POWER CONTROL OF HPS LAMPS IN A PUBLIC LIGHTING SYSTEM WITH REMOTE MANAGEMENT

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***Abstract* – This paper presents a way to control the power of a High-Pressure Sodium (HPS) lamp supplied by electronic ballast connected to a computer, in order to obtain a better exploitation of lamp's useful life and luminous capacity. An application example of this kind of lamp is used, the public lighting. Along this work, an analysis of which features should electronic ballasts present to supply the HPS lamp with quality and efficiency is made, and then the electronic ballast used in this work is chosen on literature, following the requirements. The discrete control technique is developed, improving system's efficiency without neglecting its reliability. Finally, the developed system management application is presented and results are shown.**

***Keywords* – Discrete Control, Electronic Ballasts, Intelligent System, High-Pressure Sodium Lamps, Public Lighting, System Management.**

I. INTRODUCTION

Public lighting is closely related to life quality of urban population. A well designed public lighting system guarantees the reduction of crime rates, emphasizes buildings and monuments, and provides better utilization of cities' nightlife.

In such a way, public lighting systems improvement is evident, because it is a way of better using the existent energy, reducing the need for new electrical power generating sources.

The High-Pressure Sodium (HPS) lamp is the most efficient kind of high-pressure discharge lamp, and its useful life varies from 16.000 to 28.000 hours. Considering its high luminous efficacy and long useful life, the HPS lamp should be considered the first option when lighting public ways, tunnels, roadways, squares and sidewalks.

Although, HPS lamps need specific ballasts to properly perform. Conventional electromagnetic ballast, besides being heavy and bulky, has lower efficiency than electronic one. The electronic ballast is light and compact, and allows the implementation of intelligent systems with control and monitoring of variables that define ballast and lamp behavior.

This paper consists of a power control method for an HPS lamp supplied by electronic ballast, aiming the best usage of system energy. Besides, a computer is connected to the ballast, assuring system characteristics control and allowing the remote realization of tasks, such as system turn on, consumption measurement, voltage, current and power monitoring, useful life estimation, and task scheduling. The management of several lamps in the same system also becomes easier with the resources offered by the computer.

II. TOPOLOGY

The choice of the electronic ballast used in control design has taken into account some fundamental characteristics for the proposed system. The ballast must attend lamp's needs, assuring its good performance. Besides, it must present a microcontrolled driver, with possibility of acquiring lamp voltage and current signals.

In [1], integrated electronic ballasts to supply HPS lamps are presented. The idea consists of integrating the power stage to power factor correction stage of the ballast, using a single switch for both purposes. This reduces topology cost without increasing current stress in the shared device.

Among all integrated topologies presented in [1], the Double-Flyback Half-Bridge (DFHB) electronic ballast was chosen. This topology is composed by two Flyback converters, one for power factor correction and other for power stage. Both converters operate in Discontinuous Conduction Mode (DCM) and share the same switch. A Half-Bridge inverter supplies the lamp with a low frequency square waveform, in order to avoid the occurrence of acoustic resonance phenomenon. A LC input filter is employed to filter high frequency harmonics from current on converter side to the line. Also, an ignition circuit is responsible by providing a high voltage pulse to the lamp. This ballast is an economically feasible alternative with high reliability. Figure 1 shows the ballast circuit.

III. SERIAL COMMUNICATION

To interface electronic ballast with a computer, the Serial RS-232C Standard has been chosen. It is also known as EIA RS-232C. This standard is widely used, due to its simplicity and reliability.

The used microcontroller has a Serial Communication Interface (SCI) module, which allows the realization of an asynchronous full-duplex communication with programmable baud rate. Thus, it is possible to communicate the device with computer through serial RS-232 interface. This is only possible if both devices are set to use the same baud rate.

Due to lamp inertia, the application does not demand a fast baud rate. The choice of a lower baud rate guarantees a communication without information loss. Another reason is the low cost of microcontrollers that can be used for this purpose. Hence, the chosen baud rate was 4800bps.

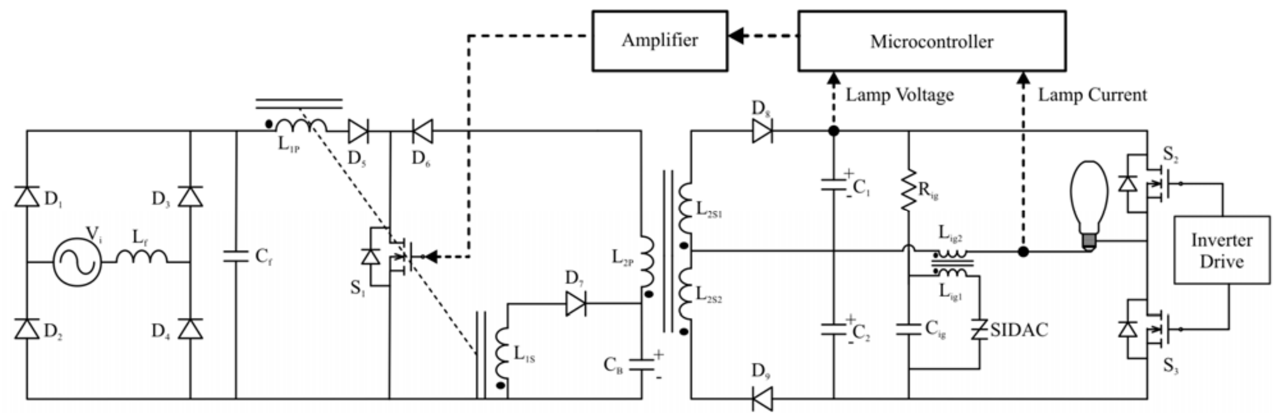

Fig. 1. Double-Flyback Half-Bridge electronic ballast.

IV. POWER CONTROL

One of HPS lamp characteristics is its equivalent resistance variation along useful life. Lamp nominal equivalent resistance can be 200% higher than a new lamp after 9.000 hours of operation [2].

According to [3], lamp luminous efficacy depends only on factors like sodium and buffer gas vapor pressure, tube diameter and electrode losses. Such factors are lamp's constructive features, and can only be changed during its manufacturing process. So, it is very interesting to keep the lamp operating always at nominal power, since luminous efficacy is not changed.

Before designing a controller capable of not only improving lamp's usage, by keeping its nominal power, but also improving or not changing ballast performance, it is needed to know the plant characteristics and, based on them, design the suitable controller.

A. Plant Characteristics

To know the plant, it is necessary to know the DCM Flyback converter transfer function and lamp model.

1) Lamp model – In [4], an electronic ballast has been developed in order to obtain the model of a 70W HPS lamp (OSRAM VIALOX® NAV® E LONGLIFE). The obtained result is the transfer function presented in (1).

$$L(s) = K_L \cdot \frac{(s + z_L)}{(s + p_L)} \tag{1}$$

Where:

K_L - Steady state lamp resistance.
z_L - Zero location.
p_L - Pole location.

For present lamp, $K_L = 75$, $z_L = -3142$ rad/s e $p_L = 18850$ rad/s.

Using the software Matlab®, lamp root locus has been obtained (Figure 2).

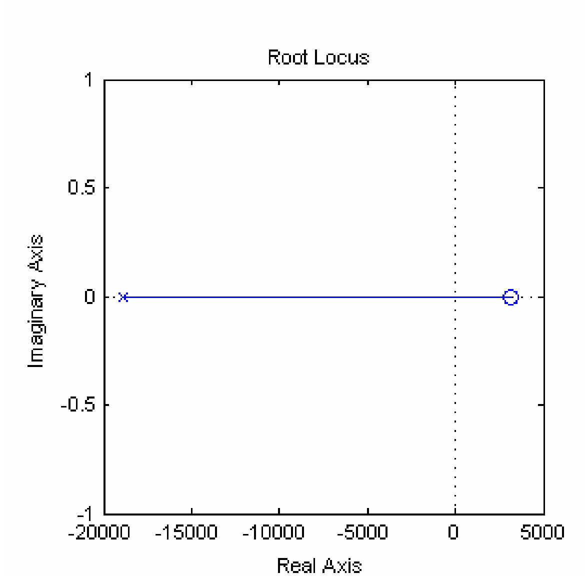

Fig. 2. Root locus of L(s).

2) DCM Flyback transfer function – According to [5], DCM converters transfer function is given by (2).

$$G_d(s) = G_{d0} \cdot \frac{1}{\left(1 + \frac{s}{\omega_p}\right)} \tag{2}$$

Where:

G_{d0} - Converter static gain.
ω_p - Pole location.

In case of Flyback converter, it is determined [5]:

$$G_{d0} = \frac{V_{out}}{D} \tag{3}$$

Where:

V_{out} - Output voltage.
D - Duty cycle.

$$\omega_p = \frac{2}{R \cdot C} \tag{4}$$

Where:

R - Load impedance.
C - Converter output capacitor.

Hence:

$$G_d(s) = \frac{V_{out}}{D} \cdot \frac{1}{\left(1 + \frac{s \cdot R \cdot C}{2}\right)} \tag{5}$$

Transfer function in (5) is obtained through converter small signal model. It allows performing voltage control through duty cycle variation.

3) Plant transfer function – To obtain the system transfer function, i.e. ballast and lamp, R has been replaced by L(s) in (5). After doing that and manipulating the expression, the transfer function G(s) has been found and it is shown in (6).

$$G(s) = K \cdot \frac{(s + p_L)}{\left(s^2 + \left(z_L + \frac{2}{K_L \cdot C}\right) \cdot s + \frac{2 \cdot p_L}{K_L \cdot C}\right)} \tag{6}$$

Where

$$K = \frac{2 \cdot V_{out}}{D \cdot K_L \cdot C} \tag{7}$$

The system is only stable when the roots of characteristic polynomial of (6) have their real part negative. This happens when (8) is true.

$$z_L + \frac{2}{K_L \cdot C} > 0 \tag{8}$$

Replacing the values of z_L and K_L, and solving (8) for C, the maximum value for the output capacitor in (9) has been obtained.

$$C < 8.48 \cdot 10^{-6} F \tag{9}$$

Finally, replacing in (6) the design values, G(s) has been obtained.

$$G(s) = 1.13 \cdot 10^6 \cdot \frac{(s + 18850)}{(s^2 + 4939 \cdot s + 1.52 \cdot 10^8)} \tag{10}$$

Using the software Matlab®, system's root locus and step response have been obtained. They are shown in Figure 3 and 4, respectively.

B. Controller Design

The controller main goal is to guarantee a null error in steady state, so the lamp power can be kept at nominal level. HPS lamps inertia leads system response to be slow. The controller that attends the requirements described above is the Proportional Integral (PI) compensator, which transfer function is given by (11).

$$G_{PI}(s) = \frac{K_P \cdot \left(s + \frac{K_I}{K_P}\right)}{s} \tag{11}$$

The transfer function of compensated system is given by (12).

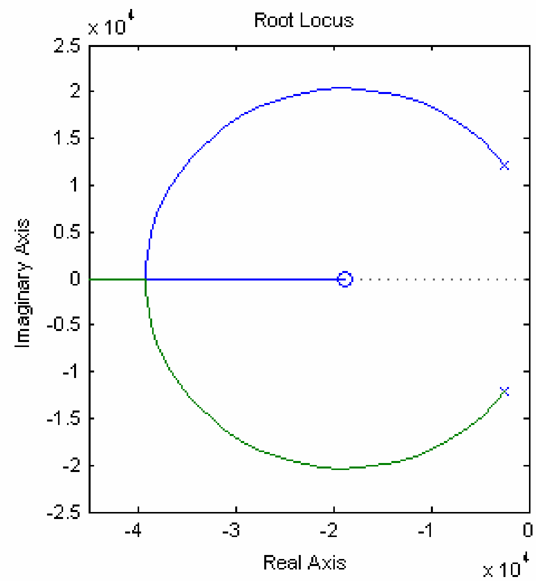

Fig. 3. Root locus of G(s).

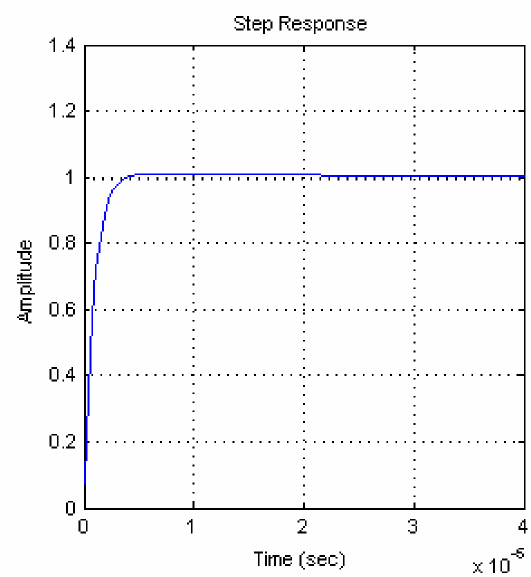

Fig. 4. Step response of G(s).

$$Gc(s) = G(s) \cdot G_{PI}(s) \tag{12}$$

$$Gc(s) = K \cdot K_P \cdot \frac{(s + z1) \cdot \left(s + \frac{K_I}{K_P}\right)}{s \cdot (s + p1) \cdot (s + p2)} \tag{13}$$

Analyzing the plant in closed loop:

$$T(s)=\frac{K_c\cdot(s+z1)\cdot\left(s+\frac{K_I}{K_P}\right)}{s\cdot(s+p1)\cdot(s+p2)+K_c\cdot(s+z1)\cdot\left(s+\frac{K_I}{K_P}\right)} \quad (14)$$

For one of the poles to be cancelled, one of T(s) denominator roots must be equal to $-K_I/K_P$.

Simplifying denominator and considering K_I as the main variable:

$$K_I^{\,2}+(p1+p2)\cdot K_P\cdot K_I+p1\cdot p2\cdot K_P^{\,2}=0 \quad (15)$$

The solution of (15) for K_I/K_P is presented in (16).

$$\frac{K_I}{K_P}=\frac{-(p1+p2)\pm\sqrt{(p1+p2)^2-4\cdot p1\cdot p2}}{2} \quad (16)$$

To cancel one of the poles, K_I/K_P must be equal to one of plant open loop poles. Although, complex poles cancellation is not possible.

Then, the remaining option is to use the third root of T(s) denominator, $K_I/K_P = 0$. But the zero in K_I/K_P just need to be small enough compared to other poles so that the pole in the origin is not cancelled and tend to this zero, which by its way, is responsible for the null error characteristic in steady state.

Chosen values have been $K_I = 1$ and $K_P = 0.001$.

V. PROPOSED METHOD

The block diagram in Figure 5 shows the devices used in the proposed system.

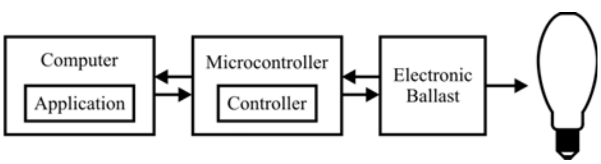

Fig. 5. Proposed lighting system diagram.

The electronic ballast is directly connected to the lamp. The microcontroller must be interconnected to this ballast in order to acquire lamp voltage and current signals, and to perform power control and switch command. The acquired signals are read by the microcontroller and sent to computer. This contains the developed application, which manipulates values and performs system management. Figure 6 shows communication between devices.

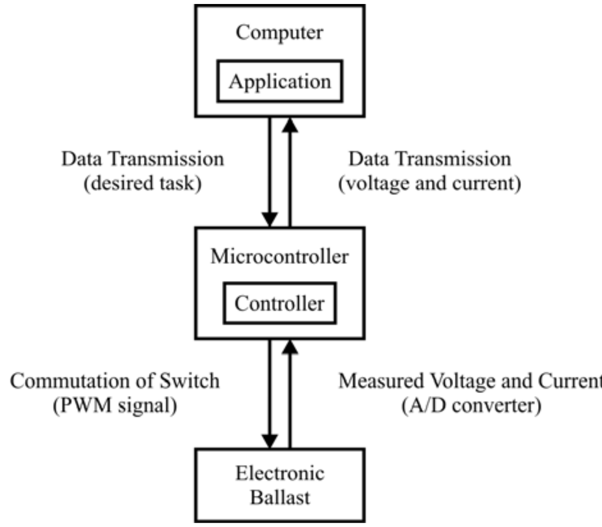

Fig. 6. Communication between devices.

The data exchange between microcontroller and computer is made by serial communication, due to the advantages of this mean, as described previously.

A. Control Method

It should be noted that the purpose of this work is lamp power control, but the controller was designed for voltage control.

Although, as soon as a microcontroller is employed to act as the controller, it is possible, in this device, to perform mathematical operations involving measured variables and reference values, in order to implement the designed controller.

The solution to control lamp power with the developed project is shown in Figure 7.

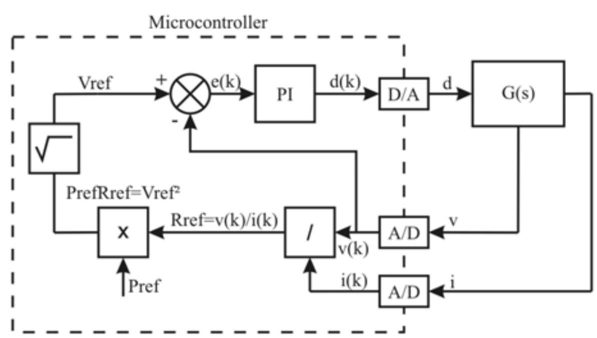

Fig. 7. Power control system block diagram.

Lamp voltage v(t) and current i(t) are acquired, having their values adjusted to analogical-digital (A/D) converter inputs on the microcontroller, becoming v(k) and i(k). The device calculates lamp resistance and creates a reference value R_{ref}. Then, the reference power, P_{ref}, is multiplied by R_{ref} resulting in the reference voltage square, V_{ref}^2. After that, the microcontroller performs the square root of this value, and the reference voltage value, $V_{ref,}$ is obtained. This value is compared with v(k), generating an error e(k), which is manipulated by the PI controller (part of microcontroller software).

Finally, controller output is the new duty cycle value d(k) that will drive the Flyback converter switch, after being amplified outside the microcontroller, becoming d(t).

B. Control Implementation

For digital controller to be implemented, a microcontroller having two A/D converters, a PWM output and serial communication interface is needed, besides having enough processing capacity to perform necessary calculations.

Both A/D converters measure lamp voltage and current. PWM output drives power stage switch, and has variable duty cycle, being the control system actuator.

Freescale Semiconductor® offers the microcontroller MC68HC908KX8®, which has all features described above. Hence, it is the chosen device.

C. Controller Discretization

For the microcontroller to have discrete PI controller inside it, it is necessary to discretize control law and adapt it to programming language accepted by the device.

In [6], it is said that the digital implementation of a PI controller can be determined using a discrete approximation to integration, the advanced regular integration.

Considering the PI controller in (11), the controller transfer function in the z domain was obtained:

$$G_C(z) = K_P + \frac{K_I \cdot Tz}{(z-1)} \tag{17}$$

The algorithm of equation that represents PI controller has been obtained adding the proportional and integral terms, and it's given by (18).

$$d(k) = \left(K_P + K_I \cdot T\right) \cdot e(k) + K_I \cdot d(k-1) \tag{18}$$

Equation (18) was easily implemented in chosen microcontroller.

D. System Management Application

The developed application for lighting system management is shown in Figure 8.

The application offers resources to turn on and manage system characteristics. Lamp useful life can also be graphically visualized, by its usage time. User can set this function to several models of lamps, just by setting the maximum lifetime, in hours, determined by manufacturer. Lamp voltage, current and power levels can be observed through a display, frequently updated.

Another important resource offered by the application is the possibility of task scheduling. User programs tasks to be automatically executed by the application. The task is easily set together with date and time to be performed. All programmed tasks can be visualized through a list, or removed from database. Figure 9 shows task scheduling window.

VI. SIMULATION RESULTS

Figures 10 and 11 show compensated system's root locus and step response and prove that, with the controller, the system presents the expected results.

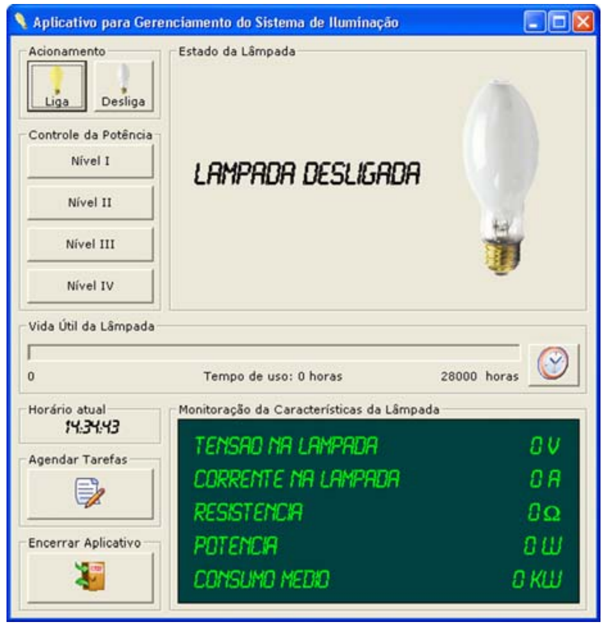

Fig. 8. Proposed system management application.

Dia	Mês	Ano	Horário	Tarefa
8	Julho	2007	20:00	Ligar a lâmpada com nível II d
8	Julho	2007	21:00	Alterar potência para nível III
8	Julho	2007	22:30	Alterar potência para nível IV
9	Julho	2007	08:00	Desligar a lâmpada
30	Abril	2008	23:00	Ligar a lâmpada com nível IV c
18	Junho	2008	06:15	Desligar a lâmpada diminuindo
3	Dezembro	2010	12:00	Alterar potência para nível I
3	Dezembro	2010	13:00	Alterar potência para nível IV

Fig. 9. Task scheduling window.

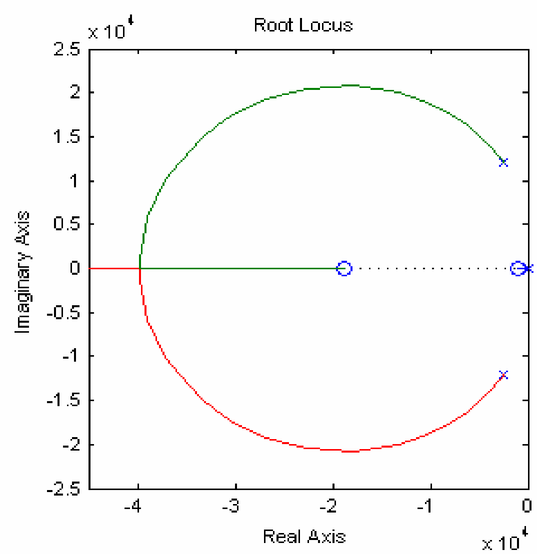

Fig. 10. Root locus of Gc(s).

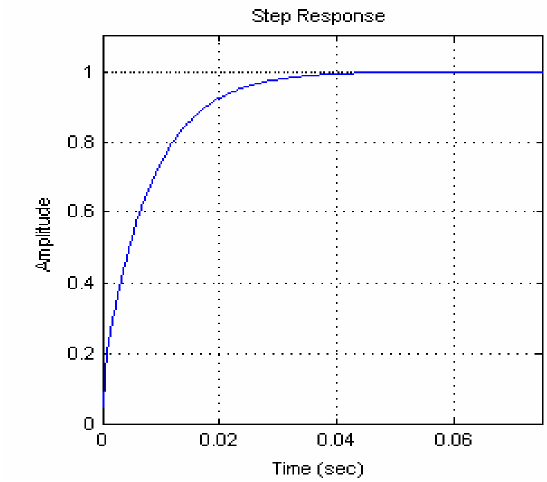

Fig. 11. Step response of Gc(s).

VII. EXPERIMENTAL RESULTS

The topology has been built in order to validate the proposed idea. The lamp was replaced by a resistance, just to analyze the controller behavior. Lamp aging was simulated by resistance increasing. Figure 12 shows system behavior when the resistance is increased from 75Ω to 100Ω. It can be seen that voltage is increased and current decreased, while the power is kept in the same level.

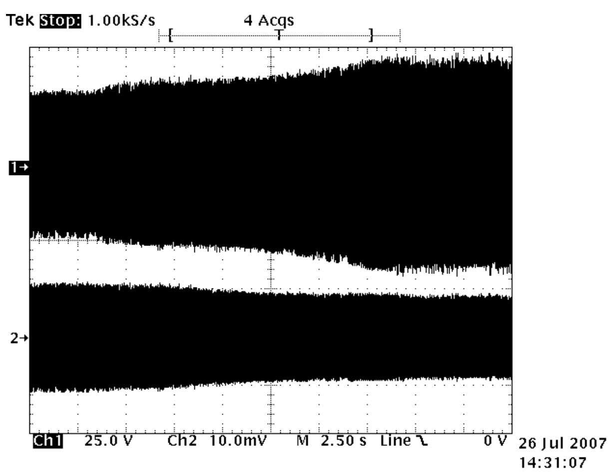

Fig. 12. Load voltage and current (25V/div; 500mA/div).

VIII. CONCLUSION

This paper presents a new way of using electric energy applied to public lighting. It proposes the use of HPS lamps supplied by electronic ballasts in public lighting, replacing standard systems and representing great amount of energy saving. Besides, the paper has the main goal of controlling lamp power in steady state, which represents a better exploitation of lamp useful life and luminous efficacy.

The Double-Flyback Half-Bridge electronic ballast has been chosen, being a low cost device that supplies the lamp with energy quality and efficiency, also being inside the standards.

Finally, the control method has been developed, based on lamp model and ballast. System plant has been analyzed and the proportional integral controller parameters, that keep lamp power constant, have been defined.

A microcontroller has been used as the controller device, allowing the performance of mathematical operations and control law with adequate speed and resolution. The device has been connected to a computer, allowing to add more resources to the system through an application, without the need of additional circuits, keeping the system cost the same. Besides, microcontroller and application programming can be protected against reading, turning the developed technology safer to use in industry.

Finally, simulation and experimental results have been performed, validating the control design. As a next step, the lamp must be used as the load, and lamp ignition process must be handled by the microcontroller software.

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