Design and Implementation of Dimmable Electronic Ballast for Fluorescent Lamps Based on Power-Dependent Lamp Model

Hung-Liang Cheng, , and Yung-Hsin Huang

Abstract—A simple and easy-to-use electric-circuit model for fluorescent lamps is deduced from experimental tests. The lamp arc is modeled as a power-dependent resistance. By incorporating the lamp model with electronic ballast, design equations for dimmable electronic ballasts using half-bridge resonant inverter are derived, and then the dimming operation characteristics can be predicted analytically. Detailed analysis and design of a dimmable electronic-ballast fluorescent-lamp circuit with frequency control are presented. Accordingly, design guidelines for determining circuit parameters are provided. An electronic ballast with half-bridge series-resonant parallel-loaded inverter is used as an example for illustrating the design procedure. A prototype circuit for a T8-36W fluorescent lamp is built and tested to verify the validity of the proposed model.

Index Terms—Dimming control, electronic ballast, fluorescent lamp model, half-bridge resonant inverter.

I. INTRODUCTION

FLUORESCENT lamps have played an important role in the artificial-light system, owing to their advantages of higher luminance efficiency and longer lamp life over incandescent lamps [1], [2]. Nowadays, high-frequency electronic ballasts have been more frequently used to drive fluorescent lamps for improving light quality. In addition to numerous benefits over electromagnetic ones, the electronic ballast can provide dimming capability with simple control circuitry [3]–[6]. The dimming feature of the fluorescent lamp has received increasing attention for the purpose of energy savings in recent years.

Among various dimmable electronic ballasts, the half-bridge resonant inverters with frequency control take advantage of a wider dimming range with simple circuit configuration and thus, are popularly adopted in practical implementation [7]–[12]. However, the analysis and design of dimmable electronic ballasts with frequency control are still not clearly addressed for lack of an applicable lamp model. The fluorescent lamps, as loads of the inverter, play principal roles in the resonant inverter and have crucial influence on the electronic ballast. For accurately predicting the operating characteristics of the fluorescent lamps and properly designing dimmable electronic ballasts, it is necessary for ballast designers to have better understanding of the lamp behavior when they are dimmed. Hence, a simple and user-friendly electrical circuit model for fluorescent lamps is essential to analysis and design of dimmable electronic ballast. Unfortunately, the electrical behavior of the fluorescent lamp is so complicated that to model the lamp by a simple electrical circuit element is difficult. Previously, several dynamic models were presented for accurately simulating the waveforms of lamp voltage and current [13]–[17]. These models are useful for predicting and simulating the dynamic waveforms of lamp voltage and current. However, they are too complicated to be used in designing dimmable electronic ballast. On the other hand, some designers modeled the fluorescent lamp simply as a constant resistance. Nevertheless, such a simple model is correct only when the lamp is operated at the rated output. Using a constant-resistance model to analyze the dimming operation leads to considerable errors because the lamp voltage and current do not remain consistent while operating at a reduced power. This implies that the equivalent lamp resistance should be power dependent.

From the test results on various types of fluorescent lamps, it is found that the model of power-dependent resistance is highly nonlinear, which still presents an intense design task to the engineers. For the sake of simplicity and not losing accuracy, this paper proposes an electric-circuit model for the fluorescent lamp in which the lamp arc is obtained from the arc voltage and arc power. The arc-voltage equation is obtained from measured data. The proposed model is useful for analyzing the performance of electronic ballasts with dimming capability.

To illustrate the validity of the proposed model, a T8-36W fluorescent lamp is used as a specific example. An electronic ballast with a half-bridge series-resonant parallel-loaded inverter is used to show the dimming operating characteristics by frequency control. Design equations are derived and then the operating characteristics of the ballast–lamp circuit within the dimming range are precisely calculated. The design considerations and the design procedure are discussed. A prototype circuit is built and tested to verify the analytical predictions.
II. MODELING FLUORESCENT LAMPS

A. Experimental Measurements

A fluorescent lamp, when operated at a high frequency, can be regarded as a resistance. On this basis, the fluorescent lamp is equivalent to an electric circuit as shown in Fig. 1 [3]. The lamp arc is represented by a power-dependent resistance $R_{arc}$ due to the fact that the arc resistance decreases as the arc power increases. It should be noted that the total lamp power $P_{lamp}$ consists of the arc power $P_{arc}$ and the power of the cathode filaments $P_{rf}$. Physically, the resistance of the filament distributes from one end to the other end. In this model, for simplicity, each cathode filament is represented by a lumped resistance $r_f$. In practice, the resistance of the cathode is dependent upon the operating temperature. For a well-designed ballast, the cathode is maintained on a proper emission temperature. Therefore, it will not cause influential error to treat the filament resistance as a constant.

A test system as shown in Fig. 2 is elaborately set up to investigate the effects on the electrical characteristics of the fluorescent lamp for the variation in the arc power. In order to ensure that the arc power is a unique parameter affecting the performance of the ballast–lamp circuit, all sample lamps should have been operated at their rated outputs for a 100-h burn-in period prior to testing, and the ambient temperature in the compartment is precisely and uniformly controlled at 25 °C. Each filament is heated by a current source $I_f$ for providing the specified filament power. Two current sources are connected in the directions shown in the figure to make the voltage drops on the two filaments be opposite to each other.

With such a connection, the arc voltage of the lamp $V_{arc}$ is equal to the measured voltage $V_{YZ}$, and the lamp arc current $I_{arc}$ is equal to the load-resonant current $I_s$. Then, the arc power is

$$P_{arc} = V_{arc} \cdot I_{arc} = V_{YZ} \cdot I_s. \quad (1)$$

In order to simulate the practical operation, the filament currents are operated at the same frequency as with the inverter and are made to have a phase difference of 90° with the arc current. Taking $I_s$ as the reference axis, the filament power can be calculated as

$$P_{rf} = \left[ \left| I_s - I_f \angle 90° \right|^2 + I_f^2 \right] \cdot \frac{r_f}{2} + \left[ \left| I_s + I_f \angle 90° \right|^2 + I_f^2 \right] \cdot \frac{r_f}{2} = \left( I_s^2 + 2I_f^2 \right) \cdot r_f. \quad (2)$$

To exclude the effects from the cathode temperature, the filament power is kept constant by adjusting $I_f$ during the tests with dimming operation.

B. Lamp Model

From numerous experimental results, one can find similar electrical behavior for different types of lamps. Figs. 3–5 show the arc voltages, arc currents, and equivalent arc resistances at different operating powers for four different types of fluorescent lamps. The arc voltages and currents can be directly measured, while the equivalent arc resistances are calculated from the measured data under the assumption of resistive-lamp behavior. All fluorescent lamps exhibit the same characteristic of negative
incremental resistance. The relationship between the equivalent arc resistance and the arc power should be approximated at least by a fourth-order polynomial equation. Such a complex equation certainly complicates the analysis. Fortunately, it is found that the arc voltage increases linearly as the arc power decreases except at very low dimming operation. In practical design, the lowest dimming setting is normally limited to 10% of the rated power for having sensible light output. Thus, the nonlinear portions of the curves will not be included in the dimmable range. Therefore, the equation of the arc voltage can be simply expressed as

$$V_{\text{arc}} = A_V + B_V P_{\text{arc}}$$

(3)

where $A_V$ and $B_V$ are constant coefficients, which can be obtained by the least mean-square method.

On the other hand, the arc current increases nonlinearly as the arc power increases. Since the lamp arc is assumed to be resistive, the arc current and the equivalent arc resistance can be expressed as

$$I_{\text{arc}} = P_{\text{arc}} / V_{\text{arc}}$$

(4)

$$R_{\text{arc}} = V_{\text{arc}}^2 / P_{\text{arc}}$$

(5)

As shown in Figs. 4 and 5, it is found that the experimental results of the arc currents and the equivalent arc resistances calculated from measured arc voltages and currents are found to be coincident with the approximate curves derived from (4) and (5), respectively. This indicates that the lamp model is consistent with the assumption of the resistive-lamp arc.

III. CIRCUIT ANALYSIS

A. Electronic Ballast

An electronic ballast with a half-bridge series-resonant parallel-loaded inverter, as shown in Fig. 6, is used as an illustration of the implementation of the proposed model. The active power switches $S_1$ and $S_2$ of the inverter are turned on and off alternately by two control signals $V_{\text{gs1}}$ and $V_{\text{gs2}}$ to drive the load-resonant circuit at high frequency, which is preferably higher than 20 kHz. $D_1$ and $D_2$ are the intrinsic body diodes of the active switches, respectively. The load-resonant circuit consists of a series-resonant energy tank and a parallel capacitor $C_f$. The resonant energy tank is composed of an inductor $L_S$ and a capacitor $C_S$. The capacitor $C_f$ is used to provide a sufficiently high voltage across the lamp during starting and then a proper filament current at steady state. In addition to these functions, $C_f$ can reduce harmonics on the lamp current and thus, can improve the crest factor of the lamp current.

By symmetrically driving the two active switches with a short dead time, a voltage source of quasi-square waveform with a dc term of $V_{\text{dc}}/2$ is applied to the load-resonant circuit. When the load quality factor of the load-resonant circuit is high enough, almost all the harmonic contents, as well as the dc term, will be filtered out by the resonant circuit. Only the fundamental current at the switching frequency will be present in the load-resonant inverter [18]. Therefore, an approximate analysis can be made by using the phasor representation of the fundamental component. The fundamental frequency is identical to the inverter switching frequency $f_s$. Fig. 7 shows the equivalent circuit of the load-resonant inverter with the circuit model of the lamp for fundamental approximation. The voltage source $V_1$ is the rms value of the fundamental component of the quasi-square voltage.

$$V_1 = \frac{\sqrt{2}}{\pi} V_{\text{dc}}.$$  

(6)

B. Thevenin Equivalent Circuit

For facilitating the analysis, Fig. 7 can be further simplified to its Thevenin equivalent circuit with respect to the lamp
arc resistance, as shown in Fig. 8. The voltage source of the Thevenin equivalent circuit is

\[ V_{\text{eq}} = V_1 \frac{Z_p}{Z_s + Z_p} \]  

(7)

and the equivalent impedance is

\[ Z_{\text{eq}} = \frac{Z_s Z_p}{Z_s + Z_p} \]  

(8)

where \( Z_s \) is the impedance of the series combination of the resonant energy tank and the resistances of the left-half side filaments

\[ Z'_s = r_f + jZ_{LC} = r_f + j \left( 2\pi f_s L_s - \frac{1}{2\pi f_s C_s} \right) = Z_s \angle \theta_s \]  

(9)

and \( Z_p \) is the impedance of the parallel capacitor in series with the resistances of the right-half side filaments.

\[ Z'_p = r_f + jZ_{cf} = r_f - j \frac{1}{2\pi f_s C_f} = Z_p \angle \theta_p. \]  

(10)

C. Starting Voltage

From Fig. 8, the arc voltage can be expressed as

\[ V_{\text{arc}} = \left| \frac{R_{\text{arc}}}{Z_{\text{eq}} + R_{\text{arc}}} \right| |V_{\text{eq}}|. \]  

(11)

Before ignition, the lamp arc can be regarded as an open circuit. The lamp starting voltage \( V_{\text{start}} \) is equal to the magnitude of the Thevenin equivalent voltage. Therefore, \( V_{\text{start}} \) can be extremely high when the inverter is operated near the resonant frequency of the load-resonant circuit. This ensures the successful ignition of the lamp by adjusting the operating frequency to be close to the resonant frequency during the starting.

D. Filament Power

In order to achieve a stable lamp arc at a reduced lamp power and prevent from shortening the lamp life, the cathodes should be maintained at proper emission temperature. In practice, it is suggested that the filament power remains constant over the entire dimmable range. There are two sources of filament heating. One comes from \( I_f \) and the other is the self-heating from the arc current \( I_{\text{arc}} \) flowing through the filaments. The self-heating current decreases when the arc power is reduced. For this reason, \( I_f \) should be increased to compensate for the reduced heating at a reduced arc current.

When calculating \( I_f \), the voltage drop on the filaments can be ignored since it is very small compared with the lamp arc voltage. Moreover, \( I_f \) and \( I_{\text{arc}} \) are almost orthogonal to each other. Then, the filament power can be calculated as

\[ P_{\text{f}} = \left[ \left( \frac{P_{\text{arc}}}{V_{\text{arc}}} \right)^2 + 2 \left( \frac{V_{\text{arc}}}{Z_{\text{cf}}} \right)^2 \right] \cdot r_f. \]  

(12)

IV. DESIGN PROEDURE

A T8-36W rapid-start fluorescent lamp is discussed as an illustrative example. The specifications of the lamp and the electronic ballast are listed in Table I. The rated power of 36 W is the total lamp power including the arc power and the filament power. At proper cathode temperature for emitting electrons, the resistance of each filament is 9.6 \( \Omega \). The dc-link voltage is 310 V. For successfully igniting the lamp at room temperature, the starting voltage \( V_{\text{start}} \) has to be greater than 220 \( V_{\text{rms}} \). In this design, the switching frequency at the rated power is chosen to be 36 kHz. At rated power operation, \( P_{\text{arc}} \) and \( P_{\text{f}} \) are specified as 33 and 3 W, respectively.

Considering the switching losses of the inverter, it is desired to operate the inverter at a frequency range by which the load-resonant circuit is always inductive. With an inductive-load circuit, an increase in the operating frequency will cause a decrease in the lamp power. On the other hand, an increase in the frequency will cause a smaller impedance of \( C_f \) and thus, a larger filament current. As a result, the filament power will be increased as the lamp arc power is reduced. This is helpful to maintain a stable arc current at a lower arc power and hence, to have a wider dimming range.

Step 1) Obtain the lamp model. The lamp model can be obtained from experimental tests. As shown in Fig. 3, the power-dependent voltage equation for the lamp is

\[ V_{\text{arc}} = 142.2 - 1.37 P_{\text{arc}}. \]  

(13)

Step 2) Calculate the parallel capacitance, \( C_f \). From (13), \( V_{\text{arc}} \) is 97.0 volts at the rated power. Substituting \( P_{\text{arc}} \) and \( V_{\text{arc}} \) into (12) to have a filament power of 3W, \( Z_{\text{cf}} \) is calculated to be 309 \( \Omega \). For the operating frequency of 36 kHz

\[ C_f = 14.3 \text{ nF}. \]
Step 3) Calculate $Z_s$ at the rated power.

Substituting (7)–(10) into (11) and rearranging, (14), which is shown at the bottom of the next page, can be obtained. Since $r_f$ is very small compared with $R_{arc}$ and $Z_p$, the last term in (14) can be ignored. Then, $Z_{LC}$ can be solved by (15). There are two solutions of $Z_{LC}$ to have the rated lamp power at 36 kHz.

$$Z_{LC} = 418.1 \, \Omega \quad \text{or} \quad Z_{LC} = -118.5 \, \Omega.$$  

Since the load-resonant circuit of the electronic ballast is preferred to be inductive, the negative solution is not adopted.

Step 4) Calculate the arc power.

Based on the equivalent circuit in Fig. 7, the magnitude of $V_1$ is given in (16), shown at the bottom of the page. Theoretically, there are infinite different pairs of $L_s$ and $C_s$ with the impedance of $Z_{LC}$ obtained at Step 3. For any given set of $L_s$ and $C_s$, $P_{arc}$ at different operating frequencies can be calculated by using (6), (9), (10), (16), and the power-dependent lamp model with the aid of computer calculations. The program flowchart is as follows. For a given switching frequency, $Z_{LC}$ and $Z_p$ are calculated from (9) and (10), respectively. A lamp power is assumed, then the arc voltage and current are calculated by using the equations shown in Figs. 3 and 4. Using the method of trial-and-error, the lamp power can be obtained by comparing the fundamental voltages calculated from (6) and (16). The calculated results are shown in Fig. 9. In the figure, each curve represents the variation of the arc power for a specific value of $C_s$. All these curves have an intersection at the point of the rated lamp power and the rated switching frequency of 36 kHz.

At this point, the values of $Z_{LC}$ for all curves are the same. As predicted, the arc power is reduced as the switching frequency is increased for all curves. As $C_s$ is decreased, the arc power becomes more sensitive to the variation of the switching frequency.

$$V_1 = \left( \frac{V_{arc} \left( Z_p^2 + Z_{LC}Z_{cf} + r_f^2 \right)}{Z_p^2} + r_f I_{arc} \right)^2$$

$$+ \left[ Z_{LC}I_{arc} + r_f V_{arc} (Z_{LC} - Z_{cf}) \right]^2 \right)^{\frac{1}{2}}. \quad (16)$$

Step 5) Chose adequate $L_s$ and $C_s$.

Fig. 10 shows the variation of the filament power with the arc power. Theoretically, the cathode temperature will not change if the filament power is kept constant during dimming operation. In practice, due to the fact that a part of the arc power would be transformed into heat, the filament power should be increased to make up for the heat required for maintaining suitable cathode temperature when the arc power is reduced at dimming operation. As shown in Fig. 10, the filament power will increase considerably with a high value of $C_s$. However, excessive filament heating can cause premature end blackening of the lamp. On the other hand, the filament power with a small $C_s$ is not high enough to maintain sufficient cathode temperature when the arc power is low. In this case, $C_s$ is chosen to be 15 nF to compromise for an adequate filament power for dimming operation. The corresponding $L_s$ is calculated to be 3.15 mH. With such a resonant circuit, the load quality factor is above three within the whole dimming range. This high quality factor can comply with the assumption of pure sinusoidal resonant current in the resonant inverter circuit.

Step 6) Determine the starting frequency.

For retaining long lamp lifetime, an adequate preheating time is required for the filament to be heated to sufficient temperature before lamp ignition. During the preheating period, the lamp is regarded as an open circuit; the resonant current only flows through the filaments and is expressed as

$$I_f = V_1/Z_s' + Z_p'.$$ \quad (17)

After the preheat time, a proper starting voltage the value of which can be calculated from (11) is applied to ignite the lamp. Fig. 11 shows the variations of $V_{start}$ and $I_f$ versus $f_s$ when the lamp has not
yet been ignited. $V_{\text{start}}$ and $I_f$ are both decreased as $f_s$ is increased. According to this figure, during preheating, $f_s$ can be controlled to be 45 kHz to have a proper current of 0.35 A for preheating the filaments. At this frequency, $V_{\text{start}}$ is 84 V, which is far below the minimal ignition voltage of the lamp. After the preheating period, $f_s$ is decreased until the lamp is successfully ignited. Once the lamp has been started up, the switching frequency goes to the frequency with the dim setting.

V. EXPERIMENTAL RESULTS

A prototype circuit was built and tested to verify the theoretical prediction. The circuit parameters are the following:

$$V_{dc} = 310 \text{ V} \quad L_S = 3.15 \text{ mH}$$
$$C_S = 15 \text{ nF} \quad C_P = 14.3 \text{ nF}.$$

The starting transient is shown in Fig. 12. The electronic ballast is switched on with an inverter frequency of 45 kHz. During the preheating period, the load-resonant current is gradually increased up to 0.35 A. After 1 s of preheating time, the inverter frequency is decreased. When the frequency goes down to 37 kHz, the resonant circuit generates a high ignition voltage on the lamp. Immediately after the lamp has been started up, the inverter frequency goes to the presetting value. In this case, the lamp is preset to operate at the rated power. Fig. 13 shows the measured waveforms of the lamp voltage and current at 100% and 15% of the rated arc power. The crest factor of the lamp current is below 1.5 for both cases. As shown in Fig. 14, the lamp power is controlled from 36 to 6.5 W by adjusting the switching frequency from 36 to 43 kHz. As predicted, the filament current increases while the arc current decreases. It is found that the experimental results agree well with the theoretical predictions except those at very low dim settings. Nevertheless, it should be remembered that the lamp power consists of the arc power and the filament power. At a very low dim setting, nearly all power is consumed by the filament. It does not have physical meaning for practical use.

$$\left[ R_{arc}^2 Z_{cf}^2 + \left( Z_p^2 + R_{arc} r_f \right)^2 \right] Z_{LC}^2 + 2 R_{arc} Z_p^2 Z_{cf} Z_{LC} + R_{arc}^2 Z_p^4 \left( 1 - \left( \frac{V_1}{V_{arc}} \right)^2 \right) + r_f \left( Z_p^2 + R_{arc} r_f \right)^2 + 2 R_{arc} Z_p^2 \left( Z_p^2 + Z_{cf} Z_{arc} r_f + r_f R_{arc}^2 Z_{cf}^2 \right) = 0. \quad (14)$$

$$Z_{LC} = \frac{-R_{arc}^2 Z_p^2 Z_{cf} + \sqrt{\left( R_{arc}^2 Z_p^2 Z_{cf} \right)^2 - \left( R_{arc}^2 Z_p^2 + Z_p^2 + R_{arc} r_f \right)^2 \left( R_{arc}^2 Z_p^4 \left( 1 - \left( \frac{V_1}{V_{arc}} \right)^2 \right) \right)}}{R_{arc}^2 Z_p^2 + \left( Z_p^2 + R_{arc} r_f \right)^2} \quad (15)$$
VI. CONCLUSIONS

An easy-to-use electrical circuit model of the fluorescent lamp for dimming operation is derived from experimental test. At high-frequency operation, the lamp can be modeled as a power-dependent resistance. Also, experimental tests prove that the lamp-discharge behavior can be represented by a simple first-order voltage equation. This circuit model leads to better understanding of the electrical behavior of the fluorescent lamp when it is dimmed. The operating characteristics can be analytically predicted on the basis of the electrical circuit model of the fluorescent lamp. By incorporating the lamp model into the dimmable electronic-ballast circuit, performance equations can be derived to determine the circuit component values and their applicable operating ranges.

A design example for driving a T8-36W fluorescent lamp is given to illustrate the design procedures step by step. The laboratory circuit with the designed circuit parameters was built and tested. The experimental results show that the design equations can precisely predict the circuit behavior within the applicable dimming range.

REFERENCES


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