A Chopper-based Electronic Ballast to Supply HID Lamps

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***Abstract* — This paper presents an electronic ballast chopper to supply a 70W high intensity discharge (HID) lamp. The ballast consists on a bipolar buck chopper operating in continuous conduction mode (CCM) and an igniter circuit. The converter supplies the lamp with a sinusoidal waveform at mains frequency. The igniter is responsible for providing the necessary high voltage for the lamp's start-up. The goal is to supply the lamp from a 220V±20% mains with a reduced number of components, decreasing the system final cost [14] without compromising the reliability. Some experimental results are presented to validate the proposed ballast, and its behavior shows it is a good choice to avoid the acoustic resonance phenomenon.**

Keywords- Acoustic resonance phenomenon, AC/AC converter, electronic ballasts, HID lamps.

I. INTRODUCTION

High intensity discharge lamps have been used in several applications. Designing an electronic ballast requires an intense study on high voltage ignition process and the acoustic resonance phenomenon (AR).

The AR occurs in steady state operation at frequencies higher than a few kilohertz [1]. This phenomenon takes place when the frequency imposed on the lamp is changed and an eigenfrequency is approached, causing the appearance of pressure waves on the gas, which disturbs the discharge path [2].

Thus, the operation of HID lamps in the frequency commonly used to supply fluorescent lamps (25 kHz – 50kHz) is not recommended due to the acoustic resonance regions that occur in this range. Besides, it is very difficult to predict the acoustic resonance inside this range because some of the lamp's characteristics, as the rated power, arc tube geometry, internal fill pressure, tube's salts composition and the lamp burning time, all alter the acoustic resonance regions.

In order to solve the acoustic resonance problem in the range of 25-50 kHz some methods are pointed in the literature.

The method proposed in [3] and [4] consists on limiting the amplitude of each power harmonic in a value under the threshold limit believed not to cause acoustic resonance. The total power delivered to the lamp remains the same. Some experimental results have been conducted in [3], showing that this scheme cannot be used to eliminate arc instabilities in a broad frequency range. It works if a center operational window, free of AR, can be chosen. The limitation of this method is that free bands change according to the lamp characteristics described above.

Another method consists on the real time identification of variations on some of the lamp's electrical parameters due to the occurrence of AR. Thus, it becomes possible to change the operating frequency, avoiding the resonance. Different parameters can be measured, as cited in [5]-[8]. In some cases the circuit used to identify electrical parameter variations is not capable to detect small disturbances.

The AR does not occur if the lamp is operated in a megahertz range [9]. However, parasitic inductances and capacitances should be taken into account on the design, what turns it much more complicated. The soft switching technique must be used to reduce the switching power losses and the EMI emission [10] but it will always be relatively high.

In [16] it is shown that a high frequency (HF) ripple below 5% on the fundamental power signal is a guarantee to avoid exciting AR in a level to cause instabilities.

The purpose of this paper is to presents a HF single-stage inverter employing a bi-directional buck topology to supply a HID lamp for commercial application, maintaining the power ripple below 5% in HF.

The proposed converter was already studied in [15] as an alternative to eliminate harmonics of power lines.

The ballast circuit is constituted of a buck converter with two complementary switches working in high frequency. The operating frequency of the buck converter is 33 kHz. The lamp is supplied with a 60 Hz sinusoidal waveform through an adequate control on the driver signals.

A circuit analysis based on its topological operating stages and a description of the ignition process are presented in section II and III. Section IV shows the space-state matrices and its feedback control in section V. Experimental results are presented in section VI to validate the theoretical analysis.

II. STEADY STATE OPERATION

The ballast topology and the igniter circuit are presented in Figs. 2 and 5, respectively.

Fig. 2 shows the proposed ballast is composed by a four quadrant buck converter, a resonant input filter and an igniter circuit.

With an appropriate operation of switches M1 and M2, it is possible to obtain a low frequency sinusoidal waveform on the load, synchronized with the power line. The ballast load is the series combination of the lamp resistance and the igniter secondary inductance. This inductance is negligible when in steady-state operation, due to the 60 Hz frequency of the applied voltage.

Capacitor C2 is the output filter, required to reduce the high frequency components on the load side. It is designed to obtain a small output voltage ripple avoiding the acoustic resonance occurrence due to the converter operating frequency (33kHz). The amplitude of this ripple reflected on the current must be kept below 5% of the 60 Hz component in order to guarantee that this high frequency do no excite the acoustic resonance [17].

Switch q is actually consisted of two MOSFET-based bidirectional switches capable of a four-quadrant operation.

III. IGNITION PROCESS

At the beginning, the lamp is an open circuit, and it is guaranteed to turn on if a 2-2.5kV pulse is applied to the terminals for a few microseconds.

After the ignition high voltage pulse, the lamp resistance drastically decreases to a value around 10% of its steady state value.

The igniter circuit needed to provide the initial breakdown voltage is composed of a bridge rectifier (BR), a large resistor R1, necessary to guarantee the SIDAC (silicon bilateral voltage triggered switch) blocking, and the capacitor C3 to store the pulse's energy. The SIDAC used was the MKP3v240 with a breakdown voltage higher than the lamp's rated voltage. Before the ignition, the voltage across C2 is typically greater than the steady state voltage, and because the converter is in this situation at no load, the C3 capacitor is charged through R1, increasing its voltage.

When the voltage across C3 reaches the SIDAC breakdown voltage one pulse is applied in T1. This pulse is transferred to the secondary and, if the capacitance of C2 is sufficiently large, a high voltage appears on the lamp.

IV. BALLAST DESIGN

The ballast is designed to supply a 70W HID lamp, to compensate power line distortions, to achieve a good power factor and still maintaining a low cost. The starting point is the quadrilateral diagram shown in Fig. 1, which states the required operating conditions for this lamp.

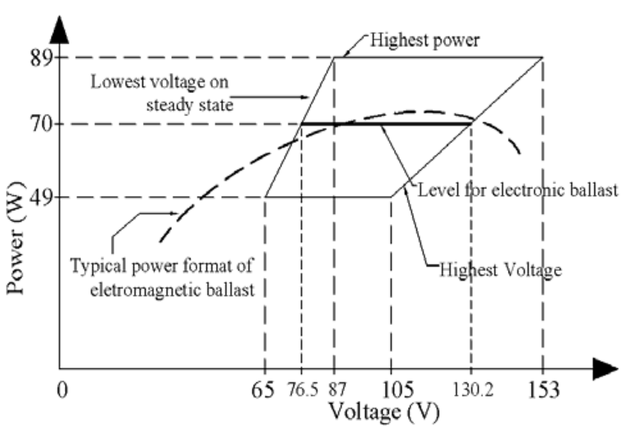

Fig. 1. Quadrilateral diagram for 70W HPS lamps

Value of output filter is found for worst case with:

TABLE I
Design Parameters

Vin_{peak}	373 V
$Vout_{peak}$	184.2 V
$D_{Average}$	0.49
$Iout_{peak}$	0.76 A
Ripple = α	0.05
f	33000 Hz

And value of lowest inductance in L2 for CCM is:

$$L2 = \frac{D(Vin - Vout)}{2.Iout.f} \tag{1}$$

To guarantee a maximum of 5% ripple on Iout, the lowest value for C2 should be:

$$C2 = \frac{(1-D)}{8.L2.f^2.\alpha} \tag{2}$$

To control this circuit it is necessary a complete dynamic model in face of small parameters disturbances caused by the mains or load. This is possible by means of a small signal model, which allows the analysis of disturbances around a steady-state operating point [16]. Considering that a publication including the input filter in this model was not found, the construction of such model is also presented.

The set of state-equations for the converter is shown in (3), and observing the rated values of each state, the operating points are defined.

The most common procedure for designing the control of this class of converters is a linearization of the corresponding state-space averaged model. This linearized model approximately governs small perturbations of the averaged quantities from their values in their rated operating condition. To do so, starting on the state-space equations (4), the equilibrium points for each stage are calculated in order to define the averaged values of the system's state variables, as shown in (5).

Expanding the averaged state-equations by means of a Taylor series and linearizing the resulting non-linear system around the equilibrium values, one obtains the desired dynamic model for the proposed system. Expressing these equations in a transfer function format, expression (6) is obtained.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & \frac{q}{L_2} & -\frac{1}{L_2} \\ \frac{1}{C_1} & -\frac{q}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{C_2.R_o} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} v_{in} \tag{3}$$

$$y = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

Where:

x_1, x_2 – Current in inductors L_1 and L_2 respectively
x_3, x_4 – Voltage in capacitors C_1 and C_2 respectively
q – Assumes 1 for switch in a or 0 for switch in b

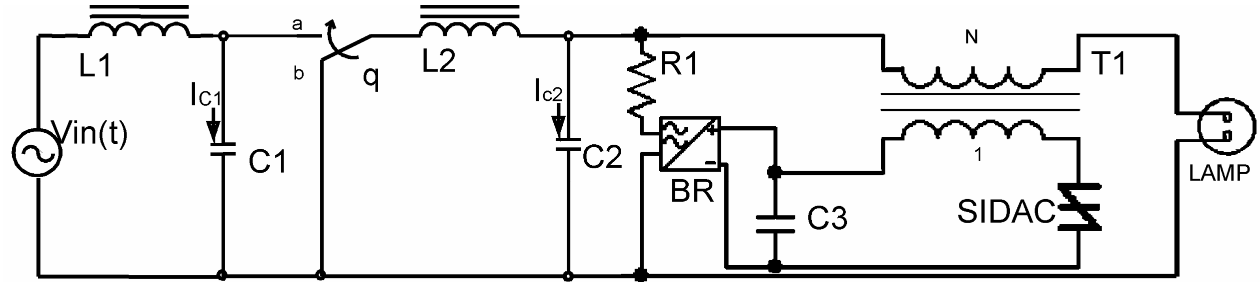

Fig. 2. Proposed Topology

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} = \begin{bmatrix} \frac{D^2}{R_0}.V_{in} \\ \frac{D}{R_0}.V_{in} \\ V_{in} \\ D.V_{in} \end{bmatrix} \quad (4)$$

$$G_2(s) = Vin \cdot \frac{s^3 \cdot C1 \cdot L1 \cdot C2 \cdot R0^2 + s^2 \cdot L1 \cdot C1 \cdot R0 + s \cdot C2 \cdot R0^2 + R0 - s^2 \cdot L1 \cdot D^2 \cdot C2 \cdot R0 - s \cdot D^2 \cdot L1}{\left(s^4 \cdot L1 \cdot C1 \cdot L2 \cdot C2 \cdot R0 + s^3 \cdot L1 \cdot C1 \cdot L2 + s^2 \cdot L1 \cdot D^2 \cdot C2 \cdot R0 + s \cdot D^2 \cdot L1 + s^2 \cdot L1 \cdot C1 \cdot R0 + s^2 \cdot L2 \cdot C2 \cdot R0 + s \cdot L2 + R0\right) \cdot R0} \quad (5)$$

Where D is the average value of the duty-cycle.

This function is the base for stability analysis and control design.

V. FEEDBACK CONTROL

Good power regulation on the lamp and dynamic performance in face of load and source disturbances were established as objectives for the control design.

The controllers for the proposed system is obtained by means of a LTI model (Fig. 3.) working at a constant operating point. To obtain the best controller for the system, a Routh-Hurwitz analysis was applied using Matlab.

The filter components as used in (5) are:

L1=1mH, L2=2mH, C1=0,33μF, C2=1μF.

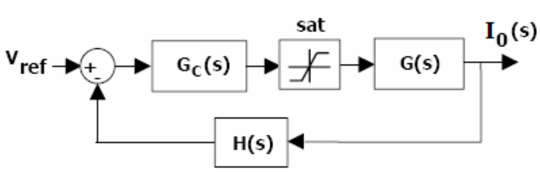

Fig. 3. Classical LTI feedback configuration

Best choice of controller found is:

$$G_C = \frac{0.1(s+800 \pm j.31680)(s+100 \pm j.2.\pi.k.60)}{(s+80000)(s \pm j.2.\pi.k.60)} \quad (7)$$

With:

k:=1, 2, 3.

Root Locus for the compensated system result in gain margin more than 15 in closed loop.

Fig. 4. shows the step response of system in closed loop.

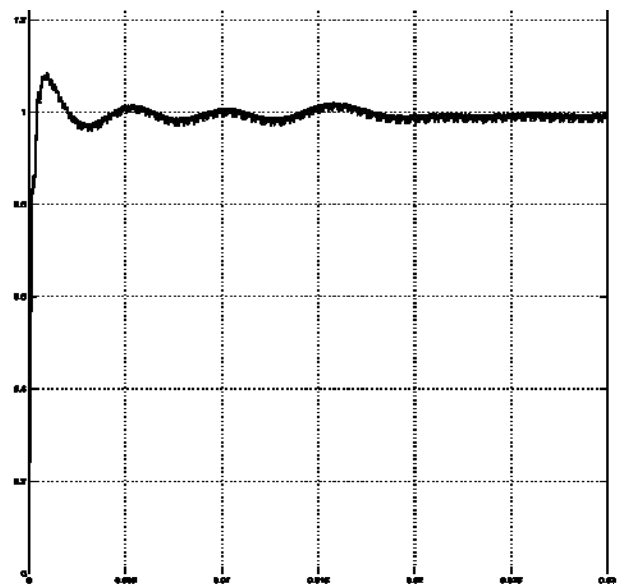

Fig. 4. Step response of system in closed loop

Response of system with sine wave in Vref to 60 Hz no present overshoot or error in steady state.

The system's circuit is shown in Fig. 5, without the ignition sub-circuit. The switches are driven with a delayed turn on to avoid short-circuit through the switches. The top switch driver is a transformer isolated inverter, a series capacitor and a resistor with a zener in parallel, as shown in [12].

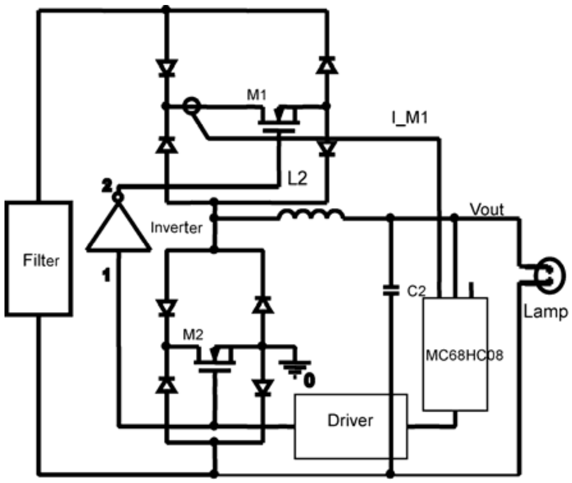

Fig. 5. System after Filter

The microcontroller used was from Freescale's HC08 family, model QY2, and is responsible to commanding and monitoring the circuit for a correct operation. The control strategy shown in Fig. 6 has been implemented in the microcontroller.

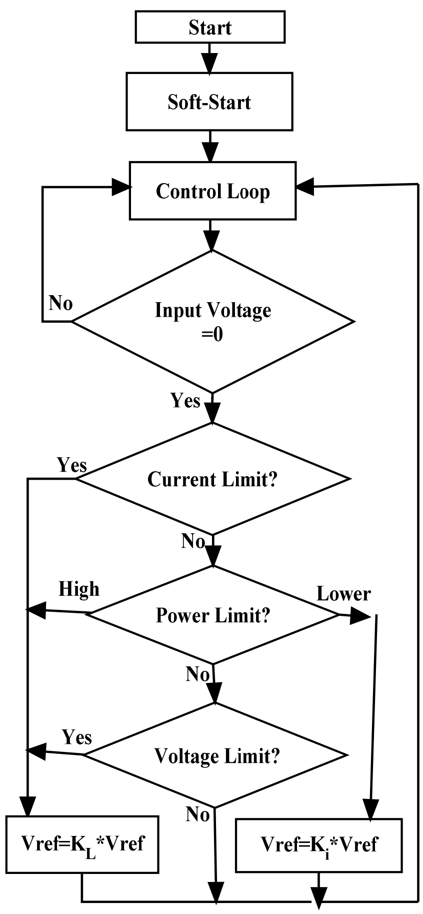

Fig. 6. Control strategy

The controller's transfer function shown in (7) was discretized at 66 kHz in order to implement the first loop shown in Fig. 6.

The limits defined for current, voltage and power in Fig. 6 are to preserve the quadrilateral diagram shown in Fig. 1.

The power limit is actually implemented to achieve power regulation, and it is performed by switching the voltage reference in steps, increasing by K_i or decreasing by K_L factors. The voltage reference is stored in the microcontroller memory as a table of 60 values of a half period of a sine function.

VI. EXPERIMENTAL RESULTS

In order to verify the proposed topology a prototype was built.

The circuit parameters have been selected by using the design procedure given in section IV. The main components of the implemented electronic ballast are summarized in table II.

TABLE II
Prototype Specifications and Components

Line Supply	220±20%
Lamp	OSRAM NAV-E 70W
Ferrite Inductor L1	1mH - EE 30-15-7 3F3
Ferrite Inductor L2	2mH - EE 41-17-12 3F3
Polyester Capacitor C1	0,33μF – 600V
Polyester Capacitor C2	1μF - 400V
Polyester Capacitor C3	47nF - 400V
Resistor R1	33KΩ - 1/2W
Bridge rectifier BR	W10G
SIDAC	MKP3v240
Diodes	MUR460
Mosfets	IRF 820
Microcontroller	MC68HC908QY2

Fig. 7. Photography of prototype

The feedback control design procedure has been presented in detail in section V. Fig. 7 shows a picture of the implemented ballast. Lamp current and voltage are presented in Fig. 8. The ripple shown are basically caused by measurement noise. The distortions shown during the zero crossing of the current is due to the delay in voltage to go up 300V for re-ignition of the lamp.

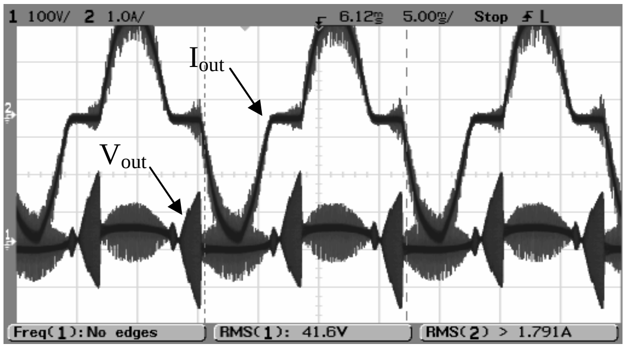

Fig. 8. Current and Voltage on lamp

Fig. 9 shows the input voltage and current waveforms with a minimum phase shift, what results in a power factor close to unity.

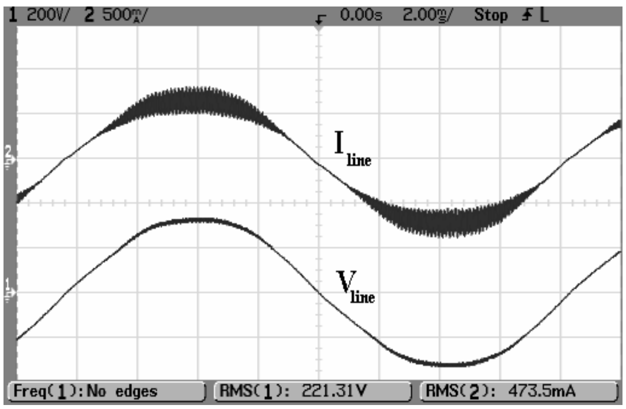

Fig. 9. Current and Voltage on line input.

VII. CONCLUSION

This paper presented an AC chopper inverter topology combined with a pulse igniter and with possibility of application in several rated power.

Comparing with systems using resonance igniter circuits this method demonstrated to be more robust and providing a higher voltage pulse, to begin the ignition process, with a small increase in the cost.

The chopper inverter is employed to supply the lamp during the ignition process and in steady state with a low frequency sine waveform to avoid the unstable effects provoked by acoustic resonance. Besides, the modulation technique used to drive the switches is simple to be implemented with low cost microcontrollers.

The M2 switch was driven directly from the microcontroller through a high speed buffer, and a simple and cheap isolated driver circuit was used for switch M1, based on a small pulse transformer and five passive components. The overall cost for drivers was maintained reasonably low.

The main contribution of this ballast is that it does not use electrolytic capacitors in the power circuit avoiding the accumulation of electronic waste and reducing the environmental impact.

Therefore, the proposed electronic ballast proved to be a viable solution to supply HID lamps from the 50-60Hz - 220V±20% mains, with longer life span, with simplicity and feasibility due to its microcontroller based command, low input current harmonics, and reduced weight, number of components and cost, when compared with its electromagnetic counterparts

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