Self-Oscillating Electronic Ballast Design Based on Control Tools

R. K. Pavão F. E. Bisogno A. R. Seidel and R. N. do Prado

Federal University of Santa Maria
Researching Group of Electronic Ballasts - GEDRE
PPGEE - NUPEDEE - UFSM
97105-900 - Santa Maria - RS – Brazil
rnprado@ieee.org

***Abstract* - This paper presents a design methodology and analysis of the self-oscillating drive circuit for electronic ballasts based on control tools. The self-oscillating electronic (SOEB) ballast is analyzed as relay control system. The describing function method and extended Nyquist criterion are used in the analysis and in the design of the self-oscillating drive circuit. It helps to find out the main parameters of the SOEB.**

I. INTRODUCTION

Nowadays, a great amount of produced electrical energy in the world is consumed in the form of artificial illumination, and any improvement in the efficiency of illuminating systems is desirable. The use of fluorescent lamps reduces the consumption of electrical energy when compared to incandescent lamps, because the former present higher efficacy (lm/W) [1]. The performance of fluorescent lamps are improved when they are supplied by electronic ballasts instead of electromagnetic ones, due their features, such as high efficacy, low audible noise, longer lamp useful life, small size, light weight, and flicker absence [1], [2] and [3].

The drive circuit is easily employed with TTL or self-oscillating circuit to use in electronic ballasts. When it uses the self-oscillating gate drive circuit, it brings additional advantages, such as reliability, low cost, and little energy consumption. In addition of characteristic of high frequency operation, the main attractiveness is the simplest configuration. The aim of this work is to solve an expression to calculate the magnetizing inductance L_m of the current transformer in the gate drive circuit, obtained through analysis with control tolls. This paper is organized as follows. Section II presents an analysis of SOEB. In Section III a design procedure is developed. In Section IV and V simulation and experimental results are presented. Finally, in Section VI some conclusions are made based on the results obtained.

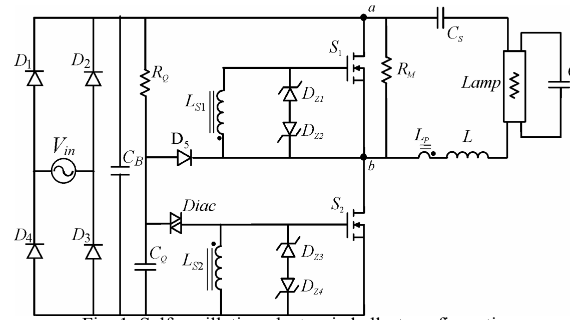


Fig. 1. Self-oscillating electronic ballast configuration

II. SELF-OSCILLATING ELECTRONIC BALLAST ANALYSIS

Operating principles, considerations on the modeling and design of the self-oscillating electronic ballast will be made in this section. Fig. 1 shows the self-oscillating electronic ballast configuration. A basic principle operation of this circuit is described follows. R_Q and C_Q form a start-up charging circuit that reaches 30V breakover of diac in approximately one second after power is applied. With diac conducting, a positive turn-on voltage pulse is applied to the gate of S_2. With S_2 turned on, the S_2 drain voltage previously held high is rapidly switched to ground thus initiating circuit oscillation. With S_2 conducting, any charge remaining across C_Q is discharge through D_5 preventing generation of further start-up pulses.

The behavior of this electronic ballast is based on the feedback of LCC resonant inductor current by means of the current transformer (CT). The secondary side of the CT is connected in complementary polarity to the gate-source terminals of Mosfets S_1, S_2 as shown in Fig. 1. In order to facilitate the understanding of the circuit operation the current transformer will be represented by a sinusoidal current source, i_S, in parallel with a magnetizing inductance, L_m, and the zener diode voltage will be assumed to be constant. As a result of these approximations it is possible to consider the magnetizing current to be linear, and the inductor current reflected to the secondary side of the transformer to be sinusoidal. Therefore, the zener current i_Z is the sum of magnetizing current, i_M and resonant current i_S as shown in the Fig. 3. When the zener current i_Z crosses zero and changes its polarity at time t_1, t_2 and t_3, also does the gate-source voltage of Mosfet (S_1, S_2).

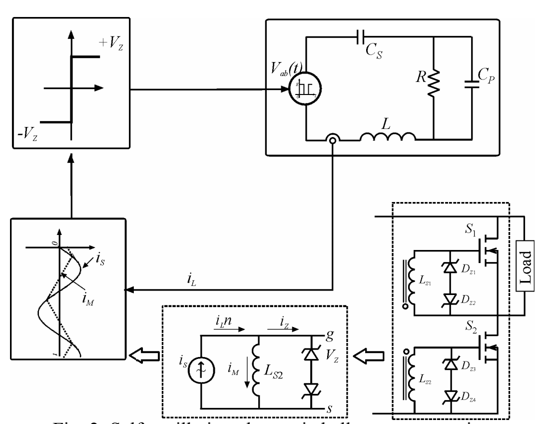


Fig. 2. Self-oscillating electronic ballast representation

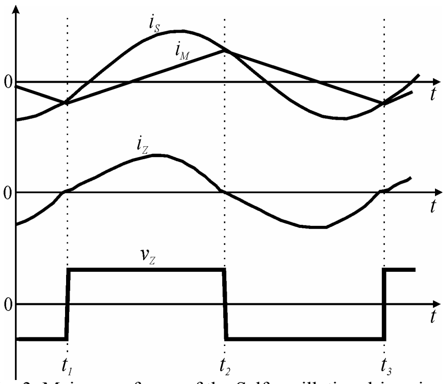


Fig. 3. Main waveforms of the Self-oscillating drive circuit

As a result, there will be a change in the conduction state of the switch S_1 and S_2. From this analysis, it is possible to conclude that magnetizing inductance L_m and diode zener voltage V_Z are the key elements to define the operation frequency of the electronic ballast in self-sustained oscillating mode.

This system can be modeled such a relay control system, and apply control tools to obtain the parameters of the gate drive circuit. Fig. 2 shows the scheme with the function of each section in the self-oscillating electronic ballast.

The scheme of Fig. 2 can be represented in terms of a block diagrams shown in Fig. 3. In order to obtain this block diagram some simplifications have been made: the fluorescent lamp has been represented by an equivalent resistance R, the gate-source capacitance of the Mosfet (S_1; S_2) and its delay times have been neglected. In addition, the input voltage has been considered to be constant.

With these simplifications, the Half-Bridge converter and dc source can be represented by a hard limit nonlinearly as shown in Fig. 4. In this figure the resonant filter and the fluorescent lamp are represented by the transfer function $G_F(s)$, from the voltage V_{ab} to the resonant current I_L. The magnetizing inductance is represented by a transfer function from the gate-source voltage to the magnetizing current I_M. In order to understand the behavior of the circuit in Fig. 4, the describing function method and extended Nyquist criterion will be used [8].

III. Self-Oscillating Electronic Ballast Design

In the last section, the SOEB was represented as a single input single output (SISO) control system reduced by means block diagrams, which represents the behavior of this electronic ballast. In this section the design of the SOEB will be made considering the analysis related above.

A. Design of Resonant Elements

Initially it is assumed that the operating frequency and power in the lamp are known. The design of resonant filter is based on the fundamental approximation and the phase angle of the resonant current and shift-phase angle between the resonant current i_S and fundamental voltage of V_{ab}. This design step is omitted here since it described in details in [6].

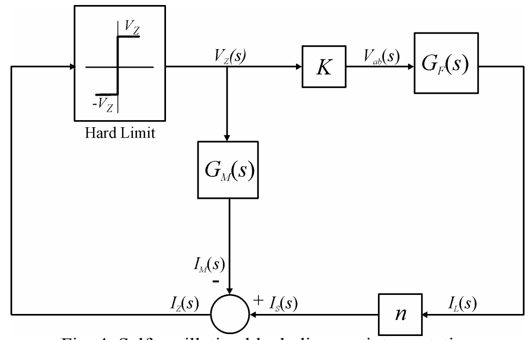


Fig. 4. Self-oscillating block diagram interpretation

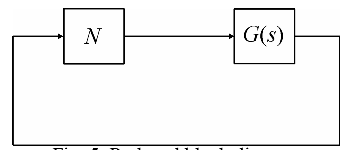


Fig. 5. Reduced block diagram

B. Self-Oscillating Electronic Ballast Considerations

Using resonant elements above determined in Section III.A, we can design the gate drive circuit, which consists in the system model, input data and to solve L_m inductance of toroidal current transformer. The block diagram of Fig. 4 can be reduced as the simplified diagram of Fig. 5.

The describing function method can be conveniently used to determine the existence of self-sustained oscillations as well as to determine stability through interpretation of Fig. 8. Resonant converters, when operating above of resonant frequency, have low-pass filter characteristic resulting in a dominant first harmonic component. Then, the analysis based on fundamental approximation is reasonable since the higher order harmonics are significantly attenuated according the frequency response in Fig. 6 [8].

Extended Nyquist Criterion and the describing function method to obtain the parameters of the drive circuit can be used. Firstly, the nonlinearity of the on-off relay is defined by describing function. Unlike of linear systems the characteristic equation of the system in Fig. 5 is defined by:

$$1+NG(j\omega)=0 \quad , \tag{1}$$

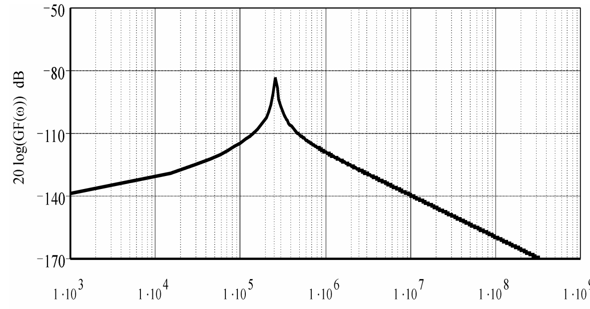
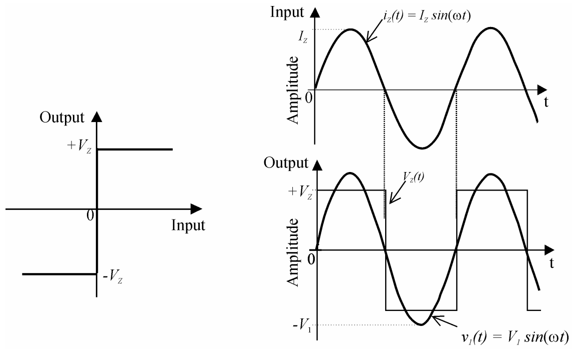


Fig. 6. Frequency response of resonant inductor current from V_{ab} input voltage



(a) (b)

Fig. 7. (a) Relay on-off (b) Input and output waveforms

and can be rewritten as

$$G(j\omega) = -\frac{1}{N}\,. \tag{2}$$

If equation (2) is satisfied, then the system may exhibit a limit cycle, therefore the interception of $G(j\omega)$ and $-1/N$ as shown in Fig. 8 gives the information of possible self sustained oscillation.

The technique of block diagram is relatively simple, though the presence of non-linear block imposes a few restrictions on the manipulation diagram already shown in Fig. 4. It requires that the nonlinearity be described by an equation in the frequency domain. The approximation is made by frequency domain by defining the describing function in terms of Fourier series for the component responses to a sinusoidal input [8].

The describing function may then be defined as the ratio of the magnitude of the fundamental term in Fourier series for the output wave to the magnitude of the input sinusoid at a phase angle that is the angle between the two sine waves and for all permissible amplitudes and frequencies of the input wave. The hard-limit and the main waveforms that is composed the gate drive circuit are shown in Fig. 7(a) and (b). In mathematical notation, if the input wave is designated by

$$I_Z(t) = I_Z \cdot sin(\omega t + \theta) \tag{3}$$

where: I_Z is the zener current and θ is the phase angle between the two sine waves.

And the output is described in Fourier series by

$$v(t) = A_0 + \sum_{m=1}^{\infty}\left(A_m \cdot cos(m\omega t) + B_m \cdot sin(m\omega t)\right) \tag{4}$$

where: A_m and B_m: coefficients of Fourier series, where m=0,1,…

As can be seen in Fig. 7 the series is composed only by odd components, and (4) becomes

$$v(t) = \sum_{m=1}^{\infty} B_m \cdot sin(m\omega t) \tag{5}$$

The fundamental frequency term of the Fourier series of output v(t) is designated by

$$v_1(t) = B_1 sen(\omega t) = V_1 sen(\omega t) \tag{6}$$

where

$$V_1 = \frac{1}{\pi}\int_0^{2\pi} v(t)\,sin(\omega t)\,d\omega t = \frac{2}{\pi}\int_0^{\pi} v(t)\,sin(\omega t)\,d\omega t \tag{7}$$

Substituting v(t)=V_Z, results

$$v_1(t) = \frac{V_Z}{\pi}\int_0^{\pi} sin(\omega t)\,d\omega t \tag{8}$$

therefore, $v_1(t)$ results

$$v_1(t) = \frac{4V_Z}{\pi}\,sin(\omega t) \tag{9}$$

From the output waveform represented by (9) and input waveform that represents the hard-limit, the describing function for the nonlinearity is defined as the following relation

$$N = \frac{4V_Z}{\pi I_Z} \tag{10}$$

Besides of define the representation of the nonlinear block (hard-limit) is necessary to define the linear elements. That is the transfer function from output voltage V_{ab} and resonant inductor current I_L, being

$$G_F(s) = \frac{s^2 + a\,s}{s^3 + a\,s^2 + b\,s + c} \tag{11}$$

where:

$$a = \frac{1}{R \cdot C_P},\quad b = \left(\frac{1}{C_S L} + \frac{1}{C_P L}\right),\quad c = \frac{1}{RC_P C_S L} \text{ and } K = \frac{E}{2Vz}$$

and the magnetizing inductance is represented by a transfer function from the gate-source voltage to the magnetizing current I_M, given by

$$G_M(s) = \frac{1}{L_m s} \tag{12}$$

Manipulating the block diagram of Fig. 4 in such a way as to reduce the block diagram to a single loop in Fig. 5, and substituting s=jω results in

$$G(j\omega) = G_F(j\omega) - G_M(j\omega) \tag{13}$$

Reorganizing (13), the final expression substituting s=jω and the resonant elements previously determined according to Section B the magnetizing inductance can be determined. The magnetizing inductance is determined making $Im(G(j\omega))=Im(KG_F(j\omega)n-G_M(j\omega))=0$, then the final expression becomes

$$L_m = \frac{L\left(\left(c - a\omega^2\right)^2 + \left(b\omega - \omega^3\right)^2\right)}{Kn\left[a\omega^2\left(a\omega^2 - c\right) + \omega^3\left(b\omega - \omega^3\right)\right]} \tag{14}$$

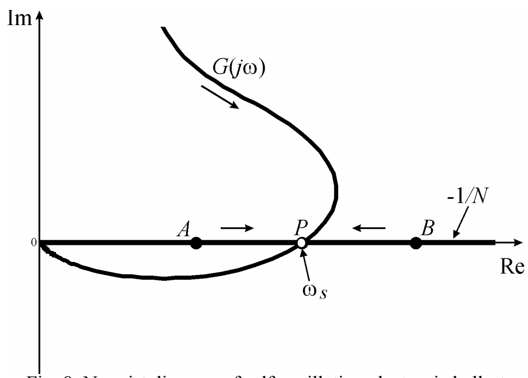


Fig. 8. Nyquist diagram of self-oscillating electronic ballast

where: $n = n_P/n_S$, n_P is the number of turns of the primary side and n_S is the number of turns secondary side of the current transformer CT.

The expression allows solve L_m for each operation frequency point according the data specification.

To verify the stability with respect L_m magnetizing inductance (P point) a stability test will be made in the next section.

D. Stability Test

Let us assume that the SOEB operates at point P, with a fundamental zener diode current I_Z, and frequency ω. In addition, suppose that due to a small disturbance, the amplitude I_Z is slightly decreased and the SOEB operation point is moved from P to A. Since the new point A is encircled by the curve $G(j\omega)$ according to the extended Nyquist criterion, the amplitude of I_Z will increase. Therefore, the operating point will move along $-1/N$ locus towards operating point P. On the other hand, if the amplitude of I_Z is disturbed, so that it is increased, the operating point will move from P to B, then the amplitude I_Z is decreased since it is not encircled by the curve $G(j\omega)$, and thus the current I_Z returns to the operating point P, as shown in Fig. 8. From the above discussion, it is concluded that SOEB presents a possible self-sustained frequency operation at the point P [8].

III. Design Procedure and Example

In this section the design procedure based on design specifications to the filter components and self-oscillating drive circuit is described. The input data are summarized in Table I.

TABLE I
INPUT DATA

Specification	
Input voltage	V_{in}=110 Vrms, 60Hz
Output Power	P=40 W
Switching Frequency	f_S=40 kHz
Zener Diode	$D_{Z1\text{-}4}$:12V
Lamp Resistance	Lamp Resistance R=270Ω

A. Design of Resonant Elements

The filter de sign is omitted here, due it is detailed in [6], and the main parameters are summarized in Table II.

TABLE II
SUMMARIZED PARAMETERS

Resonant Filter Parameters	
C_S	Polypropylene capacitor, 147nF/250 Vac
C_P	Polypropylene capacitor, 10 nF/600 Vac
L	Inductor, 800 µH, 150 turns on core EE20 IP6-Thornton
Self-Oscillating Drive Parameters	
L_M,L_{M1},L_{M2}	L_m=688 µH.: 2/12/12 Turns on core T15 IP6 – Thornton
D_{Z1},D_{Z2}, D_{Z1},D_{Z2}	Zener Diode 12 V ¼ W
Diac	DB3
R_Q	Resistor 220 kΩ/1/8W
C_Q	Ceramic Capacitor 100nF / 63 V
R_M	Resistor 470 kΩ/1/8W
D_5	High Frequency Diode UF4007
Others	
S_1, S_2	Power MOSFETs IRF740
D_1,D_2,D_3,D_4	Rectifiers Diodes 4x1N4004
R	Tubular Fluorescent Lamp 40W
C_B	Electrolytic Capacitor / 100 µF 200Vdc

B. Magnetizing Inductance

The approach done in section *II.C* allows calculate the magnetizing inductance by (14) based on analysis of electronic ballast as relay control system, resulting in L_m= 688 µH. The zener diode is chosen $V_{Z1\text{-}4}$=12 V, which are included in the design. The turns ratio of the toroidal current transformer is determined by relation of secondary transformer and primary current. As was seen in Section *E* the simple determination of magnetizing inductance is not sufficient to guarantee the self-oscillation of the drive circuit, it makes necessary analysis of stability related with P point. It determines that P point is a possible operation point with self-sustained oscillation associated when the conditions are satisfied.

IV. Simulation Results

In order to demonstrate the performance of electronic ballast simulation results are obtained from schematic circuit shown in Fig. 9. The fluorescent lamp is modeled by a tangent function [7].

The employed model gives more accuracy in the final SOEB design. The assumptions to simplify the simulation are related bellow:

-The rectified line filtered waveform in C_B capacitor is considered a constant voltage source.

-Two switches in series simulate the diac in the starting.

-The resistive losses in the elements were considered negligible.

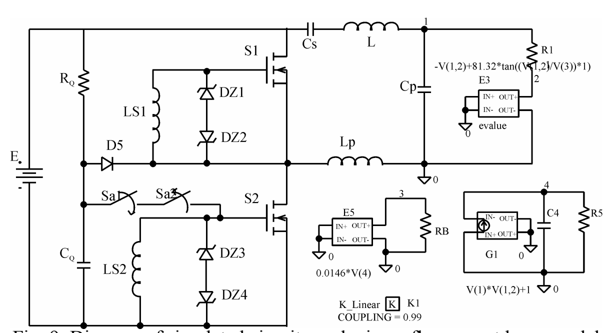


Fig. 9. Diagram of simulated circuit employing a fluorescent lamp model

The specification data are the same of the designed prototype in Table I. Fig. 10 shows the waveforms obtained from simulation. Fig. 10(a) shows the gate-source voltage in the mosfet. Fig. 10(b) shows the S_2 Mosfet voltage applied in the resonant filter and resonant current, and Fig. 10(c) and Fig. 10(d) are shown voltage and current in the switch, and high frequency voltage and current in the lamp respectively.

These results demonstrate the efficiency of the design methodology, what helps in the implementation of electronic ballast.

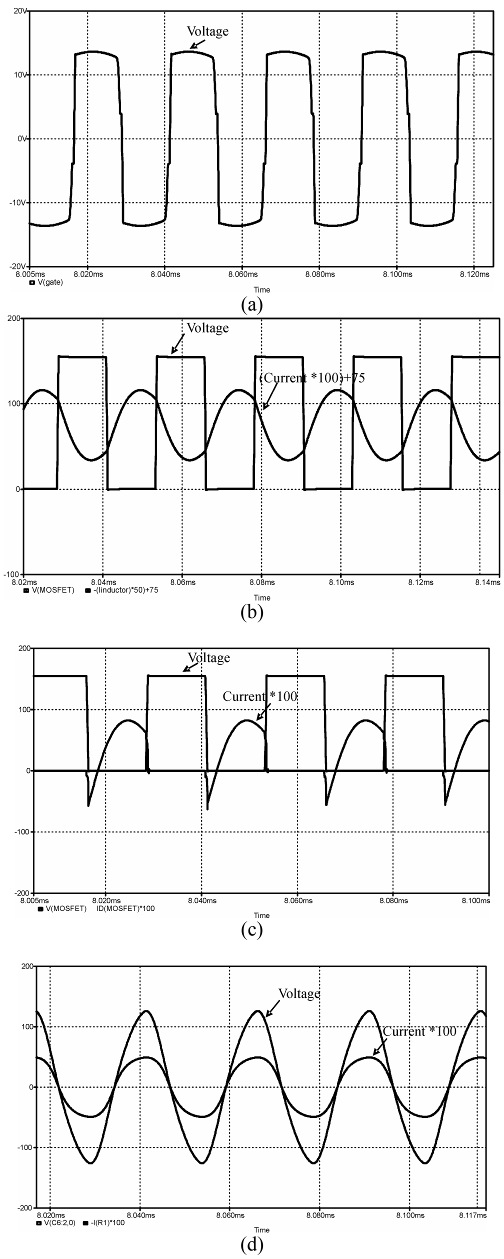


Fig. 10. Simulation Results (a) Gate voltage (b) Voltage and current applied in the filter (c) Switch Voltage and current; (d) Lamp voltage and current with f_s=40 kHz

V. EXPERIMENTAL RESULTS

According the specifications in Table I a 40 W self-oscillating electronic ballast prototype was build according the scheme of Fig. 1. A high frequency series-parallel resonant filter, which eliminates the highest output current order harmonic components, was employed.

Table II shows the complete employed prototype parameters. A self-oscillating gate drive was employed with the design methodology presented in section III.

Fig. 11 shows the experimental results obtained from the prototype of Fig. 1. Fig. 11 (a) shows the gate voltage in one of the gate drives of self-oscillating electronic ballast. The measured switching frequency at the gate drive of f_S=39.35 kHz. Fig. 11 (b) shows the resonant current and applied voltage in the filter. Fig. 10(c) shows switch voltage and current achieving ZVS operation, and Fig. 11 (d) shows the voltage and current in the lamp in high frequency f_s = 39.35 kHz. The experimental results was obtained, and the measured efficiency η = 92.5 %. The aim of this work is achieved when the approach can keeps to parameters of the self-oscillating circuit.

VII. CONCLUSION

This paper proposes a simple and efficient design method of the self-oscillating drive circuit. The SOEB is represented as a SISO control system to obtain the main drive circuit parameters. Some assumptions allows to obtain an expression for the design of the magnetizing inductance using control tools. The stability analysis using extended Nyquist criterion and the describing function method helps to validate the design. The presented design methodology allows an understanding the nonlinear behavior of the SOEB, it gives support to obtain a self sustained oscillation. Simulations and experimental results are presented to validate and to demonstrate the performance feasibility of the proposed solution.

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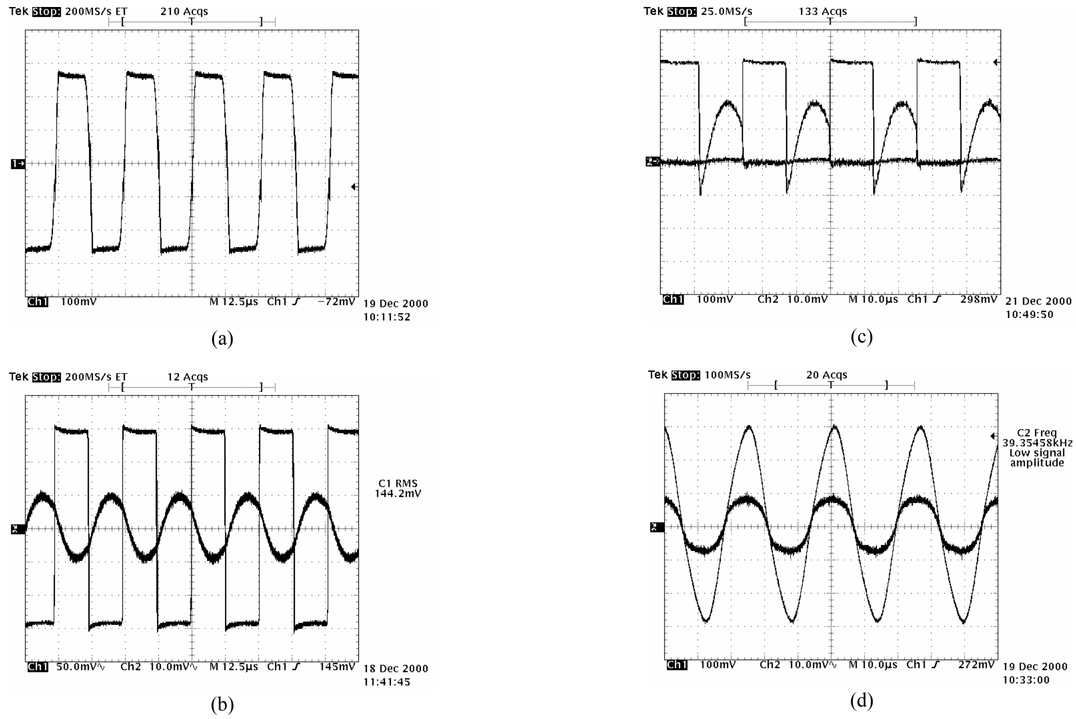

Fig. 11. Self-oscillating electronic ballast experimental results (a) Gate voltage (5 V/div, 10 µs/div); (b) Voltage and current applied in the filter 50V/div, 500 mA/div, 12.5 µs/div) (c) Switch Voltage and current (50 V/div; 500 mA/div; 10 µs/div); (d) Lamp voltage and current and current (50 V/div; 1A/div; 10 µs/div)