A Dynamic Pspice Model for High-Frequency Fluorescent Lamp with Continuous-Dimming Operation

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Abstract — A dynamic Pspice model for fluorescent lamp operating at high-frequency continuous dimming mode is presented in this paper. The new model takes the lamp current phase leading effect into account so that more accurate is expected. The model is verified by experimental results.

I. INTRODUCTION

Fluorescent lamps were first introduced to the world in the 1939 World’s Fair. They are low-pressure mercury discharge lamps. Since then, the fluorescent lamps have been the mainly lighting source due to their merits of high color rendering, soft-visualization, long life, and energy-saving.

Unfortunately, however, all gas discharge lamps cannot directly connect to a voltage source and require a so-called “ballast” circuitry for normal operation due to the very distinctive electrical characteristic of the lamps. The gas discharge lamps behave as nonlinear time-varying power resistors and the instantaneous values are influenced by the source voltage variation, the ballast circuit characteristics, and the internal physical processes within the arc discharge themselves [1]. There are interactions within the lamp-ballast systems, which great affect lamp performances. To properly design lamp-ballast systems, it is important to accurately characterize the lamp electrical model.

Many studies have been reported in the literature to establish mathematical modes for the gas discharge lamps [1-16]. However, some models are based on the physical discharge phenomena of lamps and generally far too complicated to be suitable for circuit design applications. Other models use curve-fitting method to simulate lamp’s terminal V-I characteristic and are more suitable for circuit simulations. However some of them need complex model parameter derivation procedures and most models cannot be applied for dimming ballast simulation, especially for low dimming levels such as less than 10% of dimming level where the lamps show severe capacitive features.

This paper presents a curve-fitting model for fluorescent lamps, which include the capacitive feature of the lamps. The presented model has advantages of good agreement with both of static and dynamic response of dimming lamps.

II. THE MATHEMATICAL FLUORESCENT LAMP MODEL

The fluorescent lamps and all of other gas discharge lamps belong to a very specific load family if seen from the circuit element point of view. It is well known that they have positive incremental impedance at low lamp rms current level, negative incremental impedance at moderate rms current levels, and positive impedance again at high rms current levels. However, from the time domain, i.e. lamp voltage versus time and lamp current versus time, it clearly shows positive instantaneous impedance, which is required by the positive of the energy-losses integral. This is proved by the instantaneous \( v-i \) characteristics of the lamp, where a positive slope is obviously shown. Fig. 1 shows the measured static \( V_{\text{rms}}-I_{\text{rms}} \) dimming characteristic curve of a 32-W T-8 Matsushita FHF32 lamp. Fig. 2 shows the measured time domain lamp voltage and current waveforms at five lamp power levels. Fig. 3 shows the dynamic lamp \( v-i \) characteristics at the five corresponding lamp power levels. All of the data were obtained at operating frequency of 58kHz and ambient temperature of 25°C.

The physical properties of the lamps are responsible for the above shown very distinctive electrical characteristics. A thoroughly understanding of the physical processes requires knowledge of radiation and thermal physics, which is out of the scope of this paper. Our objective in this paper is to find a simulation model which best duplicates the experimental lamp’s volt-ampere characteristics and the model is intended.

![Fig. 1. Measured \( V_{\text{rms}}-I_{\text{rms}} \) dimming characteristics of T8-32W FHF32](image-url)
to use in the dimmable ballast circuit designs.

The approach here is entirely electrical and empirical. The lamp is considered as a black box and only lamp’s terminal electrical characteristics are studied. We also concentrate our effort to model fluorescent lamp operating at high frequency because of the popularity and better performances of high frequency electronic ballast over the conventional magnetic ballast.

First we check the measured lamp $v$-$i$ waveforms, as shown in Fig. 3. Two observations are found. One is that at moderate lamp rms current levels, the $v$-$i$ characteristic shows a linear resistor with a positive cubic term, while with the decrease in lamp rms current level, the $v$-$i$ curve becomes more close to that of a linear resistor with a counter-clockwise passing direction loop. Second is that the slope of $v/i$ strongly decreases with the increased rms current value. The second observation demonstrates the fluorescent inherent negative incremental impedance characteristic. The first observation, on the other hand, would mean two more unique characteristics of the lamps, i.e., cubic nonlinearity and capacitive hysteresis with a thermal time constant (implying memory or inertia time constant). The capacitive features of
the lamp are more obvious when looking at the measured waveforms at time domain at low rms current levels as shown in Fig. 2. These two observations suggest that the lamp model could be

\[ V_{la}(t) = A(I_{rms}) I_{la}(t) + B(I_{rms}) I_{la}^2(t) + \frac{I}{C(I_{rms})} \int_0^t I_{la}(t) dt, \]

where \( V_{la}(t) \) and \( I_{la}(t) \) are the instantaneous lamp voltage and current, respectively. \( A(I_{rms}) \), \( B(I_{rms}) \), and \( C(I_{rms}) \) are coefficients which are lamp rms current dependent. The inertia time constant \( \tau \) is implied in the process of changing the instantaneous lamp current into rms current which represents the arc temperature.

III. THE PSPICE FLUORESCENT LAMP MODEL

Following [7 and 8], we ignore the cubic nonlinearity of the lamp to avoid computational intensity. The model is then simplified as

\[ V_{la}(t) = R(I_{rms}) I_{la}(t) + \frac{I}{C(I_{rms})} \int_0^t I_{la}(t) dt, \]

where \( R(I_{rms}) \) and \( C(I_{rms}) \) represent lamp linear resistor and capacitor, respectively.

Fig. 4 shows the simplified lamp model diagram where the values of \( R \) and \( C \) were obtained by fitting (2) to experimental data at 13 lamp power levels ranging from 0.31-W to 45-W. Returning to the measured time domain lamp voltage and current waveforms in Fig. 2, and considering the slopes and capacitive loops in Fig. 3, we see that it is more important to take the resistor values accurately at the higher values of the lamp current, while it is more important to take the capacitor values correctly at the lower values of the lamp current. So in stead of fitting \( R \) versus \( I_{rms} \), we fit the curve of conductance versus \( I_{rms} \). To reduce computation intensity while keep accuracy, we use three orders polynomials to fit \( 1/R \) and \( C \), which are given by

\[ \frac{I}{R(I_{rms})} = G_0 + G_1 \cdot I_{rms} + G_2 \cdot I_{rms}^2 + G_3 \cdot I_{rms}^3 \]

\[ C(I_{rms}) = C_0 + C_1 \cdot I_{rms} + C_2 \cdot I_{rms}^2 + C_3 \cdot I_{rms}^3 \]

Fig. 5 shows the curve fitting using the equations above. It is interesting to see that the conductance of the lamp is almost linearly proportional to the rms lamp current with some deviations. For comparison, Fig. 6 shows the resistor \( R \) and capacitor \( 1/C \) values versus \( I_{rms} \) using the same fitting functions.

Fig. 7 shows the Pspice subcircuit schematic diagram of the lamp model. The powerful Analog Behavior Modeling (ABM) feature provided in Pspice A/D allows for the mathematical descriptions of electronic components. Basically the lamp is modeled as a lamp-rms-current controlled voltage source whose voltage is defined by (2).
which finds its roots in the idea of hard-limiter model [4]. In the subcircuit, the time integral, $\int_{0}^{t} I_{la}(t) \, dt$, is measured by applying a copy of the lamp instantaneous current to a known capacitance, $C_{ref}$, and monitoring its voltage. The rms value of the lamp current is obtained using a RC network with a time constant in the order of the inertia time constant of the lamp [6, 7, and 16]. Fig. 8 shows the subcircuit netlist, which is placed in a model library file. This model is parameterized so that users can specify the polynomial coefficients of R’s and C’s, and the time constant $\tau$ on the symbol in the Schematic Editor. A new symbol, FHF32, represents the fluorescent lamp, with the coefficients, G0, G1, G2, C0, C1, C2, C3, and Tcst, as attributes, as shown in Fig. 9. It should be noticed that there is a trade-off between accuracy and computational intensity to select the RC time constant. The default time constant is set to be 0.1ms as referred to [6 and 16].

### IV. SIMULATION RESULTS

Fig. 10 shows the simulation circuit where the lamp model is packaged as a two-terminal device named as FHF32. The lamp power can be dimmed from 140% (45-W) down to 1% (0.32-W) by changing the dc-link voltage from 410V to 55V at the fixed switching frequency of 58kHz (except for $V_{dc} = 410V$ where $f_s = 48$ kHz).

Fig. 11 shows the simulated control-to-lamp power characteristics, which are in good agreement between them.
Fig. 12 shows the simulated lamp voltage and current waveforms at 3 current levels, and Fig. 13 shows the dynamic $v$-$i$ characteristics at the corresponding lamp current levels. Current leading feature and hysteretic loops with counter-clockwise direction are obtained. It was found that agreement between the simulated and measured waveforms was good. However, some discrepancy on the leading edges of the current waveforms is shown. It is assumed to be attributed to the nonlinearity of the lamp, which was not taken into account by the lamp model.
V. CONCLUSION
A high-frequency dynamic Pspice fluorescent lamp model is presented in this paper. The new model includes the lamp’s unique hysteretic and counter-clockwise loop characteristics. Good agreement was found between the simulated and measured results. The presented lamp model is a useful tool for understanding the high frequency operation of fluorescent lamps as well as for the design of an electronic ballast circuit with continuous dimming feature.

References