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Characterization of Acoustic Resonance in a High Pressure Sodium Lamp

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***Abstract*-With the last decades, the high pressure sodium (HPS) lamp has been supplied in high frequency in order to increase the efficacy of the lamp/ballast system. However, at some given frequencies, standing acoustic waves, namely acoustic resonance (AR), might develop in the burner and cause lamp luminous fluctuation, extinction and destruction in the most serious case. As we seek for a control method to detect and avoid the lamp AR some main characteristics of the acoustic resonances in a 150W HPS lamp are presented in this paper,. The first one is the characteristic of the lamp AR threshold power, the second one is the differences between forward and backward frequency scanning effects during lamp open loop operation. Thirdly, lamp AR behaviour in closed loop operation with an LCC half bridge inverter will be presented and leads to a new point of view and a change in the choice of the AR detection method. These characteristics allow us to further understand the AR and to better control the lamp.**

***Index Terms*-Acoustic resonance, AR threshold power, AR detection, forward and backward frequency sweeping**

I. INTRODUCTION

The HPS lamp has been developed in the last decades to be supplied in high frequency in order to improve its lifetime, power efficiency, colour and reduce ballast weight and size. However, at high frequency operation some acoustic resonances (AR) can develop in the lamp, which may lead to lamp instability such as discharge arc fluctuation, extinction and even lamp destruction in the most severe case [1]. From the theoretical point of view, AR are provoked by the propagation of an acoustic wave in the closed volume of the burner. Basically, AR occur when the lamp harmonic power frequency is equal to the AR eigenfrequency of the lamp and its amplitude is higher than a threshold value [2][3]. The intensity of AR can be classified into three degrees, slightness, seriousness and extinction [4]. Furthermore, it can also be different from lamp to lamp of the same type from the same manufacturer due to manufacturing. Presently, the problem of AR is still not completely understood. Some technical papers deal with the effect of lamp tube and electrode shape on the acoustic resonance [5][6]. Some physical models of lamp AR have also been developed to predict the eigenfrequencies [7] and to reproduce arc motions [8][9]. However, the AR power threshold is still determined experimentally. The study of threshold power is an important part of lamp characterization in order to choose an appropriate lamp supply. This issue will be presented in section II in this paper. In addition, the possibility of AR detection by the variation of lamp parameters will be also discussed in section III. Another significant feature of the AR is the different behaviour depending on the sweeping direction of the power supply frequency sweep. The study of backward frequency sweeping has revealed lamp electrical parameters before arc extinction and under what conditions an HPS lamp should be operated. This will be discussed later in part IV. In section V, lamp operation with an LCC half bridge and its AR characteristic in a closed loop control will be presented. New considerations will be provided for AR detection in closed loop control and could improve the control of the lamp under high frequency operation. Section VI will conclude this work.

II. THRESHOLD VALUE OF AR POWER

The AR power threshold indicates the excitation condition of the lamp power for the AR to take place at a given frequency. Many research activities have been carried out to find an appropriate supply waveform for the lamp in order to avoid the AR, such as square wave low frequency supply [10], square wave high frequency supply [11], amplitude modulation [12], white noise modulation[13], frequency modulation [14], and the third voltage harmonic injection strategy [15]. The basic idea of all methods is to have the distribution of power harmonic components below the AR threshold value. The analysis of lamp power ripple impacts due to AR on arc deflection was also given in [16]. In our study, we focus on the determination of this power threshold which is a main factor in the choice of lamp supply.

As illustrated in Fig. 1, a 150W SONT HPS Philips lamp (made in Belgium) is supplied by an inverter powered by a DC current source in parallel with a cascade connection of sinusoidal source through an amplifier with a transformer and a blocking capacitor C.

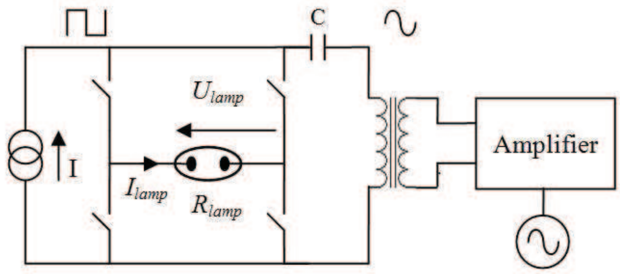

Fig. 1 AR excitation circuit for experimentation type 1

This experimental procedure was also employed to determine AR flickering instability using relative impedance parameter [17]. Otherwise, a similar experiment using series coupling of squarewave and sinusoidal sources, was previously applied in order to quantify the lamp arc flickering due to AR [18][19]. A detail procedural description of superposition DC with AC ripple for lamp AR excitation is also given in [20].

To evaluate the lamp AR threshold, the lamp instantaneous power produced by both DC and sinusoidal supplies is considered, leading to expression (1):

$$\begin{aligned} P_{Lamp}(t) &= U_{lamp}(t)I_{lamp}(t) \\ &= [U_c + U_{sm}sin(\omega t)]\,[I_c + I_{sm}sin(\omega t)] \\ &= (U_cI_c+U_{sm}I_{sm}/2) + (U_cI_{sm}+U_{sm}I_c)sin(\omega t) \\ &\quad - U_{sm}I_{sm}/2cos(2\omega t) \\ &= P_0 + P_{thr}sin(\omega t) - P_2cos(2\omega t) \qquad (1) \end{aligned}$$

U_c and I_c are the voltage and current amplitudes of the square wave supply, respectively while U_{sm} and I_{sm} are the voltage and current amplitudes of the sinusoidal supply.

Thus, the lamp instantaneous power is composed of a DC component P_0, the first harmonic component of amplitude P_{thr} at frequency ω, and the second harmonic component P_2 at frequency 2ω.

P_{thr} is used to excite the AR in order to determine the AR power threshold. According to [1][2][20], when the AR occurs at the excitation frequency ω, P_2 reaches a maximum value of only 15% of fundamental P_{thr}. As a result, the AR is only excited by the first power harmonic. This ratio indicates the variation order of P_2 to be limited in the experimental setup.

By considering that the resistance of the lamp supplied by the square wave and sinusoidal source has the same value, the power expression can be derived as:

$$\begin{aligned} P_{thr} &= U_cI_{sm} + U_{sm}I_c \\ &= I_cR_{lamp}U_{sm}/R_{lamp} + U_{sm}I_c \\ &= 2U_{sm}I_c \qquad (2) \end{aligned}$$

From (2), the power threshold at a given excitation frequency can simply be determined by measuring the sinusoidal voltage amplitude and the square wave current amplitude in the inverter. Our experiments were conducted with a 150W SONT HPS Philips 150 W lamp which was also aged with conventional ballast for more than 100 hours to reach its nominal characteristics, before being tested in formal experiments.

In our investigation, for each excitation frequency, the sinusoidal voltage amplitude is increased from 0 V to a value where the arc distortion is found inside the lamp tube. The square wave current, voltage amplitude and frequency were set to 1.5 A, 90 V and 20 Hz, respectively. The frequency of sinusoidal voltage source was manually varied from 5 kHz to 100 kHz with a frequency step of 100Hz, while its amplitude was limited to 50 Vrms corresponding to a maximum AR excitation power of 212 W. It should be noticed that in this configuration the power frequency is equal to the frequency of sinusoidal voltage supply. During the experiments, the AR appearances are perceived by human eyes.

The experimental results of AR power thresholds P_{thr} plotted in Fig. 2 present several local minimums at the eigenfrequencies. The global minimum AR threshold value of 35W is found around the eigenfrequencies of 6 kHz where the AR state is very unstable.

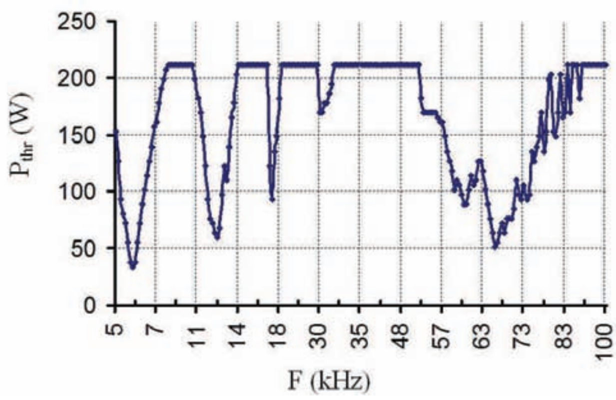

Fig. 2 AR power thresholds

In the second experimental phase, the same lamp is supplied by a sinusoidal power source, realized by a successive connection of an adjustable sinusoidal voltage source, a transformer in series with a blocking capacitor C_b and a resistive ballast R_b of 70 Ω (Fig. 3). The lamp harmonic power will be compared to the AR power thresholds obtained in the previous experiment, in order to study the AR compatibility in both supply configurations. The supply frequency is manually varied from 2 kHz to 10 kHz with a step of 100Hz during approximately 5 seconds for each step. Thus contrary to earlier experiment, the lamp power frequency in this configuration is twice the supply frequency.

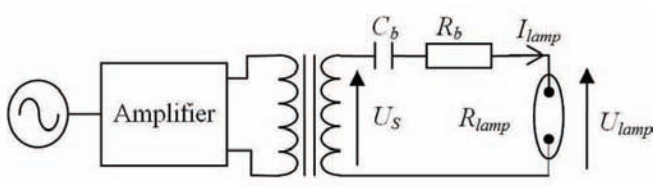

Fig. 3 Lamp sinusoidal supply circuit for experimentation

Fig. 4 (a) and (b) show the lamp AR power threshold, harmonic power, voltage, current, resistance and the AR band over the supply frequency. In addition, the discontinuous region refers to lamp arc extinction. It can be seen that as soon as the lamp power harmonic P_2 is higher than the threshold value P_{thr}, the acoustic resonance appears. Its fluctuation at each excitation frequency depends also on the injected voltage amplitude. We can see that the acoustic resonance is more intense on the left side of the AR band and gradually decreases with frequency increment.

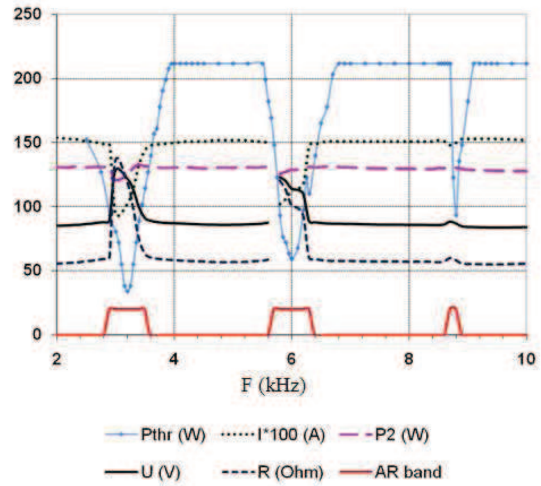

Fig. 4 A measurement on Phillips 150W HPS illustrated by lamp harmonic power P2, threshold power Pthr, lamp Rms voltage U, Rms current I and resistance R from 2 kHz to 10 kHz

Meanwhile, on the left side of the AR band usually observed a significant discharge arc distortion at low spatial frequency is observed and, on the contrary, a moderate arc bending at high spatial frequency on the right side**.** It should also be noticed that on the right side of AR bands, where the harmonic power and AR threshold powers are equal, the parameter variations are very low which. This can reduce the AR detection sensibility if they are used as AR indicators. As a result, the supply frequency should be further increased to ensure the avoidance of AR.

III. Lamp AR Detection

Several methods of AR detections have been found in technical literature that employs different strategies to predict AR occurrences. According to [4], when the lamp suffers from the AR, its output voltage was found to have a waveform similar to a signal of double side band amplitude modulation due to discharge arc instability. The detection method was based on lamp voltage amplitude variation. In [21], during the AR, low frequency ripples (5-20 Hz) are present in lamp current. The FFT method could be applied for AR measurement. The above AR detection methods may require several ripple periods in order to evaluate the AR occurrence. In paper [22], the standard deviation of lamp current and voltage was used as an indicator of AR occurrence in MH lamp. It was also given that the standard deviation of voltage presented more significant variation than that of current when the AR happened. This method is similar to the calculus of lamp Rms voltage. Paper [23] showed that the resistance variation present better sensibility than voltage and current variation. Some investigations deal with the detection of arc path distortion by optical measurement with photodiodes which gives good detection sensibility [24][18]. However, this method is still complex for implementation. Several procedures of AR detection are also described in [25].

It can be seen from earlier experimental results that lamp electrical parameters variation inside the AR band can be interpreted by the disturbances of acoustic resonance. Thus, the lamp voltage, current or resistance can be used to evaluate the occurrence of AR. According to the experiment with sinusoidal supply on a Phillips HPS lamp 150W, when an acoustic resonance occurs, the lamp current decreases while its voltage increases. Fig. 5 (a) and (b) show the voltage and current waveform in an HPS lamp Philips 150W in healthy state at 5.5 kHz and in an AR in serious state at 6 kHz, respectively. It can be noticed that the lamp peak voltage increases from 96 V to 120 V and peak current decreases from 1.7 A to 1.45 A which results in a resistance increased up to 50%. In our experiment, the resistance variation gives the most sensibility among other parameters. In summary, the variation rate of these parameters can be classified in this order: $\Delta P < \Delta I < \Delta U < \Delta R$ for open loop operation. It can thus be concluded that resistance measurement should be the most practical method in AR detection which provides good sensibility among the other electrical parameters.

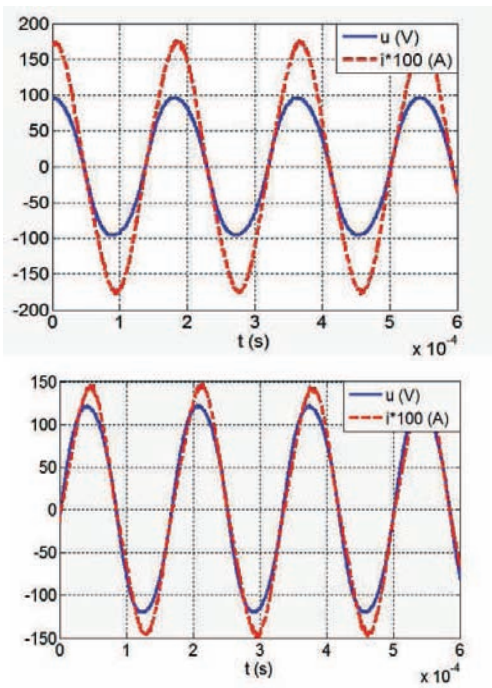

Fig. 5 Comparison of lamp current and voltage (upper) without AR (lower) with AR

However, most of commercial electronic ballasts are usually accompanied with closed loop operation in order to regulate the lamp power. Part V will present different results in the case of closed loop control.

IV. AR Hysteresis in Forward and backward frequency sweeping

The study of AR hysteresis is related to the response of AR behaviour to the variation of certain parameters of the input power when the acoustic resonance occurs. In our experiment, we also noticed that the AR behaves differently according to the frequency sweeping direction. As previously mentioned in **Erreur ! Source du renvoi introuvable.**Fig. 3, the Phillips 150W HPS lamp was supplied by the sinusoidal supply.

To evaluate this AR hysteresis characteristic, the supply frequency was increased from 2 kHz to 10 kHz and decreased back to 2 kHz so as to compare the lamp AR in both forward and backward frequency sweeping modes. **Erreur ! Source du renvoi introuvable.** (a) and (b) show the lamp forward and backward voltage (*Ufwd*, *Ubwd*) and resistance (*Rfwd*, *Rbwd*) variations over the supply frequency. The discontinuous regions of Rdecr and Vdecr waveforms in **Erreur ! Source du renvoi introuvable.** represent lamp arc extinguishing points. From the obtained results, it can be pointed out as following:

A. The AR behaves differently depending on the orientation of frequency sweeping,
B. In backward sweeping mode, the AR bands are larger, and present more significant variation than in forward mode (Fig. 6). Consequently, this can provoke some overlaps of acoustic resonances when a lamp has several AR eigenfrequencies close to each other,
C. Besides, it is important to notice that in backward sweeping, the AR state progresses smoothly from slightness to seriousness. Their highest points near extinction indicate the critical values of lamp parameters before the discharge arc extinction.

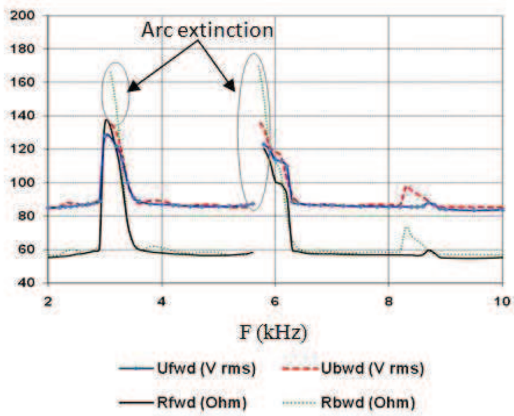

Fig. 6 Evolution of the lamp characteristics with forward (Ufwd and Rfwd) frequency sweeping and backward (Ubwd and Rbwd) frequency sweeping

According to[27], arc bending due to AR can shift the eigenfrequency, the extension of backward AR band is the consequence of frequency shifting. The significant AR hysteresis comportment may lead to a main problem in real-time AR control. Some lamp supply methods presented in literature propose an off-line solution to AR avoidance, assuming that its occurrence was already identified under lamp's previous operating conditions [12][13][14][15].

V. Lamp AR characterisation with LCC half bridge inverter supply and closed loop control

Another lamp experiment is conducted via operating the lamp with a half bridge inverter usually used for low power lamp supply (Fig. 7). The LCC circuit design method can be found in [26]. The passive components (Ls=3mH, Cs=300nF and Cp=10nF) are designed to supply the lamp at 30 kHz for ignition and around 6 kHz at stable operation, where the AR was identified. The Bode diagram of the LCC filter+lamp can be plotted in Fig. 8. Before ignition, lamp resistance is supposed to be very important (100kΩ).

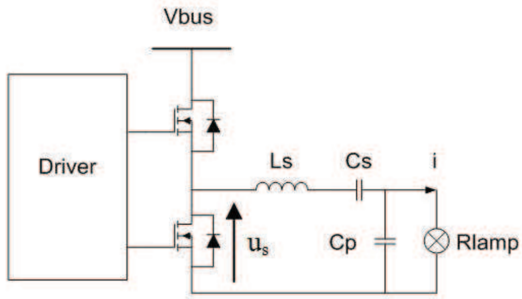

Fig. 7 Lamp supply with LCC half bridge inverter

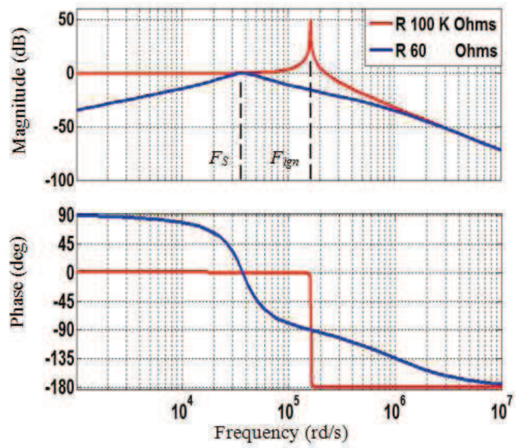

Fig. 8 Bode diagram of LCC circuit with first harmonic approach

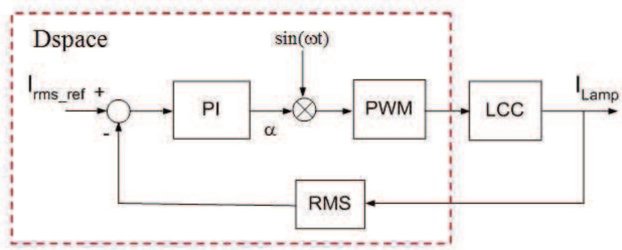

Fig. 9 Lamp control scheme

Contrarily to previous experiment with sinusoidal supply where the lamp was stabilized by resistant ballast, stabilization procedure in this case is achieved by the control of lamp RMS current through a digital PI controller implemented in a Dspace1104 board (Fig. 9). In fact, it was given from [28] that when the LCC circuit is operated at resonance series frequency f_s, its equivalent model for RMS current control corresponds to a 1st order low pass transmittance (3). As a result, a conventional PI controller can be used for ballast control.

$$H_s(\omega) = \frac{\hat{\imath}}{\hat{u}_S} = \frac{1}{2pL_S + R} \quad (3)$$

In Fig. 9, the sinusoidal signal to supply the lamp is injected via a pulse width modulation (PWM) in order to drive the inverter leg. Otherwise, the DC bus voltage *Vbus* of 450V is applied to the inverter leg. Our purpose in this study is to evaluate AR characteristics for the lamp closed loop operation. During the experiment, lamp current is controlled at a reference level of 1.4Arms. As depict in Fig. 10, the supply frequency is increasingly and decreasingly swept between 5.5 kHz and 6.2 kHz with a step of 50Hz each 2 seconds. Fig. 11 presents lamp forward and backward instantaneous equivalent resistances. Its values are obtained from the measurement of lamp RMS current and voltage. To obtain an equivalent representation of resistance variation over frequencies as in Fig. 6, lamp instantaneous resistance given in Fig. 11 is averaged for each excitation frequency during 2 seconds.

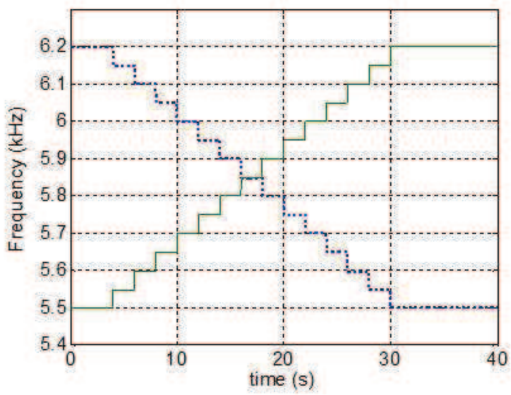

Fig. 10 Frequency sweeping

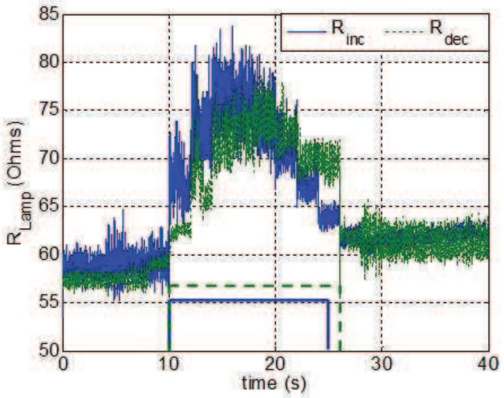

Fig. 11 Lamp forward (RInc) and backward (RDec) resistances and AR bands

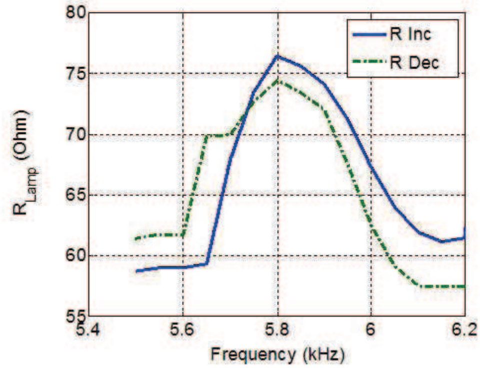

Fig. 12 Lamp forward (RInc) and backward (RDec) resistances over excitation frequency

The related result is illustrated in Fig. 12. It can be pointed out that lamp resistance increases when AR perturbations appear. The forward and backward AR bands are identified as [5.7, 6] and [5.6, 6] kHz, respectively. Thus, the hysteresis is present in both open loop and closed loop operation. Different from the earlier sinusoidal experiments, since the lamp current is presently closed loop controlled, the lamp RMS voltage and resistance variation rates are equal. Consequently, according to Fig. 11 and Fig. 12, lamp power should be the most significant variation parameter in this case ($\Delta P = \Delta U * \Delta I$). In the current controlled operation, the variation rates of parameters should be classified in the following order: $\Delta I < \Delta U = \Delta R < \Delta P$. As a result, the selection of AR indicator depends on the lamp operation strategy.

VI. Conclusion

The study of the main AR characteristics in HPS lamp was presented in this paper in order to seek for appropriate control methods to avoid the acoustic resonance. The first part concerns the AR threshold power of the lamp and its electrical parameter variations in the AR bands. Since the AR threshold value is known, any suitable lamp harmonic powers can be injected into the lamp. In addition, the study of AR detection is also included.

The second part is related to the excitation of AR sinusoidal supply and the different behaviour of AR in forward and backward frequency sweeping for an open loop lamp operation. It was shown that lamp resistance was the most sensible parameters for AR detection.

The last part concerns the study of lamp operation with an LCC half bridge inverter in a current closed loop control. The same analysis of lamp parameter variation was applied. The experimental results reveal that AR hysteresis is present in both open and closed loop. However, in closed loop control, lamp power represents the most sensible variation. The choice of AR detection indicator depends thus on lamp supply circuit and control structure.

This study will be useful for ballast designers to seek for suitable strategies in order to avoid the acoustic resonance in an HID lamp operating at high frequencies.

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