1997 IEEE International Symposium on Circuits and Systems, June 9-12, 1997, Hong Kong

A SIMPLE METHOD TO DESIGN RESONANT CIRCUITS OF ELECTRONIC BALLAST FOR FLUORESCENT LAMPS

Zhi Li[*], *Philip K.T. Mok, Wing-Hung Ki and Johnny K.O. Sin*
Dept. of Electrical and Electronic Engineering
The Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong
Tel: (852)2358-8517 Fax: (852)2358-1485 Email: eemok@ee.ust.hk
[*]Currently on leave from the University of Electronic Science and Technology of China, Chengdu, Sichuan 610054, China

ABSTRACT

A simple design method has been developed to investigate the dimming control of electronic ballast circuits for fluorescent lamps. This method is based on the steady-state calculation of the ballast at resonant frequency, f_0, and the inherent characteristics of the fluorescent lamp, i.e. the relationship between the lamp resistance and the lamp power. The inherent lamp characteristics encompass the fact that the voltage across the lamp varies with the lamp power. Including this inherent characteristic into a new lamp Spice simulation model can provide an accurate simulation result of the relations between the ballast operation frequency and the lamp power.

1. INTRODUCTION

Fluorescent lamps are preferable to incandescent lamps because of their high luminous efficacy (lumens/watts). However, in normal operation, fluorescent lamps exhibit negative resistance characteristics such that unstable conditions occur when the lamps are connected to a constant voltage high enough to cause ionization. Therefore, a ballast is needed to limit the lamp current. High frequency (>20KHz) operation of this ballast had been demonstrated to have many advantages over the 50-60 Hz operation [1,2]. The lumen output is 10-20% higher and the starting voltage of the lamp is smaller.

The high frequency electronic ballast usually consists of EMI filter, power factor corrector, high-frequency dc/ac inverter, and control circuit. When these circuits are simulated, a suitable model for the main element, fluorescent lamp, is critical. Several models for the fluorescent lamp had been developed [3-6]. However, some of these models were only suitable for low frequency (50-60 Hz) operation. The other models for high frequency operation assume a constant voltage across the fluorescent lamp at different lamp power [5,6]. However, this is not appropriate because the lamp voltage actually will change more than 50% under different lamp power.

In this paper, a new simulation model is developed to estimate the performance of the electronic ballast based on the inherent characteristics of the fluorescent lamp. This model will include the fact that the lamp voltage changes with respect to the lamp power. The purpose of this paper is to present a simple method to design the electronic ballast using steady-state calculation of the resonant circuit at f_0 and the Hspice program, together with the inherent characteristics of the fluorescent lamp. In this method, the dimming condition of the electronic ballast at different operating frequencies can be simulated more accurately.

2. INHERENT CHARACTERISTICS OF FLUORESCENT LAMPS

Fluorescent lamps are gaseous discharge lamps which produce light by discharging an electric arc through a tube filled with low-pressure gas containing mercury atoms. The gas discharge behaves like a negative temperature coefficient resistor. At high lamp power, the lamp gas is highly ionized and the resistance of the lamp is low. At low lamp power, the lamp gas is less ionized and the resistance of the lamp is high. The thermal time constant of the fluorescent lamp is in the order of a millisecond. As a result, in the traditional low frequency ballasts, voltage spikes can be seen at the beginning of every half-cycle of the lamp voltage waveform. However, in high frequency operation (>20KHz), this voltage spike does not appear simply because the lamp gas does not have enough time to ionize and recombine between half cycles [3]. Therefore, the operation of the lamps at high frequency is different to that at low frequency.

After starting, the lamp operates in steady state. At high frequency, the lamp self-regulates its rms operating voltage, V_P, by adjusting its resistance, R_P. Increasing the lamp power will increase the gas ionization; therefore, decrease the lamp resistance and thus decrease the voltage across the lamp. The V-I characteristic of the lamp should depend on the size of the lamp and not on the operating frequency of the lamp. This is the inherent characteristic of the lamp. From the V-I characteristic, the resistance R_P, power P of the lamp and the relationship of the R_P-P can be calculated. This relationship will be integrated into a new lamp Spice simulation model.

3. STEADY-STATE ANALYSIS

Fig. 1 shows a class D voltage-switching resonant inverter which is one of most commonly used high-efficiency high-frequency electronic ballast circuits. During the switching of the inverter, the voltage across the transistors M_1 and M_2 equals the supply voltage, which is a relatively low voltage. As a result, low-voltage MOSFETs with low on-resistances can be used in this inverter, resulting in low conduction losses and high efficiency.

0-7803-3583-X/97 $10.00 ©1997 IEEE

The input voltage of the resonant network is either switched to zero or V_{DD} by half-bridge transistors M_1 and M_2. The effective input waveform is therefore a square-wave with voltages between 0V and V_{DD}. The dc blocking capacitor, C_C, is large and can be approximated by a short circuit at high ballast's operating frequency.

At high frequency operation, the lamp acts like a resistor with its voltage and current waveforms in phase. The inductor, L, and capacitor, C_P form a low-pass filter with the fluorescent lamp as a resistive load, R_P. In typical ballast designs, the circuit operates around the natural resonant frequency with the resonant network Q_L greater than 1/2. Under these conditions, square-wave harmonics are rejected at 40dB/decade above the fundamental and account for less than 4% of the total lamp power [6]. Since the higher-order harmonics only account for a small percentage of the input, the voltage and current waveforms appearing at the lamp can be assumed to be sinusoidal.

A simplified version of the class D inverter is shown in Fig. 2 for ac analysis. The input voltage of the resonant circuit $v(t)$ is a square wave of magnitude V_{DD}. The fundamental component of this voltage is $v(t)=V_m \sin \omega t$ where the amplitude of $v(t)$ can be found from Fourier analysis as

$$V_m = (2/\pi)V_{DD} = 0.6366\ V_{DD} \tag{1}$$

and the rms value of $v(t)$ is 0.4502 V_{DD}.

The resonant circuit of Fig. 2 is a second-order low-pass network and can be described by the following normalized parameters: the resonant frequency ω_0, the characteristic impedance Z_0, the loaded quality factor Q_L at the resonant frequency f_0 and the damped natural frequency ω_d are given by

$$\omega_0 = \frac{1}{\sqrt{LC_P}} \tag{2}$$

$$Z_0 = \omega_0 L = \frac{1}{\omega_0 C_P} = \sqrt{\frac{L}{C_P}} \tag{3}$$

$$Q_L = \omega_0 C_P R_P = \frac{R_P}{\omega_0 L} = \frac{R_P}{Z_0} \tag{4}$$

$$\omega_d = \omega_0\sqrt{1-1/(4{Q_L}^2)} \quad \text{for } Q_L \geq 1/2 \tag{5}$$

Referring to Fig. 2 and using (2) and (4), the input impedance of the resonant circuit is

$$Z = j\omega L + \frac{R_P \dfrac{1}{j\omega C_P}}{R_P + \dfrac{1}{j\omega C_P}}$$

$$= \frac{R_P\left[1-\left(\dfrac{\omega}{\omega_0}\right)^2 + j\dfrac{1}{Q_L}\left(\dfrac{\omega}{\omega_0}\right)\right]}{1+jQ_L\left(\dfrac{\omega}{\omega_0}\right)} = |Z|e^{j\psi} \tag{6}$$

where

$$\frac{|Z|}{Z_0} = \sqrt{\frac{{Q_L}^2\left[1-\left(\dfrac{\omega}{\omega_0}\right)^2\right]^2 + \left(\dfrac{\omega}{\omega_0}\right)^2}{1+\left(Q_L\dfrac{\omega}{\omega_0}\right)^2}} \tag{7}$$

$$\psi = \arctan\left\{Q_L\left(\frac{\omega}{\omega_0}\right)\left[\left(\frac{\omega}{\omega_0}\right)^2 + \frac{1}{{Q_L}^2} - 1\right]\right\} \tag{8}$$

The current through inductor L is given by

$$i(t) = I_m \sin(\omega t - \psi) \tag{9}$$

where I_m is the amplitude of the inductor current. Using (1) and (7)

$$I_m = \frac{V_m}{|Z|} = \frac{2V_{DD}}{\pi|Z|}$$

$$= \frac{2V_{DD}}{\pi Z_0}\sqrt{\frac{1+\left(Q_L\dfrac{\omega}{\omega_0}\right)^2}{{Q_L}^2\left[1-\left(\dfrac{\omega}{\omega_0}\right)^2\right]^2 + \left(\dfrac{\omega}{\omega_0}\right)^2}} \tag{10}$$

At $f=f_0$, $$I_m \cong \frac{2V_{DD}\sqrt{{Q_L}^2+1}}{\pi Z_0} \tag{11}$$

The amplitude of the lamp current is

$$I_{Pm} = \frac{2V_{DD}}{\pi Z_0\sqrt{{Q_L}^2\left[1-\left(\dfrac{\omega}{\omega_0}\right)^2\right]^2 + \left(\dfrac{\omega}{\omega_0}\right)^2}} \tag{12}$$

At $f=f_0$, $$I_{Pm} \cong \frac{2V_{DD}}{\pi Z_0} = \frac{2V_{DD}}{\pi\omega_0 L} = \frac{2V_{DD}\omega_0 C}{\pi} \tag{13}$$

Note that I_{Pm} is independent of lamp resistance R_P at f_0. Therefore, the inverter is suitable for driving a fluorescent lamp which has a negative load resistance.

The amplitude of the voltage across the C_P and R_P is

$$V_{Pm} = \frac{2V_{DD}}{\pi\sqrt{\left[1-\left(\dfrac{\omega}{\omega_0}\right)^2\right]^2 + \left[\dfrac{1}{Q_L}\left(\dfrac{\omega}{\omega_0}\right)\right]^2}} \tag{14}$$

At $f=f_0$, $$V_{Pm} \cong \frac{2V_{DD}Q_L}{\pi} \tag{15}$$

When the lamp is off, its resistance R_P is high and thus Q_L is high. Therefore, from (15), the peak lamp voltage is high which is necessary for striking the lamp. From (12), the output power is given by

$$P=\frac{R_P I_{Pm}^2}{2}=\frac{2V_{DD}^2 R_P}{\pi^2 Z_0^2\left\{Q_L^2\left[1-\left(\frac{\omega}{\omega_0}\right)^2\right]^2+\left(\frac{\omega}{\omega_0}\right)^2\right\}}$$

$$=\frac{2V_{DD}^2 Q_L}{\pi^2 Z_0\left\{Q_L^2\left[1-\left(\frac{\omega}{\omega_0}\right)^2\right]^2+\left(\frac{\omega}{\omega_0}\right)^2\right\}} \quad (16)$$

At $f=f_0$, $$P\cong\frac{2V_{DD}^2 R_P}{\pi^2 Z_0^2} \quad (17)$$

The formulae derived above can be used to design resonant circuit. Note these formulae are for the steady-state running condition and the circuit component values are calculated by these formulae only correctly at $f=f_0$.

4. MEASUREMENT

To measure the inherent characteristics of the fluorescent lamp, a high voltage (>150V) high frequency (>20KHz) power supply is needed. However, this type of power supply was not available. The circuit as shown in Fig. 3 was set up to do the measurement [7].

A self-oscillating half-bridge driver IR2151 control IC was used. The IR2151 supplies two drive outputs, one low side output to drive M_2 and the other floating high side output to drive M_1. These outputs alternate so that M_1 and M_2 generate a square wave output for driving the lamp circuits. IR2151 also includes a built-in 1.2 μs deadtime to prevent cross conduction of M_1 and M_2. At V_{DD}=311V, the square wave output is 140V rms and the frequency is set by the R_1 and C_1. The programmable oscillator frequency is given by [8]

$$f=\frac{1}{1.4(R_1+75\Omega)C_1} \quad (18)$$

by fixing C_1 and regulating R_1.

D_1 is a 400V, 1A, ultra-fast recovery diode and C_2 is a 0.1μF, 600V metallized polypropylene capacitor. M_1 and M_2 are IRF830 HEXFET power MOSFETs. T is a positive temperature coefficient thermistor (PTC) used as pre-heating control of the ballast. In the resonant tank, C_C=0.1μF, L=1.3mH and C_P=9.4nF.

The fluorescent lamp is a PHILCAP, F40T10/D, 40W, DAYLIGHT lamp. The lamp current and voltage are monitored by a current probe amplifier and digitizing oscilloscope. Table 1 shows the measured values for V_P and I_P, under different operating frequencies.

From the measurement data, the power and lamp resistance can be calculated. The results are also listed in Table 1. The measured data is plotted in Fig. 4 with the lamp resistance, R_P, as a function of lamp power, P. A second order polynomial function is used to fit the data and the polynomial function is also illustrated in Fig. 4 for comparison. This polynomial function builds the backbone of the fluorescent lamp model.

5. SIMULATION MODEL

The simulation was performed using Hspice simulation program. Fig. 5 shows the circuit model used to realize the fluorescent-lamp in the Hspice circuit simulator. Although original Berkeley SPICE 2 does not have the capability to model arbitrary functions, most newer commercial versions do. In the schematic of the fluorescent lamp model, V_{sns} is for sensing the lamp current and $V(1)$ is the lamp voltage. G_p is the instantaneous lamp power given by

$$G_P=V(1)*I(V_{sns}) \quad (19)$$

the average lamp power, P_L is generated via a simple RC filter at $V(5)$ [3]. Using the fluorescent lamp R_P-P characteristic measured in the previous section, the lamp resistance is given by

$$R_P=1648-56.6187[V(5)]+0.546711[V(5)]^2 \quad (20)$$

In the simulation, the simulation time should be long enough to give a stable curve for measurement. Table 2 gives some simulation results. Comparing with Table 1, it is clear that the simulation is close to the measurement with less than 5% error.

In the operating region of the lamp under high frequency, the relationship between the power and resistance is correlative, but is independent of frequency and resonant circuit elements. If the power is given, the lamp resistance, lamp voltage and lamp current are fixed. Therefore, for a particular resonant circuit and DC power supply voltage, certain operating frequencies of the electronic ballast correspond to certain output lamp power. The relationship of these frequencies to the output lamp power can be simulated with the above fluorescent lamp model.

6. DESIGN PROCEDURE

The Class D inverter in Fig. 1 is designed to drive one F40 fluorescent lamp. The lamp represents a pure nonlinear resistance. From the measurement data of the lamp, the rms values of the lamp voltage and current at full power (40W) steady-state operation are V_P=103V and I_P=0.385A. Hence, the resistance of the lamp is $R_P=V_P/I_P$=264Ω. Power from 220V AC main is rectified by a full bridge rectifier to approximate 311V (i.e. V_{DD}=311V). Assume also that $f=f_0$=45.5KHz for full power operation. Then, from (15), (4) and (3), the resonant circuit elements Q_L, Z_0, L and C_P can be found to be 0.736, 358.7Ω, 1.25mH and 9.75nF, respectively. The dimming operation of this ballast at different power levels and different operation frequencies can be simulated and optimized using the above described lamp model.

A systematic design approach can be summarized as follows:

1. measure the lamp characteristic curve;
2. obtain the polynomial equation to fit the lamp characteristic;
3. estimate the circuit parameters by the theoretical formulae described in this paper;
4. using the steady-state calculation, by keeping the circuit parameters and then stepping up the frequency, one can

easily get the voltage, current and power of the lamp as a function of frequency;

5. the values of the resonant circuit elements can also be adjusted and optimized according to the method mentioned above.

7. CONCLUSION

A simple design method is presented here to investigate the electronic ballast circuit. This method is based on the steady-state calculation of the ballast circuit at resonant frequency and the inherent characteristics of the fluorescent lamp.

A new high frequency fluorescent lamp simulation model has been developed which include the relationship of the lamp voltage to the lamp power. This model is very helpful for designing high frequency dimmable electronic ballast circuits which operate at different frequencies.

ACKNOWLEDGMENT

This work was supported by the RGC Competitive Earmarked Research Grant, Hong Kong Government, HKUST765/96E.

REFERENCES

[1] E.E. Hammer, "High frequency characteristics of fluorescent lamps up to 500 KHz", J. Illuminating Eng. Soc., pp. 52-61, Winter 1987.

[2] E.E. Hammer, "Fluorescent lamp starting voltage relationship at 60Hz and high frequency", J. Illuminating Eng. Soc., pp. 36-46, Oct. 1983.

[3] U. Mader and P. Horn, "A dynamic model for the electrical characteristics of fluorescent lamps", Ind. Appl. Soc. Annual Meeting, vol. 2 , pp. 1928-1934, Houston, TX, 1992.

[4] Y. Sun, "Pspice modeling of electronically ballasted compact fluorescent lamp systems", Ind. Appl. Soc. Annual Meeting, vol. 3, pp. 2311-16, New York, NY, 1993.

[5] K. K. Sum and U. Mader, "The self-oscillating parallel resonant inverter as an electronic fluorescent lamp ballast", High Frequency Power Conversion Conf., 1995.

[6] U. Mader, "Steady-state analysis of a voltage-fed inverter with second-order network and fluorescent lamp load", Proceeding of 11th Applied Power Electronics Conf., San Jose, CA, 1996.

[7] International Rectifier, Design Tips, DT 94-3A.

[8] International Rectifier, Data Sheet IR2151.

Table 1: Experimental lamp data at V_{DD}=311V

F (KHz)	38.8	39.6	41.9	45.7	49.6	53.9	57.6	60.4	63.0
$V_{P(rms)}$ (V)	93.5	97.1	100.1	103.5	107.0	110.7	115.0	118.7	122.4
$I_{P(rms)}$ (A)	0.540	0.470	0.430	0.385	0.340	0.300	0.246	0.210	0.166
R_P (Ω)	173.0	206.6	232.8	268.8	314.7	369.0	467.5	565.2	737.3
P (W)	50.5	45.6	43.0	39.8	36.4	33.2	28.3	25.0	20.3

Table 2: Simulation results (L=1.3mH, C_P=9.4nF)

F (KHz)	47.6	59.5	63.3
P (W)	40.0	28.6	20.1
$V_{P(rms)}$(V)	100.8	114.5	124.3
$I_{P(rms)}$ (A)	0.401	0.250	0.162

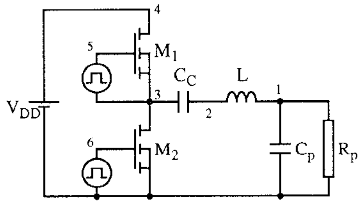

Fig. 1: Class D resonant inverter

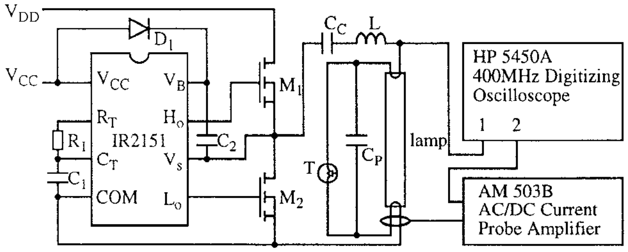

Fig. 3: Experimental circuit for measuring the I-V characteristic of the fluorescent lamp

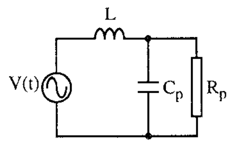

Fig. 2: Simplified circuit for the steady-state ac analysis

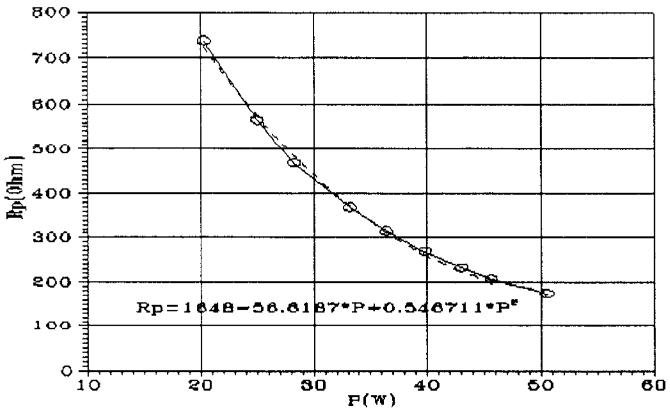

Fig. 4: Lamp resistance as a function of lamp power

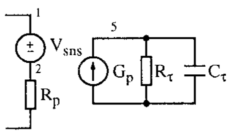

Fig. 5: Schematic of the fluorescent lamp model for Hspice simulation