A SIMPLE DESIGN CRITERION FOR HPS ELECTRONIC BALLASTS SUPPLIED BY LOW VOLTAGE SOURCES

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***Abstract* — This paper describes the development of a design criterion for high-pressure sodium (HPS) lamps electronic ballasts (EB) supplied by low voltage sources. The proposed design criterion is based on the rated RMS current of the HPS lamp, as is usual, however the merit of the present work consists in the simplicity of the electronic ballast topology which is not implemented with an LCC filter. When the EB is off-line and hence the input voltage is high (hundreds of volts) the LCC topology is usually used to provide the necessary high voltage (thousands of voltages) for lamp ignition and to limit the lamp current. The main limitation of this topology is the initial high current stress in the switches, which is necessary to generate the ignition lamp voltage. Notwithstanding, when the EB is supplied by a low voltage source the utilization of an LCC filter is not recommended since this high current stress in the switches becomes higher (may be tens to hundreds of amperes). To overcome this problem an igniter circuit is used. To limit the lamp current an inductor (the ballast) is used and to block any DC component of the lamp current a capacitor is connected in series with the inductor. Because of this simple design philosophy, the passive components can be easily determined based on rated RMS current of the HPS lamp. An EB prototype for 70 W HPS lamp was built to operate from a low voltage lead-acid battery (12 V). The obtained results validated the presented design methodology.**

I. INTRODUCTION

The purpose of this paper is to report the development of a stand-alone single stage electronic ballast (EB) for 70 W HPS lamps supplied by 12 V lead-acid battery. To achieve this purpose three different electronic ballast topologies using a half-bridge inverter, a full bridge inverter and a push-pull inverter are investigated for this application.

There are many kind of high-pressure lamps and EB [1 to 8] and, however, this work will focus only the high-pressure sodium lamps (HPS), widely used in outdoor lighting and known by its high luminous efficiency. The HPS lamps, like any other HID lamps, need ballast to operate correctly. The ballast is an additional equipment connected between the power line and the discharge lamp that has two main functions: to guarantee lamps ignition through the application of a high voltage pulse between the lamp electrodes and to limit the current that will circulate through it. Without current limitation, the lamp would be quickly destroyed, due to the negative resistance characteristic of the HPS lamp, as it may be observed in Fig. 1.

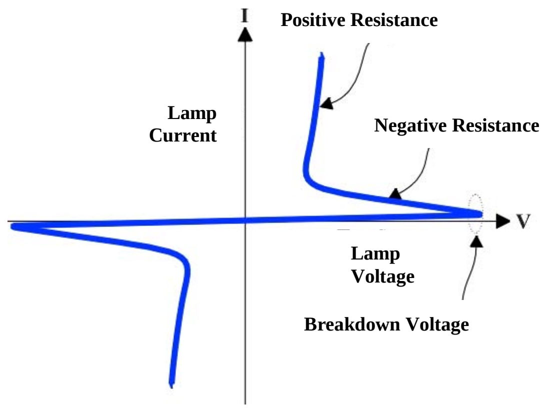

Fig. 1. Typical voltage x current curve for HID lamps.

In the next section, the main focus is to discuss which topology is more suitable to implement a low voltage (12 V lead-acid battery) electronic ballast for a 70 W HPS lamp. Following is presented the design criterion for the chosen ballast and a prototype was built in order to obtain the experimental results to validate the proposed topology and design criterion shown in section III.

II. STUDIED ELECTRONIC BALLASTS

The electronic ballasts schematic circuits based on a half-bridge inverter, a full bridge inverter and a push-pull inverter are represented in Fig. 2, Fig. 3 and Fig. 4 respectively.

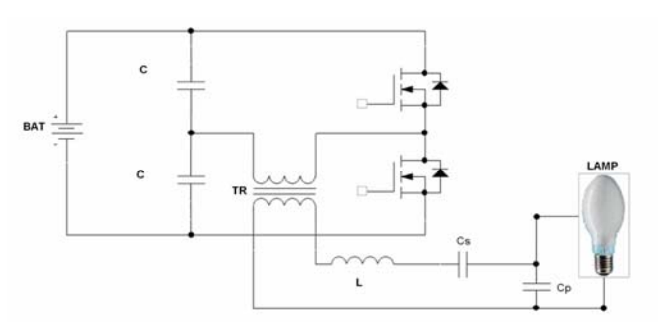

Fig. 2. Half Bridge Electronic Ballast.

Fig. 2 shows a half-bridge (HB) EB inverter connected to the LCC filter. Using this topology it is theoretically possible to supply the 70 W HPS. However it is clear that this topology has important disadvantages. First of all, it reduces the available voltage by half which double the drain current in the transistors. A floating drive is needed, as well as two extra capacitors comparing with the push-pull structure. The current stresses in the switches, during the lamp start-up, is extremely high and leads to over-designed transistors and transformer during lamps steady-state operation to avoid saturation.

The second electronic ballast structure under analysis is the full bridge (FB) inverter topology as showed in Fig. 3. As is well known using a FB inverter it is possible to use all the available battery voltage in consequence the current stress in the switches is reduced by half comparing with the HB inverter. But in this case two additional transistors are necessary. Also the floating drive stills necessary. Using the same LCC topology, the lamp start-up current still high and the transformer remains over-designed in steady-state to allow lamp ignition. Therefore it is clear that the LCC topology is not adequate for this application. To overcome this inconvenience the natural solution is to use an additional igniter. Using the igniter the high current stress in the switches during the lamp start-up is avoided.

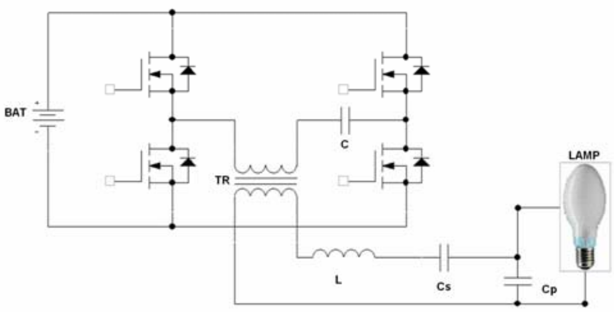

Fig. 3. Full Bridge Electronic Ballast.

The third studied topology was the Push-Pull inverter which can generates high frequency AC power voltage to drive the 70 W HPS lamp. The entire electronic ballast structure consists of: one upper transformer, to increase the input voltage which comes from the battery; one LC series circuit, where the inductor L is the high frequency ballast and the capacitor C that blocks any DC component to the lamp current, therefore it is designed to offer low impedance to the lamp current. Also an igniter is used to start up the HPS lamp in order to avoid high current stresses in the transformer. Fig. 4 shows an electrical diagram of the proposed circuit. This arrangement provides appropriate lamps ignition voltage and current and also rated voltage and current for steady state operation. The igniter is composed by a voltage doubler, since the transformer output voltage is matched with lamp rated voltage which is low, an auxiliary upper winding in the inductor L and a SIDAC semiconductor to start the HPS lamp when the output voltage doubler capacitors are charged . The Push-Pull high frequency inverter consists of two MOSFETs (M_1 and M_2) and a transformer (T). This structure was chosen by its simplicity in implementation and also avoids problem of fine tuning on lamps ignition and high current stresses on the switches and transformer.

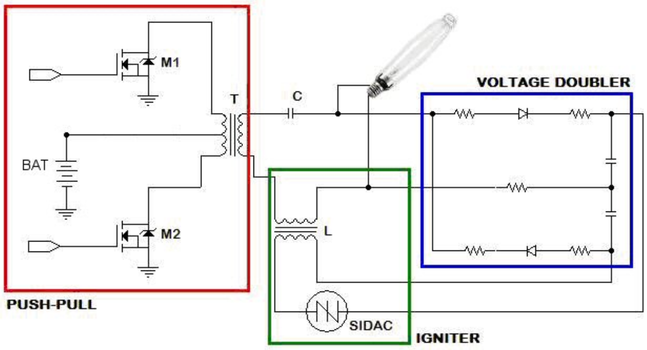

Fig. 4. Studied Electronic Ballast.

III. BALLAST DESIGN CRITERION

In order to verify the performance of the proposed ballast, 70 W HPS lamp electronic ballast was designed. The rated lamp voltage (V_{lamp}) was obtained from the lamp's manufacturer datasheet and its value is 70 V_{RMS} for a 70 W HPS Lamp. The electronic ballast input power voltage comes from the output of a battery. Consequently, this ballast is mains independent. In the present design example, the battery voltage adopted was considered to vary from 10 to 14 V_{DC}. The switching frequency chosen was 21 kHz just to avoid audible noise.

Assuming the resistive behavior of the lamp, we can estimate the value of its resistance (R_{lamp}), where R_{lamp} represents the nominal power of the lamp after ignition using (1).

$$R = \frac{V_{lamp}^{\ \ 2}}{P} \cong 70\Omega \qquad (1)$$

Where:
P - Lamp rated power.

The Push-Pull inverter generates an almost perfect square wave. Therefore, this inverter could be represented by a square wave voltage source. A simplified EB topology is shown in Fig. 5 where the inductor *L* represents the inductance of the igniter transformer, the capacitance *C* represents the circuit capacitor and the resistance R_{lamp} represents the HPS lamp equivalent resistance.

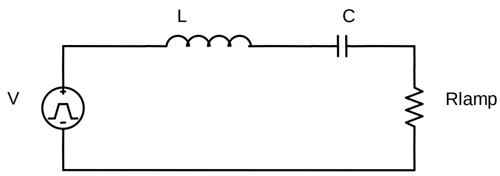

Fig. 5. Equivalent EB topology.

Aiming to design the L and C components, a Fourier analysis of this simplified circuit is proposed in order to determine the optimum values of these components. Equation (2) presents fourier decomposition of a square wave signal for a given frequency and amplitude E_2 (transformer output voltage).

$$V(t) = \frac{4E_2}{\pi}\sum_n\left(\frac{1}{n}\sin\left(n\omega t\right)\right) \qquad (2)$$

Consequently, the lamp current can be obtained by simple circuit laws. The results are presented in (3).

$$i_{lamp}(t) = \frac{4E}{\pi}\sum_n\left[\frac{1}{n\sqrt{\left(n.\omega.L - \frac{1}{n.\omega.C}\right)^2 + R^2}}\sin\left(n.\omega.t - \tan^{-1}\left(\frac{n.\omega.L + \frac{-1}{n.\omega.C}}{R}\right)\right)\right] \qquad (3)$$

Since the HPS lamp has a RMS rated current equal to 1A, it is necessary to express (3) in conformity with the RMS definition. However, the RMS value of the input current could be easily obtained from (3). This procedure results in one only equation and two variables: *L* and *C*. In order to overcome this difficulty, a simplified solution is approached in this paper, which consists to initially neglect the capacitor influence since its main function is to block the DC component of the HPS lamp current. In this case, (3) may be rewritten as (4).

$$i_{lamp}(t) = \frac{4E}{\pi}\sum_n\left[\frac{1}{n\sqrt{(n\omega L)^2 + R^2}}\sin\left(n\omega t - \tan^{-1}\left(\frac{n\omega L}{R}\right)\right)\right] \qquad (4)$$

Applying the RMS definition in (4) for the HPS lamp rated current, it is easy to obtain the L value (L=1.94 mH). Given that the capacitor C is essential to this EB, the real inductor is selected in way to be 10 percent bigger than the simplified one. Thus, L= 2.13 mH.

In order to determine the *C* value, it is used the last value of L (2.13 mH) in (3), resulting in a capacitor of 322.7 nF.

These calculations were performed using a Mathcad® spread sheet considering the first two odd harmonics components only. A simulation was performed in the mentioned software. Fig. 6 shows the voltage source inverter output and the lamp current.

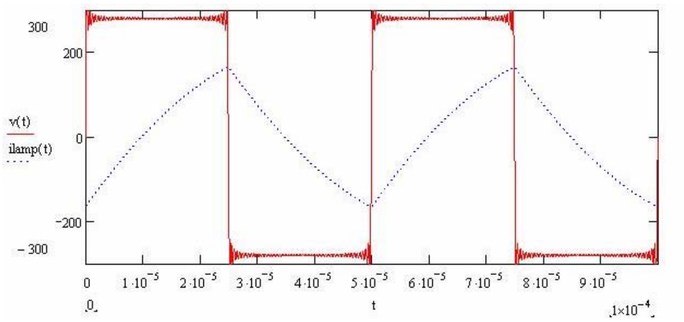

Fig. 6. Voltage source inverter and lamp current.

The transformer was designed in order to provide 280 V peak in the secondary of the push-pull inverter. Since the battery operates with 12 V DC (E_1), the transformer turns ratio (TR = N_2/N_1) may be easily obtained as 23, according to (5), where N1 is the number of turns in the primary windings (N_P = $2N_1$) and N_2 the number of turns in the secondary winding.

$$TR = \frac{N_2}{N_1} = \frac{E_2}{E_1} \qquad (5)$$

Fig. 7. Electronic Ballast Prototype.

IV. EXPERIMENTAL RESULTS

Using the proposed design criterion an experimental prototype was implemented as shown in Fig. 7.

From the implemented EB, it was obtained a set of waveforms acquisitions which are illustrated as follows. Fig. 8 shows the voltage (channel 1) and the current (channel 2) on the lamp. It may be observed that the frequency is below the projected one in order to compensate the non-idealities of the components, since this topology permits to adjust the output voltage by a frequency shift [1]. From this figure, the resistive behavior of the HPS lamp when operated at high frequency is easily observable.

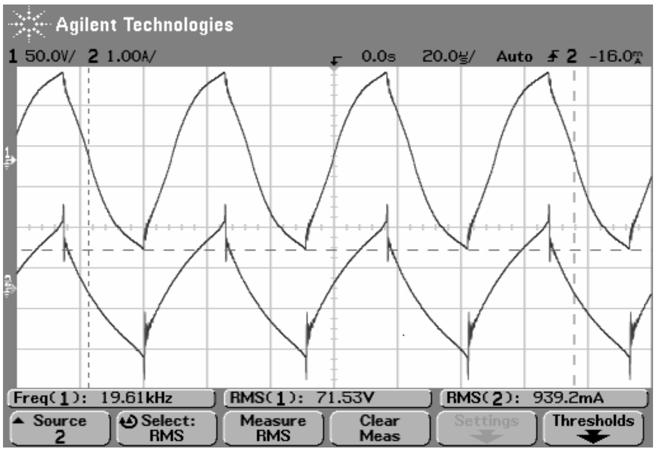

Fig. 8. Voltage and current on the lamp.

Fig. 9 presents the output voltage of the Push-Pull inverter without any snubber circuit and with an important dead time to avoid core saturation. The main purpose here is to show the square wave main characteristic of push-pull hard switch inverter.

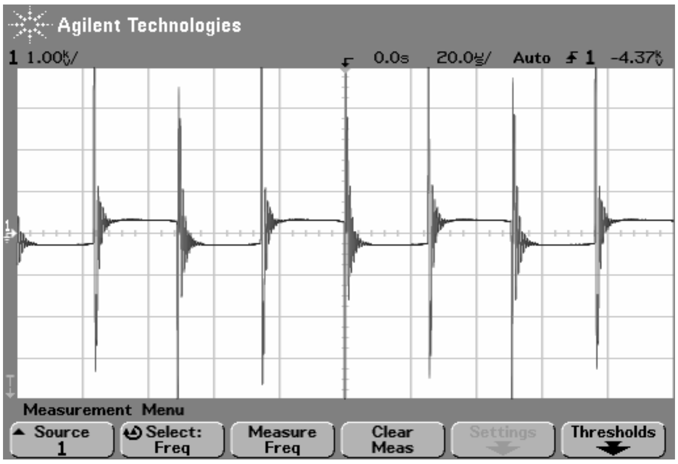

Fig. 9. Output voltage of the Push-Pull inverter.

Fig. 10 shows a detail of the MOSFET gate signal which is quite good and provides around 20 V to the MOSFET gate source circuit, minimizing the conducted component losses.

The igniter circuit works properly. During the development of this EB, the main difficulties were experimented in the design and carrying out of the magnetic components due to the high current levels in the primary winding of the Push-Pull inverter. To solve this problem the Skin effect was considered. Also the maximum magnetic core induction was limited under the rated specification. Special attention was taken in the transformer winding isolation. In order to increase the efficiency the switches were implemented using two MOSFETs in parallel.

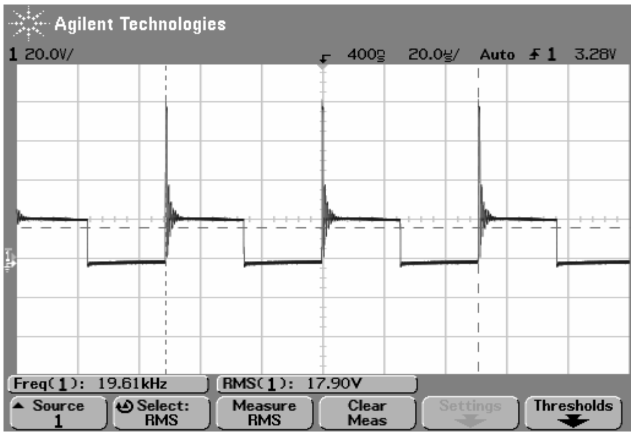

Fig. 10. Detail of the MOSFET gate signal.

V. CONCLUSION

In this paper it was presented the study and design of an EB for HPS lamp based in a push-pull hard switch inverter with an ignition circuit implemented in order to reduce the current stresses in the switches and transformer's saturation during start-up while using conventional LCC ballast.

The experimental results demonstrated the functionality of the proposed ballast fed by a 12 V lead acid battery, which presents competitive cost, when compared with similar equipments, with the advantage that it may work in stand-alone renewable energy systems.

The design procedure proposed is extremely simple and was validated by experimental results.

This circuit presents a time constant of 10 s approximately, which is acceptable for a circuit that does not have human intervention and also for HPS lamps that presents a warm-up period higher then 1 min.

The acoustic resonance phenomenon was not observed neither analyzed in this case.

The luminous efficiency of the HPS lamp, working at high frequency, do not increase on the contrary of what happens with the fluorescent lamps.

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