HF Multiresonant Electronic Ballast for Fluorescent Lamps with Constant Filament Preheat Voltage

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Abstract- **A novel HF multiresonant ballast for fluorescent lamps is analyzed, simulated, and tested experimentally. The ballast includes two major resonant networks. The lamp is driven by a parallel resonance arrangement that acts as a current source. During warm up the filaments are driven by a secondary winding of a series resonant inductor. The series resonance branch, which is active during warm up, feeds the filament and shorts out the voltage across the lamp. Simulation and experimental results suggest that the inherent features of the proposed ballast topology will prolong lamp life.**

1. INTRODUCTION

It is generally recognized that the life of a hot cathode fluorescent lamp is strongly dependent on the filaments' conditions during warm up and normal operation [1-4]. In particular:

1. The filament should be first heated to an optimum temperature (about 1000^0K). Too low or too high temperatures will damage the filaments' coating due to sputtering and/or evaporation.
2. During filament preheat, the voltage across the lamp should be kept as low as possible. A high voltage across lamp will initiate glow discharge that is considered harmful to filament.
3. Only after the filaments' optimum temperature is reached, the voltage of the lamp should rise to the ignition level.
4. Once the lamp is ignited, the forced filament excitation should be reduced since the filaments are designed to maintain the desired temperature when the nominal lamp current is passing through them.
5. The crest factor of the lamp's current should not exceed about 1.7 to avoid excessive current densities at the filaments' surfaces.

Aside from filament consideration, fluorescent lamp ballasts need to be designed for stable operation:

6. The ballast should behave as a current source to ensure stable operation. The classical criterion for stable operation (based on static VA curves) requires that the total incremental resistance (of ballast and lamp) be positive at the intersection of the lamp and ballast's VA curves [5].

Only by following all the requirements (points # 1-6) long lamp life can be achieved. It should be stressed though, that correct filament preheat and lamp ignition processes are the dominant factors in the design of high quality ballasts.

Two fundamentally different drivers could be used for filament preheating: a current or a voltage source [2]. An example of the current source approach is the parallel resonant converter topology used in many commercial HF electronic ballasts (Fig. 1) [4]. In this case, the filaments preheating current is identical to the current of the parallel capacitor (C_p). Preheating is accomplished by running the converter at a switching frequency that is close to the resonant frequency, forcing thereby the required current through the filaments [4]. The preheat switching frequency should be higher than the resonant frequency, so the required current can be reached with a lower voltage across C_p and hence with a lower lamp voltage (point #2 above). Operation above resonant frequency also helps to achieve soft switching in a half-bridge topology (Fig. 1).

In the parallel resonant topology, filament resistance plays little role in determining the filament current during preheat. This is due to the fact that the series impedance is much

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higher than the filament resistance. Or putting it in a different way, the voltage across the filaments is much lower than the drive voltage.

An alternative approach for filaments preheat is to drive the filament by a voltage source. This was investigated in [2] that proposes a push-pull topology. In that case, filament voltage-source drive was realized by an auxiliary converter that was run during the preheat period. Another important feature of the ballast proposed in [2] is a low (practically zero) lamp voltage during the preheat period (point #2 above). This was accomplished by turning off the main push-pull power inverter during preheat period. It was argued that a voltage source filament drive is a better choice considering the observed spread of filaments resistance between manufacturers and from batch to batch.

The push-pull configuration presented in [2] has two main drawbacks: (1) the relatively high voltage stresses on the main power switched (about $\pi/2$ times the bus voltage) and (2) the need for an extra inverter for filament preheat.

In this paper we present a novel topology that shares some of advantages of the push-pull ballast (voltage source filament drive and low lamp voltage during ignition) but does not have the problem of high voltage stress and the need for extra power switch for filament drive.

II. PROPOSED TOPOLOGY AND INTUITIVE ANALYSIS

The proposed ballast is based on the multiresonant converter of Fig. 2. It consists of a resonant network (L_1, C_1) powering the lamp and includes a series resonant circuit (L_2, C_2) that is applied during the warm-up period to drive the filaments. Capacitor C_b is used for DC blocking. Since a half-bridge drives the circuit, the voltage stress of the main switches is limited to the bus voltage V_b. The ballast can drive a number of lamps that are connected in series. Furthermore, since it behaves as a current source (as discussed below) it will maintain the same lamp current if loaded by any number of serially connected lamps - up to the maximum specified. The filaments are driven by low voltage windings that are coupled to inductor L_2. This inductor is placed in series with the C_2 capacitor to form a series resonant network used to generate the extra filament drive needed during warm up. The basic operation of the ballast during warm up and steady state will be first discussed by using an intuitive analysis based on approximate equivalent circuits. A more rigorous discussion is given in the next Section.

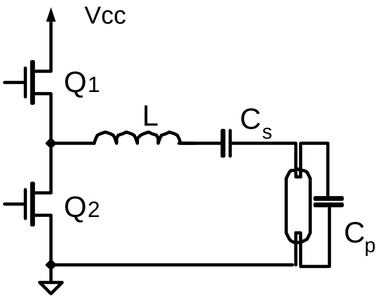


Fig. 1. The classical resonant converter used in many commercial HF ballasts for fluorescent lamps.

Assuming that $L_1C_1 > L_2C_2$ one can consider the circuit as having two major resonant frequencies:

$$\omega_{01} = \frac{1}{\sqrt{L_1C_1}} \tag{1}$$

$$\omega_{02} = \frac{1}{\sqrt{L_2C_2}} \tag{2}$$

Notice that:

$$\omega_{02} > \omega_{01} \tag{3}$$

The ballast is programmed to operate between the two frequencies. At warm up the switching frequency $f_{s.w}$ will be:

$$f_{s.w} \approx \omega_{02}/2\pi \tag{4}$$

and during normal operation the switching frequency f_s will be:

$$f_s \approx \omega_{01}/2\pi \tag{5}$$

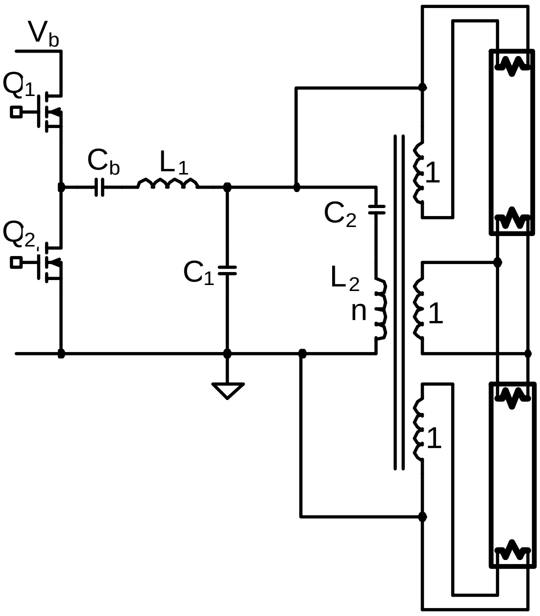


Fig. 2. Topology of proposed ballast based on a multiresonant resonant converter.

During warm-up (prior to ignition) the lamp load can be neglected and the equivalent circuit of the ballast can be represented by Fig.3a. Here we assume sinusoidal excitation (first harmonics approximation) that is justified by the fact that the operation is around resonant frequencies and that the quality factor of network (Q) is high. The filaments are reflected to the primary:

$$R_f^* = n^2 \frac{R_f}{n_f} \qquad (6)$$

where

R_f^* - reflected equivalent resistance of all filaments
R_f –filament resistance of a single lamp
n_f – number of filaments
n –turns ratio (see Fig. 2)

Under normal operating conditions, the lamps can be represented by a linear resistor R_{lamp} [6] as shown in Fig. 3b.

Further simplification of the equivalent circuit can be obtained by applying the fact that, in practical designs, the current via R_f^* will be smaller than the current via L_2. Under this assumption, the equivalent circuit during warm up can be represented by Fig. 4. When this circuit is driven by the switching frequency $f_{s.w}$ (4), L_2 and C_2 form a short circuit and V_{lamp} potential is close to zero. Consequently, little current is passing via C_1 and therefore $I_{in} \approx I_2$ (Fig. 4). Hence:

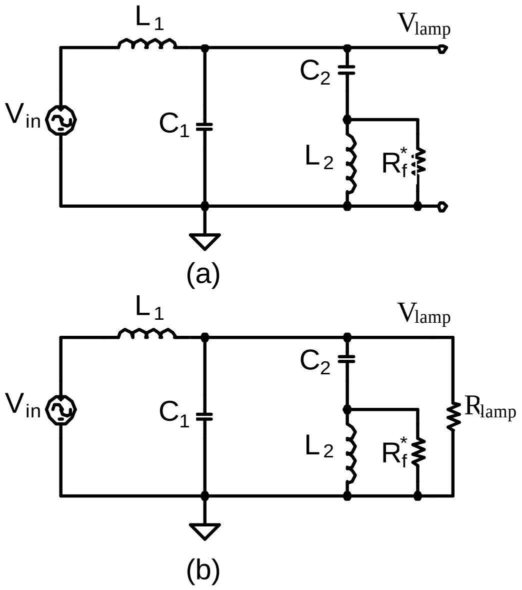


Fig. 3. Equivalent circuits of proposed ballast period; (b) under normal operating conditions.: (a) during warm-up

$$I_{in.w.rms} = \frac{V_{in\,(1)pk}}{\sqrt{2}\omega_{s.w}L_1} \qquad (7)$$

where

$I_{in.rms}$- rms input current of ballast during warm-up period

$V_{in\,(1)pk} = \frac{4}{\pi}V_{in}$ - peak of the first harmonic input voltage

V_{in}- amplitude of input voltage square wave $\omega_{s.w} = 2\pi f_{s.w}$

Therefore, the rms voltage across the L_2 ($V_{L2.w.rms}$) and the rms filaments voltage at the warm-up period ($V_{f.w.rms}$) will be:

$$V_{L2.w.rms} = I_{in.w.rms}\omega_{s.w}L_2 = \frac{V_{in\,(1)pk}}{\sqrt{2}}\frac{L_2}{L_1} \qquad (8)$$

$$V_{f.w.rms} = \frac{V_{L2.w.rms}}{n} = \frac{V_{in(1)pk}}{\sqrt{2}n}\frac{L_2}{L_1} \qquad (9)$$

The above approximate analysis suggests that the voltage across the lamps during warm-up is close to zero. A more rigorous examination should take into account the effect of the filament loading (Fig. 3b). The parallel combination of R_f^* and L_2 can be translated (at a given operating frequency, $f_{s.w}$) to a serial network (Fig. 5a) where:

$$R_f^{**} = \frac{R_f^*}{1+\left(\frac{R_f^*}{2\pi f_{s.w}L_2}\right)^2} \qquad (10)$$

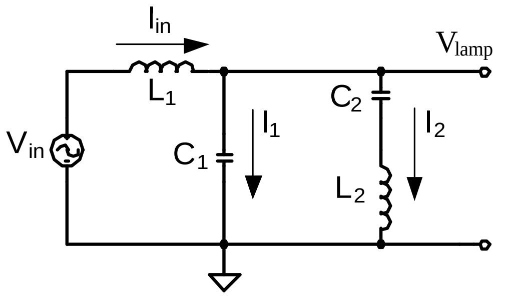


Fig. 4. Simplified equivalent circuit of proposed ballast during warm-up period.

and

$$L_2^{**} = \frac{L_2}{1+\left(\dfrac{2\pi f_{s.w} L_2}{R_f{}^*}\right)^2} \qquad (11)$$

If

$$f_{s.w} = \frac{1}{2\pi\sqrt{L_2^{**} C_2}} \qquad (12)$$

then the circuit of Fig. 5a reduces to Fig. 5b. It follows that the voltage across the lamps during ignition will not be zero but it can be made low by proper design.

During normal operation, the equivalent circuit (Fig. 3b) can be reduced to Fig. 6. C_{eq} represents the residual impedance of C_2L_2 at the normal operating frequency f_s. At this frequency, which is below the series resonant frequency, the combination L_2C_2 looks capacitive. Hence, parallel resonant is reached at a switching frequency ω^*_{01} that is be somewhat lower than ω_{01}:

$$\omega_{01}^* = \frac{1}{2\pi\sqrt{L_2(C_1 + C_{eq})}} \qquad (13)$$

For operation at ω^*_{01}, and neglecting second order effects, the circuit behaves at a current source. This can be shown by deriving the voltage across the load and dividing the expression by the resistance of the load. Following this procedure one will find that the parallel resonance network acts like a current source whose rms ($I_{cs.rms}$) will be:

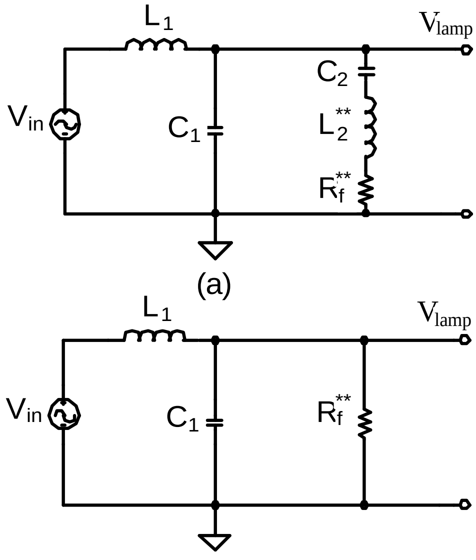


Fig. 5. Equivalent circuits of proposed ballast during warm-up period after conversion of L_2 and reflected filament resistance to a series network: (a) general case case; (b) when drive frequency matches the series resonance of $L^{**}_2C_2$.

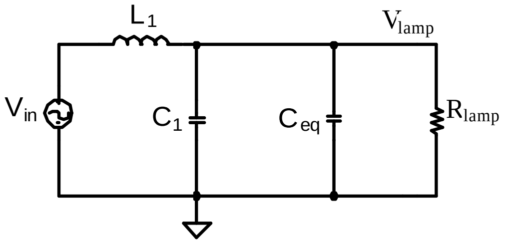


Fig. 6. Reduced equivalent circuit of proposed ballast under normal operating conditions. C_{eq} represents the residual impedance of C_2L_2 at the operating frequency f_s.

$$I_{cs.rms} = \frac{V_{in(1)pk}}{\sqrt{2}Z_r} \qquad (14)$$

where

$$Z_r = \sqrt{\frac{L_1}{C_2 + C_{eq}}} \qquad (15)$$

is the characteristic impedance.

Hence, once designed for a given lamp current, the ballast will deliver this current to one or more lamps connected in series.

III. ANALYSIS OF STEADY STATE CONDITIONS

From the approximate analysis given above it should become clear that derivation of accurate closed form equations for all modes of operation of the proposed ballast is complex – if not impossible. However, by applying mathematical (e.g. Mathcad) or simulation (e.g. SPICE) software packages can easily carry out numerical analyses. Nonetheless, since analytical expressions can provide a better insight into the operation of the ballast, we present below the derivation of the ballast's output characteristics. In the followings, the loading of the filaments is neglected.

During stable lamp operation the rms currents in the circuit's branches are (Fig. 3) :

$$I_{1rms} = \omega_s C_1 V_{lamp.rms} \qquad (16)$$

where

$$\omega_s = 2\pi f_s$$

$$I_{2rms} = \frac{V_{lamp.rms}}{\omega_s L_2} \frac{1}{1-(\dfrac{\omega_{02}}{\omega_s})^2} \qquad (17)$$

$$I_{lamp.rms} = \frac{V_{lamp.rms}}{R_{lamp}} \qquad (18)$$

The voltage across the inductor L_2 will be:

$$V_{L2rms} = \frac{V_{1amp.rms}}{1-(\frac{\omega_{02}}{\omega_s})^2} \qquad (19)$$

The ballast VA characteristic in per unit system can be obtained from a following expression:

$$V_{lamp.rms}{}^{*} = \frac{\sqrt{1-I_{lamp.rms}{}^{*2}(\frac{\omega_s}{\omega_{01}})^2}}{1-(\frac{\omega_s}{\omega_{01}})^2[1+\frac{C_2/C_1}{1-(\frac{\omega_s}{\omega_{02}})^2}]} \qquad (20)$$

where

$$V_{lamp.rms}{}^{*} = \frac{V_{lamp.rms}}{V_{in(1)rms}} \qquad (21)$$

$$I_{lamp.rms}{}^{*} = \frac{I_{lamp.rms}}{I_{bas}} \qquad (22)$$

$$I_{bas} = \frac{V_{in(1)rms}}{\sqrt{\frac{L_1}{C_1}}} \qquad (23)$$

IV. NUMERICAL CALACULATIONS, SIMULATIO AND EXPERIMANTAL

Bellow we consider a two lamp ballast having the following design parameters:

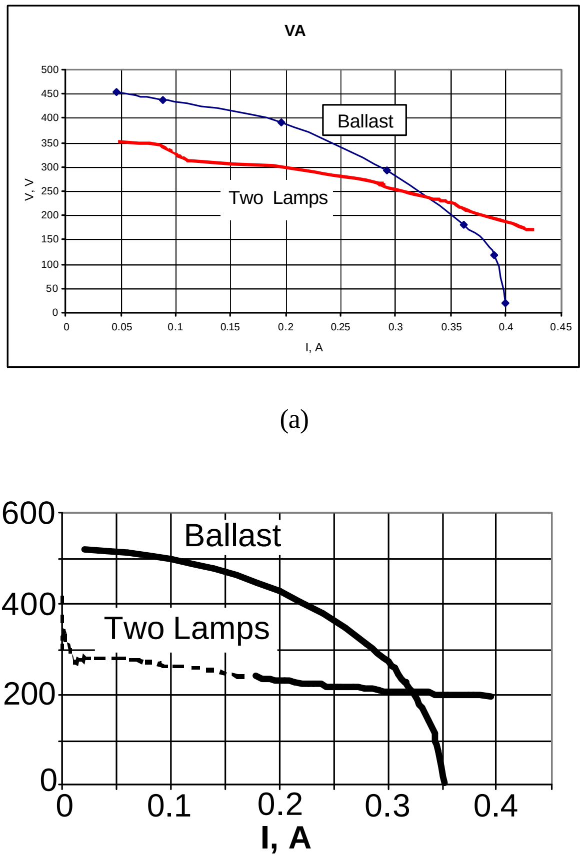
L_1=3.39mH; L_2=5.73mH;C_1=5.66nF; C_2=2.65nF.

V_{in}=200 V; f_s =23.5 kHz; $V_{lamp.rms}$=2*100 V; $I_{lamp.rms}$=0.34 A; $V_{f.w.rms}$=5.079 V

The output VA characteristic was calculated by (20) taking into account (1), (2), (21)-(23) and was measured experimentally. Good agreement was found between the results (Fig. 7).

The complete ballast system was simulated using Orcad (PSPICE) software. A behavioral model [7] that emulates the electrical characteristic at steady state was used to represent the lamp. The schematics (Fig. 8) of the simulation model includes the basic power stage, coupling to the filaments and analog behavioral dependent sources that emulate the lamps. Simulation and experimental results were found to be very close (Fig. 9). The crest factor of lamp current was found to be 1.6.

The start up sequence was measured on the experimental ballast loaded by two lamps. It was found that the lamp voltage prior to ignition was about 22 Vrms per lamp (Fig. 10).



(a)

(b)

Fig.7. VA characteristics of the ballast and of two lamps. (a) Calculated; (b) Measured.

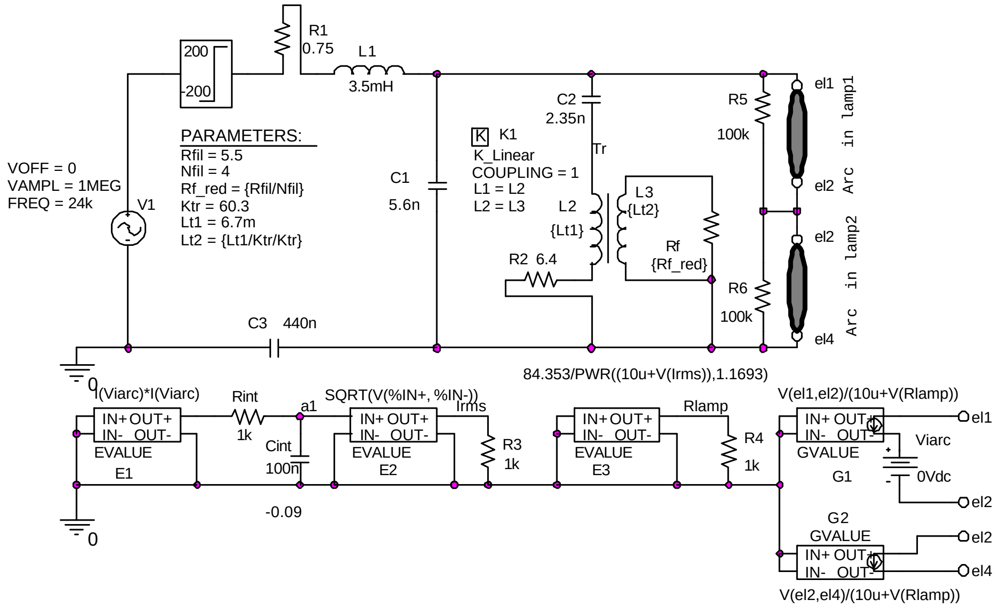
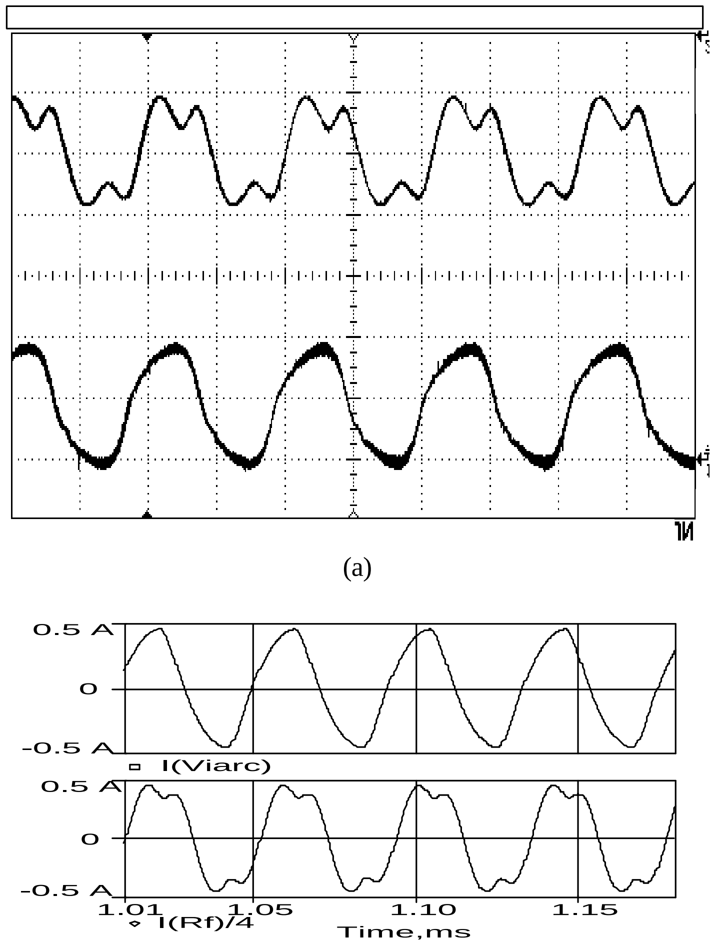


Fig.8. Orcad schematics for ballast and two lamps SPICE simulation model.



(a)

(b)

Fig.9. Lamp (upper traces) and filament (lower traces) currents. (a) Experiment. (b) Simulation. Upper traces: lamp current - 0.5A/div; Lower traces: filament current - 0.5A/div. Frequency: 23kHz.

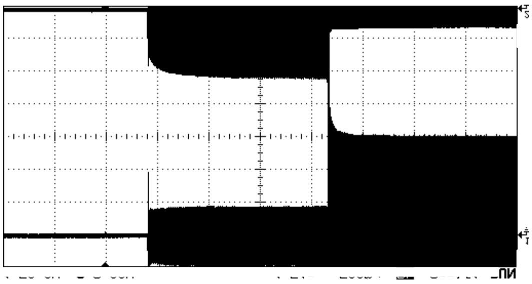


Fig.10. The process of warm up and ignition. Upper trace: lamp voltage - 50 V/div; Lower trace: filament voltage - 5 V/div. Horizontal scale: 0.5 S/div.

V. DISCUSSION AND CONCLUSIONS

The proposed multiresonant ballast topology proposed here provides a highly controlled warm up process. The filaments are fed by a voltage source with tight tolerance while the lamps' voltage during the preheat period is very low. The numerical calculation and the simulation results support the validity of the models developed in the paper. The two resonant network provide sufficient decoupling between the warm up stage and the steady operation so that each can be designed for optimum performance.

Four experimental ballasts (with 2 lamps each) were run continuously under the following conditions: ON time 5 minutes. OFF time 5 minutes. Up to the time of writing this paper the lamps were run for 8.5 months – a total of 36,500 switching. None of the lamps failed nor did any lamp show blackening around the filaments. We have also run in parallel two sets of four, 2-lamp ballast, of two reputable manufacturers. The design of these ballasts is based on a parallel resonant inverter with current fed filament warm up. Considerable blackening was found in practically all the lamps driven by these ballasts. Furthermore, after about 7 and then after 7.5 months of the continuous on-off experiment, two lamps driven by ballasts made by one manufacturer, failed (open filaments). Of course, blackening and failure may have not been due to the fact that a current source is used to drive the filament during warm up. However, it certainly points out to the fact that the design of the ballasts is deficient as far as warm up and ignition are concerned.

An extra benefit of the proposed topology is it's current source nature. This permits the serial connection of any number of lamps (up to a practical limit) so that one ballast can be used to drive one lamp or more. It was also found that the current source is strong enough to ignite the serially connected lamps even if one of the lamps has a broken filament. In such a case the lamp with the broken filament will be cold ignited while the good lamps will be subjected to the normal warm up sequence. This feature provides extra life a lamp fixture and will ease maintenance.

The number and stress of the power switching components are similar to the ones in ballast based on the parallel resonant topology. The extra performance is achieved by additional components (C_2 and L_2). However, the parallel resonant ballast will require an inductor and capacitor per lamp. That is, for ballasts for two lamps or more the bill of material of proposed ballast should not be significantly different from the parallel resonance ballast.

The results of this study suggest that the proposed multi-resonance inverter topology is an excellent design choice for fluorescent lamp ballasts. In practical applications a front-end power factor correction circuit will be required. This will insure compliance with the relevant standards and regulation and will also provide a stable bus voltage and hence constant operating conditions of the lamps.

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