Analysis and Design of a HID Lamp Ballast with Sinusoidal Waveform Superposed with 3rd Harmonic

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***Abstract.*- This paper deals with the supply of HID lamps at high frequency avoiding acoustic resonances in the arc discharge. With the proposed ballast the lamp is supplied with a sinusoidal waveform superposed with third harmonic, thus approximating to the square waveform but reducing the harmonic content. The proposed topology is based on two half bridges operating at frequencies equal to the fundamental and third harmonics, plus a simple LLC resonant tank. In this way, the two harmonics, fundamental and third, are superposed in the lamp current. The complete analysis of this new power topology is also performed in the paper, obtaining both output voltage and switch currents. A design procedure for a 35W metal halide lamp is also presented. The experimental results obtained from the prototype probe that lamp operation is stable at frequencies where acoustic resonances were previously observed supplying with pure sinusoidal waveforms.**

I. INTRODUCTION

The use of high intensity discharge (HID) lamps in lighting applications has increased greatly in the last decades, mainly due to their good features as high luminous efficacy, high life, reduced size and good color rendering. Particularly, metal halide (MH) lamps exhibit the best color properties of all HID lamps, thanks to the use of adequate metals for the discharge gas [1]. In addition, with the use of new ceramic materials for the discharge tube instead of previous quartz tubes, their color temperature remains nearly constant during their entire life.

The main limitation when supplying HID lamps at non-audible frequencies is the rising of standing pressure waves in the plasma. These waves are called acoustic resonances. The conditions that must be fulfilled for the acoustic resonances to appear are: (a) the frequency of the lamp power is equal to certain eigenvalues of the lamp and (b) the mean lamp power is higher than a certain threshold value. Unfortunately, these two conditions are easily fulfilled when supplying the lamp a typical non-audible frequencies and near to the nominal lamp power. As a consequence, the standing pressure waves will appear and the electric arc will fluctuate, snake and sometimes extinguish. The lamp light is highly distorted and results inadequate for normal lighting purposes. The lamp resonance frequencies depend on lamp geometry, lamp gas and operating conditions, and can be theoretically obtained by solving the acoustic wave equation [2][3]. However, theoretical resonance frequencies greatly differ from the actual values for each lamp due to manufacturing tolerances.

In the last years, several techniques have been investigated by researches order to obtain a stable operation of HID lamps at high frequency. The following techniques have been reported in the literature:

a. Selection of a free-resonance frequency window to supply the lamp [5][6][7]. This is difficult to achieve, especially in MH lamps, due to manufacturing tolerances. Usually, the free-resonance window will change from lamp to lamp or even for the same lamp during lamp aging.
b. Selection of the operating frequency above all or below all the resonance frequencies [4][5][6][8][9][10]. This solution conducts to low frequency operation (about 500 Hz) or extra high frequency operation (about 700 kHz). The low frequency operation increases size and weight, whereas a very high frequency produces higher switching losses and EMI.
c. Operation of the lamp with constant power [8][9][10][11]. This can be performed by operating the lamp with both dc current or square waveforms. Dc current presents the disadvantage of aging only one of the two lamp electrodes, reducing the lamp life to half. Square waveforms is an interesting solution but only at low frequencies, since at high frequencies a high EMI is generated and especially the RFI emitted by the discharge itself is high [13].
d. Use of suitable frequency modulated waves following different modulation patterns [4][12]. Recent studies show limitations of this technique when it is applied in a free-resonance frequency window [4].

The technique investigated in this paper consists on the operation of the lamp with sinusoidal waveform superposed with third harmonic. This technique has been firstly reported as a feasible solution by Koshimura et al in [5][6]. It consists on supplying the lamp with a sinusoidal waveform plus its third harmonic in phase. The idea is to approximate the lamp cur-

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rent and voltage waveforms to the square waveform, but using only two harmonics. The main advantages are that EMI and RFI emitted by the discharge are much lower than those for the pure square waveform.

In the following, section II presents the topology proposed in this paper. The topology is analyzed in detail in section III, obtaining the important design characteristics. Section IV presents a design example based on the performed analysis. Experimental results are provided in section V. Finally, some conclusions are given in section VI.

II. PROPOSED TOPOLOGY

Fig. 1 illustrates the proposed topology for supplying the lamp with sinusoidal waveform plus third harmonic. It is based on the use of two half bridges, one operates with a switching frequency equal to the fundamental frequency and the other one operates with a switching frequency equal to three times the fundamental frequency. Two LC resonant circuits are used to supply the lamp from each branch. Capacitors C_{B1} and C_{B3} are used to block the dc component. Therefore, two LC resonant circuits are employed to supply the lamp from each branch, L_1 and C from leg 1 and L_3 and the same capacitor C from leg 3.

When operating the proposed inverter, two resonant tanks will introduce different phase delays to the lamp voltage and current. Therefore, the phase of the gate signals of one leg should be adjusted in a value φ in order to give the same phase delay for the fundamental and the third harmonic.

Fig. 2a shows the output voltages V_1 and V_3 , showing the delay φ between them. Fig. 2b shows the voltage across the lamp and its two harmonic components in phase. Fig. 3 shows the instantaneous lamp power waveform and its harmonic content when using harmonics first and third. As can be seen, the instantaneous lamp power presents only three significant harmonics: second, fourth and sixth, apart from the mean value. The rest of harmonics have a negligible amplitude.

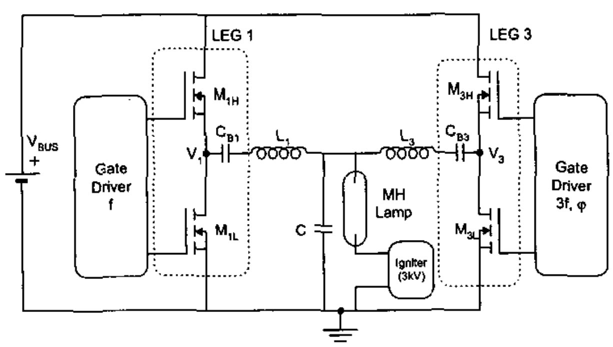

Fig. 1. Proposed power stage for sinusoidal plus third harmonic lamp supply.

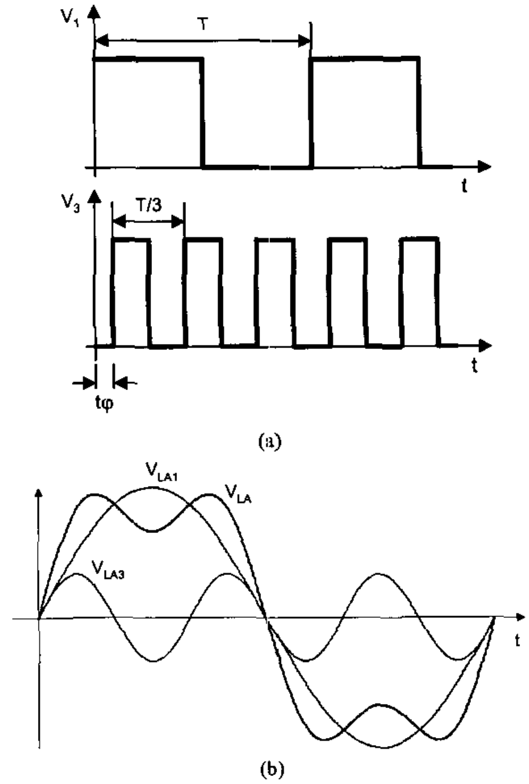

Fig. 2. (a) Output voltage of legs 1 (V_1) and 3 (V_3), (b) Lamp voltage and harmonic content.

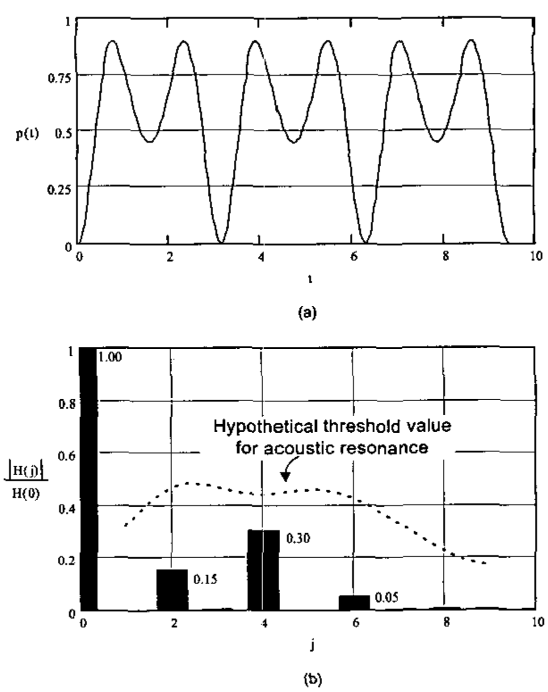

Fig. 3. (a) Instantaneous output power, (b) Output power harmonic content

The basic idea in the proposed topology to avoid acoustic resonances is that if the amplitude of all of these harmonics is lower than the threshold value needed for acoustic resonance to raise, the operation of the lamp will be stable.

When the lamp is supplied with a pure sinusoidal waveform, the instantaneous lamp power presents only one harmonic at a frequency double of the current frequency and with an amplitude 50% the mean value. However, in the proposed topology the maximum harmonic content in the lamp power is only equal to 30% the mean value, thus reducing the possibilities of acoustic resonances to appear.

Fig. 4 shows the simplified block diagram of the control circuit used to generate the gate signals for the two legs. The control circuit is based on the UC3875 integrated circuit. This device is used to generate the gate signals in full-bridge topologies with phase-shift control. As shown in Fig. 4, one of the output signals is used to directly command leg 3. The control signals of leg 1 are obtained by dividing the other output of the UC3875 by three. Two switches S1 and S2 are used to select the different outputs of the UC3875, thus having all the combinations for the phase delay between leg 1 and 3.

III. Analysis of the Power Topology

The equivalent circuit of the power stage is shown in Fig. 5. Leg 1 generates a square waveform V_1 of frequency f and amplitude equal to half the bus voltage. Leg 3 generates a square waveform V_3 with the same amplitude, frequency 3f and with a delay angle equal to φ in relation to V_1. The effect of blocking capacitors has been neglected, because they are selected to have an equivalent impedance negligible compared to that of the other resonant elements. Since sources V_1 and V_3 has different frequencies, the superposition law is used in order to analyze the circuit. Per unit values are employed in the analysis in order to obtain more general results. The base values and parameters used for normalizing are the following:

$$\alpha = \frac{L_1}{L_3} \quad Z_B = \sqrt{\frac{L_1}{C}} \quad \omega_B = \frac{1}{\sqrt{L_1 C}} \quad V_B = \frac{2V_{bus}}{\pi\sqrt{2}} \tag{1}$$

Fig. 6a shows the normalized equivalent circuit for a per unit switching frequency nΩ when considering only the effect of the voltage source V_1. The voltage source V_3 is then replaced by a short circuit. By analyzing this circuit, the per unit lamp voltage is obtained as follows:

$$M_{LA1,n} = \frac{1/n}{1+\alpha-(n\Omega)^2 + j\dfrac{n\Omega}{Q}} \qquad n = 1,3,5,7\ldots \tag{2}$$

For design purposes, it is also important to know the input current to the resonant tank. From the circuit of Fig. 6a the per unit currents through each inductor can be obtained as follows:

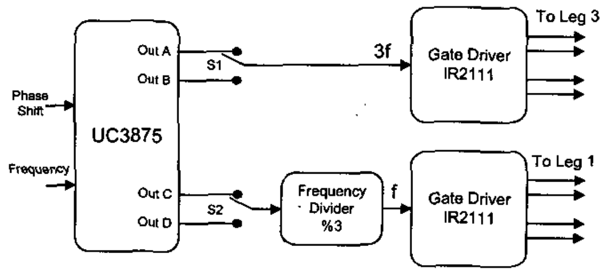

Fig. 4. Simplified control circuit block diagram

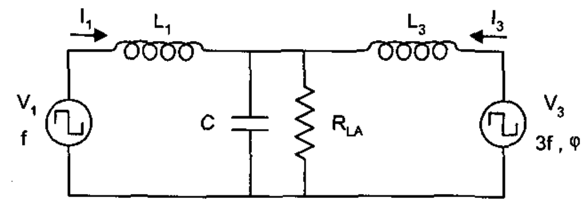

Fig. 5. Equivalent circuit of the power stage

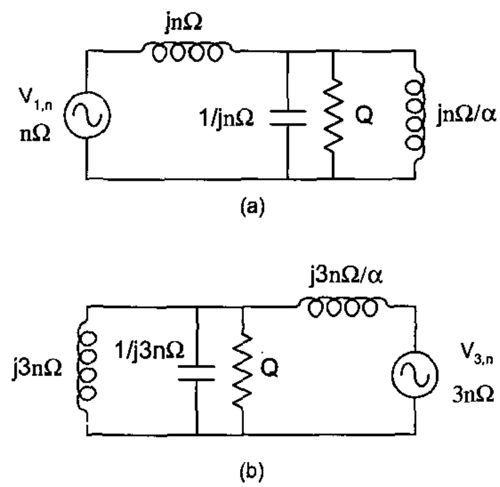

Fig. 6. Equivalent circuits using superposition law.

$$J_{L11,n} = \frac{1}{n}\,\frac{1 - jQ\left(\dfrac{\alpha}{n\Omega} - n\Omega\right)}{Q\left(1+\alpha-(n\Omega)^2\right) + jn\Omega} \tag{3}$$

$$J_{L31,n} = -\frac{M_{LA1,n}}{jn\Omega/\alpha} \tag{4}$$

The second subscript "1" in equations (2)-(4) indicates that these components are obtained considering only the harmonics of voltage source V_1.

Fig. 6b illustrates the equivalent circuit when considering only the effect of the third harmonic given by the voltage source V_3. The voltage source V_1 corresponding to the first harmonic is replaced by a short circuit. The lamp voltage obtained from this circuit is the following:

$$M_{LA3,n} = \frac{1/n}{1+\frac{1}{\alpha}-\frac{9(n\Omega)^2}{\alpha}+j\frac{3n\Omega}{Q\alpha}} \qquad (5)$$

and currents through the inductors L1 and L3 due to the third harmonic have the following expressions:

$$J_{L13,n} = -\frac{M_{LA3}}{j3n\Omega} \qquad (6)$$

$$J_{L33,n} = \frac{1}{n}\frac{1-jQ\left(\frac{1}{3n\Omega}-3n\Omega\right)}{Q\left(1+\frac{1}{\alpha}-\frac{9(n\Omega)^2}{\alpha}\right)+j\frac{3n\Omega}{\alpha}} \qquad (7)$$

The second subscript "3" in equations (2)-(4) indicates that these components are obtained considering only the harmonics of voltage source V_3.

By combining equations (2)-(4) with equations (5)-(7) using the superposition law, the different voltages and currents of the circuit can be obtained.

The per unit lamp voltage can be approximated from (2) and (5) by using the fundamental harmonics, as shown in the following expression:

$$M_{LA} = \sqrt{\left\|M_{LA1,1}\right\|^2+\left\|M_{LA3,1}\right\|^2} \qquad (8)$$

Fig. 7 illustrates the output voltage characteristics as a function of the per unit switching frequency (Ω) for different values of the per unit load (Q), for a particular case with α=1.5. This characteristic is obtained by plotting equation (8). As can be seen, two natural resonant frequencies appear in this type of topologies, due to the double nature of the power supply.

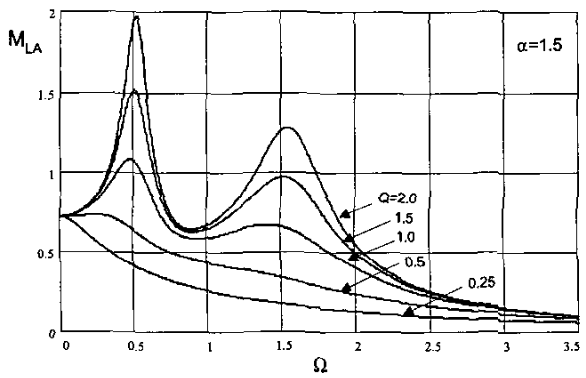

Fig. 7. RMS lamp voltage of the proposed topology as a function of the per unit switching frequency (Ω) and load (Q) for α=1.5.

These natural resonant frequencies can be obtained from equations (2) and (5), by equaling the denominators to zero with Q=∞ and solving for Ω, the following values are obtained for the natural resonant frequencies:

$$\Omega_{OH} = \sqrt{1+\alpha} \qquad (9)$$

$$\Omega_{OL} = \frac{1}{3}\sqrt{1+\alpha} \qquad (10)$$

where Ω_{OH} and Ω_{OL} are the highest and lowest natural resonant frequency respectively.

IV. Design Example

The aim of the proposed topology is to supply the lamp with a sinusoidal waveform with superimposed third harmonic, in order to approximate the lamp voltage and current to the square waveform but with a minimum harmonic content. Therefore, the following conditions should be satisfied:

1.- The amplitude of the fundamental component should be equal to three times the amplitude of the third harmonic:

$$\left\|M_{LA1,1}\right\| = 3\left\|M_{LA3,1}\right\| \qquad (11)$$

2.- The fundamental component and the third harmonic should be in phase:

$$\arg(M_{LA1,1}) = \arg(M_{LA3,1}) \qquad (12)$$

The first condition should be fulfilled by a proper design of the converter. The second condition is fulfilled by varying the phase shift between legs 1 and 3 using the control circuit previously shown in Fig. 4.

Fig. 8 represents the ratio of the fundamental component to the third harmonic as a function of the per unit switching frequency (Ω) for different values of the per unit load (Q), for the particular case of α=1.43. A ratio of 3 is obtained for Ω=1 and Q=1.4. In this operating point the per unit lamp voltage are M_{LA1}=0.6237, M_{LA3}=0.2079 and M_{LA}=0.6574.

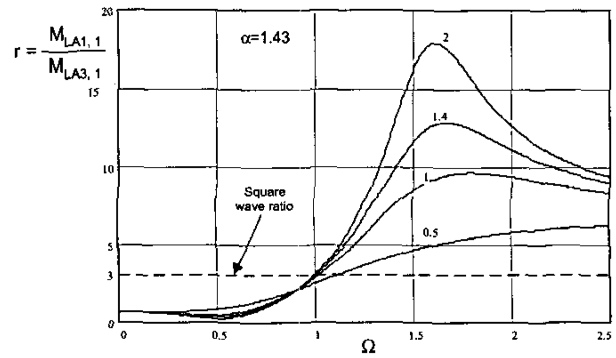

Fig. 8. Fundamental to third harmonic ratio as a function of the per unit switching frequency (Ω) and load (Q) for α=1.43.

The MH lamp used for this first prototype is a 35W HCI-T from OSRAM. As reported in [4], it is very difficult to obtain any stable operation of this lamp between 20kHz and 40kHz, due to the high density of acoustic resonances in this frequency range. Therefore, the selected switching frequency will be 30 kHz for the fundamental component.

For this lamp, the voltage and current measured at high frequency were 87.7 Vrms and 0.512 Arms. The equivalent resistance at high frequency is then 171 Ω. The selected switching frequencies are 30kHz for leg 1 and 90kHz for leg 3.

The base voltage can be then calculated as follows:

$$V_B = \frac{V_{LA}}{M_{LA}} = \frac{87.7}{0.6574} = 133.4\,V \tag{13}$$

and the bus voltage needed is obtained from (1):

$$V_{bus} = \frac{\pi\sqrt{2}V_B}{2} = 296\,V \tag{14}$$

In order to calculate the resonant elements, the first step is to obtain the base impedance and natural resonant frequency as follows:

$$Z_B = \frac{R_{LA}}{Q} = \frac{171}{1.4} = 122.1\,Ohm. \tag{15}$$

$$f_O = \frac{fs}{\Omega} = \frac{30\cdot 10^3}{1} = 30\,kHz \tag{16}$$

The resonant elements can now be calculated from simple equations:

$$L_1 = \frac{Z_B}{2\pi\, f_O} = \frac{122.1}{2\pi\; 30\cdot 10^3} = 0.648\,mH \tag{17}$$

$$L_3 = \frac{L_1}{\alpha} = \frac{0.648}{1.43} = 0.453\,mH \tag{18}$$

$$C = \frac{1}{2\pi\, Z_B\, f_O} = \frac{1}{2\pi\; 122.1\; 30\cdot 10^3} = 43.4\,nF \tag{19}$$

V. Experimental Results

Fig. 9 shows the electrical diagram of the control circuit. The UC3875 is used to generate the basic drive signals with the corresponding phase shift. Several digital gates together with a 4518 counter are used to divide one of the phase-shifted signals by three. IR2111 circuits are then used to drive the two half bridges.

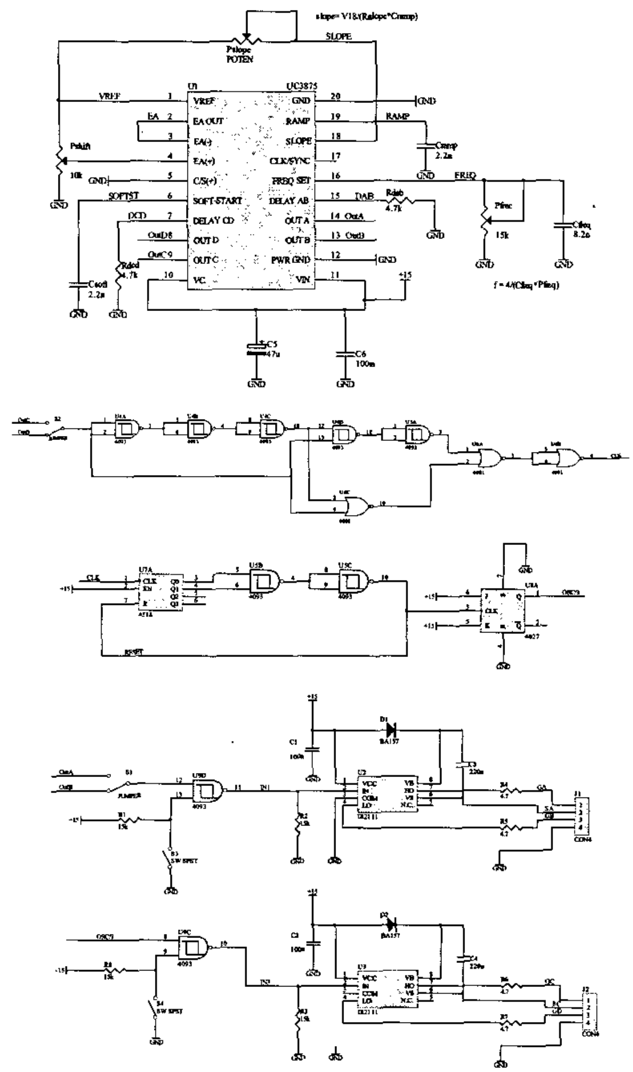

Fig. 9. Electric diagram of the control circuit.

From the design results obtained in previous section, a laboratory prototype has been built. MOSFETs IRF840 from International Rectifier were used as power switches. Blocking capacitors are selected to have a small impedance at switching frequency, a value of 2.2μF and rated 250V were used.

Fig. 10 illustrates the operating waveforms of the lamp at the nominal power. The measured rms lamp voltage and current were 89.6V and 0.464A. The measured average lamp power was 41.2W, very close to the nominal power. Presence of acoustic resonances is determined by measuring lamp electric and photometric parameters, this is, voltage, current, power and light intensity using an photodiode detector. At this operating point and even at lower power levels acoustic resonances were not detected.

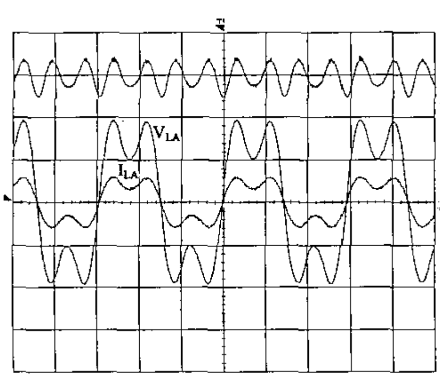

Fig. 10. Measured lamp voltage, current and power waveforms from the lab prototype. (50V/div, 1A/div, 10μs/div)

Fig. 11 illustrates the voltage and current at the input of leg 1. As can be seen zero voltage switching is obtained for the switches in this leg. Finally, Fig. 12 shows the voltage and current at the input of leg 3. For this leg, different commutations modes are obtained, what could make necessary the use of fast recovery diodes.

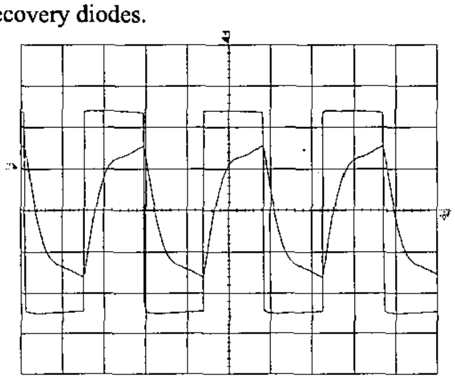

Fig. 11. Measured voltage and current waveforms in leg 1. (50V/div, 0.5A/div, 10μs/div)

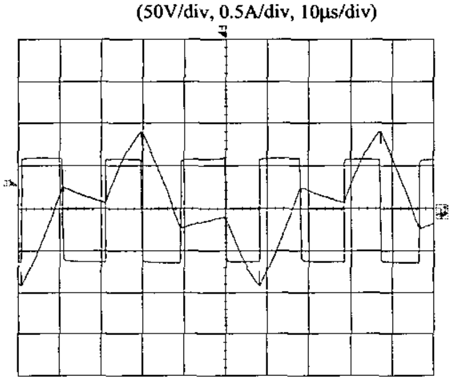

Fig. 12. Measured voltage and current waveforms in leg 3. (100V/div, 1A/div, 5μs/div)

VI. Conclusions

In this paper a new topology for supplying HID lamps with sinusoidal waveform with superposed third harmonic has been proposed. By using the proposed technique, the lamp is supplied with an approximated square waveform, but reducing the harmonic content and therefore EMI and RFI. The proposed topology could be expanded to inject the fifth or more harmonics, achieving a higher approximation to the square waveform. A design procedure has been also proposed in order to have the adequate amplitude and phase of each harmonic component. A laboratory prototype was developed for a 35W MH lamp with ceramic discharge tube. Experimental results probe that lamp operation is stable at operating frequencies where acoustic resonances were previously observed when supplied with pure sinusoidal waveforms. As conclusion, the proposed technique could be a feasible solution for stable operation of HID lamps.

Acknowledgement

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