

A Low Cost and Reliable Dimmable Ballast Topology with Inherent Power Regulation and Insensitivity to Lamp Characteristics

C.P. Liu N.K. Poon M.H. Pong Y.P. Chan D.D.C. Lu
 Department of Electrical & Electronic Engineering,
 Power Electronics Laboratory, The University of Hong Kong, Pokfulam Road,
 Hong Kong, China
 Email: cp@eee.hku.hk, nkpoon@eee.hku.hk, mhp@eee.hku.hk

Abstract— The output power of the proposed dimmable ballast topology is self-regulated and insensitive to the lamp characteristics. Accurate dimming operation with rather constant filament power can be realized simply by open loop control of the switching frequency of the converter. It can provide reliable operation during lamp ignition with fault conditions or even short circuit without the need of current sensing circuits. Prototype was built for experimental verifications. For completeness, a simple ultra low dimming method is also proposed together with the theoretical dimming limit considered.

I. INTRODUCTION

A common way to realize high frequency electronic ballast for fluorescent lamp is shown in Fig. 1a. The high frequency AC voltage source can be generated by a half-bridge circuit with a series capacitor and then drives the lamp through a LC network. The lamp exhibits resistive characteristic at high frequency after ignition and a commonly used simplified LCR model is shown in Fig. 1b with the filament resistors R_1 , R_2 , R_3 and R_4 inserted. The LC network provides several important functions. During lamp ignition, the frequency of the AC voltage source is set to the resonant frequency of the LC network. Because lamp resistance R_{lamp} is very high and can be treated as open circuit before ignition, the LC network exhibits very low impedance to the voltage source and absorbs the energy to build up high voltage across the capacitor to ignite the lamp. To guarantee reliable operation during the ignition period, fast response protection circuit is required to close monitoring the inductor current or the capacitor voltage because if the lamp fails to turn on, the current flowing through the LC network is nearly unlimited and can build up continuously to a dangerous level that will saturate the inductor and burn out the semiconductors that generating the voltage source. Another function of the LC network is to facilitate the dimming operations. One of the most frequently used methods is to control the current delivered to the lamp by control the impedance of the inductor. This can be realized by varying the frequency of the AC voltage source in the range below the resonate frequency of the LC network. The drawback is that the determination of the inductance and actual output power to the lamp depends much on the lamp characteristics. Another dimming control method is to control the phase ϕ between the AC voltage

source and the inductor current proposed in [1]. It provides a linear dimming curve between the lamp power and ϕ but a special controller with phase detection is required.

A topology with inherent output power regulated characteristic is proposed for electronic ballast realization. It can provide reliable operation during lamp ignition with fault conditions or even short circuit without the need of current sensing and fast acting protection circuits because of the inherent power limiting features and the lamp power can be adjusted easily and accurately by open control of the switching frequency or the DC link voltage.



Fig. 1a Practical electronic ballast configuration

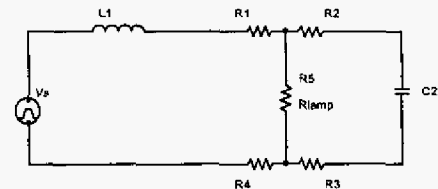


Fig. 1b Simplified equivalent circuit model

II. BASIC OPERATION IDEA

The basic idea of the topology is proposed in [2][3]. The power regulated feature is based on the charging and discharging characteristics of capacitor with suitable voltage clamping. The basic circuit configuration is shown in Fig. 2. Unlike conventional half-bridge circuit, C_3 and C_4 are not intended to operate at constant voltage.

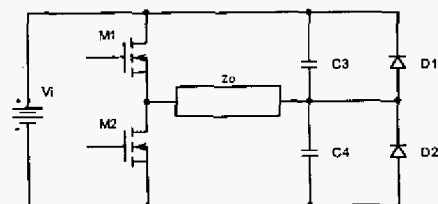


Fig. 2a Circuit diagram with transformer parameters and output filter

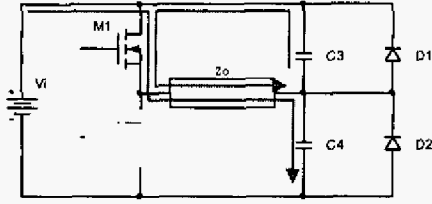


Fig.2b Power transfer when M1 is on

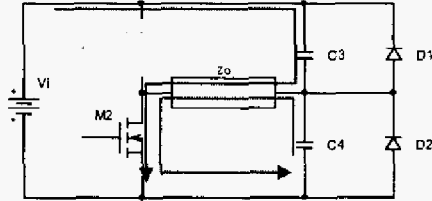


Fig.2c Power transfer when M2 is on

M_1 and M_2 are driven on and off alternatively with duty cycle of 50%. Negligible dead time is inserted during the on and off transitions of M_1 and M_2 to prevent cross conduction. In Fig. 2b, M_1 is driven on and M_2 is off, with the assumption that the initial voltage of C_3 and C_4 are V_i and zero respectively, the energy stored in C_3 discharges to Z_o through M_1 while C_4 will be charged up by the input voltage V_i through Z_o . When C_4 is charged up to V_i , the voltage across C_3 is zero and all the stored energy has been released to Z_o . Further discharging and charging of C_3 and C_4 is ceased even when Z_o is inductive because of the present of clamping diodes D_1 and D_2 . At this time, the total energy E_c delivered to Z_o is equal to CV_i^2 if $C_3 = C_4 = C$. If Z_o is purely resistive, E_c dissipates simultaneously to Z_o just after the discharging and charging of C_3 and C_4 . If Z_o is not purely resistive, energy will circulate among Z_o , C_3 , D_1 and M_1 for a certain time t_c until the energy equal to E_c dissipates to the resistive part of Z_o . Similarly, when M_2 is on and M_1 is off which is shown in Fig.2c, the same amount of energy E_c will dissipate to Z_o and completed one period of operations. If the switching frequency is f_s , the total power P_o delivered to Z_o is given by equation (1) provided that the on time of M_1 and M_2 is greater than t_c plus the charging time of C_3 and C_4 .

$$P_o = 2CV_i^2 f_s \quad (1)$$

Equation (1) shows that the output power is insensitive to Z_o and can be controlled by the switching frequency f_s , the supply voltage V_i or the capacitance of C_3 and C_4 and the maximum power that can delivery to the LC network during resonate startup is limited.

III. DETAILED OPERATION AND DESIGN PROCEDURES OF THE PROPOSED DIMMABLE BALLAST

Dimmable ballast can be realized by replacing Z_o with the LCR circuit described in section I. The circuit configuration is shown in Fig. 3a with a transformer T_1

added to increase the design freedom. The reflected equivalent model is shown in Fig. 3b. A design example is given in this section which uses the proposed topology to drive a T8 TLD36W/54 fluorescent lamp with dimming range from 100% to 25% of full lamp power. Only switching frequency control is applied for dimming operation for simplification. From equation (1), the output power is proportional to the switching frequency when the DC link voltage and the capacitance of C_3 and C_4 are fixed.

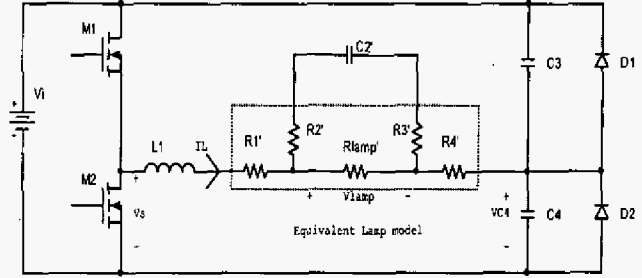


Fig.3a Proposed dimmable ballast configuration

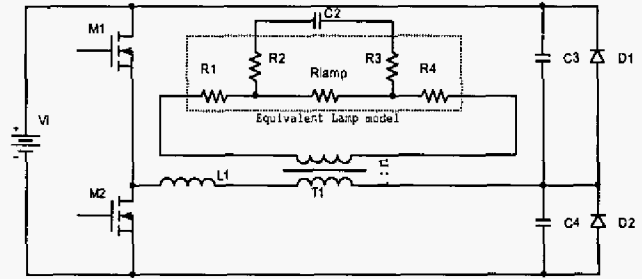


Fig.3b Equivalent reflected circuit proposed in Fig.3a

To avoid the switching frequency from entering the audible range, the switching frequency at full output power is set to be 110 kHz. This implies at 25% dimming operation, the switching frequency is 27.5 kHz. With V_i chosen to be 300VDC, C_3 and C_4 is then calculated by equation (1). 2nF is selected for C_3 and C_4 and the expected output power is 39.6W which is a little bit higher than the required power for T8 TLD36W/54 to account for the power loss of the ballast. The resonate frequency of the LC network formed by L_1 and C_2' is also set to 110 kHz for resonate lamp ignition. C_2 is chosen to provide sufficient heater current and if possible to set at a value such that the LCR network formed by L_1 , C_2 and R_{lamp} at full output power is nearly critically damped during the energy circulating period described in II to reduce voltage ringing. In this design example, the turn ratio of T_1 is 1: 1.67 and C_2 is chosen to be 2.35nF formed by two 4.7nF standard capacitor in series connection. The reflected capacitance C_2' is 6.55nF and L_1 is then calculated to be 300uH with resonant frequency = 113.5 kHz. Fig. 3c shows the expected waveforms of the proposed ballast at full output power

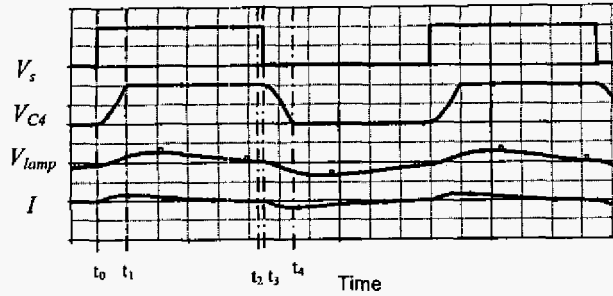


Fig.3c The expected operating waveforms of the designed ballast prototype at full output power

From t_0 to t_1 (M_1 is on and M_2 is off):

During this period, $V_s = V_i$ and C_4 is being charged up and C_3 is discharging. The reflected Lamp voltage V'_{lamp} is given by the equation (2).

$$LC_2 \frac{d^3 V'_{lamp}}{dt^3} + \frac{L}{R'_{lamp}} \frac{d^2 V'_{lamp}}{dt^2} + \left(1 + \frac{C_2}{2C_4}\right) \frac{dV'_{lamp}}{dt} + \frac{V'_{lamp}}{2C_4 R'_{lamp}} = 0 \quad (2)$$

$$\text{Where } V'_{lamp}(t_0) = 0, \quad \left. \frac{dV'_{lamp}}{dt} \right|_{t=t_0} = 0, \quad \left. \frac{d^2 V'_{lamp}}{dt^2} \right|_{t=t_0} = \frac{V_i}{LC_2}$$

The inductor current is given by equation (3).

$$I_L(t) = C_2 \frac{dV'_{lamp}}{dt} + \frac{V'_{lamp}}{R'_{lamp}} \quad (3)$$

and V_{C4} is given by equation (4)

$$V_{C4}(t) = \int_0^t C_2 \frac{dV'_{lamp}}{dt} + \frac{V'_{lamp}}{R'_{lamp}} dt \quad (4)$$

The turns ratio of transformer T_1 should be chosen such that the reflected capacitance C_2' and lamp resistance R'_{lamp} is large enough and small enough respectively to provide enough I_L to charge up C_4 to V_i well within the on period of M_1 .

From t_1 to t_2 (M_1 is on and M_2 is off)

C_4 is charged up to V_i and D_1 start to conduct. The energy stored in L_1 and C_2 continuously deliver to the Lamp. Since D_1 and M_1 are on, the LCR network changes to a parallel connected LCR network when the heater resistances are neglected. The energy delivery time t_c depends on the Q factor of the LCR network. For $Q \leq 0.5$, almost all power can deliver to the lamp during the on time of M_1 . During dimming operation, the lamp resistance increases and hence increases the Q factor. This increases the energy delivery time but fortunately, the switching frequency is reduced during dimming operation, so there is much more time reserved.

From t_2 to t_3 (M_1 is on and M_2 is off)

All energy has been delivered to the lamp.

From t_3 to t_4 (M_1 is off and M_2 is on)

The operation is similar to the period from t_0 to t_1 and will not be discussed here.

IV. EXPERIMENTAL RESULTS

A prototype was built according to the design parameters given in III. The parameters shown in Fig. 3c were measured from the prototype. Fig. 4a, Fig. 4b and Fig. 4c shows the waveforms at full lamp power, dimmed to 50% and 25% respectively. $CH1 = V_s$, $CH2 = V_{C4}$, $CH3 = V'_{lamp}$ and $CH4 = I_L$. Table 1 shows the measured results of some important parameters. The calculated input power according to equation (1) matches with the results. In addition the filament power tends to increase and compensate the decrease in lamp power which favors the dimming operation.

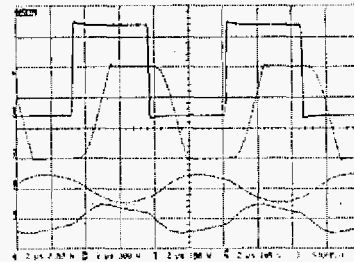


Fig.4a Maximum output power

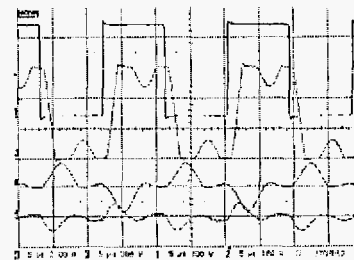


Fig.4b Dimmed to 50%

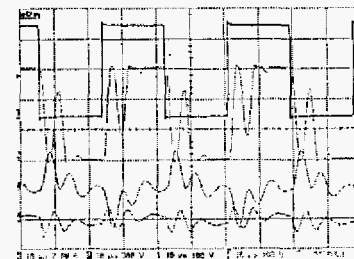


Fig.4c Dimmed to 25%

V. PRACTICAL CONSIDERATION

Commercial dimmable ballasts may require very low dimming levels (<10%). Our current demonstration shows that in order to achieve such low levels, the operating frequency or the DC link voltage of the ballast theoretically has to be very low, which causes audible problem and also the instability of the lamp. We therefore proposed a 2-dimensional dimming method which integrates with the topology described in section II [2] [3] in order to achieve ultra low dimming levels to the theoretical limit of 0%.

The basic idea is to introduce a duty cycle factor D , which is superimposed on the operating frequency as seen in Fig. 5. During the ON cycle period, normal switching operation continues. When OFF cycle begins, there is no switching operation, i.e. no power is delivering to the output.

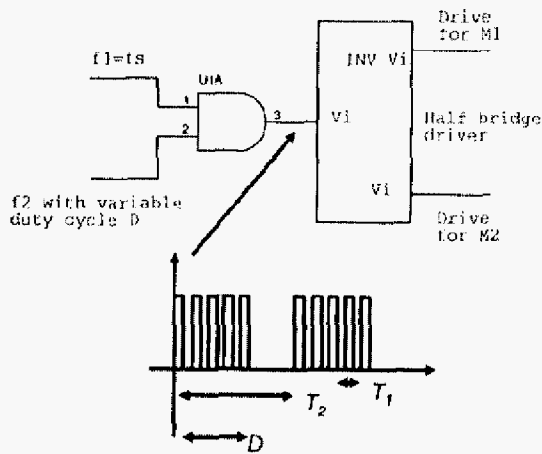


Fig.5 Simplified model with corresponding switching waveform

The output power is simply given by equation (5)

$$P_o = 2CV_i^2 f_s D \quad (5)$$

The duty cycle of the switching circuit gives an extra dimension to control the power. A high enough frequency is selected to avoid the fluorescent lamp turns off unintentionally, i.e. the frequency of the ON period is high enough so that the lamp does not realized for some part of times there are no energy delivered to it.

Input Voltage V_i	Input power	Calculated input power	Lamp power	Lamp rms	Filament current	Filament power	Total output power
300.0V	39.53W	39.6W	33W ($f_s = 110\text{KHz}$)	0.350Arms	0.178Arms	1.301W	34.302W
300.0V	19.60W	19.8W	16W ($f_s = 55\text{KHz}$)	0.160Arms	0.210Arms	0.798W	16.798W
300.0V	10.65W	9.9W	7.2W ($f_s = 27.5\text{KHz}$)	0.065Arms	0.244Arms	0.865W	8.065W

Table 1 Measured experimental results

VI. CONCLUSION

A topology with inherent output power regulation for implementation of dimming ballast is presented. The output power to the lamp can be controlled easily and accurately by controlling the switching frequency (verified experimentally), the DC link voltage or two capacitor values (verified mathematically) without the need of feedback control. The inherent power limiting features provides more reliable operation during resonant lamp ignition even without current sensing and fast response protection circuit. The calculation of output power to lamp is simple and insensitive to the lamp characteristics. All these features can greatly simplify the design and hence lowering the cost. A ballast prototype was built and some design considerations are stated. Waveforms and important parameters are measured and matched with the calculated results. The measured results also show that the filament power is rather constant during dimming operation which favors the lamp life. Dimming level consideration is discussed with a proposed solution to achieve ultra low dimming levels to the theoretical limit of 0%.

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