Electronic Ballast for High-Pressure Sodium Lamps

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Abstract— In this paper is presented an electronic ballast developed to operate a 400W high-pressure sodium lamp in high frequency. In the text are showed power circuit, ignitor circuit and their waveforms to prove the applicability of design procedure. The acoustic resonance phenomenon is also discussed, besides techniques used to avoid it. A boost converter controlled by a UC3854 integrated circuit performs the power factor correction stage.

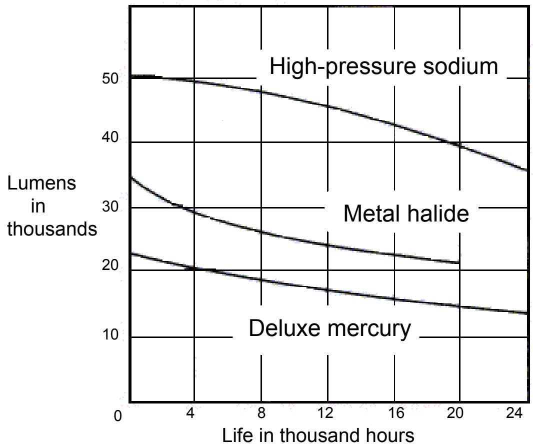
I. Introduction

Nowadays, when the energy saving is one of the most important subjects in the modern human life, and knowing that great part of the generated energy is used in artificial illuminating, the need of more efficient lighting systems is becoming more important at each day.

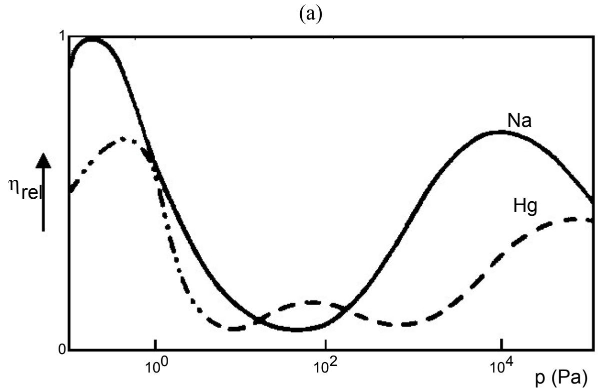
One of the most usual postures, used to make this a reality, is changing the lamp technology. For instance, it is common changing mercury lamps for high-pressure sodium lamps, which presents greater efficacy lumens/watt. In Fig.1 is shown a comparison between mercury lamps, metal halide lamps and high-pressure sodium lamps efficacy.

As can be noticed in Fig. 1, a 400W high-pressure sodium lamp always presents higher efficacy than a high pressure mercury lamp, even if an old sodium lamp was compared to a new mercury lamps. It is useful therefore where large quantities of light are required at low cost, without color discrimination; for example in street lighting, aircraft runway indication and floodlighting.

A common characteristic to major kinds of discharge lamps is the need to ignite and stabilize the discharge, which make necessary using auxiliary devices, like ballast beyond an ignitor circuit. Conventional magnetic ballasts are inexpensive and simple, but require a power factor capacitor, separate high voltage ignitors to start the lamp, are large, heavy, low efficient and have little provision for control of lamp input power due to the increase of the lamp voltage with age or compensation of varying power line voltage.



(a)



(b)

Fig. 1 – a) Typical Lumen Maintenance Curves for 400W High-Intensity Discharge Lamps [1] and b) Relative Luminous efficacy as function of Sodium or Mercury Vapor Pressure [20].

It is possible improve system lighting efficiency using auxiliary devices that present low losses. The physical size, weight and watts loss of an electronic ballast components become significantly less as frequency increases. In comparison with conventional 60Hz electromagnetic ballast, as a consequence of the use of high frequency electronic ballast the re-ignition and extinction peaks disappear, resulting in a longer lamp lifetime and even the lamp efficacy increase (above eight per cent). The reason is due principally to a reduction in anode and cathode losses as the lamp approaches unity power factor with increase in frequency [6], [9].

In this paper it is presented an electronic ballast for high-pressure sodium lamp whose efficiency is higher than electromagnetic 50 or 60Hz conventional ballasts, even knowing that these lamps, when operated in high frequency, can present a phenomenon that muddles lamps working called acoustic resonance.

II. High-Pressure Sodium Lamps

These lamps are constructed with two envelopes. The inner arc tube is resistant to sodium attack at high temperatures and has a high melt point. The outer envelope serves to prevent chemical attack of the arc tube metal parts and isolate the inner parts from the ambient temperature. Its typical construction is presented at Fig. 2 [1].

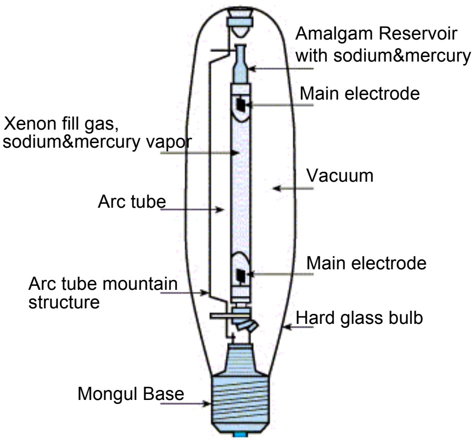


Fig. 2 – High-pressure Sodium Lamp [1].

As already said before, since the high-pressure sodium lamp does not contain a starting electrode, a high-voltage, high frequency pulse voltage is used to ionize the starting gas. This way it is necessary an especial developed circuit to supply an adequate ignition voltage.

In comparison with other electric discharge lamps, such as the fluorescent, the high-pressure lamps require an appreciable warm-up period to reach a steady state vapor pressure and full light output [6]. Just after starting, these lamps have a very low arc voltage and consequently require a high current to generate sufficient power to warm-up the arc tube to a final steady-state temperature.

III. Acoustic Resonance

When high-pressure sodium lamps are operated at current frequencies higher than mains frequency, their operation can be complicated by standing waves called acoustic resonance phenomenon. These acoustic resonances can lead to changes in arc position, to colour changes or to unstable arcs, which sometimes causes the lamp extinguish. In the specific case of high-pressure sodium lamp, sufficient shock energy may crack the arc tube at a point opposite the bottom electrode [6]. Acoustic resonances occur when lamp power varies at specific frequencies or within specific range frequency bands. In addition, many times electronic ballast deliver a non-sinusoidal lamp current, leading to higher order harmonics in the lamp power, which can also cause instabilities [2]. A lot of ballast topologies or control methods have been proposed to avoid instability caused by acoustic resonances.

One approach is operate the lamp at a frequency well away from frequencies in the acoustic resonance range. This can be achieved using a dc-type ballast where a periodical energy input can be avoided but in the case of high power, dc operated HID lamps are hampered by cataphoretic effect. Some low frequency ballasts were proposed to avoid acoustic resonances with the cost of low system efficiency, EMI problems and a tuned sound, in the specific case of 400Hz [9].

Operation above the maximum resonance frequency range [10-12] is another approach but the efficiency of the converter is still very low to use in medium or high power lamps and pre-determination of the lowest frequency above which acoustic resonance can be prevented is still required [9].

Based on the fact that a sufficiently low amplitude of the power spectrum that is required to eliminate acoustic resonance a randomized switching scheme can suppress instabilities efficiently if the center frequency and the bandwidth of injected noise are properly choose [8-9].

According to [3], an important change happens in the lamp behavior, when resonance acoustic is excited, the arc impedance increases, as evidenced by increase in lamp operating voltage and a decrease in lamp current. If necessary, this can be used to detect resonance occurrence using expensive control loop circuit [7], [9] and [14-18]. Still according to [3] there is some power frequency bands were no resonances are detected and to 400W high-pressure sodium lamps, there is a band between 91kHz and 110kHz. Because of this, the inverter frequency commutation adopted is 50Khz, which leads to a 100kHz power frequency in the lamp.

IV. Inverter

All of this study is based in a half-bridge inverter followed by a filter, that supplies a suitable current to the lamp. The inverter was switched at fixed 0.5 duty cycle and a fixed frequency of 50kHz generated initially by an integrate circuit, the UC3524 and actually by a microprocessor PIC16C73B. A bootstrap IC IR2110 is used to drive the MOSFET's. The DC voltage supply (400V) was chosen because it is the most common voltage found when the inverter is supplied by a BOOST converter, that can provide high power factor to the structure.

A. Ignitor Circuit

As it already stated before, a common characteristic to major kinds of discharge lamps is the need of a high voltage to ignite. Between several topologies studied and tested, it was chosen that one traditionally found in fluorescent electronic ballast, that is based on resonance, i.e., it is used a inverter followed by a LCC filter operating with a frequency commutation near of de filter resonance frequency before the lamp strike (Fig. 3).

It is important to say that several others circuits were assembled and tested too, but LCC filter was chosen because its good behavior in this case.

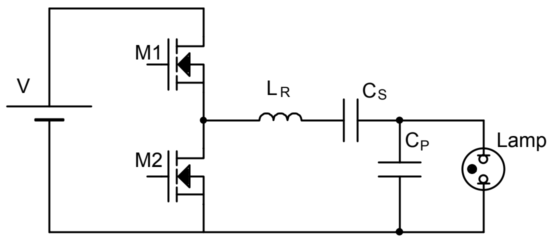


Fig. 3 – Resonant Inverter.

The LCC filter design procedure is based on these following rules:

a) Before lamp striking, its impedance is so high that the circuit can be analyzed without its presence. This way, the resonance frequency is given by equation (1).

b) During this first step operation, the frequency commutation should be so near of the filter resonance frequency as possible, which makes a high voltage been applied over the lamp.

c) The power circuit needs undergo the high current level circulating during this process.

d) After the lamp strike, the capacitor C_P influence is reduced, but not eliminated, and the circuit should be analyzed like to impedances connected in series. During this step, the theoretical resonance frequency is given by equation (2).

e) During all the time, the frequency commutation should be higher than the filter resonant frequency.

$$fo_A = \frac{1}{2.\pi.\sqrt{L_R.Ceq}} \qquad (1)$$

$$fo_D = \frac{1}{2.\pi.\sqrt{L_R.C_S}} \qquad (2)$$

At the equation (1) Ceq represents the equivalent capacitance from the C_S and C_P association.

Through this considerations, and knowing the frequency commutation and inverter voltage supply, the filter parameter obtained were:

L_R ➔ 150µH

C_S ➔ 1µF

C_P ➔ 85nF

Based on this parameters one prototype were implemented and its mainly results are presented. The first acquisition (Fig. 4) shows the voltage waveform applied over the lamp during the startup process.

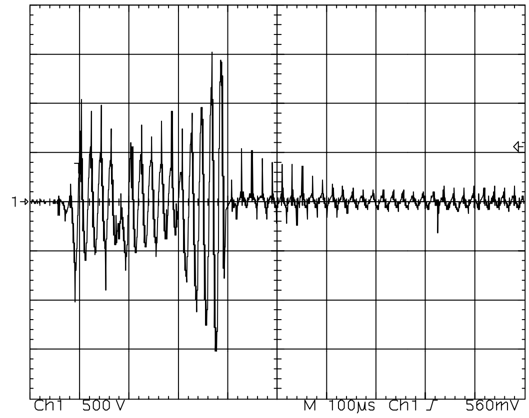


Fig. 4 – Ignition Lamp Voltage Using the Resonant Circuit.

The theoretical voltage waveform that should be applied at the lamp (Fig. 5), is different from that one obtained in the real circuit. This difference probably is caused by the transient inverter source supply that, associated with the LCC filter transient, result in this behavior. Tests using smaller supply voltages, that were not enough to strike the lamp, showed that theoretical behavior could be obtained at the practical circuit.

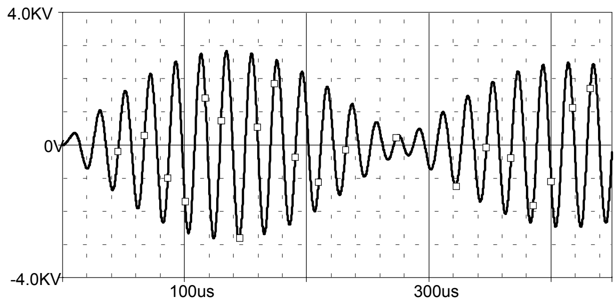


Fig. 5 – Theoretical Ignition Lamp Voltage Using the Resonant Circuit.

Fig. 6 shows lamp voltage (Ax2), current (Ch2) and power (M1) at steady state. As can be noticed, this circuit makes possible obtain the lamp strike and its influence at the lamp behavior during the normal operation is null. In addition the voltage and current waveforms applied in the lamp are almost sinusoidal.

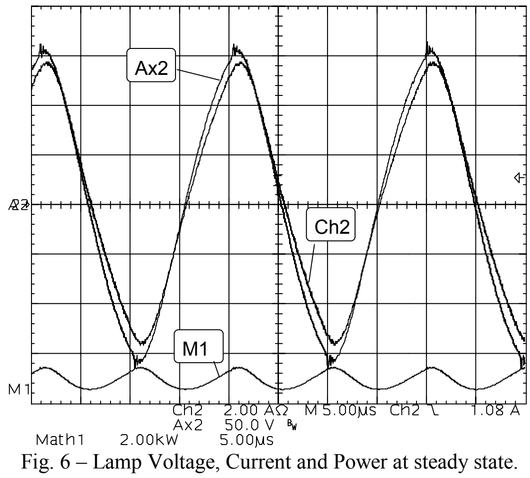


Fig. 6 – Lamp Voltage, Current and Power at steady state.

In this situation, the power at the lamp was 396W, the voltage was 105V and the current was 3.72A.

The MOSFET’s commutation behaviors are showed at Fig. 7.

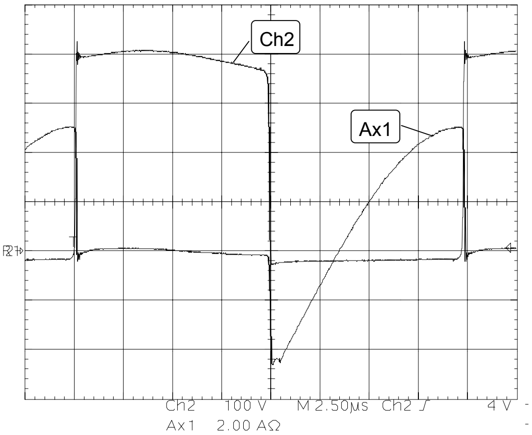


Fig. 7 – Voltage and Current in one of the MOSFET.

As the frequency commutation is higher than filter resonance frequency, ZVS commutation is obtained.

B. Detected Resonance

As stated before, the frequency commutation was chosen because according with [3] there is a band between 91kHz and 110kHz where no resonance are detected to this kind of lamps. At Fig. 8 a discharge picture when the lamp is operated at 50kHz is showed. As can be noticed, the arc path is normal.

Fig. 8 – Discharge Picture – Resonance Free.

Even when older one replaced the original lamp, no acoustic resonances were detected. Notwithstanding, resonances were detected when the lamp was operated in other commutation frequencies into the range indicated by [3]. This can be easily noticed through the pictures at the Fig.9 and Fig. 10.

Fig. 9 – Discharge Picture – Resonance at 52kHz.

In both cases (≅ 52kHz and ≅ 48kHz) the arc path is distorted. This behavior was observed with a new lamp. When the old lamp was used, instead of an arc change shape been registered, the lamp just extinguished at these frequencies.

These results prove that this technique do not guaranty any resonance occurrence.

Fig. 10 – Discharge Picture – Resonance at 48kHz.

V. Input Stage

Finally, in this section the ballast input stage is presented. It has been used a boost preregulator controlled by a UC3854 integrated circuit. The design procedure followed the recommendations extracted from [19].

The main specifications for the converter are the minimum and maximum line voltage (160Vac – 260Vac), the maximum output power (420W), the output voltage (400Vdc) and the switching frequency (100kHz). The circuit obtained following [19] recommendations, took to the circuit showed at Fig. 11, where the main values are:

LB=3mH

RS=0,25Ω

DB=MUR460

M1=2 x IRFF840

The input voltage and current at the worst situation to the converter, when the maximum input current is registered, that happens when it is operated the minimum input voltage, is presented at Fig. 12.

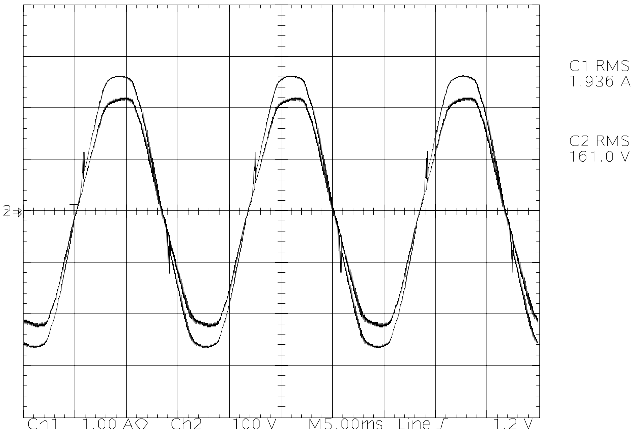


Fig. 12 – Input voltage and input current.

The waveform of Fig. 12 suggests that the electronic ballast can appear resistive to the AC line, thus reducing the harmonic current content.

VI. Conclusion

This paper presented a study about the development of high-pressure sodium lamp electronic ballast. A brief theoretical study about this kind of lamp was presented. Based on this information it was chosen a frequency commutation that, during the tests, didn't excited acoustic resonances, even when the lamp were changed by another two old lamps. It is important to say that when the prototype was operated around the main frequency (50kHz), still inside of the frequency range indicated by [3] as acoustic resonance free, some arc path changes were registered. In some cases, the lamp extinguished. These behaviors prove that acoustic resonance manifested. This way it is possible conclude that same power lamps (400W) assembled by different manufactures have different behaviors when they are drive in high frequency. The presented information can be used as the base to future studies, because the prototype operated the lamps suitably without the need of a complex control or pulse switch generation circuit in a unique point.

To make this ballast able to be connected directly to the mains voltage, it was necessary implement a simple input stage. This was made using a boost converter controlled by a UC3854, providing a high power factor and the necessary 400V bus voltage.

A complete ballast using the inverter topology associated with the boost PFC converter that provided the control to obtain a constant lamp power input to compensate for changes in line voltage was obtained.

The control of the power of the lamps may be realized measuring the voltage and the current in the output of the boost PFC converter. Although this idea was not yet implemented, we believe that it is very simple and should give good results.

Other propositions to avoid instability caused by acoustic resonance are actually been study and will be present in future publications.

Finally, it was observed that one of the problems inherent to the high-pressure sodium lamps is the slow running-up luminous flux, which can be partially solved through the high frequency operation. The time necessary to the lamp reaches the nominal power using high frequency ballast, when compared to ac line ballast, is drastically smaller. Normally it is smaller than the half time registered in mains frequency ballast.

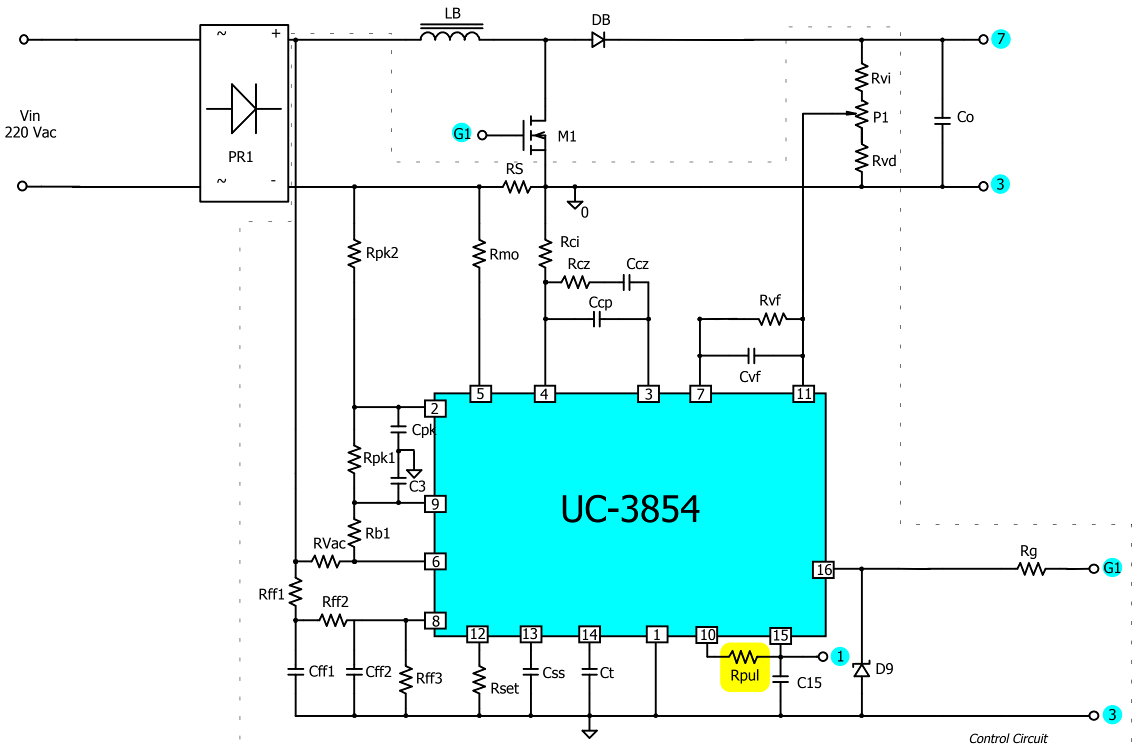


Fig. 11 – Input PFC Circuit.

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