ACOUSTIC RESONANCE REJECTION VIA VOLTAGE MODULATION METHOD FOR HPS LAMPS

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***Abstract*— A voltage modulation method in order to prevent acoustic resonance (AR) in HPS lamps is presented. Two voltage modulation techniques via PWM inverter are proposed. The first one injects harmonic components in the lamp voltage reference. The second one consist of high frequency voltage modulated by a low frequency waveform. These techniques allow the control of crest factor other than rejecting the AR.**

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

I. INTRODUCTION

High pressure sodium (HPS) lamps present some nice characteristics, such as high light efficiency, long lifetime (around 24,000 hours) and pleasant colors, which justify its large scale use in public lighting. The main challenge when designing electronic ballasts for HPS lamps is to avoid acoustic resonance, which consists on gas pressure fluctuation inside the discharge tube of the lamp when supplied by high frequency power source (from a few kHz to hundreds of kHz). The most relevant effects of the acoustic resonance are the light movement and fluctuation, usually called flicker, the light arc extinction due to its lengthening, the destruction of the discharge tube owing to overheating and, even when the arc is not extinguished, there are, eventually, temperature and R_a variations [1].

There are ways to avoid the occurrence of the acoustic resonance and its nuisance, that consist basically in three strategies: first, avoid frequencies where the acoustic resonance occurs; second, to switch frequencies whenever the acoustic resonance is detected which implies in methods for detecting it; third, even when operating the ballast in frequencies where acoustic resonance occurs, to avoid to excite it through spreading the frequency spectrum. There are several methods in literature dealing with this problem:

1) 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];
2) Using very high frequencies, avoiding the whole range where acoustic resonance occurs, normally higher than $500kHz$ [5], [6];
3) 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];
4) 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];
5) Driving the lamp with DC current also avoids acoustic resonance [13];
6) Using square current waves of high frequency also prevents the acoustic resonance but this approach implies in high levels of electromagnetic interference (EMI), specially radio frequency emitted by the discharge itself;
7) A way of reducing the interference levels of the approach 6) above and yet, preventing the occurrence of acoustic resonance is to superimpose some harmonics (the third and the fifth, for instance) to the high frequency sinusoidal fundamental wave. The resulting wave would be approximately square [14], [15] in terms of spreading the frequency modes, without the inconvenience of high EMI levels;
8) Modulating the voltage applied to the lamp, i.e., a high frequency current modulated by a low frequency waveform [16].

The present paper studies both the harmonic injection technique and the modulated high frequency voltage by a low frequency waveform technique in a PWM inverter-based ballast, aiming at the rejection o acoustic resonance.

This paper has the following structure: First, the introduction discusses the acoustic resonance phenomena and reviews some approaches proposed in the literature to prevent it. Following the introduction, Section II presents the proposed harmonic injection technique and voltage modulation applied to the lamp. Section III discusses the LC filter design in terms of the constraints imposed by the presence of the (third) harmonic. Section IV presents and discusses the experimental results obtained with these techniques, while in the conclusions, the impact of the method proposed on the acoustic resonance rejection is emphasized.

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.

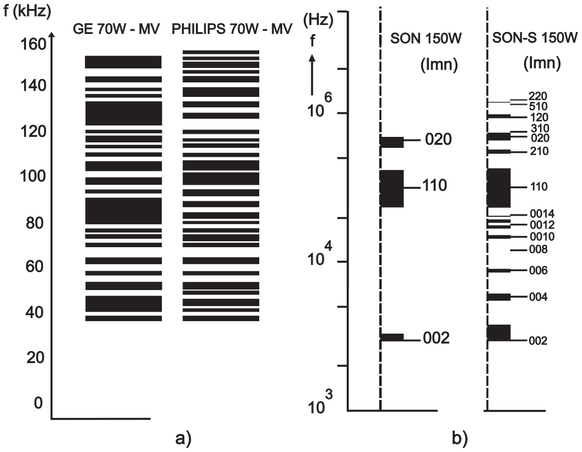


Fig. 1. a)AR free frequency bands for lamps of same power and different manufacturers [17] and b) same manufacturer and different type or power [1]

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 [17] whereas, Figure 1 b) shows it for 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 present paper deals with this problem, investigating a new approach that consists first, in injecting harmonics to the supply voltage of the lamp through a PWM inverter (as mentioned in Section I Method 7, above) and second, using a frequency operation range not frequently used in electronic ballasts which is $(1-10)kHz$. In order to validate the proposed method, the influence of the third harmonic amplitude in the rejection of the AR is studied.

The harmonic injection approach is based on the spread of the frequency spectrum of the power delivered to the lamp thus reducing the power associated to each frequency. The idea behind the method is that if any of the frequencies applied to the lamp corresponds to an AR frequency, its intensity (power) would not be enough to excite this phenomenon.

The approach presented by Alonso *et al.* [14] is based on the harmonic injection where the fundamental frequency is supplied by one of the inverter legs switching with frequency f through an LC filter and a third harmonic frequency is then supplied by the second leg switching at frequency $3f$ and phase delay through a second LC filter.

The method presented in [14] is based on the independent control of each of the inverter legs and on the design of separate filters for the desired harmonics. The main characteristics of this approach consist on the need of one filter for each harmonic injected, increasing the number of components of the ballast, and, the need of one inverter leg for each harmonic injected, that implies the need of extra inverter legs in the case of injecting harmonics higher than the third, amounting thus to the complexity of the inverter in such case. These two situations would definitely imply in heavier and more expensive ballasts in the case of higher order harmonic injection. On the other hand, changes on the ballast operating frequency would demand a complete redesign of the filters.

The proposed method consists in injecting harmonics through their addition them to the fundamental reference signal of the pulse width modulation inverter which will synthesize the voltage applied to the resonant filter feeding the stationary voltage to the lamp. The main feature of this method is its modularity since the harmonics are injected via software.

The reference voltage signal of the PWM is given as:

$$v_{ref} = \sum_{i=1}^{n} a_i \sin(2i\pi f_{fund} t) \tag{1}$$

where f_{fund} is fundamental frequency of the supply voltage.

An immediate advantage of this approach is the need of a single output LC filter no matter how many harmonics are injected. Another important feature is the simplicity with which reference signals are generated without the burden of calculating the phase shift ϕ between gate signals of each inverter leg.

Another 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]. 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:

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

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). Reference [18] asserts that ballasts with higher crest factors may result in depreciation of lumen output or reduced lamp life.

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 the present work a fundamental frequency of $12kHz$ has been chose 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.

The considered technique allows to limit the voltage peaks, in such a way that the crest factor is (also limited) set in 1.8. Figure 2 shows this operating characteristic for a resistive load of 80Ω, with $f_{fund} = 12kHz$ and $f_{mod} = 300Hz$. The f_{PWM} frequency is $32kHz$.

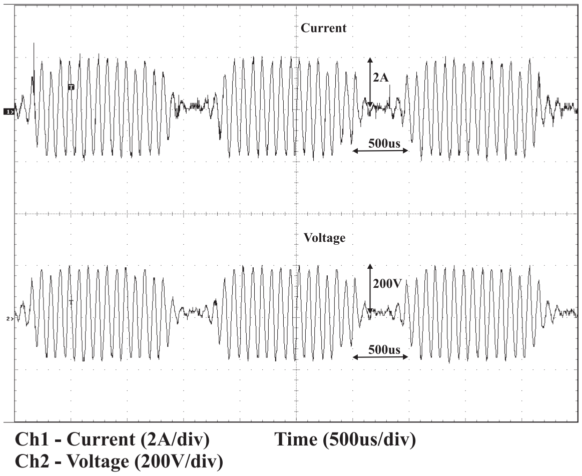


Fig. 2. Waveforms of the measured voltage $(200V/div)$ and current $(2A/div)$ in the load resistive

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 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.

Figure 3 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.

In order to establish the sampling rate needed to synthesize the supply voltage to the lamp with injected harmonics and thus reject AR, two indexes are used The standard deviation (STD) of the power applied to the lamp with respect to the analytical value and The total harmonic distortion (THD) of the current in the lamp.

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.

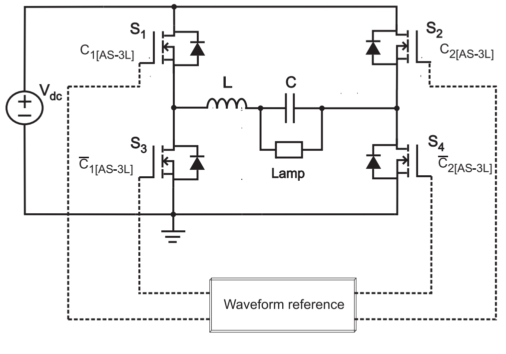


Fig. 3. Diagram of the full bridge inverter with the LC filter

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:

$$\begin{aligned} \tau_{A1}(k) &= \frac{T}{2} + \frac{T}{2V_{dc}} v_{ref}(k) \qquad (3) \\ \tau_{A2}(k) &= T - \tau_1(k) \qquad (4) \end{aligned}$$

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.

III. THE LC FILTER DESIGN

Harmonics injection through PWM using a full bridge inverter demands a specific design for the LC filter at the output. This is based on two conditions necessary to the appropriate behavior of the proposed method: the fundamental and the third harmonic must *i)* be injected without attenuation and *ii)* with the smallest phase shift possible.

The LC filter is a 2^{nd} order filter whose Transfer Function is given as:

$$G(s) = \frac{1}{\left(\frac{s}{\omega_0}\right)^2 + \frac{s}{\omega_0 Q} + 1} \qquad (5)$$

where its frequency response is shown in Figures 4(a) and 4(b). Condition *i)* is guaranteed by:

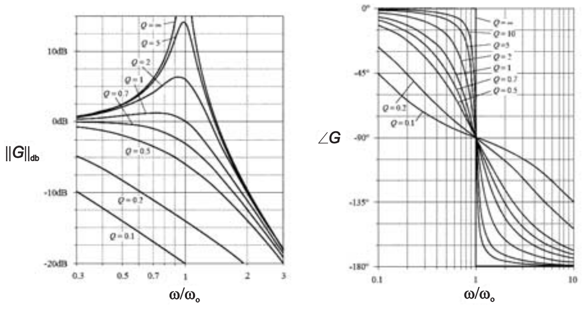
$$\omega \ll \omega_0 \Rightarrow \|G\| \rightarrow 1 \qquad (6)$$

where ω_0 is the cut-off frequency.

The cut-off frequency is defined as a function of the third harmonic frequency ω_{3h} according to the following expression:

$$\omega_0 = \omega_{3h} \alpha \qquad (7)$$

where α is a scaling factor to be determined by the specifications of the filter design. Note that, for frequencies satisfying (7), it is guaranteed that there is practically no attenuation, which is demanded by condition $i)$ above.



(a) Filter gain (b) Filter phase

Fig. 4. a) Filter gain and b) phase as a function of the frequency for different values of Q

Figure 4 shows the impact of the quality factor Q in the LC filter design. $Q = 0.7$ has been chosen, which satisfies conditions i) and ii) without overshoot for any frequency of interest.

Figure 5 shows the frequency response of the filter, using $Q = 0.7$, for different values of α. It can be seen that for values of $\alpha < 4$ there is an attenuation of the third harmonic and a phase shift between this harmonic and the fundamental one. On the other hand, values of $\alpha > 8$ the LC filter with the switching frequency specified, does not attenuate properly fifth harmonic components (noise). Therefore, the value of $\alpha = 6$, has been chosen.

The quality factor, Q, of a resonant parallel LC circuit is given as $Q = \frac{R}{\omega_0 L}$. Therefore, the inductance value of the filter is as:

$$L = \frac{R_{lamp}}{\omega_0 Q}. \tag{8}$$

Given that the natural frequency of the parallel resonant circuit is as $\omega_0 = \frac{1}{\sqrt{LC}}$. The filter capacitance value results:

$$C = \frac{LQ^2}{{R_{lamp}}^2}. \tag{9}$$

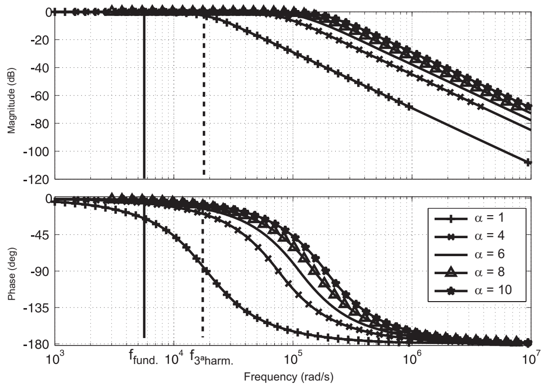


Fig. 5. Filter gain and phase as a function of the frequency for different values of α

IV. EXPERIMENTAL RESULTS

For the experimental tests of the proposed techniques 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.

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.

Tests were performed for fundamental frequencies of $3kHz$ and $3.5kHz$, using a switching frequency of $f_{PWM} = 32,768Hz$. The LC filter components used are $L = 840\mu H$ and $C = 100nF$.

The first technique consisting in the injection of a third harmonic component on the voltage reference waveform was tested. Figure 6 shows the current and the voltage measured in the lamp (GE) operating at its rated values ($100V_{rms}$ and $1.5A_{rms}$), with fundamental frequency of $3.5kHz$ and switching frequency of $f_{PWM} = 32,768Hz$.

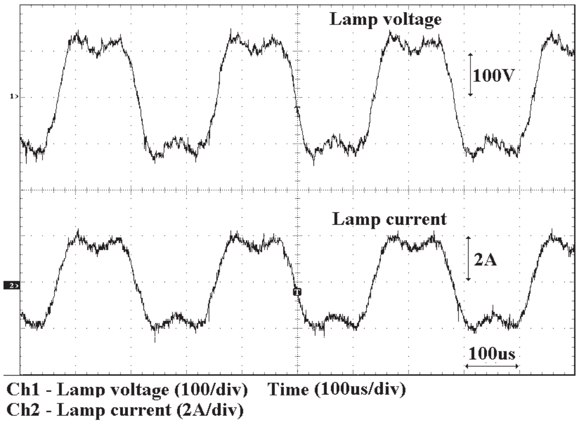


Fig. 6. Waveforms of the measured voltage $(100V/div)$ and current $(2A/div)$ in the $HPS - 150W$ lamp

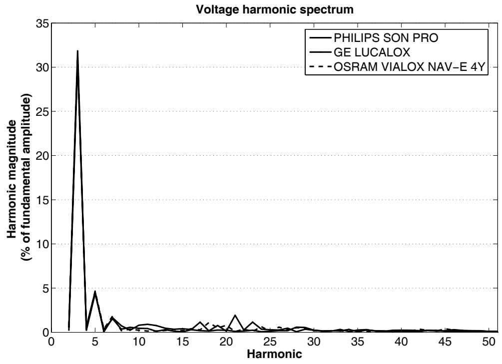


Fig. 7. Voltage harmonic spectrum, $f_{PWM} = 32,768Hz$

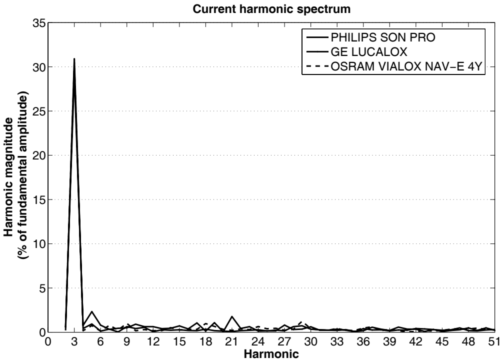


Fig. 8. Current harmonic spectrum, $f_{PWM} = 32,768Hz$

Figures 7 and 8 show the harmonic spectrum of the voltage and current, in the tested lamps, respectively. It can be noticed that the third harmonic injected via PWM in the voltage is 31.1% of the fundamental while the same harmonic present in the current wave is 29.7% of its fundamental component, for the GE lamp.

In order to evaluate the impact of the proposed approach on the rejection of the acoustic resonance (AR), two frequency bands have been defined: [1] This corresponds to the frequency band of $(3.0 - 3.6)kHz$ centered at $3.3kHz$ where AR is known to happen to the lamp used in the experimental tests; and [2] This corresponds to the frequency band below $3kHz$ where it is known that AR does not occur for the lamp used in the tests.

Tests were made for fundamental frequencies of $3kHz$ and $3.5kHz$ (band 1) in order to verify the effectiveness of the approach studied and no AR occurred. On the other hand, when a $3.5kHz$ sinusoidal voltage waveform was applied to the lamp, AR occurred and the electrical arc was extinguished.

Some other tests were performed for frequencies lower than $3kHz$ (band 2) using injection of the third harmonic via PWM, as proposed and no AR was observed. Therefore, it can be stated that the proposed technique does not excite the acoustic resonance phenomenon.

Several tests were performed varying the third harmonic amplitude between 5% and 40% of the fundamental component using fundamental frequencies in the band were AR occurs (band 1). For these tests the fundamental frequency was chosen to be $3.5kHz$ and the switching frequency as $32,746Hz$. The impact of the third harmonic in the avoidance of AR is evaluated by varying its amplitude as shown in Figure 9.

Figure 9 shows three regions delimitated according to the third harmonic component amplitude, a_3, as defined in (1). The AR free region corresponds to the harmonic component $29\% < a_3 < 40\%$ of the fundamental amplitude, for all three lamps. Increasing the third harmonic amplitude $a_3 > 40\%$ was not done due to the limitation of the DC link voltage (overmodulation).

The second technique consisting in a high frequency voltage reference modulated by a low frequency waveform was thus tested.

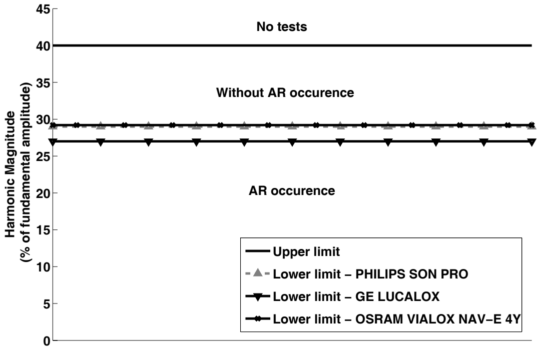


Fig. 9. Operating regions of the lamp defined by the third harmonic amplitude

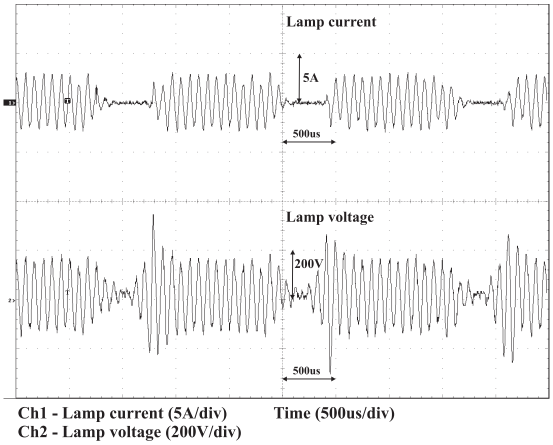


Fig. 10. Waveforms of the measured voltage $(200V/div)$ and current $(5A/div)$ in the $HPS - 150W$ lamp

Figure 10 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.

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. 10 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 [15]. Notice that the the ignition frequency, $73,610Hz$. Figure 11 shows experimental results of the measured voltage in the lamp during the ignition process.

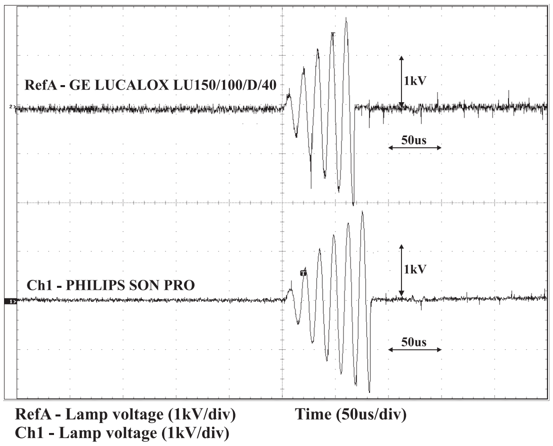


Fig. 11. Waveform of ignition voltage $(1kV/div)$ applied in $HPS-150W$ lamps

V. CONCLUSION

Two different techniques used to avoid acoustic resonance were presented. These techniques propose an alternative method based on voltage modulation. The first one injects harmonic components in the lamp voltage reference. The second one consist of high frequency voltage modulated by a low frequency waveform.

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.

One of the main features of the proposed technique is modularity and simplicity for the synthesis of the lamp supply voltage waveform. Controlled third harmonic injection in the lamp voltage is done aiming at avoiding AR. This is based on the spread of the frequency spectrum of the power delivered to the lamp thus reducing the power associated to each frequency. Therefore, if any of the injected frequencies applied to the lamp correspond to an AR frequency its intensity (power) would not be enough to excite this phenomenon.

With this purpose in mind, several tests were performed for frequency bands where acoustic resonance normally occurs and where it does not. It was shown that, when injecting a third harmonic component with an appropriate amplitude, AR is always avoided. It can be seen that it also reduces the crest factor of the lamp current.

When diminishing the third harmonic component below a certain relative value with respect to the fundamental, the acoustic resonance is not rejected anymore. The reason is that, whenever the fundamental frequency is close to any of those where AR occurs, the energy associated with this frequency is, now, high enough to excite AR.

When using a low frequency modulation of the reference voltage synthesized through a PWM the acoustic resonance does not occur, even in a frequency range where it is expected. This due to the fact that the power in the lamp has a low frequency oscillation which avoids the excitation of the acoustic resonance.

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

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