A NEW PSPICE FLUORESCENT LAMP MODEL BASED ON THE EXPONENTIAL FUNCTION

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Abstract – **This paper introduces a new Pspice fluorescent lamp model based on the exponential function, arranged in a similar way as in the well-known equation used to describe the voltage and current relationship in a p-n semiconductor junction, sometimes referred as the Shockley equation. The paper also describes some previous Pspice fluorescent lamp models, showing their basic equations, schematics implementation and typical simulation waveforms. This approach can be used to provide a comparison among the main models published in the recent technical literature, including the new proposed model. Experimental waveforms are also presented to serve as a reference basis. The new exponential model depends upon two parameters, which can be basically determined by means of two strategies. In both cases, the user has a very simple, accurate and fast numerical simulation model, mainly free of convergence errors.**

KEYWORDS

Fluorescent Lamp, Pspice Lamp Model, Electronic Ballasts.

I. INTRODUCTION

Lately the search for the rational use of the electric energy has boosted the research on fluorescent lamps driven by high frequency electronic ballasts.

The behavior of fluorescent lamps became an important investigation topic, and several mathematical models, mainly adapted to Pspice® simulator, have been proposed in the last years trying to cover this issue. Simplicity, accuracy and the ability to describe the power dependent behavior of the lamp are some of the features a good model should exhibit. By this way, electronic ballast designers can simulate their ballasts (normally based on a rectifier in association to some kind of high frequency inverter) even they include a dimmable function. Another desirable characteristic is that the model does not present numerical convergence problems, what is rather common in more complex approaches.

The aim of this paper is to present a brief review of the main Pspice fluorescent lamp models as well as to introduce a new model based on the exponential function.

The great majority of previous models describe the fluorescent lamp based on its V-I characteristic, as illustrated in the Fig. 1 for a 40W PHILIPS TL /75 RS tubular fluorescent lamp. Those kind of models do not take into consideration the physical characteristics of the lamp, such as arc length, gas pressure, cathode heating, lamp internal temperature and ignition effects. Instead, their mathematical equations try to reproduce the high frequency lamp behavior provided by the V-I curves for a certain number of power levels.

Researchers have tried to model Fig. 1 curves using straight lines [1], quadratic or parabolic functions [2], cubical equations [3] [1], tangential functions [4] and a sum of exponential functions [5] [6]. Some of these approaches will be reviewed in the next section. Then, the new exponential model will be described. A discussion, comparing several available Pspice models, closes the paper.

II. A REVIEW ON SELECTED MODELS

Before reviewing some specific models it is important to present experimental lamp waveforms, which will be useful for comparison purposes. Fig. 2a and Fig. 2b show voltage and current waveforms for nominal power (40W) and half-power (20W) respectively. Those waveforms have been obtained by means of a 50 kHz half-bridge inverter feeding a resonant circuit including a 1.05 mH inductor, a 160nF series capacitor and an 11.5nF capacitor in parallel with the lamp. In order to obtain a 40W and 20W operation the dc bus voltage had to be changed from 304V to 136V, respectively.

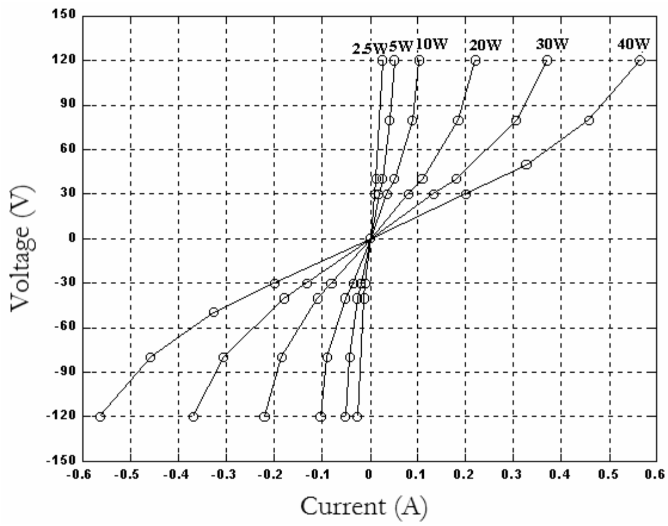

Fig. 1 – 40W Lamp V-I Dynamic Characteristics

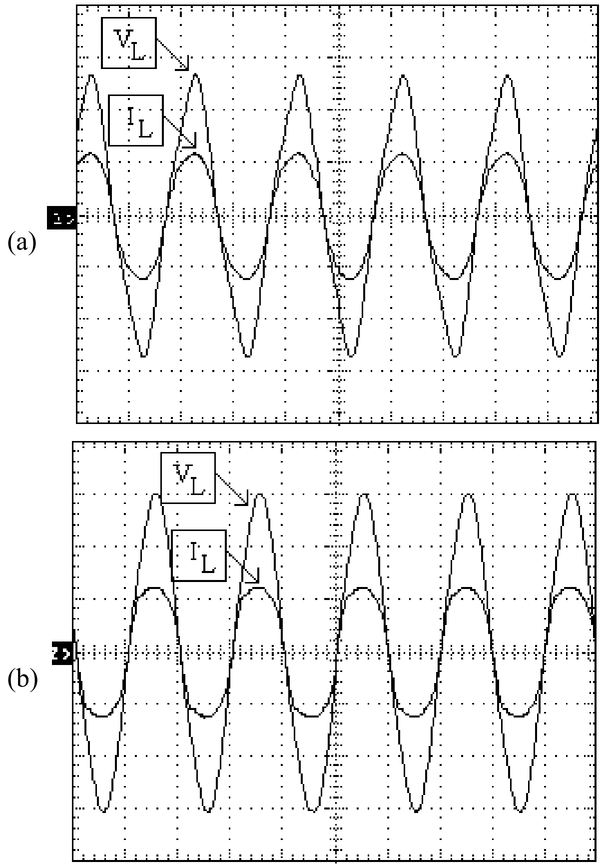

Fig. 2 – Current and voltage experimental waveforms (10 µs/div).
(a) 40 W (50 V/div; 500 mA/div);
(b) 20 W (50 V/div; 200 mA/div).

A) Linear Model

Curves of Fig. 1 can be roughly understood as straight lines crossing the origin of V-I plane [1]. In this case, the lamp performs as a power dependent resistance. In the form of equation:

$$v_L = R(P_L) \cdot i_L \tag{1}$$

where v_L and i_L are the instantaneous voltage and current of the lamp, while P_L is the average lamp power, which is proportional to the lamp gas ionization. This variable is simply the low-pass filtered version of the instantaneous lamp power $v_L(t).i_L(t)$.

A wide range, dc to high frequency, linear model can be accomplished defining $R(P_L)$ in (1) by:

$$R(P_L) = \frac{V_{dc}^{\;2}}{P_L + P_{Lo}} \cdot \tag{2}$$

In (2), V_{dc} is the lamp dc voltage (which is essentially constant above a near zero current) and can be obtained experimentally [9].

The term P_{Lo}, introduced in (2), has been employed to avoid division by zero and consecutive convergence problems. Fig. 3 shows the lamp theoretical V-I curves according to equation (2) for a range of power levels, including the dc characteristic (for the chosen lamp brand V_{Ldc} has been assumed to be 105V). Fig. 4 shows the Pspice® implementation (Cadence™, Student Version 9.1) of the linear model along with a typical high frequency electronic ballast equivalent circuit (V_i-L-C_s-C_p).

Note that in Fig. 4 the average lamp power, P_L, has been obtained by means of a low-pass filter with a 1 ms time constant. This filter is associated to the GVALUE voltage controlled-current source, which has the instantaneous lamp power as its input. This strategy is very common in nearly all kind of Pspice models found in the literature. Fig. 5 depicts the simulated current and voltage waveforms adopting the same parameters used to obtain the waveforms of Fig. 2 (changing dc bus voltage from 304V to 136V). Note that the model could not respond for such a large variation, especially at rated power. Note also that waveforms do not entirely agree with the experimental ones.

B) Second Order (Quadratic) Model

Reference [8] suggests the V-I curves of Fig. 1 could be described by a second-order equation, such as in (3).

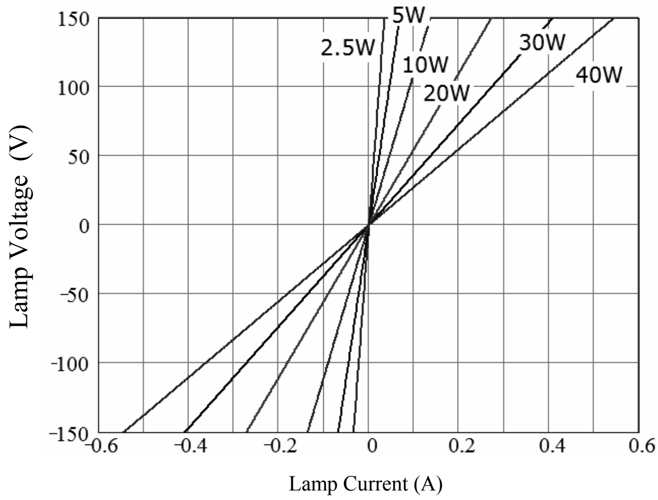

Fig. 3 – Theoretical linear model V-I curves.

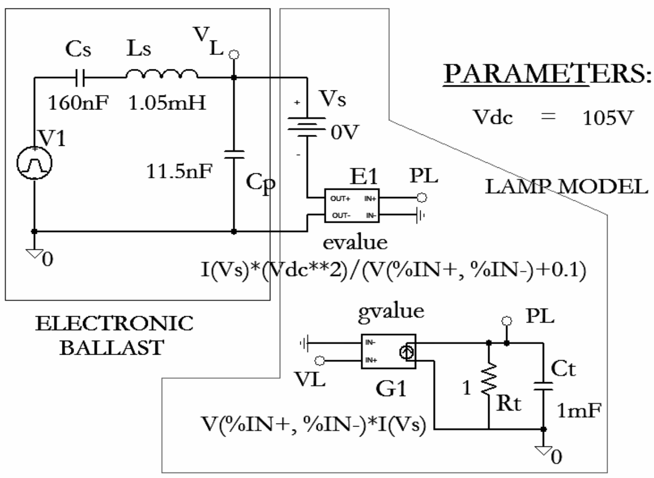

Fig. 4 – Pspice circuit for linear model.

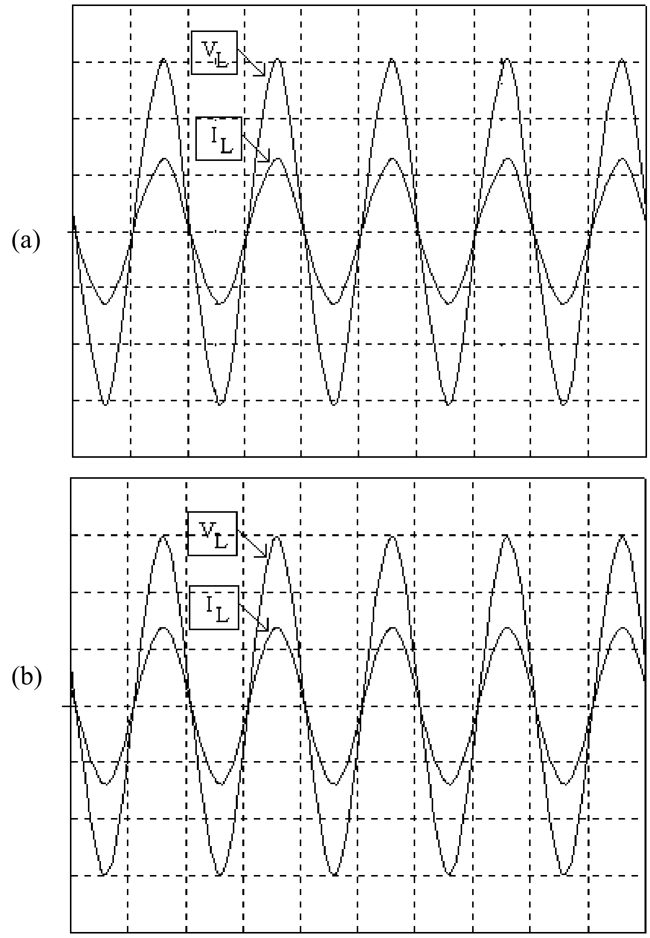

Figura 5. Pspice simulated waveforms using the linear lamp model (10μS/div).
(a) 46 W (50V/div; 500mA/div); (b) 20 W (50V/div; 200mA/div).

$$v_L = k \cdot i_L{}^2 . \tag{3}$$

A good approach on second-order models is provided in [8]. According to this work the high frequency lamp resistance should obey equation (4).

$$R = \frac{V_S}{I_{rms}} - R_S \ . \tag{4}$$

Where R_S and V_S are constants that can be obtained by means of experimental data (computing R for several rms current values). Equation (5) define this model.

$$i_L = \frac{v_L}{\dfrac{V_S}{I_{rms}} - R_S} . \tag{5}$$

Fig. 6 details the Pspice implementation of the quadratic lamp model, including the same electronic ballast equivalent circuit used in Fig. 4. Note that the rms value of lamp current, I_{rms}, has been accomplished by means of several Pspice resources, such as ABM, GVALUE and EVALUE. A large resistance in parallel with the lamp model has been introduced in order to avoid Pspice restriction rules (floating node). Moreover, convergence errors have been solved by including an initial condition for the filter capacitor, Ct, voltage.

Fig. 7 show simulated lamp voltage and current waveforms. It is easy to conclude that this kind of model provides better results than the previous one. However, waveform shapes are not as alike as the experimental counterparts.

C) Tangent Model

A more accurate lamp model can be obtained by assuming the curves of Fig. 1 as a family of trigonometric tangential curves [4]. In the form of equation:

$$v_L = A(P_L) \cdot \tan\left(\frac{i_L}{B(P_L)}\right) \tag{6}$$

In equation (6), P_L is the average lamp power, as in (1). Parameters $A(P_L)$ and $B(P_L)$ can be derived by means of exhaustive experimental measurements taken from a conventional electronic ballast feeding the desired fluorescent lamp. By varying dc bus voltage and/or inverter switching frequency it is possible to obtain a great amount of data, useful to determine $A(P_L)$ and $B(P_L)$ variation profiles. Doing so, authors assumed $A(P_L)$ as a constant (in practice, an arithmetic mean among measured data) and $B(P_L)$ has been approximated by a second-order polynomial.

Fig. 8 details the Pspice implementation of tangent lamp model, including the same electronic ballast equivalent circuit used in Fig. 4. Note that the average power P_L has been processed by means of a 0.5ms time constant low pass filter. From this figure, it is possible to conclude that $A(P_L) = 68.76$ and $k_a=2.09\text{x}10^{-4}$, $k_b=5.87\text{x}10^{-3}$ and $k_c=9.26\text{x}10^{-3}$ are the second order polynomial coefficients of $B(P_L)$.

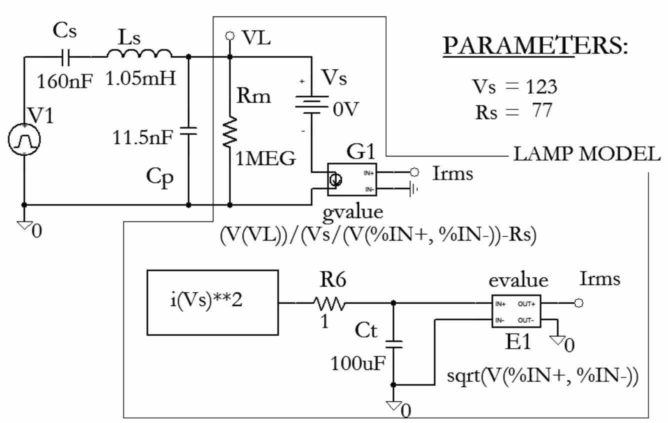

Fig. 6 – Pspice circuit for linear model.

(a)

(b)

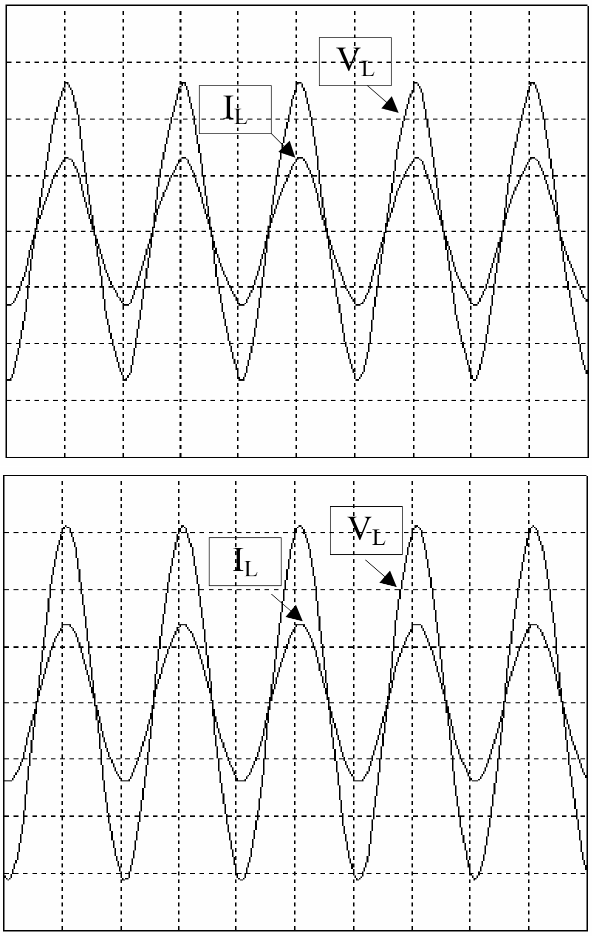

Figura 7. Pspice simulated waveforms using the quadratic lamp model (10μS/div).
(a) 39.4 W (50V/div; 500mA/div); (b) 20.9 W (50V/div; 200mA/div).

(a)

(b)

Fig. 9. Pspice simulated waveforms using tangential approximation (10μS/div).
(a) 38 W (50V/div; 500mA/div); (b) 20.2 W (50V/div; 200mA/div).

Fig. 9 presents simulated waveforms for comparison purposes with waveforms from Fig. 2. It is easy to conclude that they are very close in shape as well as present a good quantitative concordance.

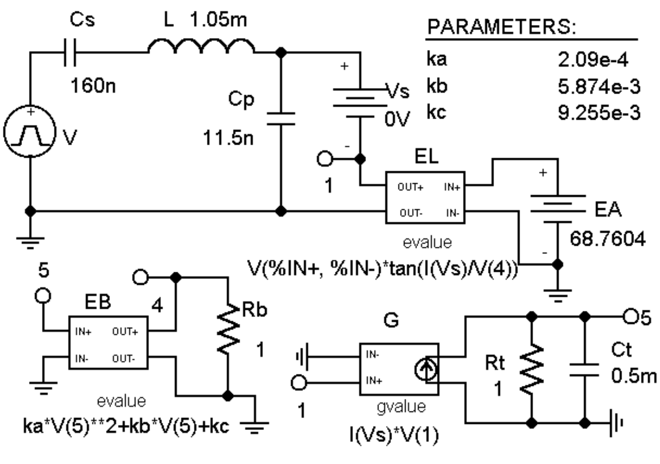

Fig. 8 – Pspice schematics of tangent based lamp model.

III. EXPONENTIAL MODEL

The proposal of this model is to approach the V-I characteristic of the fluorescent lamp by a simple exponential equation arranged in a similar way as used in the Shockley equation to describe the p-n junction behavior. However, the format of the Shockley equation can only accounts for the first quadrant V-I plane of the fluorescent lamp. So, slight changes must be employed, as follows:

$$v_L = sign(i_L)\cdot K(P_L)\cdot\left\{e^{\left[N(P_L)\cdot|i_L|\right]}-1\right\} \tag{7}$$

In (7), the function "sign( )" seeks to rebuild the curve for the third quadrant of the V-I plane. To final accomplish this task, the absolute value of the lamp current has been used in the exponent inside brackets of (4). The parameters $K(P_L)$ and $N(P_L)$ are determined using a similar method as used for the tangent model [4], i.e. based on experimental measurements one can define values or equations to represent the parameters.

Two possible procedures have been evaluated and verified simple and accurate enough. The first one is to consider $K(P_L)$ equals to the lamp average power and try to find a function to describe $N(P_L)$, which is basically inversely proportional to P_L. The other strategy is to assume $K(P_L)$ as a constant, what leads to $N(P_L)$ described by a very simple expression too. Due to the lack of space, only the first approach will be presented here. For a more detailed description of this model and results including the other strategy ($K(P_L)$ as a constant) see reference [9]. Fig. 10 shows theoretical V-I curves based on equation (4) for $K(P_L)$ equals to the lamp average power. Note that these curves are very close from the experimental ones and much improved regarding the linear model counterpart. Deriving model parameters consists of a very similar process comparing with the other approaches. In this case, based on experimental data, one can use curve-fitting numerical applications in order to find the best equation law to describe $N(P_L)$.

Fig. 11 presents the Pspice implementation of the approach mentioned above, while Fig. 12 depicts the simulation waveforms to be compared with Fig. 2, Fig. 7 and Fig. 9. It is easy to check a very good agreement with the experimental results in Fig. 2, as well as with tangent model results of Fig. 8.

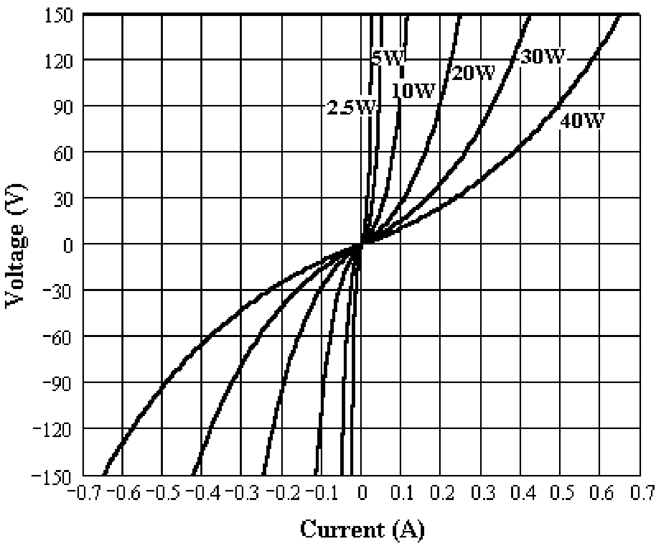

Fig. 10 – Theoretical exponential based V-I curves using K=P_L.

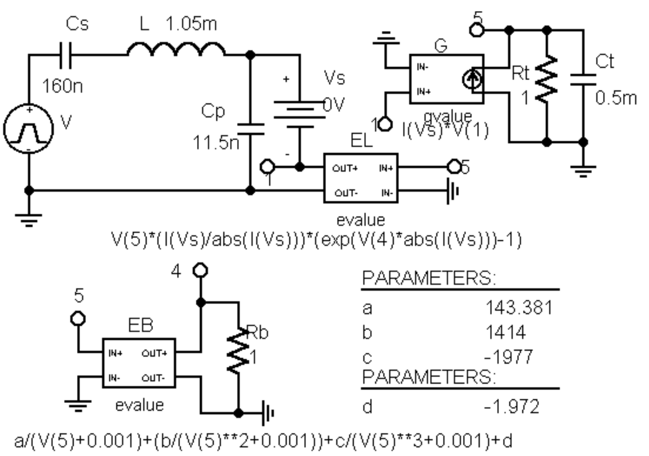

Fig. 11 – Schematics of exponential based lamp model using $K=P_L$.

IV. OTHER MODELS

As mentioned in Section I, a number of other mathematical approaches have been proposed to describe the lamp behavior when submitted to a high frequency operation. Some of these models have been reproduced by the authors of this paper and a brief comparison has been considered in [7]. Those qualitative results will be also used in the next section.

Some other alternatives are still being proposed nowadays, what points for a huge interest on this subject by industries and researchers [10] and [11]. The ambient temperature has been considered in these approaches and has been shown to influence the lamp behavior (average power and illuminance). However, this subject is out of the scope of this paper since, by using a simpler lamp model, design engineers can easy check their dimmable electronic ballast operation. Of course, depending upon ambient temperature, the simulated power level may not exactly agree with the experimental one. Nevertheless, for a fixed temperature, it is still possible to have a reasonable comprehension about the ballast-lamp system behavior.

V. DISCUSSION

Power dependent V-I lamp curves can be used to guide a number of specific fluorescent lamp models, mainly focusing the test of dimmable electronic ballasts.

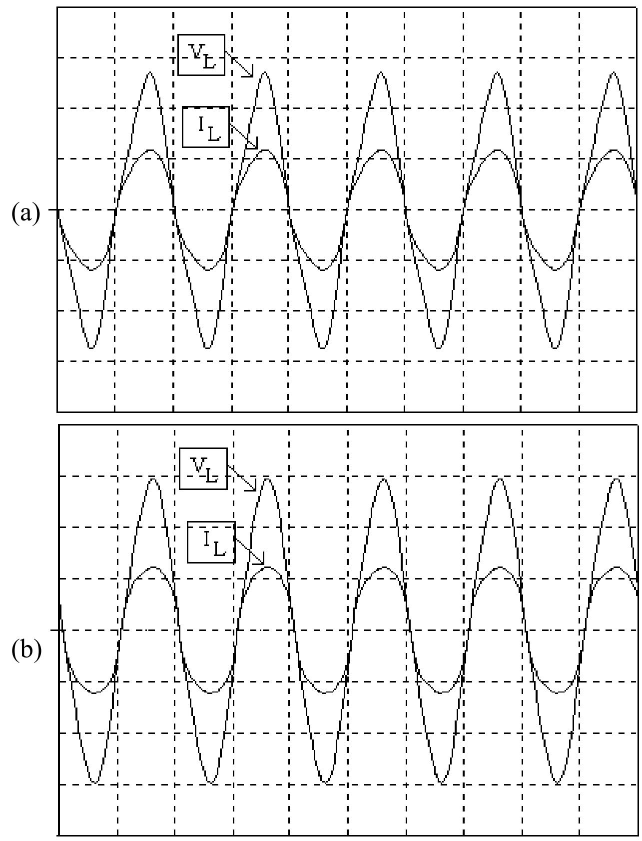

Fig. 12. Pspice simulated waveforms using exponential approximation for K=P_L (10 µs/div):.
(a) 40.18 (50V/div; 500mA/div) W; (b) 19.80 W (50V/div; 200mA/div).

The first order (linear) approximation, despite its simplicity and few convergence problems, is not capable to reproduce a wide lamp power variation. Other Pspice models have been presented in the recent years using quadratic, cubic and tangent approximations. They can provide a better reproduction of lamp behavior, what is especially useful to test dimmable electronic ballasts. This paper has introduced a new exponential-based fluorescent lamp model that made use of a very simple and known equation. Very few convergence problems have been found during simulation tests, what confers to this new model the required simplicity feature. Table I provides a comparison among selected models, including the new one, taking into consideration some important model details. The full rated lamp power, 40W, has been used to serve as a reference. Note that the linear model presented the biggest error concerning this parameter.

VI. CONCLUSION

This paper introduced a new dynamic high frequency model applied to fluorescent lamps, useful to test electronic ballasts even in the presence of dimming capability. The model is based on the exponential function adapted from the well-known equation used to describe the voltage and current relationship in a p-n semiconductor junction (Shockley equation). Three other models have been reviewed in the paper to provide a comparison basis, along with experimental waveforms. The new model has proved to be accurate, free of convergence errors and very simple to be implemented.

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REFERENCES

[1] Mader, U., Horn, P. A Dynamic Model for the Electrical Characteristics of Fluorescent Lamps. *IEEE – IAS'92*, 1992, pp. 1928-1934.

[2] Ribarich, T. J., Ribarich, J. J. "A New High-Frequency Fluorescent Lamp Model". *IEEE IAS Annual Meeting*, 1998, Volume 3, pp. 2094-2098.

[3] M. Sun and B. L. Hesterman, "Pspice High-Frequency Dynamic Fluorescent Lamp Model". *IEEE Transactions on Power Eletronics,* 1998, Volume 13, Issue 2, pp. 261-272.

[4] Cervi, M.; Fortes, E.C.; Seidel, A.R.; Bisogno, F.E. and do Prado, R.N. "Fluorescent Lamp Model Employing Tangent Approximation". *IEEE IAS Meeting 2001,* pp. 866-871.

[5] N. Onishi, T. Shiomi, A. Okude and T. Yamauchi, "A Fluorescent Lamp Model for High Frequency Wide Range Dimming Electronic Ballast Simulation", *IEEE Applied Power Electronics Conference and Exposition, APEC '99,* 1999, Volume: 2, pp. 1001 -1005.

[6] Cervi, M.; Seidel, A.R.; Bisogno, F. E. and do Prado, R.N. "Fluorescent Lamp Model Based on the Equivalent Resistance Variation". *IEEE Industry Applications Conference, IAS '02*, 2002, Volume: 1, pp. 13-18.

[7] Cardoso, H. H. and Braga, H. A. C., "Modelos de Lâmpada Fluorescente Visando Simulação no Pspice". *CBA 2001*, pp. 473-479. (in Portuguese).

[8] Ben-Yaakov, S.; Shvartsas, M.; Glozman, S., "Statics and Dynamics of Fluorescent Lamps Operating at High Frequency: Modeling and Simulation". IEEE APEC'99, 1999, Volume 1, pp. 467-472.

[9] Cardoso, H. H. Marques, R. N. and Braga, H. A. C. "Parameter Estimation for a New Pspice Fluorescent Lamp Model Based on the Exponential Function". *Proceedings of International Symposium on Industrial Electronics,* CD-ROM, 2003.

[10] Moo, C.S.; Hsieh, Y.C.; Yen, H.C.; Lee, C.R.; "Fluorescent lamp model with power and temperature dependence for high-frequency electronic ballasts", *IEEE Transactions on Industry Applications*, Volume: 39 Issue: 1 , Jan.-Feb. 2003, pp.: 121 -127.

[11] Wakabayashi, F. T., Canesin, C. A., "A New model for tubular fluorescent lamps operated at high frequencies for dimmable applications", *IEEE ISIE 2003*, CD-ROM.

TABLE I
Comparison among models.

Model Type	Complexity	Convergence Problems	Power Dependence	Lamp Power (W)
Experimental	-	-	-	40W
Resistive	None	None	No	40W
Linear [1]	Low	None	Limited	46W
Quadratic [2], [8]	Average	Few	Yes	39.4
Tangential [4]	High	Few	Yes	38.0
Cubic [1], [3], [7]	Very High	Many	Yes	43.0
Exponential [9]	Average	Few	Yes	40.2