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Harmonic distortions of the AC waveform for a Hg HID lamp

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Abstract

Different behaviors for the lamp electrical voltage and current over time have been recorded when a tungsten filamentary resistance in a vacuum bulb has been used as ballast in series with a mercury HID lamp operating in the following conditions: with the external bulb and without it. By Fourier analysis the harmonic distortions of the AC waveform from the nominal sine wave caused by odd harmonics of third and fifth order have been observed mainly on the measured lamp voltage. The harmonic distortions effect was very small on the measured current when operating the lamp with the external bulb and almost negligible when operating the lamp without external bulb. Spectral measurements showed that the light quality of the lamp is drastically influenced by the presence or absence of the external jacket with phosphor coating.

1 Introduction

Electric discharge lamps have a negative resistance, determining excessive current through the lamp that could very rapidly damage the lamp if connected directly to the public power line. To provide the proper starting and operating voltage and current, to initiate and to sustain the arc discharge between the two electrodes of a plasma discharge lamp is necessary to introduce in lamp circuit of a device called ballast to make an interface between main supply and the lamp([1] and [2]). Ballast technology has continually developed to improve the performance and the life of the lamp. A ballast has some technical characteristics (ballast factor, power factor, lamp current crest factor, total harmonic distortion) to see the energy efficiency, how much distortion they cause in power wave form and how much light it produces [3].

Total harmonic distortion (THD) represents the distortion in percentage of the alternating current (AC waveform) from the nominal sine wave when operating a ballast and a lamp[3]. A high harmonic distortion value can produce unpleasant effect such as: overheating of capacitors, neutral wires, transformers and other circuit components.

As known, the low pressure discharge lamps are operated at high frequency (in the range from 150 and 300 kHz), having as an important advantage the increase of efficiency of the lamp drivers, compared with a conventional lamp driver operating at a frequency of 50 Hz.

The high intensity discharge (HID) lamps are mostly operated in an AC mode at frequencies between 50 and 400 Hz. The main reason for the limitation of the operating frequency range is found in the occurrence of acoustic resonances[4]. This appearance was first reported by Campbell [5]. The main acoustic resonances are found in the frequency region between 10 and 150 kHz. These acoustic resonances can lead to an unstable lamp operation and in the case of very strong excited waves to the destruction of the discharge vessel.

This work analyses the impact of the presence or not of the external bulb coated with "phosphor " on the intensity and on the harmonic distortions of the AC wave form recorded for the lamp electrical potential and current when a filamentary tungsten resistance in a vacuum bulb has been used as ballast in the circuit of a Hg HID lamp. The consequently changes in the Hg optical emission line intensities will be also discussed.

2 Experimental results and discussion

The discharge starting in a HID lamp is depending on some important factors as the following: geometry and material of the discharge tube, composition and pressure of the gas and vapor filling, material and construction of electrodes and auxiliary electrodes, influences of the environment, electrical supply. Usually in every discharge lamp an inert gas or mixture of inert gases is added to the metal filling to initiate a discharge in the lamp, but usually the lamp will not start at normal mains voltage.

After starting, the lamp runs up to the stable operating conditions, leading to a high pressure in the discharge tube. The time to reach 80 % of full light output is called the run-up time[3].This run-up time depends on the type of ballast. A ballast with a high short-circuit current will have a short run-up time, but when the short-circuit current is too high, it will overload the lamp electrodes and so will diminish lamp life. Therefore a maximum current during running-up is specified per lamp type. If the discharge is extinguished, the vapor pressure remains high for a while until the lamp has cooled down. During this time the voltage available for re-ignition is in most cases insufficient to re-ignite the lamp. The time between the moment of extinction and the moment when the vapor pressure is low enough to permit re-ignition, is called the re-ignition time of the lamp, of course only valid if the mains supply is available. This time depends on the temperature of the discharge tube, the pressure in the discharge tube and the height and energy level of the ignition peak.

A commercially available high intensity Hg discharge lamp with a nominal power of 125 W has been used in our experiments. This lamp has the arc tube enclosed in an evacuated outer bulb with "phosphor" coating, which isolates the hot arc tube thermally from the surroundings. For ballast we used a tungsten filament in a vacuum bulb that served as a series resistor having 24.4 Ω at room temperature, for the high-pressure mercury discharge lamp operating at 13 W. Additionally to the current-limiting element, an ignition device (a resistor of 10 kΩ) is needed to start the discharge.

Limitation of lamp current by means of a simple resistor is similar to that used in self-ballasted blended-light lamps. This filament, incorporated in the lamp, also takes part in the light production of the lamp and for that reason, the luminous efficacy of blended-light lamps is lower than that of other HID lamps. On the other hand, the advantage of this system without external ballast is that an installation with incandescent lamps can easily be converted to a system with a much longer life by simply replacing the incandescent lamps by blended-light lamps [6].

The discussion will be focused on the changes in time of the electrical lamp parameters in both situations: when the lamp has an external bulb coated with "phosphor"(A-case) and then when the external bulb is thrown away (B-case). The evolution versus time of the measured arc voltage values for these two situation are given in Figure 1. The electrical behavior in time of the discharge can be explained by the decrease of the electrical conductivity resulting from the pressure increase due to the plasma heating and is controlled by the resistive ballast that is a current-limiting element.

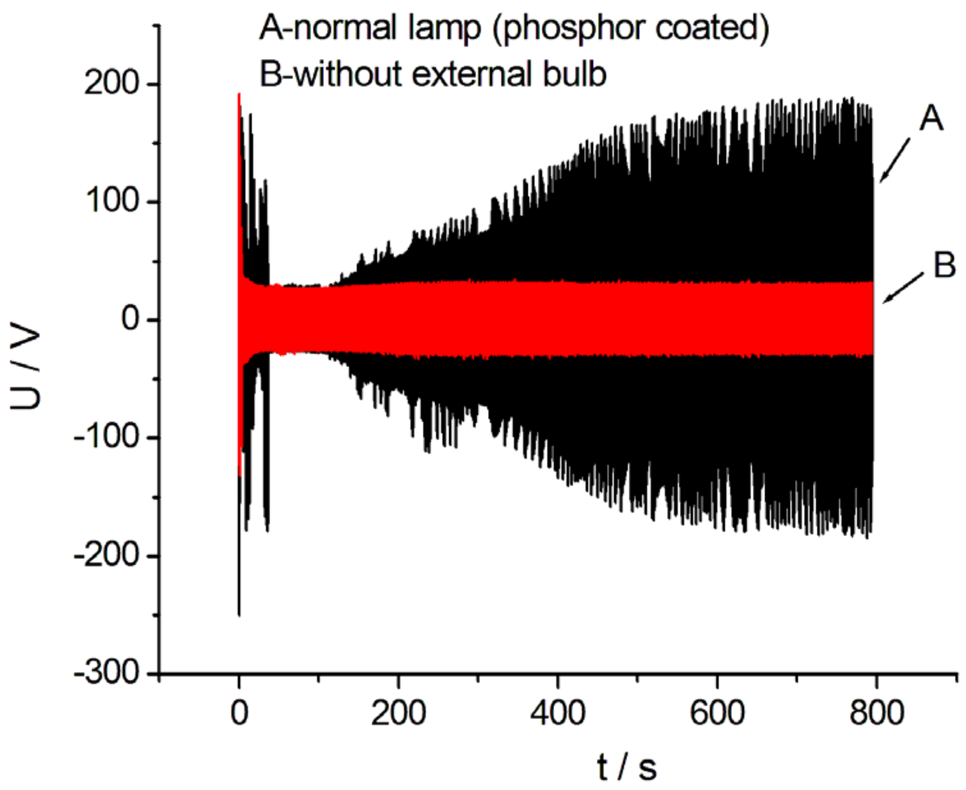

Figure 1-Lamp potential over time in two cases: (A)-HID lamp having an external bulb coated with phosphor; (B) -HID lamp without the external jacket.

If we set a value of 240 V for the effective main voltage, we recorded very high values for the lamp voltage at the ignition moment: the amplitude is around 190 V for the (B-case) and 180V for the (A-case). Then a rapidly decrease in time is observed, but with different rates followed by complete different time behaviors for the two situations: the decrease until about 30 V is more accelerate for the lamp without the external bulb (in about 4 seconds) then keeping a constant value, due to the high thermal loses with the external environment, while for the normal lamp this fall in voltage is intermittent and is taking place in about 36 seconds from the ignition, then remaining constant until 132 seconds but after that the voltage amplitude is continually raising until a value of 186 V in steady state.

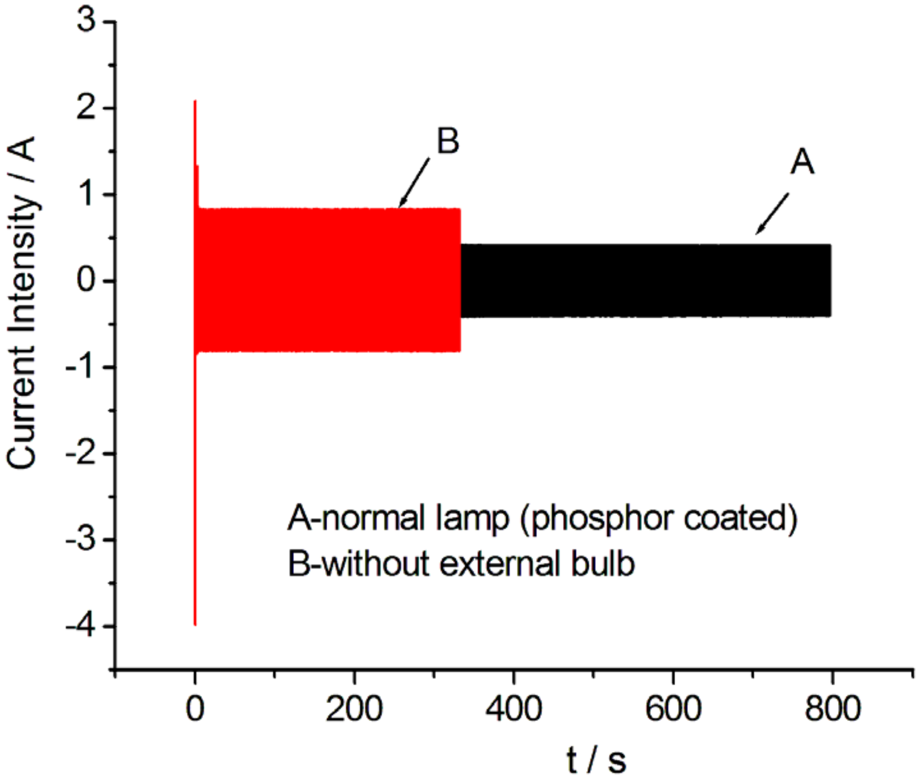

Figure 2-Lamp current intensity versus time for the two cases: A-with external jacket; B-without the outer bulb.

From Figure 2 is seen that the current has different behaviors: in about 0.14 seconds after the ignition moment there is a fall from 4 A to 0.84 A in (B- case) and from 3 A to 0.45 A in (A- case), but the final constant values of 0.8 A in (B-case) and of 0.4 A in (A-case) were attained in about 1.3 s.

For the chosen ballast for our experiment we could find the lamp current using a Thevenin equivalent circuit, where the output resistance is the one corresponding to the incandescent tungsten filamentary resistance that has a temperature dependence of the type, $R=R_0\,[1+\alpha(T-T_0)]$ and a losing power by thermal radiation in conformity with Stephan-Boltzmann low, $U_R I_R = \sigma T^4$, where σ is Stephan-Boltzamann constant. The thermal increase of ballast resistance in time will compensate the lamp low-frequency negative impedance during their warm-up phase.

By analyzing the time evolution of the lamps' electrical characteristics we observed the appearance of harmonic signals. These harmonic currents induce, in some cases, constraints that cause ominous effects on the supply network (unnecessary losses in ballasts and supply transformer, etc.).

All the gas-discharge lamps stabilized by ballasts have harmonics in the lamp current because the voltage across the discharge tube is more or less a square wave of changing polarity every half cycle.

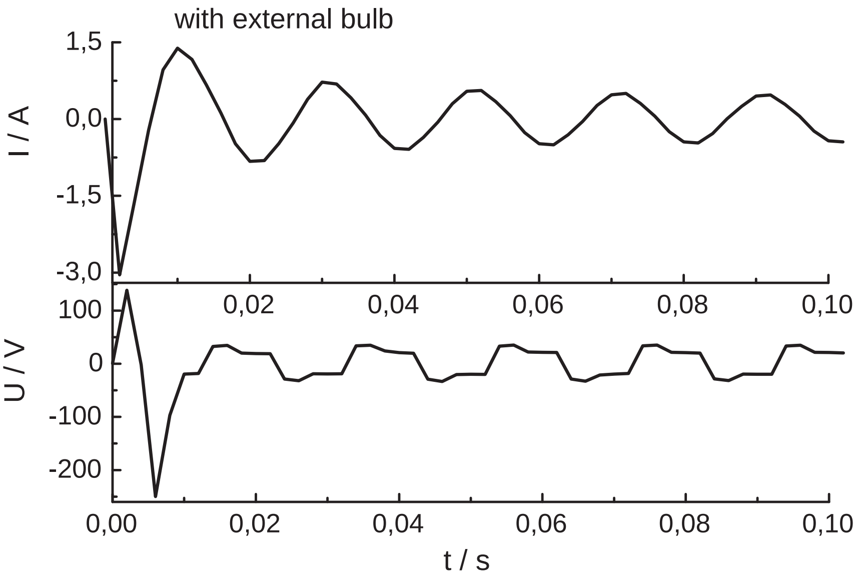

Figure 3-The wave form lamp voltage is affected by harmonics much more than the current in the lamp circuit.

This is graphically represented by a square wave voltage (see Figure 3), made up (by Fourier analysis) from the fundamental sine-wave of the mains supply and a great number of odd harmonics.

The voltage across the ballast is the vector difference between the supply voltage and the lamp voltage, so the harmonics of the lamp voltage appear also in the ballast voltage. As the ballast determines the current, there will be odd harmonics in the lamp current too. Even with a pure sine-wave ballast voltage there will be some harmonics in the ballast current, but this effect is small, compared with the harmonics caused by the lamp.

The n^{th} harmonics level (in percentage) is defined in ref. [6] as the ratio between the value of the amplitude of the FFT n^{th} order harmonic (A_n) and the amplitude value of the fundamental (A_0):

$$\gamma_n = \frac{A_n}{A_0} \times 100\%$$

We will make the following notations: $\alpha_n^{(V)}$, $\alpha_n^{(I)}$ are the n^{th} harmonics level for the lamp voltage and lamp current, respectively, in the (A-case) when the lamp has an external bulb); $\beta_n^{(V)}$, $\beta_n^{(I)}$ are the n^{th} harmonics level for the lamp voltage and lamp current, respectively, in the (B-case) when lamp is operated without external bulb.

International requirements have been drawn up for the proportion of the harmonics in supply mains currents. According to EN 60555-2, for lighting equipment having an input power > 25 W, and the latest EN 61000-3-2 (IEC 1000-3-2) ([7], [8]), the maximum percentage of harmonics for the input current are: second harmonic: 2 %; third harmonic: 30×P.F. % (where P.F. = power factor of the circuit); fifth harmonic: 10 %; seventh harmonic: 7 %; ninth harmonic: 5 %; the n^{th} harmonic should be: $11<n<39$: 3 %

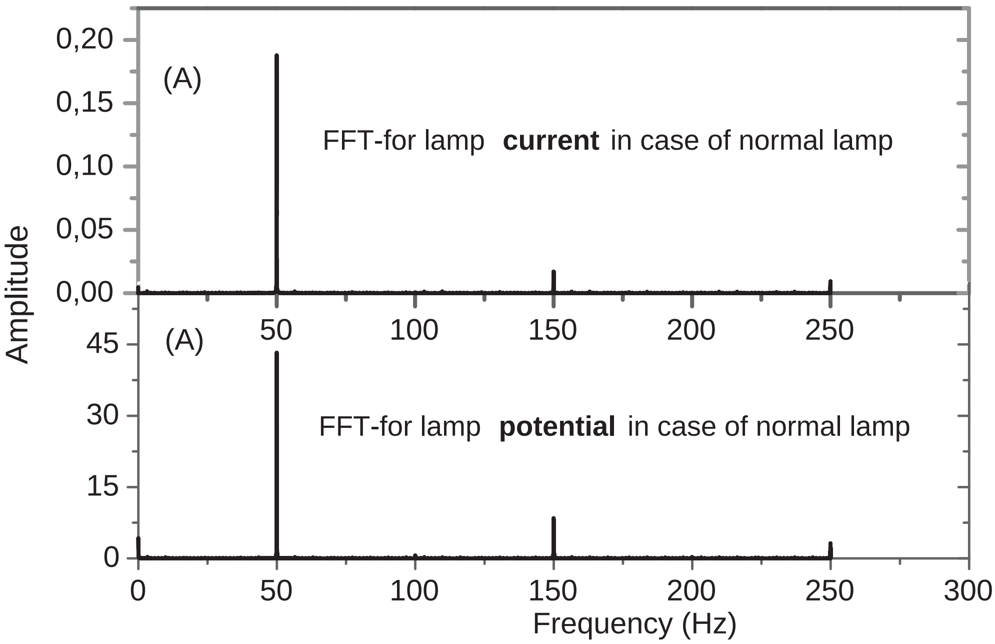

Figure 4-Results of Fourier analysis for potential and current wave form in the case-A (with the outer bulb).

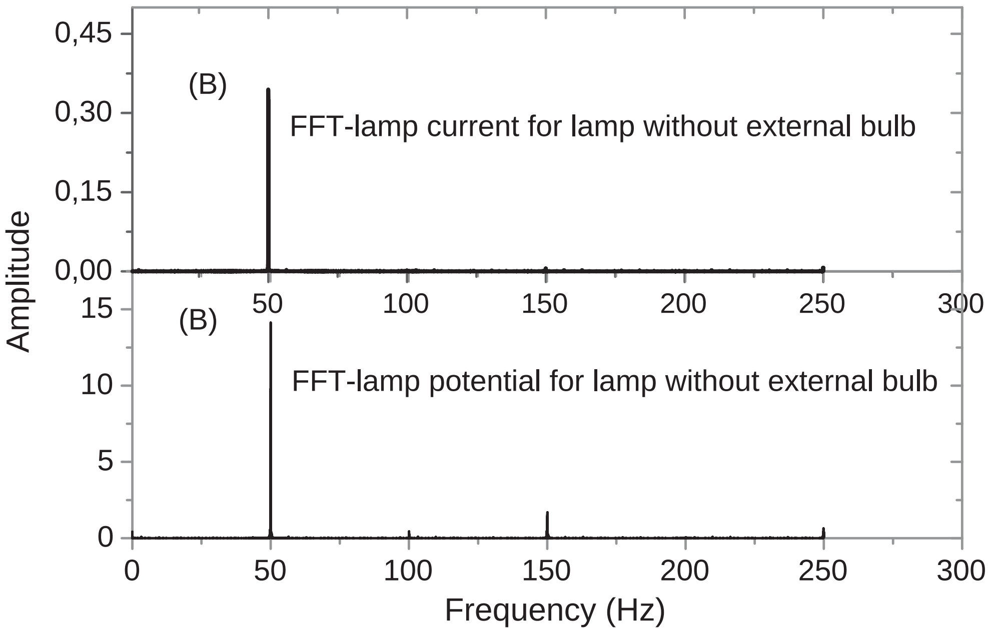

Figure 5-The amplitudes of fundamental wave and of the first four possible harmonics for potential and current in the case-B (when the outer bulb is eliminated)

Table 1

n^{th} **harmonics level**	$\alpha_n^{(V)}$	$\beta_n^{(V)}$	$\alpha_n^{(I)}$	$\beta_n^{(I)}$
fundamental	100 %	100%	100%	100%
second harmonics	1.95%	2.94%	0%	0%
3^{rd} harmonics	19.83%	14.4%	9.12%	1.39%
5^{th} harmonics	7.5%	3.61%	5.75%	1.39%
total distortion (δ)	20.19%	15.13%	10.78%	1.96%

Analyzing the Table 1 where are given the calculated values for the current harmonics level as well as the total harmonics distortions produced on the lamp potential and electric current from the FFT graphs shown in Figure 4 and Figure 5, we have to notice that the 3^{rd} (of 150 Hz) current harmonics level equal with 19.83% measured for AC lamp potential in the (A-case) is higher than 14.4 %, value corresponding to the lamp without external bulb (B-case). The ratio between 3^{rd} (of 150 Hz) harmonics level and those of 5^{th} (of 250 Hz) harmonics level is $\left(\alpha_3^{(V)}/\alpha_5^{(V)}\right) = 2.6$ for (A-case) and $\left(\beta_3^{(V)}/\beta_5^{(V)}\right) = 3.9$ for (B-case). The presence of the 3^{rd} and 5^{th} harmonics is remarked also in the waveform of current intensity I(t), mainly in (A-case), the total harmonics distortions being very small (under 2%) in the (B-case).

The total harmonics distortion coefficient (δ) of the current waveform estimates the combined effect of all harmonic distortions and is defined by the following formula:

$$\delta = \frac{\sqrt{\sum A_n^2}}{A_0} \times 100\%$$

In our cases the total harmonic distortions are important for the lamp potential, being higher in the (A-case) of the lamp with external jacket ($\delta_{A-case} = 20.19\%$) compared with that of (B-case) ($\delta_{B-case} = 15.3\%$) for the lamp without outer bulb, but their values are in conformity with the limits established by international requirements.

In steady operation, the temperature in the arc is depending on tungsten filament resistance used as ballast. The energetic electrons collide with the heavy-atom particles present in the plasma, thus exciting them from the ground state to higher energy levels. The excitation energy is then released as an electromagnetic radiation with the spectral characteristics according to the composition of the fill.

The spectral power distribution of the mercury discharge depends, to a very great extent, on the pressure at which it is operating. At low pressures (as in fluorescent lamps) the output is predominantly in the ultraviolet, but as pressure increases (like in HID lamps) so does the self-absorption for ultraviolet of 253.73 nm resulting in the visible Hg lines becoming relatively stronger. Above about one atmosphere pressure, a very small amount of continuum radiation begins to enter the spectrum and this progressively increases in strength as pressure continues to rise. On the other hand, the 253.73 UV radiation that passes through the lamp discharge tube causes the phosphor coating on the walls of the lamp to glow. The time evolution of emission spectra of the Hg discharge lamp has been recorded with an Ocean Optics Spectrometer S-2000 UV-VIS by using a detector CCD with an Interface ADC500 in the range 186.2 nm to 877.47 nm[9]. The spectrometer was pre-calibrated by OceanOptics, Inc..

Spectra were recorded for every of two different situations: without the outer bulb (B-case) and with it (A-case). In Figure 6 are shown the two spectra recorded at t=100 s. In (B-case) all the Hg atom lines are observed, including UV 253.73 nm. As shown also in other papers ([10], [12], [11]) for the case when the "phosphor" coating is present, (A-case), the Hg resonance line of 253.73 nm is found completely absent from the spectrum because is absorbed by "phosphor".

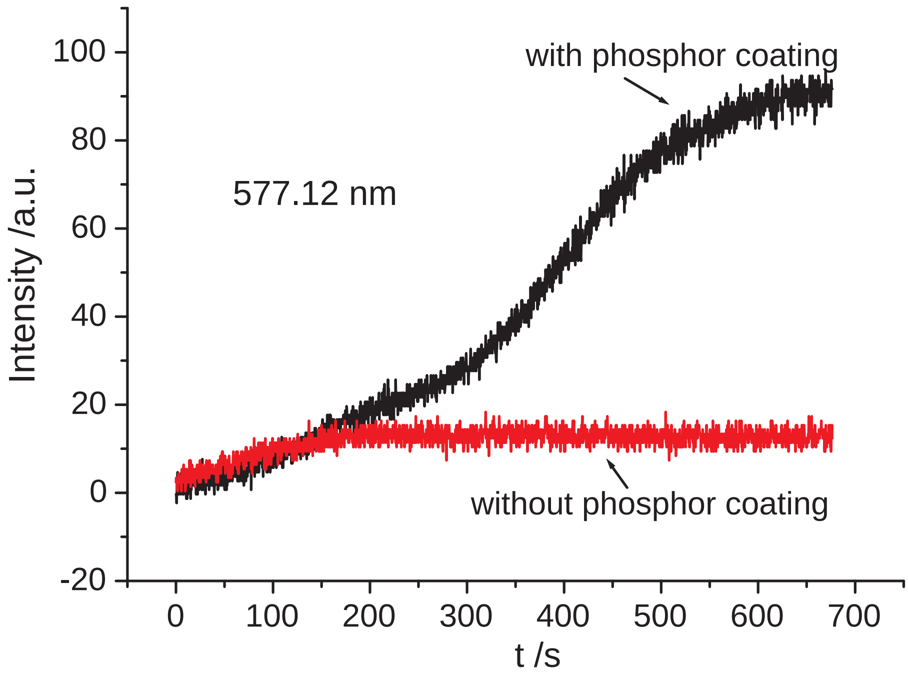

Figure 6-Time dependence of the optical emission line intensity of yellow 577.12.nm in the two situations: case-A (with an outer bulb phosphor coated) and case-B (without it)

The yellow 577.12 nm mercury emission line intensity versus time shown in Figure 6, for the two cases in discussion describes the optical transition, $6^3D_2 \longrightarrow 6^1P_1$,as shown in ref.[13]. The shape of intensity versus time curves for all the other Hg lines, except 253.73 nm line (see also ref. [14]) is similar with that of the 577.12 nm line. In the case without external bulb the steady state is already achieved at around 200 s measured from the ignition moment, as the thermal equilibrium between the burner walls and the ambient environment is established more rapidly. In the other case (with the external bulb and phosphor coating) the steady state is attained much more later, at about 700 s from the lamp starting. This happens because the outer bulb isolates the burner from environment and the burner wall temperature will be much higher, implying also a hotter discharge resulting in intensities becoming more than four times higher than in the former case.

3 Conclusions

This paper investigates the evolution in time of lamp potential and current recorded in the case of a high pressure Hg lamp before (A-case) and after the elimination of the external jacket (B-case). In steady state regime the lamp potential is higher in the (A-case) than in the (B-case) but the ratio of the amplitudes of the current intensities corresponding to the two cases has an opposite sign. The Fourier analysis revealed the presence of the odd harmonics in the time dependence of the electrical parameters of the lamp, being more pronounced in (A-case) than in (B-case). Another observation is that the total harmonics distortions is higher for the time dependence of lamp potential function compared with that of current intensity. As expected, we recorded also lower intensities for emission Hg lines in the case of lamp without external bulb compared with those corresponding the normal lamp. Surprisingly the steady state seems not to be attained until 700 s in the (A-case) (of lamp with outer bulb coated with phosphor). This is explained by the fact that the outer bulb isolates the burner from environment and the burner wall temperature will be much higher, implying also a hotter discharge.

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