. These lamps provide a reasonable color reproduction (it has IRC 23 color reproduction index). They are available up to 130 lm/W of luminous efficiency and color temperature of 2100 K, approximately.

The HPS lamps, as any other HID lamps, need ballasts to operate correctly. The ballast is an additional equipment, connected between the power line and the discharge lamp. It has two main functions: to guarantee lamp ignition through the application of a high voltage pulse between the lamp electrodes and to limit the current that will circulate through it. The lamp would be quickly destroyed without current limitation, due to the negative resistance characteristic of the lamp, as one can observe in figure 1.

The HPS lamps have many particularities when they operate at high frequencies, such as:

• They can be modeled as a resistance, when in steady state;
• Features controllable luminous intensity;
• The spectrum color reproduction can be modified;
• Presents the acoustic resonance phenomenon, which can result in the arc extinguishing and even lamp destruction;

Lamp Current

I

Positive Resistance

Lamp Voltage

Negative Resistance

Breakdown Voltage

Fig. 1. Typical voltage x current curve for HID lamps.

In order to obtain low cost electronic ballast for HPS lamps with HPF a single stage converter was conceived. The idea is very simple: Since, in high frequency, the HPS lamps have a resistive behavior, why an electronic ballast, implemented using a full-bridge inverter associated with a LCC filter could not be connected directly to a full bridge rectifier? This paper presents a study, which allows verifying the feasibility of this idea, including a design criterion, a simulation study and also experimental results achieved for a 250 W prototype. The obtained results have been demonstrated the viability of this power electronics converter.

II. THE STUDIED ELECTRONIC BALLAST

The studied single stage high power factor electronic ballast for high pressure sodium lamps structure incorporates a bridge rectifier, a full bridge inverter in association with a LCC filter and an input LC filter to minimize the EMI generated by the electronic ballast. Figure 2 shows an electrical diagram of the proposed circuit. The $C_F$ capacitor in this figure has two main functions: receiving the reactive current from the electronic ballast and working as line filter with the $L$ inductor. The assumed resistive lamp behavior at high frequency associated with the small capacitance of the $C_F$ capacitor, in the range of nanofarads, on the bridge rectifier provides high power factor to the electronic ballast.

III. BALLAST DESIGN CRITERIA

To verify the performance of the proposed system, an LCC electronic ballast, for a 250W HPS lamp, was designed. A simplified version of the electronic ballast is presented in the figure 3. In this figure the bridge inverter is represented as a square wave source, the total equivalent series resistance of the system is shown as $R_{ESR}$. The rated lamp voltage ($V_{lamp}$) was obtained from the lamp’s manufacturer datasheet and its value is 100 $V_{RMS}$. To design the LCC ballast it was added 20% to the rated lamp voltage ($V_{lamp}$) to consider loses and the reignition effect, which will be discussed in the experimental results chapter. The electronic ballast input power voltage comes from the output of an input bridge rectifier; consequently, this input voltage is mains-dependent. In the present design example the mains voltage adopted was $V_{mains} = 220 V_{RMS}$. The chosen switching frequency was 68 kHz. Assuming the resistive comportment of the lamp, we can estimate the value of its resistance ($R_{lamp}$) after ignition using equation 1.

$$R_{lamp} = \frac{V_{lamp}^2}{P} \cong 40 \Omega$$

Where $P$ is the lamps’ power.

As it was indicated in [2], the best ratio between the switching frequency and the resonance frequency before the lamp turns on is $\omega_0/\omega_s = 3$, guaranteeing the high voltage generation for the lamp ignition and limiting the peak current at the MOSFET to acceptable levels. If it was adopted to work at resonance $\omega_0 = \omega_s$, in theory we would have the possibility of an infinite voltage generation over the lamp, which could be good for a quickly lamp turn on. On the other hand, the switches current would also rise to infinite because the impedance of the circuit formed by $L$, $C_s$ and $C_p$ ideally is null just before the lamp is turned on. This operation mode will result in the MOSFET’s and driver’s destruction.

The first design criteria used in this study is intended to guarantee the lamp ignition. Conventional electromagnetic HPS lamps ballast are normally designed to supply to the lamp a high peak voltage ($V_{cp}$) to assure its ignition, a typical ignition voltage is about 4 kV. In this work, the same minimal ignition voltage was adopted. The equivalent series resistance was estimated.
to be about $R_{ESR}=10.0 \, \Omega$, which is a quite big value. The skin effect has great influence over it. After ignition, the lamp’s voltage frequency drops to one third of the ignition frequency, reducing significantly the magnitude of $R_{ESR}$.

An expression was obtained to determine the peak voltage across the capacitor $C_p$. Equation 2 shows more explicitly that the expression shown in equation 2 is only valid before the lamp starts up.

\[
V_p = \sqrt{\frac{8 \cdot V_{\text{mains}}}{\pi}} \cdot \frac{3 \pi}{1 - e^{-2\pi Q}} (2)
\]

Manipulating equation (2) one can obtain the value of the quality factor in equation (3).

\[
Q = \frac{\frac{3 \pi}{2 \ln \left(1 - \frac{\sqrt{8 \cdot V_{\text{mains}}}}{V_p}\right)}}{27.87} (3)
\]

With the quality factor, the value for $L$ may be easily obtained, as shown in equation 4.

\[
L = \frac{Q \cdot R_{ESR}}{\omega_0} = \frac{27.87 \cdot 10 \Omega}{6 \pi 68 \, \text{kHz}} = 217.4 \mu \text{H} (4)
\]

The resonance frequency may be calculated using equation (5).

\[
F_r = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot \frac{1}{C_p} - \frac{1}{C_s}}} (5)
\]

Using a switching frequency three times lesser than the resonance frequency equation 5 may be simplified as shown in (6). The effect of the capacitance $C_s$ is almost null, considering the fact that the $C_s$ capacitor must be much bigger than the $C_p$ capacitor, so that most of the ignition voltage is applied on $C_p$ capacitor.

\[
F_r = \frac{1}{6 \cdot \pi \cdot \sqrt{L \cdot C_p}} (6)
\]

Manipulating equation (6), the value for the capacitor $C_p$ can be obtained, as seen in equation (7).

\[
C_p = \frac{1}{(6 \cdot \pi \cdot F) \cdot L} \approx 2.8 \, \text{nF} (7)
\]

To determine the real value of the $R_{ESR}$, an experimental circuit using a 202 $\mu \text{H}$ inductor including the lamp source cable and a 2.7 nF $C_p$ capacitor was stimulated with a 50 V peak-peak square wave signal, which generated a 800 V peak-peak signal over the lamp terminals, allowing the determination of $R_{ESR}$ using equation 2. This $R_{ESR}$ was obtained experimentally and its value was about five ohms. Therefore, the real circuit quality factor is $Q = 53.74$ which could results in a lamp peak voltage about $V_{cp} = 7.5 \, \text{kV}$ however, probably, before the lamp achieve this voltage, it will be already turned ON.

After lamp ignition, the ballast must guarantee that the RMS voltage at the lamp does not overcom e the rated value. A good studying method comes from the frequency domain approach proposed by Bum & Hee in [2]. This approach takes into account only the first harmonic of the full bridge output voltage $V_{ab}$ (see figure 2). Bum & Hee have presented the first harmonic peak amplitude for a half bridge inverter considering an ideal fixed DC bus voltage ($E$). In this topology an ideal fixed DC bus are not available. Instead of the DC bus voltage is supplied by the input full bridge rectifier ($V_{DC \, BUS}$), without a conventional bulk capacitor. Therefore, varying as an absolute sinusoidal wave $V_{DC \, BUS} = V_{pk} \sin(\omega t)$.

From these results, it is possible to determine the harmonic’s RMS value for a full bridge inverter, which is displayed in equation 8 for a fixed DC bus. To use this approach, for the present case, the first harmonic component for the full bridge inverter output voltage $V_{ab}$ must be determined. The first harmonic’s RMS value was obtained using the same expression 8, but replacing the fixed DC bus voltage ($E$) by the mains RMS voltage ($V_{\text{mains}}$), resulting in expression 9.

\[
V_{ab \, RMS} = 2 \frac{\sqrt{2} V_{pk}}{\pi} (8)
\]

\[
V_{\text{mains}} \, RMS = \frac{2 \sqrt{2} V_{\text{mains}}}{\pi} (9)
\]

The RMS lamp voltage $V_{lamp}$ can be obtained using the transfer function approach in the frequency domain for the circuit shown in figure 3. Equation 10 presents this result:
\[ G = \frac{V_{\text{lamp}}}{V_{\text{abs RMS}}} = \frac{R_{\text{lamp}}}{R_{\text{ESR}} + \frac{1}{SC_p}} \] (10)

From the absolute value of the transfer function \(|G_s|\), it is possible to obtain an expression to determine the \(C_s\) capacitor, assuming a null \(R_{\text{ESR}}\), one can obtain a simplified expression to determine the \(C_s\) capacitor. This expression is shown on equation 11.

\[ C_s = \frac{1}{\omega^2 \left( L - \sqrt{\frac{R_{\text{lamp}}^2 \cdot \delta}{\omega^2 + 1}} \right)} = 62.8nF \] (11)

Where,

\[ \delta = \frac{V_{\text{lamp RMS}}}{V_{\text{lamp}}} \cdot \omega \cdot \omega = \left( \frac{\omega L C_p - \frac{1}{\omega^2}}{\omega^2} \right)^2. \]

IV. SIMULATION RESULTS

To validate the proposed system, a full-bridge electronic ballast with the following specifications - 250W HPS lamp, 220 V\(_{\text{AC}}\) grid connected and operation frequency of 68 kHz - was simulated using the software PSIM\(^\text{®} 6.0\), modeling the lamp as a resistance. This model does not take into account the nonlinearities of the lamp, and it is used as a first setup for the designed ballast. Figure 5 shows the voltage and current in the mains. The voltage and current in lamp is shown in figure 6. This simulation results allowed calculating the crest factor. Reference (6) asserts that ballasts with higher crest factors may result in depreciation of lumen output or reduced lamp life, but the authors did not find any standards restricting this value. Simulations point out a crest factor of about two when using this ballast. Fluorescent lamp standards specify a maximum crest factor of 1.8 for HPS lamps.

V. EXPERIMENTAL RESULTS

A Full-bridge electronic ballast for a 250 W HPS lamp, 220 V\(_{\text{AC}}\) grid connected and operating at a frequency of 68 kHz was built using a \(C_s\) of 55 nF implemented with five 11 nF Capacitors in parallel. A \(C_p\) of 2.7 nF implemented with three 8.2 nF capacitors in series a L of 220 \(\mu\text{H}\) and a \(C_F\) of 470 nF implemented with a single commercial capacitor. The output bridge rectifier \(C_F\) capacitor value was obtained experimentally in order to minimize the input current THD, and to avoid undesirable bus over voltage. All capacitors used are polypropylene ones, gently supplied by Epcos.

In figure 7 is shown the DC bus voltage, where we may observe the \(C_F\) capacitor influence. The resistive characteristic of the electronic ballast is evidenced.

Figure 8 shows the voltage and current in the mains without EMI filtering. A high frequency noise is observed at every current peak. This is because most of the energy is transferred from the mains to the lamp, at this peaks. The main conducted EMI generators in this topology are the full-bridge inverter diodes, because the implemented prototype was built with IRFP460 MOSFET and its intrinsic diodes, which are not fast ones.

A commercial input filter was used to minimize the conducted EMI. A little improvement in the injected current noise in to the mains was observed. Figure 9 presents voltage and current in the mains with EMI filtering.
The lamp voltage and current in a low frequency period can be observed in figure 10. It is possible to see from this figure that the lamp turns on and off each semi cycle. These re-ignition periods are attributed to the nonlinear characteristic of the lamp and to DC bus voltage, which drops to zero every semi cycle. This may lead to experimental component adjustments, especially on \( C_s \) capacitor of the LCC filter.

In the figure 11, it can be observed the voltage and current in the lamp in a dimmed situation. The power supplied to the lamp in this case is 60 W. The lamp turn-off intervals are clearly shorter than with rated power.

The mains voltage and current in a low frequency period can be observed in figure 12 for the previously described dimmed situation.

In the figure 13, it can be observed the voltage and current in the lamp at full power a high frequency period. From this figure, it is possible to observe the EMI generation at every diode commutation. To minimize this phenomenon, fast diodes and snubber circuits are recommended.
VI. CONCLUSION

In this work a study of a single stage, high power factor electronic ballast for high-pressure sodium lamps is presented. A simple design criterion was shown, which permits to determine easily the LCC parameters, using only a set of equations, without any abacus. A simulation analysis was also presented, based on a classical lamp model, which consists of assuming the resistive lamp behavior at high frequencies. This model allows only in the obtainment of approximated results, because this topology turns the lamp off at the vicinity of mains zero crossings. A 250W electronic ballast prototype was built, based on a full-bridge, high frequency inverter, working at 68 kHz. The obtained experimental results were very encouraging. As one may observe on figure 9, which presents the input voltage and current, showing that a high power factor (never less than 0.92) was achieved. This ballast could represent a low cost high power alternative for high-pressure sodium lamps because it avoids the use of an external PFP. By this topology, it is also possible to drive a 400W HPS lamp. Some drawbacks were observed in this circuitry, as the high harmonic distortion in the input current. To minimize this inconvenience, a low frequency filter must be used, which results in bulky components. The ballast does not work properly at commercial voltages lower than 220 V_{RMS}, because the lamp needs 100 V_{RMS} to work properly - see equation (9). To solve this problem a line-to-line voltage connection is proposed. From nominal power to half of it, the dimming functionality was obtained. The phenomenon of the acoustic resonance was not observed, however it was not the objective of this study to analyze the impact in acoustic resonance. More studies regarding the influence of this topology on acoustic resonance must be done.

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