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Characterization of Acoustic Resonance in a High Pressure Sodium Lamp

L. CHHUN^{1,2}, P. MAUSSION^{1,2}, S. BHOSLE^{1,2} and G. ZISSIS^{1,2}

¹Université de Toulouse; INPT, UPS; LAPLACE (LABoratoire PLAsma et Conversion d'Energie) ENSEEIHT, 2 rue Charles Camichel, BP 7122, F-31071 Toulouse cedex 7, France

²CNRS; LAPLACE; F-31071 Toulouse, France

E-mail : pascal.maussion@laplace.univ-tlse.fr

Tel: 33 (0)5.61.58.84.64

Fax: 33 (0)5.61.63.88.75

Abstract-In 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. Two main characteristics of the acoustic resonances in a 150W HPS lamp are presented in this paper and we seek for a control method to avoid the lamp AR. The first one is the characteristic of the lamp AR threshold power, and the second one is the differences between forward and backward frequency scanning effects. Both 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 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, it is provoked by the propagation of an acoustic wave in the closed volume of the burner. Basically, it generally occurs 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]. The intensity of AR can be classified into three degrees, slightness, seriousness and extinction [3]. Furthermore, it can also be different from lamp to lamp of the same type from the same manufacturer due to the manufacturing tolerance. Presently, the problem of AR is still not completely understood. Certain literatures deal with the effect of lamp tube and electrode shape on the acoustic resonance [4][5]. Some physical models of lamp AR have also been developed to predict the eigenfrequencies [2][6]. 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 the convenient 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 main feature of the AR is that it behaves differently according to the direction of sweeping frequency of the power supply. 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.

These characteristics of AR allow us to further understand the AR properties in order to improve the control of the lamp under high frequency operation.

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 researches 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 [7], square wave high frequency supply [9], amplitude modulation [8], frequency modulation [10], and the third voltage harmonic injection strategy [11]. The basic idea of all methods is to have the distribution of power harmonic components below the AR threshold value. 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 HPS lamp is supplied by an inverter powered by a DC current source in parallel with a cascade connection of sinusoidal supply through an amplifier with a transformer and a blocking capacitor C.

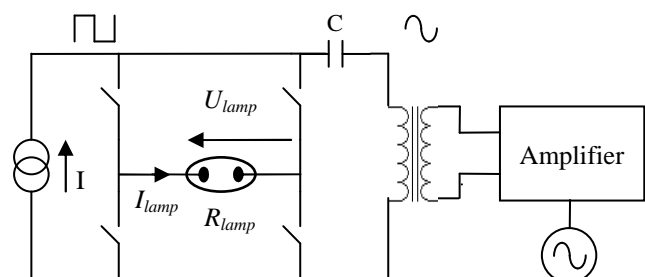


Fig. 1 AR excitation circuit for experimentation type 1

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

$$\begin{aligned}
 P_{Lamp}(t) &= U_{lamp}(t) \cdot I_{lamp}(t) \\
 &= (U_c + U_{sm} \cdot \sin(\omega t)) \cdot (I_c + I_{sm} \cdot \sin(\omega t)) \\
 &= (U_c \cdot I_c + U_{sm} \cdot I_{sm} / 2) + (U_c \cdot I_{sm} + U_{sm} \cdot I_c) \cdot \sin(\omega t) \\
 &\quad - U_{sm} \cdot I_{sm} / 2 \cdot \cos(2\omega t) \\
 &= P_0 + P_{thr} \cdot \sin(\omega t) - P_2 \cos(2\omega t)
 \end{aligned} \tag{1}$$

U_c and I_c are the voltage and current amplitude of the square wave supply, respectively while U_{sm} and I_{sm} are the voltage and current amplitude 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 to determine the AR power threshold. Otherwise, according to [2], when the AR occurs at the excitation frequency ω , P_2 has only maximum value of 15% of fundamental P_{thr} . As a result, the AR is only excited by the first power harmonic.

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:

$$\begin{aligned}
 P_{thr} &= U_c \cdot I_{sm} + U_{sm} \cdot I_c \\
 &= I_c R_{lamp} U_{sm} / R_{lamp} + U_{sm} \cdot I_c \\
 &= 2 \cdot U_{sm} \cdot I_c
 \end{aligned} \tag{2}$$

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 Philips 150 W high pressure sodium 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 varied from 5 kHz to 100 kHz, while its amplitude was limited to 50 Vrms corresponding to a maximum AR excitation power of 210 W. It should be noticed that in this configuration the power frequency is equal to the frequency of sinusoidal voltage supply.

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.

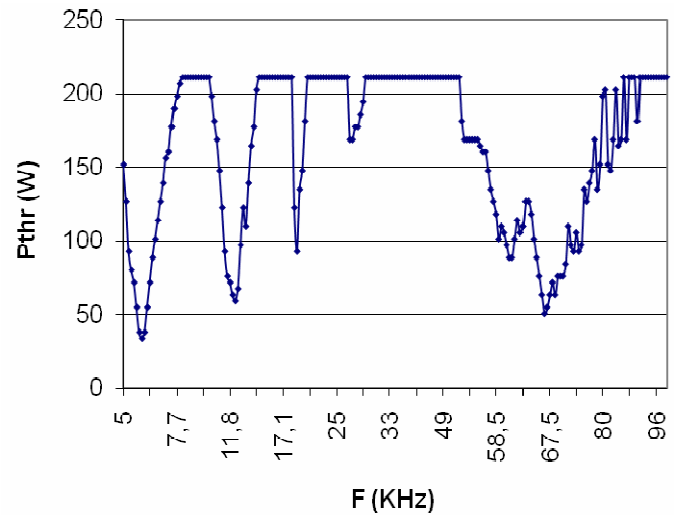


Fig. 2 AR power thresholds

In the second experimental phase, the HPS 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. The supply frequency is varied from 2 kHz to 50 kHz; thus contrary to earlier experiment, the lamp power frequency in this configuration is twice the supply frequency. Fig. 4 (a) and (b) show the lamp AR power threshold, harmonic power, voltage, current, resistance and the AR window over the supply frequency, from 2 kHz to 10 kHz and from 20 kHz to 50 kHz, respectively. The AR was not found in the experiment from 10 kHz to 20 kHz, and is not presented here. In addition, the discontinuous region refers to lamp arc extinction. As shown in the figure, as soon as the lamp power is higher than the threshold value, 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 window and gradually decreases with frequency increment.

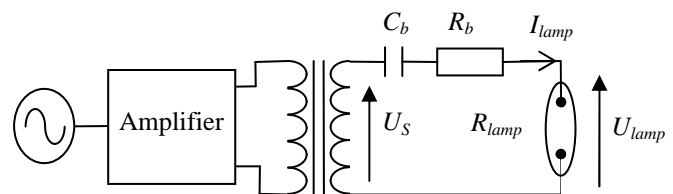


Fig. 3 Lamp sinusoidal supply circuit for experimentation type 2

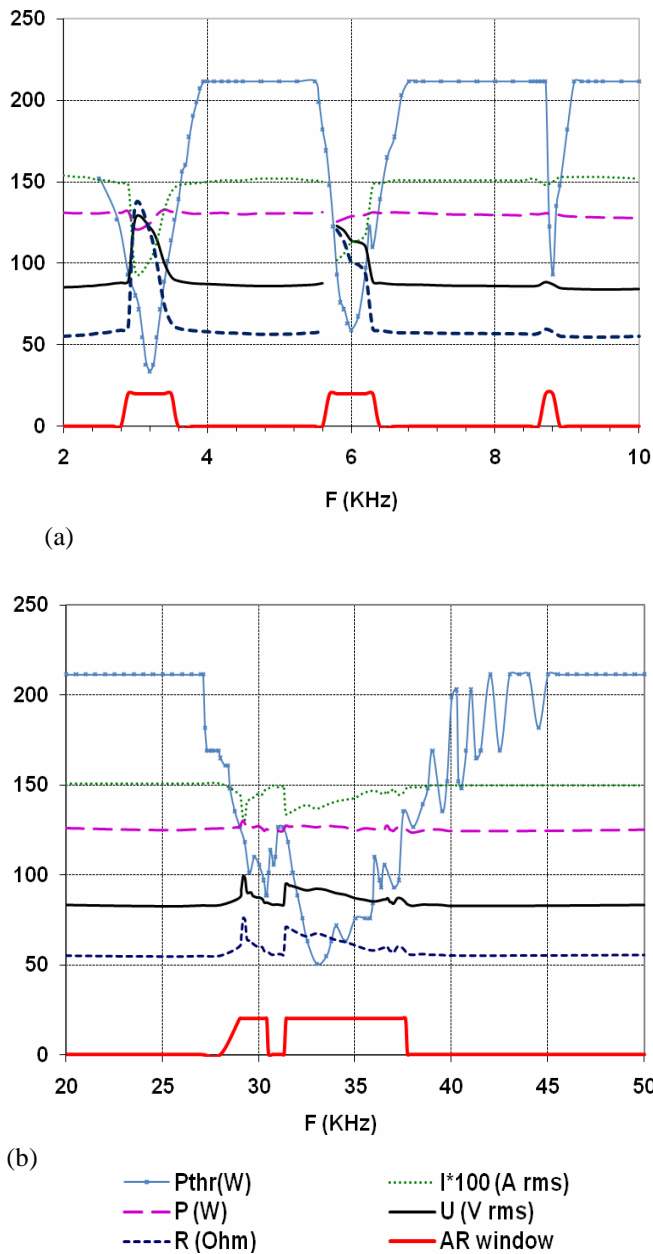


Fig. 4 Phillips 150W HPS lamp harmonic power, threshold power, voltage, current and resistance (a) from 2 kHz to 10 kHz (b) from 20 kHz to 50 kHz

Meanwhile, on the left side of the AR window is usually observed an important discharge arc distortion at low spatial frequency 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 windows, where the power harmonic 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

It can be seen from earlier experiment results that lamp electrical parameters variation inside the AR window 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 of these parameters can be classified in this order: $\Delta P < \Delta I < \Delta U < \Delta R$.

Several methods of AR detections have been found in literatures that employ different strategies to predict AR occurrences. According to [3], 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.

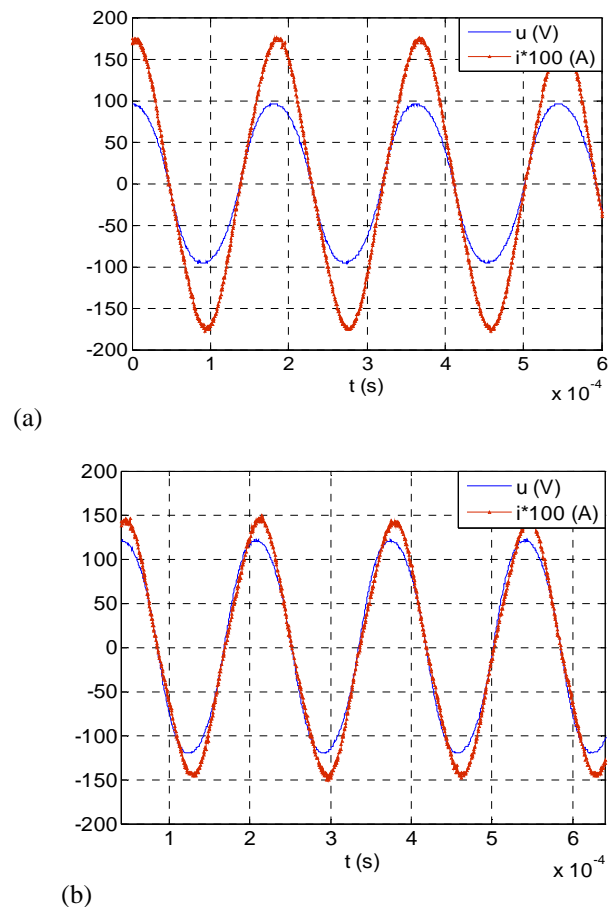


Fig. 5 Comparison of lamp current and voltage (a) without AR (b) with AR

In [12], 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 [13], 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 [14] have shown that the resistance variation present better sensibility than voltage and current variation.

Some investigation deals with the detection of arc path distortion by optical measurement with photodiodes which gives good detection sensibility [15]. However, this method is still complex for implementation. Several procedures of AR detection can also be found in [16].

It can thus be concluded that resistance measurement is the most practical method in AR detection which provides good sensibility among the other electrical parameters.

IV. AR HYSTERESIS IN FORWARD AND BACKWARD FREQUENCY SWEEPING

The study of AR hysteresis is related to the response of AR behavior 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 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 45 kHz and decreased back to 2 kHz so as to compare the lamp AR in both forward and backward frequency sweeping modes. Fig. 6 (a) and (b) show the lamp forward and backward voltage (U_{fwd} , U_{bwd}) and resistance (R_{fwd} , R_{bwd}) variations over the supply frequency. From the obtained results, it can be pointed out as following:

- The AR behaves differently depending on the orientation of frequency sweeping,
- In backward sweeping mode, the AR windows are larger, and present more significant variation than in forward mode. Most of them lead to lamp extinction at the left side of AR windows, as illustrated by the discontinuous regions in Fig. 6. Consequently, this can provoke some overlaps of acoustic resonances when a lamp has several AR eigenfrequencies close to each other,
- The discontinuous regions of R_{decr} and V_{decr} waveforms in Fig. 6 represent lamp arc extinguishing points. Their highest points indicate the critical values of lamp parameters before the discharge arc extinction. Besides, it is important to notice that in backward sweeping, the AR state progresses smoothly from slightness to seriousness.

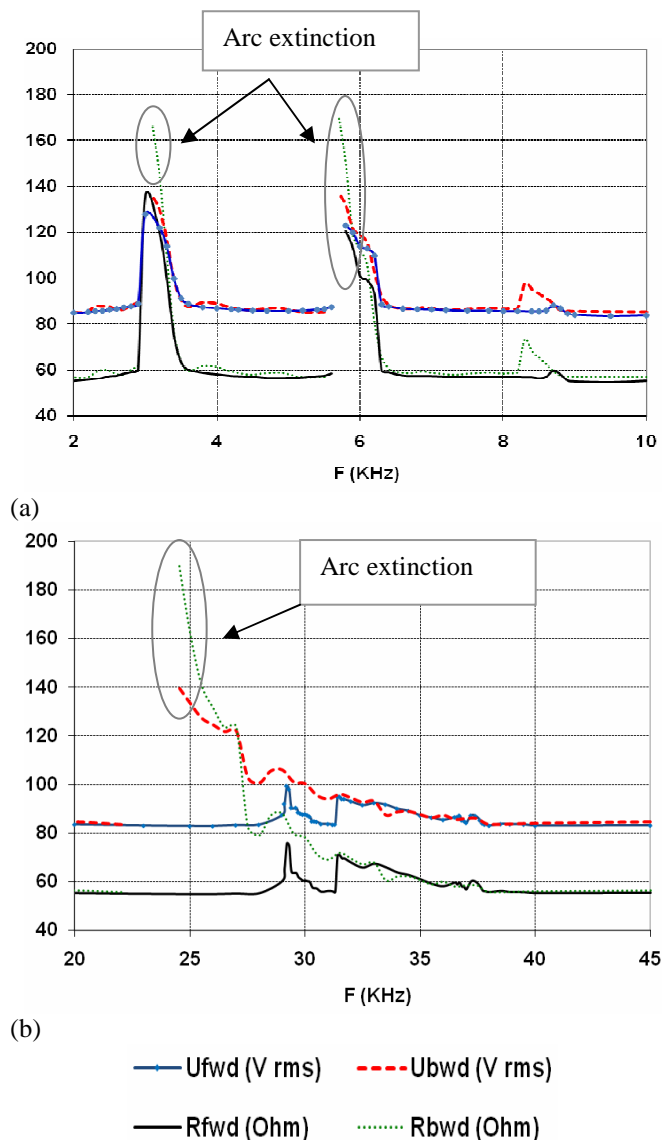


Fig. 6: Evolution of the lamp characteristics with forward (U_{fwd} and R_{fwd}) frequency sweeping (a) and backward (U_{bwd} and R_{bwd}) frequency sweeping (b).

Thus, it could be easy to determine the critical extinction parameters in this configuration. In our experiment, as soon as the voltage and current attained these values, the lamp extinguished in about one or two seconds. Consequently, in the lamp control procedure, it is important to effectively modify the lamp supply frequency before it reaches this critical state,

- Otherwise, when the lamp encounters the AR, it is highly risky to avoid it by decreasing the supply frequency. On the contrary, it is possible to increase the supply frequency through the AR window to reach a region free from AR, without extinguishing the lamp arc [9].

The significant differences in AR compartment due to the hysteresis may lead to a main problem in real-time

AR control. Most of the control methods presented in literatures propose an off-line solution to AR avoidance, assuming that its occurrence was already found under previous lamp operating condition.

Our future work will also deal with the backward frequency sweeping for the detection of acoustic resonances by lamp electrical parameter variations in lamp control.

V. CONCLUSION

The study of two 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 windows. Since the AR threshold value is known, any suitable lamp harmonic powers can be injected in the lamp. In addition, the study of AR detection is also included. The second part is related to behavior of AR in forward and backward sweeping. The analysis of backward frequency sweeping could provide the limited conditions for a lamp to be operated safely, and especially the lamp electrical parameter values before its extinction which can be used to control the lamp extinction when the AR occurs. This study will be useful for ballast designers to seek for suitable control strategies in order to avoid the acoustic resonance in an HID lamp operating at high frequency.

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