Electronic Ballast for High Pressure Sodium Lamps without Acoustic Resonance via Controlled Harmonic Injection Synthesized with PWM

L.M.F. MORAIS, P.F. DONOSO-GARCIA, S.I.SELEME JR, P. C. CORTIZO
Universidade Federal de Minas Gerais
Departamento de Engenharia Eletrônica
31270-901 Belo Horizonte, MG - BRASIL
Email: lenin@cpdee.ufmg.br, pedro@cpdee.ufmg.br, seleme@cpdee.ufmg.br, porfirio@cpdee.ufmg.br

Abstract: This paper presents a study and analysis of a electronic ballast for high pressure sodium lamps followed by simulation and experimental results. The acoustic resonance control technique consists in the injection of current harmonics fed to the lamp, which are synthesized by the full bridge inverter via PWM through an LC filter. The controlled harmonic spectrum of current supplied has been used in order to avoid acoustic resonance. Another interesting feature of this approach is the reduction of the crest factor of the lamp current. Acoustic resonance happens when the inverter is operating in high frequency, which has certain advantages as the use of smaller and less costly passive elements, although the switching losses increase and acoustic resonance may occur. The use of currents with harmonics is a way of avoiding the excitation of this resonance due to the frequency spread. The LC filter design is also presented, which allows the desired harmonics to pass with controlled amplitudes, while filtering undesired high frequency components. Furthermore, simulation and experimental results of the proposed electronic ballast are presented to verify the analytical discussions and the design specifications.

I. INTRODUCTION

Acoustic resonance, which occurs due to pressure oscillations of the gas inside the discharge tube, is by far the most challenging defy when designing HPS electronic ballast [1]. The most relevant effects of the acoustic resonance are light flicker, arc extinction, destruction of the discharge tube due to overheating [1] and also, temperature and color rendering index variation.

The alternatives to avoid this problem, cited in the literature, are the following:

i. Use of constant frequency between 20kHz and 200kHz, choosing a free resonance frequency window [2, 3, 4]. Although simple, this is not an effective solution because the resonance free windows can vary with time, making it very difficult to find a resonance free window for every lamp;
ii. Use of frequencies above the acoustic resonance occurrence range, which are normally greater than 500kHz [5]. This solution implies higher switching losses and Electromagnetic Interference - EMI, on one hand, and additional complexity in the ballast design;
iii. Operation of the circuits using some modulation strategy, activated by the sensing of the acoustic resonance in order to change the inverter frequency when it happens, avoiding the evolution of the resonance and its consequences [6, 7]. Recent studies have shown, though, that this technique is not very effective when applied to low power lamps [8];
iv. Use of low frequency square wave current [9, 10]. In this case, low frequency operation results in the increasing of weight and size of the passive elements and the inclusion of the power factor correction – PFC stage usually decreases the efficiency of the ballast;
v. Use of high frequency square wave current. This solution generates high levels of EMI, especially RFI, emitted by the discharge itself. One way of reducing these EMI is to approximate the square wave form by adding some higher order odd harmonics to the fundamental sine wave (the third and the fifth harmonics, for instance) [11]. Nevertheless, this technique is not quite well investigated;

Feeding the lamp with DC current also avoids acoustic resonance [12], but this solution reduces the lifetime of standard lamps drastically and can only be used for special lamps [13].

II. INJECTION OF HARMONICS VIA PWM

In a recent paper [11] a method for the injection of harmonics is presented, based on the design of passive filters associated with the correspondent harmonics and on the digital control of the inverter lags. The main disadvantage of the method is the need of one filter for each harmonic component, which increases the number inverter lags, of passive elements, weight and cost, along with the increase of the complexity of the inverter control.

The approach proposed in the present work consists on the injection of harmonics to the fundamental sine wave via PWM, operating the inverter at switching frequency range adequate to the operation of the inverter. The controlled harmonic injection in the lamp is synthesized via PWM with a reference sinusoidal waveform plus the desired harmonics in order to avoid acoustic resonance. The advantages of the method are the use of one single LC filter allied with the simplicity of the reference signal and its synthesis with the inverter. The PWM is easily generated, digitally, as in our case, with a DSP

(TMX320F2812).

As a first step, our approach will be implemented in a frequency range where acoustic resonance doesn't occur. Next, it will be applied where this resonance has been observed with standard methods in order to validate our method.

Figure 1 shows the diagram of the full bridge inverter with the LC filter used for the proposed method. The sampling frequency of the signal is related to the switching frequency (f_{PWM}) of the inverter. Therefore, the asymmetric three level PWM has been chosen, due to the fact that its sampling frequency is twice the one of the symmetric PWM.

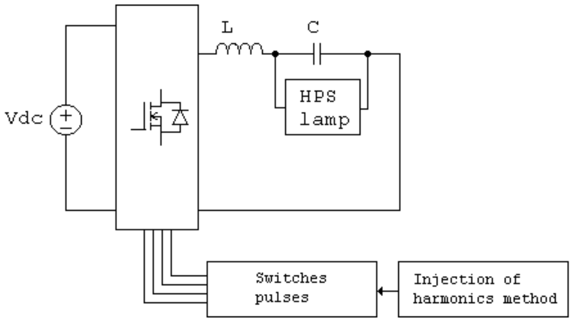

Fig.1: Diagram of the full bridge inverter with LC filter and switching control

With the controlled harmonic injection technique it is possible to investigate the meaningful values of magnitudes of the harmonics a_i, in Equation (1), to avoid acoustic resonance.

$$s_{ref} = \sum_{i=1}^{n} a_i \sin(2i\pi t) \quad (1)$$

Figure 2 depicts the voltage waveforms for three switching frequencies: f_{PWM}=15kHz, 25kHz and 50kHz. The reference waveform is composed of the fundamental frequency of 1kHz (a_1=1) and the third harmonic with a_3=1/3 of the amplitude of the fundamental. The LC filter used has the following parameters: L=833µH, C=92nF. The lamp equivalent resistance is: R_{lamp}=66.6Ω. Admitting that with an almost square waveform (fundamental + 3rd harmonic), the lamp can be considered as a resistance.

In order to evaluate the sampling frequency needed to synthesize a reference waveform good enough to reject acoustic resonance, two parameters were used:

1)The Standard Deviation (STD) of the lamp power and 2) The Total Harmonic Distortion (THD) of the current.

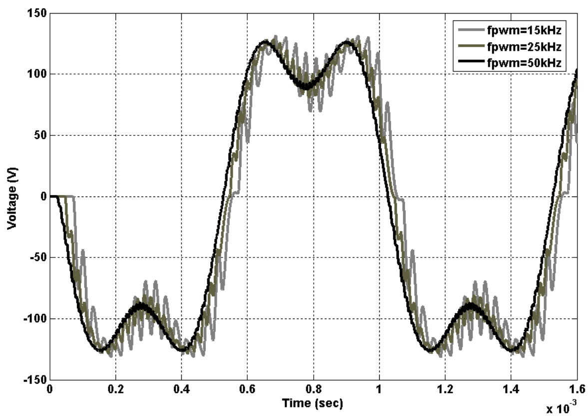

Fig.2: Voltage waveforms applied to R_{lamp} for different f_{pwm}

Figure 3 presents a comparison of the symmetric two level PWM (S-2N) and the asymmetric three level PWM (S-3N), with different switching frequencies.

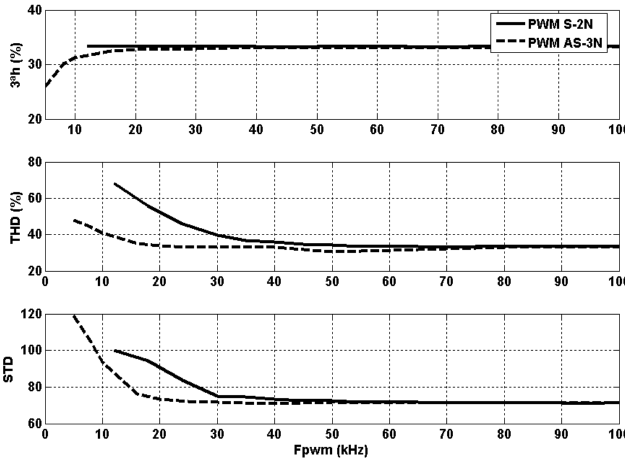

Fig.3 : a) Third harmonic current amplitude, b) THD of the current and c) STD of the power

III. LC FILTER DESIGN

Figures 4 and 5 present the frequency response (gain and phase, respectively) of the LC filter with different quality factors, Q.

The filter design is based on the specification that the fundamental and the 3rd harmonic are injected with no attenuation and no phase shift. The corner frequency was chosen as 6 times the 3rd harmonic frequency and the quality factor Q=0.7, in order cope with its specifications. This can be seen also from Figures 4 and 5.

Figure 6 presents the frequency response of the designed LC filter.

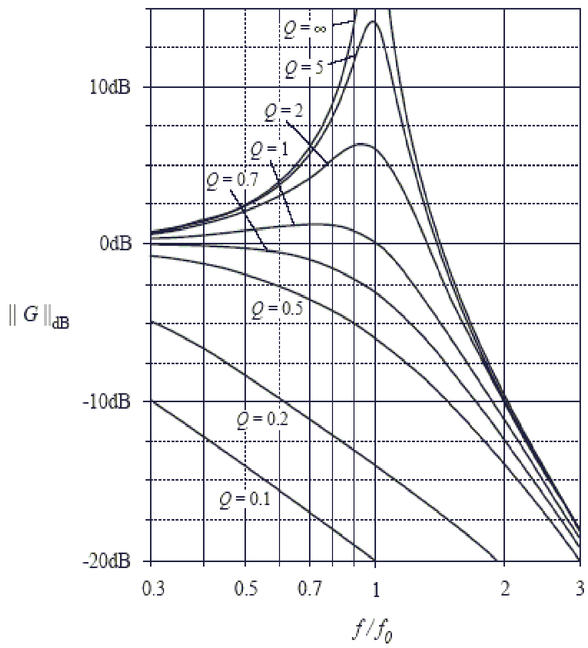

Fig. 4: Filter gain *versus* frequency for different values of Q

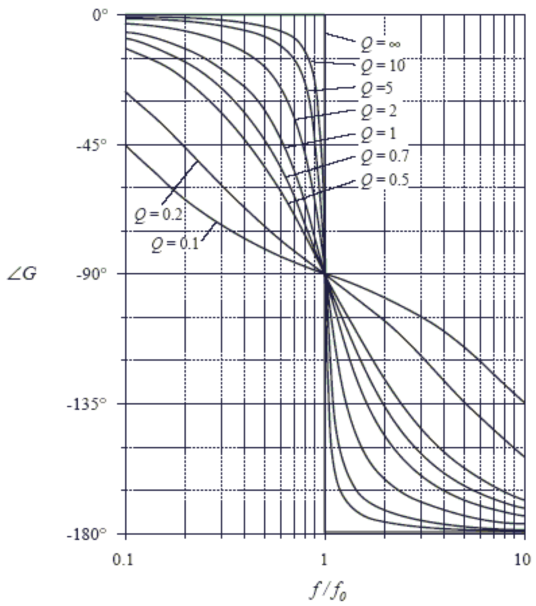

Fig.5: Filter phase *versus* frequency for different values of Q

The equations for the inductance, L and the capacitance, C, as a function of the quality factor, Q and the lamp resistance, R_{lamp}, are:

$$L = \frac{R_{lamp}}{2\pi Q f_0} \quad (2)$$

$$C = \frac{Q^2 L}{R_{lamp}^2} \quad (3)$$

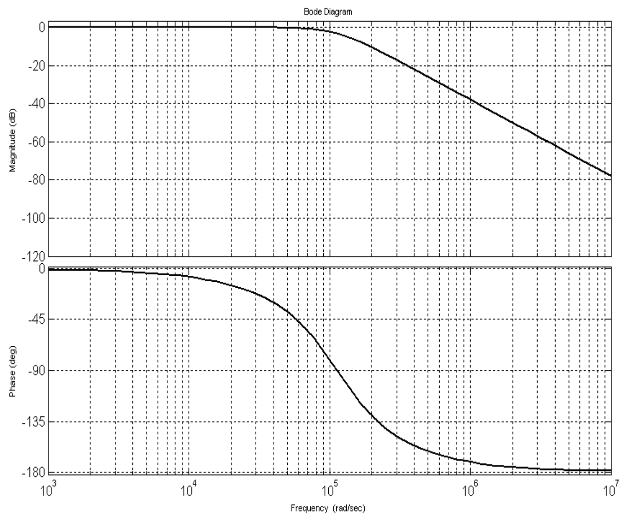

Fig. 6 : Frequency response of the designed LC filter, L=833µH, C = 92nF e R_{lamp} = 66.6Ω.

IV. IGNITION

A parallel resonant circuit, as shown in Figure 7, is used for the ignition of the lamp, with the inverter operating at high frequency. The ignition is performed using a frequency (f_{ig}) close to the resonance. The commutation to the steady state frequency (f_{PWM}) is done after a period of time, which guarantees the ignition of the lamp. The insertion of capacitor C_{ss} is made by the switch S_6 at this moment. Thus, the equivalent capacitance (C_{ss} + C_{ig}) is the one designed for the filter in Section 3.

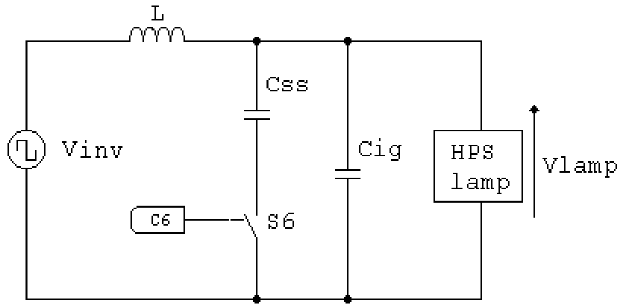

Fig. 7: Scheme of the ignition circuit

The frequency response equation of the resonant circuit is given as:

$$\frac{V_{lamp}(j\omega)}{V_{inv}(j\omega)} = \frac{1}{\sqrt{\left(1-\left(\frac{\omega}{\omega_O}\right)^2\right)^2 + \left(\frac{\omega}{\omega_O Q}\right)^2}} \quad (4)$$

where

$$\omega_O = \frac{1}{\sqrt{L \cdot C_{ig}}} \quad (5)$$

$$Q = \frac{R}{\omega_O L} \quad (6)$$

Before the ignition, the lamp behavior is that of an open circuit ($Q \rightarrow \infty$). Therefore, the resonant circuit without load will provide an output voltage in the lamp, which depends exclusively on the LC components.

For the designed values of L=833µH, C_{ig}=5nF and f_{ig}=73kHz, the voltage needed for the ignition is achieved. Figure 7 shows the frequency response curve of this process.

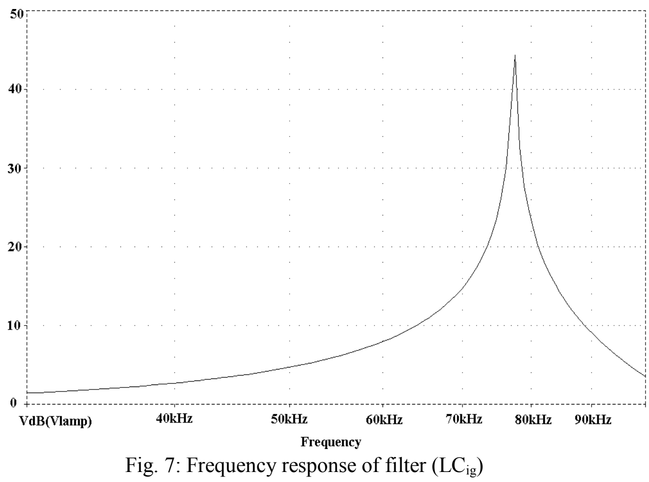

Fig. 7: Frequency response of filter (LC_{ig})

V. BOOST – POWER FACTOR CORRECTOR

The power factor correction is an important stage, very common in electronic ballasts nowadays, due to technical norms requirements.

Figure 8 shows a complete diagram of the electronic ballast emphasizing the power factor corrector (PFC) boost converter with the control loops (current and voltage). A zero order holder (ZOH) samples the output voltage V_o at 120Hz, thus avoiding the propagation of the rectifier bridge modulation.

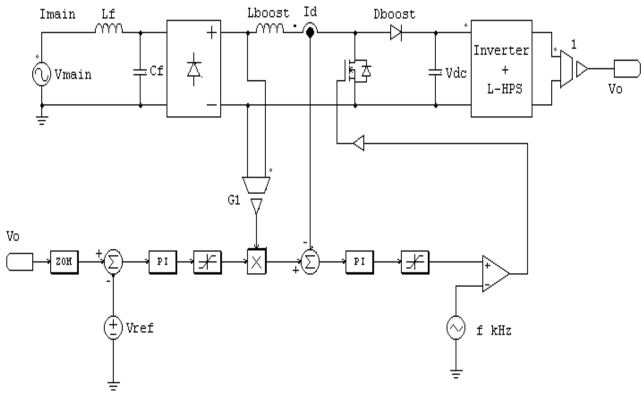

Fig.8 : Complete diagram of the electronic ballast emphasizing the power factor corrector (PFC) and control loops

The line current and voltage waveforms (127V_{rms}, 60Hz) obtained in simulation are shown in Figure 9.

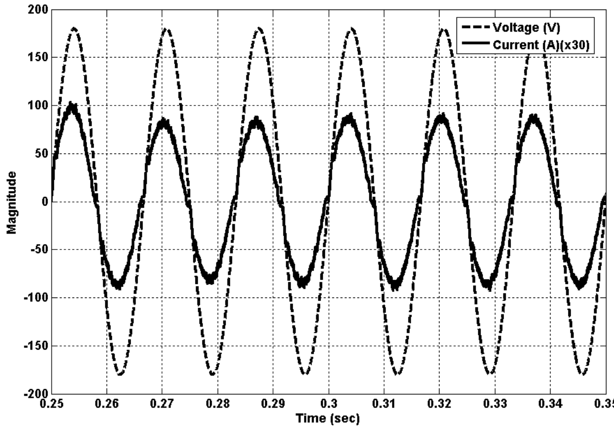

Fig. 9: Line input voltage and current waveform

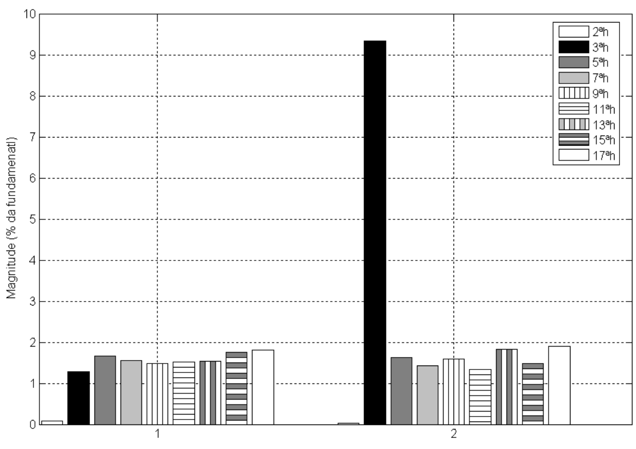

Fig. 10 :Spectrum of the input current for methods 1 (120Hz sampling) and 2 (ordinary)

Figure 10 presents the harmonic spectrum of the input current for method 1 [14] compared to that of method 2 ordinarily used, where the output is sampled at the same frequency as the inductor current of the boost converter (I_d).

Notice that, although both approaches satisfy the IEC-1000-3-2 norm for class C equipments [15], the THD for the method 1 is 4.95%, while that of the ordinary procedure is 9.56%.

VI. EXPERIMENTAL RESULTS

An electronic ballast using GE Lucalox LU150/100/D/40 lamp was built and tested (see Figure 1 for the inverter and LC filter diagrams).

Tests were done for fundamental frequencies of 3kHz and 3.5kHz, with f_{PWM}=32768Hz. The values of the LC filter are L=840µH, C=105nF. Note the $C = C_{ig} + C_{ss}$, where C_{ig}=5nF/3,2kV and C_{ss}=100nF/250V.

Figure 11 shows the measured lamp voltage during ignition. The ignition frequency is 73kHz. Note that the peak breakdown voltage is approximately 1750V.

The voltage and current of the lamp at steady state, operating at nominal condition (100V_{rms} and 1.5A_{rms}), with a fundamental frequency of 3.5kHz and f_{PWM}=32768Hz, is shown in Figure 12.

Figures 13 and 14 show the harmonic spectrum of current and voltage, respectively, where it can be seen that the 3rd harmonic component injected via PWM in the lamp voltage is 31.1% of the fundamental, whereas the current 3rd harmonic component is 29.7%.

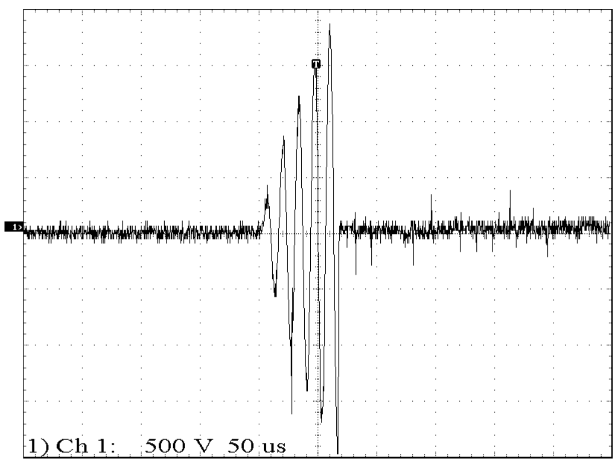

Fig. 11: Measured lamp voltage waveform in ignition

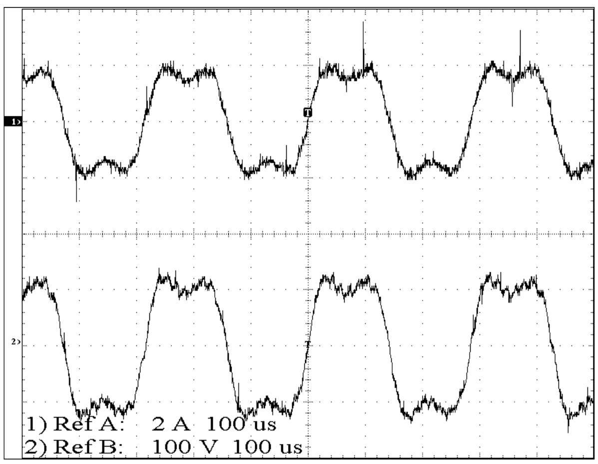

Fig. 12: Measured lamp voltage and current waveforms

As it can be observed from the experimental results, the THD is quite dependent on the switching frequency and on the voltage waveform.

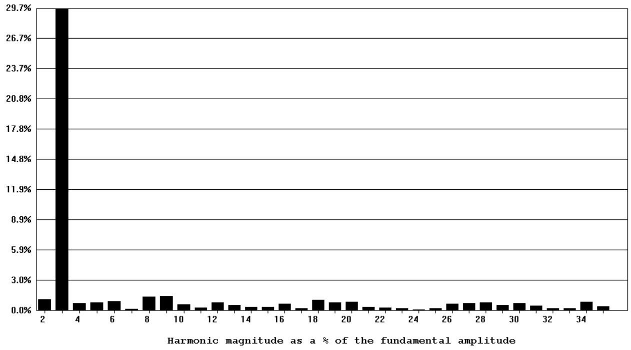

Fig 13: Harmonic spectrum of current with f_{pwm} = 32768Hz

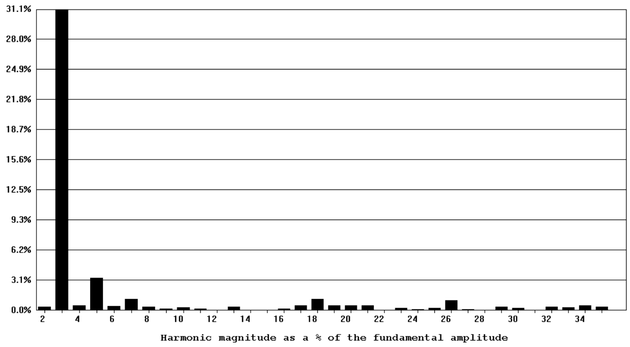

Fig 14: Harmonic spectrum of current with f_{pwm} = 32768Hz

According to [1] one of the acoustic resonance bands for the 150W lamp occurs at 3.3kHz. In the tests performed with the mentioned lamp at frequencies of 3kHz and 3.5kHz with the proposed approach, the acoustic resonance was not observed.

Some other tests were also performed at frequencies lower than 3kHz where the acoustic resonance was not observed. In other words, it shows that our approach does not excite this phenomenon. See also Figure 15 with the arc path at 3.5kHz (fundamental frequency), without acoustic resonance.

Finally, the inverter voltage waveform is presented in Figure 16, which is a three level PWM

Fig 15: Picture of the arc path of the lamp operating at fundamental frequency of 3.5kHz

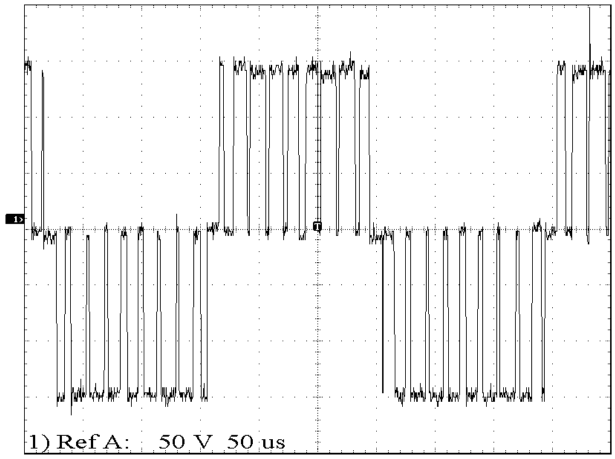

Fig. 16: Inverter voltage waveform

VII. Conclusion

This work presents a controlled harmonic injection technique via PWM. The full bridge inverter is driven by a three level asymmetric PWM with a switched LC resonant filter designed for the lamp ignition and steady state operation.

One of the main features of this approach is the simplicity and modularity on the synthesis of the voltage waveforms applied to the lamp. The inclusion of harmonics to the fundamental voltage reference is used to avoid acoustic resonance. A third harmonic with 1/3 of the amplitude of the fundamental voltage is included in order to, not only reject acoustic resonance but also reduce the crest factor in the lamp. Further analysis and results will follow with different fundamental frequencies and harmonic profiles, applied to different lamps from various manufactures.

Several tests were done: 1) in a frequency range, which presents acoustic resonance; 2) in a lower range of frequencies where acoustic resonance is not reported. In all these tests the acoustic resonance was not observed.

Acknowledgment

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