HARMONICS INJECTION IN HPS ELECTRONIC BALLAST WITH MODULATION INDEX CONTROL

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Abstract – **The modulation index control is used in this work to control the lamp power supply permitting the removal of the output transformer out of the inverter-resonant filter setup. The Acoustic resonance in HPS lamps can be avoided by using a controlled PWM inverter and third harmonic injection.**

Experimental and simulation results are shown for the control of the inverter power subject to variation in the input voltage. Results for different DC bus voltages are also provided which attest the transformer removal and avoid the acoustic resonance with different modulation indexes. An ignitor for high-intensity discharge lamps, based on forced oscillation via an external periodic voltage square wave, supplied by a digitally controlled inverter, is also presented. The crest factor of the current can also be reduced by this approach.

Keywords - **Acoustic Resonance Avoidance, HPS Lamps, Harmonic Injection, Modulation Index, PWM.**

I. INTRODUCTION

High pressure sodium (HPS) lamps present some interesting characteristics, such as high light efficiency, long lifetime (around 32,000 hours) and pleasant colors, which justify its large scale use in public lighting. Standard HPS lamps have their color rendering index, Ra, as defined by the CIE-1974, around 25 in a scale ranging from 0 to 100. New models of these lamps present better indexes for the color reproduction, going up to 85 in the CIE-1974 range, although with shorter lifetime and lower light efficiency [1].

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 Ra variations [2].

There are several ways to avoid the occurrence of the acoustic resonance and its nuisance, that consist basically in three strategies: first, to avoid frequencies where the acoustic resonance occurs [3]-[9]; second, to switch frequencies whenever the acoustic resonance is detected which implies in methods for detecting it [10],[11],[12]; third, even when operating the ballast in frequencies where acoustic resonance occurs, to avoid exciting it through spreading the frequency spectrum [13]-[21],[28]. Each and every one of these alternatives has its advantages and drawbacks as will be pointed out further.

An interesting way of achieving the harmonic injection, while varying the voltage and power supplied to the lamp is to modulate the voltage applied to the lamp, i.e., a high frequency current modulated by a low frequency waveform [23],[24].

Note that the PWM inverter provides technical means for both, the modulation index variation and the harmonic injection necessary to avoid the acoustic resonance.

The reminder of the paper is organized as follows. The harmonic injection method is revisited in the next section. The proposed topology and some typical waveforms are presented in the third section. The fourth section shows the ignition circuit of the ballast and presents experimental results, while the conclusions are presented in the last section.

II. HARMONIC INJECTION METHOD

As it was mentioned [16], using a specific constant frequency in the (20–200) kHz range where Acoustic Resonance (from now on named as AR) 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. The occurrence of AR happens in a large spectrum of frequencies and does not show a predictable pattern [1]. Apart from that, these frequencies may change over the lifetime of the lamp.

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 the introduction) and second, using a frequency operation range not frequently used in electronic ballasts which is (1–10) kHz. Generally, an operation frequency above 20 kHz is used, for audible noise issues, but due to problems with the AR, we decided to decrease the operation frequency to a range close to that used when feeding of the lamps with square wave voltages [22],[28],[29].

The harmonic injection approach is based on spreading 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.

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The proposed method consists in injecting harmonics through their addition to the fundamental reference signal of the PWM 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 (1) where f_{fund} is fundamental frequency of the supply voltage:

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

Where:
i - the harmonic order,
a_i - magnitude of the harmonic.

An immediate advantage of this approach is the need of a single output filter no matter how many harmonics are injected. Another important feature is the simplicity achieved. Indeed, reference signals are generated without the inconvenient in calculating the phase shift between gate signals of each inverter leg. For details on the PWM implementation to synthesize the voltage waveform in (1), see [16].

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.

Harmonics injection, through PWM using a full bridge inverter, demands a specific design for the 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 1) be injected without attenuation and 2) with the smallest phase shift possible [16].

III. PROPOSED TOPOLOGY

Figure 1 presents the diagram of the full bridge inverter used in the proposed method. The driving signals and their respective complementary signals, which correspond to the asymmetrical three level (AS3L) PWM, are described in detail in [16]. The choice of the PWM AS3L is due to a better synthesis of the voltage waveform applied to the lamp for the same frequency, when compared to the symmetrical two level PWM. Note that the dc voltage corresponds to the PFC Boost converter output.

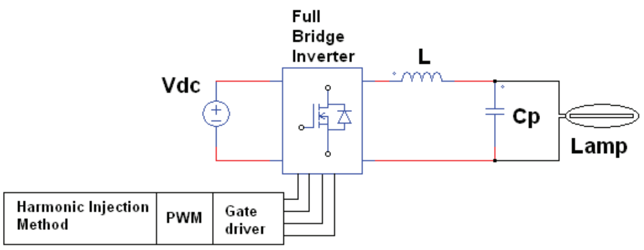


Fig. 1. Diagram of the full bridge inverter with the LC filter.

The use of a Boost DC-DC converter in the ballast aims at correcting its power factor. In order to reduce cost and size, the PFC Boost output voltage is normally high. This implies a smaller inductor. Given that the full voltage range of the reactor is 110-220Vrms, using a Boost converter implies that the converter output voltage is greater than the supply voltage to the lamp. This is case even when a full-bridge inverter is used to generate a square-wave to the lamp or pure harmonic injection. Therefore a transformer has to be used to adjust the voltage applied to the lamp. In general, electronic ballasts with Boost PFC, as shown in Figure 2.a., demand the use of a transformer at the output, in order to provide the nominal voltage of the lamp.

In order to eliminate the transformer at the ballast output, which is generally used with PFC Boost converters the voltage regulation via the inverter is proposed. Same examples PFC boost converters can be found in [3],[11],[16],[25],[28].

The proposed topology, as shown in Figure 2.b., avoids the inconvenience of the transformer by controlling the modulation index of the inverter as a means of regulating the output voltage and, at the same time, allowing the use of a small boost inductor. Therefore, the ballast weight and size are reduced. On the other hand, the harmonic injection technique to avoid acoustic resonance can be also applied in together with the lamp voltage regulation.

For places where the grid voltage is 220 V@50/60 Hz, the dc link voltage is 311V, which is the input to the PFC Boost converter. With this input voltage it is possible to have the usual 400 V at its output, which is the dc link voltage. Thus, the input current control renders a low THD, within the limits imposed by the IEC-61000-3-2 standard.

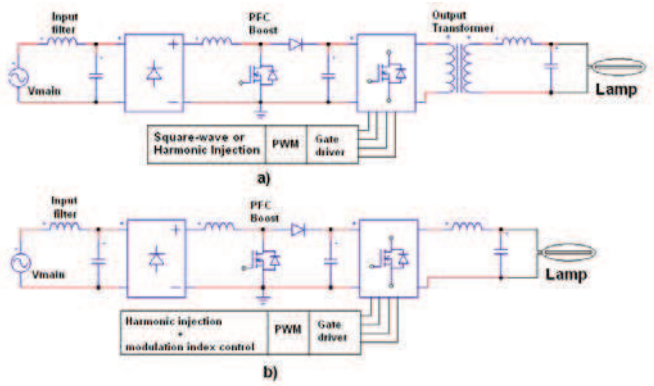


Fig. 2. a) Block diagram of the conventional electronic ballast, with output transformer and b) Block diagram of the proposed electronic ballast, controlling the modulation index.

For places where the grid voltage is 110/127 V@50/60 Hz, the dc link voltage is 155/180 V. In this case, the PFC Boost converter output voltage can be established at 250 V. In order to illustrate the two conditions described above, Figure 3 shows the voltage waveforms at the inverter output with two different voltages at the PFC stage output: 250 V and 400 V. The lamp nominal voltage and power are 100 Vrms and 150W, respectively. It is worth mentioning that the nominal voltage in the lamp can be obtained using a transformer with an appropriate transforming ratio. Thus, the modulation indexes would be always, $m_1 = 1$ and $m_3 = 0.33$, where m_i is the modulation index of the i^{th} harmonic.

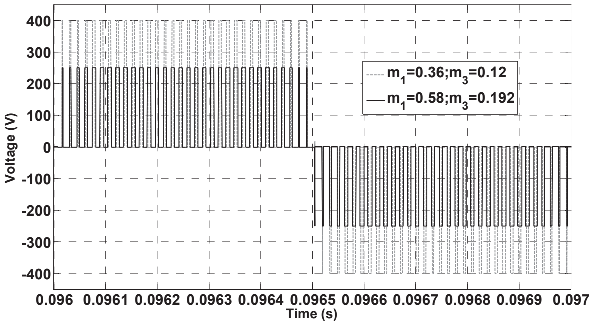


Fig. 3. Waveform of the inverter output voltage (100 V/div) for two different DC bus.

In order to validate the proposed approach, the simulations of the lamp voltage are provided for both, the conventional and the proposed topology.

Table I presents the modulation indexes as a function of the PFC converter output voltage. Note that the voltage ratio 400/145 corresponds to the voltage supplied to the lamp using a transformer. The other voltage ratios correspond to the ballast without transformer, i.e., the modulation index for the fundamental frequency, (m_1), is less than 1, and the one for the third harmonic, (m_3), less than 0.33.

TABLE I
Modulation indexes for different values of the DC Link voltages – PFC converter output

Modulation index	V_{inv} (V)		
	With transformer (400/145)	w/o transformer 250	w/o transformer 400
m_1	1	0.58	0.36
m_3	0.33	0.19	0.12

Figure 4.a. presents the voltage waveform of both the conventional and the proposed electronic ballast. For the conventional ballast (with transformer) the modulation indexes are, $m_1 = 1$ and $m_3 = 0.33$. Given that the voltage output of the PFC stage is 400 V, in the case of the conventional ballast, the transformer has a transformation ratio of 1:0.36 (400:145). For the proposed topology, the modulation indexes are $m_1 = 0.36$ and $m_3 = 0.12$, which provide the nominal voltage in the lamp without the output transformer. In the case where the dc link voltage is 250 V, the following modulation indexes are: $m_1 = 0.58$ and $m_3 = 0.19$. The switching frequency used in the experimental setup was f_{PWM} =32.768 kHz.

Figure 4.b. shows the harmonic spectra of the lamp voltage for both cases. It is worth noticing that the modulation index reduction, which occurs in the proposed approach, implies in a higher harmonic distortion. Nevertheless it is not a significant problem, since this distortion occurs in high frequency, as it can be seen from the figure. In other words, the acoustic resonance approach technique of harmonic injection is preserved.

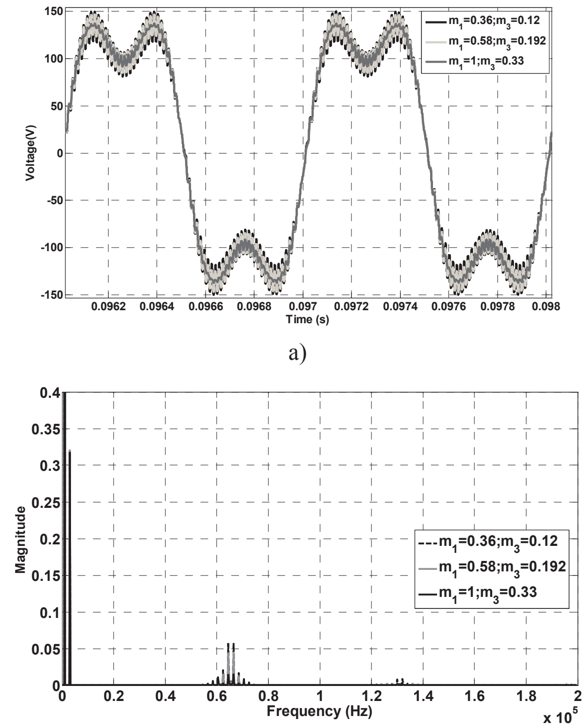


Fig. 4. a) HPS lamp voltage waveform for the proposed ballast with reduced modulation index and the conventional ballast and b) harmonic spectra of the lamp voltage for both cases.

IV. IGNITION CIRCUIT

The proposed ignition circuit is based on a parallel resonant circuit. The parallel resonant circuit is excited with an external periodic voltage square wave through an inverter [26]. The voltage amplitude is V_{dc}, and voltage frequency, ω_{ign}, is close to the resonance frequency of the circuit depicted in Figure 5.

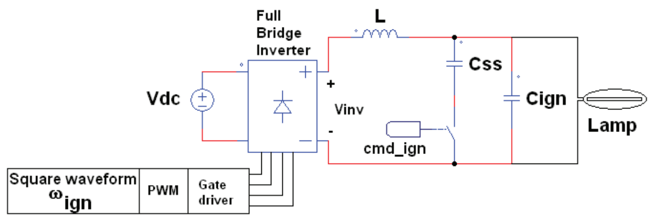


Fig. 5. Diagram of the ignition circuit proposed.

The time response of the voltage waveform in this type of circuit has a lobular form. The analysis of this phenomenon, as will be done later on, allows the determination of the necessary ignition frequency, f_{ign}, and the external square wave amplitude, V_{inv}, in order to have voltage lobes in the lamp with pre-specified amplitude and duration. The lobe amplitude is determined from the standard ignition voltage of the lamp. The lobe duration is a consequence of the pre-specified number of ignition trials [26].

The maximum ignition frequency, F_{ign_max}, is calculated for each possible PFC output voltage (250 V or 400 V) in order that the voltage lobe maximum value does not exceed the rated voltage of the ignition capacitor C_{ign}. The ignition frequency, F_{ign}, must be smaller than F_{ign_max}.

The gain G_{inv} depends on the topology of the inverter used, given as: a) full bridge inverter: $G_{inv} = 4/\pi$ and b) half bridge inverter: $G_{inv} = 2/\pi$.

The ignition voltage amplitude, V_{ign}, can be given as a function of the inverter gain, G_{inv} and the desired voltage gain, designed in order to obtain the ignition voltage, G_{ign}, as:

$$V_{ign} = G_{inv} G_{ign} G_{mod} V_{inv} \quad (2)$$

The gain G_{mod} in (2) is equal to 0.5, due to the amplitude modulation of the signals. The procedure for designing the ignition circuit is as follows [26].

1. The maximum voltage ignition, V_{ign}, is chosen and the gain G_{ign}, expressed in decibel, is calculated in order to achieve the desired V_{ign} as:

$$G_{ign}(j\omega_{ign}) = 20\log\left(\frac{V_{ign}G_{mod}}{V_{dc}G_{inv}}\right) \quad (3)$$

2. The ignition frequency, V_{ign}, is determined by the frequency response of the parallel LC inverter, given by:

$$G_{ign}(s) = \frac{1}{\sqrt{(s/\omega_0)^2 + (s/\omega_0 Q) + 1}} \quad (4)$$

where $Q = R/\omega_0 L$ and $\omega_0 = 1/\sqrt{LC}$. Note that V_{ign} is the frequency with which the inverter shall operate until the ignition of the arc.

The ignition gain, expressed as a function of the ignition frequency, obtained from (3), is given as:

$$|G_{ign}(j\omega_0)| = \frac{1}{\sqrt{(1-(\omega_{ign}/\omega_0)^2)^2 + (\omega_{ign}/\omega_0 Q)^2}} \quad (5)$$

Table II presents the ignition frequency values as a function of the PFC output voltage for L = 833 μH and C_{ign} = 5 nF [16]. The ignition voltage is 2.8 kV.

TABLE II
Ignition frequencies for each DC link voltage (PFC output voltage)

Vdc (V)	Fign (kHz)	Fign_max (kHz)	Gain (2.8kV/Vdc)
120	73.61	74.61	25
250	68.55	70.76	12
400	62.21	66.04	7.5

One of the main advantages of using an ignition circuit, which forces the oscillation of the lamp voltage, is the inherent limitation of current and voltage on the ballast components, diminishing their stress. This is due to the fact that the ignition occurs in a natural way, as the voltage reaches the necessary amplitude for that particular lamp. There is no need for the nominal voltage to be constantly applied to the lamp as it is in regular resonant ignitors.

V. POWER CONTROL

Other than providing for index modulation and harmonic injection, the controlled PWM inverter can regulate the lamp voltage and guarantee nominal power in the lamp at any circumstance, such as a change in the lamp impedance with time (slow variation) or DC link voltage perturbations (fast variations).

This can be accomplished by using the lamp current and voltage measurement and feeding them back to the inverter by an appropriate control law. Figure 6 presents the block diagram of the power controller, which has the basic features of controlling the modulation index and injecting harmonics in the voltage. Note in this diagram the presence of the saturation block at the controller output that prevents the inverter to operate with over modulation. Note also, the gain, k = 0.345, which provides the injection of the third harmonic with an amplitude slightly larger than 1/3 of the fundamental. The controller was designed taking into account slow dynamics on the lamp impedance variation, which can be modeled as a slow time varying resistance. Inverter input DC voltage (fast dynamics) variations were also considered [27], [29].

In order to maintain the output power constant and compensate for the lamp aging, one has to use its current and voltage measurements. As it can be seen from the block diagram of the lamp power control, in Figure 6, this is done via the dynamical adjustment of the modulation index of the PWM inverter. Note that the saturation block at the controller output is used to avoid this value to exceed the maximum comparative amplitudes of the PWM for both, the fundamental and the third harmonic signals. The controller design takes into account the inverter input voltage variation and assumes a slow variation of the lamp impedance that when fed by a high frequency voltage can be modeled as a resistance. The resistance variation due to the aging of the lamp is not a dynamical concern, since it is slow. The perturbation rejection of the PI has to be tuned and respond to the inverter input voltage variation.

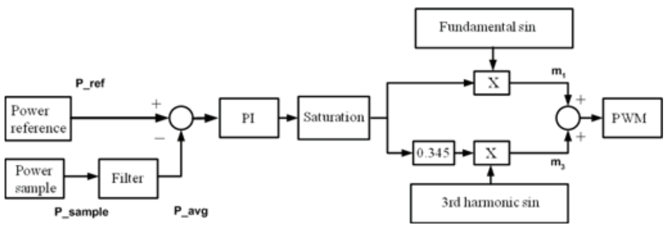


Fig. 6. Block diagram of the power controller using the modulation index compensation.

VI. EXPERIMENTAL RESULTS

For the experimental test of the proposed technique, an electronic ballast was implemented to supply the following 150 W lamps: GE Lucalox LU150/100/D/40; OSRAM VIALOX NAV-E 4Y; and PHILIPS SON PRO.

The switches used in the experimental tests were IGBTs (IRGB20B60PD1), with nominal current and voltage capacities, 13 A/600 V and limiting switching frequency, 150 kHz. The inductor has an E42 type ferrite core (Thornton) and the capacitor parameters are 100 nF/500 V (Epcos). The single IGBT gate drivers used are MC33153P (On Semiconductor).

A DSP from Texas Instruments (TMS320F2812) was 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 [15]. Note that the use of microprocessors imply in the reduction of the total amount of components of the ballast [29].

Table III presents the comparison of the modulation indexes of simulation and experimental results for different values of the DC link voltage. The m_1 e m_3 values between the simulated and experimental results are different due to voltage drops which occur in the system, therefore they were increased to maintain the rated voltage at the lamp.

TABLE III
Comparison of the modulation indexes of simulation and experimental results for each value of the DC link voltage

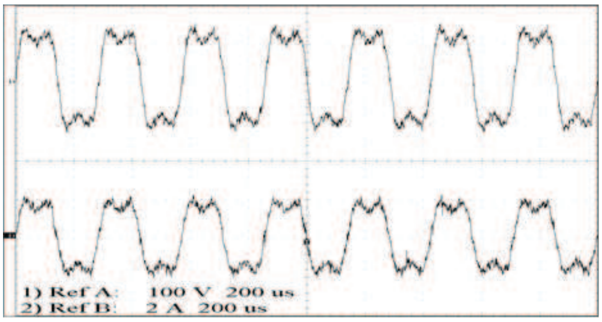
	Simulation		Experimental	
Vdc (V)	m_1	m_3	m_1	m_3
145	0.95	0.30	1	0.33
215	0.63	0.21	0.67	0.22
250	0.58	0.19	0.60	0.20
270	0.53	0.17	0.56	0.19
360	0.38	0.14		
400	0.34	0.12		

Figure 7.a. shows the current and the voltage measured in the lamp (GE) operating at its rated values (100 Vrms and 1.5 Arms), with fundamental frequency of 3.5 kHz and switching frequency of 32.768 kHz, with the following modulation indexes: m_1 = 1 and m_3 = 0.33. Figure 7.b. presents the lamp current and voltage waveforms. In this case, the transformer is removed and therefore, the modulation indexes are: m_1 = 0.60 and m_3 = 0.20, for the experimental situation.

The peak value of the current in the lamp shown in Figure 7.a. is 1.8 A whereas it is 2 A in Figure 7.b. Not that in both cases the rms value of the current is 1.5 A. Thus, the crest factor is 1.2 and 1.33, respectively, for these two different modulation indexes.

Figure 8.a. and 8.b. show the current and the voltage harmonic spectra, respectively, for two different configurations: the curves in black are those for the circuit including the transformer, where the modulation indexes are, m_1 = 1 and m_3 = 0.33; the curves in gray are for the circuit without transformer, where the modulation indexes are, m_1 = 0.60 and m_3 = 0.20. For the voltage and current waveforms in the lamp, using m_1 = 0.60 and m_3 = 0.20 (Fig. 8.b.), the THD obtained were 34.85% for the voltage and 35.01% for the current. Note that the DC link voltage is 250 V and the PWM switching frequency is, f_{PWM} = 32.768 kHz.

Figure 9 shows the three level PWM inverter output voltage and lamp voltage waveforms for two different DC bus voltages. Figure 9.a. shows the electronic ballast with transformer, with modulation indexes: m_1 = 1 and m_3 = 0.33 and Figure 9.b. shows the electronic ballast without transformer, where V_{dc} = 250 V and the modulation indexes are: m_1 = 0.60 and m_3 = 0.20, in Figure 9.c. shows the electronic ballast without transformer, where V_{dc} = 270 V and the modulation indexes are: m_1 = 0.56 and m_3 = 0.19.



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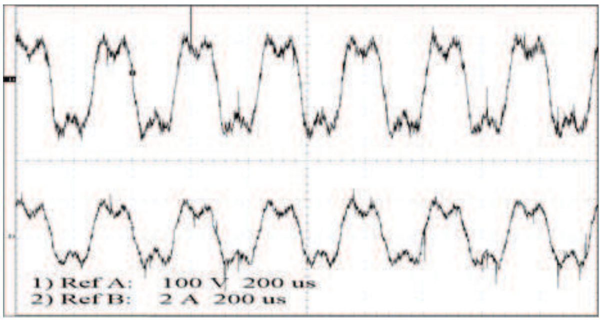
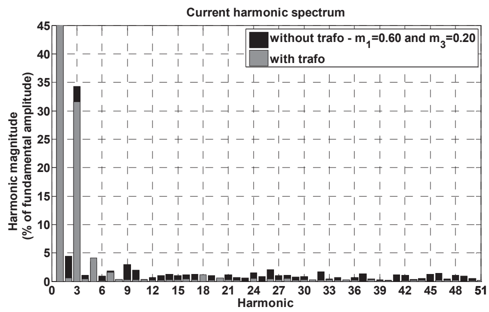


b)

Fig. 7. a) Waveforms of the measured voltage (100 V/div) and current (2 A/div) in the lamp, for modulation indexes m_1=1 and m_3=0.33, b) without transformer, V_{dc}=250 V, m_1=0.60 and m_3=0.20.



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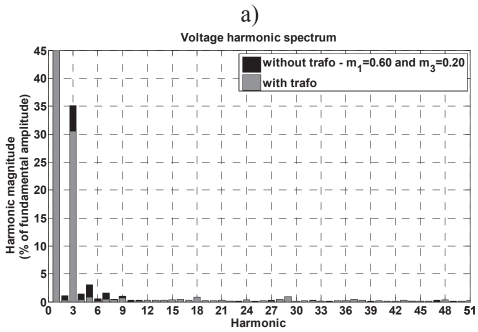
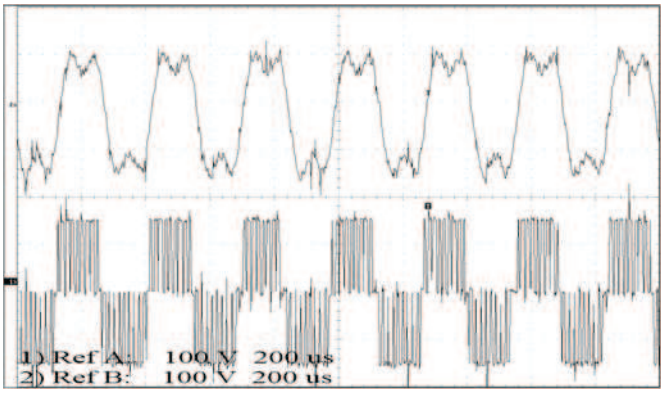


b)

Fig. 8. a) Current harmonic spectrum, f_{PWM} = 32,768Hz , for modulation indexes m_1=1 and m_3=0.33, b) Current harmonic spectrum, f_{PWM} = 32.768 kHz V_{dc} = 250 V, m_1=0.60 and m_3=0.20, without transformer.



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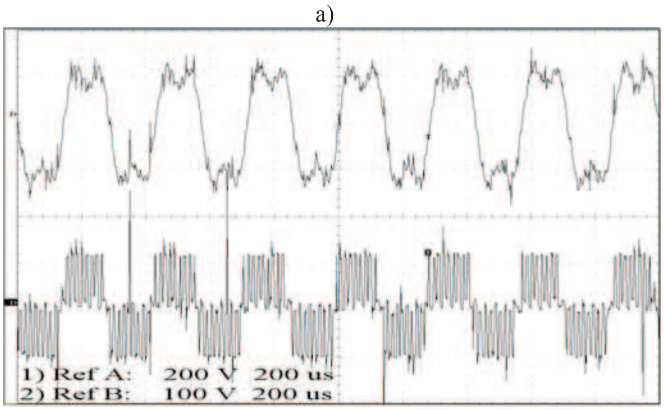

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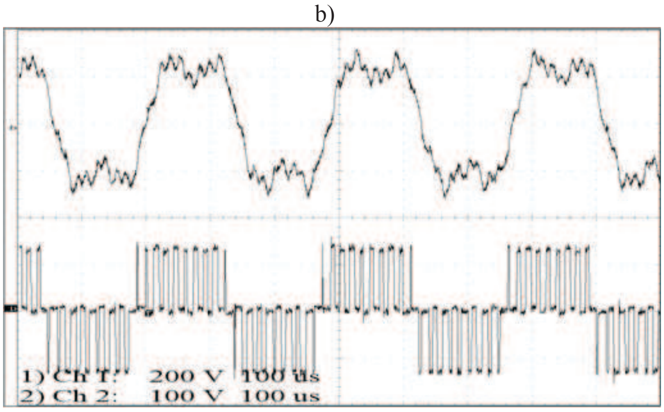
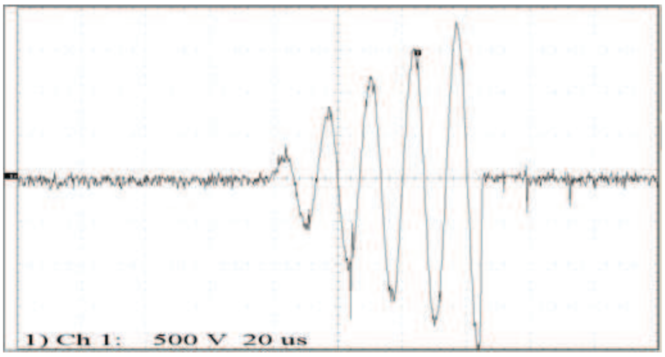


c)

Fig. 9. Waveform of the inverter output voltage and lamp voltage (100 V/div), a) with transformer, m_1= 1, m_3 = 0.33 and b) without transformer, V_{dc} = 250 V, m_1 = 0.60, m_3 = 0.20 and c) without transformer, V_{dc} = 270 V, m_1 = 0.56, m_3 = 0.19.

Figure 10 shows experimental results of the measured voltage in the lamp during the ignition process for F_{ign} = 73 kHz (a) and F_{ign} = 67 kHz (b). For F_{ign} = 73 kHz, the DC link voltage is 120 V, whereas for F_{ign} = 67 kHz, the DC link voltage is 250 V. The ignition is performed with the same inverter circuit of the steady state operation. It is based on the forced oscillation (beating) of the voltage frequency [26].



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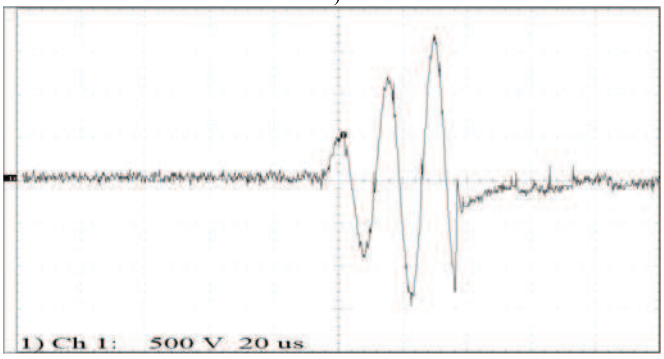

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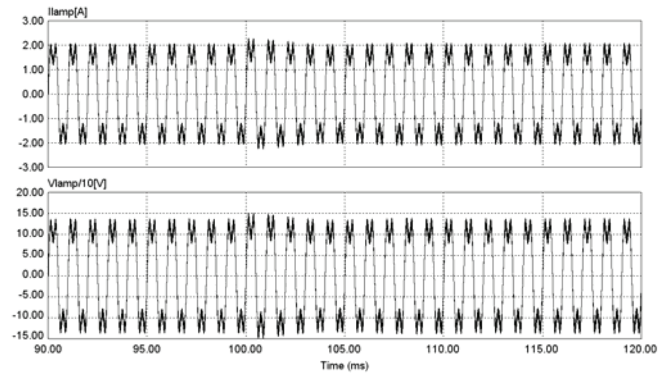
Fig. 10. Waveform of ignition voltage (500 V/div) applied in HPS-150W lamp, a) F_{ign}=73 kHz and b) F_{ign}=67 kHz.

Figure 11 presents simulation results of the power control response which is based on the modulation index control for a 10% variation of the DC link voltage (270V). Figure 11.a. shows the lamp current (Ilamp) and voltage (Vlamp/10) waveforms, whereas Figure 11.b. shows the fundamental (m_1) and the third harmonic (m_3) sinusoidal waveforms with their respective modulation indexes. Finally, Figure 11.c. depicts the measured (P_sample/100) and reference (P_ref/100) (nominal) power as well as the average power (P_avg/100).



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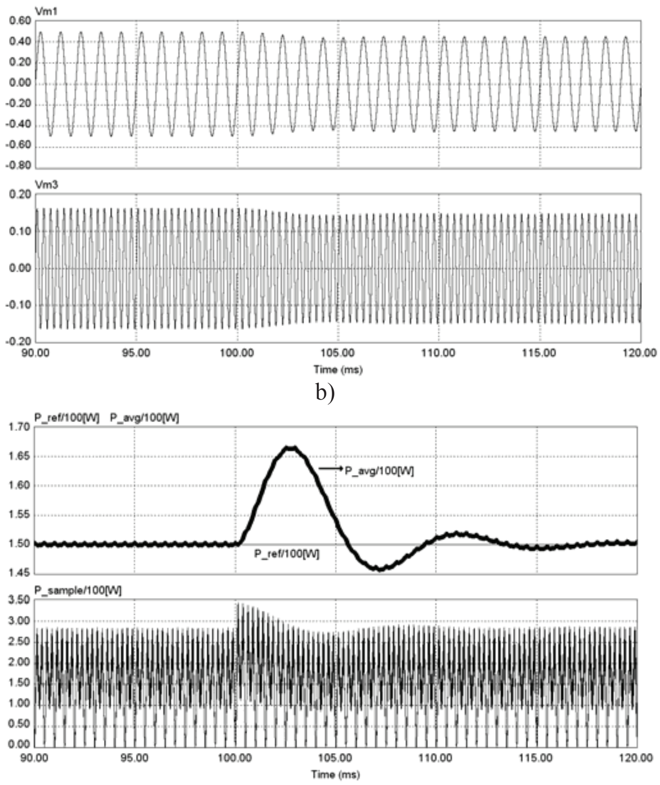

b)

c)

Fig. 11. a) lamp current and voltage , b) fundamental, m_1, and third harmonic, m_3, waveforms and c) reference (nominal), average and sample power both for a 10% DC voltage variation occurring at 100 ms.

All the tests in the lamps were performed in regions where acoustic resonance occurs, following the procedures adopted in [16] and, in none of the tests this phenomenon was observed. Furthermore, the generated harmonic powers were analyzed and stayed below 5%, in agreement with that presented in [15].

VII. CONCLUSIONS

A full bridge inverter operating with an asymmetrical three level PWM was built and equipped with a 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 spreading 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. Acoustic resonance was shown to be avoided with the third harmonic injection approach.

The ignition circuit proposed and studied in this paper has shown, through experimental results, the capability of producing the necessary voltage amplitude for the ignition of the lamp.

The control of the modulation index in the inverter provides the regulation of the HPS lamp voltage without the need of an output transformer, thus reducing, cost, volume and weigh of the ballast. Also, the possibility of varying the lamp voltage with the inverter modulation index makes it possible to provide nominal power to the lamp, even with variations on its parameters, along its entire lifetime.

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