Microcontrolled Electronic Ballast for Fluorescent Lamps with High Power Factor, Controlled Luminescence and Presence Detection

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Abstract – This work presents a dual 40W fluorescent lamp lighting system. This converter consists of a power factor correction stage, a half-bridge resonant inverter, a motion detection circuit and a lighting control sensor. An analysis of the boost pre-regulator operating in the transition mode – power supply voltage from 90V to 260V – is presented. This analysis comprises experimental results. An analysis of a half-bridge resonant inverter, followed by an example of the project and experimental results are presented. A microcontroller is used to drive, control and protect the resonant inverter, which was also analyzed according to its operation. Finally, a study of secondary power supplies is carried out for the proposed structure.

I – INTRODUCTION

The structure presented incorporates an electronic ballast with high power factor, multi-voltage input, automatic control of the luminosity and presence detection.

The input stage is composed of a boost converter operating in critical conduction mode. Besides presenting a high power factor at the input, it can operate between a wide range of input voltages (90 to 260V). To control/command the input stage, a CI L6560 from SGS-THOMSON [4] was used.

In order to activate the lamps, the half-bridge resonant inverter will be used, controlled by a PIC12C67I microcontroller from MICROCHIP. The use of an imposed frequency command is made necessary since the resonant inverter's commutation frequency needs to be varied, to therefore obtain a variation in the luminosity. Fig. 1 presents a simplified diagram of the proposed structure.

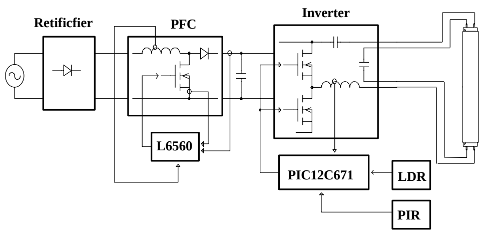

Fig. 1 – Block diagram

The protection circuit of the resonant inverter and the secondary power supply will be studied also.

II – INPUT STAGE

Since the power of the structure is reduced, a pre-regulator with the boost converter operating in critical conduction mode using a low-cost integrated circuit for the command/protection was chosen [4]. The boost converter is projected to operate throughout a wide variety of input voltages (90 to 260 volts). Due to the variation in the luminosity of the lamps, the boost converter will operate with variable loads, this implies that both the commutation frequency and the duty cycle of the boost transistor will vary. Fig 2 shows the main components of the input stage.

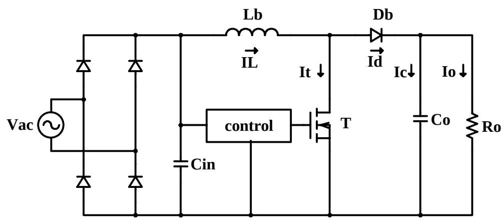

Fig. 2 – Pre-regulator Input Stage

Operating with a variable load, the output power of the boost converter varies from 30 to 100% of the rated power. It is important to remember that the DC bus voltage (output voltage of the boost converter) must remain constant at a value of 400V.

Another operating condition occurs when the presence detector doesn't detect a presence in the area, causing the lamps to be turned off. This will cause the boost converter to operate practically without a load. In all of the operating conditions, the DC bus voltage must remain constant, which implies that the integrated circuit for controlling the pre-regulator must always be fed.

A. Experimental Results

The following sequence shows the experimental results of the input stage; these results were obtained from an implemented prototype.

Figs. 3, 4, and 5 show the input voltage, the input current, and the DC bus voltage for three distinct values of input voltage.

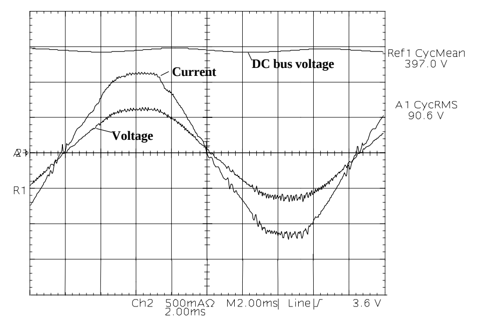

Fig. 3 – DC bus voltage, current and input voltage – 90Vac

It can be noticed, in Figs. 3 and 4, that the input current is practically sinusoidal and is in phase with the voltage, which results in a high power factor.

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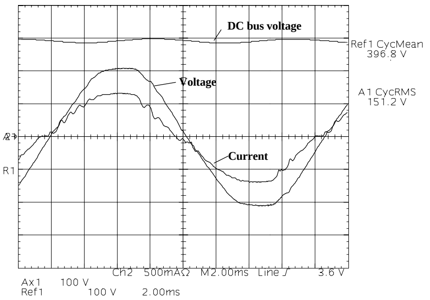

Fig. 4 – Dc bus voltage, current and input voltage – 150Vac

In Fig. 5, observe that the current leads the voltage and has a considerable harmonic distortion. This makes the power factor depreciated for this input voltage. The distortion in the current waveform as well as its angular dislocation in relation to the voltage, is due to the influence of the secondary power supply and will be studied further in the section that discusses secondary power supplies. Observe that as the input voltage increases, the power factor decreases. It is important to state that the power factor must always be greater than 0.92.

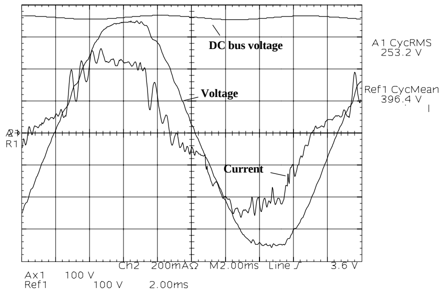

Fig. 5 – DC bus voltage, current and input voltage – 250Vac

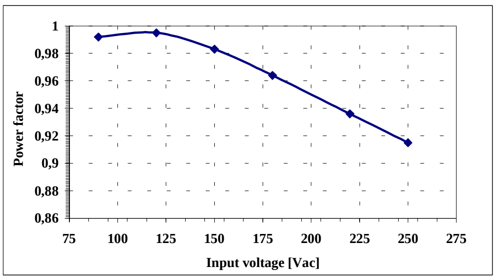

Fig. 6 – The unfolding of the power factor in relation to the input voltage

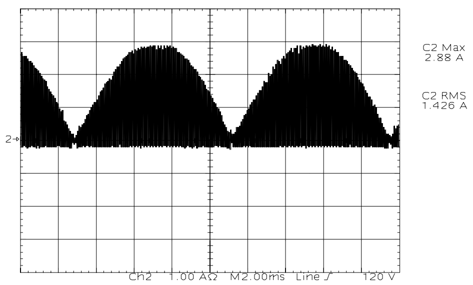

Fig. 7 – Current in the boost inductor for an input voltage of 90Vac

III – Resonant Inverter

In this work, two 40W fluorescent lamps are to be activated. Through research in bibliographical references [1] and [2], the most appropriate structure is the half-bridge resonant inverter, which allows simple command and has a widely studied and known operation. The voltage stresses on the transistors don't surpass the value of the DC bus voltage and only one of the transistors requires isolated base or gate command, depending on the type of transistor used. The resonant circuit that composes the inverter load is made up of the resonant inductor, the series capacitor, the parallel capacitor and a fluorescent lamp [1].

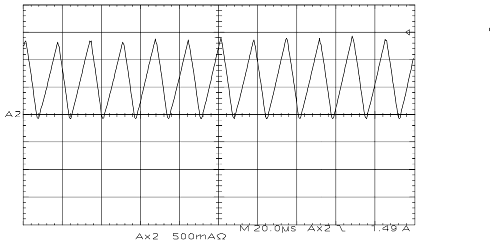

Fig. 8 – Detail of the current in the boost inductor

The command circuit will operate by means of an imposed frequency and will be generated by a microcontroller. The command signal generated will also control the luminosity, the presence detection and the current overshoot protection in the resonant circuit. Fig. 9 presents the resonant circuit with the components that compose the power circuit.

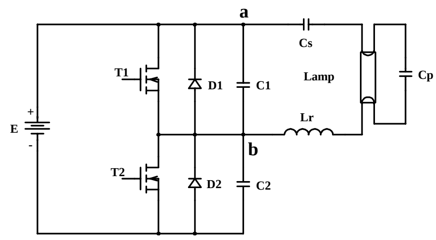

Fig. 9 – Inverter and resonant circuit

Where:

E – DC bus voltage;
L_r – Resonant inductor;
C_s – Series capacitor;
C_p – Parallel capacitor;
T_1 and T_2 – power transistors 1 and 2;
D_1 and D_2 – Intrinsic diodes of power transistors 1 and 2;
C_1 and C_2 – Auxiliary capacitors for commutation.

By the placement of the power transistors, it can be observed that their operation is complementary. This means that a rectangular voltage with an amplitude equal to E will appear between points a and b in the resonant circuit. This voltage, called V_{ab}, has a high frequency alternating component which will be submitted to the resonant circuit and cause a sinusoidal current to circulate through L_r, C_s, C_p and the lamp. The continuous component of Vab will be blocked by capacitor C_s.

To provide an inductive characteristic to the resonant circuit, allowing the entrance of the transistors in ZVS conduction mode, the commutation frequency of the inverter will be greater than the resonance frequency. Aiming to reduce losses in the blocking commutation, two auxiliary capacitors, C1 and C2, are placed to help in the commutation. The function of these two capacitors is to delay the voltage rise in the transistor that is being blocked, allowing the reduction of the simultaneous presence of the voltage and current in the transistor during the commutation. When MOSFET transistors are used, an intrinsic capacitance already exists which should be taken into consideration when choosing capacitors C1 and C2. Fig. 10 shows the behavior of voltage Vab and the current in Lr.

A. Equational Considerations

The voltage applied to the resonant circuit varies from 0 to E. This is the same as saying that the voltage is asymmetrical and has a rectangular format, because for each half commutation period it assumes a value between 0 and E. As said before, the continuous component of the voltage is blocked by capacitor C_s. This allows an analysis considering that the voltage applied to the resonant circuit is symmetrical with values between -E/2 and +E/2.

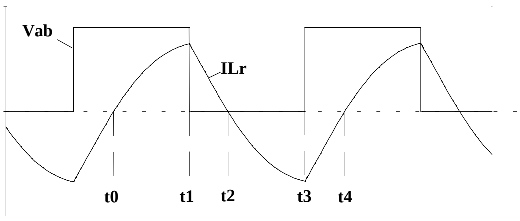

Fig. 10 – Voltage Vab and the current in Lr

Studies [3] and [2] show that the entire mathematical development of the converter can be done considering only the fundamental component of voltage V_{ab}. The contribution of the other harmonic components is very small in comparison with the fundamental component. [3] suggests a more refined mathematical development taking the third harmonic into consideration.

The circuit is described by the following second order differential equation:

$$V_{ab\max} \cdot sin(\omega \cdot t) = L_r \cdot C_{eq} \cdot \frac{d^2}{dt^2} \cdot V_{ceq}(t) + V_{ceq}(t) \quad (1)$$

Where:

Vabmax: Amplitude of the input voltage;

ω: Angular frequency of the input voltage.

The solution of Equation (1) depends on the relation between the input frequency and the resonance frequency of the LC circuit (L_r and C_{eq}). Expression (2) shows how to determine the resonance frequency of the LC circuit.

$$F_r = \frac{1}{2 \cdot \pi \cdot \sqrt{L_r \cdot C_{eq}}} \quad (2)$$

B. Starting Transient

During the starting transient, the equivalent resistance of the lamp is very high allowing to substitute capacitors Cs and C_p with their equivalent capacitance, C_{eq}. Fig. 11 shows the equivalent model of the resonant circuit during the starting transient. The maximum values of voltage and current applied to the lamp are determined by the difference between the commutation and the circuit resonance frequencies. Solving Equation (1), when the commutation frequency is different from the resonance frequency, provides a solution for the voltage across the equivalent capacitance, as follows:

$$V_{ceq}(t) = \frac{V_{ab\max}}{\left(L_r \cdot C_{eq} \cdot \omega_s^{\ 2}\right)} \cdot \left(\frac{\omega_s}{\omega_{os}} \cdot \sin(\omega_{os} \cdot t) - \sin(\omega_s \cdot t) \right) \quad (3)$$

and for the current through the resonant inductor:

$$I_{Lr}(t) = \frac{V_{ab\max} \cdot \omega_s}{L_r \cdot \left(\omega_s^{\ 2} - \omega_{os}^{\ 2}\right)} \cdot \left(\cos(\omega_{os} \cdot t) - \cos(\omega_s \cdot t)\right) \quad (4)$$

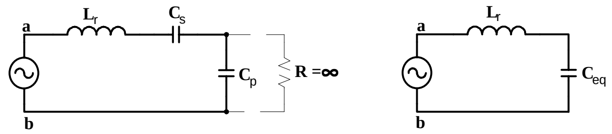

Fig. 11 – Equivalent model for the resonant starting circuit

By way of the equations, the presence of two overlapped frequencies in the circuit can be detected and the difference between them controls the maximum values of voltage and current in the resonant circuit. Equations 3 and 4 are represented graphically in Fig. 12. The amplitude modulation phenomenon of the values of voltage and current is called beating.

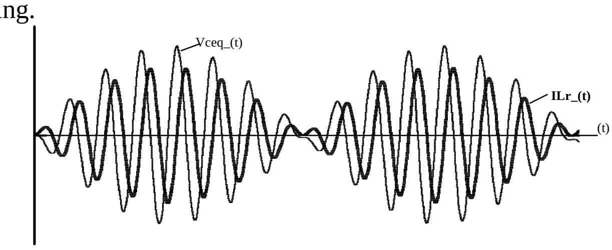

Fig. 12 – Voltage across the equivalent capacitor (V_{ceq}) and the current in the resonant inductor (I_{Lr})

C. Steady-State Analysis

Once the lamp is ignited, the starting transient of the circuit ends. From this point on it presents an finite resistance characteristic, when operating at a high frequency. The transfer function relating the voltage across the lamp (Vo) and voltage Vab is presented in Equation (5).

$$\frac{V_o(s)}{V_{ab}(s)} = \frac{R \cdot C_s \cdot s}{R \cdot L_r \cdot C_p \cdot C_s \cdot s^3 + C_s \cdot L_r \cdot s^2 + R \cdot \left(C_p + C_s\right) \cdot s + 1} \quad (5)$$

$$\frac{IL_r(s)}{V_{ab}(s)} = \frac{R \cdot C_s \cdot C_p s^2 + C_s \cdot s}{R \cdot L_r \cdot C_p \cdot C_s \cdot s^3 + C_s \cdot L_r \cdot s^2 + R \cdot \left(C_p + C_s\right) \cdot s + 1} \quad (6)$$

D. Project Methodology for the Resonant Circuit

During the starting transient, the resonance frequency is:

$$f_{RT} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_r \cdot C_{eq}}} \quad (7)$$

Where:

$$C_{eq} = \frac{C_s \cdot C_p}{C_s + C_p} \quad (8)$$

The steady-state resonance frequency is expressed in Equation (9):

$$f_{RR} = \frac{1}{2\pi \cdot \sqrt{L_r \cdot C_s}} \quad (9)$$

In order to obtain an inductive characteristic in the resonant circuit, operation should occur with a commutation frequency greater than the steady-state resonance frequency.

$$f_s = 4 \cdot f_{RR} \quad (10)$$

The relationship between theses two frequencies implies in a commitment between the voltage harmonic distortion applied to the lamp and the amount of reactive energy circulating in the circuit. The greater the relation between the two frequencies, the lower the harmonic distortion. However, the smaller the relation is, a smaller amount of reactive energy will circulate. In the structure here presented, a lower harmonic distortion was chosen because a greater circulation of reactive energy isn't very significant due to the structure's low power. Adopting the methodology presented in [2] and adapting it for circuits with an imposed frequency, a relation between C_p and C_s is obtained.

$$C_s = 9 \cdot C_p \tag{11}$$

By means of Equation (12), the value of Lr is calculated.

$$L_r = \frac{16}{C_s \cdot (2 \cdot \pi \cdot f_s)^2} \tag{12}$$

To determine the value of C_s, steady-state operation is considered in which s=jωs. Taking the absolute value of Equation (5), we have:

$$\left|\frac{V_o(j \cdot \omega s)}{V_{ab}(j \cdot \omega s)}\right| = \frac{R \cdot C_s \cdot \omega s}{\sqrt{\left[1 - C_s \cdot L_r \cdot \omega s^2\right]^2 + \left[R \cdot \omega s \cdot \left(C_p + C_s - L_r \cdot C_p \cdot C_s \cdot \omega s^2\right)\right]^2}} \tag{13}$$

Where:

$$\omega s = 2\pi \cdot f_s \tag{14}$$

Considering the rated voltage and current of the lamp, the input voltage and the commutation frequency, it is possible to determine the value of C_s.

$$C_S = \frac{V_{LRMS} \cdot 15}{V_{ab} \cdot R \cdot \omega s} \tag{15}$$

E. *Example of a Resonant Circuit Project*

Since the luminous efficiency is greater for lamps operating at a frequency higher than 20kHz, the power that will be applied to each lamp will suffer a 15% reduction [3]. This will make the luminous efficiency be equal to a lamp being supplied at a low frequency.

Project parameters:

E = DC bus voltage
Vlrms = RMS value of the lamp's operating voltage;
Ilrms = RMS value of the lamp's operating current;
fs = Commutation frequency.

The lamp's equivalent resistance is determined by the voltage and current values provided by the manufacturer:

$$R = \frac{V_{LRMS}}{I_{LRMS}} = \frac{111}{0.315} = 352\ \Omega \tag{16}$$

To determine the value of Cs, it is necessary to have the value of Vab, which can be determined by substituting the values in Equation (17).

$$V_{ab} = \frac{\sqrt{2} \cdot E}{\pi} = \frac{\sqrt{2} \cdot 400}{\pi} = 180\,\text{V} \tag{17}$$

The value of ωs is defined by:

$$\omega s = 2 \cdot \pi \cdot f_s = 186.6106 \quad \text{rd/s} \tag{18}$$

Substituting (17) and (18) in (15), Cs is determined.

$$C_S = \frac{111 \cdot 15}{180.6 \cdot 352.38 \cdot 186.6106} = 140.2 \quad \text{nF} \tag{19}$$

Since this is a non commercial capacitance value, it is so rounded to the nearest available value.

$$C_s = 150\,[\text{nF}] \tag{20}$$

The value of Lr is then determined by Equation (21).

$$L_r = \frac{16}{150 \cdot 10^{-9} \cdot (2 \cdot \pi \cdot 29.7 \cdot 10^3)^2} = 3.06 \quad \text{mH} \tag{21}$$

And, finally, Cp is defined.

$$C_p = \frac{150 \cdot 10^{-9}}{9} = 16.67 \cdot 10^{-9} \tag{22}$$

Using a commercial value for capacitors:

$$C_p = 18\,[\text{nF}] \tag{23}$$

F. *Experimental Results*

Fig. 13 presents the waveforms of the lamp's current and voltage.

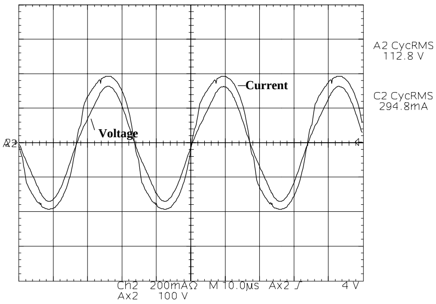

Fig.13 – The lamp's voltage and current

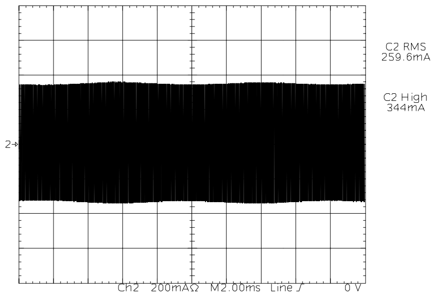

Fig. 14 – The lamp's current ripple

Observe that the format of the current that circulates through the lamp is practically a sinusoid, which causes low harmonic distortion. In Fig. 14, by observing the current ripple that flows through the lamp, it is possible to determine the crest factor of the current as 1.325 A. Fig. 15 presents the voltage and current in one of the transistors of the resonant inverter. Notice how the transistor starts conducting with zero voltage across it.

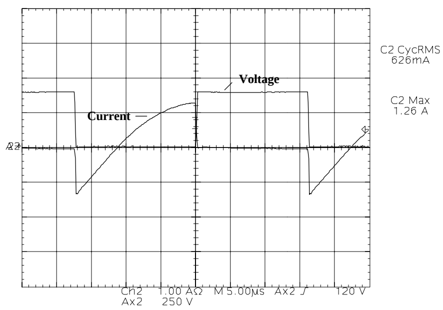

Fig. 15 – Voltage and current in transistor T2

IV – The Control, Command and Protection of the Resonant Inverter

It is desired to control the luminosity as a function of the intensity of lighting in the area. Another function that should be carried out by the electronic ballast here proposed is presence detection, which should turn off the lamps when no one is present in the area. A protection circuit will also be implemented in order to turn the resonant inverter off if one of the lamps does not ignite or if it is removed from the fixture.

To carry out these tasks, a PIC12C671 microcontroller, manufactured by MICROCHIP, was chosen. This microcontroller model has only 8 pins and presents an average consumption of 25mA, a maximum operating frequency of 10MHz, four 8-bit A/D converters, besides one 8-bit timer. Fig. 16 presents the control/command and protection circuit of the resonant inverter.

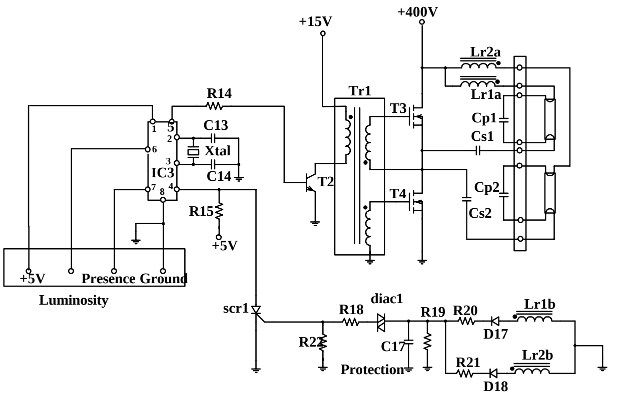

Fig. 16 – Control, command and protection circuit of the resonant inverter

A. Controlling the Lighting Intensity

Taking into consideration the strong dependency between the inverter's commutation frequency and the power supplied to the lamp, the control of the system will fall upon the command signal of the transistors. The commutation frequency will suffer a variation in direct proportion to the luminosity variation of the area, because the latter determines how much energy will be supplied to the lamp. Fig. 17 shows the variation of the power supplied to the lamp as a function of the commutation frequency of the resonant converter. Notice that the power supplied to the lamp suffers an almost 70% reduction, without loss of stability, with a frequency variation between 29.7kHz and 36kHz.

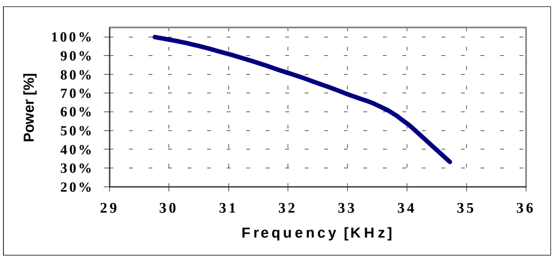

Fig. 17 – Variation of the power supplied to the lamp as a function of the commutation frequency

B. Presence Control

The area to be controlled is monitored by use of a passive infra-red sensor. When a presence is detected, the amount of infra-red radiation received by the sensor is changed and a signal is generated which indicates movement in the area. This information should be read by the microcontroller which then starts the lamp or keeps it turned on.

The starting of the lamp consists of two stages: pre-heating and ignition. The pre-heating stage is realized by applying a 36.7kHz frequency to the inverter during 400ms. To guarantee the ignition of the lamp directly after the pre-heating stage, a 29.7kHz frequency is applied to the inverter during 2s. Only after this period does the luminosity control start to operate.

V-Protection of the Resonant Circuit

Fig. 18 presents the protection circuit of the resonant inverter.

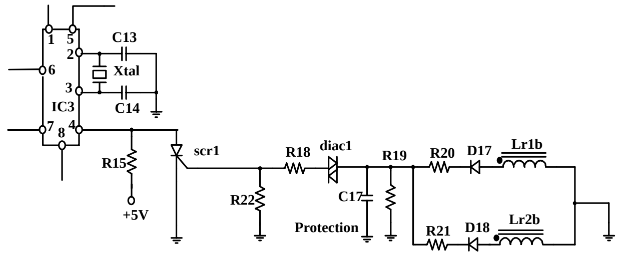

Fig.18 – Inverter's protection circuit

Under normal operating circumstances scr1 is blocked, not allowing current to flow through R15. As a consequence, a +5V voltage will appear at IC3's (microcontroller) pin 4. As long as a high state is maintained at this pin, the microcontroller will continue to generate the inverter's command signal, depending only upon the presence control and the luminosity.

Resonant inductors Lr1a and Lr2a have an auxiliary winding whose induced voltage is rectified and filtered, causing a continuous voltage to appear across capacitor C17. If a short circuit should occur at the lamp's terminals, the voltage reaches the "gate on" value of diac1 (33V), scr1 will be gated on causing the logic state of the input pin of the microcontroller to change, which generates an interruption in the microcontroller, causing the inverter's command signal to be eliminated and the program to go back to the beginning. Since scr1 will continue to conduct as long as current flows through it, the program will not allow the lamps to ignite again. For the lamps to ignite, the current through scr1 must cease. This can be implemented as follows:

- Adding a reset button to the circuit by way of a normally open push-button switch in parallel with the anode and the cathode of scr1;
- Turning the ballast off and then turning it on again;

The microcontroller's program can be altered in order to allow a certain number of "turn-ons".

Since the resonant circuits of each lamp are independent, removing one of the lamps doesn't interfere in the operation of the other. If both lamps are removed the inverter will operate without a load because the lamps' filament is in series with the resonant circuit. This allows the lamps be changed with the ballast turned on.

A-Secondary Power Supply

The need for secondary power supplies for feeding integrated circuits has proven to be the main disadvantage in the use of imposed frequency command in electronic ballasts. It is necessary to incorporate an secondary power supply.

To feed the circuits of the structure, two different DC voltage values are necessary, 5V and 15V. The 15V power supply feeds the boost converter's control integrated circuit and the pulse transformer which will activate the transistors of the resonant inverter. The 5V power supply feeds the microcontroller and the presence detection circuit. Fig. 20 shows the complete scheme of the proposed structure.

The ICI integrated circuit requires a supply voltage greater than 14V in order to operate correctly. Below this voltage, the command pulses of the transistor are turned off. By means of resistor R3 connected between the input rectifier and the integrated circuit's supply pin, it is possible to supply the energy necessary for the integrated circuit to generate the small width pulses during the starting stage. Thanks to this, current starts to circulate through the boost inductor. The manufacturer of this integrated circuit [4] recommends that this characteristic be used to generate a power supply by means of an auxiliary winding of the boost inductor, which is formed by the auxiliary winding of boost inductor Lbc, C6, C7, D6, D7 and D8.

When the presence detector turns the lamps off when no one is present in the area, the boost converter operates practically without a load and the secondary power supply, formed by the auxiliary winding, will cease to supply energy.

Since the presence detection and microcontroller circuits should continue to be fed, another secondary power supply was added. This power supply is formed by C10, C11, D8, D9, D10, D11 and C9. The presence of capacitors C10 and C11 causes a power factor degradation, as shown in Fig. 5.

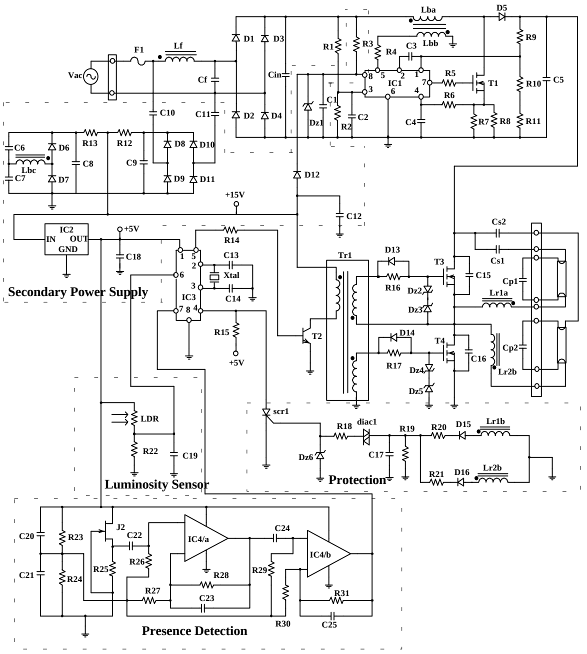

Fig. 20 – Complete scheme of the proposed circuit

The implemented structure can be applied as an lighting system for flights of stairs in buildings. The presence detection system would substitute the traditional hall time control with the advantage of not needing a switch in order to be activated. The luminosity control would save energy because natural lighting would be considered by the luminosity sensor. If a set of rechargeable batteries and an elevating voltage converter were added to the present structure, it could also be used for emergency lighting. This would cause a reduction in installation costs because just one fixture with two fluorescent lamps could, at the same time, work as lighting for normal conditions or as an emergency light. To reduce the cost of the batteries when operating as an emergency light, operation using a reduced lighting intensity is possible because the safety standards predict this situation.

Conclusion

The low-cost input stage is composed of a boost pre-regulator operating in critical conduction mode and provides a high power factor to the structure for an input voltage varying from 90 to 260V.

The problem of using this conduction mode is the input filter's volume. For the proposed structure an inductor was made, which contributed to reduce the harmonic distortion but at low or no load, increases the harmonic distortion due to the resonance whith the filter capacitor and, consequently, degrading the power factor. It can be said that the choice of the input stage is a commitment involving: power, cost, efficiency and power factor correction. Another necessary characteristic for the input stage is the possibility of operation throughout a load range, having to operate, also, without a load, when the lamps are turned off by the presence detector. The experimental results obtained for the input stage were in accordance with what was expected, with the exception of the harmonic distortion of the input current.

To activate the lamps, a half-bridge resonant inverter, commanded by an imposed frequency, was used. This is an uncommon type of control for electronic ballasts due to its higher implementation cost. This choice is justified by the larger joint value of the structure, the possibility of controlling the lighting intensity with the inverter through frequency variation and by the good reproducibility that this type of command provides.

The circuit responsible for the control, command and protection of the inverter is a microcontroller. This choice is due to its great flexibility which allows operating modifications without having to alter the hardware.

The protection circuits and the secondary power supplies were presented. The experimental results were very good, having only small differences with regard to the theoretical results.

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