MULTIFREQUENCY ELECTRONIC BALLAST FOR T5 FLUORESCENT LAMPS WITH VOLTAGE-PREHEATING

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***Abstract* – In this paper it is analyzed, simulated and experimentally tested an electronic ballast for a 28W/T5 fluorescent lamp with voltage-preheating. The lamp is driven by a LC series, C parallel resonant filter. During preheating period the lamp filaments are driven by secondary winding of a LC series resonant filter, after preheating time this circuit is switched off, eliminating filament power. This work presents a rapid cycle test to determinate the compatibility between fluorescent lamp and ballast.**

***Keywords* – Electronic ballast, T5 fluorescent lamp.**

I. INTRODUCTION

In the last years, it have had an evolution in use of the more efficient illuminating systems, certainly motivated by increase of energy cost in most countries. The investment necessary to generate and to distribute electric energy is so large that governments adopt programs to promote the use of more efficient equipment systems. The conservation of electric energy has as main objective to improve the way to use the energy, without losing the comfort and the advantages that it provides. It means to reduce consumption, reducing costs, without losing, at any moment, the efficiency and the quality of the services.

To increase the efficiency in lighting systems some alterations are currently accomplished, as example: to substitute fluorescent lamps by incandescent lamps, the use of electronic ballasts in place of magnetic ballasts, the use of more efficient fixtures and lamps.

For more efficient fluorescent lamps, the latest technologies have been incorporated and new substances been used in combination with new coating technologies. Hanover Fair in 1995, great European manufacturers had presented the T5, a new fluorescent lamp with less diameter, shorter, more efficient and developed for being the successor of T8 [1].

Nowadays, the T5 fluorescent lamps are little used in Brazil, because it's more expensive than T8 fluorescent lamps, however, as the T8/32W fluorescent lamps are substituting the 40W/T12, in the future 28W/T5 will go to substitute the 32W/T8. The T5 fluorescent lamps had been developed especially to operate with electronic ballast and provide high efficiency when fed in high frequency. As these lamps are more expensive than standard fluorescent lamps, its lifetime is a very important parameter in the project of the electronic ballast.

This work presents analysis, development of an electronic ballast with voltage preheating for one 28W/T5 fluorescent lamp and rapid cycle test to determine the rated lifetime of lamp with the proposed electronic ballast.

II. RAPID CYCLE TEST FOR T5 FLUORESCENT LAMPS

To determinate the rated lifetime of fluorescent lamps, the Illuminating Engineering Society of North America (IESNA) specifies a test method using a large sample of lamps. This method consists of burning cycles, at which the lamps remain ON during 3 hours and OFF during 20 minutes. Using this method, it is possible to determine the mean time between failures (MTBF). This method may take up to 3 years to get results for a specific lamp and ballast. Recently, rapid cycle methods, intended to reduce this testing time have been published [2].

Fluorescent lamp lifetime is determined by the loss of the electron-emitting coating on the electrodes. Some of the coating is eroded from the electrodes each time the lamp is started, and additional evaporation and erosion also occurs during lamp operation. Electrode temperature directly affects the evaporation and erosion of the emitting material, therefore affecting the lamp lifetime. Since electrode temperature is hard to measure directly, electrode resistance may be used as a related parameter [3] and [4]. A method proposed in [2] establishes the OFF time for rapid cycle test for T8 lamps and compact fluorescent lamps, based in the measurement of the electrode resistance change after power extinguishes in the lamp. The same analysis will be applied in this work to define the appropriate OFF time for rapid cycle test for T5 fluorescent lamp. The OFF time for rapid cycle test is determined by how long electrode temperature takes to stabilize. From three of the major lamp manufacturers, two 28W/T5 fluorescent lamps were randomly selected and measured from each manufacturer. The results obtained for the three lamp companies were basically the same, therefore, results for only one manufacturer will be shown. After the first minute the lamp resistance decreases 80% and, five minutes latter, 95%. Only after eleven minutes the electrode resistance reaches the rated lamp resistance 100% at ambient temperature, as shows in Fig. 1.

These results are similar to T8 lamps and demonstrate that, for any rapid test cycles, if the lamp OFF time is less than 5 minutes, the electrode does not cool completely. This reduces the damage to the electrode during lamp starting, and will probably result in overestimation of the lamp's MTBF [2]. Choosing an appropriate ON time is also very important, some lamp manufacturers suggest that during rapid cycle test

0,5 to 7 minutes ON time should be used to help the electrodes "cure" [5].

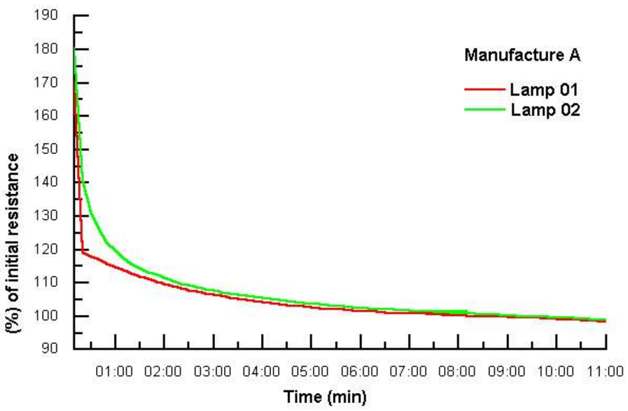


Fig. 1. "A" Manufacturer lamp resistance (%) versus time.

III. PROPOSED TOPOLOGY

For a long lifetime and a stable light output, the electronic ballast should fulfill the strict requirements for preheating and steady state operation, as following [6]:

- The filament should be first heated to an optimum temperature (about 1000K). Depending on the available time for preheating, the ballast should provide a preheating voltage or current within the limits, as shown in the Table I. Too low or high temperatures will damage the filaments coating, due to sputtering and/or evaporation;

- During filament preheating, 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 filament's optimum temperature is reached, the voltage of the lamp should rise to the ignition level. Limits are shown in Table II;

- Once the lamp is ignited, the ballast should behave as a current source to ensure stable operation. The crest factor of the lamp's current should not exceed 1.7.

TABLE I
T5 standard linear lamps–Voltage-controlled preheating

Lamp type	Preheating Voltage	Preheating time 0,5s	1,0s	1,5s	2,0s	3,0s	R_{SUB}
14, 21, 28, 35W	Min. V	8,8	7,0	6,4	6,0	5,6	30Ω
	Max. V	11,6	9,3	8,4	7,9	7,4	30Ω

Adapted from Philips Silhouette T5 [7].

TABLE II
T5 standard linear lamps – Lamp ignition

Lamp Type, Ambient Temperature Range		10°C to 60°C
14W		
max. during preheat period	V (rms)	130
min. for ignition	V (rms)	230
21W		
max. during preheat period	V (rms)	200
min. for ignition	V (rms)	340
28W		
max. during preheat period	V (rms)	240
min. for ignition	V (rms)	425
35W		
max. during preheat period	V (rms)	275
min. for ignition	V (rms)	530

Adapted from Philips Silhouette T5 [7].

Selection of a preheating method depends on the types of filaments and on time available for ignition lamps [8]. Two fundamentally different drivers could be used for filament preheating [6] and [8]: a current source or a voltage source.

A. Current Source Filament Preheating

A circuit diagram of conventional half-bridge series-resonant parallel load electronic ballast, used in many commercial types of ballast, is shown in Fig. 2, in which the ballast has the following demerits:

- It always takes the same time interval for preheating filaments regardless of hot or cold filaments. It would result in sputtering when filaments are hot [8].

- The filaments are placed inside the LC resonant filter (C_S, L and C_P), resulting in excessive lamp voltage during preheating and excessive filament current during runtime [6].

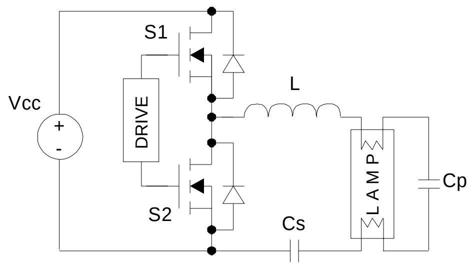


Fig. 02. Circuit diagram of a conventional series-resonant parallel-load electronic ballast.

On the other hand, the ballast using a series resonant inverter presents some advantages, like simple configuration and high efficiency. In order to reduce the intrinsic disadvantages of this topology, Chin et al [3] presents an alternative method to achieve a current filament preheating, the circuit is shown in Fig. 03.

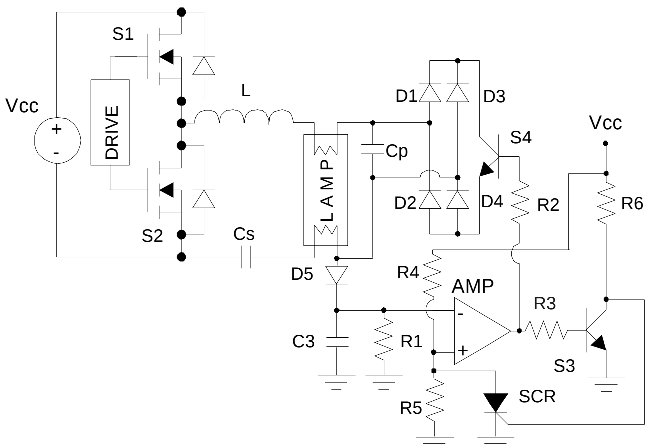


Fig. 03. Electronic ballast with current source filament preheating.

This method is simple and consists of shunting the lamp with an auxiliary switch. During the preheating operation, the lamp voltage may be maintained at zero to eliminate the glow current, by turning on the auxiliary switch S4. Once the cathode temperature has reached the optimum emission temperature, the shunt switch is turned off. Then, an ignition voltage is applied to start the lamp. As a result, the lamp may be started up without the adverse effects on the lamp lifetime. The main drawback of this method is that, after the lamp ignition, the filament power consumes about 0,5W for each filament.

B. Voltage Source Filament Preheating

An alternative approach for filament's preheating is to drive the filaments by voltage source, as shown in Fig. 04. This circuit is based on a multi-resonant converter, using the secondary windings of the resonant inductor to preheat the filaments.

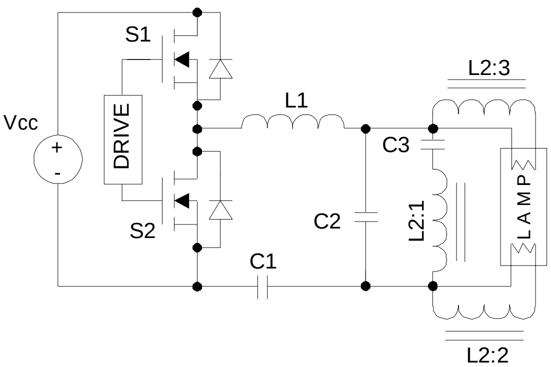


Fig. 04. Electronic ballast with voltage source filament preheating.

This circuit consists of two resonant filters the LC series C parallel (L_1, C_1 and C_2) powering the lamp and a series resonant filter (L_2, C_3) that is applied during preheating period to drive the filaments.

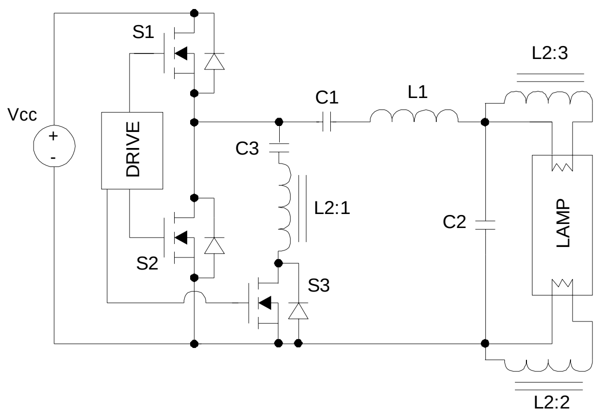


Fig. 05. Topology of proposed ballast based on a voltage source filament preheating.

The circuit showed in Fig. 04 keeps the filaments heated after lamp ignition, consuming energy in the filament. To eliminate this disadvantage the electronic ballast proposed, shown in Fig. 05, has a switch (S_3) in series with the LC series filter, after the preheating period the switch S_3 is turned off blocking the filament's power consumption.

The drive works in two different frequencies, preheating frequency and RUN frequency. Where the first one is higher than the second one, as shown Fig. 06. The LCC filter was designed to work at RUN frequency and the LC series filter was designed to operate at preheating frequency. During preheating operation, the secondary windings ($L_{2:2}$; $L_{2:3}$) supply the filaments and the LC series C parallel filter keeps the low voltage across the lamp. After this period the frequency changes to the RUN frequency and a high voltage is applied to capacitor C_2 providing the necessary voltage for lamp ignition.

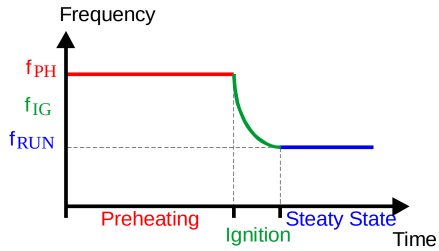


Fig. 06. Warm up, start up and steady state frequency range.

IV. DESIGN PROCEDURE

The design of the proposed electronic ballast involves two main resonant filters. The first on is the LC series C parallel, and second one is a simple LC series filter.

A. LCC Filter

The LCC filter design is based on [9]. This method consists on choosing the correct phase angle (ϕ) of the LCC filter. The phase angle methodology uses the following approximations:

- Fundamental approximation [10];
- The fluorescent lamp is represented by an equivalent model in steady state *(R)* and in the starting scenario *(10R)* [12];
- The filters' components are ideal and time invariant.

1) Phase Angle (ϕ)

The phase angle is determined in order to guarantee the lamp ignition, the lamp rated power in steady state and to achieve soft switching commutation with zero-voltage switching (ZVS).

The phase angle is determined by (1):

$$\phi = \arctan\left[\frac{\omega}{R}\left(\left(L_1 - \frac{1}{C_1\omega^2}\right)\left(1 + C_2{}^2R^2\omega^2\right) - R^2C_2\right)\right] \qquad (1)$$

Where R is the lamp resistance, $\omega=2\pi f_S$, ϕ is the filter impedance phase angle and V_{rms} is the *RMS* value of the fundamental voltage.

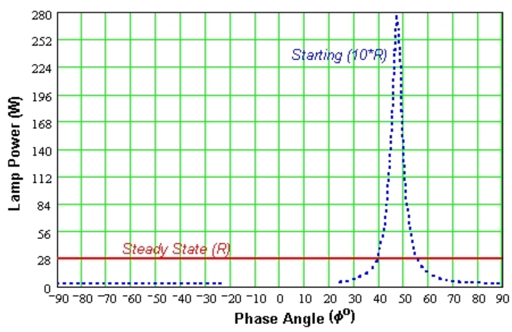


Fig. 07. Power in fluorescent lamp in steady state (*R*) and starting (*10R*) versus phase angle (ϕ).

To provide the lamp starting voltage, nominal power in steady state and operation with ZVS, ϕ may be graphically obtained by plotting P versus ϕ (Fig. 07), considering the power in the lamp starting and steady state by:

$$P(\phi)=\frac{V_{rms}{}^{2}R\left(R^{2}\omega^{2}C_{2}(\phi)^{2}+1\right)}{R^{2}+\omega^{2}\left[\left(L_{1}(\phi)-\frac{1}{\omega^{2}C_{1}}\right)\left(R^{2}\omega^{2}C_{2}(\phi)^{2}+1\right)-R^{2}C_{2}(\phi)^{2}\right]^{2}} \quad (2)$$

2) Parallel capacitor C_2

Through the phase angle (ϕ) determined in Fig. 07, it is possible to determine parallel capacitor (C_2) by:

$$C_{2}(\phi)=\frac{1}{R\omega}\sqrt{\frac{P(R^{2}+(R\cdot\tan(\phi))^{2})}{V_{rms}{}^{2}R}-1} \quad (3)$$

3) Resonant inductor L_1

By choosing a typical C_1 value to block the *DC* component to the fluorescent lamp, the series inductor can be found by (4):

$$L_{1}(\phi)=\frac{R\cdot\tan(\phi)\cdot\omega^{-1}+R^{2}C_{2}(\phi)}{(R^{2}\omega^{2}C_{2}(\phi)^{2}+1)}+\frac{1}{\omega^{2}C_{1}} \quad (4)$$

From (1), (2), (3) and (4) the filter LCC component are determined to fulfill with the requirements to correct lamp power, guaranteeing a waveform with low crest factor.

B. LC Filter

The C3 capacitor, the L2 inductor and the two secondary windings form the LC filter, which's design is based on [11]. This method consists on choosing the correct quality factor Q_L through the parameterized impedance. The main function of the LC filter is to provide the correct filament voltage during preheating operation. This value depends on the lamp type, as shown in Table I. During preheating operation the switch S_3 is turned on and the LC filter is connected to the power circuit. The preheating circuitry may be modified to simplify the circuit analysis, the switches S1, S2 and the source V_{cc} are substituted by a square wave source $V_{E(t)}$, with low level in zero and high level in V_{cc}. Fig. 08 shows the equivalent *AC* circuit.

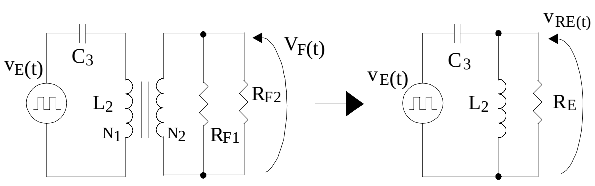


Fig. 08. Equivalent *AC* preheating circuit, (a) filaments of the one lamp (b) filaments reflected to the primary.

The gain of the equivalent *AC* circuit is given by (5) and represents the ratio between output voltage V_{RE} and input voltage V_E. The gain may be used to calculate the *N* (turns ratio).

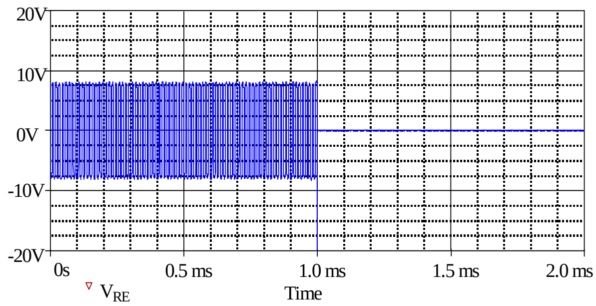
$$\left|\frac{V_{RE}}{V_{E}}\right|=\frac{1}{\sqrt{\left(1-\frac{1}{U^{2}}\right)^{2}+\left(\frac{1}{U.Q_{L}}\right)^{2}}} \quad (5)$$

Where: $Q_{L}=\frac{R_{E}}{\omega_{0}L_{2}}=\omega_{0}R_{E}C_{3}$, $\omega_{0}=\frac{1}{\sqrt{L_{2}C_{3}}}$, $U=\frac{\omega}{\omega_{0}}$ and R_E represents the equivalent filament resistance reflected to transformer's primary winding ($L_{2:1}$).

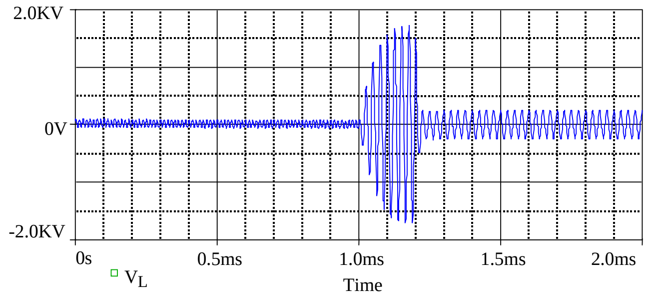
$$\left|\frac{Z(j\omega)}{R_{E}}\right|=\sqrt{\frac{\left(\frac{U}{Q_{L}}\right)^{2}+\left(U^{2}-1\right)^{2}}{U^{2}Q^{2}+\left(U^{2}\right)^{2}}} \quad (6)$$

V. SIMULATION RESULTS

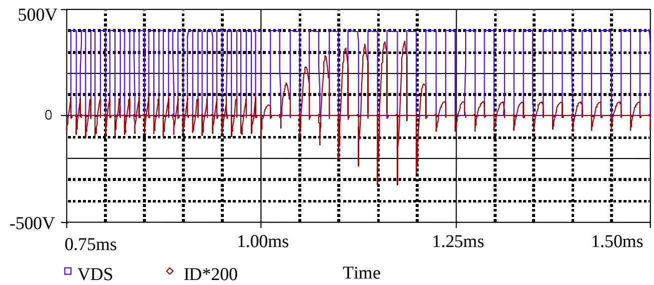
Some simulations were carried out in order to verify the behavior of the proposed ballast under preheating, startup and steady state operation.



(a) Filament voltage.



(b) Lamp voltage.



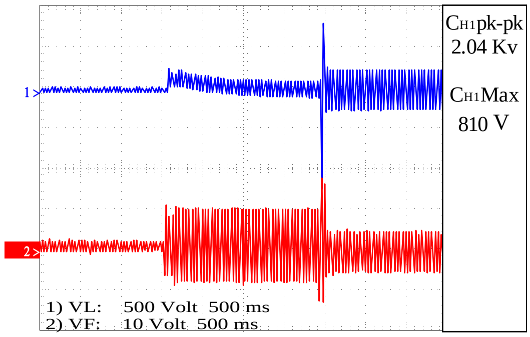
(b) Voltage and current in one of the switches

Fig. 09. Simulation results during preheating, startup and steady state operation.

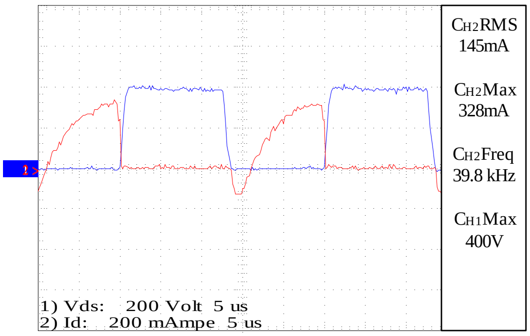
Fig. 9 (a) shows the filament voltage, (b) lamp voltage and (c) voltage and current in one of the switches during preheating, startup and steady state operation. In this simulation the fluorescent lamp was represented by resistance *(R)* in steady state and in the starting scenario the resistance is assumed as *(10*R)*. These simulations results illustrate the feasibility of this system.

VI. EXPERIMENTAL RESULTS

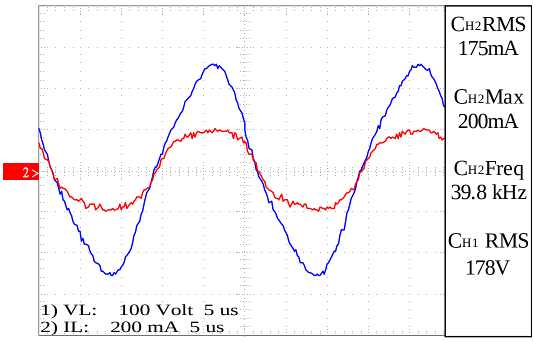
Two electronic ballast prototypes were built for a single T5/28W fluorescent lamp, in order to verify the lamp's MTBF. The first one was a conventional half-bridge series-resonant parallel load electronic ballast prototype without preheating filaments.



(a) Lamp voltage (CH1) and filament voltage (CH2).



(b) Voltage and current in one of the switches



(c) Lamp's voltage and current.

Fig. 10. Waveforms obtained from the prototype on Fig. 11.

The second one is a prototype of the proposed electronic ballast based on a voltage source filament preheating. This circuit is shown in the Fig. 11 and 12. Table III shows the input data specification, resonant filters parameters and the main components of the implemented circuit, and Fig. 10 shows its experimental results. The drive circuit was implemented using the dedicated circuit IR2153, the switching frequency in steady state (f_{RUN}) is 40kHz and in preheating (f_{PH}) is 80kHz. The power factor corrector was implemented with the boost converter working in critical mode, represented by *DC* source (V_{CC}).

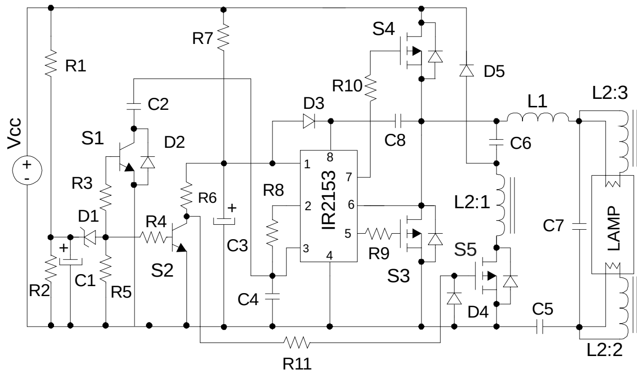


Fig. 11. Prototype circuit of the proposed electronic ballast.

Fig. 12. Prototype of the proposed electronic ballast.

TABLE III
Summarized Parameters

Input Data	
Input Voltage	V_{IN}=220V_{RMS}, 60Hz
Output Power	P=28W
Equivalent Lamp Resistance	R=995Ω
Bus Voltage	V_{CC}=400V_{RMS}
Preheating Time	2 seconds
Steady State Frequency	f_{RUN}=40kHz
Preheating Frequency	f_{PH}=80kHz
Drive Parameter	
R1	Resistor 470kΩ+470kΩ/1/5W
R2	Resistor 82kΩ/1/3W
R3, R4, R5, R6	Resistor 10kΩ/1/3W
R7	Resistor 40kΩ+40kΩ/1/5W
R8	Resistor 8,9kΩ/1/3W
R9, R10, R11	Resistor 56Ω/1/3W
C1, C3	Electrolytic Capacitor 47µF/50V
C2, C4	Plastic Capacitor 1nF/50V
C8	Plastic Capacitor 100nF/50V
D1	Zener Diode 13V/1/2W
D2, D3, D4, D5	Diode 1N4937
S1, S2	Bipolar Transistor BC337
S3, S4	Power MOSFET's IRF830
S5	Power MOSFET's IRF730
CI	Half-Bridge Drive IR2153
Filter Parameters	
C5	Plastic Capacitor 100nF/400V_{DC}
C6	Plastic Capacitor 27nF/400V_{DC}
C7	Plastic Capacitor 3,9nF/2000V_{DC}
L1	Resonant Inductor, 4,4mH
L2:1	Resonant Inductor, 2,4mH
L2:2, L2:3	Secondary Winding, 2,5µH

Fig. 10(a) shows the lamp voltage and the filament voltage during preheating and startup operation. During preheating the filament voltage is 7,5 Vrms and the lamp voltage is 55Vrms. These values fulfill the requirements in Table I and II. Fig. 10(b) shows the voltage and current in switches (S_3) during steady state operation, may be seen that switches operate in ZVS. Fig. 10(c) shows the voltage and current lamp during steady state operation, the waveforms shows that the LCC filter has a correct design, because of the sinusoidal waveform of both. Voltage and current envelopment were verified to show the low crest factor in the lamp. Electrical measurements were done in the proposed electronic ballast and results are shown in Table IV. Simulations and experimental results were found to be very close.

TABLE IV

Electrical Measurements	
Input Power	31,2W
Input Current	0,140A
Power Factor	0,99
Total Current Harmonic Distortion	7,2%
Output Power	27,5W
Output Frequency	39,0kHz
Efficiency	88%
Crest Factor (lamp current)	1,5

VII. DISCUSSION

To verify the compatibility between proposed electronic ballast and T5 fluorescent lamp, two cycle tests were made with three different ballasts, results shown in Table V. The first one uses the cycle time used by ballast manufacturer, 30 seconds ON and 30 seconds OFF, these cycles are repeated until lamp failure. The second one uses the cycle time found on the cooled filament, as seen in section II, 30 seconds ON and 5 minutes OFF. To compare the influence of the preheating filaments in the lamp lifetime was tested an electronic ballast with voltage preheating as proposed, an electronic ballast without preheating (electronic ballast proposed without LC filter) and commercial electronic ballast found in Brazilian market (without preheating).

TABLE V

Electronic Ballast Type	Rapid Cycle Test	
	30s ON and 30s OFF	30s ON and 5min OFF
Electronic ballast with voltage preheating, as proposed	57600 cycles	20160 cycles
Electronic ballast without preheating	1440 cycles	2880 cycles
Commercial electronic ballast, without preheating	1800 cycles	2304 cycles

The first rapid cycle test was conclude after 40 days. The rapid cycle test used by ballast manufacturer determines a minimum number of cycles until the lamp failure. This number takes into account the expected lamp's lifetime and how many cycles occur during real application. As an example, in the most common application the lamp is turned ON and OFF four times in 12 hours, so the minimum expected number of cycles within this period is 6700. Therefore, only the electronic ballast proposed should be approved.

The second rapid cycle test was concluded after 70 days. The lamp manufacturer specifies a rapid cycle test with 30s ON and 4.5 min. OFF, so the minimum expected number of cycles within 70 days is 20000 [7]. In this situation, only the proposed electronic ballast should be approved. However, it is necessary to do some statistical analysis with large lamp samples to assert that T5 fluorescent lamp reached the expected life, when supplied with the proposed electronic ballast.

VIII. CONCLUSION

The proposed multifrequency electronic ballast topology provides a highly controlled preheating process. The filaments are fed by a voltage source with tight tolerance, while the lamp voltage during the preheating period is very low. The circuit was analyzed, simulated and experimentally tested, and the results support the validity of the model developed in this paper. The two resonant filters provide sufficient decoupling between the preheating and the steady state operation, so that each may be designed for optimum performance. Furthermore, the filaments' power is eliminated after the preheating time, increasing system efficiency.

The rapid cycle test point out the importance of the preheating circuit in the T5 lamp lifetime. Therefore, the electronic ballast proposed is an excellent choice for T5 fluorescent lamps. This electronic ballast may be easily implemented for two lamps, adding one more secondary winding to connect lamps in series.

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