

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.

Index Terms—Electronic ballast, fluorescent lamps, resonant inverter, SPICE simulation.

I. 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]–[6]. In particular, we have the following.

- 1) The filaments should be first heated to an optimum temperature (about 1000 K). 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 the 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 as a current source to ensure stable opera-

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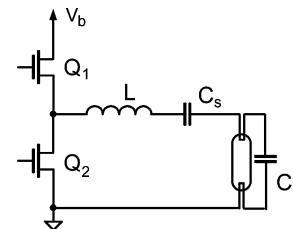


Fig. 1. Conventional resonant converter used in many commercial HF ballasts for fluorescent lamps.

tion. The conventional criterion for stable operation (based on static VA curves) requires that the total incremental resistance (of ballast and lamp) should be positive at the intersection of the lamp and ballast's VA curves [7].

Only by following all the aforementioned requirements, 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 series-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 series-resonant frequency, forcing thereby the required current through the filaments [4]. The preheat switching frequency should be higher than the resonant frequency, so that the required current can be reached with a lower voltage across C_p , and hence, across the lamp [aforementioned point 2)]. Operation above resonant frequency also helps to achieve soft switching in a half-bridge topology (Fig. 1).

In the conventional half-bridge topology (Fig. 1) as well as in other ballast circuits, such as the E-class amplifier topology [5], filament resistance plays little role in determining the filament current during preheat. This is due to the fact that the series impedance is much 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 approach was investigated in [2], where a push-pull topology was proposed. In that case, the filament voltage-source drive was realized by an auxiliary converter running during the preheat period. Another important feature of the ballast proposed in [2] is a low (practically zero) lamp voltage during the preheat period [aforementioned point

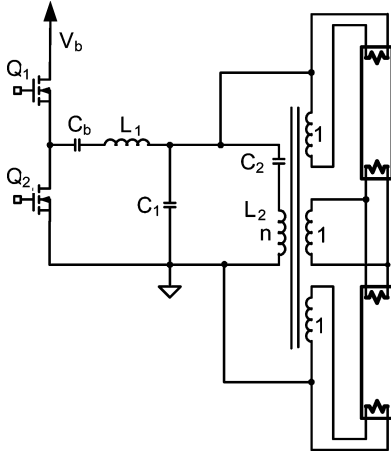


Fig. 2. Topology of proposed ballast based on a multiresonant converter.

2)]. This was accomplished by turning off the main push-pull power inverter during the 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 switches (about $\pi/2$ times the bus voltage) and 2) the need for an extra inverter for filament preheat. Similarly, the independent filament heating circuit presented in [6], which is connected to the center point of the half bridge, also requires a second inverter that increases the cost of the ballast.

In this paper, we present a novel topology that shares some 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 a 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 later), 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.

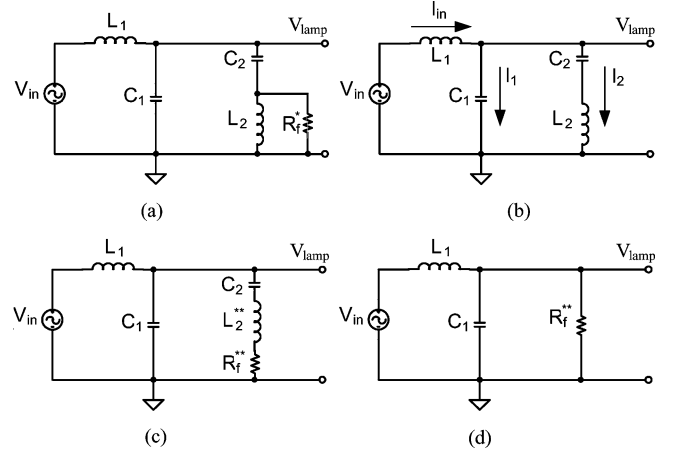


Fig. 3. Equivalent circuits of proposed ballast during warm-up period. (a) General model. (b) Neglecting the current via filament resistances of the lamps. (c) After conversion of L_2 and reflected filament resistance to a series network. (d) When drive frequency matches the series resonance of $L_2^*C_2$.

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

$$\omega_{01} = \frac{1}{\sqrt{L_1C_1}} \quad (1)$$

$$\omega_{02} = \frac{1}{\sqrt{L_2C_2}}. \quad (2)$$

Notice that

$$\omega_{02} > \omega_{01}. \quad (3)$$

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

$$f_{s,w} \approx \frac{\omega_{02}}{2\pi} \quad (4)$$

and during normal operation, the switching frequency f_s will be

$$f_s \approx \frac{\omega_{01}}{2\pi}. \quad (5)$$

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

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

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).

An intuitive insight into the general behavior of the circuit during warm-up can be obtained by assuming as a first-order

approximation that the current via R_f^* is smaller than the current via L_2 . This is justified by the fact that, for practical designs, one finds

$$R_f^* = n^2 \frac{R_f}{n_f} > X_{L_2} = \omega L_2. \quad (7)$$

Under this assumption, the equivalent circuit during warm-up can be represented by Fig. 3(b). In the case 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. 3(b)]. Hence

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

where

$I_{in,w,rms}$ 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 $V_{in} = V_b/2$;
 $\omega_{s,w} = 2\pi f_{s,w}$.

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

$$V_{L_2,w,rms} = I_{in,w,rms} \omega_{s,w} L_2 = \frac{V_{in(1)pk}}{\sqrt{2}} \frac{L_2}{L_1} \quad (9)$$

$$V_{f,w,rms} = \frac{V_{L_2,w,rms}}{n} = \frac{V_{in(1)pk}}{\sqrt{2}n} \frac{L_2}{L_1}. \quad (10)$$

The earlier 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. 4]. 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. 3(c)] where

$$R_f^{**} = \frac{R_f^*}{1 + (R_f^*/2\pi f_{s,w} L_2)^2} \quad (11)$$

and

$$L_2^{**} = \frac{L_2}{1 + (2\pi f_{s,w} L_2/R_f^*)^2}. \quad (12)$$

If

$$f_{s,w} = \frac{1}{2\pi \sqrt{L_2^{**} C_2}} \quad (13)$$

then the circuit of Fig. 3(c) reduces to Fig. 3(d). It follows that the voltage across the lamps during ignition will not be zero, but it can be made low by proper design.

Under normal operating conditions, following the preheat stage, the lamps can be represented by a linear resistor R_{lamp} [8], as shown in Fig. 3(a). Neglecting the current via R_f^* that is much smaller than the current via L_2 we reduce the equivalent circuit [Fig. 3(a)] to Fig. 4. C_{eq} represents the residual impedance of $C_2 L_2$ at the normal operating frequency f_s . At this frequency, which is below the series resonant frequency, the combination

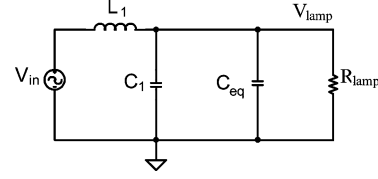


Fig. 4. Equivalent circuit of proposed ballast under rated operating conditions; neglecting the current via filament resistances and representing by C_{eq} the residual impedance of $C_2 L_2$ at the operating frequency f_s .

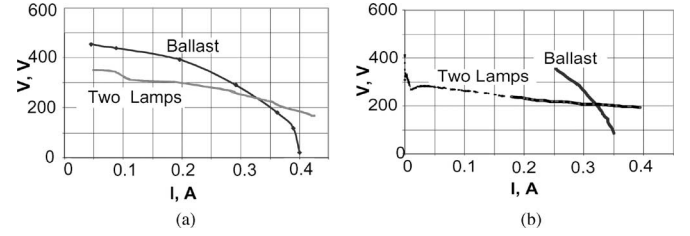


Fig. 5. VA characteristics of the ballast and of two lamps. (a) Calculated. (b) Measured.

$L_2 C_2$ looks capacitive

$$\frac{1}{\omega_s C_{eq}} = \frac{1}{\omega_s C_2} - \omega_s L_2 \quad (14)$$

where $\omega_s = 2\pi f_s$.

Hence, resonance is reached at a switching frequency ω_{01}^* that is somewhat lower than ω_{01}

$$\omega_{01}^* = \frac{1}{\sqrt{L_1(C_1 + C_{eq})}}. \quad (15)$$

For operation at ω_{01}^* and neglecting second-order effects, the circuit behaves as 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 resonant network acts like a current source whose rms ($I_{cs,rms}$) will be

$$I_{cs,rms} = \frac{V_{in(1)pk}}{\sqrt{2}Z_r} \quad (16)$$

where

$$Z_r = \sqrt{\frac{L_1}{C_1 + C_{eq}}} \quad (17)$$

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 earlier, it should become clear that the 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, one can easily carry out numerical analyses. Nonetheless, since analytical expressions can provide a better insight into the operation of the

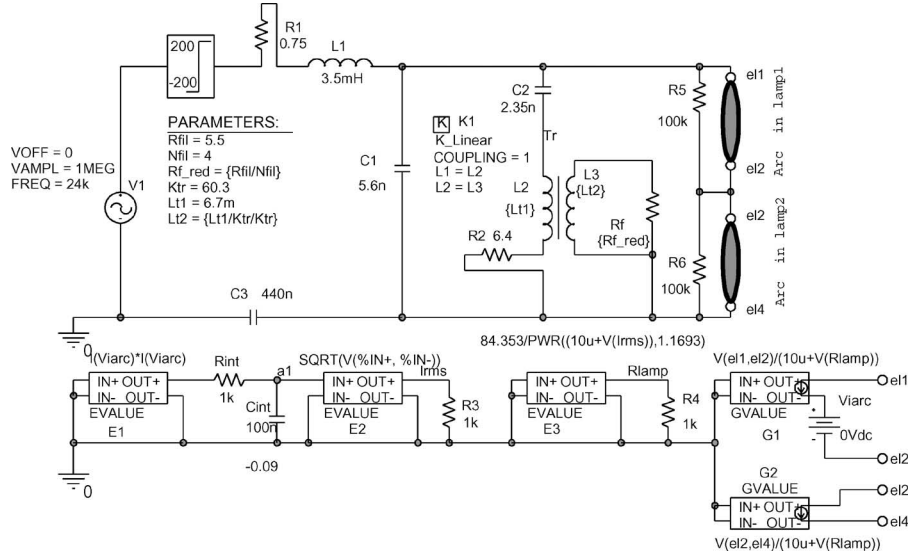


Fig. 6. PSPICE/Orcad schematics for ballast and two lamps SPICE simulation model.

ballast, we present later the derivation of the ballast's output characteristics. In the following, the loading of the filaments is neglected.

During stable lamp operation and assuming that $R_f^* = \infty$, the rms currents in the circuit's branches are [Fig. 3(a)]

$$I_{C_1.rms} = \omega_s C_1 V_{lamp.rms} \quad (18)$$

$$I_{C_2.rms} = \frac{V_{lamp.rms}}{\omega_s L_2} \frac{1}{1 - (\omega_{02}/\omega_s)^2} \quad (19)$$

$$I_{lamp.rms} = \frac{V_{lamp.rms}}{R_{lamp}}. \quad (20)$$

The voltage across the inductor L_2 will be

$$V_{L_2.rms} = \frac{V_{lamp.rms}}{1 - (\omega_{02}/\omega_s)^2}. \quad (21)$$

The ballast VA characteristic in per unit system can be obtained from the expression

$$V_{lamp.rms}^* = \frac{\sqrt{1 - I_{lamp.rms}^2 (\omega_s/\omega_{02})^2}}{1 - (\omega_s/\omega_{01})^2 \left[1 + \frac{C_2/C_1}{1 - (\omega_s/\omega_{02})^2} \right]} \quad (22)$$

where

$$V_{lamp.rms}^* = \frac{V_{lamp.rms}}{V_{in(1).rms}} \quad (23)$$

$$I_{lamp.rms}^* = \frac{I_{lamp.rms}}{I_{bas}} \quad (24)$$

$$I_{bas} = \frac{V_{in(1).rms}}{\sqrt{L_1/C_1}}. \quad (25)$$

IV. NUMERICAL CALCULATIONS, SIMULATION, AND EXPERIMENTAL

Next we consider a two-lamp ballast (Fig. 2) having the following design parameters:

$$L_1 = 3.39 \text{ mH}; \quad L_2 = 5.73 \text{ mH}; \quad C_1 = 5.66 \text{ nF};$$

$$C_2 = 2.65 \text{ nF}; \quad V_{in} = 200 \text{ V}; \quad f_s = 23.5 \text{ kHz};$$

$$V_{lamp.rms} = 2 \times 100 \text{ V}; \quad I_{lamp.rms} = 0.34 \text{ A}; \quad V_{f.w.rms} = 5.079 \text{ V}.$$

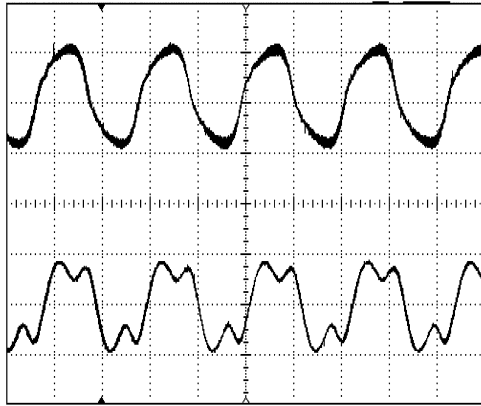
The output VA characteristic (Fig. 5) was calculated by (22), taking into account (1), (2), and (23)–(25), and was measured experimentally. Good agreement was found between the measured and calculated results (Fig. 5).

The complete ballast system was simulated using Orcad (PSPICE) software. A behavioral model [9] that emulates the electrical characteristic at steady state was used to represent the lamps. The schematics of the simulation model (Fig. 6) includes the basic power stage, coupling to the filaments, and analogue behavioral dependent sources that emulate the lamps. Simulation and experimental results were found to be very close (Fig. 7). The crest factor of lamp current was found to be 1.6.

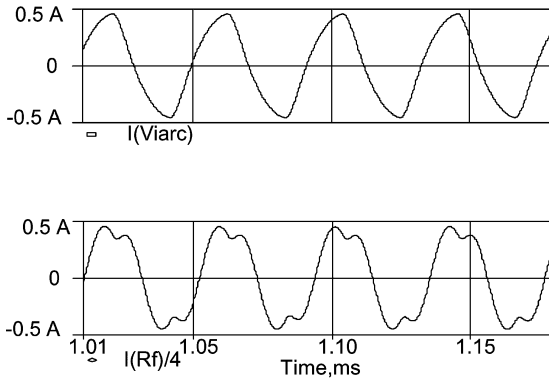
The startup sequence was measured on the experimental ballast loaded by two lamps. It was found that the lamp voltage prior to ignition was about 22 Vrms per lamp (Fig. 8).

V. DISCUSSION AND CONCLUSIONS

The proposed multiresonant ballast topology 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 networks provide sufficient decoupling between the warm-up stage and the steady



(a)



(b)

Fig. 7. Lamp (upper traces) and filament (lower traces) currents. (a) Experiment. (b) Simulation. Vertical scale (both traces), 0.5 A/div; horizontal scale, 0.05 ms/div; frequency, 23 kHz.

operation, so that each can be designed for optimum performance.

Four experimental ballasts (with two lamps each) were run continuously under the following conditions: ON time 5 min. OFF time 5 min. Up to the time of writing this paper, the lamps were run for 18 months—a total of 75 000 switching cycles. None of the lamps failed nor did any lamp show blackening around the filaments (Table I). We have also run in parallel two sets of four 2-lamp ballasts, of two reputable manufacturers. The design of these ballasts is based on a parallel resonant inverter with current fed filament at warm-up. Considerable blackening was found in practically all the lamps driven by these ballasts (Fig. 9). 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 not have 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 its 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

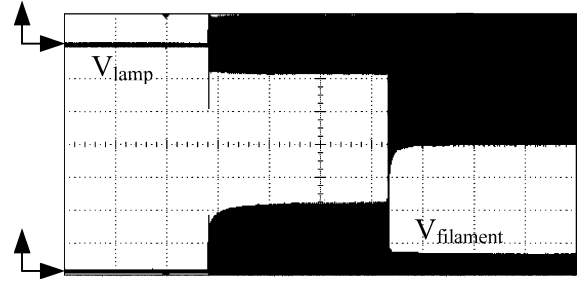


Fig. 8. Process of warm-up and ignition. Upper trace, lower part of the lamp voltage—50 V/div. Lower trace, upper part of the filament voltage—5 V/div. Horizontal scale, 0.5 s/div.

TABLE I
COMPARISON OF BALLASTS PERFORMANCE

| Running time, months | Manufacturer | | | | | | | | | | | | |
|----------------------|--------------|---|---|---|-------------|---|---|---|-------------------|---|---|---|--|
| | A | | | | B | | | | Proposed topology | | | | |
| | Ballast No. | | | | Ballast No. | | | | Ballast No. | | | | |
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | |
| 5.8 | | | | X | | | | | | | | | |
| 6 | X | | | X | | | | | | | | | |
| 7 | O | | | X | | | | | | | | | |
| 7.5 | | | | O | | | | | | | | | |
| 13 | X | | X | X | X | | | | | | | | |
| 18 | X | X | X | X | X | X | X | X | X | | | | |

X – blackening; O – filament break (open).

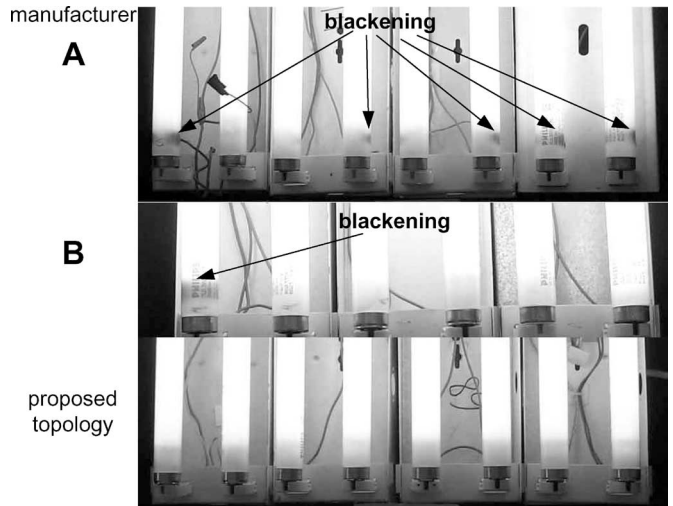


Fig. 9. Lamp-end blackening after 60 K on-off cycles (13 months). First and second rows above: lamps driven by commercial ballasts (Companies A and B) that apply current fed filament warm-up. Bottom row: lamps driven by proposed ballast. See text for further details.

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 to a lamp fixture and will ease maintenance.

The number and stress of the power switching components are similar to the ones in a 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 multiresonant 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.

APPENDIX DESIGN GUIDELINES

The following procedure is suggested for ballast design.

Input data:

Input square wave voltage— V_{in} ;

Rated switching frequency (HB frequency)— f_s ;

Lamp data:

Lamp nominal current— $I_{lamp,rms}$, nominal voltage— $V_{lamp,rms}$; filaments preheating voltage— $V_{f.w,rms}$; filaments nominal voltage— $V_{f.st,rms}$.

Choose first resonant frequency of system: $f_1 = (1.1 \div 1.2)f_s$.

Choose second resonant frequency of system: $f_2 = 2f_1$.

Calculate secondary partial resonant frequency

$$f_{02} = \frac{f_1 + f_2}{2} = \frac{3}{2}f_1.$$

Set preheat frequency:

$$f_{s.w} = f_{02}.$$

Calculate turns ratio [from (21)]

$$n = \frac{V_{lamp,rms}}{V_{fil,st,rms}} \frac{f_s^2}{|f_s^2 - f_{s.w}^2|}.$$

Calculate inductors ratio [from(9)]

$$A_L \equiv \frac{L_1}{L_2} = \frac{0.9}{n} \frac{V_{in}}{V_{f.w,rms}}.$$

Calculate Inductor L_1 [from (22) and definitions (1),(2)]

$$L_1 = 0.159 \frac{V_{lamp,rms}/I_{lamp}}{f_s} \times \sqrt{0.81 \left(\frac{V_{in}}{V_{lamp,rms}} \right)^2 - \left(1 - \frac{f_s^2 f_{s.w}^2}{f_1^2 f_2^2} + A_L \frac{f_s^2}{f_s^2 - f_{s.w}^2} \right)^2}.$$

Calculate inductor L_2

$$L_2 = \frac{L_1}{A_L}.$$

Calculate capacitor C_2 [from (2)]

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

Calculate capacitor C_1 by applying the relationship between full system resonant frequencies and partial resonances (1), (2):

$$f_{01}^2 = \frac{f_1^2 * f_2^2}{f_{02}^2} = \frac{f_1^2 * f_2^2}{f_{s.w}^2} \Rightarrow C_1 = \frac{1}{(2\pi)^2} \frac{1}{L_1} \frac{f_{s.w}^2}{f_1^2 f_2^2}$$

Example

Input data:

$$V_{in} = 200 \text{ V}_{rms}; \quad f_s = 23.5 \text{ kHz};$$

$$V_{lamp,rms} = 2 \times 100 \text{ V}; \quad I_{lamp} = 0.34 \text{ A}; \quad V_{f.w,rms} = 5.079 \text{ V};$$

$$V_{f.st,rms} = 1.646 \text{ V}.$$

Output data—ballast parameters:

$$L_1 = 3.4 \text{ mH}; \quad L_2 = 5.73 \text{ mH}; \quad C_1 = 5.5 \text{ nF}; \quad C_2 = 2.65 \text{ nF};$$

$$n = 61.$$

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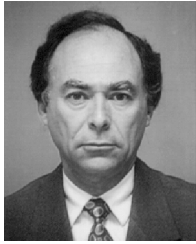
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