ITERATIVE METHOD FOR ANALYSIS OF DIMMABLE SELF-OSCILLATING ELECTRONIC BALLAST UNDER BUS VOLTAGE CONTROL

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Abstract – **This paper presents a predictive method of the self-oscillating electronic ballast (SOEB) behavior under dimming conditions. This work is focused on the bus voltage variation dimming method, where a closed analysis is not possible to carry out without considering the interaction among inverter bus voltage, fluorescent lamp power/resistance nonlinear behavior, and frequency operation of the SOEB. Thus, an iterative method is proposed in order to predict the oscillating frequency related with the fluorescent lamp power under bus voltage variation. Experimental results for a T8 32 W fluorescent lamp are obtained in order to compare simulation results, and verify the feasibility of the proposed method.**

Keywords - **Dimming, Electronic Ballast, Fluorescent Lamp, Self-Oscillating.**

I. INTRODUCTION

The importance of the lighting systems and the use of fluorescent lamps (FL), as well the electronic ballast advantages over the electromagnetic one, are recognized and have been reported in many researches [1]-[3].

Typical electronic ballast consists of two stages: power factor correction (PFC) and half-bridge (HB) series resonant parallel-loaded inverter (LCC) [4]. The PFC stage must be able to meet standards of power factor and current harmonic content [5]. The resonant filter should provide the heating of the filaments, lamp starting, soft-switching and direct current absence in the FL [6]. The inverter gate driver can be implemented by integrated circuits (ICs), but the self-oscillating command circuit (SOCC) is a good alternative, since it presents simplicity, robustness, absence of ICs and their auxiliary sources [1], [7], [8].

Attractive features can be added to the electronic ballast in order to save energy and provide environmental comfort for users. This is possible, for instance by introducing the dimming capability. The classic dimming methods are known as: switching frequency (f_S) variation, duty-cycle (D)

variation, changing the resonant filter parameters (Z_{FILTER}) and by controlling the bus voltage (V_{BUS}) [9]. In practice the combination of these methods can be used in order to improve the performance of electronic ballasts. Several solutions have been presented in the literature to implement dimmable electronic ballasts with SOCC, using different dimming methods [3], [4], [10], [11].

In the Dimmable Self-Oscillating Electronic Ballast (DSOEB) where changing the f_S is not the selected dimming method, the f_S of the SOCC is, by the nature of its operation, load dependent [8], [12]. Thus, it is very difficult to control or predict the exact operating f_S of the DSOEB in dimming conditions. Therefore, during the dimming, it is not known the relationship among the DSOEB f_S, FL power, and the control parameter used (D, V_{BUS} or Z_{FILTER}) to dim the lamp.

In the DSOEB the f_S and the control parameter used (D, V_{BUS} or Z_{FILTER}) to dim the FL are different for each FL power dimming level. Thus, the relationship of these parameters values will be defined according to the DSOEB operating point. If the operating point in the system is predicted it is possible to predict the dimming range, points of FL instability, zero voltage switching (ZVS) [3], electromagnetic interference (EMI), and resonant inductor design.

The DSOEB is usually designed for the nominal lamp power, with V_{BUS} and f_S as design parameters [3], [4], [10]. However, the operating point during the whole dimming range is defined empirically. Alternatively, this paper presents an iterative method to predict the DSOEB operating point, where the V_{BUS} is changed to dim the lamp and the correspondent f_S and lamp power is calculated. As referred in [13] V_{BUS} dimming technique is better compared to the other methods owing to the higher efficiency obtained during the entire dimming range. The proposed iterative method provides the relationships among V_{BUS}, f_S, and the FL power, besides evaluating the system stability under dimming conditions.

This paper is organized as follows: In section II the proposed method is presented. Section III shows experimental results and the paper is summarized with the conclusions in Section IV.

II. PROPOSED ITERATIVE METHOD

Figure 1 shows the self-oscillating electronic ballast (SOEB), where the V_{BUS} voltage variation is used for the DSOEB. In this paper, the aim is to predict the operating frequency and FL power of the DSOEB. The PFC is not considered in the analysis because this stage provides the V_{BUS} source. The process related to how the V_{BUS} is changed in the PFC circuit will not be considered here. In addition, the heating current circuit will not be taken into account in the SOCC analysis. First the design of the LCC resonant filter is presented. As next step the SOCC analysis and design will be shown. Then, the proposed iterative method is presented.
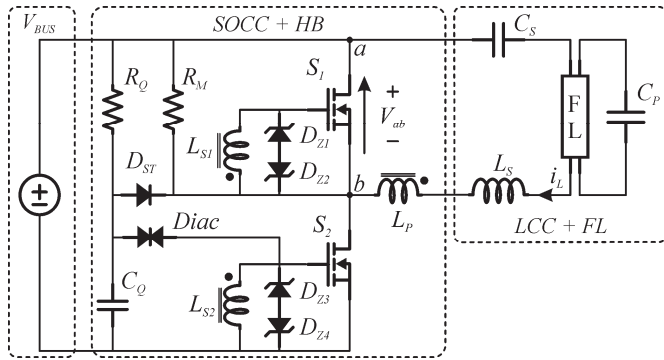

Fig. 1. Self-Oscillating Electronic Ballast (SOEB).

A. Half-bridge Resonant Filter Design

The design of HB inverter consists in determining the LCC resonant filter components, which provide the heating of the filaments, FL starting, soft-switching and direct current absence in the FL [6], [14], [15].

In this work, the resonant filter is designed using the fundamental of the input filter square-wave-voltage (V_{ab}) approach and the equivalent resistance model of the FL [14], [15]. The resonant inductor L_S and the series resonant capacitor C_S are determined according to the methodology presented in [2]. The parallel resonant capacitor C_P is designed considering the heating of the filaments of the FL at the rated power [2], [16]. Thus, the LCC filter is designed for the rated FL power. Table I shows the design specifications and respective components.

B. Self-Oscillating Command Circuit Analysis and Design

1) Representation of SOEB circuit – The behavior of the SOEB shown in Figure 1 is based on the feedback of LCC current (i_L) by means of the current transformer CT, composed of L_P, L_{S1} and L_{S2}. The secondary side of the CT is connected to the gate-source terminals of MOSFETs S_1, S_2 in complementary polarity [3].

Figure 2 shows the equivalent circuit of the SOCC and the respective main waveforms, where, i_S is the resonant current and L_m is the magnetizing inductance, both reflected to secondary side of the CT. The zener current i_Z is the subtraction of the magnetizing current i_m and i_S. When i_S is equal to i_m, the i_Z current crosses zero according to the time instants t_1, t_2, and t_3 (Figure 2). As a result, the gate-source

voltage (V_Z) of switches S_1 and S_2 change the state between on or off according to the polarity of i_z.

Figure 1 can be represented in terms of a block diagram as shown in Figure 3.a [8], where the HB inverter and the dc source (V_{BUS}) are represented by a hard-limit nonlinearity.

TABLE I
Resonant Filter Parameters

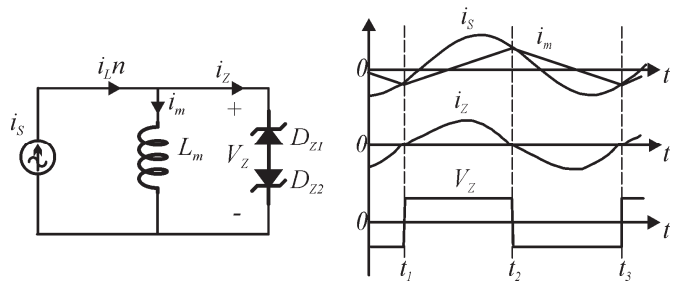|	*Design Specification*	
Bus voltage		300 V
Switching frequency		35 kHz
Fluorescent lamp		OSRAM T8 32W
FL resistance		540 Ω
FL Nominal voltage		130 V_{RMS}
	Resonant Filter	
L_S	Series resonant inductor	2.64 mH
C_S	Series resonant capacitor	170 nF
C_P	Parallel resonant capacitor	8.2 nF

Fig. 2. Equivalent circuit, and mains waveforms of the SOOC.

In addition, $G_F(s)$ is the transfer function from voltage V_{ab} to the resonant current i_L, given by (1), and $G_M(s)$ is the transfer function from the gate-source voltage (V_Z) to the magnetizing current i_m, defined by (2) [8]:

$$G_F(s) = \frac{s^2 + as}{s^3 + as^2 + bs + c} \qquad (1)$$

$$G_M(s) = \frac{1}{L_m s} \qquad (2)$$

where:

$$a = \frac{1}{R_{FL}C_P}; b = \frac{1}{L_S C_S} + \frac{1}{L_S C_P}; c = \frac{1}{R_{FL}L_S C_S C_P}.$$

In order to determine the behavior of the circuit in Figure 1, the describing function (DF) method and the extended Nyquist criterion (ENC) are used [8], [17]. Thus, to use the DF and ENC, Figure 3.a can be represented in terms of reduced block diagrams as shown in Figure 3.b. The DF that is associated with the hard limit nonlinearity is given by (3), and the linear elements transfer function is defined in (4):

$$N(I_Z) = \frac{4V_Z}{\pi I_Z} \qquad (3)$$

$$G(s) = G_M(s) - KG_F(s)n \qquad (4)$$

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where $K = V_{BUS}/(2V_Z)$ is the gain to obtain V_{ab} from V_Z, $n = n_P/n_S$, n_P and n_S are the number of turns of the CT primary and secondary windings, respectively.
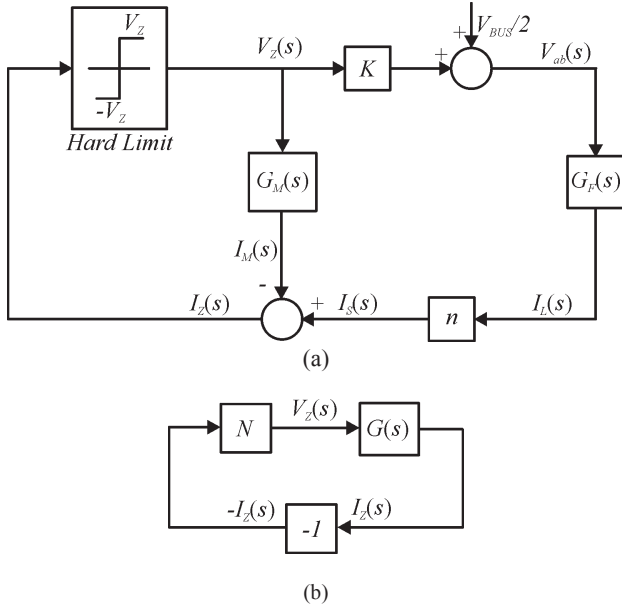

Fig. 3. SOEB block diagram (a) and reduced block diagram (b).

Analyzing Figure 3.b, being $s = j\omega$, if the self-sustained oscillation exists, the amplitude of i_Z, and the value of f_S or angular frequency $\omega = 2.\pi.f_S$ can be determined from the system characteristic equation, given by (5) [8]. Rearranging (5) it becomes (6).

$$1 + N(I_Z)G(s) = 0 \qquad (5)$$

$$G(s) = -\frac{1}{N(I_Z)} \qquad (6)$$

The frequency response of $G(j\omega)=G(s)$ and the negative inverse describing function $-1/N(I_Z)$ can be plotted in the complex plane as shown in Figure 4. If both curves intersect, then there is a limit cycle and the values of I_Z and ω correspond to the intersection point and the solution of (6) [8], [17]. However, the system just present self-sustained oscillation when the $G(j.\omega)$ crosses $-1/N(I_Z)$ in clockwise direction.

Observing the plot of Figure 4 the negative inverse describing function presents only the real part and it intercepts $G(j\omega)$ at a determined frequency ω_S. Thus, (7) can be applied. Substituting (4) in (7), (8) is obtained. Then, the magnetizing inductance L_m can be solved using (8) [8]. Therefore, it is possible to develop a design procedure for the SOCC that determines a possible value of f_S for stable operation.

$$\text{Im}(G(j\omega)) = 0 \qquad (7)$$

$$\frac{-1}{\omega L_m} - \frac{Kn}{L_S}\frac{\omega a(c - \omega^2 a) + \omega^2(\omega b - \omega^3)}{(c - \omega^2 a)^2 + (\omega b - \omega^3)^2} = 0 \qquad (8)$$
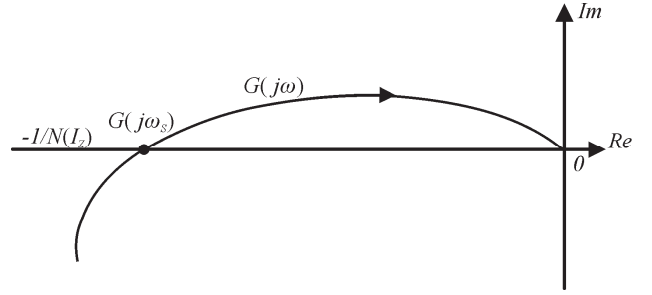

Fig. 4. Nyquist plot of SOEB.

2) SOCC design – The SOCC design consists in determining the magnetizing inductance L_m from the main design specifications: value of zener voltage and current to protect the MOSFETs and to define a limit of magnetizing current, the FL power, f_S, and V_{BUS}. In this work the SOCC is designed following the methodology presented in [8], and using the same design specifications shown in Table I. The self-oscillating command circuit components are presented in Table II.

TABLE II
Self-Oscillating Command Circuit Components

Self-Oscillating Command Circuit		
L_P, L_{S1}, L_{S2}	Current Transformer Inductance	49/411/411 µH
N_P, N_{S1}, N_{S2}	Windings Number of Turns	4/12/12
D_{Z1}-D_{Z4}	Zener Diode	12 V; 1/2 W
S_1, S_2	MOSFET	IRF740
Start Circuit		
R_Q/ R_M	Resistor	270 kΩ/ 470 kΩ
C_Q	Capacitor	100 nF
Diac	Diac	DB3

In order to evaluate the dimming range, FL stable operation, ZVS, and the size of resonant inductor the operating point should be previously determined. Thus, in the next section an iterative method to predict the DSOEB operating point is proposed.

C. Proposed Iterative Method

Figure 5 summarizes the proposal of this paper through a flowchart. Each step of this method is explained as follows:

1) Initialization – Firstly, it starts by defining the LCC filter, the SOCC components, and the design parameters previously known.

2) Define P_i – In the next step P_i is defined as the desired FL power, which is used to calculate the respective V_{BUS_i} necessary to supply the HB inverter, for the resulting f_{SO_i} of the DSOEB.

3) $R_{FL}(P_i)$ – In this step the FL resistance is calculated by (9), which represents the FL resistance as a function of its own power according the FL model shown in 0.

$$R_{FL}(P_i) = 2274e^{-0.046P_i} + 8945e^{-0.204P_i} \qquad (9)$$

4) Calculate f_{SO_i} – At this point, P_i, $R_{FL}(P_i)$ and the supposed respective V_{BUS_k} are known, and the self-oscillation frequency (f_{SO_i}) can be determined by solving (6). Initially V_{BUS} is supposed to be $V_{BUS\_k=0} = V_{BUS}$, being k an intermediary index in the loop to obtain f_{SO_i} when $P_{SO\_k} \approx P_i$.

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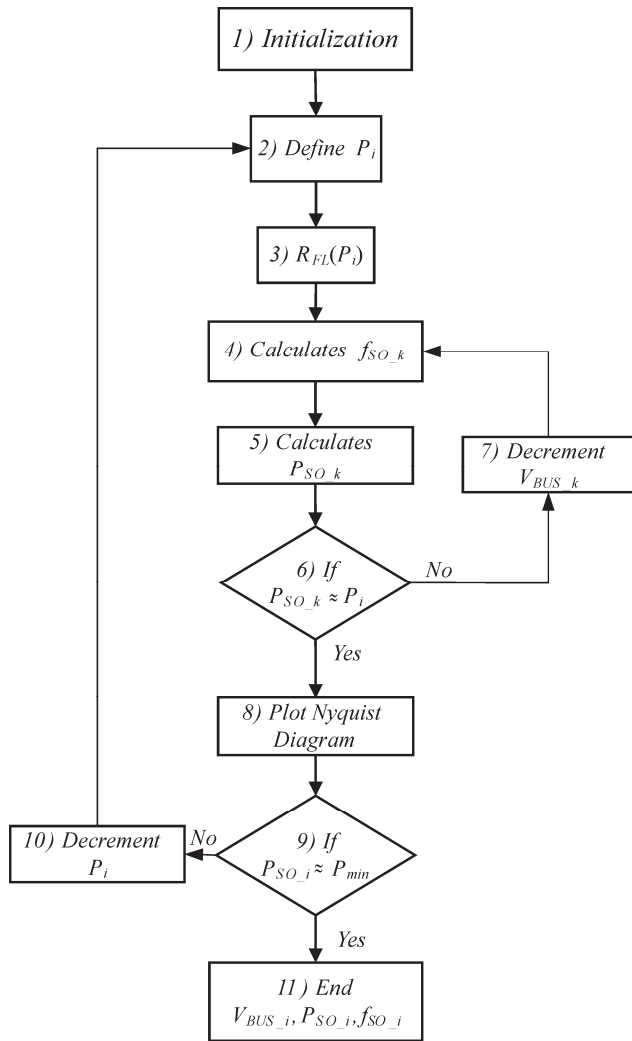Eletrôn. Potên., Campo Grande, v. 20, n.1, p. 68-75, dez. 2014/fev. 2015

Fig. 5. Flowchart of the proposed iterative method to predict the DSOEB operating point under V_{BUS} dimming technique: flowchart.

5) Calculates P_{SO_k} – With the calculated f_{SO_k}, and knowing the filter parameters, the lamp power with the operating f_{SO_k} is calculated. The FL power P_{SO_k} is calculated by [6]:

$$P_{FL} = \frac{\left(\frac{V_{BUS}\sqrt{2}}{\pi}\right)^2 R_{FL}\left(1+C_p^2 R_{FL}^2 \omega^2\right)}{R_{FL}^2 + \omega^2\left(\left(L_S - \frac{1}{C_S \omega^2}\right)\left(1+C_p^2 R_{FL}^2 \omega^2\right) - R_{FL}^2 C_P\right)^2}. \quad (10)$$

6) First decision – If the calculated power P_{SO_k} is close to the desired FL power P_i, then the respective V_{BUS_i} and f_{SO_i} are known. The error adopted is 1%.

7) Decrement V_{BUS_k} – V_{BUS_k} is decremented and the program return to step 4, with a new supposed V_{BUS_k+1}.

8) Plot Nyquist Diagram – The Nyquist diagram is plotted, and with the extended Nyquist criterion it is possible to evaluate if the system presents a self-sustained oscillation.

9) Second decision – At step 9, if the P_{SO_i} is close to the minimum FL power, using 1% error, then execution goes to step 11 and the process is finished. The minimum FL power depends on the desired dimming range which the operating points will be known.

10) Decrement P_i – If P_{SO_i} is greater than the minimum FL power, P_i is decremented. The same process is repeated until the P_i is close to the minimum FL power adopted.

11) End – The flowchart produces three vectors that are related to the FL power, V_{BUS} and the f_S of the DSOEB.

It is important to mention that the FL equivalent resistance is not constant when the FL power is changed. Therefore, adding the FL model in this method provides better results than when this characteristic of the FL is not considered.

III. EXPERIMENTAL RESULTS

In this section the proposed iterative method is implemented and tested. The implementation can be carried out using any software that allows iterative calculus, as MATLAB. Tables I and II summarize the design parameters and used components. In order to show the feasibility and to evaluate the proposed method, experimental results were obtained with three different filters, where the first analysis is carried out with the designed filter. The other two filters are similar to the designed one, where only capacitor C_P is changed, L_S and C_S were maintained constant, in order to evaluate this method comparing with experimental results. For instance, C_P values of 6.8 nF and 10 nF were tested. Then, the operating point for this three filters are compared, between experimental and proposed iterative method results.

Figure 6 shows the DSOEB operating point under dimming by changing the V_{BUS}. This figure shows the experimental results and calculated values obtained from the proposed method. It is possible to verify a good approximation between the results for three different filters values considering the C_P variation: 1) $C_P = 8.2$ nF for the designed filter, 2) $C_P = 6.8$ nF, and 3) $C_P = 10$ nF.

Usually, the first analysis performed in the DSOEB is to consider the f_S constant. Figure 7.a shows the results of FL power for this situation. It can be seen worst results comparing the proposed iterative method. Figure 7.b shows the relative error of the FL power and f_S for the predicted values using the iterative method, taking as reference the experimental results. Besides, it is shown also the FL power error considering a fixed f_S approximation. As it can be seen, the maximum error of the FL power and f_S for the proposed method results are 4.5% and 3%, respectively. Once for the fixed f_S approximation the FL power relative error is greater than 25%.
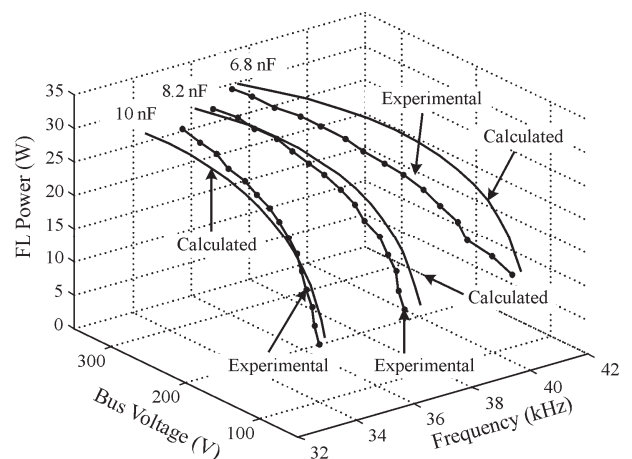

Fig. 6. DSOEB operating point under V_{BUS} technique dimming.

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Figures 8.a and 8.b show the result for $C_P = 10$ nF. Figure 8.a shows the comparison between the proposed method and fixed f_S approximation results. The maximum f_S error is lower than 4.5% for the whole dimming range, and the maximum FL power error is lower than 4.5% for dimming until 13 W for the proposed method. Once for dimming level lower than 13 W the maximum error is lower than 8.5%, being acceptable compared to the error for the fixed f_S approximation that is greater than 30%. In Figure 9 the results for $C_P = 6.8$ nF are shown. Analyzing the proposed method results the maximum

error for FL power and f_S are 7.5% and 5.5%, respectively, while for the fixed f_S approximation the maximum error is greater than 15%.

Figure 10 shows the experimental waveforms for the designed filter ($C_P = 8.2$ nF). Figures 10.a, 10.b and 10.c show the FL power, voltage and discharge current. As can be seen, a wide dimming range is obtained, between 31.6 W and 10 W, similar to the predicted one, which was between 32.05 W and 10.10 W.
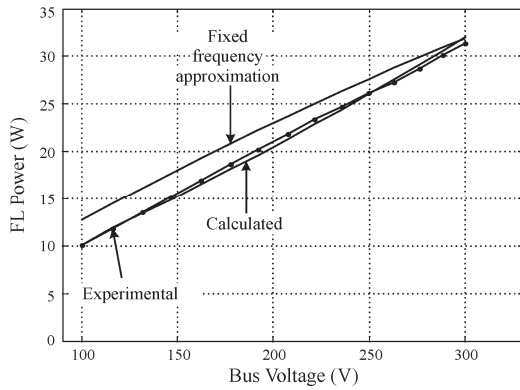

(a)

(b)
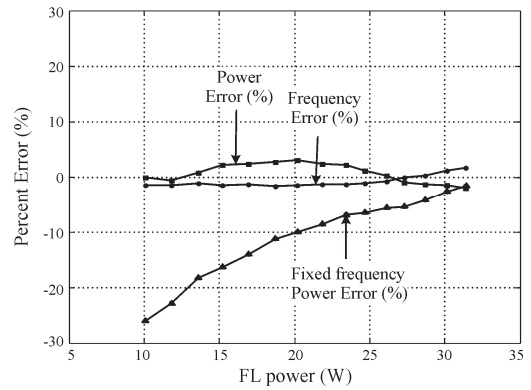
Fig. 7. Comparison among experimental results, fixed frequency approximation, and proposed iterative method result for the designed resonant filter: (a) FL Power versus V_{BUS} for the designed resonant filter. (b) Percent error.
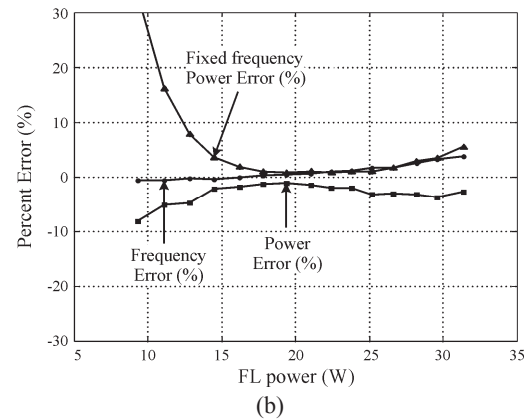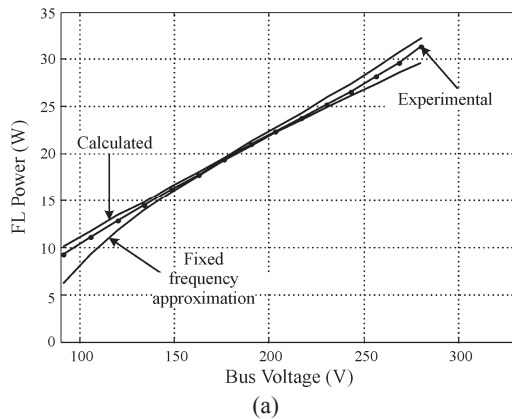

(a)

(b)

Fig. 8. Comparison among experimental results, fixed frequency approximation, and proposed iterative method result for the designed resonant filter with $C_P = 10$ nF: (a) FL Power versus V_{BUS} for the designed resonant filter; (b) Percent error.
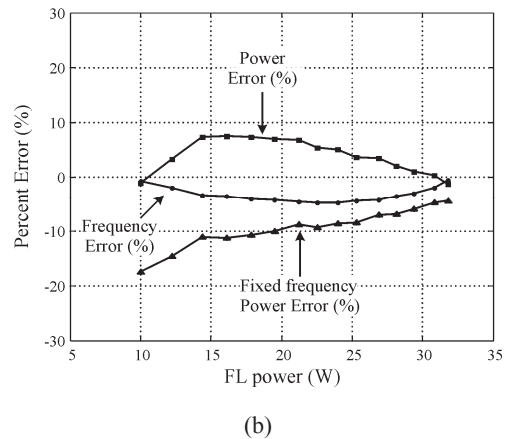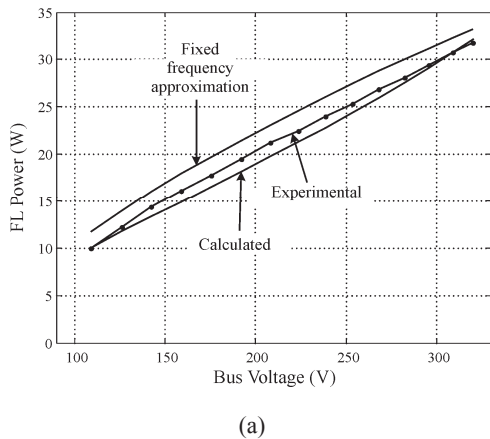

(a)

(b)

Fig. 9. Comparison among experimental results, fixed frequency approximation, and proposed iterative method result for the designed resonant filter with $C_P = 6.8$ nF: (a) FL Power versus V_{BUS} for the designed resonant filter; (b) Percent error.

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On the other hand, the predicted frequency for the maximum and minimum FL power are 34.88 kHz and 37.53 kHz, respectively, also close to the experimental one, 36.06 kHz a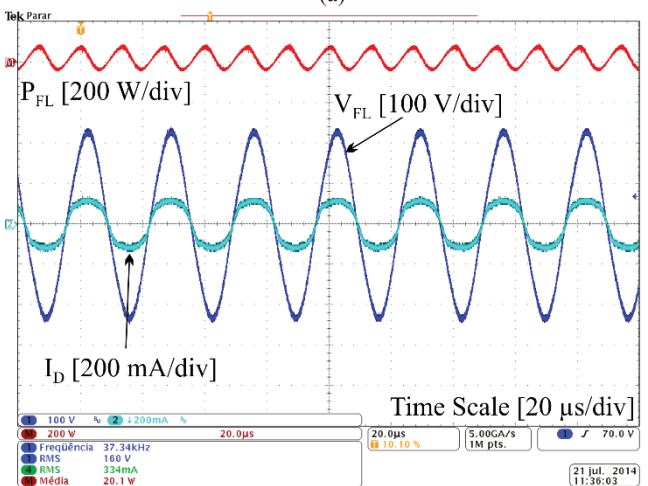nd 36.39 kHz. In addition, Figure 10.d, 10.e and 10.f show the MOSFET S_2 voltage and current, where it can be seen that the ZVS is achieved for both maximum, medium and minimum power. Once, when S_2 turn on, the resonant current circulates through the body diode, negative current.
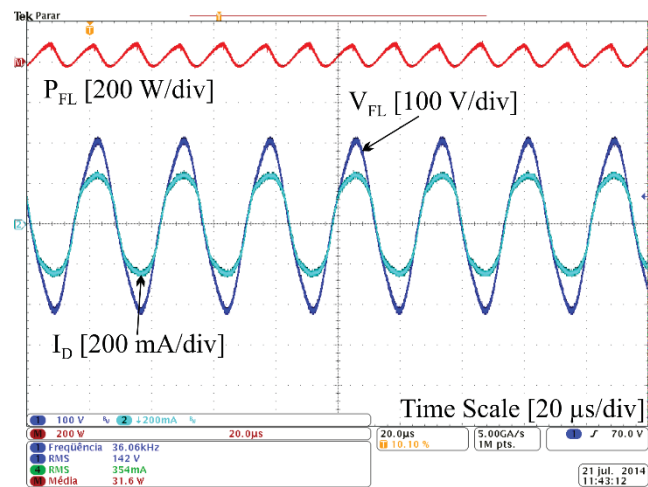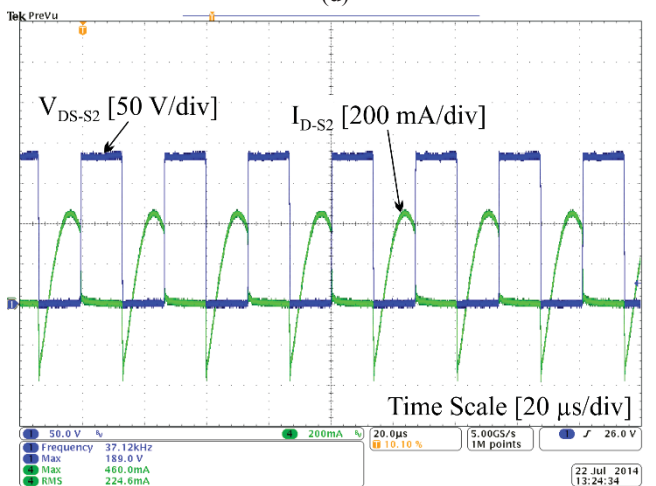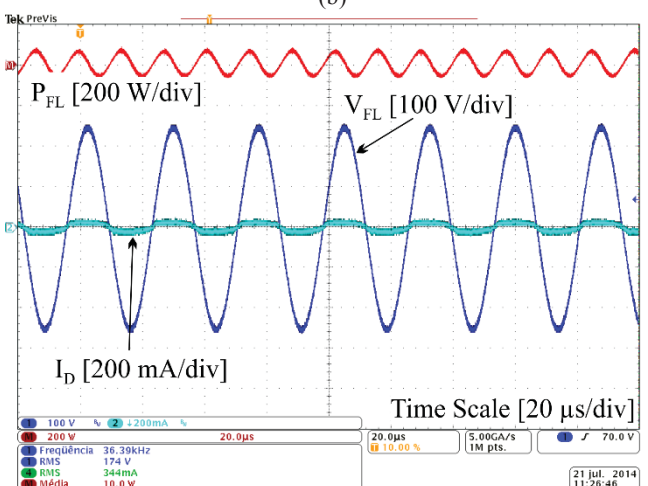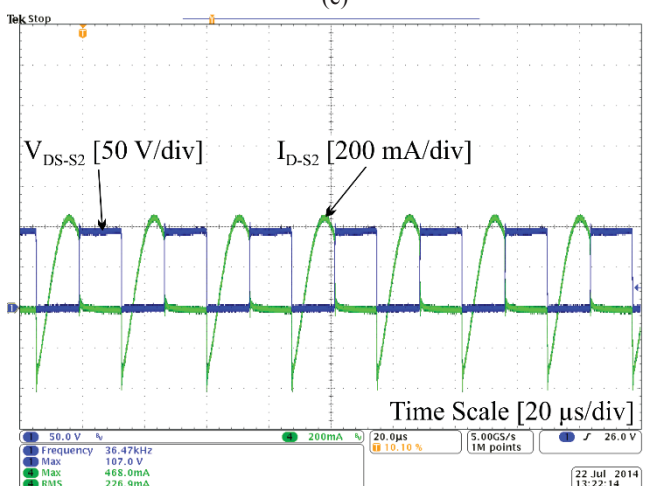

(a)
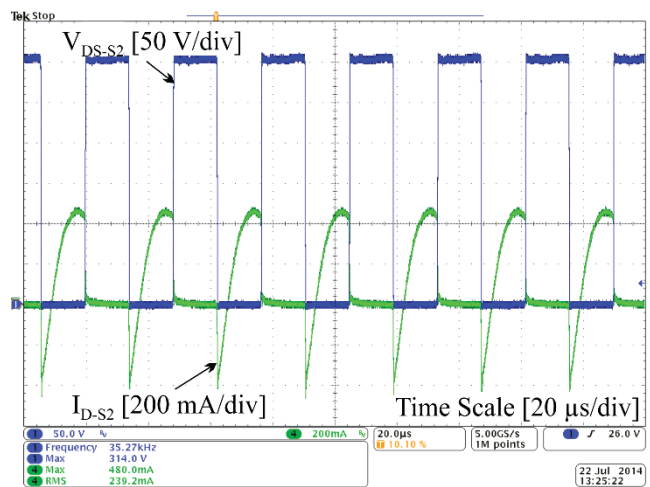
(d)

(b)

(e)

(c)

(f)

Fig. 10. Experimental waveforms for C_P = 8.2 nF: (a) FL voltage (V_{FL}), discharge current (I_D), and power (P_{FL}), for the maximum FL power (31.6 W); (b) FL voltage, discharge current, and power, for medium FL power (20.1 W); (c) FL voltage, discharge current, and power, for minimum FL power (10 W); (d) S_2 Drain-source voltage (V_{DS-S2}), and current (I_{D-S2}) for the maximum FL power (31.6 W); (e) S_2 Drain-source voltage, and current for the medium FL power (20.1 W); (f) S_2 Drain-source voltage, and current for the minimum FL power (10 W).

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Another interesting feature of the implemented method is the possibility to evaluate the system stability under dimming conditions. Figure 11, 12 and 13 show the Nyquist diagram of the DSOEB for each FL power operating point. Then, using the extended Nyquist stability criterion it is possible to verify if the system presents self-sustained oscillation, since the $G(j\omega)$ crosses $-1/N(I_Z)$ in clockwise direction.
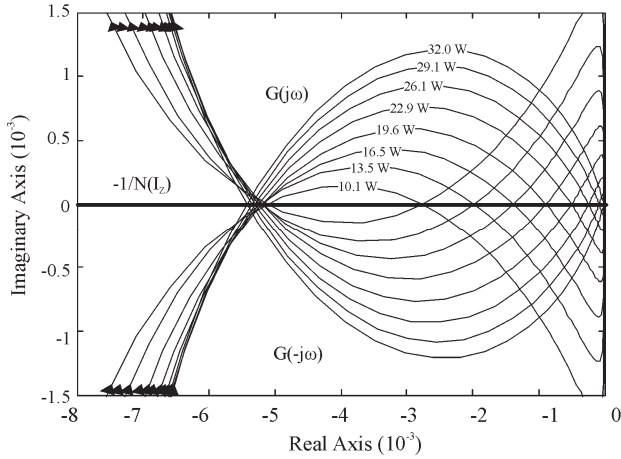

Fig. 11. Nyquist Diagram of the DSOEB for the designed resonant filter.
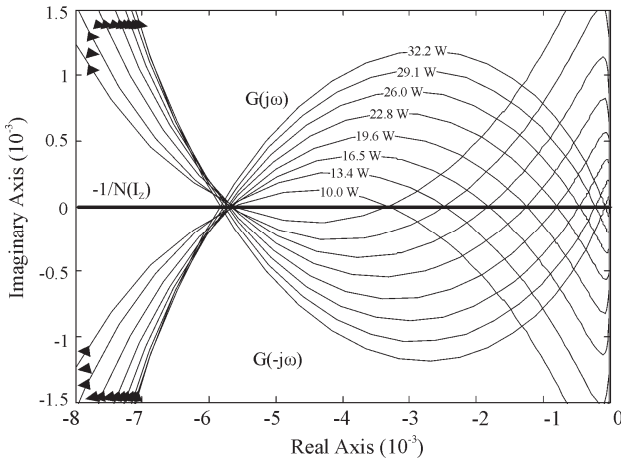

Fig. 12. Nyquist Diagram of the DSOEB for the designed resonant filter, with $C_P = 10$ nF.
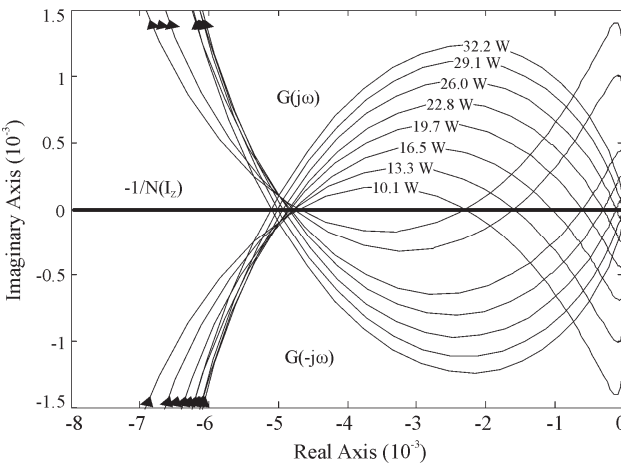

Fig. 13. Nyquist Diagram of the DSOEB for the designed resonant filter, with $C_P = 6.8$ nF.

IV. CONCLUSION

In this work an iterative method was implemented to predict the switching frequency, fluorescent lamp power, and the bus voltage in the self-oscillating dimmable electronic ballast, with bus voltage dimming technique.

Experimental results confirm the feasibility of the proposed method, with a negligible relative percent error for the FL power and switching frequency by comparing experimental and calculated values by the proposed iterative method. Besides, it is possible to evaluate the system stability under dimming conditions.

ACKNOWLEDGEMENT

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