MEASURING THE EQUIVALENT RESISTANCE OF ELECTRODES' FILAMENTS OF TUBULAR FLUORESCENT LAMPS, DURING DIMMING OPERATION

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***Abstract* – This paper presents a methodology for determining the value of equivalent electrical resistance of fluorescent lamps' electrodes during dimming operation. This methodology is capable to provide accurate values, which can be employed in new models of fluorescent lamps. Moreover, according to recent literature, the values of equivalent electrical resistance of the electrode can also be used in the evaluation of the lifetime of fluorescent lamps. It should be highlighted that, despite its simplicity, the proposed methodology for determining the values of resistance is completely new and provides conditions for obtaining very accurate results.**

***Keywords* – Fluorescent Lamps, Electrodes' Filaments, Dimming Control**

I. INTRODUCTION

The specification of electronic ballasts should be based in a lamp-ballast compatibility analysis [1], in order to maximize the system efficacy and to minimize problems of unreliable starting, end darkening, and reduced lamp life [2].

One parameter used to evaluate the lamp life is the electrode operating temperature. Nevertheless, according to [1], since the electrode temperature is difficult to be measured, the analysis of the voltage over the electrode can be employed in an indirect evaluation of its operating temperature. Recently, new studies have been developed in order to establish a relation between the electrode equivalent resistance (measured in the ignition) and the lamp life. Actually, the parameter that has been investigated is the ratio between the "hot" resistance (R_H, measured in the glow-to-arc transition) and the "cold" resistance (R_C, measured with the lamp turned off, considering a time interval of at least 5 minutes after its turn-off) [1].

According to [3], the value of the ratio R_H/R_C must be situated between 4.25 and 6.25, ensuring the proper electrode temperature for the lamp ignition, minimizing the occurrence of excessive sputtering and/or excessive evaporation of the electrodes' emissive coating. It is important to notice that, as commented in [3], the upper limit (6.25) is not considered as the maximum value that the ratio R_H/R_C can reach, but it is recommended by some lamp manufacturers. The value of R_C can be determined with a precision ohmmeter, capable to measure values of few ohms [3]. Concerning R_H, its measurement cannot be directly obtained because it is not possible to connect the ohmmeter to the lamp during its operation. Thus, a method for the determination of R_H is proposed in [4], employing a data acquisition system, which stores the instantaneous values of voltage and current through the electrode. Then, these data are processed in a specific software (MathCad, MATLAB, etc) and the value of R_H is obtained using the Ohm's Law (R_H=v/i).

It should be highlighted that, according to [3] and [4], the value of R_H is computed with the data stored immediately before the lamp ignition (glow-to-arc transition). Therefore, employing this methodology, the value of R_H is only suitable for evaluations of the ignition processes. During dimming operation, it is possible to evaluate the voltage over the electrode in order to analyze the lamp-ballast compatibility [1 and 5]. However, for ballast designers, the determination of the electrode equivalent resistance during dimming operation should represent an important parameter, because it would permit the prediction of the voltage over the electrode. Therefore, it would be possible to establish an optimized design procedure for the electronic ballast, reducing the occurrence of lamp-ballast incompatibilities. Moreover, the determination of the values of R_H during dimming operation would provide important additional information, considering the current trend towards the adoption of R_H/R_C ratio as a reliable parameter for evaluating the lamp life.

According to this context, this paper presents a methodology for obtaining the values of R_H during the lamp operation. It should be noticed that, despite its simplicity, the new methodology represents an innovation, because it permits to calculate the value of R_H during dimming operation. In addition, it should be highlighted that the methodology proposed in this paper provides values of R_H that would be employed in fluorescent lamp models used in the design of dimming electronic ballasts. Moreover, it is informed that these values of R_H are more accurate than the values usually employed in lamp models described in the literature [6 and 7]. Thus, it is possible to affirm that the values of R_H obtained through the methodology proposed in this paper can be employed in the evaluation of lamp-ballast compatibility, and in the design of dimming electronic ballasts, permitting the prediction of the compliance with recommendations about voltage over the electrode, and values of R_H/R_C ratio.

II. EQUIVALENT RESISTANCE MODEL OF THE FLUORESCENT LAMP'S ELECTRODE

In order to understand the proposed methodology for the determination of the values of R_H, it is necessary to present the lamp model, considering the electrodes. Since the application explored in this paper is limited to high-frequency dimming electronic ballasts, the fluorescent lamp can be admitted as a variable resistance, dependent on the power processed through the lamp, and on the ambient temperature [8 and 9]. Fig. 1 shows how the electrode resistances are usually incorporated in the lamp model. According to [7], R_A and R_B assume different values depending on the adopted model (power or voltage). It is informed that the voltage model is employed in several papers, where the resistances can be represented by:

$$R_A = R_B = \frac{R_H}{2} \tag{1}$$

However, according to experimental results presented in the following sections of this paper, preliminary measurements indicate that the expression represented by (1) cannot be considered suitable for the development of accurate theoretical analyses. Therefore, a proper methodology for the determination of the values of R_A and R_B during dimming operation is described in this paper, permitting the development of analyses about the variation of R_A and R_B (and R_H, consequently), depending on the power processed through the lamp.

III. DETERMINATION OF THE VALUES USED IN THE EQUIVALENT RESISTANCE ELECTRODE MODEL

Based on the fluorescent lamp model showed in Fig. 1, the equivalent schematic circuit of the lighting system ("conventional" electronic ballast + lamp) can be represented by Fig. 2.

In the real lighting system, only the parameters $i_A(t)$, $i_B(t)$, $i_{Lamp}(t)$, and $v_{AB}(t)$ can be measured (their waveforms can be acquired using a digital oscilloscope). It is important to note that the point M, represented in the model of Fig. 2, is not physically accessible, which impedes the measurement of $v_{AM}(t)$ and $v_{MB}(t)$. As a consequence, it is not possible to

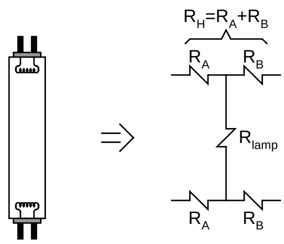


Fig. 1. Resistive model of fluorescent lamp, considering the electrodes.

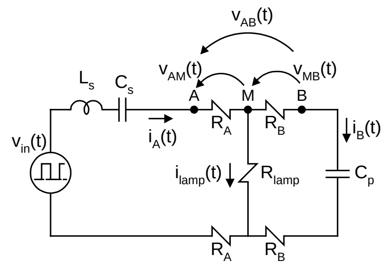


Fig. 2. Equivalent circuit of the lighting system (electronic ballast + fluorescent lamp).

calculate the values of R_A and R_B through the direct employment of the Ohm's Law ($R_A=v_{AM}/i_A$, and $R_B=v_{MB}/i_B$). Despite this fact, according to the model of Fig. 2, it is possible to write:

$$v_{AB}(t) = v_{AM}(t) + v_{MB}(t) \tag{2}$$

$$v_{AM}(t) = R_A.i_A(t) \tag{3}$$

$$v_{MB}(t) = R_B.i_B(t) \tag{4}$$

From (2), (3), and (4):

$$v_{AB}(t) = R_A.i_A(t) + R_B.i_B(t) \tag{5}$$

Since the parameters $v_{AB}(t)$, $i_A(t)$, and $i_B(t)$ can be easily obtained using a digital oscilloscope, the expression represented by (5) presents two unknown terms for each acquisition point (for each value of t). Thus, considering an acquisition of n points (n values of t), it is possible to obtain a system with n equations from (5), with only two unknown terms (R_A and R_B). So, the solution of this system can provide the values of R_A and R_B.

It should be highlighted that the measurements (acquisitions) of $v_{AB}(t)$, $i_A(t)$ and $i_B(t)$ are performed during the stable operation of the fluorescent lamp (after the ignition), which differs from the methodology presented in [4]. In addition, if a dimming control is imposed to the lamp, the acquisition of $v_{AB}(t)$, $i_A(t)$ and $i_B(t)$ can be properly developed for other operating points (different values of power processed through the lamp), without any significant constraint.

Therefore, it is possible to obtain an accurate estimate of the effects of dimming control on the values of R_A and R_B, permitting the development of an investigation about the movement of the hot spot in the electrode under dimming conditions [10]. In addition, as commented before, the values of R_A and R_B can be employed in the development of a new fluorescent lamp model, providing more accurate information for ballast designers than the usual models presented in the literature [6 and 7].

However, despite the apparent simplicity in the determination of R_A and R_B, it is necessary to observe that the solution of the system with n equations will require a proper methodology, since the values of $v_{AB}(t)$, $i_A(t)$, and $i_B(t)$ are obtained from a data acquisition set, which implies in inherent presence of noise. Thus, without a proper solving methodology, the system with n equation will be inconsistent.

In fact, this is a typical problem concerning laboratorial measurements with noise. For each acquisition point, the noise content will be different. Nevertheless, the system remains the same, which means that the linear dependence must be sustained. In this context, without considering the presence of noise, the number of points (equations) that exceeds the number of variables must be a linear combination of equations, and the solution of this system must be unique and equal to the solution of a linear system with full rank (invertible square matrix). However, the noise content does not permit to achieve this solution.

Thus, the alternative is to “minimize the effects of the noise”, which means to find the projection of the system into its vector space such as the error between the solution and the acquired data is minimized. The technique employed for solving this system is the Least Square Approximation [11].

In general terms, supposing that the system with n equations can be represented by:

$$A.x = b \tag{6}$$

where: A is a n by m matrix, n > m, representing the measurements of currents i_A and i_B;
b is a vector with n lines, representing the measurements of voltage v_{AB};
x is a vector with m lines, representing the unknown terms R_A and R_B;
m is the number of unknown terms;
n is the number of points obtained with acquisition data set,

then, using the Least Square Approximation, the solution of (6) is expressed by:

$$x = (A^T.A)^{-1}.A^T.b \tag{7}$$

The values of R_A and R_B obtained from (7) are adopted as the values that have to be used in the evaluation of the electrode resistance during the lamp operation.

IV. EXPERIMENTAL RESULTS

The validation of the proposed methodology for the determination of R_A and R_B is performed by the comparison with experimental data.

According to (1) until (7), the calculation of R_A and R_B is based on the acquisition of the waveforms of $v_{AB}(t)$, $i_A(t)$ and $i_B(t)$. Therefore, a digital oscilloscope with four channels was employed for the data acquisition (Tektronix – TDS420A). One voltage probe (P6138A) and two current probes (TM502A/A6302) were used in the experimental set. Moreover, the waveforms were acquired together, with the same trigger.

The voltage source $v_{in}(t)$ presented in Fig. 2 represents the association of a DC voltage source (250V) and a Half-Bridge converter controlled by the IR2155, from International Rectifier. A trimpot is used in the circuitry of the IR2155, allowing the variation of the switching frequency and, consequently, the obtaining of dimming operation.

As commented before, the main objective of this paper is concerned to the investigation of the effects of dimming operation on the equivalent resistances of the lamp model. Therefore, the experimental results were obtained for a fixed ambient temperature, which was equal to 25°C.

The fluorescent lamp employed in the experiment is a F32T8/BF, manufactured by GE – General Electric. The parameters of the Half-Bridge inverter and the SRPL filter are specified according to table I.

TABLE I
PARAMETERS EMPLOYED IN THE BALLAST

V_{DC}	250V
Nominal Switching Frequency	50kHz
S_1, S_2	IRF830A
L_S	1.45mH
C_S	180nF
C_P	5.6nF

Fig. 3 illustrates the experimental arrangement used to obtain the waveforms required for the analysis.

Each set was acquired in a different condition of power processed through the gas column of the lamp (P_{lamp}), in order to permit the evaluation of the influence of dimming control on the values of R_A and R_B.

The values of R_A and R_B are determined using the data presented in Fig. 4 and the Least Square Approximation [11].

These values are summarized below:

- P_{lamp}≅32W: R_A=2.0Ω; R_B=8.0Ω
- P_{lamp}≅25W: R_A=2.1Ω; R_B=9.5Ω
- P_{lamp}≅20W: R_A=2.9Ω; R_B=9.8Ω
- P_{lamp}≅15W: R_A=3.1Ω; R_B=10.25Ω
- P_{lamp}≅10W: R_A=3.3Ω; R_B=10.4Ω

In order to verify the consistence of the values of R_A and R_B obtained from the proposed methodology, Fig. 5 shows a graphical comparison among:

- $v_{AB}(t)$ acquired with the oscilloscope (original),
- $v_{AB}(t)$ reconstructed using the values of R_A and R_B calculated in this paper ($R_A \neq R_B$), and
- $v_{AB}(t)$ reconstructed using the values of R_A=R_B=5Ω (voltage model, from [6 and 7]).

According to Fig. 5, it is possible to observe that the values of R_A and R_B determined in this paper are much more accurate than the values defined according to the model presented in [6 and 7]. Therefore, the employment of the model presented in [6 and 7] can introduce significant errors in the theoretical results, hindering the analysis about the operational conditions of the electrodes.

Besides the accurate estimate of R_A and R_B, the methodology proposed in this paper permits to investigate the influence of the dimming control on these parameters, and, consequently, on R_H.

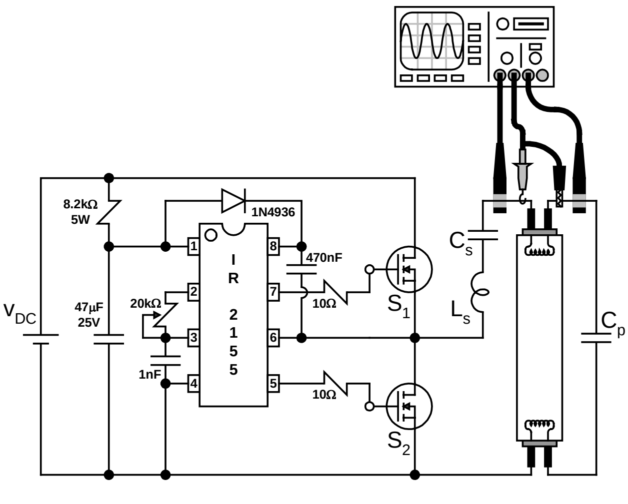
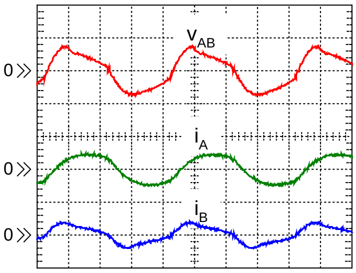
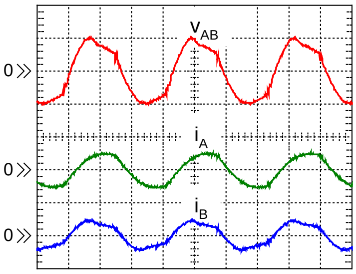


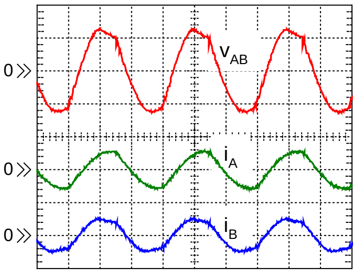
Fig. 3. Experimental arrangement for the measurement of $v_{AB}(t)$, $i_A(t)$ and $i_B(t)$.



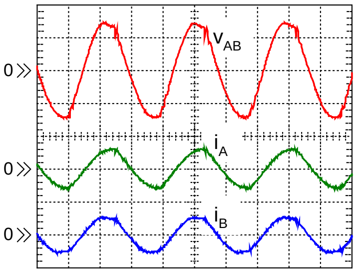
(a) P_{lamp} = 32W (f = 50kHz)
v_{AB}: 5V/div ; 5μs/div
i_A, i_B: 1A/div ; 5μs/div



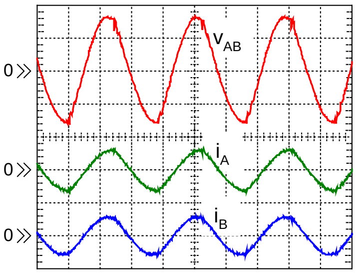
(b) P_{lamp} = 25W (f = 61.5kHz)
v_{AB}: 5V/div ; 5μs/div
i_A, i_B: 1A/div ; 5μs/div



(c) P_{lamp} = 20W (f = 67.5kHz)
v_{AB}: 5V/div ; 5μs/div
i_A, i_B: 1A/div ; 5μs/div

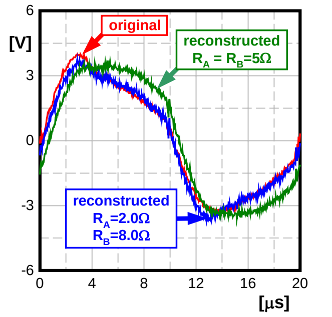


(d) P_{lamp} = 15W (f = 69.3kHz)
v_{AB}: 5V/div ; 5μs/div
i_A, i_B: 1A/div ; 5μs/div

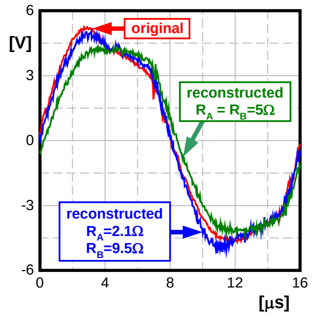


(e) P_{lamp} = 10W (f = 70.8kHz)
v_{AB}: 5V/div ; 5μs/div
i_A, i_B: 1A/div ; 5μs/div

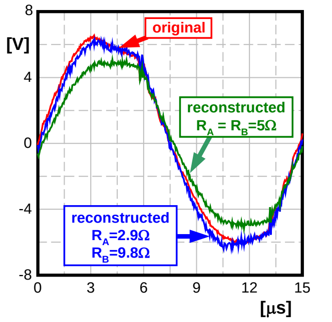
Fig. 4. Sets of experimental data used for the determination of R_A and R_B.



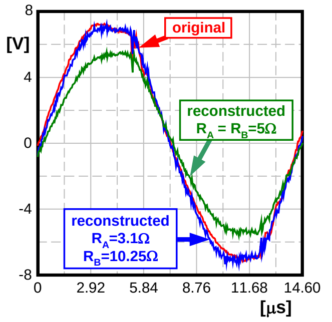
(a) P_{lamp} = 32W



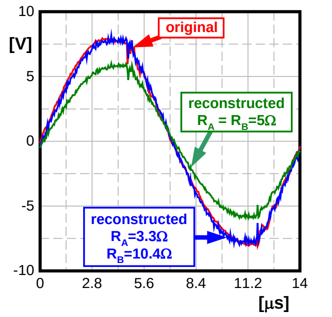
(b) P_{lamp} = 25W



(c) P_{lamp} = 20W



(d) P_{lamp} = 15W



(e) P_{lamp} = 10W

Fig. 5. Waveforms of the voltage over the electrode, for different dimming conditions.

Fig. 6 shows the values of R_A, R_B, and R_H as functions of the power processed through the gas column of the lamp (P_{lamp}). Based on this figure, it is possible to verify that the dimming control presents significant influence on the values of R_A, R_B and R_H.

The values of power dissipated in the equivalent resistances are depicted in Fig 7. The rms values of $i_A(t)$ and $i_B(t)$ were measured using a function of the digital oscilloscope (Tektronix – TDS420A). From Fig. 7, one can observe that, for low dimming conditions, most of the total power dissipated in the equivalent resistances comes from R_B. In addition, when the power processed through the lamp is increased, the difference between P_A and P_B is reduced.

Fig. 8 shows the values of power dissipated in the electrode, considering the voltage model presented in [6 and 7] (R_A=R_B=5Ω). Comparing the results presented in Figs. 7 and 8, it is possible to conclude that the adoption of R_A=R_B can be responsible for the incorporation of significant errors in the analysis of the electrodes, during dimming operation.

Therefore, the methodology presented in this paper can provide important information to support the research concerning dimming electronic ballasts and their influence on lamp life [10]. In addition, it should be noticed that, from the use of the methodology proposed in this paper, the analyses of lamp life based on R_H/R_C ratio would be extended to the dimming operation.

V. CONCLUSIONS

This paper presented a methodology for an accurate determination of the electrode equivalent resistance of tubular fluorescent lamps. The methodology represents a new approach in the procedure for the obtaining of the values that compose the electrode model.

The comparison among the reconstructed data and the experimental results shows that the proposed methodology is plenty valid. Moreover, comparing the waveforms of the voltage over the electrode, obtained with the resistances calculated in this paper ($R_A \neq R_B$) and the resistances from the model usually employed in the literature (R_A=R_B), it can be observed that the methodology proposed in this paper is capable to provides much better results.

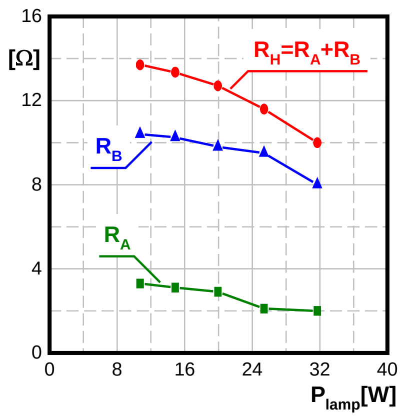


Fig. 6. Values of electrode's equivalent resistances, considering dimming operation.

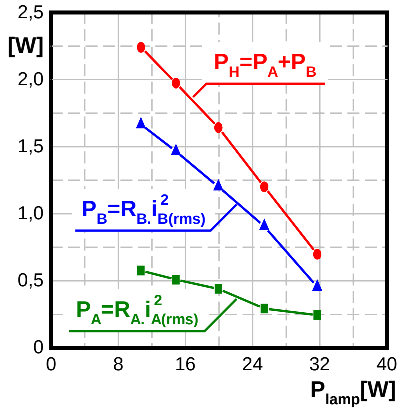


Fig. 7. Values of power dissipated in the electrode, considering $R_A \neq R_B$ and dimming operation.

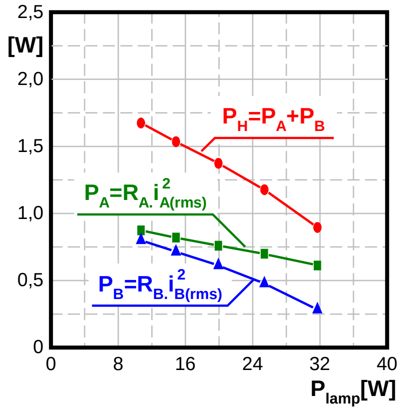


Fig. 8. Values of power dissipated in the electrode, considering R_A=R_B=5Ω and dimming operation.

Among the potential applications of the methodology proposed in this paper, it is possible to highlight the evaluation of lamp-ballast compatibility during the design procedure of dimming electronic ballasts, and the evaluation of the lamp life, through the estimate of the electrode temperature during dimming operation.

In addition, according to the results obtained for R_H, the methodology proposed in this paper can be extended to permit the determination of the behavior of R_H as a function of several parameters employed in the design of dimming electronic ballasts, such as: power processed through the lamp, ambient temperature, switching frequency, dc link voltage, resonant filter, etc. In this case, the new model of R_H would be used to enhance the fluorescent lamp models, providing conditions for a detailed evaluation of the lamp-ballast compatibility during dimming operation, using an estimate of the electrode temperature.

It should be highlighted that, despite the experimental results do not plenty comply with ANSI recommendations (2.5V < $v_{AB(rms)}$ < 4.0V), this fact does not invalidate the methodology proposed in this paper.

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