A NOVEL STATIC MODEL FOR TUBULAR FLUORESCENT LAMPS IN DIMMABLE APPLICATIONS, AND HIGH FREQUENCIES OF OPERATION

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Abstract – **This paper presents a new static model for tubular fluorescent lamps (T12 bulb) operated at high frequencies. The main goal of this paper is to investigate the effects of ambient temperature and nominal switching frequency of operation in the static characteristics of tubular fluorescent lamps. The methodology for obtaining the model is based on several two-dimensional mathematical regressions, used to provide the behavior of the fluorescent lamp according to different independent variables, namely: power processed through the lamp and ambient temperature. In addition, the proposed model can be easily converted to a lamp equivalent resistance model, which can be useful for ballast designers. Finally, the curves obtained using the new model are compared to the correspondent experimental data, in order to verify the accuracy of the proposed methodology.**

KEYWORDS

Fluorescent lamp static model, high frequencies, dimmable applications.

I. INTRODUCTION

In the last years, the use of high frequency electronic ballasts has been increased because of their several advantages, such as reduced volume and weight, suppression of stroboscopic effect and audible noise, dimming capability, and high efficiency. In addition, fluorescent lamps operated by high frequency ballasts (above 20kHz) present higher luminous efficiency (lumens/Watt) than those ones operated by line frequency magnetic ballasts (50Hz – 60Hz) [1].

The design of these electronic ballasts depends on the model adopted for the fluorescent lamp. During the last years, several dynamic and static models have been proposed for these lamps [2-7].

Usually, dynamic models provide conditions to investigate the interactions between the lamp and the ballast, analyzing instabilities and even phenomena like striation, when the lamp is in an ultra-low dimming condition [8].

Static models represent the fluorescent lamp as an equivalent resistance, due to its V-I (rms values of voltage and current through the lamps) characteristic [2]. This approach is much simpler than the dynamic models, and can be useful for designing the ballast in specific operating point. However, the V-I characteristic changes during the dimming operation, which means that the model must be admitted as a variable resistance, as a function of the rms value of processed power (P) [2]. The curve of this equivalent variable resistance, during dimming operation, can be obtained using the rms values of voltage (V) and current (I) through the lamp [3, and 6]. Employing mathematical regression methods, it is possible to determine a refined static model for the fluorescent lamp, concerned to the processed rms values. So, the design of ballasts becomes more accurate, because this kind of model provides conditions to predict the behavior of some important variables, such as switching frequency range during dimming operation, and phase-shift of the current drained by the set of resonant filter plus fluorescent lamp.

When proposing a model for fluorescent lamps, it is necessary to take into account that their V-I characteristics present significant changes according to the ambient temperature (T) [9-10], and, in a minor scale, according to the nominal switching frequency (f_{nom}). A good model that incorporates the influences of ambient temperature is presented in [10]. However, it is not usual to find either analyses concerned to effects of different nominal switching frequencies in the V-I characteristics or analyses about illuminance as a function of power processed through the lamps.

Thus, this paper presents a simple methodology to determine a new static model for fluorescent lamps operated in high frequencies. The effects of different ambient temperatures and different nominal switching frequencies on the voltage over the lamps, and on their illuminance levels, are analyzed. In order to make the model more useful for ballasts designers, the V-I curves are replaced by V-P curves, as presented in [3], where P is the rms value of the power processed through the lamp.

II. PROPOSED MODEL FOR TUBULAR FLUORESCENT LAMPS

The proposed model is based on different sets of experimental data, obtained from implemented ballasts operating in different nominal switching frequencies (f_{nom}) and different ambient temperatures (T). It should be noticed that the experimental results were obtained in a closed-shielded and temperature controlled environment. In addition, overloads were imposed to the lamps, in order to obtain a more accurate description of the nominal operating point (P_{nom}=40W).

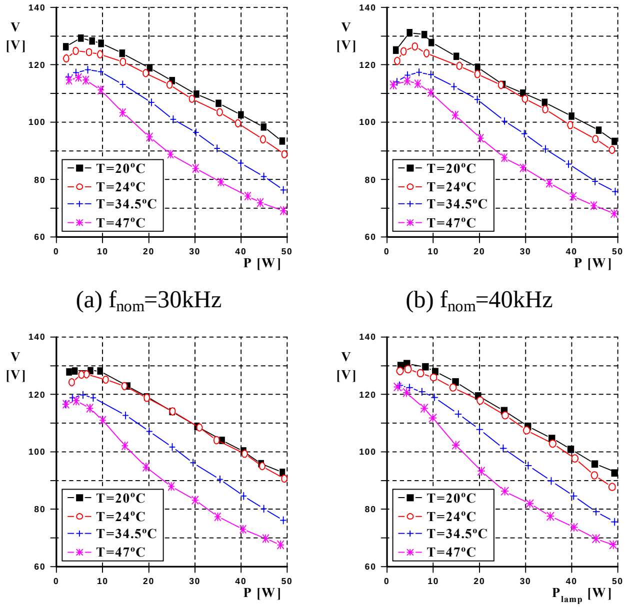
Fig. 1 shows the V-P curves, and Fig. 2 shows the illuminance curves, derived from experimental data sets, for a T12 bulb fluorescent lamp. It is important to inform that the illuminance levels were measured with a digital luxmeter (MLM1332 – Minipa), and these data were normalized (L_{rel}, in [p.u.]) according to one value considered as standard (in this case, adopting a ballast processing 40W, at 40 kHz and 24°C).

From Figs. 1 and 2, it is possible to observe that the influence of ambient temperature on the lamps characteristics is very strong, and it must be included in the lamp model in order to provide conditions to the development of an accurate design. It is also possible to conclude that the V-P curves, as well as the relative illuminance ones, present a similar tendency, which means that they can be expressed by the same kind of mathematical expressions.

Fig. 3 shows the comparison among some data sets obtained for different nominal switching frequencies, and in the same ambient temperature. It is possible to note that the influence of the nominal switching frequency is not strong enough to justify its inclusion in the fluorescent lamp mathematical model, considering the analyzed range of f_{nom}.

Fig. 4.a shows the switching frequency (f) as a function of P, for different conditions of ambient temperature. From this figure, it is possible to note that, if the switching frequency of the ballast is kept constant (e.g., open-loop control techniques), the power processed through the lamp, and, consequently, its illuminance, can present significant variations according to the ambient temperature.

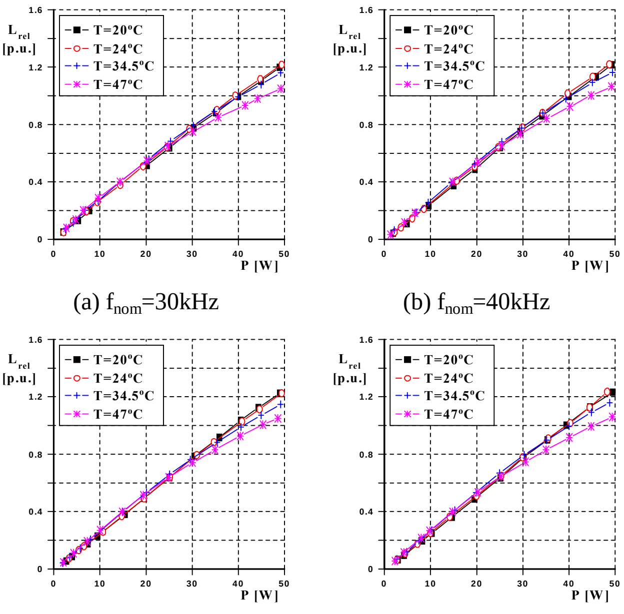
Fig. 4.b shows the current through the fluorescent lamp (I) as a function of P, for different ambient temperatures. According to this figure, it can be verified that, in higher ambient temperatures, the fluorescent lamp requires more current to sustain the power, and, consequently, its illuminance level, which can decrease the lamp useful lifetime.



(a) f_{nom}=30kHz (b) f_{nom}=40kHz

(c) f_{nom}=50kHz (d) f_{nom}=60kHz

Fig. 1 – rms values of voltage over the fluorescent lamp (V), as a function of P, for different values of T and f_{nom}.



(a) f_{nom}=30kHz (b) f_{nom}=40kHz

(c) f_{nom}=50kHz (d) f_{nom}=60kHz

Fig. 2 – Relative illuminance levels from the fluorescent lamp (L_{rel}), as a function of P, for different values of T and f_{nom}.

A. V-P characteristics

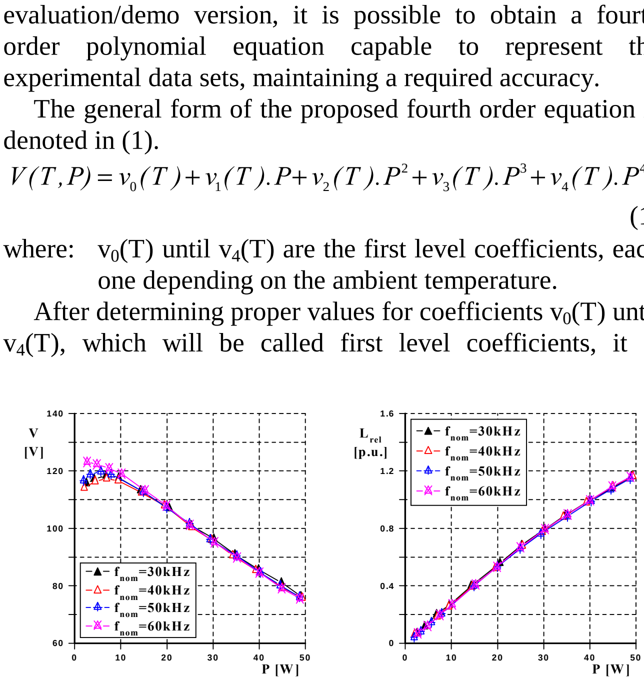
Some lamp models represent the V-P (or V-I) characteristic as a first order linear equation [3, and 11]. However, it is possible to verify in Fig. 1 that this characteristic presents a different behavior when the lamp is in a low dimming condition (P<10W). So, in [6], a fifth order polynomial equation is used to provide a more accurate model. However, using specific softwares, such as Origin evaluation/demo version, it is possible to obtain a fourth order polynomial equation capable to represent the experimental data sets, maintaining a required accuracy.

The general form of the proposed fourth order equation is denoted in (1).

$$V(T,P)=v_0(T)+v_1(T).P+v_2(T).P^2+v_3(T).P^3+v_4(T).P^4 \quad (1)$$

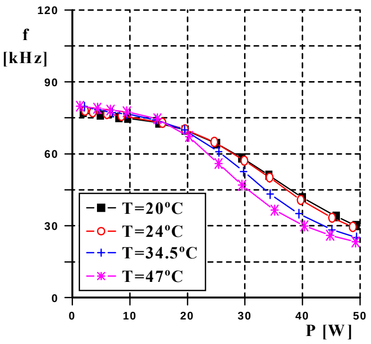
where: $v_0(T)$ until $v_4(T)$ are the first level coefficients, each one depending on the ambient temperature.

After determining proper values for coefficients $v_0(T)$ until $v_4(T)$, which will be called first level coefficients, it is

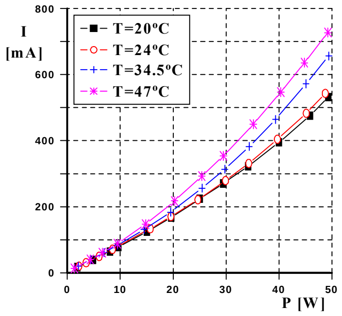


(a) T=34.5°C (b) T=34.5°C

Fig. 3 – (a) V versus P, and (b) L_{rel} versus P, for a fixed value of T and different values fnom.



(a) f_{nom}=40kHz



(b) f_{nom}=40kHz
Fig. 4 – (a) f versus P, and (b) I versus P, for different values of T and a fixed value of f_{nom}.

possible to obtain equations capable to describe properly each different set of experimental data presented in Fig. 1. The variations in these coefficients represent the changes in the V-P curves of Fig. 1. So, writing these coefficients as functions of ambient temperature (T), the fluorescent lamp model can be established.

In order to perform this three-dimensional (3D) regression (V versus P versus T), it is possible to use two two-dimensional (2D) regressions. In this way, the first 2D regression is used to determine the equations of V as functions of P, resulting in one set of coefficients for each different value of T. Therefore, using the same regression software employed before, it is possible to determine new equations capable to describe the behavior of the first level coefficients as functions of T, resulting in a new set of coefficients, called second level coefficients. These second level coefficients are the last ones required in this model.

From the experimental data showed in Fig. 1, the first level coefficients are determined through 2D regressions, using the software Origin evaluation/demo version. Table I shows these values, according to their correspondent ambient temperature (T).

TABLE I
First Level Coefficients

	T [°C]			
	20	24	34.5	47
$v_0(T)$	125.5598	122.3859	115.1590	117.2896
$v_1(T)$	1.2997	1.1413	1.3317	0.3252
$v_2(T)$	-0.1373	-0.1117	-0.1385	-0.1358
$v_3(T)$	0.0034	0.0026	0.0032	0.0039
$v_4(T)$	-2.8841E-5	-2.1203E-5	-2.4940E-5	-3.4421E-5

As commented before, 2D regressions will be performed on the first level coefficients, considering their variation according to T. Fig. 5 shows the values of first level coefficients as a function of T. The lines connecting the dots are derived from fitting curves provided by software.

The general form of equations used to describe the first level coefficients as a function of T is represented as follows:

$$v_i(T) = vs_{i,0} + vs_{i,1}.T + vs_{i,2}.T^2 \qquad (2)$$

where: i = index of the first level coefficients;
$v_i(T)$ is a first level coefficient; and
$vs_{i,0}$ until $v_{i,2}$ are second level coefficients.

The values of second level coefficients ($vs_{0,0}$ until $vs_{4,2}$), determined via software, are presented in Table II.

Using the values presented in Table II and the sets of equations described in (1) and (2), it is possible to obtain the novel static model for the fluorescent lamp. The data presented in Table I are not used in this model. These data are implicit in the values of the second level coefficients.

TABLE II
Second Level Coefficients

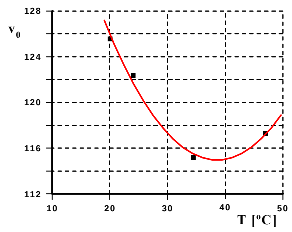
$vs_{0,0}$	162.37633
$vs_{0,1}$	-2.4576
$vs_{0,2}$	0.03184

$vs_{1,0}$	-0.7991
$vs_{1,1}$	0.1550
$vs_{1,2}$	-0.00278

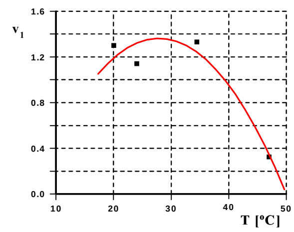
$vs_{2,0}$	-0.11871
$vs_{2,1}$	-3.8550E-4
$vs_{2,2}$	0

$vs_{3,0}$	0.0058
$vs_{3,1}$	-2.0092E-4
$vs_{3,2}$	3.43775E-6

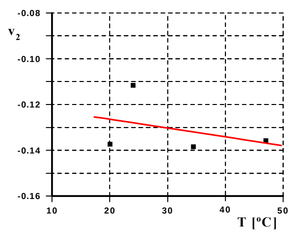
$vs_{4,0}$	-6.14784E-5
$vs_{4,1}$	2.58124E-6
$vs_{4,2}$	-4.28405E-8



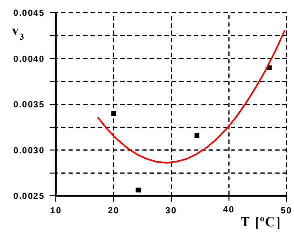
(a) v_0



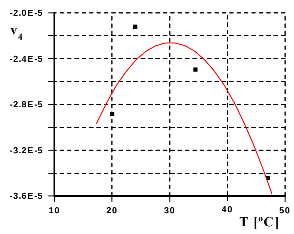
(b) v_1



(c) v_2



(d) v_3



(e) v_4
Fig. 5 – First level coefficients, as a function of T.

B. Relative illuminance characteristics

The same methodology described to obtain the equation of V(T,P) can be employed to obtain the equation of relative illuminance $L_{rel}(T,P)$. A second order polynomial equation can be used to represent the relative illuminance as a function of P and T, according to (3).

$$L_{rel}(T,P) = L_0(T) + L_1(T).P + L_2(T).P^2 \quad (3)$$

where: $L_0(T)$ until $L_2(T)$ are the first level coefficients of relative illuminance.

Using the software Origin evaluation/demo version, it is possible to obtain these first level coefficients, which are summarized in Table III.

These coefficients are plotted in the graphs presented in Fig. 6. From this figure, it is possible to note that these coefficients can be written as linear functions of T, according to the following equation:

$$L_j(T) = Ls_{j,0} + Ls_{j,1}.T \quad (4)$$

where: j = index of the first level coefficients;
$L_j(T)$ is a first level coefficient of $L_{rel}(T,P)$; and
$Ls_{j,0}$ until $Ls_{j,1}$ are the second level coefficients of $L_{rel}(T,P)$.

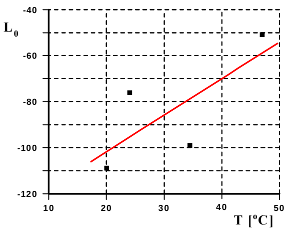
New 2D regressions are performed in the data presented in Table III, in order to determine the second level coefficients, which are presented in Table IV.

The data presented in Table IV and the sets of equations described in (3) and (4) can represent the relative illuminance of fluorescent lamps, as a function of P and T.

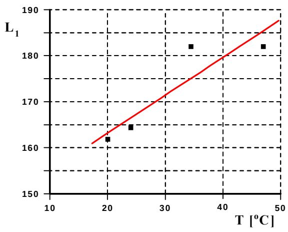
III. COMPARISON BETWEEN THE PROPOSED MODEL AND EXPERIMENTAL DATA

Fig. 7 shows the sets of experimental data (dots) and the curves (solid lines) generated with the proposed model, from (1) to (4). According to this figure, it is possible to verify that the model presents good accuracy, describing the behavior of the fluorescent lamp, for a range from 2.5W until 40W of processed power. The proposed model does not cover low levels of power processed through the lamp (P<2.5W), because, in this particular condition, the phenomenon of striation is amplified and can be visually detected.

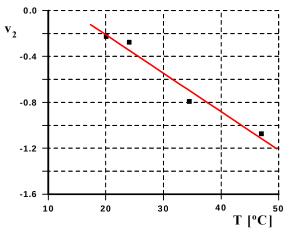
Some inaccuracies can be observed in this model, especially in the V-P graph at T=20°C. However, these



(a) L_0



(b) L_1



(c) L_2

Fig. 6 – First level coefficients of relative illuminance.

TABLE III
First Level Coefficients of L_{rel} (T,P)

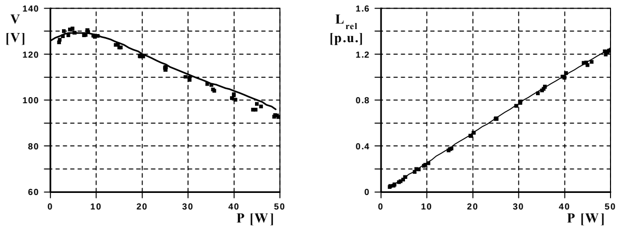
	T [°C]			
	20	24	34.5	47
L_0(T)	-108.82234	-76.10645	-99.01401	-50.83447
L_1(T)	161.81644	164.30821	182.0283	181.97835
L_2(T)	0.22603	-0.27557	-0.7928	-1.07303

TABLE IV
Second Level Coefficients of L_{rel} (T,P)

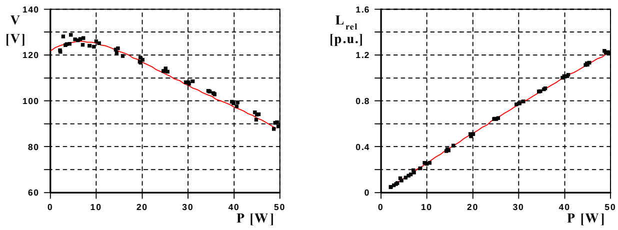
$Ls_{0,0}$	-133.54535
$Ls_{0,1}$	1.58888

$Ls_{1,0}$	146.74
$Ls_{1,1}$	0.82208

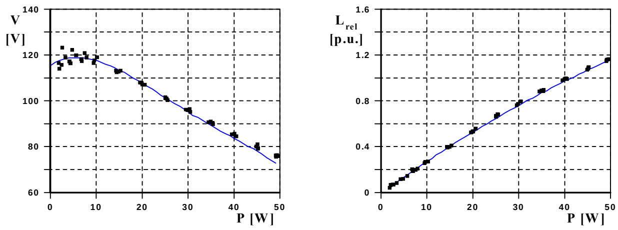
$Ls_{2,0}$	0.4576
$Ls_{2,1}$	0.03345



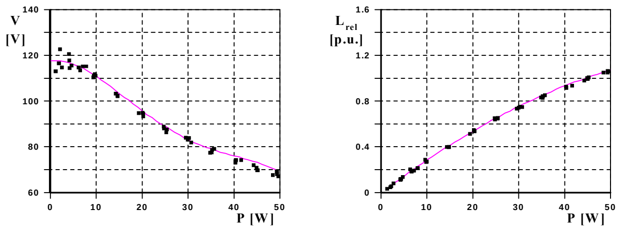
(a) T=20°C



(b) T=24°C



(c) T=34.5°C



(d) T=48°C

Fig. 7 – Comparison among experimental data (dots) and the proposed model (solid lines) for fluorescent lamps.

inaccuracies are lower than 2%, and they can be considered negligible. However, if necessary, some additional empirical adjusts in the second level coefficients can be performed, improving this model.

For ballasts designers, it is important to obtain the lamp equivalent resistance, which would be used in the design methodology in order to predict the behavior of some important parameters, during dimming operation, such as: rms value of lamp current, and rms value of current through the resonant inductor. This equivalent resistance ($R_{eq}(T,P)$) can be easily obtained using (5).

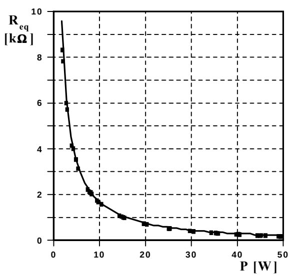
$$R_{eq}(T,P) = \frac{V^2(T,P)}{P} \qquad (5)$$

Fig. 8 shows a comparison among four different sets of experimental data (dots) and the model proposed in (5) (solid lines). From this figure, it can be observed that the curves generated with (5) fit the experimental data, which means that the proposed model can provide a good accuracy to the design process of dimmable electronic ballasts.

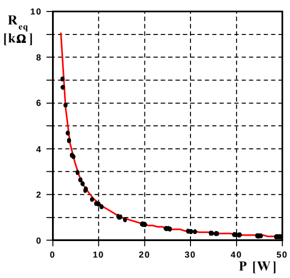
In addition, simulations have been developed in order to provide an improved evaluation of the proposed lamp model, when it is employed for designing electronic ballasts. The simulated circuit and an implemented prototype were designed according to the data presented in Table V. The fluorescent lamp employed in the prototype is a GE-F40T12 / Super Daylight. Fig. 9 shows the simplified schematic circuits of the implemented ballast and the simulated circuit, based on the classical resonant Half-Bridge inverter.

TABLE V
Ballast Parameters

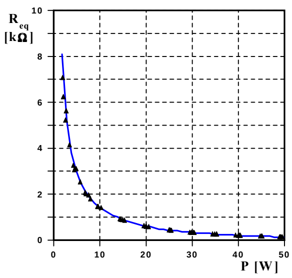
Input and Output Data		Ballast Parameters	
$V_{in(dc)}$	310V	L_s	1.4mH
P_{nom}	40W	C_s	180nF
T	24°C	C_p	6.8nF
f_{nom}	40kHz	S_1, S_2	IRF840



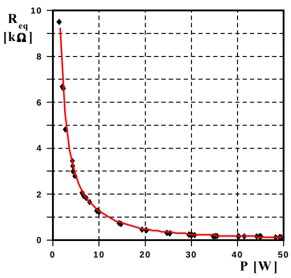
(a) T=20°C



(b) T=24°C

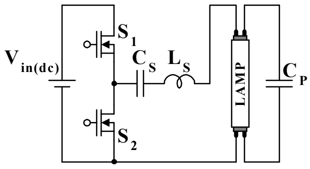


(c) T=34.5°C

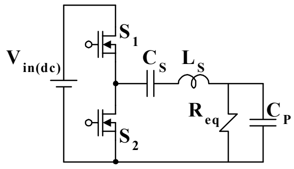


(d) T=47°C

Fig. 8 – Comparison among experimental data (dots) of lamp equivalent resistance and the proposed model $R_{eq}(T,P)$.



(a) implemented ballast



(b) simulated circuit

Fig. 9 – Simplified schematic circuits.

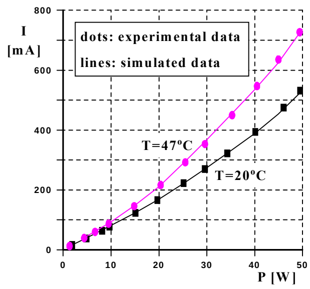
The circuit has been simulated in the PSpice 4.02 software. Table VI presents the parameters employed for simulating several operating points of this circuit. The values of power (P) and switching frequency (f) were measured in the prototype, and used in the simulations, in order to verify the lamp model accuracy. The values of the equivalent lamp resistances (R_{eq}) are determined according to (5).

Fig. 10 shows a comparison among the simulation results (lines) and the experimental data (dots), measured in the prototype.

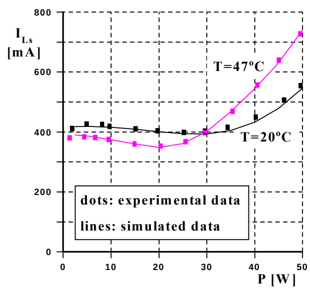
TABLE VI
Parameters used for Simulations

	T=20°C		T=47°C	
P [W] (*)	f [kHz] (*)	R_{eq} [Ω]	f [kHz] (*)	R_{eq} [Ω]
2.5	74.83	6573	76.60	5500
5	74.46	3335	76.49	2690
10	73.64	1641	75.85	1223
15	72.26	1036	73.51	709.5
20	69.70	721.3	68.17	455.1
25	65.32	533.2	57.03	312.9
30	58.70	412.3	45.17	229.0
35	50.25	330.5	36.56	177.6
40	41.70	271.3	31.00	143.8
45	34.80	224.2	27.12	118.4
50	29.65	181.5	23.97	94.5

(*) measured data



(a)



(b)

Fig. 10 – (a) rms value of current through the lamp (I) versus P, and (b) rms value of I_{Ls} versus P, for different values of ambient temperature (T).

According to Fig.10, it is possible to conclude that the simulation results fit properly into the experimental data measured in the prototype.

Moreover, in Fig. 10.b, it can be observed that, for values of P lower than 30W, the current processed through L_s is sustained in high rms values, which are almost constant. In this way, it can be admitted that the currents processed through the MOSFETs are also sustained in significant rms values. Thus, it is possible to conclude that low values of power processed through the lamp implies in reducing the efficiency of this conventional electronic ballast, because of the conduction losses verified in the power circuit, which can be considered proportionally high when compared to the power processed through the lamp.

IV. CONCLUSIONS

This paper presented a new static model for tubular fluorescent lamps – T12 bulb, suitable for designing dimmable electronic ballasts.

This new model incorporates the effects of ambient temperature in its parameters, increasing its accuracy and reliability. The model is based on experimental data of a fluorescent lamp (GE-F40T12 / Super Daylight), which V-P characteristics are depicted for different conditions of temperature and nominal switching frequency.

The proposed model is conceived through two different kinds of equations: the first kind describes the V-P characteristic, while the second kind is a set of equations used to determine the behavior of the first level coefficients regarding to the ambient temperature. Thus, the rms value of the voltage over the fluorescent lamp can be described as a 3D function, depending on the values of processed power, and ambient temperature.

In addition, the model establishes a relation among the lamp illuminance, the processed power, and the ambient temperature.

In order to provide a model that can be easily employed for designing the lamp ballasts, it is possible to define an equivalent resistance, which mathematical expression is directly derived from the V(T,P) function. Simulation results presented in this paper confirm that the employment of the proposed model is useful for ballast designers, specially for determining the rms values of currents processed through the resonant filter and through the fluorescent lamp.

According to the comparison among experimental data and the lamp model, it is possible to conclude that the proposed methodology succeeds in incorporating the effects of ambient temperature in the V(T,P) and in the L_{rel}(T,P) expressions.

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