LUMINOUS EFFICIENCY EVALUATION OF FLUORESCENT LAMPS UNDER EFFECT OF DIMMING

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Abstract – **This paper proposes a simple circuit to measure the output light of dimmable electronic ballasts, evaluating its efficiency. The work consists on choosing an appropriated sensor and environment to make the measurement of lamp output light at only one point, comparing the results to the integrating sphere. Using this developed luminous meter, it is done a comparative study between electrical power and light when the lamps are dimmed with and without filament pre-heating. In order to show the experimental results of the luminous meter it is used the self-oscillating dimmable electronic ballast supplying two independent lamps, also explaining the ballast behavior and design. Finally, graphics about the main lamp luminous characteristics are presented, in order to illustrate some important parameters when the lamps are dimmed.**

KEYWORDS

Luminous Evaluation, Dimming, Fluorescent Lamps, and Self-Oscillating.

I. INTRODUCTION

Electronic ballasts supplying fluorescent lamps have become one of the most popular lighting systems because of its higher luminous efficiency (lm/W), no flicker, audible noise absence, lighter weight and volume [1].

Dimmable electronic ballasts are becoming attractive devices to save electrical energy in many places that can use natural illumination, like: houses, offices, classrooms, etc. Therefore, many works in the literature have been developed, as [2], and [3]. These works use the integrating sphere to evaluate ballast output light. However, this equipment is bulky, heavy and expensive.

To evaluate the output light, comparing to nominal output light, we are proposing to measure only one point, when using the same ballast and lamp. Therefore, it is a simple and cheap circuit to evaluate dimmable ballast output light.

An important point to increase lamp life is the filament pre-heating. However, we do not have the clear information, in the literature, if this pre-heating also increases the output light. So, this point must be evaluated.

Besides, dimmable ballasts known in the literature use dedicated circuits to change the switching frequency; consequently, changing the lamp power. Self-oscillating electronic ballast is one good alternative to substitute these dedicated ballasts, due its simplicity and feasibility. Dimmable self-oscillating electronic ballast was proposed in [4].

Another good alternative to achieve a better ballast efficiency is to supply two independent lamps from the ballast; one work proposing two independent lamps behavior is presented in [5].

II. LUMINOUS METER

This luminous meter has been developed to substitute the integrating sphere in the luminous evaluation of dimmable electronic ballasts. In order to develop the LM there are some items to be taken into account: choosing the correct sensor, sensor circuit, environment, and calibration.

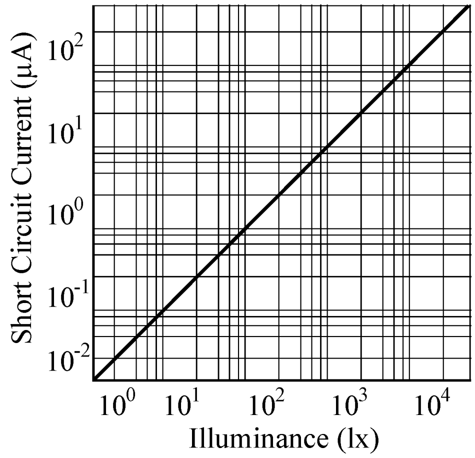
1)Sensor:
The key point to the LM is choosing the correct sensor. It was verified that the sensor more indicated to measure visible light (linear response) is the photodiode. Therefore, it was chosen a sensor with following features: sensitivity up to 10^5 lx, excellent linearity, and flat glass window with built-in color correction filter for visible radiation (giving an approximation to the spectral response of the human eye). Sensor linearity and spectral response can be observed in Fig. 1 a) and b), respectively.

2) Sensor Circuit:
It was noted that the photodiode short circuit current is linear with the illuminance. Therefore, we need a circuit to turn this current signal into a measurable voltage signal. Figure 2 shows the circuit, and its response is shown in (1).

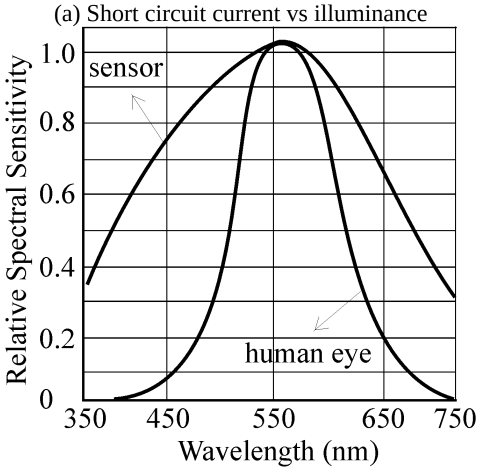
$$V_0 = I_R R \tag{1}$$

3) Environment
We have been chosen a wood box of 30 x 30 x 135 cm painted of opaque black inside to put the sensor and the luminary to supply two independent lamps. The size of the box is big enough to do not suffer thermal variation inside and it is painted of opaque black, so the sensor do not measure reflected light in the wall of the box. Figure 3 shows a scheme of proposed meter.

4) Calibration
In order to verify the response of the meter it was used a 200 W incandescent lamp, which its output light is proportional to electrical power. Table I shows obtained results, and plotted graphic is shown in Fig. 4.



(a) Short circuit current vs illuminance



(b) Relative spectral sensitivity vs wavelength

Figure 1 - Sensor Characteristics

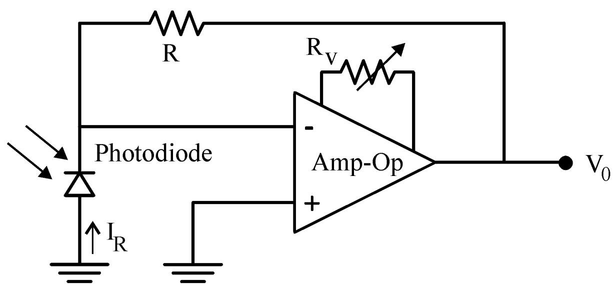


Figure 2 - Sensor circuit

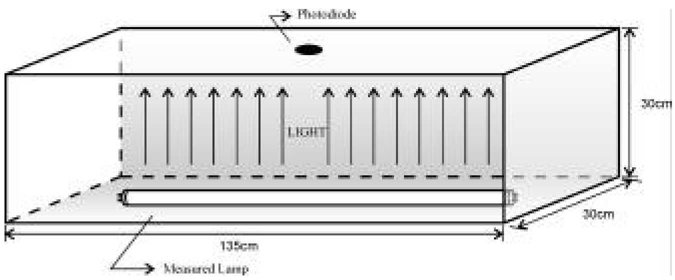


Figure 3 - Luminous Meter

TABLE I
Incandescent lamp light meter response

Lamp Power (W)	V_0 (V)
200	5.2
150	3.4
100	1.95
50	0.6

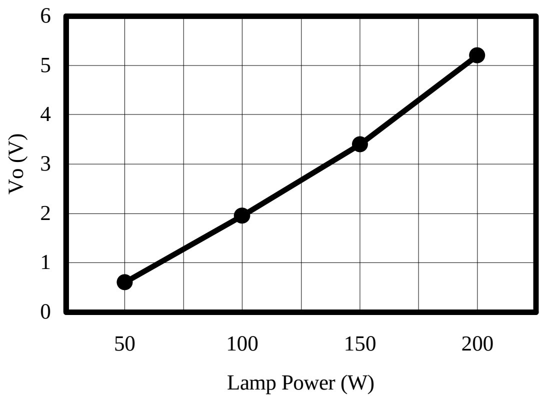


Figure 4 - Incandescent lamp light meter response

III. DIMMABLE SELF-OSCILLATING ELECTRONIC BALLAST SUPPLYING TWO INDEPENDENT LAMPS

3.1) Dimmable Self-Oscillating Electronic Ballast

Traditional self-oscillating electronic ballast (SOEB) is presented in [4]. Using this analysis we can study the dim feature.

A. Self-Oscillating Dimmable Electronic Ballast (SODEB)

Also in [4] it was demonstrated that current i_Z has an important role in defining the SOEB operating frequency. The current i_Z in traditional SOEB depends on both the zener voltage V_Z and magnetizing inductance L_m, in order to change the frequency. Since both V_Z and L_m are usually constant, one alternative to change the current i_Z is adding an additional network at secondary side of the CT, here it is named B_D and it is shown in Fig. 5. A LR network is the configuration for the implementation of the network B_D.

The next subsection presents qualitative analysis of the SOEB with additional branch BD (SODEB).

B. Qualitative Analysis of Self-Oscillating Electronic Ballast with Dimming Capability using the LR Network

The use of the additional LR network allows increasing the slope of the resulting current i_D which is the sum of the magnetizing current, i_M, and the LR network current i_{BD} as shown in Fig. 6. It is possible to see from Fig. 6 that as i_{BD} increases, also the switching frequency does. The commutation point changes from the point A to the point A_L. As a result, the smaller dimming resistor R_d, the larger is the operating frequency, which leads to a smaller lamp power.

Also, as presented in [4], a CR network could be used to change the switching frequency of the self-oscillating electronic ballast. Differently of the LR network, as smaller the value of the resistor R, as lower is the switching frequency. However, in this work, we decide to use the LR network.

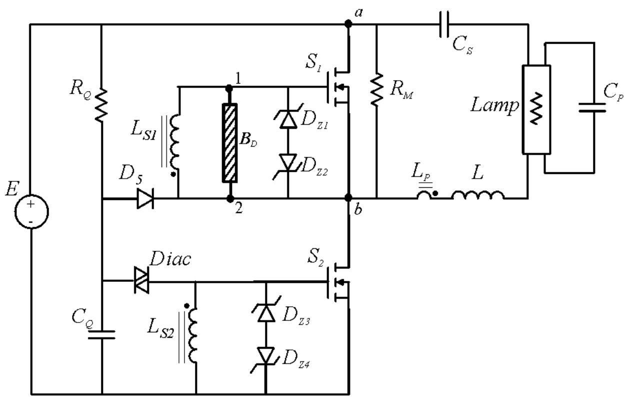


Figure 5 - Self-oscillating dimmable electronic ballast

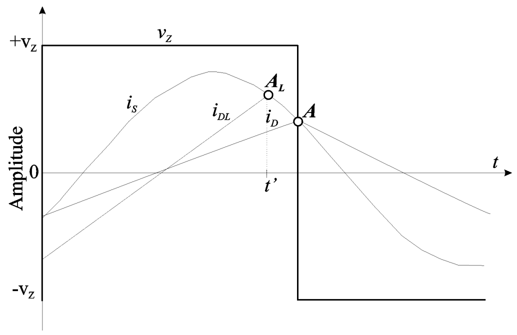


Figure 6 - LR network effect in the self-oscillating electronic ballast

C. Electronic Ballast Design Procedure for Dimming Feature

In this section the SODEB is modeled as a single input single output (SISO) nonlinear system with hard limit nonlinearity. The design procedure is developed in steps for LR network.

The design steps for the SODEB in this case are:

a) STEP 1 - Selection of Resonant Filters Parameters

Initially it is assumed that the lamp operating frequency and power are known. Design of resonant filter is based on the fundamental approximation and the phase angle of the resonant current and shift-phase angle between the resonant current i_S and fundamental voltage of V_{ab}. This design step is omitted here since it is described in details in [4].

b) STEP 2 - Selection of the Switching Frequency Range of the Self-oscillating Electronic Ballast with Dimming Feature

In this step, it is defined the frequency range of the SODEB, in order to ensure the operation with zero voltage switching (ZVS). It is possible to see the variation of the lamp power due to the frequency variation, where it is indicated the maximal ω_{max} and minimal ω_{min} operation frequency, in Fig. 7.

By selecting the minimal switching frequency of the ballast higher than resonant frequency it is possible to ensure ZVS for the entire frequency operation range. Since the contribution of the current in the LR network increases operation frequency.

c) STEP 3 - Design of the Magnetizing Inductor L_m

In order to determine L_m it should be considered the operation at the minimal switching frequency where R_d is equal to infinite. This analysis is done in [4], L_m value can be found by:

$$L_m = \frac{L\left(\left(c - a\omega^2\right)^2 + \left(b\omega - \omega^3\right)^2\right)}{Kn\left[a\omega^2\left(a\omega^2 - c\right) + \omega^3\left(b\omega - \omega^3\right)\right]}, \quad (1)$$

where s = jω; a = 1/RC_P; b = 1/L(C_S+C_P); c = 1/R$C_S C_P$L; K = E/2V_Z; and R = R_{LAMP}.

L_m is found where n = n_P/n_S, n_P is the number of turns of the primary side and n_S is the number of turns of the secondary side of the current transformer CT.

d) STEP 4 - Design of Dimming Inductance L_d

Similarly as carried out for the magnetizing inductance L_m is the value of the inductance of the LR network, L_d is obtained considering its maximal impact on the circuit operation that is when R_d is equal to zero. As a result, the converter operates at the maximum frequency ω_{max} [4]. L_d is found by:

$$L_d = \left(\frac{\omega Kn\left[\omega^2\left(b\omega - \omega^3\right) + a\omega\left(c - a\omega^2\right)\right]}{L\left(\left(b\omega - \omega\right)^2 + \left(c - a\omega^2\right)^2\right)} + \frac{1}{L_m}\right)^{-1} \quad (2)$$

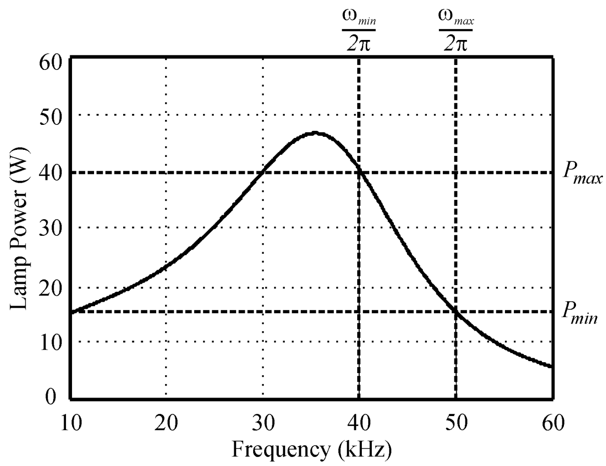


Figure 7 - Lamp power due to the switching frequency

D. Independent Two-Lamp Behavior

The idea of the lamp arrangement is presented in [5]. Attaching the idea of the dimmable self-oscillating ballast with the two-lamp idea, it is presented the studied ballast in the Fig. 8.

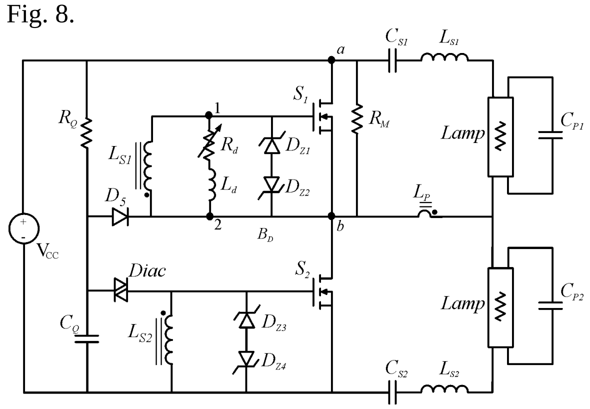


Figure 8 - Proposed ballast

IV. EXPERIMENTAL RESULTS

After developed the light meter, we start making the measures with two F40D Daylight fluorescent lamps (OSRAM). It was observed that up to the lamps warm up, any measure will not be correct, because the lamps have a thermal inertia, which is shown in the Fig. 9.

Figure 9 shows that the lamps take about 2:30h to stabilize (error less than 1%). However, in [3] the author pre-warm the lamps at least 28 min, out of the integrating sphere, and move them into the integrating sphere waiting 8 min to start the measure. Therefore, it causes an error of about 2%.

In order to evaluate fluorescent lamp luminous efficiency, it was demonstrated, in Fig. 10, output light versus input power for the ballast without pre-heating supplying two lamps. We observe that, since 30% (output light), input power is, approximately, proportional to output light.

Table II shows experimental results of the luminous meter. It was analyzed the ballast with and without filament pre-heating. P_1 is the input power of the ballast without filament pre-heating, and V_1 is the respective sensor voltage, which is proportional to the light. P_2 is the input power of the ballast with filament pre-heating, and V_2 is the respective sensor voltage.

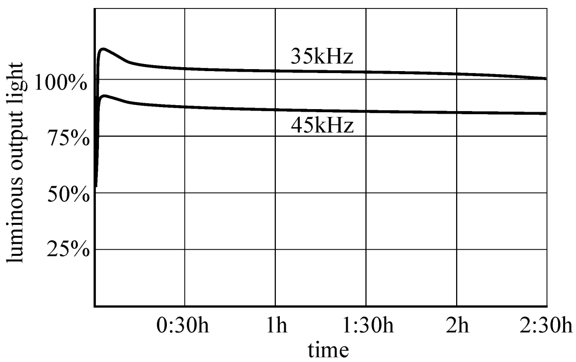


Figure 9 - Fluorescent lamp thermal stabilization

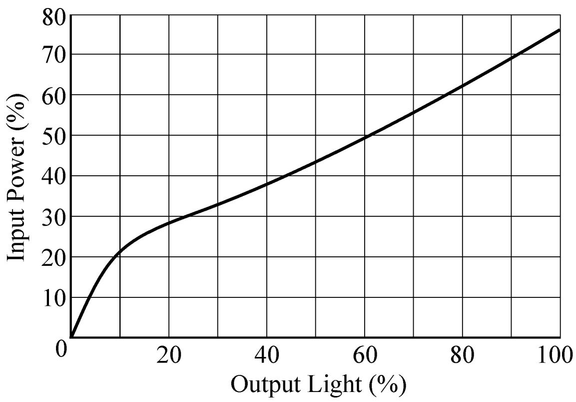


Figure 10 - Output light versus input power

TABLE II
Experimental results

Switching Frequency	P_1 (W)	V_1 (V)	P_2 (W)	V_2 (V)
40 kHz	75,5	8,33	74,34	9,1
45 kHz	82,8	8,47	79,9	9,36
50 kHz	82,5	7,77	77,9	8,74
55 kHz	82,3	5,82	71,5	7,98
60 kHz	70,64	4,76	57,6	6,27

In order to compare the luminous efficiency of the ballast, with and without filament pre-heating, it is presented the result of output light (sensor voltage) divided by the input power in the Table III as the ballast efficiency ($_1$ and $_2$), together with the lamp voltage value (V_{L1} and V_{L2}). Efficiency result can be seen graphically in the Fig. 11. It was considered that the ballast with filament pre-heating at 45kHz represents =100%, and further results are compared to this choice.

V. DISCUSSION

In this section it is discussed the fluorescent lamp behavior when dimmed with and without filament pre-heating. We observed that, without filament pre-heating, the lamp lost its luminous efficiency, which can be seen in the Fig. 11. We note that, at the maximum switching frequency (60kHz), the ballast presented a luminous efficiency of about 60%; however, when the ballast is dimmed with filament pre-heating, this luminous efficiency is about 93%. It happens because, without filament pre-heating, the lamp needs to increase the cathode voltage to keep the term ionic emission when dimmed, this fact can be verified in the Table III, which shows the lamp voltage increase of the ballast without filament pre-heating. This extra-cathode-voltage of the ballast without filament pre-heating also decreases the lamp life, because of the cathode sputtering.

Other important point to be observed is the lamp thermal inertia. We observe that it is necessary to warm the lamp by 30 min to have an error less than 2%; and, to have an error less than 1%, it is necessary to warm the lamp by 150 min.

TABLE III
Efficiency comparison

Switching Frequency	$_1$ (%)	V_{L1} (V)	$_2$ (%)	V_{L2} (V)
40 kHz	94,2	90,7	104,5	87,5
45 kHz	87,3	89,12	100	84,7
50 kHz	80,4	91,86	95,8	85,1
55 kHz	60,4	101,8	95,2	89,3
60 kHz	57,5	101,8	92,9	92,4

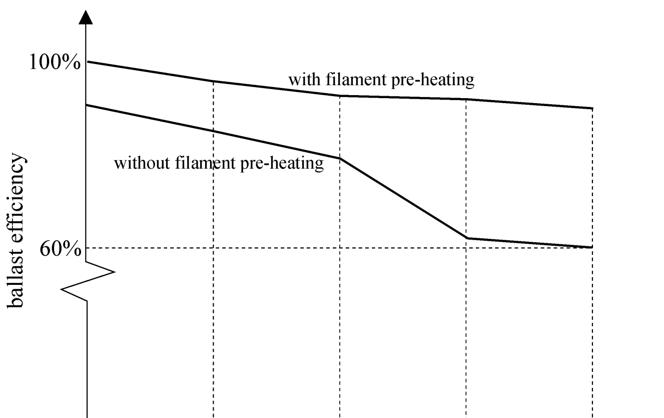


Figure 11 - Ballast efficiency comparison

VI. CONCLUSION

A simple alternative to measure fluorescent lamp emitted light has been proposed, which has low cost and dimension, differently of the integrating sphere, which is approximately 60 times larger than the developed luminous meter. Besides low cost and size, developed luminous meter has linear response versus light, as shown in Fig. 4. In addition, lamp characteristics were shown, like its thermal inertia and luminous efficiency.

It is important to emphasize that this meter only can be used to one type of lamp, because it evaluates the light at only one point, and different lamps can emit light differently. So, this meter can evaluate the dimmed ballast efficiency correctly, which was the purpose of the work.

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