Letters to the Editor

Modeling the High-Frequency Behavior of a Fluorescent Lamp: A Comment on "A PSpice Circuit Model for Low-Pressure Gaseous Discharge Lamps Operating at High Frequency"

Sam Ben-Yaakov

Abstract—**The shortcomings of the model presented by Wu *et al.* are pointed out and an improved SPICE-compatible equivalent circuit that dodges the limitations is presented. It is shown that the proposed model is useful in emulating the fluorescent lamp response to a change in excitation frequency.**

Index Terms—**Electronic ballasts, fluorescent lamps, modeling, simulation, SPICE.**

I. Introduction

In the above paper,[1] a SPICE-compatible model for emulating the high-frequency behavior of fluorescent lamps is proposed. The model is based on the observation that, for a given high-frequency rms current (I_{rms}), the lamp behaves, to a first approximation, as a pure resistor (R_{eq}), the value of which can be estimated from

$$R_{eq} = \frac{V_s}{I_{rms}} - R_s \tag{1}$$

where V_s, and R_s are constants of the lamp.

Equation (1) and its experimental verification were presented earlier by Gulko and Ben-Yaakov [1], a fact that seems to be overlooked in the above paper.[1]

The SPICE-compatible equivalent circuit proposed by Wu *et al.* includes a continuous integration scheme to derive the rms current (I_{rms}). Integration is carried out from time zero ($t = 0$) by feeding a voltage source to an RC circuit and then dividing the result by time. Consequently, the rms current (I_{rms}) obtained by this approach could be accurate only for $t \ll RC$. However, since integration is carried out from time zero, transient phenomena at power turn–on would distort the emulated waveforms. Hence, application of the proposed model would require considerable tinkering and trial-and-error runs until the right I_{rms} is captured for one given steady-state condition. This scheme, at its best, is restricted to steady-state conditions and cannot be used to observe, in a single SPICE run, various effects such as a change in excitation frequency.

II. The Proposed SPICE-Compatible Equivalent Circuit

The shortcoming of the model presented by Wu *et al.* is overcome by the SPICE-compatible equivalent circuit shown in Fig. 1. In this model, the lamp is represented as a dependent current source (G_1) that emulates a variable resistance according to (1). The output of the dependent voltage source E_1 is proportional to the square of the lamp current [i(lamp)]. Namely, the voltage at node (isq) is

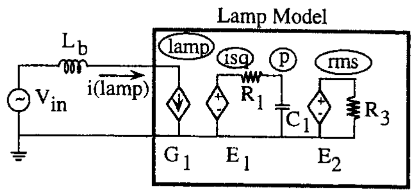

Fig. 1. Proposed fluorescent model connected to a high-frequency ballast. See text for definitions of G_1, E_1, and E_2.

$$v(isq) = [i(\text{lamp})]^2 \tag{2}$$

where the notation $v(x)$ means the voltage at node "x."

This $\{v(isq)\}$ signal is then passed through a low-pass filter (R_1C_1, Fig. 1) to obtain its low-frequency component. For frequencies $f > 1/(2\pi R_1 C_1)$ and for times $t > R_1C_1$, the average voltage on C_1 [node (p)] will be

$$v(p) = \frac{1}{T}\int_0^T v(isq)\,dt = \frac{1}{T}\int_0^T [i(\text{lamp})]^2\,dt. \tag{3}$$

The average voltage across the capacitor C_1 (node "p" in Fig. 1) is, thus, a smoothed value of the squared rms current. The filtered I_{rms} is then obtained by E_2 (node "*rms*" in Fig. 1) as the square root of the average voltage across the capacitor C_1 (node "p"). Consequently,

$$v(\text{rms}) = \sqrt{\frac{1}{T}\int_0^T [i(\text{lamp})]^2\,dt}. \tag{4}$$

The definitions of the dependent sources are, thus (per the notation of Fig. 1),

$$G_1 \equiv \frac{v(\text{lamp})}{\frac{V_s}{v(\text{rms})} - R_s} \tag{5}$$

$$E_1 \equiv \{i(\text{lamp})\}^2 \tag{6}$$

$$E_2 \equiv \sqrt{v(p)}. \tag{7}$$

It is interesting to note that the R_1C_1 section of this model possibly has a physical meaning: the time constant associated with the conductance change of the fluorescent lamp plasma as the power level is changed. This interpretation is consistent with the assumption that the dynamics of lamp inductance change as a function of lamp power variations can be approximated by a first-order process. It also appears that this time constant is related to the zero at the right-half side of the complex plane predicted and verified by [2] and [3]. A comprehensive analysis of this subject is beyond the scope of this letter. However, the simulation results given below seem to support this conjecture.

Manuscript received December 14, 1997; revised August 18, 1998. Abstract published on the Internet August 25, 1998. This work was supported by a grant from the Israel Science Foundation.

The author is with the Power Electronics Laboratory, Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel (e-mail: sby@bguee.ee.bgu.ac.il).

Publisher Item Identifier S 0278-0046(98)08473-1.

[1] T.-F. Wu, J.-C. Hung, and T.-H. Yu, *IEEE Trans. Ind. Electron.*, vol. 44, pp. 428–431, June 1997.

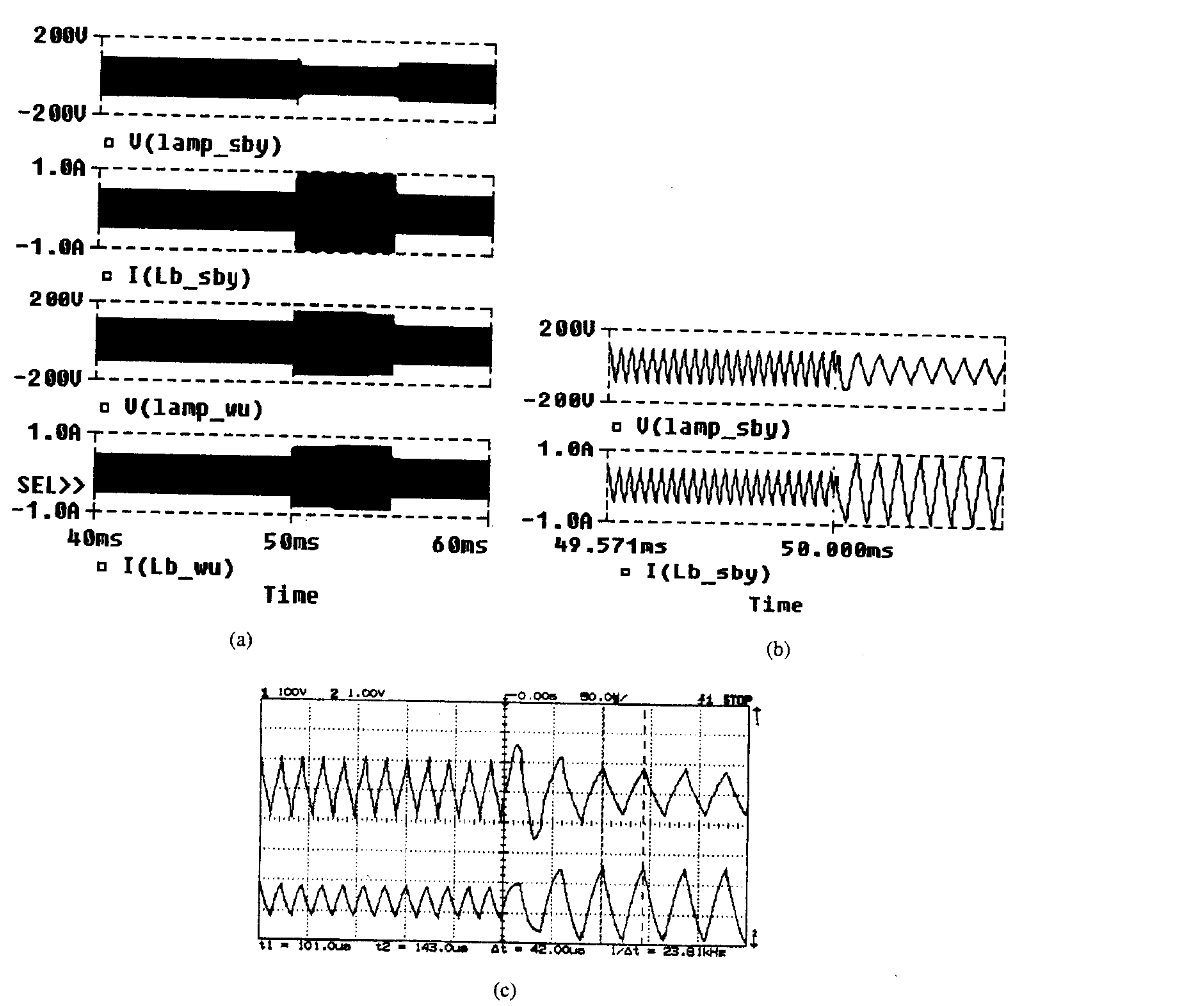

Fig. 2. Lamp response to a step in excitation frequency (50–25 kHz). (a) Upper two traces: lamp voltage and current obtained by the model of Fig. 1. Lower two traces: lamp voltage and current obtained by the model of Wu *et al.* (b) Zoomed portion of upper two traces of (a). (c) Experimental results for 50–23.8 kHz step. Upper trace: lamp voltage (100 V/div). Lower trace: lamp current (1 A/div). Horizontal scale: 50 μs/div.

The main difference between the model of Fig. 1 and that proposed by Wu *et al.* is the fact that they chose RC to be "infinitely" large and in the definition of E_2 (corresponding to E_3 in the paper by Wu *et al.*). They defined it as a function of running time (time):

$$E_2(Wu) \equiv \sqrt{\frac{R_1 C_1 V_{C1}}{\text{time}}} \quad (8)$$

Consequently, the output of E_2 has a meaning only during a short section of the SPICE simulation run after steady state is reached. This model cannot cope with a change of operating conditions, such as a power level variation, during a given simulation run. On the other hand, the model of Fig. 1 can be run continuously for any given length of time and it will respond accurately to a change in operating conditions. This is due to the fact that, when a low-pass filter is used as an integrator, it acts like "window averaging" with a memory time in the order of the time constant. Correct integration is obtained for signal frequencies which are higher than the corner frequency of the filter. The steady-state values can be reached rather quickly during simulation by setting the initial condition of C_1 close to the expected steady-state value. This will also help prevent convergence problems.

III. Verification

The performance of the proposed model compared to that of Wu *et al.* is demonstrated by considering the case of a basic electronic ballast of Fig. 1. In this simulation, we applied lamp parameter (V_s, R_s) of a commercial lamp (OSRAM-L-18W/10) and C_1 and R_1 values that were found to fit the dynamic behavior of the lamp: $V_s = 75$ V; $R_s = 60\ \Omega$; $R_1 = 1$ kΩ; and $C_1 = 50$ nF. The parameters of the ballast were $V_{\text{in}} = 200$ V(peak) squarewave; $L_b = 1$ mH.

For the Wu *et al.* model simulation, the parameters were as above, except $R = 1$ kΩ, $C = 1$ mF, and the algorithm was according to the paper by Wu *et al.*

To further verify the proposed model, an experimental setup was built around a commercial lamp (OSRAM-L-18W/10) with an excitation voltage and inductor (L_b) values identical to the ones used in simulations.

The results shown in Fig. 2 are for a frequency (f_s) step from 50 to 25 kHz and back. The simulation results of Fig. 2(a) clearly show that the proposed model copes very well with the step change. The model responds quickly to the change and produces the correct current and voltage waveforms before and after the transitions. The model of Wu *et al.*, on the other hand, starts with the correct quasi-steady-state value according to (1), but responds erroneously to the change. Following the step (at 50 ms) both the current $I(Lb - wu)$

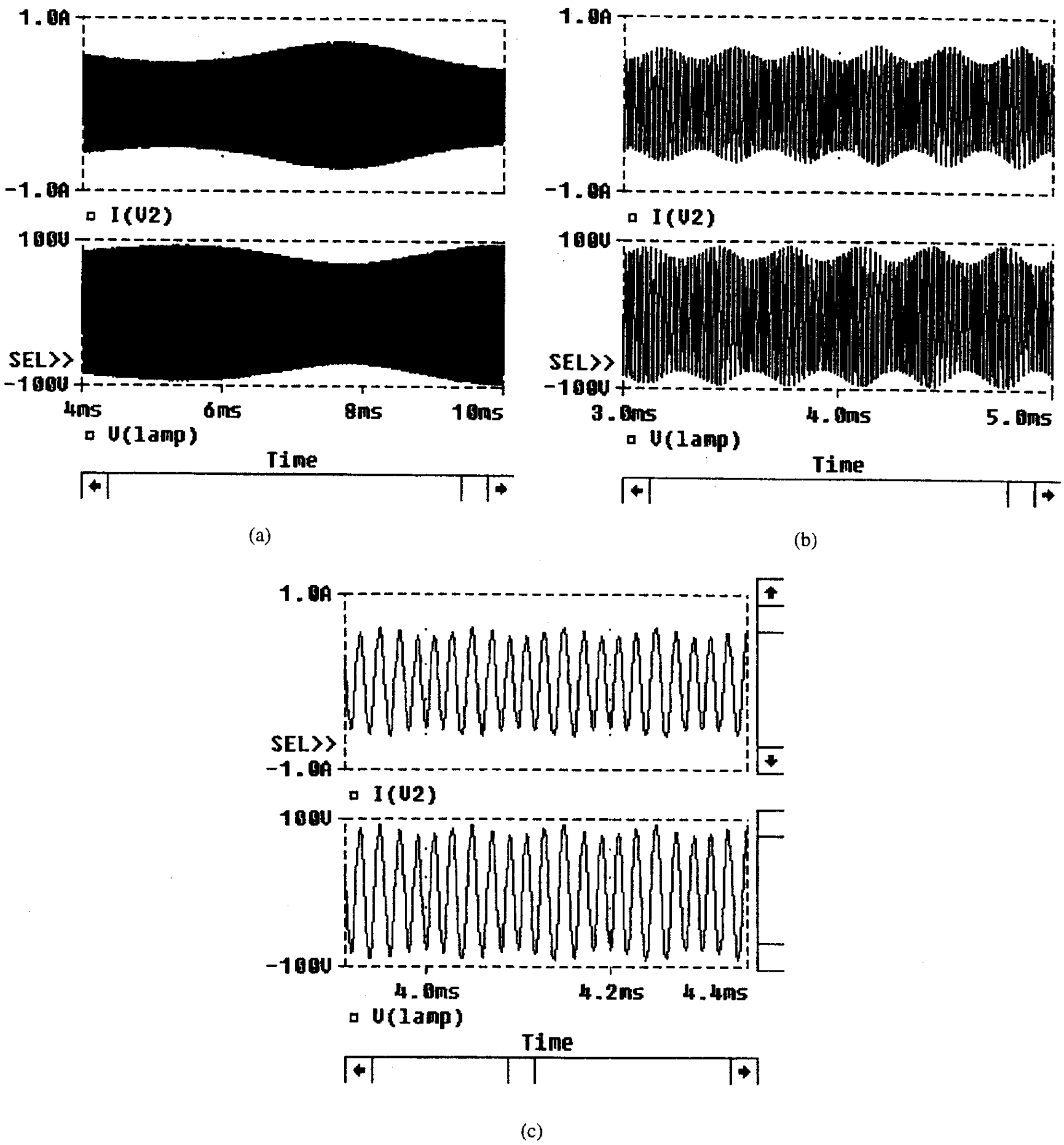

Fig. 3. Simulating the response of a fluorescent lamp to a modulation on the high-frequency excitation. (a) Modulation frequency 200 Hz. (b) Modulation frequency 3 kHz. (c) Modulation frequency 10 kHz. Upper traces: Lamp current. Lower traces: lamp voltage. Carrier frequency: 50 kHz.

and the voltage $V(lamp\_wu)$ go up—in violation of (1). If the step portion would have been extended for a very long time (as compared to 50 ms) but smaller than the time constant (1 s), the voltage would have approached the correct value. This is a result of the fact that the model of Wu *et al.* has a very long memory due to the integration scheme used.

The experimental results for a step change of 50–23.8 kHz are shown in Fig. 2(c) and compared to the simulation results in Fig. 2(b) that are an expanded portion of Fig. 2(a). As can be clearly seen, the match is excellent. The experimental run was used to fit R_1, C_1 to the commercial lamp. The time constant (50 μs) corresponds to a cutoff frequency of about 3.2 kHz. So, even at the lower frequency range (25 kHz), the ripple at point p was rather low (35 mV peak) as compared to the dc component (570 mV). The ripple may cause some distortion of the voltage waveform, but then, the assumption that the fluorescent lamp is a pure resistor at high frequency is only an approximation. This is evident even for the experimental results given in the paper by Wu *et al.* Comparison between the current and voltage traces clearly show a marked difference, attesting to the nonlinearity of the system. If the time constant R_1C_1 is made larger, the ripple at node "*rms*" will be lower, but the response will be sluggish. The question of the "right" time constant certainly needs further investigation.

The dynamic behavior of the model was further explored by modulating the high-frequency drive by a low-frequency component. The simulation results of Fig. 3 show a negative incremental impedance at low modulation frequency [200 Hz, Fig. 3(a)], a complex impedance at 3 kHz [Fig. 3(b)] that reverts to a positive incremental resistance at high modulation frequency [Fig. 3(c)]. This behavior is very similar to the one documented by [2] and [3] and observed experimentally by us. They have pointed out that the 180° phase variation can be interpreted as resulting from a small-signal transfer function that includes a stable pole and a zero at the right-half side of the complex plane.

IV. Conclusions

The proposed model of Fig. 1 was shown to follow the static behavior of a fluorescent lamp and to emulate well the response of a given lamp–ballast combination to a step dimming/lightening. It is thus concluded that the R_1C_1 integrator has an advantage over a formal integration algorithm when averaging the squared lamp current. The present study further suggests that a single R_1C_1 might be sufficient to represent the dynamic behavior of a fluorescent lamp operating at high frequency. Furthermore, the proposed model was found to emulate a fluorescent lamp behavior that was interpreted by [2] and [3] as due to a zero at the right-half side of the complex plane. These exciting preliminary results seem to indicate that the proposed static model could be expanded to emulate the dynamics of fluorescent lamps in open- and closed-loop configurations. These issues are now under investigation in our laboratory.

References

[1] M. Gulko and S. Ben-Yaakov, "Current-sourcing parallel-resonance inverter (CS-PPRI): Theory and application as a fluorescent lamp driver," in *Proc. IEEE APEC'93*, 1993, pp. 411–417.
[2] E. Deng, "I. Negative incremental impedance of fluorescent P," Ph.D. dissertation, Dep. Elect. Eng., California Inst. Technol., Pasadena, 1995.
[3] E. Deng and S. Cuk, "Negative incremental impedance and stability of fluorescent lamp," in *Proc. APEC'97*, 1997, pp. 1050–1056.