AN ELECTRONIC BALLAST WITH HIGH POWER FACTOR FOR COMPACT FLUORESCENT LAMPS[*]

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Abstract - This paper introduces a new low cost, high power factor electronic ballast for compact fluorescent lamps. The proposed ballast uses the power factor correction and a half-bridge converters integrated. Another feature of this work is that the self-oscillating technique is used. The MOSFET's gate drive can be implemented with simplicity and low cost. Theoretical analysis is presented and a very simple design methodology is obtained since the integrated topology can be treated separately, as two independent converters. Simulation and experimental results are provided to verify the principle of operation and the high power factor of the proposed topology.

1. INTRODUCTION

The rational utilization of energy has been encouraged in recent years. Artificial lighting has an important responsibility on the consumption of overall generated electricity. The incandescent lamps have been replaced by fluorescent lamps due to its higher efficiency and longer lifetime when compared with the first one.

The Compact Fluorescent Lamps have been an attractive choice because of its simplicity to substitute the incandescent lamps.

As well as all gas discharge lamps, the fluorescent lamps need a ballast to prevent their destruction by excessive current because of their negative impedance. The electromagnetic ballasts have been replaced by electronic ballasts because of theirs widely known advantages [1].

In Fig. 1 a self-oscillating half-bridge series-parallel resonant converter is shown. The majority of the available Compact Fluorescent Lamps utilizes this topology for the electronic ballast nowadays.

At start-up, high voltage is needed to ionize the lamp. Since the lamp can be considered an open-circuit before ionization the self-oscillating technique provides this high voltage. An evident problem of this topology (Fig. 1) is its input current. The input stage is a full-wave rectifier with a capacitive filter, so the input current waveform becomes like a pulse, the power factor becomes small and harmonic currents appear. A possible solution is to make use of a preregulator stage of power factor correction based on a boost converter. Nevertheless, this solution increases the cost and size because of employment of two stages of power processing.

This work proposes an integrated topology. The power factor correction and the resonant power inversion converters are combined on a single power processing stage. Thus, the number of controlled semiconductors is reduced, consequently, cost and size too.

2. THE PROPOSED CIRCUIT AND PRINCIPLE OF OPERATION

The circuit shown in Fig. 2 is the resonant power inverter stage. Since the converter operates at high frequency the fluorescent lamps can be modeled as a resistive load [5], [6]. The voltage source E could be a large capacitor with a negligible ripple.

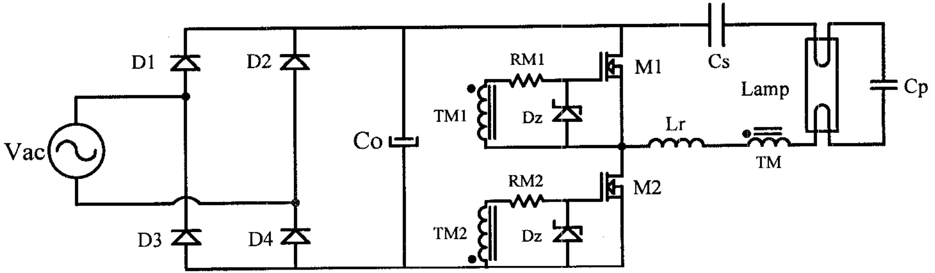

Fig. 1 - A self-oscillating half-bridge series-parallel resonant converter used in electronic ballast for compact fluorescent lamp.

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[*] **Patent required**

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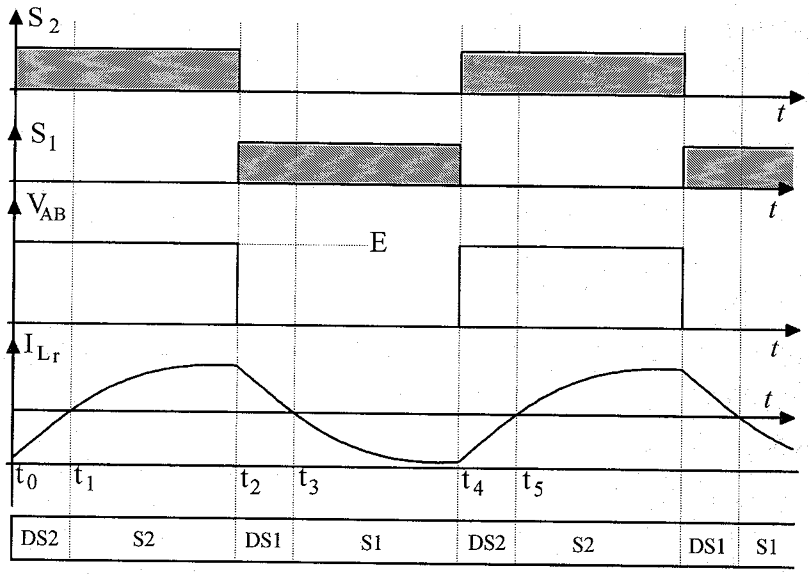

Fig. 3 - Theoretical main waveforms of the inverter.

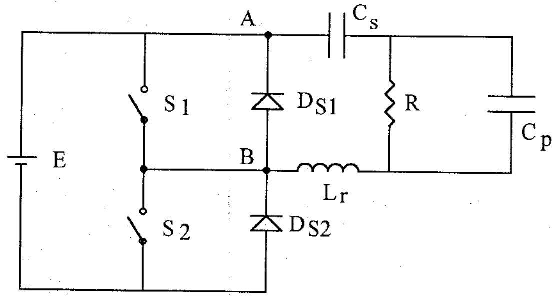

Fig. 2 - The resonant power inversion stage.

If the switching frequency is higher than the resonant frequency the ZVS is ensured and at steady-state the topology has the theoretical idealized relevant waveforms depicted in Fig. 3.

Fig. 4 shows a circuit that can be used to correct the power factor in a topology that utilizes direct rectification of AC input voltage to produce a DC voltage. This technique employs a boost converter operating at discontinuous conduction mode that manages the input current to follow the waveshape of the AC input voltage [2], [3].

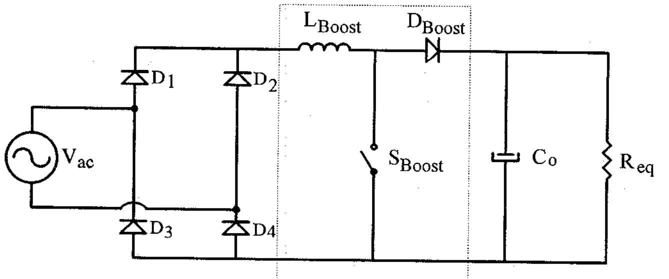

Fig. 4 - Boost converter used for power factor correction.

The waveshape of L_{Boost} current is shown in Fig. 5. In this case, for the sake of understanding and visualization the switching frequency was attributed with a low value, only twenty times higher than the frequency of the AC input voltage. When the converter operates at high switching frequency the harmonics of the input current can be almost eliminated with a small size filter.

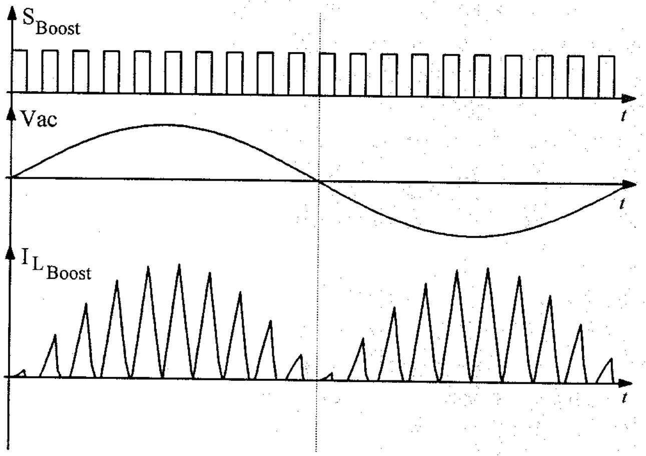

Fig. 5 - L_{Boost} current waveform of the boost converter operating at discontinuous conduction mode.

If the two converters examined above are in cascade operation as shown in Fig. 6, a high power factor topology can be obtained. Nevertheless, this solution increases the cost and size because of the employment of three semiconductor switches and a gate drive for the S_{Boost} switch.

Fig. 7 shows the proposed solution that eliminates one semiconductor switch. In this topology, the switch S_2 is utilized by both boost and the resonant power inversion converters. Thus, a single power processing stage is obtained.

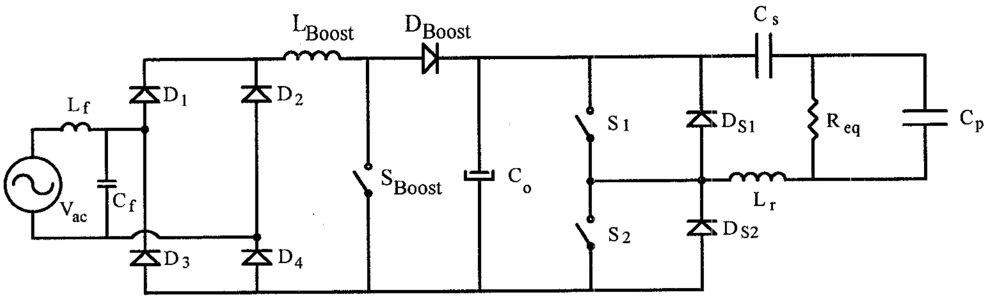

Fig. 6 - Boost and inverter converters at cascade operation

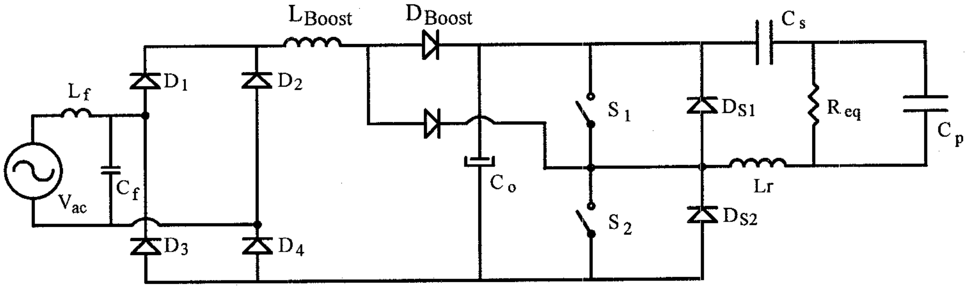

Fig. 7 - Proposed topology

3. MATHEMATICAL ANALYSIS

The following assumptions are made to establish the mathematical analysis:

- The proposed topology can be analyzed as two independent converters: the power factor correction stage and the inverter stage;
- At start-up the fluorescent lamp will be considered an open-circuit and after the ionization, at steady-state, it will be assumed as a resistive load.

Design of the resonant parameters:

At start-up, the self-oscillating technique provides a start-up resonant frequency ($\omega_{OSStart\text{-}Up}$) that will be made equal to the switching frequency ($\omega_{Switching}$). The equation (1) gives the relationship between the resonant parameters and the start-up resonant frequency.

$$\omega_{OSStart-Up} = \omega_{Switching} = \frac{1}{\sqrt{L_r \cdot \left(\frac{C_S \cdot C_P}{C_S + C_P}\right)}} \qquad (1)$$

The steady-state resonant frequency ($\omega_{OSRunning}$) can be expressed by the following equation:

$$\omega_{OSRunning} \cong \frac{1}{\sqrt{L_r \cdot C_S}} \qquad (2)$$

If the switching frequency is higher than the steady-state resonant frequency the ZVS is ensured. Assuming that:

$$\omega_{Switching} = 4 \cdot \omega_{OSRunning} \qquad (3)$$

Fig. 8 shows the equivalent circuit of the inverter, at steady-state, with the resonant parameters, where R is the resistive model of the fluorescent lamp. The voltage source shown in the Fig. 8 has a DC component that is filtered by the series capacitor (C_S) so, the relevant waveform of the voltage source is a square wave. Equation (4) shows the relationship between the lamp rated voltage and the fundamental component of the voltage source (it is assumed to be a square wave) at frequency domain.

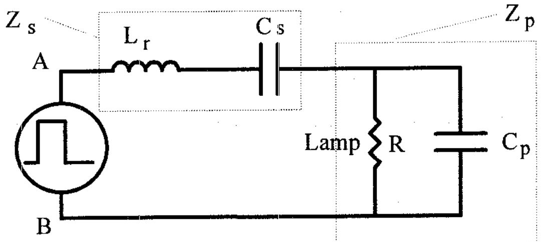

Fig. 8 - Equivalent circuit of the inverter.

$$\left|\frac{V_{Lamp}(j\omega)}{V_{AB}(j\omega)}\right| = \left|\frac{Z_P(j\omega)}{Z_S(j\omega) + Z_P(j\omega)}\right| \qquad (4)$$

From equations (1), (2), (3) and (4) the resonant parameters are given by:

$$C_S = 15.\frac{V_{Lamp}}{Vin}.\frac{1}{R.\omega_{Switching}} \tag{5}$$

$$C_P = \frac{C_S}{15} \tag{6}$$

$$L_r = \frac{16}{C_S.\left(\omega_{Switching}\right)^2} \tag{7}$$

Design of the Boost Inductor

In agreement with [3] the Boost Inductor can be calculated with the following equations:

$$D = 1 - \alpha \tag{8}$$

$$\alpha = \frac{V_{PK}}{V_O} \tag{9}$$

$$Y_1(\alpha) = -2 - \frac{\pi}{\alpha} + \frac{2}{\alpha.\sqrt{1-\alpha^2}}.\left[\frac{\pi}{2} + \tan^{-1}\left(\frac{\alpha}{\sqrt{1-\alpha^2}}\right)\right] \tag{10}$$

$$L_{Boost} = \frac{V_{PK}^{\ 2}}{\omega_{Switching}.P_O}.\frac{(1-\alpha)^2.Y_1(\alpha)}{\alpha} \tag{11}$$

where:

D - duty cycle

V_{PK} - peak value of the input voltage

V_O - output voltage to supply the inverter stage

P_O - rated power of the fluorescent lamp

4. DESIGN EXAMPLE

The following input data were considered in a design example:

- rms AC input voltage: *110 V;*
- compact fluorescent lamp rated power: *20 W;*
- compact fluorescent lamp rms voltage: *110 V*;
- switching frequency: *50 kHz.*

Boost Inductor:

The self-oscillating technique incites the duty cycle to assume the following value: D = 0.5, so α = 0.5

$$\alpha = \frac{V_{PK}}{V_O} \Rightarrow V_O = \frac{V_{PK}}{\alpha} = \frac{\sqrt{2}.110}{0.5} = 311\text{V}$$

$$Y_1(0.5) = 1.391$$

$$L_{Boost} = \frac{\left(\sqrt{2}.110\right)^2}{2.\pi.50.10^3.20}.\frac{(1-0.5)^2.1.391}{0.5} = 2.676 \text{ mH}$$

Resonant parameters:

$$V_{AB} = \frac{4.\left(\frac{V_O}{2}\right)}{\pi} \cong \frac{4.\left(\frac{311}{2}\right)}{\pi} \cong 198 \text{ V}$$

$$R = \frac{V_{Lamp}^{\ 2}}{P_O} = \frac{110^2}{20} = 605\ \Omega$$

$$C_S = 15.\frac{110.\sqrt{2}}{198}.\frac{1}{605.2.\pi.50.10^3} = 62 \text{ nF}$$

$$C_P = \frac{C_S}{15} = \frac{62.}{15} = 4.133 \text{ nF}$$

$$L_r = \frac{16}{C_S.\left(\omega_{Switching}\right)^2} = \frac{16}{62.\left(2.\pi.50.10^3\right)^2} = 2.615 \text{ mH}$$

The simulation and experimental results were obtained with the following commercial values for the capacitors:

$C_S = 68$ nF $\qquad C_P = 4.7$ nF

5. SIMULATION RESULTS

The topology designed was simulated in a digital computer and results are shown in Fig. 9. This figure shows the input current and input voltage. The power factor obtained by simulation was 0.992 with a THD of 12.6% at the input current.

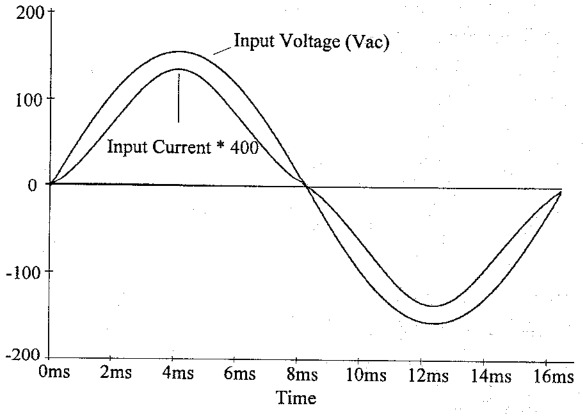

Fig. 9 - Input voltage and input current (x400) obtained by simulation.

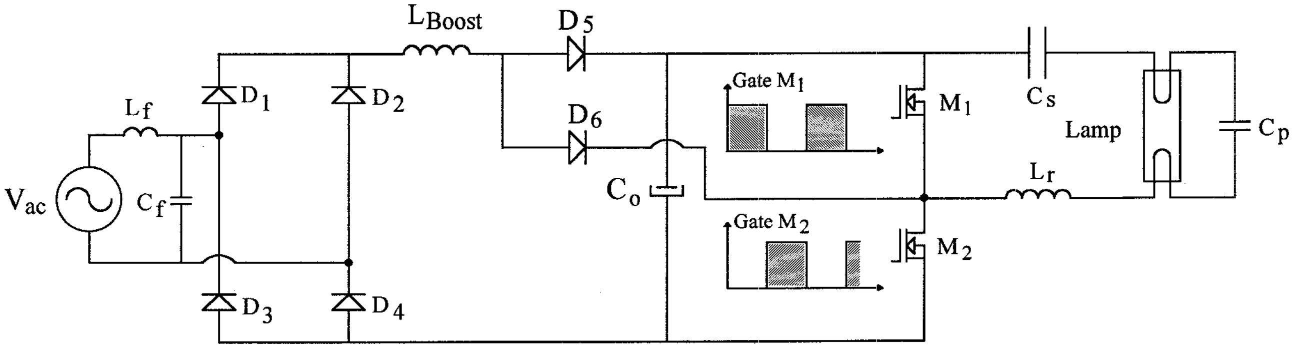

Fig. 10 - Power diagram of the implemented electronic ballast.

EXPERIMENTAL RESULTS

In order to verify in laboratory the operation of the electronic ballast, a prototype has been designed and assembled (Fig. 10).

A 50 kHz switching frequency with 0.5 duty cycle was imposed by an external gate drive circuit.

The parameters and the component specifications for the prototype are the following:

- Vac = 110 V AC 60Hz
- Lf = 15.1 mH
- Cf = 68 nF
- D1-D4 - MUR120
- D5-D6 - MUR140
- L_{Boost} = 2.5 mH
- Co = 22 µF/ 350V
- M1, M2 - IRF730
- Cs = 68 nF
- Cp = 4.7 nF
- Lr = 2.4 mH

Typical waveforms were obtained with the prototype and are shown in the figures 11 to 16.

In Fig. 11 is shown the lamp voltage and current.

The resonant inductor current I_{Lr} is standed out in Fig. 12.

Fig. 13 shows the voltage and current of the MOSFET M_1 where it is possible to see that the MOSFET's commutate under zero voltage, assuring low switching losses.

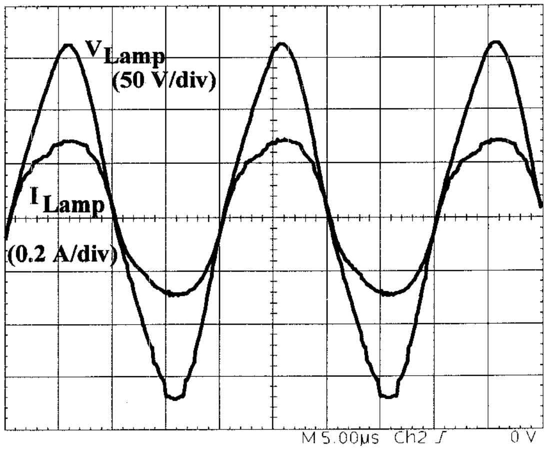

Fig. 11 - Lamp voltage and current.

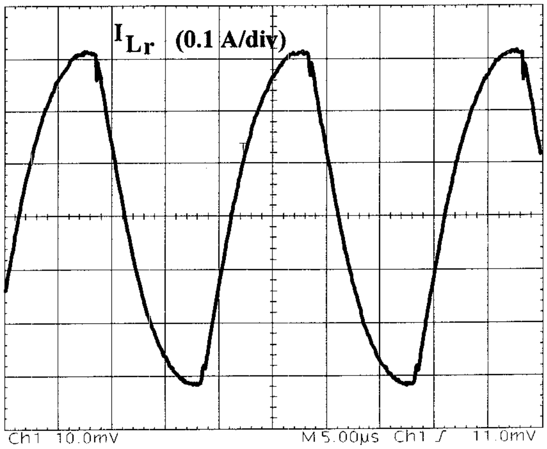

Fig. 12 - Resonant inductor current.

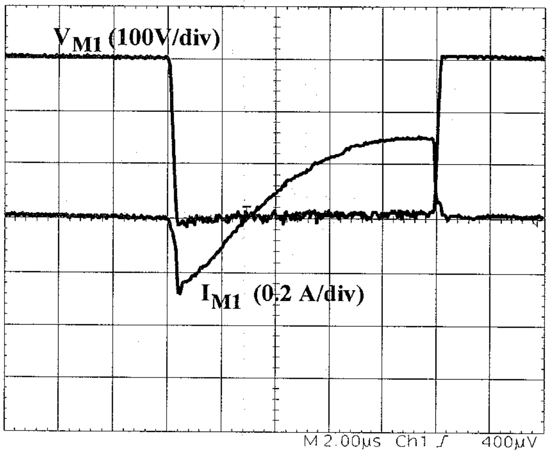

Fig. 13 - Voltage and current of MOSFET M_1.

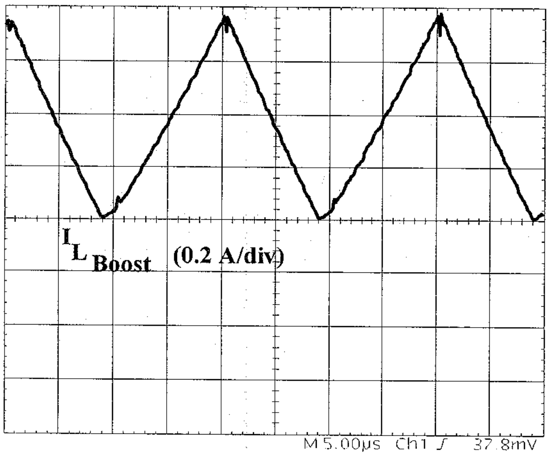

Fig 14 - Boost inductor current at peak of the input voltage.

In Fig. 14 it is possible to see the critical conduction mode that takes place in the boost inductor during the peak of the input voltage. The voltage across capacitor C_o with a negligible ripple in Fig. 15 demonstrates that the stroboscopic effect in the fluorescent lamp is not present.

In Fig. 16 it is shown the obtained input voltage and current of the electronic ballast. The measured power factor for 20 W (lamp rated power) was equal to 0.992 with a THD of 13% in the input current.

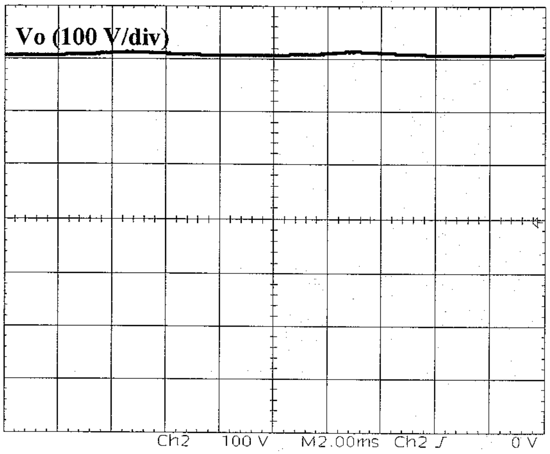

Fig. 15 - Voltage across capacitor C_o.

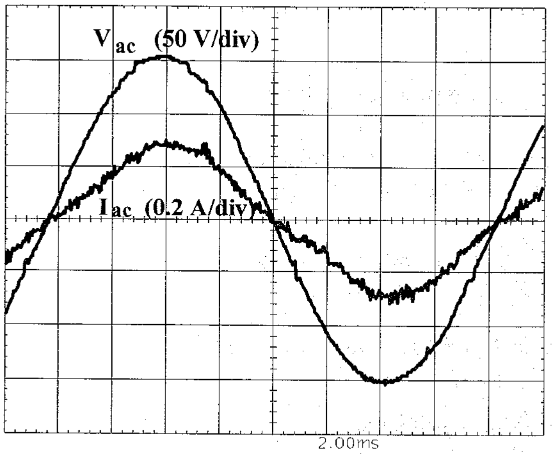

Fig. 16 - Input voltage and input current.

To verify the proposed ballast with the self-oscillating technique, a commercial ballast (220 V rms line voltage) operating at 33 kHz of a 20W compact fluorescent lamp was used. The Boost inductor was calculated for these specifications (switching frequency and lamp rated power) and it was added to the ballast. Fig. 17 shows the commercial ballast diagram and Fig. 18 the same circuit with the addition of the designed stage of power factor correction. The resonant parameters are unknown.

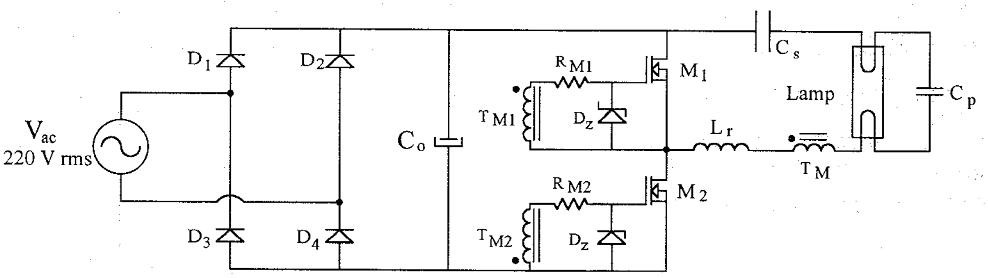

Fig. 17 - A 20W / 33 kHz commercial electronic ballast.

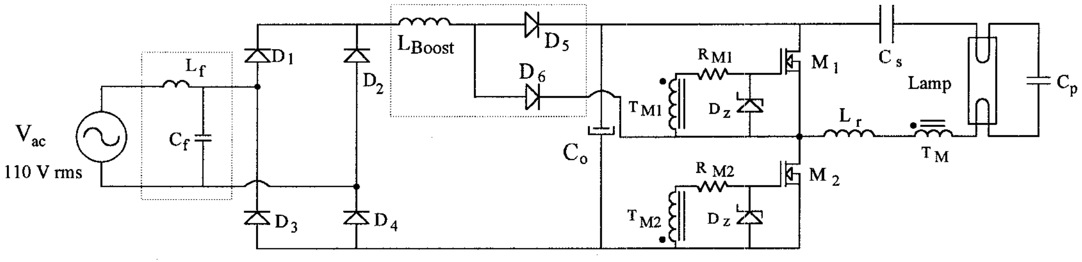

Fig. 18 - Commercial electronic ballast with the stage of power correction and input filter (dotted).

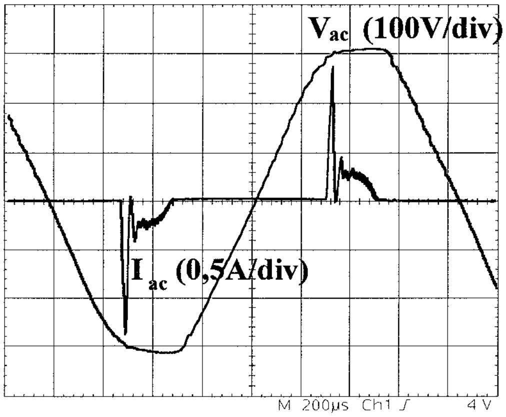

Fig. 19 - Input voltage and input current obtained with the circuit of Fig. 17.

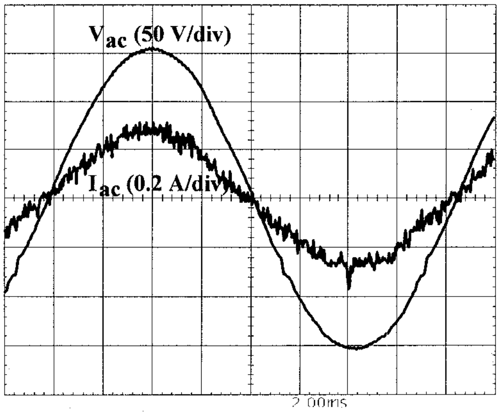

Fig. 20 - Input voltage and input current obtained with the circuit of Fig. 18.

Fig. 19 shows the input voltage and input current obtained with the circuit presented in Fig. 17 (Power Factor equal to 0.46). In Fig. 20 it is possible to see the results obtained in the input current of the modified commercial electronic ballast (Power Factor equal to 0.992).

CONCLUSIONS

This paper introduced a new electronic ballast topology with high power factor for compact fluorescent lamps. The topology can be treated as two independent converters: the inverter and the power factor correction stage. These converters can be designed separately. The utilization of the self-oscillating technique allows that the MOSFET's gate drive can be implemented with simplicity and low cost.

Mathematical analysis, a design procedure and a design example have been performed. Experimental results have been obtained for one 20 W compact fluorescent lamp operating at 50 kHz switching frequency (imposed) and 110 V rms line voltage. Also, a commercial electronic ballast, self-oscillating, was used to demonstrate simplicity of the design methodology and the efficiency of the proposed topology. The results confirmed the expected high power factor of the electronic ballast, without introducing stroboscopic effect.

ACKNOWLEDGMENT

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REFERENCES

[1] Peter Wood, "High Frequency Discharge Lamp Ballasts Using Power MOSFET's, IGBT's and High Voltage Monolithic Drivers", PCI Proceedings - June 1989, pp 307 - 324.

[2] J. L. Freitas Vieira, Márcio A. Có & Luciano D. Zorzal, "High Power Factor Electronic Ballast Based on a Single Power Processing Stage", PESC'95, pp.687-693.

[3] Kwang-Hwa Liu & Young-Lin Lin, "Current Waveform Distortion in Power Factor Correction Circuits Employing Discontinuous-Mode Boost Converters", IEEE PESC, 1989, pp.825-829.

[4] D. Ruiz Caballero, & Ivo Barbi, "Electronic System for Fluorescent Lighting: Contribution for Resonant Converter Parameter Design", Brazilian Power Electronics Conference - COBEP'91, pp.56-59.

[5] P. A da Silva Jr., A. J. Perin, & I Barbi., "Electronic Ballast for High Performance of Fluorescent Lamps", Brazilian Power Electronics Conference - COBEP'95, pp.489-494.

[6] U. Mader & P. Horn, "A Dynamic Model for the Electrical Characteristics of Fluorescent Lamp", IEEE-IAS / 92, Proceedings, pp. 1928-1934.