APPLICATION OF MODULATED SIGNALS IN ELECTRONICS BALLAST FOR HPS LAMPS

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***Abstract*— This work presents a study of modulation techniques for synthesis in electronic ballasts presenting two main features. First, by modulating low frequency waveforms via high frequency PWM one assures acoustic resonance rejection. Second, by using saturated sinusoidal low frequency lobes, one controls the crest factor on the lamp voltage. A brief review of similar techniques is done and experimental results of the proposed approach are presented.**

***Keywords* - Acoustic resonance avoidance, HPS lamps, PWM, modulation low frequency.**

I. Introduction

The acoustic resonance phenomenon in High-Pressure Sodium lamps (HPS) is a relevant subject when supplying these lamps with medium or high frequency via electronic ballast [1]. There are several techniques and methods to prevent this phenomenon in literature.

The proposed solutions for the problem may be classified in groups characterized by: i) Choosing a constant frequency from $(20-200)kHz$ where, specifically, in a small range around the chosen frequency, the acoustic resonance does not occur [2], [3], [4]; ii) Using very high frequencies, avoiding the whole range where acoustic resonance occurs, normally higher than $500kHz$ citemso, cardesin; iii) Operating with circuits, that somehow detect the occurrence of the acoustic resonance and switch, through some modulation strategy, the frequency of the inverter before the resonance evolutes with some drastic consequence [7], [8], [9]; iv) Using square current waves in low frequency, this method avoids the AR because the instantaneous power of a square wave is theoretically constant [10], [11], [12]; v) Driving the lamp with DC current, avoiding acoustic resonance [13]; vi) preventing the occurrence of acoustic resonance by superimposing some harmonics (the third and the fifth, for instance) to the high frequency sinusoidal fundamental wave. The resulting waveform would be approximately square [14], [15] and viii) Modulating the voltage applied to the lamp, i.e., a high frequency current modulated by a low frequency waveform [16], [17], [18], [19].

The mentioned techniques and methods described above present specific characteristics, with advantages and disadvantages [10], [14], [15]. For the modulation techniques, in particular, which use high frequency to synthesize low frequency waveforms, the advantage is to have only one power stage, therefore, it implies a reduction of the cost, volume and weight of the ballast, other than present high power factor. However, the main inconvenient is to guarantee crest factors in the lamps below standard limits.

This work presents a study of modulation techniques for the voltage synthesis in electronic ballasts presenting two main features. First, by modulating low frequency waveforms via high frequency PWM one assures acoustic resonance rejection. Second, by using saturated sinusoidal low frequency lobes, one controls the crest factor on the lamp voltage.

The structure proposal for this work is the following one: First, the Introduction section, presenting the problem and considering its solution. After that, a section describing the high frequency PWM used to synthesize the low frequency waveform and the applied topologies of the ballast for this purpose. The third section describes a way to vary the crest factor in the lamps for supplying in high frequency modulated low frequency lobes, other than analyzing the parameter and frequency variation impact on the crest factor. The fourth section presents experimental results of the proposed technique with crest factors within standard values. Conclusions compose the final section.

II. Voltage Waveform Study

As it was mentioned before, using a constant frequency in the $(20-200)kHz$ range in a specific value where acoustic resonance does not occur is not an efficient strategy due to dependency of this phenomenon to the lamp power, manufacturer, shape and also with the aging of the lamp.

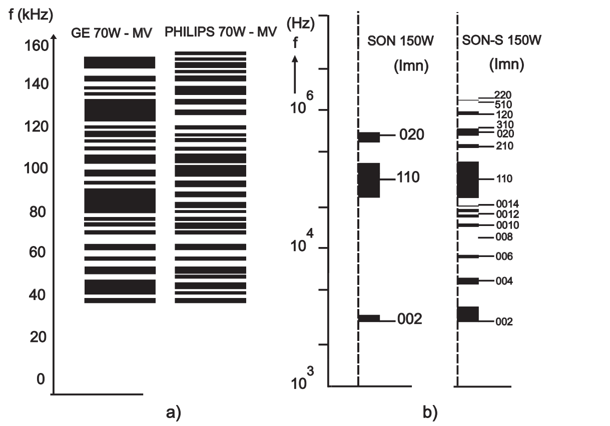


Fig. 1. a)AR free frequency bands for lamps of same power and different manufacturers [20] and b) same manufacturer and different type or power [1]

Figure 1 a) presents acoustic resonance (from now on named as AR) free frequency bands for two lamps of the same power and different manufacturers [20] whereas, Figure 1 b) shows it from two other lamps of different type or power and the same manufacturer. It is quite clear for these two examples that the occurrence of AR happens in a large spectrum of frequencies and does not show a predictable pattern [1].

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 LC_sC_p filter and an input LC_f filter to minimize the EMI generated by the electronic ballast [16]. 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. Simulations and experimental results "point out"a crest factor of about two when using this ballast [16].

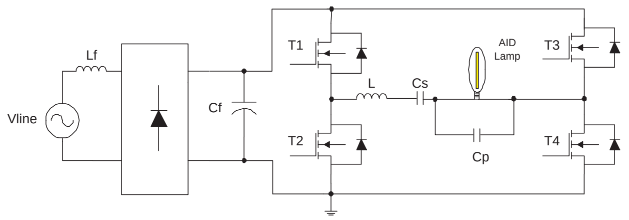


Fig. 2. Diagram of the ballast using modulated signal [16]

Figure 3 shows the AC-AC converter implemented as an electronic ballast [17]. This converter presents a high power factor and a soft switching for the high frequency AC lamp current, which increases the efficiency of the converter. The ballast will then supply a high frequency current modulated in low frequency. Its volume is small due to its single power stage. The current waveform shown in [17] presents a crest factor around of two. Nevertheless, it has been pointed that a high crest factor HPS lamps is not such a problem as it is for fluorescent lamps [21].

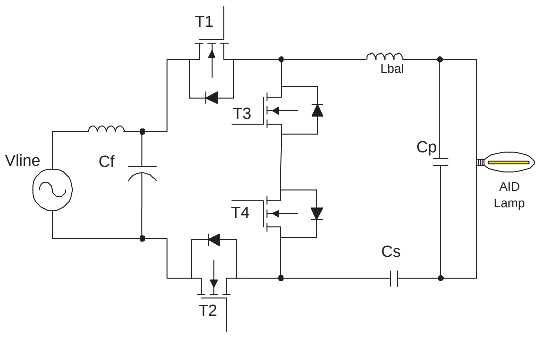
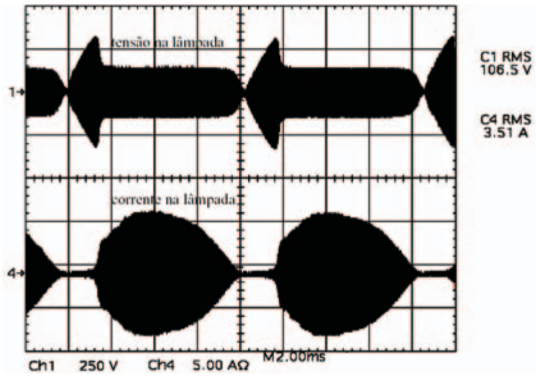
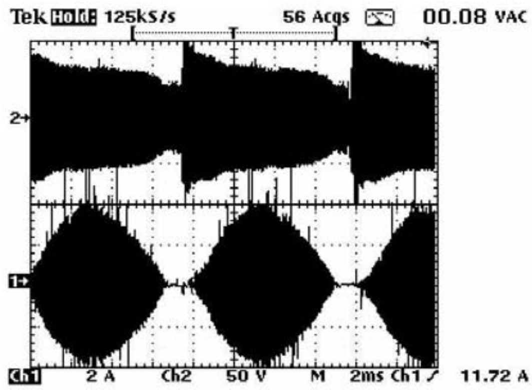


Fig. 3. Diagram of the ballast based on a $AC-AC$ converter [17]



(a)



(b)

Fig. 4. Waveforms of the measured voltage and current in the lamp, a) [17] e b) [16]

A feasible approach to avoid acoustic resonance in HPS lamps consists in applying to the lamp a high frequency voltage modulated by a low frequency waveform. This low frequency modulation avoids the acoustic resonance [16], [17]. This is implemented in the present work generating a modulated signal as the reference to the PWM. This reference signal is constituted by a fundamental frequency multiplied by the modulating frequency as:

$$v_{ref} = sin(2\pi f_{fund} t) * sin(2\pi f_{mod} t). \qquad (1)$$

Satisfying the conditions:

$$\begin{cases} v_{ref} > v_{sat}, & v_{ref} = 0.5; \\ v_{ref} < -v_{sat}, & v_{ref} = -0.5, \end{cases} \qquad (2)$$

where v_{sat} is designed to satisfy standard values for the crest factor. Note that v_{sat} and v_{ref} are normalized relative values ranging from zero to 1.

Figure 5 presents the diagram of the inverter used in the proposed method. As mentioned before, it is quite simple to add new harmonic components to the lamp voltage as well as to synthesize different and arbitrary voltage waveforms. The harmonic injection via PWM is digitally made and therefore modifications in the injected signals are easily implemented by software.

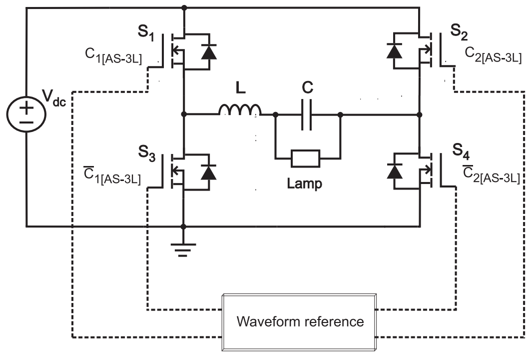


Fig. 5. Diagram of the full bridge inverter with the LC filter

The Asymmetrical Three Level (AS-3L) PWM presents better performance for frequencies below $30kHz$ [15]. Therefore, the AS-3L PWM which presents an equivalent sampling frequency four times that of the S-2L PWM was chosen.

The switching frequency was chosen to be around $30kHz$ which, according to the two indexes to measure the quality of the synthesized waveform, was the best cost-benefit choice available, rendering the best voltage waveform for the lowest frequency.

In the AS-3L PWM, there are three voltage levels at the inverter output (V_{dc}, $-V_{dc}$ or 0) and the measurement of the voltage for the synthesis of the PWM is made at twice the switching frequency, rendering an asymmetrical modulation respecting the switching frequency, with:

$$\tau_{A1}(k) = \frac{T}{2} + \frac{T}{2V_{dc}} v_{ref}(k) \quad (3)$$

$$\tau_{A2}(k) = T - \tau_1(k) \quad (4)$$

where τ_{A1} and τ_{A2} specify the conduction time intervals of the switches imposed by the gating signals $C_{1[AS-3L]}$ and $C_{2[AS-3L]}$ and their respective complementary signals, $\overline{C}_{1[AS-3L]}$ and $\overline{C}_{2[AS-3L]}$. Notice that T is the PWM period and V_{dc} is the DC link voltage.

Figures 6 and 7 present the waveforms of the synthesized voltages and the control signals for the IGBT gate, for $v_{sat} = 0.5$ and $v_{sat} = 0.1875$.

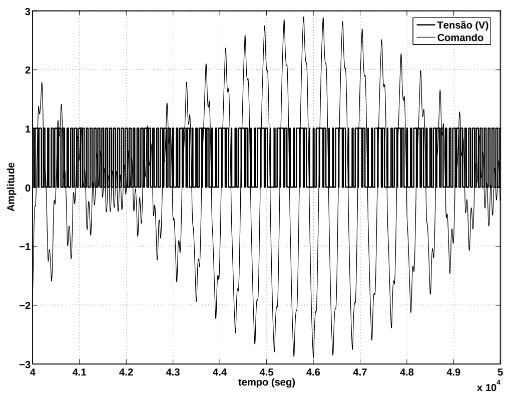


Fig. 6. Voltage waveform synthesized and gate command waveform, $v_{sat} = 0.5$.

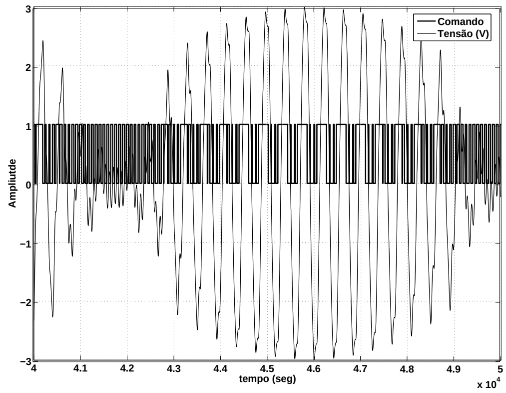


Fig. 7. Voltage waveform synthesized and gate command waveform, $v_{sat} = 0.1875$.

III. Crest factor characterization

In order to evaluate the modulated signals used to supply the HPS lamps some parameters were considered, as for instance, the switching frequency, (F_{PWM}), the fundamental frequency, (f_{fund}), the modulating frequency and the saturation voltage, (v_{sat}). These parameters were varied and their influence on the crest factor, while providing nominal power to the lamp, was quantified.

Figure 8 presents the variation of the crest factor (CF) as a function of the saturation voltage (v_{sat}) for three different switching frequencies (F_{PWM}). The results are obtained through the simulation of the electronic ballast response in which the voltage reference is given by (1).

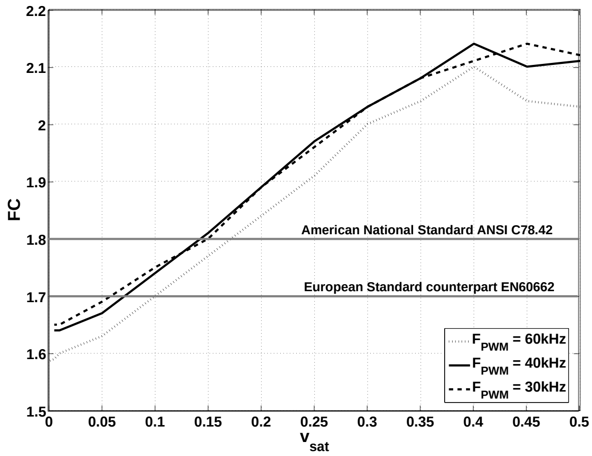


Fig. 8. CF as a function of v_{sat}, for three different frequencies F_{PWM}

It can be seen from this figure, maintaining v_{sat} constant, that the increase on F_{PWM} gives a smaller crest factor.

The variation of the rms voltage value applied to the lamp, with relation to the DC voltage, and the crest factor as a function of saturation voltage can be seen in Figure 9. Where, $F_{PWM} = 60kHz$.

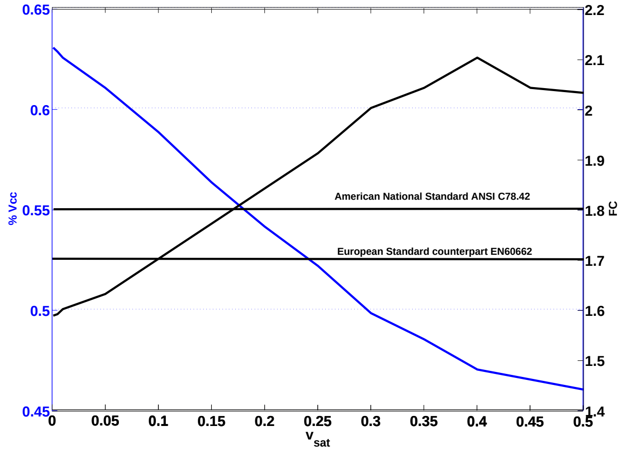


Fig. 9. CF and V_{cc} variation as a function of v_{sat}

In order to assure a crest factor less than 1.8, the reference signal is saturated and thus, limiting the crest factor within the norm values (American National Standard ANSI C78.42, Part IV "relevant lamp data sheets", sets its maximum value at 1.8 and European Standard counterpart EN60662, is even more restrictive, setting the maximum at 1.7). Reference [22] asserts that ballasts with higher crest factors may result in depreciation of lumen output or reduced lamp life.

It is worth mentioning that recent studies point out that a low frequency modulation of the voltage supplied to the lamp reduces the possibilities of acoustic resonance occurrence, although it is not proved that it really avoids it [18]. In order to prove the complete rejection of this phenomenon, it would be necessary to a fundamental frequency in a band where the acoustic resonance occurs.

An important issue to be analyzed is the ration between the fundamental and the modulating frequencies, $a = \frac{f_{mod}}{f_{fund}}$, which guarantees acoustic resonance rejection. In [16] a ratio $a = 0,0017 = \frac{120}{68k}$ is proposed. In [17], $a = 0,002 = \frac{120}{60k}$.

In the present work a fundamental frequency of $12kHz$ has been chosen and modulating frequencies of $150Hz$ and $300Hz$ have been tested in simulation. In the experimental setup a modulating frequency of $300Hz$ was used due to a faster variation in the instantaneous power.

It is important to notice that the filter used in the setup is designed to mitigate the harmonics generated by the PWM and filter the lamp current. In other words, its cut-off frequency is adjusted above $18kHz$. The switching frequency used in this work is smaller than the one in [16]. Additionally, dimmerization can be easily added to the ballast by simply adjusting the reference signal of the voltage waveform.

IV. Experimental Results

The technique consisting in a high frequency waveform reference modulated by a low frequency voltage PWM was tested. For the experimental tests of the proposed technique, an electronic ballast was implemented to supply the following $150W$ lamps: GE Lucalox LU150/100/D/40, OSRAM VIALOX NAV-E 4Y, PHILIPS SON PRO. The LC filter components used are $L = 840\mu H$ and $C = 100nF$.

A DSP from $TexasInstruments^{®}$ (TMS320F2812) is used to generate the driving pulses of the full bridge inverter both for the ignition process and the steady state operation, as well as the pulses for the power factor correction stage and the ballast fault protection.

Figures 10 and 11 show the impact of the variation of v_{sat} in the voltage waveform applied to a resistive load (80Ω). Notice that v_{sat} impacts not only the crest factor but also the rms voltage applied to the resistive load and the DC voltage. The fundamental frequency f_{fund} used was $12kHz$ and the modulating frequency, f_{mod}, $300Hz$.

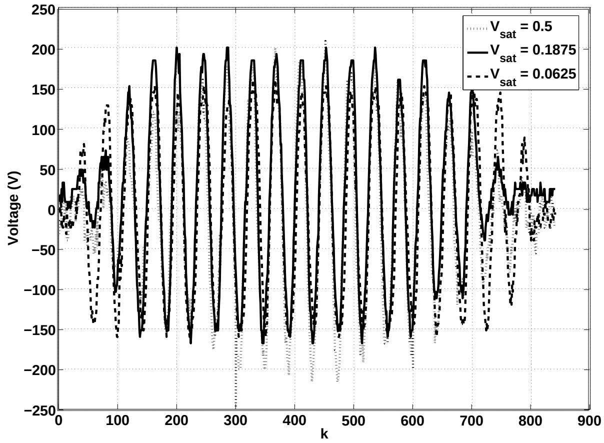


Fig. 10. Voltage waveforms in resistive load for different values of v_{sat}

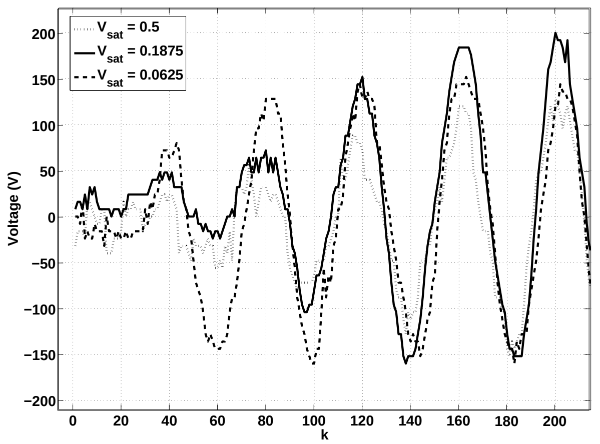


Fig. 11. Detail of voltage waveforms in resistive load for different values of v_{sat}

Figure 12 shows this operating characteristic for a resistive load of 80Ω, with $f_{fund} = 12kHz$ and $f_{mod} = 300Hz$. The f_{PWM} frequency is $32kHz$, with $v_{sat} = 0.1875$.

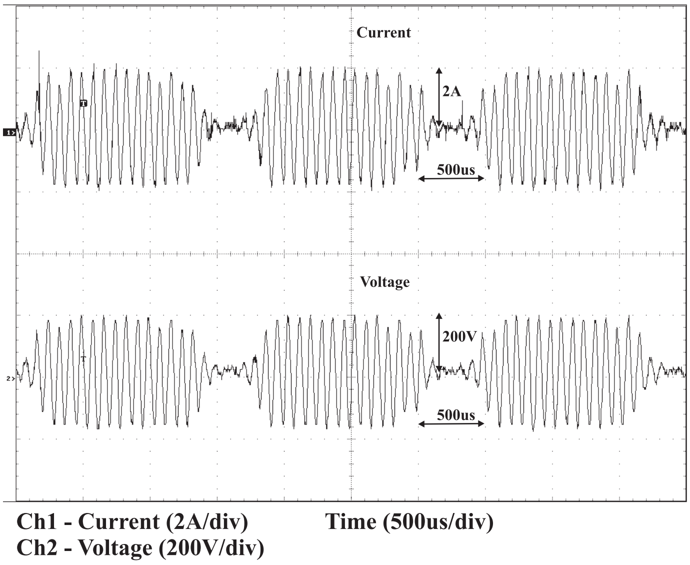


Fig. 12. Waveforms of the measured voltage $(200V/div)$ and current $(2A/div)$ in the resistive load

Figure 13 presents the voltage and current waveforms applied to the lamp in the heating process, for $f_{fund} = 6kHz$, $f_{mod} = 300Hz$ e $v_{sat} = 0.1875$. It can be noticed that, due the large displacement between the voltage and current the power factor is deteriorated.

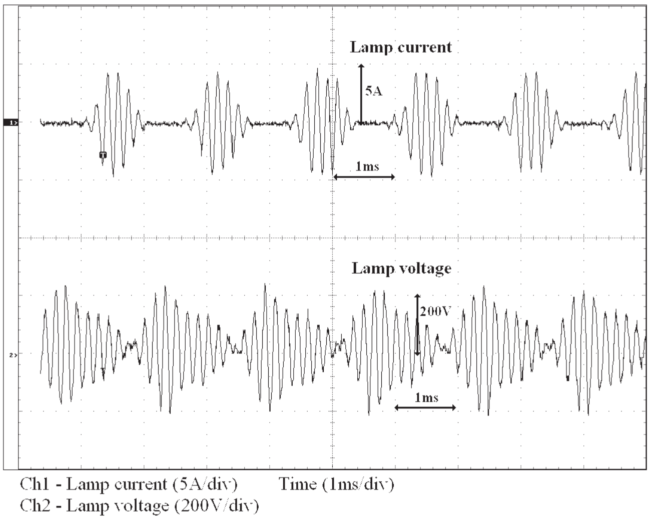


Fig. 13. Waveforms of the measured voltage $(200V/div)$ and current $(5A/div)$ in the $HPS - 150W$ lamp - when heating

Figure 14 presents the voltage and current waveforms applied to the lamp in steady-state, for $f_{fund} = 6kHz$, $f_{mod} = 300Hz$ e $v_{sat} = 0.1875$. When compared with Figure 15, in which $f_{fund} = 12kHz$, it can be observed that there is an improvement in the crest factor using a lower DC voltage.

Figure 15 shows the voltage and current waveforms in the lamp at full power. Both high and low frequency components of the waveforms can be observed, which denote the nonlinear characteristic of the lamp [1]. It can be seen also that the lamp turns on and off each semi-cycle. This is due to the nonlinear characteristic allied to the fact that the voltage reference goes to zero each low frequency semi-cycle. The experimental validation of this technique was done for different types of lamps from different manufacturers.

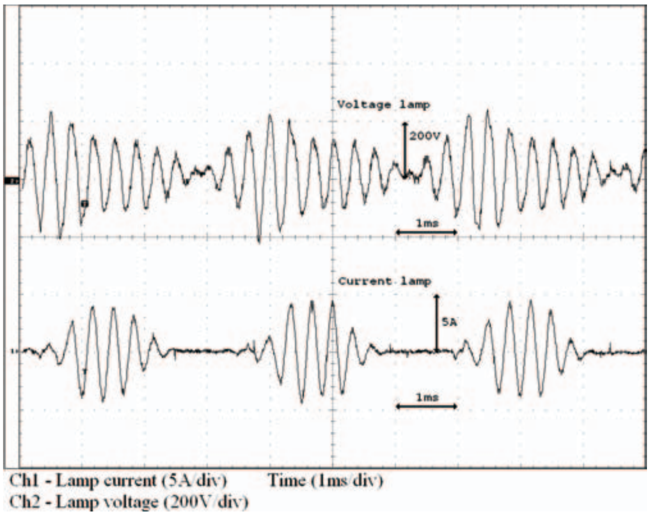


Fig. 14. Waveforms of the measured voltage $(200V/div)$ and current $(5A/div)$ in the $HPS - 150W$ lamp - in SS

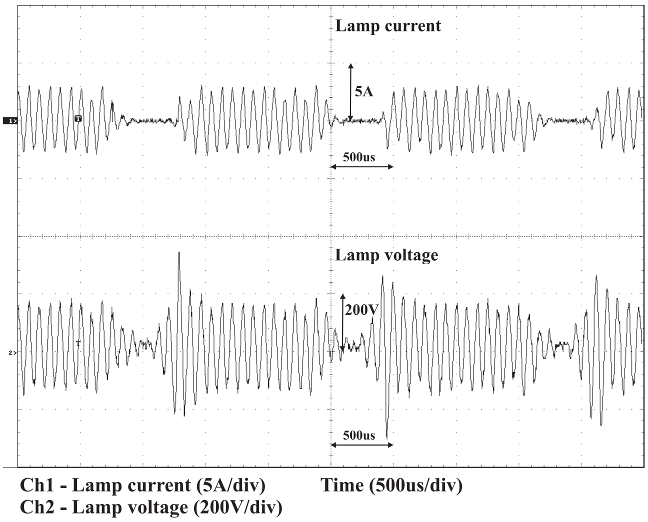


Fig. 15. Waveforms of the measured voltage $(200V/div)$ and current $(5A/div)$ in the $HPS - 150W$ lamp

Through the analysis of the DC current and visualization of the arc it was observed that AR did not occur. The second technique did not imply in the appearance of flicker and nor referring audible noise to the lamp.

It can be observed in Fig. 15 that the maximum value of the lamp current is $3.0A$ and its rms value, $1.72A$. Therefore, the crest factor is 1.754, which satisfies the ANSI standard.

The ignition is performed with the same inverter circuit of the steady state operation using a lower frequency. It is based also on the forced oscillation of the voltage frequency [19]. Notice that the the ignition frequency, $73.610kHz$. Figure 16 shows experimental results of the measured voltage in the lamp during the ignition process.

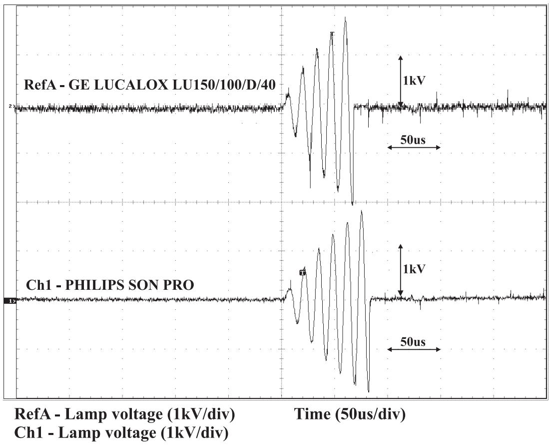


Fig. 16. Waveform of ignition voltage $(1kV/div)$ applied in $HPS-150W$ lamps

V. Conclusion

A full bridge inverter operating in an asymmetrical three level PWM was built, equipped with an LC filter designed for both ignition and steady-state operation.

When using a low frequency modulation of the reference voltage synthesized through PWM, the acoustic resonance does not occur, even in a frequency range where it is expected. This is due to the fact that the power in the lamp has a low frequency oscillation which avoids the excitation of the acoustic resonance. By limiting the modulating signal with saturating value v_{sat} it is possible to shape the crest factor thus, using the DC voltage more efficiently.

In order to prove the complete rejection of this phenomenon, it would be necessary to a fundamental frequency in a band where the acoustic resonance occurs.

The ignition circuit used, through experimental results, the capability of producing the necessary voltage amplitude for the ignition of the lamp.

It is known that acoustic resonance is more severe to 70W HPS and MH lamps. Applying the proposed approach to such lamps, from different manufacturers, in order to complement and enlarge the validation of this technique, is part of the continuity of this work.

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