Digitally Controlled Universal Electronic Ballast for Tl5 Fluorescent Lamps

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Abstract— **This paper presents the development of universal electronic ballast for TL5 lamps. The intent is to efficiently operate the maximum number of TL5 lamps with different power ratings at nominal power, using a resonant variable inductance, provided by a magnetic regulator, while maintaining the switching frequency constant. A microcontroller and additional digital circuitry are used to command a dc-dc buck converter to supply the necessary dc control current to the magnetic regulator and to regulate the switching frequency of the half-bridge resonant inverter that supplies the lamp. The selection of the resonant capacitance is done in order to comply with the SoS limits established for each lamp. Experimental results with lamps ranging from 14 to 49W, operating with high efficiency and high output, are presented in this project. The microcontroller generates the high frequency. The signal from the microcontroller is given to the gate of the two switches (FET). The switches energize the power transformer through regulated current source. The output of the transformer is given to the lamp.**

Keywords- **Electronic ballast, electrode heating, lamp detection, magnetic regulator, SoS limits, universal ballast, variable inductance**

I.INTRODUCTION

Electronic ballasts offer greater control because of the inclusion of different power converters in their configuration. Depending on the complexity of the ballast or the intended installation, they can vary from very simple circuits to more complex circuits involving microprocessors, which is fairly common in commercial solutions[10].

The term universal ballast or multiwatt electronic ballast refers to those electronic ballasts that are able to supply different lamps without requiring any physical change in the hardware. In such cases, the ballasts incorporate the necessary intelligence to measure the electrical characteristics of the lamps wired to their output, and are able to adjust their internal operation in order to correctly ignite and supply these lamps, simultaneously guaranteeing safe electrode operation and, consequently, a higher lamp life. From the commercial point of view, these ballasts allow lighting distributors and fixture manufacturers to stock far fewer types of ballasts and this in turn reduce costs[2],[3].

Digitally controlled electronic ballasts are capable of supplying a set of T8 fluorescent lamps. This ballast is based on a new magnetic control technique. A magnetic regulator, which is a magnetic device with a variable inductance, s used to replace the resonant inductor of the half-bridge resonant inverter that normally drives the lamp.

In this paper, a prototype for digitally controlled universal ballast for T5 lamps is proposed. This ballast is capable of supplying tubular fluorescent lamps in the range of 14 to 49W, high efficiency (HE) series and high output (HO) series. HO lamps deliver more light than standard T5 lamps and are available in higher wattages. The prototype uses the same control technique, yet, in this particular case, the universal ballast will exhibit a constant frequency operation.

An important aspect of the design procedure is related to the adequate selection of the operating frequency and the resonant circuit parameters. In order to guarantee safe electrode operation, special attention is given to the selection of the resonant capacitance, in order to comply with the sum of squares (SoS) limits established for each selected lamp. These limits are based on the maximum permissible current that may pass through the electrodes.

In Section II, a short review on other universal ballast control techniques together with some considerations on automatic lamp detection methods is provided. In Section III, lamp and topology selections are presented, as well as the control technique. Section IV discusses the design procedure for the resonant tank parameters and Section V presents the hardware and design configuration. Finally, Sections VI presents conclusions, respectively.

II. CONTROL AND LAMP DETECTION TECHNIQUES IN UNIVERSAL BALLASTS

A. Control Techniques

The ability to supply different lamps is based on controlling each lamp current by shifting the operating frequency. However, using the same resonant circuit involves a large range of operating frequencies, which may not be feasible, due to high switching losses and electromagnetic interference (EMI) stresses[2]. This is one of the main reasons why the magnetic regulator control technique was suggested as an efficient alternative. In order to recognize the advantages and simplicity of this type of control, it is important though to recall some of the previous techniques. One of the first methods[1] suggests adapting the switching frequency and the dc voltage that supplies the resonant converter together, or selectively changing simultaneously both the switching frequency and the duty ratio of the inverter signal.

Another method suggests, after lamp ignition and recognition, to sense its voltage which is then stepped down and modified in order to provide a control signal to determine the switching frequency of the inverter.

B. Lamp Detection

An important issue in universal electronic ballasts is lamp detection. Any mismatch of ballast and lamp power rating may damage the lamp or the electronic ballast. Fluorescent lamp recognition methods have already been addressed and several techniques have been proposed for T12, T8, and T5 lamps .

In [9], an automatic lamp detection method is proposed that can differentiate the lamp power of T8 and T12, in the range of 18 to 70W, by measuring the lamp voltage after the lamp ignition. With this method, the electronic ballast supplies the lamp at a fixed frequency during the detection period.

In order to overcome this drawback, another method that enables the ballast to determine the connected lamp power rating and drive the lamp with proper operating frequency was proposed. This method avoids the mismatch due to lamp voltage overlapping. It presents an automatic lamp detection using lamp power regulation and frequency detection. To ensure that the lamp is recognized correctly, a possibility weight distribution is used. An algorithm is then applied to regulate the power and define the appropriate switching frequency.

In [10], another algorithm for lamp detection and operation for T5, T8, and T12 fluorescent lamps is proposed. A fuzzy logic controller analyzes the heated lamp electrodes, the lamp voltage, and the lamp current. Then, a classification system is generated that maps the lamp characteristics into distinct groups in order to automatically detect each lamp.

III. PROPOSED ELECTRONIC BALLAST

A. Lamp Selection

T5 fluorescent lamps represent the front line in fluorescent lighting. T5 lamps may be of HE or HO, and the available power ratings range from 14 to 35W for the HE series, and from 24 to 80W for the HO series (Philips) .These lamps are characterized by a high lamp voltage, and in some cases, low current. This is the reason why they are conventionally manufactured for high-frequency operation. Due to their smaller diameter, compared to conventional tubular lamps, they need less material, which means lower construction costs. They are also environmental friendly because they have less mercury. Given their smaller volume and that they achieve maximum light output at temperatures around 35 ◦ C, which is a normal temperature in luminaries, T5 lamps allow the development of lighting systems where space limitations are a major concern.

B. Topology Selection and Control Technique

Each TL5 lamp is supplied by a voltage-fed resonant inverter connected to a parallel-loaded resonant circuit, as shown in Fig. 1.

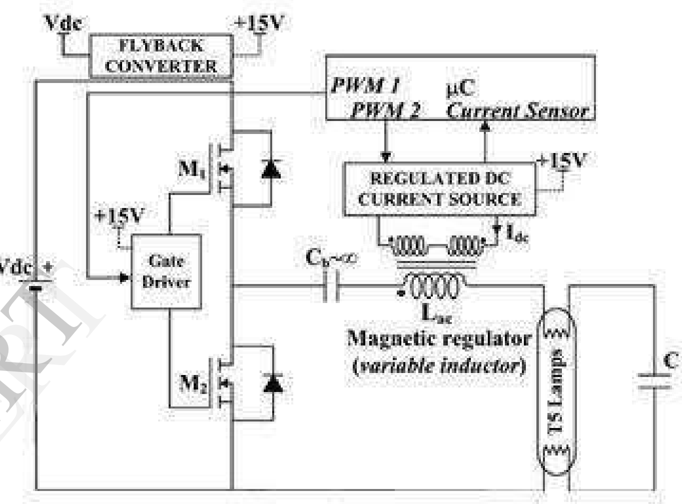

Fig. 1. Schematic of the proposed electronic ballast.

In order to function properly, the ballast requires two additional dc-dc converters and a microcontroller unit micro coulomb. The two bidirectional switches and the dc voltage source Vdc provide a square-wave voltage source that drives the resonant circuit formed by the magnetic regulator, with the variable inductance Lac , the resonant capacitor C, and the fluorescent lamp. If the quality factor of this resonant circuit Q is sufficiently high, the resonant current will be nearly sinusoidal. For this ballast, the rms value of the lamp voltage is

$$V_{lamp} = V_{in1}/\sqrt{(1-\omega^2 L_{ac}C)^2 + (\omega L_{ac}/R_{lamp})^2} \quad (1)$$

where Vin is the rms value of the fundamental component of the resonant-circuit input voltage after a dc-blocking capacitor Cb . This dc-blocking capacitor, which will have a high value, is necessary in order to prevent dc current value to flow through the lamp. The presence of this a current would easily damage the electrodes and reduce lamp life. If a lower value of Cb is used, it must be included as a design parameter and the behavior of the circuit would no longer be that of an LC circuit but instead that of an LCC circuit. Both configurations are used in ballast circuits; however, the *LC* circuit configuration is simpler.

Taking into account (1), the output lamp power can be defined as

$$P_{lamp} = V^2_{lamp}/R_{lamp} = V^2_{in}(R_{lamp})/(P^2_{lamp}(1 - 2L_{ac}C) + (\omega L_{ac})2) \quad (2)$$

where $V_{in} = 4((V_{dc}/2)/(\pi \sqrt{2})) = (\sqrt{2}/\pi) V_{dc}$.

The ballast operating procedure will be as follows: after the lamp recognition, a control current is delivered to the magnetic regulator which will then change its inductance according to the estimated value for the attached lamp. This control current is supplied by a regulated dc-current source, a dc-dc buck converter working in continuous conduction mode. In fact, the variation of the inductance is imposed by the dc current I_{dc} that is supplied to the control windings of the magnetic regulator. The microcontroller is also able to measure the dc current. The control of I_{dc} is done by adjusting the duty cycle of a pulse width modulation (PWM) signal, generated by the microcontroller and applied to the converter, according to a voltage reference V_{ref}. Based on the methodology presented in [10], this voltage reference would be defined according to the results obtained from the application of the fuzzy logic algorithm proposed in [10].

IV. RESONANT CIRCUIT DESIGN

A. Standard Design Procedure

The primary goal is to operate different TL5 lamps at nominal power while maintaining the same switching frequency f_s and the same resonant circuit capacitance. For the half bridge inverter connected to a parallel-loaded resonant tank, the maximum voltage gain can be approximated by Q at the natural frequency f_o, Q being the normalized load, as represented in (4). This equation can be used to calculate the base impedance of each resonant circuit Z_b, for each lamp, using the nominal values for the lamp voltage V_{lamp}, and the lamp resistance R_{lamp} If the desired operating frequency for the lamps f_s is selected,can be used to estimate the values for L_{ac} and C

$$V_{in} = 4 \cdot ((V_{dc}/2)/(\pi . \sqrt{2})) = \sqrt{2} V_{dc}/\pi \quad (3)$$

TABLE I
CAPACITANCE AND INDUCTANCE THEORETICAL VALUES

Lamp	C [nF]	L_{ac} [mH]
TL5 HE series (14/21/28/35)	3.48	2.35
TL5 HO24W	6.15	1.33
TL5 HO39W	6.94	1.17
TL5 HO49W	5.33	1.53

$$Q = V_{lamp}/V_{in} = R_{lamp}/Z_b, \text{ for } f_s = f_o \quad (4)$$
$$Z_b = \sqrt{L/C}, \text{ for } f_s = f_o \quad (5)$$
$$L_{ac} = Z_b/2\pi f_o \quad (6)$$
$$C = 1/2\pi Z_b f_o. \quad (7)$$

The rms value of the lamp discharge or arc current I_D can be defined as

$$I_D = V_{lamp}/R_{lamp}. \quad (8)$$

It implies that if the circuit is operated at $f_s = f_o$, (8) can be rewritten as follows:

$$I_D = V_{lamp}/R_{lamp} = V_{in}Q/R_{lamp} = V_{in}/Z_b \quad .(9)$$

Taking into account the preceding considerations, the capacitance and inductance values for the selected lamps may be calculated, respectively, by rewriting (6) and (7)

$$L_{ac} = V_{in}/(2 \cdot \pi \cdot f_s \cdot I_D) \quad (10)$$

$$C = I_D/(2 \cdot \pi \cdot f_s \cdot V_{in}) \quad (11)$$

For this prototype, the input dc voltage was set at V_{dc} = 310V and the switching frequency at f_s = 55 kHz.The estimated parameters for each lamp are presented in Table I.

B. Conditions to Obtain Zero Voltage Switching (ZVS)

According to [7], when $Q < 1$, the resonant frequency f_r does not exist and the circuit operates as an inductive load at any f_s. If $Q \geq 1$, and $f_s > f_r$, then the switches are loaded by an inductive load. In both situations, ZVS is achieved, since the resonant current lags the inverter output voltage.

TABLE II
Q, f_r, AND f_o VALUES WITH A SINGLE 4.7-*n*F Capacitor

Lamp	Q	f_o [kHz]	f_r [kHz]
TL5 HE14W	0.683	47.93	-
TL5 HE 21W	1.024	47.93	10.36
TL5 HE 28W	1.391	47.93	33.31
TL5 HE 35W	1.74	47.93	39.23
TL5 HO24W	0.47	63.68	-
TL5 HO39W	0.659	67.79	-
TL5 HO49W	1.286	59.28	37.27

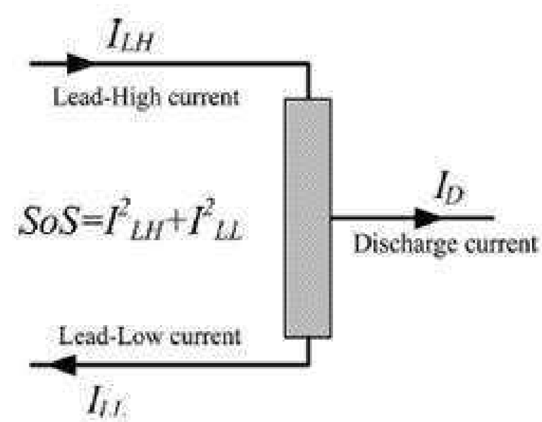

Fig. 2. Lamp electrode currents definition.

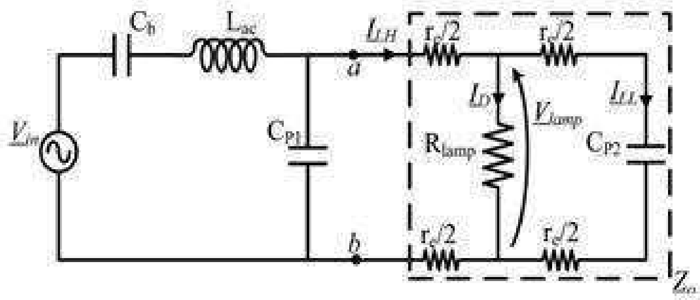

Fig. 3. Equivalent circuit.

When $Q \geq 1$, the resonant frequency is given by the following equation:

$$fr = fo \sqrt{1 - 1/Q2}, \ fo = 1/2\pi \sqrt{LC} \qquad (12)$$

Considering the selected capacitor value and assuming the same inductance values for each lamp, the recalculation of the *fo* and *Q* for each resonant circuit shows that *Q* is below 1 for the HE 14W, HO 24W, and HO 39W, thereby behaving as an inductive load, whereas for the remaining lamps the circuit is resonant. This can be seen in Table II.

The lifetime of a fluorescent lamp is determined by the lifetime of the electrodes and their temperature must be kept within certain limits. If they are too hot, enhanced evaporation of the emissive material and severe end blackening will take place. If they are too cold, sputtering of the emitter will occur [6], [8]. Both situations lead to significantly reduced lifespan of the lamp.

TABLE III

Lamp Voltage, Discharge Current, Electrode Resistance,And Sos Limits

Lamp	V_{lamp} [V]	I_D [mA]	r_e [Ω]	I_{LHmax} [mA]	I_{LLmax} [mA]
TL5 HE14W	82±10	170±40	40	240	170
TL5 HE21W	123±10	170±40	40	240	170
TL5 HE28W	167±17	170±40	40	240	170
TL5 HE35W	209±20	170±40	40	240	170
TL5 HO24W	75±8	300±30	12	475	370
TL5 HO39W	112±10	340±70	12	475	370
TL5 HO49W	191±20	260±50	16.5	370	275

C. Capacitance Selection Based on the SoS Limits

The temperature of the electrodes is primarily influenced by the three currents represented in Fig. 2. One way to evaluate the conditions for proper operation of the electrodes is based on the SOS definition

$$\text{SoS} = I2LH + I2LL; \ ILH > ILL. \qquad (13)$$

The currents *ILH* and *ILL* have been measured with a current probe around the lead in wire. The higher one is named *ILH* and the lower one named *ILL*. By taking both lead in wires together through a current probe, *ID* can be measured. As will be demonstrated, a capacitor value of 4.7 nF will not obey the SoS limits presented in Table III, as retrieved from [8].

In order to obey these limits, a dual capacitor configuration is implemented. The parallel capacitance of the resonant filter *C* is split into two capacitances, *CP* 1 and *CP* 2 , as shown in Fig. 3. These capacitors must be designed for the worst case, which is defined as a lamp that has the minimum values for *ILH* max and *ILL*max and the highest lamp voltage. As shown in Table III, the minimum values for *ILL* and *ILH* correspond to the TL5 HE series, and the HE 35 W presents the highest lamp voltage. The required inductance value will not be affected by the selection of a different resonant capacitor value, so, through both analyses, the inductances are assumed to be the initial values, as defined in Table I.

Thus, *CP* 2 is limited by the minimum *ILL* current and the highest lamp voltage. These two values establish the maximum value for *CP* 2 .

$$|V \text{lamp}| = |ILL| \cdot (1/j\omega sCP2 + re) \ (14)$$

According to Table III, the rated heated electrode resistance for the HE series is 40 Ω and the nominal lamp voltage for the HE 35 W lamp is 209V.

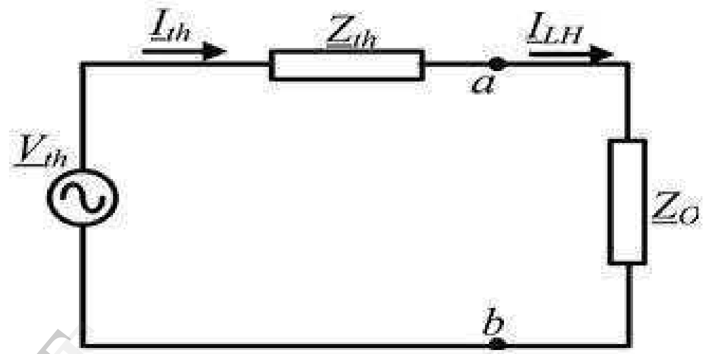

Fig. 4. Th´evenin's equivalent circuit.

This current can be determined by Th´evenin's theorem applied to the *a* and *b* terminals as shown in Fig. 4.

From Fig. 4, the following equations can be established

$$ZO = (re + (1/j\omega sCP2)) \cdot R\text{lamp}/R\text{lamp} + re + (1/j\omega sCP2) + re \qquad (15)$$

$$Z\text{th} = ((1/j\omega sCb) + j\omega sL\text{ac}) \cdot (1/j\omega sCP1)(1/j\omega sCb) + (1/j\omega sCP1) + j\omega sL\text{ac} \qquad (16)$$

$$V\text{th} = (1/j\omega sCP1)(1/j\omega sCb) + (1/j\omega sCP1) + j\omega sL\text{ac} \cdot VS \qquad (17)$$

where *ZO* is the load impedance, obtained by the combination of the lamp resistance, electrode resistance, and *CP* 2 ; *Z*th and *V* th are Th´evenin's equivalent impedance and voltage. Finally, the current *Z*th can be determined by

$$I\text{th} = ILH = V\text{th}/(Z\text{th} + ZO). \qquad (18)$$

TABLE IV

Q, *fr* , and *fo* Values With a Capacitance of 3.3 nF

Lamp	Q	f_o [kHz]	f_r [kHz]
TL5 HE14W	0.572	57.21	-
TL5 HE 21W	0.858	57.21	-
TL5 HE 28W	1.165	57.21	29.36
TL5 HE 35W	1.458	57.21	41.64
TL5 HO24W	0.394	75.99	-
TL5 HO39W	0.553	80.9	-
TL5 HO49W	1.078	70.75	26.36

The impedance of the circuit can be determined as follows:

$$Z = 1/j\omega\, sCb + j\omega\, sL + ZO \cdot \quad (1/j\omega\, sCP\ 1\ )ZO + (1/j\omega\, sCP\ 1\ ) \quad (19)$$

D. Magnetic Regulator

The working principle of this device is to control its main inductance value through the variation of the permeance in different regions of the core. The selected magnetic regulator structure is presented in Fig. 9.

The winding *N*2 , placed in the central leg of the core, corresponds to the variable inductance winding, defining its initial value. Both *N*1 and *N*3 windings are assembled on the side legs of the core. When a dc control current is flowing through them, it will generate two magneto motive forces, which will allow the variation of the initial *L*ac value. The maximum value of inductance *L*ac is obtained for a zero dc control current *I*dc. As the current is increased, *L*ac decreases due to saturation.

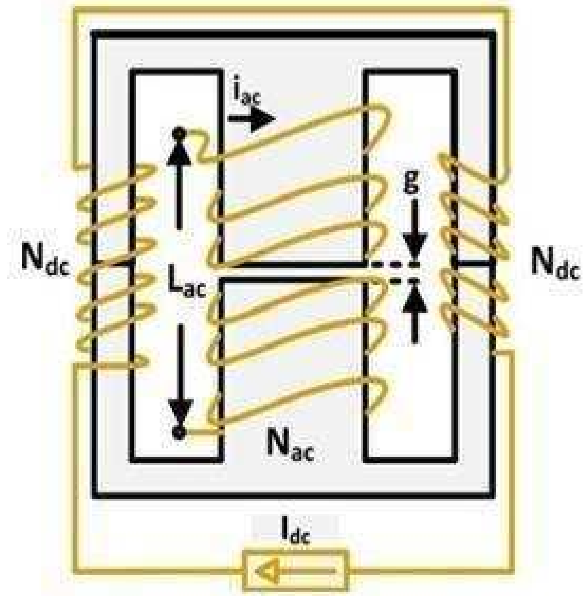

Fig. 9. Structure of the magnetic regulator and prototype.

V. EXPERIMENTAL PROTOTYPE

Fig. 10 shows the implemented circuit for the voltage-fed resonant ballast. The main driver, IR2111, is responsible for the command of the half-bridge inverter. This is accomplished using a HCLP3120 driver, which grants electrical isolation from the power stage. A digital 16-bit PWM, PWM1, as previously shown in Fig. 1, is applied to the gate driver in order to establish the inverter switching frequency *fs* at 55 kHz according to the selected value. This PWM signal is generated by a programmable system-on-chip CY8C29446.

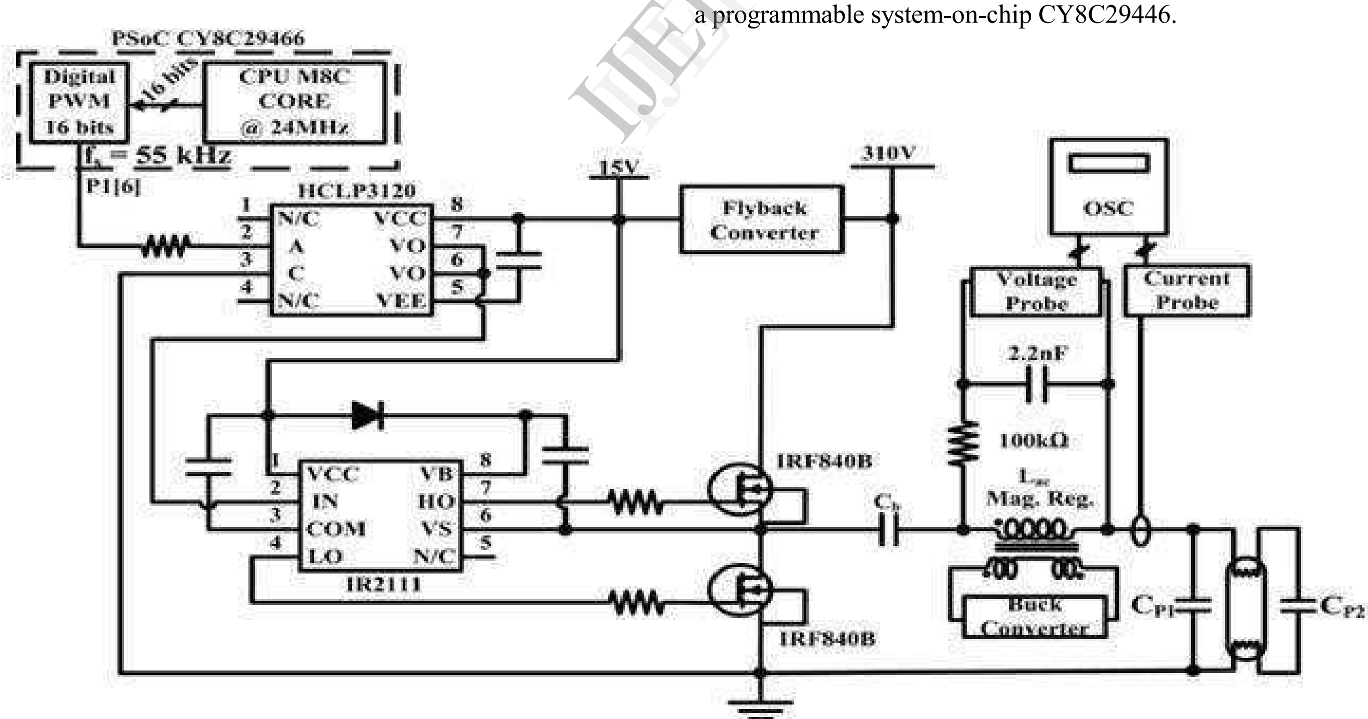

Fig. 10. Schematic of the voltage-fed resonant ballast.

An HCPL3120 optocoupler is used to provide electrical isolation to the control stage from the power stage. The diode D2 is used to block any induced ac voltage from the magnetic regulator due to asymmetries in the construction of the magnetic regulator, and due to the magnetic nonlinearity coupling. The flyback converter employs the integrated circuit, IC, VIPer 50A. This IC combines on the same chip a PWM circuit with a vertical power MOSFET (700 V/1.5 A/5.7Ω) working in discontinuous conduction mode. The design of this converter is based on the software tool provided by the manufacturer, ST Microelectronics, [4].

VI.CONCLUSIONS

This paper presents the development of a prototype for a universal electronic ballast for TL5 fluorescent lamps. The ballast was implemented using a resonant inverter with a constant switching frequency and a magnetic regulator. ZVS operation was verified for all tested lamps as shown in the presented experimental results. Each SoS limit was respected using a dual parallel capacitor configuration and a good performance was obtained for the entire prototype.

Even if these lamps can be identified by the analysis of the lamp voltage, a better solution to identify T12, T8, and T5 amps has been proposed in [10]. If a discrete set of operating frequencies together with the variable inductance are used as control parameters, the next obvious step would be to include dimming as a new feature in the prototype. In such case, the concern would be to design an EMI filter capable of dealing with this set of frequencies. However, even in these conditions, for each lamp, and using a similar magnetic control technique, the role of reducing the luminous flux level would only be dictated by the variable inductance.

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