DESIGNING DIMMABLE ELECTRONIC BALLASTS WITH FREQUENCY CONTROL

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Abstract **– Two-stage high power factor dimmable electronic ballasts for fluorescent lamps are worldwide accepted as the industry standard due to its robustness and absence of non linear electrophoresis phenomenon. Despite of the design simplicity in comparison to the single-stage one, the design of the resonant filter and the problem of adequate filament heating, in the opinion of the authors, are not completely analyzed in the publications. A design method for frequency controlled dimmable electronic ballast proposed in the paper takes into account the filaments heating for the case of the most popular LCC resonant filter, while the filament heating is performed by the parallel capacitor of the filter. The calculated results are verified by experimental tests of a laboratory prototype circuit.**

Keywords **– design, dimming, electronic ballasts, fluorescent lamps.**

I. INTRODUCTION

Dimmable electronic ballasts (DEB) for fluorescent lamps (FL) feeding permit to reduce the electric power consumption and to offer more lighting comfort for the users, besides the advantages of non dimmable electronic ballasts [1], [2]. There are four basic methods for FL dimming: 1) frequency control, that is, by the switching frequency (f_S) variation; 2) voltage control, that is, by *DC* bus voltage variation; 3) duty cycle variation; 4) switching one of the resonant filter capacitors. In practice, it is possible to combine some of these methods to achieve higher efficiency. The frequency control dimming is the most popular method due to simplicity of the DEB circuit. The main disadvantage of this method is reduced ballast efficiency at low levels of FL power [3], [4]. Voltage control dimming is the most efficient one throughout wide dimming range, but the DEB circuit is more complex due to PFC with variable voltage output.

Dimming by duty cycle variation [6] has the advantage of constant f_S, however the half bridge inverter looses soft-switching when duty cycle is reduced below 23% [18]. Another disadvantage is non linear electrophoresis phenomenon which eliminates the light output of one of the FL extremities. A possible solution is the *Toggled Duty Cycle Operation* method proposed in [7], however it makes impossible single-stage high PFC implementation.

Dimming by switching of one of the resonant filter capacitors, a recently proposed method has some disadvantages too. Thus, the DEB described in [8], even keeping 96% power factor and 80% efficiency in wide dimming range (100% to 10%), presents the problem of non linear electrophoresis. The DEB operates in closed-loop, but the stability has not been analyzed. The same dimming method was used in [9], reporting relatively narrow dimming range (100% to 50%), besides the circuit utilizes four power switches. Section II presents some analysis of frequency controlled electronic ballasts. A LCC resonant filter design is introduced in Section III. Section IV describes the obtained experimental results and compares it with the theoretical ones and, finally, Section V includes some conclusions about the proposed design method.

II. FREQUENCY CONTROL DIMMING

Fig. 1 shows a generic diagram of frequency controlled DEB and the bus voltage V_{DC} is constant.

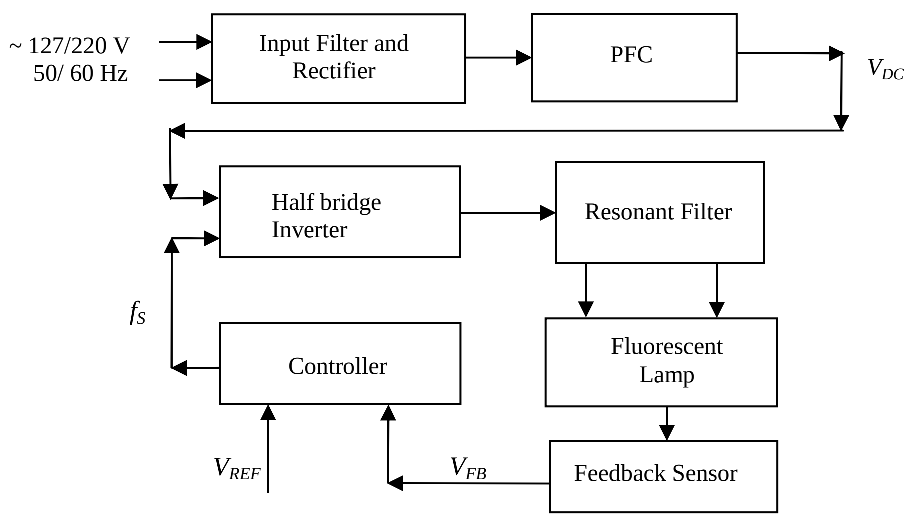

Fig. 1. Generic diagram of frequency controlled DEB; V_{REF} is the reference voltage and V_{FB} is the feedback one.

The diagram represents a half-bridge series resonant parallel-load inverter, which includes a LCC resonant filter, controlled in closed-loop.

Closed-loop control is required to obtain a stable operation in wide dimming range. As a feedback sensor, a resistor in series com a FL can be used. One another control scheme, proposed in [10], is a PLL (Phase Lock Loop), based on the phase shift between the inverter output voltage and the resonant inductor current. This case, a resistor in series with the inverter inferior switch source serves as a resonant current sensor.

Fig. 2 is an equivalent circuit of the series resonant parallel-loaded inverter.

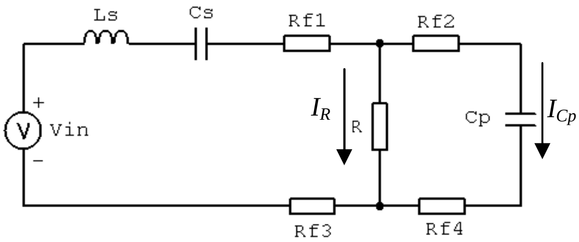

Fig. 2. Equivalent circuit of a series resonant parallel-loaded inverter.

In Fig. 2, the resistances R_{f1}, R_{f2}, R_{f3} and R_{f4} model the FL filaments, while R stands for the FL equivalent resistance and is a function of FL arc power. For the sake of simplicity, the input V_{in} is supposed to be the V_{DC} amplitude square-wave voltage with 50% duty-cycle. The filaments resistances can be neglected sense their values are more than 20 times smaller than the impedances of the reactive components of the resonant filter. This way, the input to output transfer function is:

$$\frac{V_R(s)}{V_{in}(s)} = \frac{R \cdot C_S \cdot s}{L \cdot C_P \cdot R \cdot C_S \cdot s^3 + L_S \cdot C_S \cdot s^2 + R \cdot (C_P + C_S) \cdot s + 1} \tag{1}$$

where $V_R(s)$ and $V_{in}(s)$ are the Laplace transformations of the output and input voltages, respectively; s stands for the Laplace transformation variable.

From (1), the n-th output voltage can be expressed as following:

$$V_{R,n} = \frac{V_{in,n}}{\left[\left(\frac{C_P + C_S}{C_S} n^2 \omega^2 L_S C_P\right)^2 + \left(\frac{1}{n\omega C_S R} - \frac{n\omega L_S}{R}\right)^2\right]^{1/2}} \tag{2}$$

where $V_{R,n}$ is the amplitude of the FL n-th harmonic voltage; $V_{in,n}$ is the amplitude of the inverter output n-th harmonic voltage, $\omega = 2 \cdot \pi \cdot f_S$.

Supposing the resonant filter has high quality factor, resonant filter design considers only the fundamental harmonic. The fundamental FL current harmonic, modeling the FL by a resistor, is

$$I_{R,1} = \frac{V_{R,1}}{R} \tag{3}$$

Thus, the LF power is:

$$P_{R,1} = \frac{V_{R,1} \cdot I_{R,1}}{2} = \frac{V_{R,1}^{\,2}}{2\,R} \tag{4}$$

From (2) and (4), it can be deduced the FL rated power $P_{R,nom}$:

$$P_{R,nom} = \frac{V_{in,1}^{\,2}}{2R\left[\left(\frac{C_P + C_S}{C_S}\ \omega^2 L_S C_P\right)^2 + \left(\frac{\omega L_S}{R} - \frac{1}{\omega R C_S}\right)^2\right]} \tag{5}$$

Finally, the following equation defines the L_S values:

$$\left(\omega^4 C_P^{\,2} + \frac{\omega^2}{R^2}\right) L_S^{\,2} - \left[2\left(\frac{C_P + C_S}{C_S}\right)\omega^2 C_P + \frac{2}{R C_S}\right] L_S - \\ - \left(\frac{C_P + C_S}{C_S}\right)^2 + \frac{1}{\omega^2 R^2 C_S^{\,2}} - \frac{V_{in,1}^{\,2}}{2\,R\,P_{R,nom}} = 0 \tag{6}$$

From (6), two values of L_S can be derived and the positive one should be chosen for the resonant filter design.

Analyzing (5) one can conclude that the FL power depends on input voltage V_{in}, resonant filter parameters, FL equivalent resistance and f_S. Here only the frequency control dimming is discussed, assuming that the resonant filter input voltage is constant and defined by the PFC stage, generally between 380 and 400 V DC for the 220 V RMS mains.

III. LCC RESONANT FILTER DESIGN

A. Discussion of the Previously Proposed Design Methods

Several papers have discussed LCC resonant filter design, however the FL filament power has not been considered [12] or, as in [11], an inadequate filament thermal has been applied. However, FL filament heating directly influences the lamp life, because too little heat reduces lamp life due to sputtering, while too much heat does it due to a high rate of the filament emission-mix evaporation [14].

In the case of LCC filter, as shown in Fig. 2, there are two currents in the FL filaments, I_R and I_{Cp}. In [13], a filament thermal model has been reported as following:

$$P_e = \frac{1}{3} \cdot (I_R)^2 \cdot R_e + (I_{Cp})^2 \cdot R_e \tag{7}$$

where P_e is the filament power, R_e is the filament resistance. However, as related in [14], when no separate heating circuit is provided, most of the filament heating arises from electron bombardment during the half-cycle when the filament is acting as anode.

Fig. 3 shows a diagram of filament heating, as presented in [15], which includes some additional heating circuit. That publication affirms that the heating only by LCC, as shown in Fig. 2, is not adequate, however without any proof. The currents I_{LL} and I_{LH} are not equals and its values depend on the hot-spot position and on discharge current I_d.

The method SoS (*Sum of the Squared lead wire currents*) permits to evaluate the efficiency of filament heating schemes through the following equations [15]:

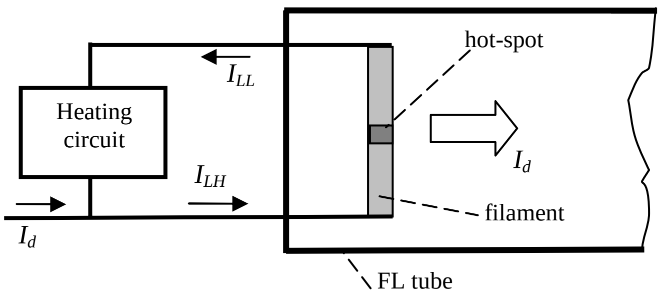

Fig. 3. Filament heating diagram [15].

$$\left(I_{LL}^2 + I_{LH}^2\right)_{MIN} = X - Y \cdot I_d$$
$$\left(I_{LL}^2 + I_{LH}^2\right)_{TARGET} = X - z \cdot Y \cdot I_d \qquad (8)$$

where X, Y and Z are the constants defined by the FL manufacture, subscribe *MIN* stands for the minimum value, *TARGET* is the best value.

The equations (8) can be utilized for LCC filter design, when no additional heating circuit is used, so C_P conducts I_{LL}. FL in high frequency (above 20 kHz) acts as a resistor, consequently the current I_d has 90° phase lag in the relation to I_{LL}. This way, the value of C_P can be calculated as:

$$I_{LH}^2 + I_{LL}^2 = X - z \cdot Y \cdot I_d \qquad (9)$$

$$I_{LH}^2 = I_d^2 + I_{LL}^2 \qquad (10)$$

$$I_{Cp} = I_{LL} = \sqrt{\frac{(X - z \cdot Y \cdot I_d - I_d)^2}{2}} \qquad (11)$$

$$V_L = I_{Cp} \cdot \omega \cdot C_P \qquad (12)$$

where V_L is the FL rated voltage.

Finally

$$C_P = \frac{V_L}{\omega \cdot I_{Cp}} \qquad (13)$$

As the authors have not had the *X, Y* and *z* information, an approximated was applied. The method uses the FL tube temperature to evaluate the efficiency of the filament heating circuit. Fig. 4 shows the scheme used to heat the FL filament without discharge arc.

Experiments were performed with a TLD T8/32W Philips FL. The cold filament resistance R_C was 3 Ω and after heating by 5.5 V voltage source the hot resistance R_H was 12.8 Ω, thus resulting in R_H/R_C ratio equals to 4.25. This value corresponds to the filament temperature of about 1000°C, which is considered the optimal one [14] for thermo ionic emission. At 27°C ambient temperature, the temperature of the tube filament region was measured as 56°C in 30 minutes after beginning. Later this value was used for filament heating evaluation in dimming operation.

B. LCC Resonant Filter Design Procedure

The design procedure of the LCC resonant filter is summarized as follows.

1. Choose V_{CC} value. If boost PFC is used and the mains is 220 V, V_{DC} can be chosen between 380 and 400 V. Choose $f_{S,\,MIN}$, for example, above 42 kHz to avoid interference with IR remote controls [16].

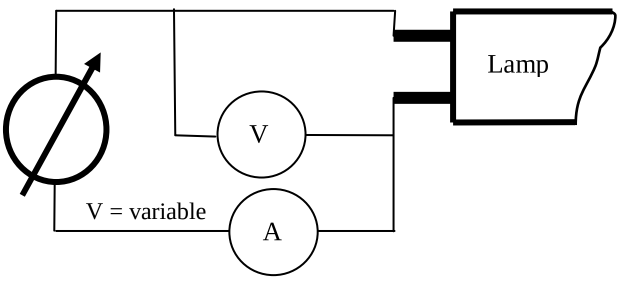

Fig. 4 Scheme used to heat the FL filament.

2. Choose I_{Cp} value at $f_{S,MIN}$, $I_{Cp,\,MIN}$. Initially, this value can be chosen equal to 0.15 A. The filament current measured during the test (Fig. 4) was 5.5/12.8=0.43 A without the arc, however, when the FL is on, additional filament heating occurs due to the discharge current. This way, for TLD T8/32W the value of $I_{Cp,\,NOM}$ is 0.43 A.

3. Calculate C_P: $$C_P = \frac{I_{Cp,MIN}}{2 \cdot \pi \cdot f_{S,MIN} \cdot V_{100\%}} \qquad (15)$$

where $V_{100\%}$ is the FL RMS rated voltage.

4. Choose C_S between 100 and 220 nF. Simulations have shown that any C_S value from this range almost does not modify the dimming curve, while L_S varies in about 5%.

5. Calculate L_S as in (6).

6. Simulate a dimming curve using (5).

7. Using $I_{Cp}(s)/V_{in}(s)$ transfer function, simulate $I_{Cp}(f_S)$ curve. This transfer function is

$$\frac{I_{Cp}(s)}{V_{in}(s)} = \frac{C_P C_S s^2}{R C_P C_S L_S s^3 + C_S L_S s^2 + R(C_P + C_S)s + 1} \qquad (16)$$

8. Find a $f_{S,\,MAX}$ value at which I_{Cp} achieve their maximum value, $I_{Cp,\,MAX}$. At $f_{S,\,MAX}$ the FL will be dimmed till the lowest power level. If $I_{Cp,\,MAX}$ is higher than $0.9 \cdot I_{Cp,\,NOM}$ than reduce $I_{Cp,\,MIN}$. If $I_{Cp,\,MAX}$ is lower than $0.7 \cdot I_{Cp,\,NOM}$ than increase $I_{Cp,\,MIN}$. The coefficients 0.7 and 0.9 have been obtained experimentally to guarantee the desired filament temperature at the minimum dimming level.Go to step 3.

9. Implement the DEB prototype and test the temperature of the tube in dimming operation.

A MATLAB program was developed to execute the design procedure, considering the first three harmonics. Fig. 5 shows the dimming curve obtained for TLD T8/32W lamp with the following resonant filter: Ls = 1.6 mH; Cs = 220 nF; Cp = 5.8 nF.

Fig. 6 shows the RMS C_P current in dimming. The value of $I_{Cp,\,MIN}$ has been adjusted to 0.2 A which resulted in $f_{S,MAX}$ =72.5 kHz and $I_{Cp,\,MAX}$ = 0.395 A.

Fig. 7 shows the L_S RMS and peak currents in dimming.

The L_S RMS current should be used to select an inductor winding wire, however the highest peak current of 0.62 A is less than the peak L_S current during ignition, I_{IGN}. The latter is calculated as follows:

$$I_{IGN} = V_{IGN} \cdot 2 \cdot \pi \cdot f_{IGN} \cdot C_P \qquad (16)$$

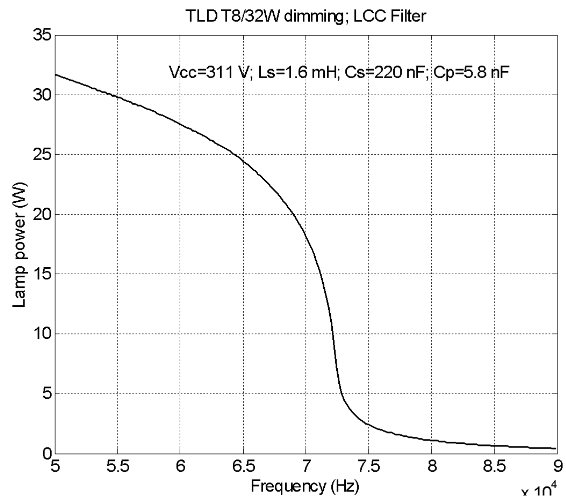

Fig. 5. Simulated dimming curve.

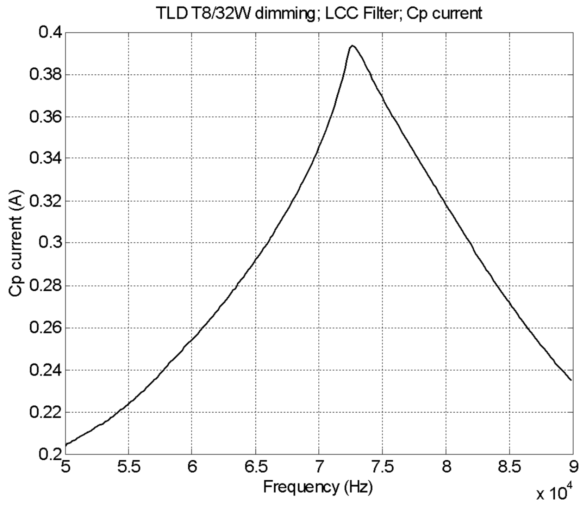

Fig. 6 C_P current in dimming.

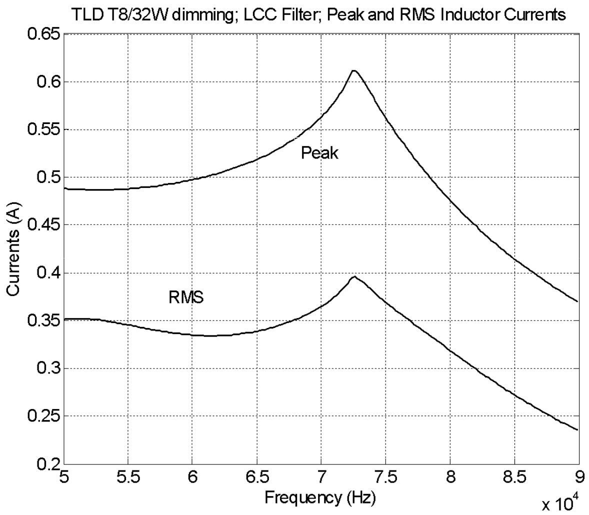

Fig. 7. L_S RMS and peak currents in dimming.

where V_{IGN} is the C_P peak voltage during ignition, f_{IGN} is the f_S during ignition. Fig. 8, which shows the FL voltage before ignition as a function of f_S, permits to choose the f_{IGN} value.

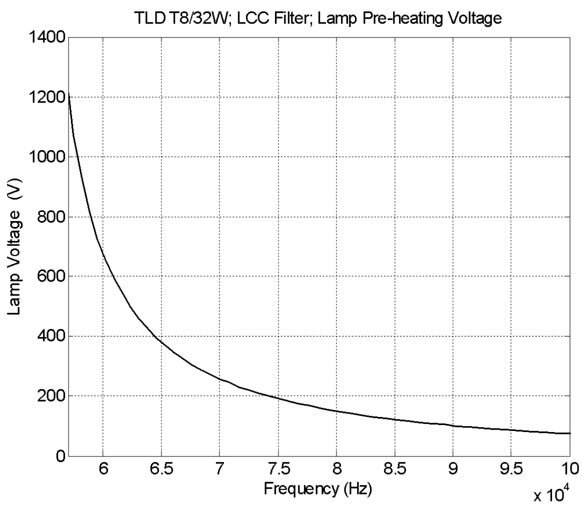

Fig. 8. FL peak voltage before ignition *vs*. f_S.

TLD T8/32W strikes at 400 V if the its filaments were heated adequately, so f_{IGN} can be chosen as 64 kHz. Finally, by (16), the I_{IGN} is calculated as 0.94 A and this value should be used to choose the inductor core. The curve in Fig. 8 was calculated by (2) for R=50 kΩ which is a reasonable value of the FL resistance before ignition.

IV. EXPERIMENTAL RESULTS

The proposed design method has been verified through a DEB prototype implementation and testing, using the numerical values as shown in Fig. 5. A IR21592 International Rectifier ballast controller was used to control the half bridge power switches [19]. Fig. 9 shows the measured dimming curve and the simulated one.

It can be observed that the measured curve is very close to the simulated one. The efficiency of the filament heating scheme has been verified employing the method described in Section III. The tests have been conducted at ambient temperature of 27^{o}C. The TLD T8/32W FL was dimmed to three different power levels, and the tube temperature measurements were made in 20 minutes after each power adjustment. Table I shows the obtained results.

Table I shows that, at rated power, the temperature in the middle of the FL tube was 16^{o}C above the ambient one, while the temperature of the tube extremities was about 15^{o}C above the temperature of 56^o C verified during the test described in Section III. This confirms that at the rated power the heating scheme functions adequately.

Figures 10 to 12 show the FL current envelope for different power levels. The filament overheating was observed as incandescence when the FL runs at 1 W power level.

TABLE I.
DEB with LCC filter: temperature measuring.

Local	**Temperature**
Rated Power (32 W)	
Left tube extremity	70^{o}C
Right tube extremity	71^{o}C
Middle of the tube	43^{o}C
Middle Power (15 W)	
Left tube extremity	64^{o}C
Right tube extremity	65^{o}C
Middle of the tube	38^{o}C
Lowest Power (5 W)	
Left tube extremity	58^{o}C
Right tube extremity	59^{o}C
Middle of the tube	28^{o}C

At the power level of 15 W, the temperature of the tube extremities has rose only 1^{o}C less than the one at the middle of the tube. This way, the filament heating scheme at the middle power range functions well too.

At the lowest power (5 W), the temperature of the tube extremities has rose about 2^{o}C above the temperature of 56^{o}C verified during the temperature test (Section III). This analysis permits to conclude that the DEB with LCC filter, if designed correctly, can provide correct filament heating without using any kind of auxiliary heating circuit. The 100 to 20% dimming range was verified experimentally. Some auxiliary heating circuit should be employed in DEB with a wider dimming range [17].

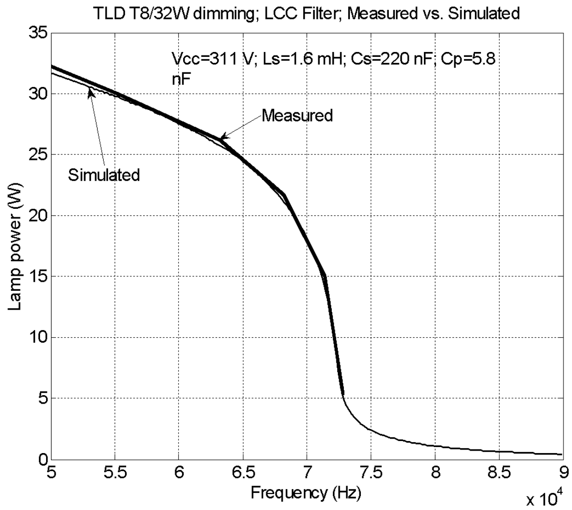

Fig. 9 Measured and simulated dimming curves.

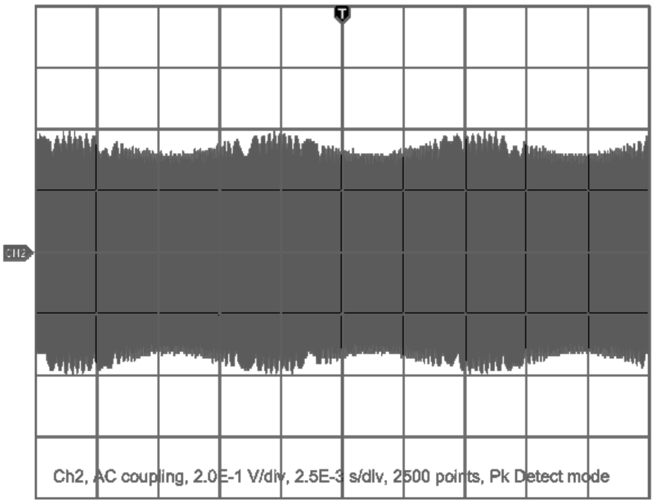

Fig. 10 Lamp current envelope at 250 mA (0.2 A/div); P_R=30 W.

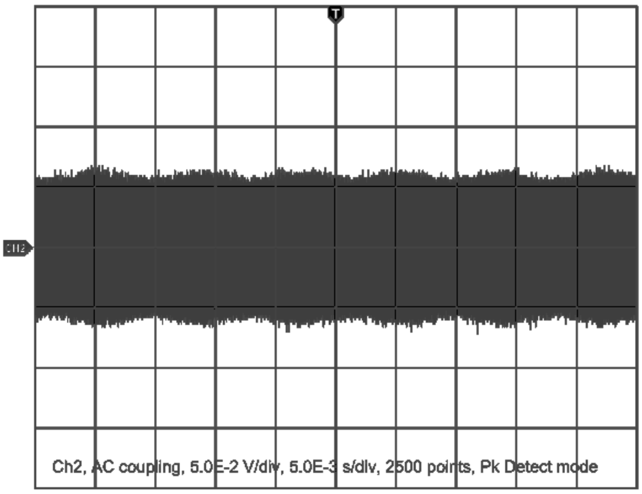

Fig. 11 Lamp current envelope at 50 mA (0.05 A/div); P_R=5 W.

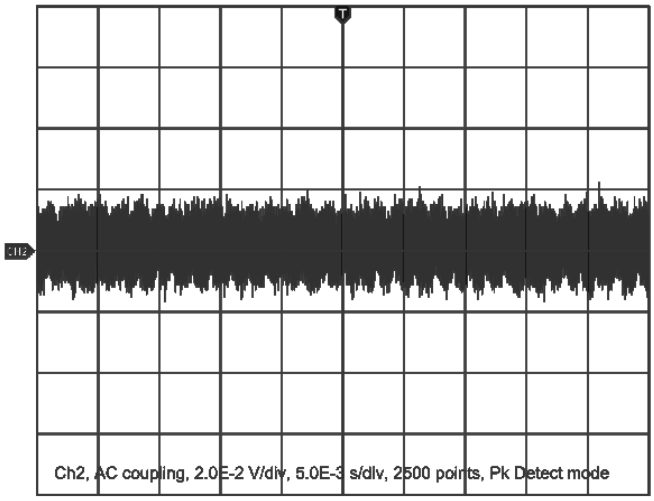

Fig. 12 Lamp current envelope at 9mA (0.02 A/div); P_R=1 W. Filament overheating observed as an incandescence.

V. CONCLUSION

The paper presents a brief analysis of dimming methods and points the frequency control one as the industry choice. A LCC filter design method, proposed in the paper, permits to design DEB without any additional filament heating circuit. A developed numeric simulation procedure, implemented in MATLAB, calculates dimming curve, C_P and inductor currents in dimming operation, facilitating the design calculations. A proposed temperature measuring method permits to verify the efficiency of the filament heating scheme. The tests of an implemented prototype verified the developed design method for the 100 to 20% dimming range.

VI. ACKNOWLEDGMENT

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