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Holloway, A.J., Tozer, R.C. and Stone, D.A. (2009) A physically based fluorescent lamp model for a SPICE or a simulink environment. *IEEE Transactions on Power Electronics*, 24 (9). pp. 2101-2110. ISSN 0885-8993

<https://doi.org/10.1109/TPEL.2009.2020901>

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A Physically Based Fluorescent Lamp Model for a SPICE or a Simulink Environment

Arran J. Holloway, Richard C. Tozer, *Senior Member, IEEE*, and Dave A. Stone

Abstract—This paper describes a method of modeling fluorescent lamps. The lamp model can be implemented in all major circuit simulation software packages, an example has been given for SPICE and Simulink. The model is based upon a simplified set of physical equations that gives the model validity over a wider range of operating conditions than current fluorescent lamp SPICE models allow for. The model can be used to model any low-pressure mercury-buffer gas fluorescent lamps by entering key lamp parameters, length, radius, cold-spot temperature, and buffer gas fill pressure. If fill pressure is not known, a default value dependent on lamp radius is used. The model shows good agreement over a wide range of operating frequencies and lamp powers.

Index Terms—Fluorescent lamps, gas discharges, lighting, modeling, simulation, SPICE.

I. INTRODUCTION

FLUORESCENT lamps have played an important role in both industrial and domestic lighting for the last half a century [1]. With an increasing use of compact fluorescent lamps in homes and new regulation discouraging the use of incandescent lamps, their importance for lighting has never been greater. Increasingly, there is a move away from low-frequency magnetic ballasts toward high-frequency electronic ballasts. The use of high-frequency electronic ballasts increases the lamps efficiency and reduces flicker. Electronic ballasts also allow the lamp to be dimmed and allow control for integrated lighting systems.

To assist in the optimization of electronic ballasts, it is necessary to have an accurate and computationally efficient model of the fluorescent lamp that is capable of modeling the lamp at different frequencies, dimming levels, and under transient conditions.

The first attempt to create a fluorescent lamp model that was suitable for circuit simulation was undertaken by Francis in 1948 [2]. He suggested that it should be possible to describe a fluorescent lamp with a differential equation based on the following three postulates: the rate of increase of electron density is proportional to the current and voltage, the rate of decrease of the electron density is proportional to the electron density, and the instantaneous resistance is inversely proportional to the electron density. Unfortunately, it proved impossible to reconcile this equation with experimental results. The equation was

later modified in [3] but was still incapable of providing accurate results for high- and low-frequency operation.

Subsequently, with an increasing shift toward high-frequency electronic ballasts, authors concentrated on the high-frequency operation only. Unlike the model proposed by Francis, which attempted to use some physical reasoning to construct the model, these models were based purely on empirical behavior. The models were thus applicable only over a narrow range of operating conditions centered on the conditions evident when the required experimental data were collected. They all used a variation in modeling the lamp as a resistor with some form of power dependence to model the lamp's static $V-I$ characteristics [4]–[10].

Mader and Horn [4] attempted to create a more general model that worked for both low and high frequencies. Experimental data were required to obtain the coefficients of the model for different lamp types. The model was capable of modeling the low- and high-frequency behavior but required different coefficients for each case.

The alternative to using such behavioral model is to use a self-consistent collisional radiative (SCCR) model. SCCR models are accurate over a large range of operating conditions and also provide a useful insight into the workings of the discharge, however, although S.C.C.R models have recently been implemented in MATLAB [11] and PSPICE [12], the computation time required makes them unattractive to circuit designers.

Recently, there has been growing interest in the construction of a more generic model suitable for circuit simulation that works over a much greater range of operating conditions and does not require experimental data to be collected. Zisis and Buso [13] were the first to present a model that did not require experimental data using the lamp's parameters to accommodate different lamps. Although, at low frequencies the shape of the $V-I$ characteristics matched experimental results, the voltage was approximately 65% of the experimental data while the current was 50% higher. The model also became purely resistive at high frequencies instead of the characteristic "S" shape seen in the $V-I$ characteristic that fluorescent lamps possess. This model focused on finding the electron density only, neglecting the electron mobility. It represented the first step toward the creation of a model based upon a simplified set of physical laws.

More recently, attempts have been made to describe the fluorescent lamp's operation using a model of a high-pressure discharge as a framework [14]. This approach gives reasonably accurate results at both high and low frequencies. The model uses a genetic algorithm to tune the model to each lamp type.

This paper presents a model that works over a wide range of operating conditions without the need for experimental data. Conditions where physical relationships are of a type that can

Manuscript received October 20, 2008; revised February 11, 2009. Current version published August 21, 2009. Recommended for publication by Associate Editor M. Alonso.

The authors are with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, U.K. (e-mail: a.holloway@sheffield.ac.uk; r.c.tozer@sheffield.ac.uk; d.a.stone@sheffield.ac.uk).

Digital Object Identifier 10.1109/TPEL.2009.2020901

be readily computed, they have been used. Places where the physical processes require iterative solutions, e.g., calculation of electron temperature, a behavioral approximation based on the results of an SCCR model [11] has been employed. We show that this approach leads to a model that predicts well the behavior of lamps over a frequency range 50 Hz to 50 kHz.

The first section covers the physical reasoning behind the model. The second section describes how the model can be implemented. Section three explores the validation of the model over a wide range of possible operating conditions including low frequency (50 Hz) and high frequencies (tens of kilohertz), over a wide range of power levels. This section also demonstrates the model's ability to accommodate different lamp geometries without requiring experimental data collection. Section III also illustrates an example of the model being used to simulate a resonant dimming ballast. The simulation of the dimming ballast also investigates the model's ability to correctly describe step changes in frequency and power.

II. FLUORESCENT LAMP MODEL

The model concentrates on the physical processes that determine the electrical conductivity of the lamp. In determining the lamps conductivity there are two important parameters: the number of electrons available to carry current in the plasma and the mobility of those electrons. The latter plays an important role in determining the lamp's nonlinear high-frequency behavior. The failure to model the electron mobility in [13] explains why this model becomes resistive prematurely at high frequencies.

We begin by solving the ionization balance equation to determine the number of electrons in the discharge. This is done by finding the rate at which electrons are created through ionization and the rate at which they are removed through recombination with ions at the wall. The electron mobility is then calculated and Ohm's law is used to calculate the lamp's conductivity.

As for any fluorescent lamp model, it is necessary to make assumptions about the way in which the lamp behaves. This model makes the following assumptions about the lamp's behavior.

- 1) The lamp is axially homogenous.
- 2) Only the positive column has been considered; the electrode regions have been ignored.
- 3) The displacement of species through cataphoresis has not been considered as this happens over a much longer time period than a 50-Hz cycle.
- 4) The lamp is already ignited, the model does not correctly predict the breakdown stage, however, it is capable of predicting transient events once the lamp is lit.
- 5) The ions do not play a significant role in the discharge as charge carriers, being much heavier than the electrons.
- 6) Volume recombination is negligible.

A. Electron Temperature

One method of calculating the electron temperature is to solve the energy balance equation. This uses the idea that the difference between the electrical energy supplied to the lamp and the energy lost through the plasma's loss mechanisms, such as radiation, ionization, and thermal losses, allows the average electron

temperature to be calculated. This is the method employed in SCCR models; it has also been used in the semiphysical SPICE model [14]. The problem with solving the energy balance equation is that it requires the calculation of the rate of transitions between all the energy levels, or lumped pseudoenergy states, which is a computationally intense process. To reduce the computational intensity of this calculation, an approximation to the power lost through radiation given in [14], is given by

$$P_{\text{rad}} = a_2 e^{(-e a_e / k T_e)}. \quad (1)$$

This is based upon the use of the Boltzmann factor that expresses the probability of an energy state compared to the ground energy state. However, the use of the Boltzmann factor is only suitable for gasses that are in local thermal equilibrium (LTE). In the low-pressure-discharge regime normally found in a fluorescent lamp the electrons are typically at a temperature 40 or 50 times greater than the buffer gas and ions, therefore, it is not possible to say that they are in LTE. Results from our SCCR model [15] show that a simple exponential function does not provide a good fit to the power lost through radiation.

The model presented here uses a behavioral approximation to the electron temperature (2) that was found by inspection of the results from our SCCR model for different lamps under a wide variety of operating conditions

$$T_e = 4000 \sum_{i=0}^n e^{(-a_i / V^2)} + 4000. \quad (2)$$

A satisfactory fit with the results from the SCCR model could be obtained using only four terms, $a_1 = 50$, $a_2 = 520$, $a_3 = 4000$, and $a_4 = 20\,000$. In practice, using this approximation has shown good results over a wide set of operating conditions and allows a significant reduction in the computation time required.

B. Ionization Rate

The ionization rate determines the rate at which electrons are created in the plasma. In a gas where the species are in LTE, the ionization rate can be found as follows:

$$\psi_{\text{ion}} = e^{E/kT_e} \quad (3)$$

where E is the ionization energy of mercury (10.43 eV). Using (3), it was possible to produce a model that could accurately model either the low- or high-frequency operation but not both. Fig. 1 shows how the relationship between the ionization rate and the electron temperature changes at low and high frequencies. This clearly indicates that the ionization rate is not dependent upon the electron temperature alone. A second relationship describing ionization rate in terms of electron temperature and electron density was devised. Using the new relationship given in (4), it is possible to get a reasonable approximation to the ionization rate over a wide range of frequencies.

$$\psi_{\text{ion}} = e^{b_1 T_e (n_e^{b_2}) / b_3}. \quad (4)$$

The use of (4) gives relatively poor agreement with the SCCR model, as shown in Fig. 1, but it does provide a better match

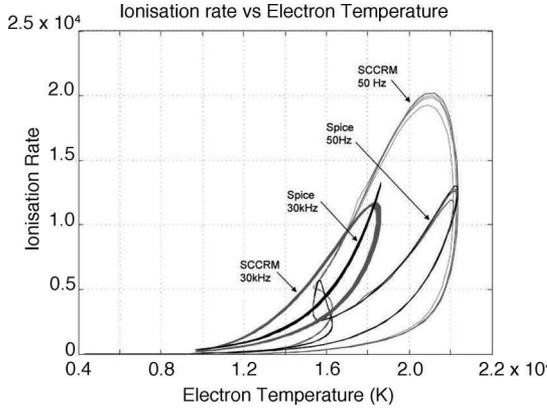


Fig. 1. Ionization rates for a T8 1.2 m fluorescent lamp, SCCR model (grey) and SPICE-compatible (black) at 50 Hz and 30 kHz.

than (3). Evidence suggests that the V - I prediction of the model are not very sensitive to the difference in shape between (4) and the SCCR model. The values for b_1 , b_2 , and b_3 are 0.00042, 0.48633, and 7.45×10^8 , respectively. The values were found using a genetic algorithm that used data from the SCCR model to find the optimum values for the fit.

C. Recombination Rate

The recombination rate is the rate at which electrons and ions move to the wall where they recombine with each other, as this is the dominant recombination method within lamps. It is widely accepted that the electrons and ions move to the wall under ambipolar diffusion, where an electric field is set up to retard the movement of the otherwise fast moving electrons to balance their speed with the heavier mercury ions.

Making the usual assumption [16] that the electron density follows a zeroth-order Bessel function, the recombination rate is given by (5), where D_a is the ambipolar diffusion coefficient given by (6) and R is the lamp radius.

$$\psi_{\text{recombination}} = \left(\frac{2.405}{R} \right)^2 D_a \quad (5)$$

$$D_a = \frac{\mu_e D_i + \mu_i D_e}{\mu_e + \mu_i} \quad (6)$$

Making the assumption that the heavy particles are in LTE, we can use the Einstein relationship to calculate the ion diffusion coefficient (7). The ion mobility in a mercury-argon gas mixture is found using Blanc's law (8), where χ_{Hg} and χ_{Ar} are correction factors given in Table I taken from [17], and the gas temperature is assumed to be 45° higher than the wall temperature.

$$D_i = \frac{kT_{\text{gas}}\mu_i}{e} \quad (7)$$

$$\mu_i = T_{\text{gas}} 8.069 \times 10^{0.5} \left(\frac{P_{\text{Hg}}}{\chi_{\text{Hg}}} + \frac{P_{\text{Ar}}}{\chi_{\text{Ar}}} \right)^{-1} \quad (8)$$

TABLE I
CORRECTION FACTORS FOR ION MOBILITY IN A MERCURY-ARGON MIX

| Parent Gas | Correction Factor |
|------------|-------------------|
| Mercury | 0.018 |
| Argon | 0.134 |

The mercury pressure used in (8) is calculated using the empirical formula (9) from [18].

$$\ln(1000P_{\text{Hg}}) = 30.804 - 0.8254\ln(T_{\text{wall}}) - \frac{7564}{T_{\text{wall}}} \quad (9)$$

The model assumes that the wall temperature is the same as the cold spot temperature. The equation for the electron diffusion coefficient D_e uses a relationship between the electron temperature found from the SCCR model.

$$D_e = T_e 4.5 \times 10^{-7} + T_e \times 10^2 - T_e 0.0087 + 200. \quad (10)$$

D. Electron Mobility

Our investigations have indicated that the characteristic ‘‘S’’ shape seen in the V - I characteristics of fluorescent lamps is the result of the changing electron mobility rather than any significant changes in electron density. At frequencies, below a few hundred hertz, it is the change in electron density that dominates the shape of the V - I characteristic.

Making the same assumption as in (7) that the electrons are in LTE with each other it is possible to use the Einstein relation to calculate the mobility, μ_e (11).

$$\mu_e = \frac{eD_e}{kT_{e_{hf}}} \quad (11)$$

The electron diffusion coefficient D_e has already been calculated in (10). As the electron mobility is instrumental in defining the high frequency V - I characteristic but less important at low frequencies, a better approximation to the electron temperature at high frequency has been used instead of the electron temperature that has been used for the rest of the calculations (2), this has been named $T_{e_{hf}}$. This gives a much better fit for the high-frequency behavior while not affecting the low-frequency behavior in any appreciable manner. A satisfactory fit with the results from the SCCR model could be obtained using six terms, $c_1 = 10$, $c_2 = 80$, $c_3 = 2500$, $c_4 = 4000$, $c_5 = 8000$, and $c_6 = 12000$.

$$T_{e_{hf}} = 2500 \sum_{i=0}^n e^{(-b_i/V^2)} + 4000. \quad (12)$$

E. Lamp Conductivity

The lamp conductivity can be calculated using Ohm's law once the electron mobility and density are known. The electron density is found by solving the following electron ionization

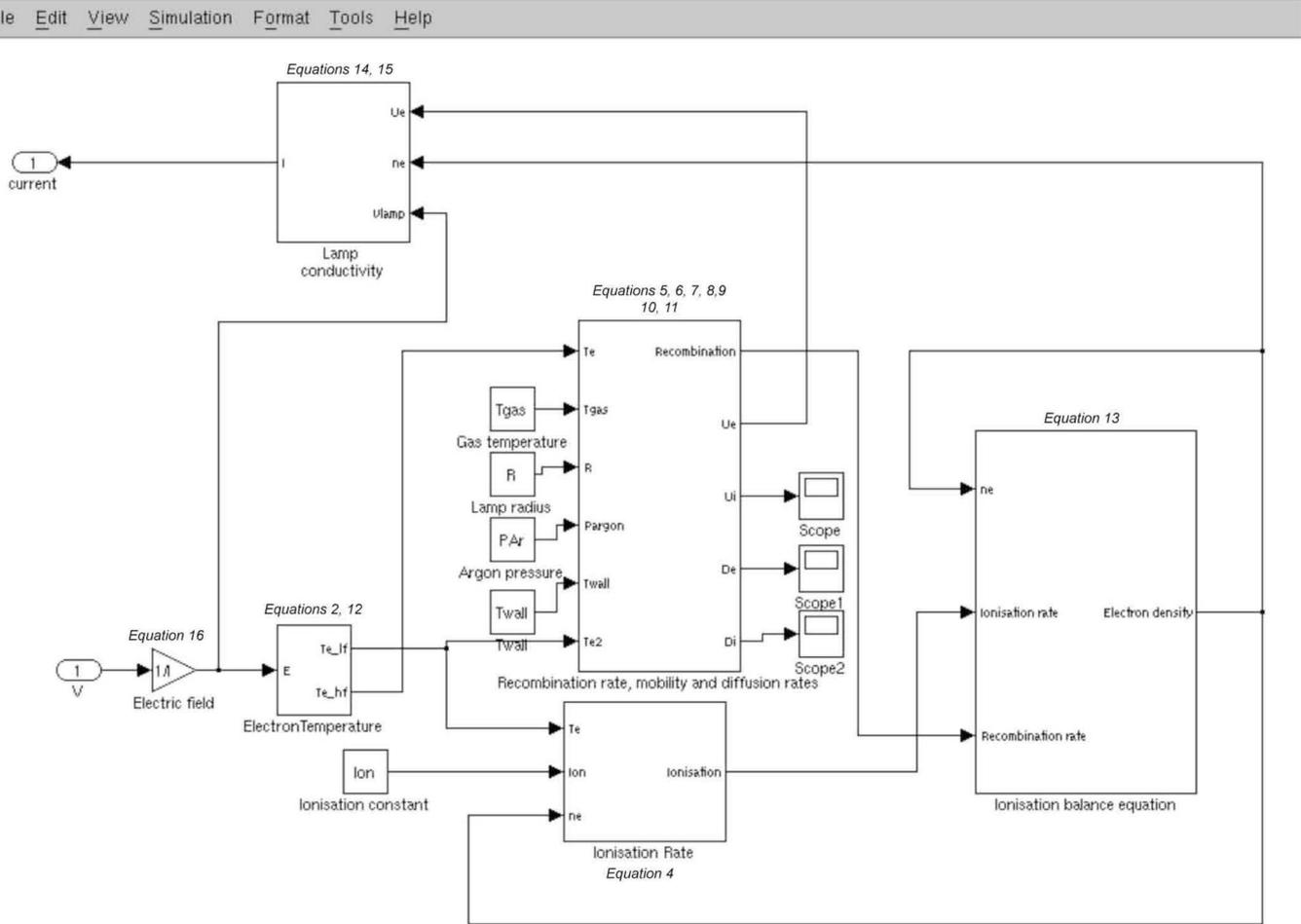


Fig. 2. Simulink implementation of the model.

balance equation:

$$n_e = \int \psi_{\text{ionization}} - \psi_{\text{recombination}}. \quad (13)$$

The electron mobility has already been calculated in (11). The current density is calculated by

$$J = en_e \mu_e E. \quad (14)$$

The lamp geometry is accounted for by

$$I_{\text{lamp}} = J \left(\frac{2.405}{R} \right)^2 2\pi R^2 \quad (15)$$

$$V_{\text{lamp}} = E \times \text{lamp length}. \quad (16)$$

F. Model Implementation

The model has been implemented in both SPICE and Simulink. The Simulink version, shown in Fig. 2, can be used in conjunction with either SimPowerSystems or the Plexsim power toolboxes. In both cases when using the model, it is only necessary to provide information about the tubes length, radius, wall

TABLE II
LAMP VARIABLES

| Tube type | Radius (mm) | Length (m) | Argon pressure (Torr) | Wall Temp (K) |
|-----------|-------------|------------|-----------------------|---------------|
| T5 | 8 | 0.8 | 7 | 313 |
| T8 | 13 | 1.2 | 5 | 313 |
| T12 | 18 | 1.2 | 3 | 313 |

temperature, and argon pressure. Suggested values are given in Table II for T5, T8, and T12 tubes for the wall temperature and argon pressure under normal household operating conditions. The constants used in the model were obtained by fitting the results from an SCCR model, for example, the relationship between the electron temperature and the lamp voltage, over a wide range of conditions. The values given for the constants in this paper represent the optimum values for use over a wide range of conditions typically expected in fluorescent lamp operation.

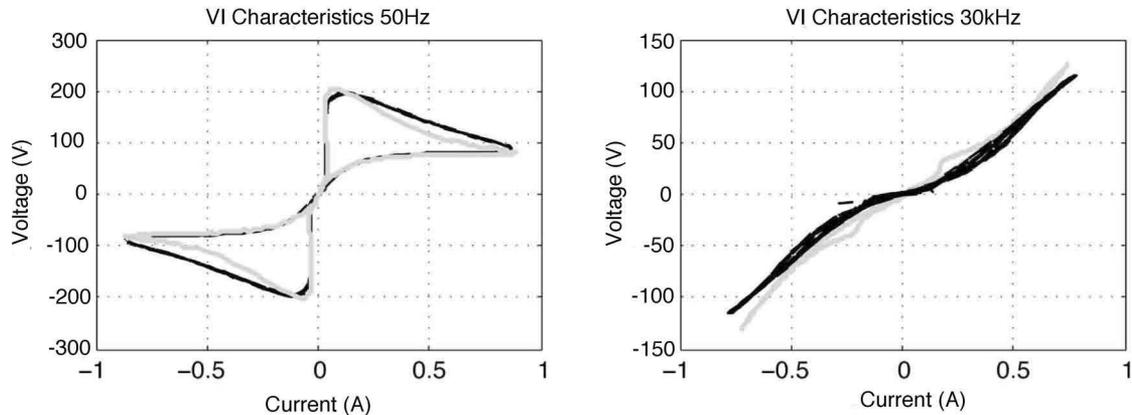


Fig. 3. Simulated and experimental V - I characteristics for a T8 1.2 m fluorescent lamp at 50 Hz (top) (grey: experimental; black: simulated).

Using these values should allow a reasonable approximation to the V - I characteristics for most lamp types under most drive conditions. If a more accurate fit is needed for a particular lamp or drive condition, it is possible to modify these constants, for example, using a genetic algorithm, as presented by [14], however, it is anticipated that the generic constants presented here would be sufficient for most situations.

As well as calculating the terminal V - I characteristics of the lamp it also provides some information about the lamp's internal parameters such as the electron density, mobility and temperature, the recombination and ionization rates, and ion mobility.

III. MODEL VALIDATION

The model has been compared with experimental results for a T5, 0.8 m lamp, a T8 1.2 m lamp, and T12 1.2 m and 1.8 m lamp. All the lamps were manufactured by Osram. The model's validity has been tested over a frequency range from 50 Hz to 50 kHz at various power levels.

A. Resistive Ballast

A resistive ballast was chosen as the primary method of validating the model because it is the simplest method of observing the lamp under identical conditions over the entire frequency range. In practice, a resonant ballast is used at high frequency and an inductor used at low frequency. Using a resistive ballast instead of an inductive one at low frequency has the added benefit of allowing the observation of the reignition of the lamp that occurs at low frequencies.

The experimental setup used consisted of a laboratory MOSFET power amplifier that drives a mains toroidal step-up transformer to provide the high voltage needed to strike and run the lamp. A 300- Ω noninductive resistive ballast was placed in series with the lamp to limit the current. The lamp's electrodes were constantly heated using an isolated flyback converter configured to provide a constant power to the electrodes.

1) *Lamp Operation at High and Low Frequencies:* One area that lamp models for circuit simulation have been deficient in is the ability for the model to work at high and low frequencies without adjusting any model parameters. With the switch

to electronic ballasts running at high frequencies the majority of lamp models have focused on the high-frequency operation where the lamp starts to behave as a resistor. This model, being based upon the physical laws governing the lamp's operation, works equally well for both high and low frequencies.

Fig. 3 shows both the high-frequency and low-frequency operation for a T8 1.2 m fluorescent lamp. Good agreement is shown between the experimental and simulated results. The model correctly predicts the magnitude of the reignition spike on the 50 Hz voltage waveforms. The model does not predict the notches that are visible in the 30 kHz V - I characteristics. These notches are caused by the onset of oscillations in the plasma, believed to be caused by instabilities at the electrodes, which have not been considered in this model.

2) *Lamp Operation at Different Power Levels:* Fluorescent lamps exhibit a negative resistance behavior, the larger the current through the lamp the smaller the voltage across it becomes. Fig. 4 shows the V - I characteristics for a lamp driven at increasing lamp powers at 30 kHz. The discrepancy between the experimental results and the simulated results at different power levels is most likely caused by the use of a constant gas temperature in the model.

3) *Accommodating Different Lamp Types:* Ideally, a lamp model would not require the collection of experimental data for it to function properly. The model presented in this paper requires only the lamp length, radius, argon pressure, and wall temperature to be known in order to predict the lamps operation.

The model's ability to correctly simulate the three commonly available fluorescent lamp sizes, T5, T8, and T12 without the collection of experimental data has been shown in Figs. 5 and 6 for low-frequency and high-frequency operation, respectively. The values for the lamp length, radius, and argon pressure used are given in Table II. It has proved difficult to obtain exact values of the argon pressure for commercial lamps—it is regarded by manufacturers as commercially sensitive information. The values for the argon pressures are therefore estimated. As the lamp's radius is decreased to reduce the radiation trapping the argon pressure is increased to offset the increased recombination rate that would otherwise result. The estimated argon pressures in Table II look reasonable with a corresponding increase in argon pressure to a decrease in the lamp radius. The wall temperature

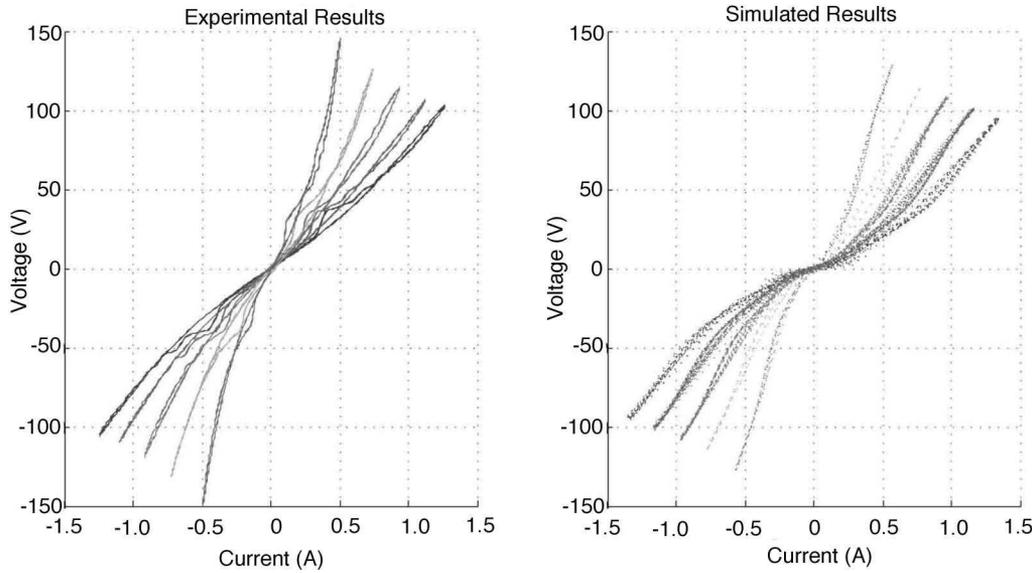


Fig. 4. Experimental (left) and simulated (right) $V-I$ characteristics for a T8, 1.2 m fluorescent lamp at 30 kHz running at different power levels.

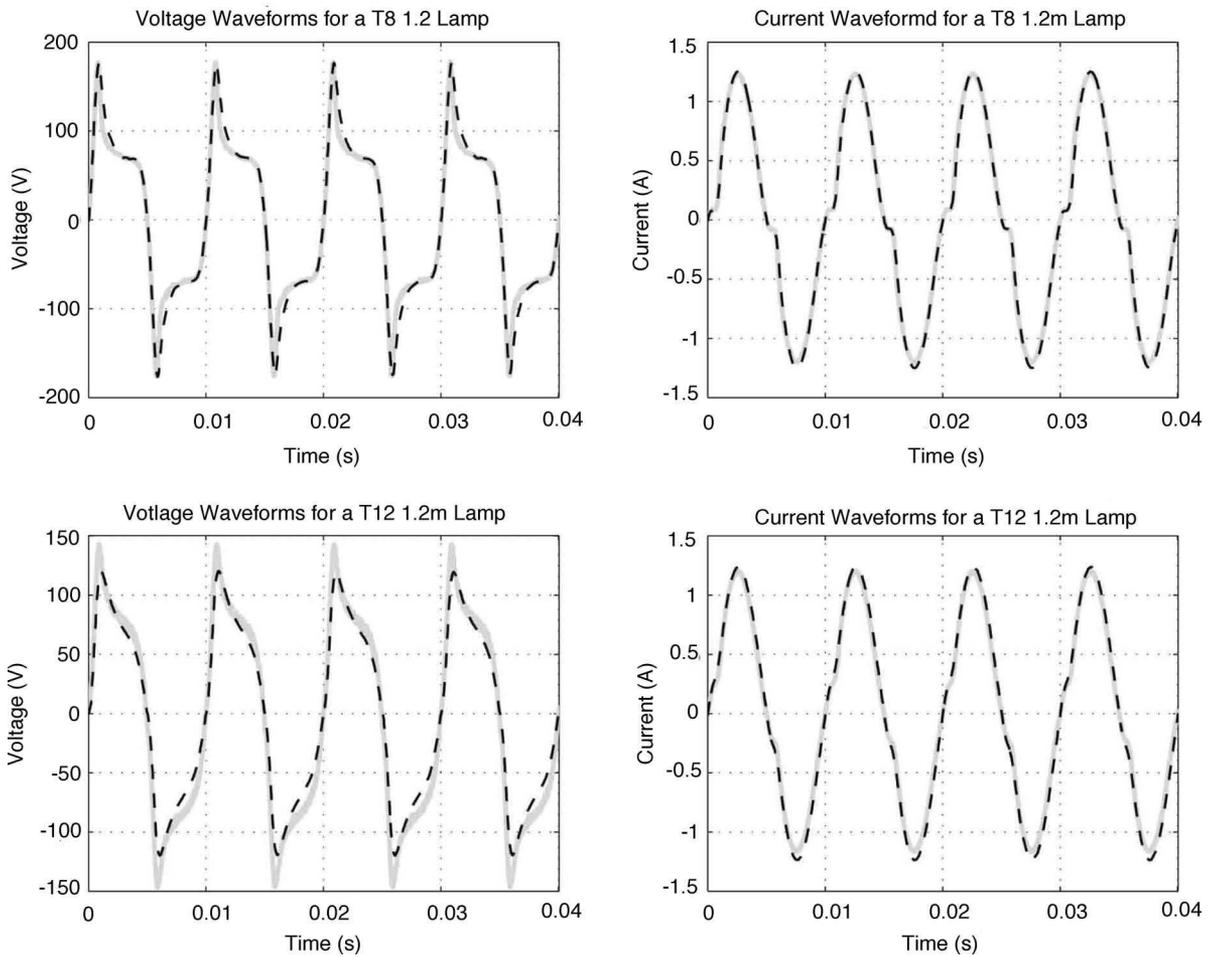


Fig. 5. Voltage and current waveforms for a 1.2 m T8 and T12 lamp. Supply voltage of 450 V, 50 Hz (solid lines: experimental; dashed lines: simulated).

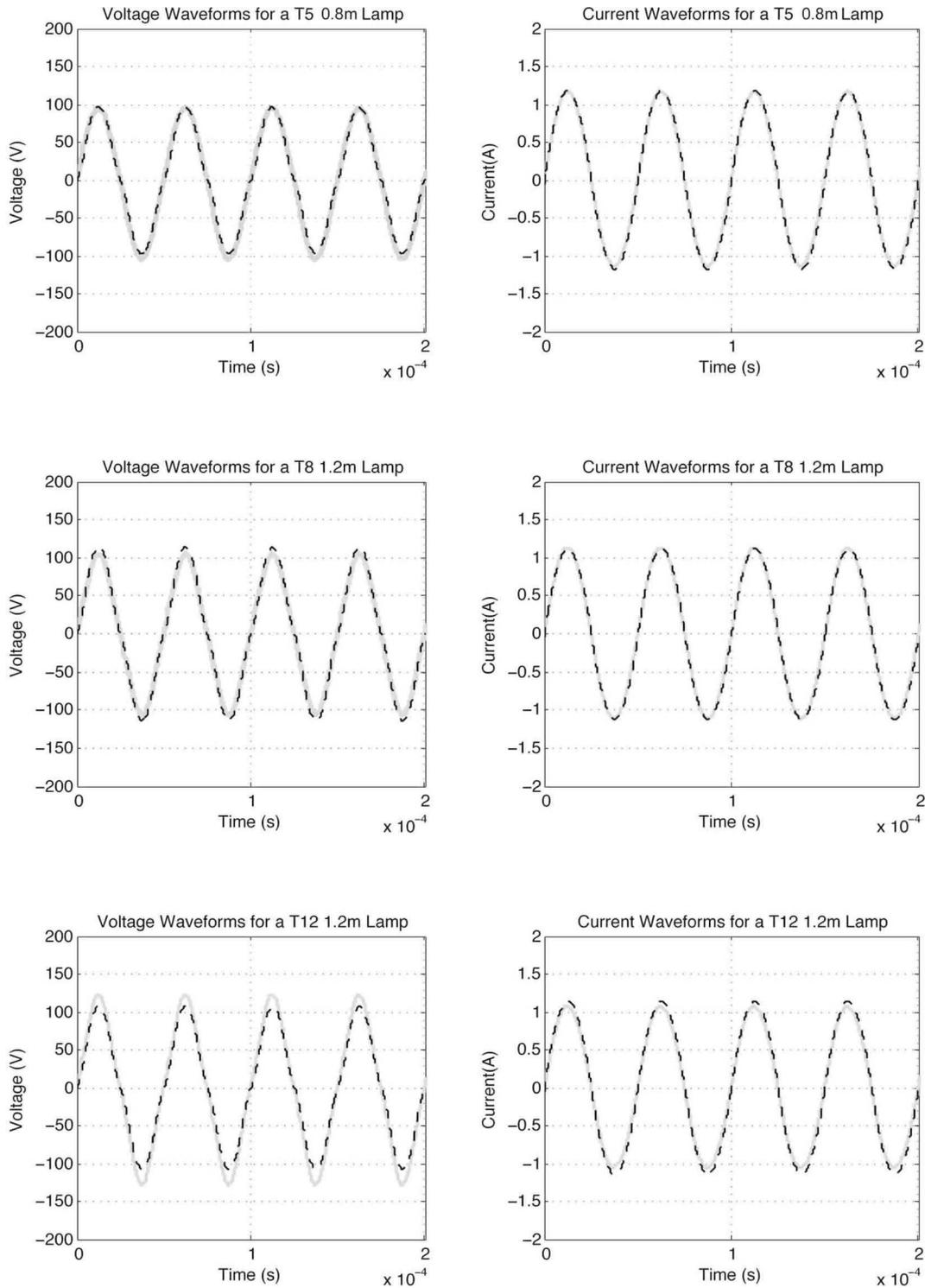


Fig. 6. Voltage and current waveforms for a 1.2 m T8 and T12 lamp and a 0.8 m T5 lamp. Supply voltage of 450 V, 30 kHz (solid lines: experimental; dashed lines: simulated).

is primarily determined by the lamp power and the ambient temperature. In practice, under normal operating conditions, a wall temperature of 313 K can be used with acceptable results.

The model shows good agreement for the T5 and T8 fluorescent lamps, however, it slightly underestimates the mag-

nitude of the voltage for the T12 lamp. The error in the case of the T12 lamp may be a result of using an incorrect argon pressure. The model's ability to predict the behavior of different lamps without collecting experimental data is not only a convenience to the user, but also shows that the

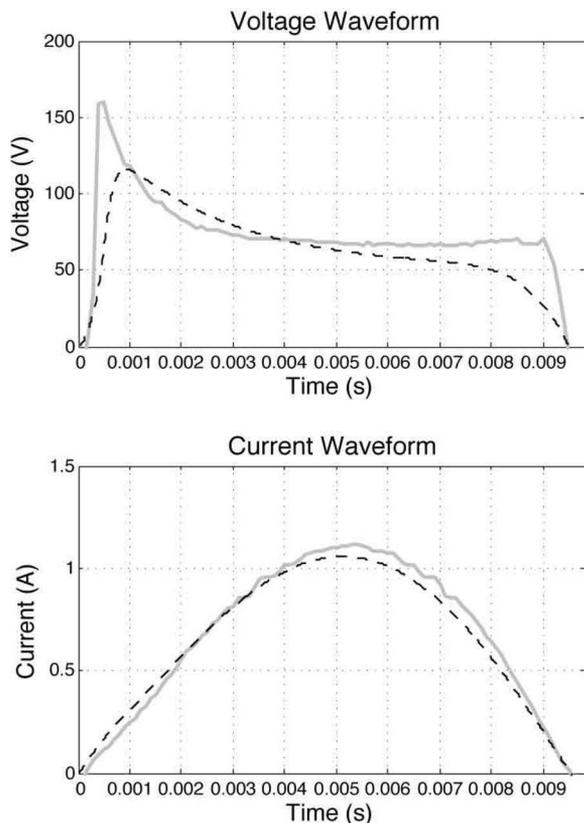


Fig. 7. Voltage and current waveforms for a 1.2 m T8 and T12 lamp with a 1-H inductive ballast (solid lines: experimental; dashed lines: simulated).

model is a reasonably good physical approximation to the lamp.

B. Inductive Ballast

Although the use of magnetic ballasts are gradually being phased in preference for electronic ballasts, they are still in widespread use and continue to sell in large quantities. This experiment demonstrates the model's ability to simulate a fluorescent lamp that is driven using a magnetic ballast. A 1-H inductor was used for the ballast. The core was suitably large to prevent saturation. The rest of the setup was identical to that presented earlier. The experiment was performed on a T8 1.2 m lamp at 50 Hz with a supply voltage of $350V_{pk}$, this is similar to the conditions in domestic magnetic ballasts in the EU.

The model correctly predicts the lamp current (see Fig. 7) but underestimated the magnitude of the reignition spike on the voltage waveform. Once the lamp is reignited, the model is in reasonably close agreement with the experimental results. There is a discrepancy between the accuracy with which the model predicts the lamp's behavior at low frequency with a resistive ballast, which is generally quite good, and the accuracy achieved with an inductive ballast. The magnitude of the reignition peak is particularly sensitive to small variations in lamp parameters, this results in small errors in the model causing large differences between the predicted and experimental results. Currently, it is

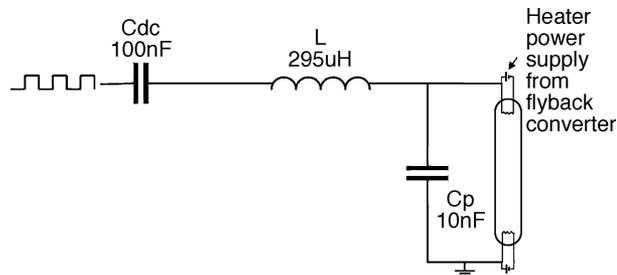


Fig. 8. Resonant ballast driven by a half bridge running from a 100 V supply.

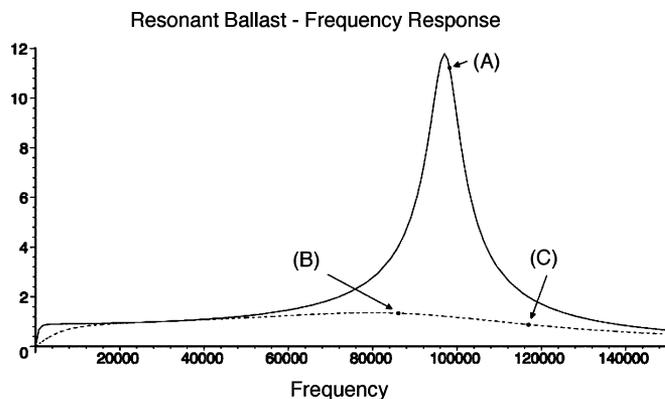


Fig. 9. Before ignition the ballast operates at point A. After ignition the circuit Q -factor is reduced and the lamp operates at point B. To dim the lamp the frequency is increased above resonance to point C.

unclear whether the error is due to an error in the model or the incorrect modeling of the ballast.

C. Example Using a Dimming Resonant Ballast

To demonstrate the model's ability to handle step changes in frequency and power, a dimming resonant ballast has been constructed. The ballast consists of an inductor in series with a parallel combination of the lamp and a capacitor (see Fig. 8). A dc-blocking capacitor has been incorporated to allow the ballast to run from a unipolar supply. The ballast is driven using a half-bridge arrangement. Before the lamp is lit, the circuit has a very high Q -factor that generates a voltage large enough to strike the lamp, once the lamp is lit the Q -factor drops considerably (Fig. 9). Dimming is achieved by increasing the frequency above resonance. The primary aim of this experiment is to investigate the model's ability to handle a step change in frequency causing a step change in the lamp power.

The frequency was changed from the resonant frequency of 90–110 kHz resulting in approximately 50% dimming.

The step change in frequency can be seen in Fig. 10. The experimental and simulated voltage and current waveforms show similar behavior to the experimental results with a sudden drop in voltage following the step change followed by a gradual increase to the steady-state voltage. Although the steady-state magnitude of the current and voltage are in good agreement with experimental results at both dimming levels, the time taken for the model to settle to the steady-state value is considerably longer than observed experimentally.

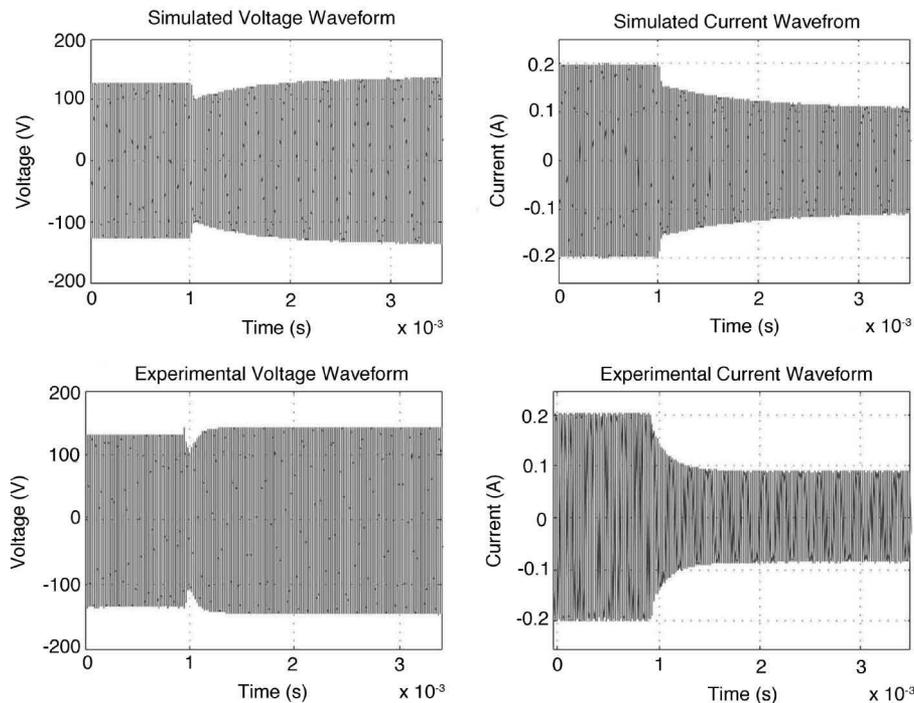


Fig. 10. Voltage and current waveforms for both experimental (top) and simulated (bottom) step change in frequency from 90 to 110 kHz. This represents a change from 100% lamp power to 50%.

IV. CONCLUSION

A model for a fluorescent lamp has been presented that is suitable for use in circuit design. The model uses physical laws, where possible, and resorts to approximations found from an SCCR model where the solution requires iterations to solve it, for example, the electron temperature.

The model can be used to model any low-pressure mercury-buffer gas fluorescent lamps by entering key lamp parameters, length, radius, cold-spot temperature, and buffer gas fill pressure. If fill pressure is not known, a default value dependent on lamp radius is used.

The model has been shown to provide good agreement with experimental results for both low (50 Hz) and high (tens of kilohertz) frequencies at a wide range of lamp power levels. It has also been shown that it is possible to model a wide range of fluorescent lamp types by providing only key lamp parameters.

The model is suitable for modeling both inductive ballasts and resonant ballasts. The model's ability to handle step changes in frequency and power has also been demonstrated with an example of a dimming resonant ballast.

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Arran J. Holloway received the M. Eng. degree in electronic engineering in 2005 from the University of Sheffield, Sheffield, U.K., where he is working toward the Ph.D. in the modeling of low-pressure mercury–argon lamps, with a particular emphasis on models suitable for ballast simulation.



Richard C. Tozer (M'83–SM'98) received the B.Eng. and Ph.D. (CCD device applications) degrees from the University of Sheffield, Sheffield, U.K., in 1970 and 1975, respectively.

After completing the Ph.D. degree, he became a Lecturer at the University of Essex, Colchester, U.K., where he was engaged in active sound cancellation. Since 1980, he has been a Lecturer with the University of Sheffield, where he is currently involved in teaching analog circuit design. His current research interests include the application of analog circuits to a wide range of experimental and instrumental problems and is currently centered around amplitude probability distribution (APD) noise measurement and novel excitation modes for fluorescent lamps.

Dr. Tozer is a Chartered Engineer and a member of the IEE.



Dave A. Stone graduated in B.Eng. in electronic engineering from the University of Sheffield, Sheffield, U.K., in 1984, and the Ph.D. degree from the University of Liverpool, Liverpool, U.K., in 1989.

He joined as a member of academic staff specializing in power electronics and machine drive systems with the University of Sheffield, where he is currently a Senior Lecturer. His current research interests include resonant power converters, hybrid-electric vehicles, battery state-of-charge and state-of-health monitoring, EMC, and novel lamp ballasts for low-

pressure fluorescent lamps.