A 250W HIGH PRESSURE SODIUM LAMP HIGH POWER FACTOR ELECTRONIC BALLAST USING AN INDIRECT FREQUENCY CHANGER

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***Abstract* – An electronic ballast with high power factor (HPF) for high pressure sodium (HPS) lamps is presented. Traditionally power factor correction stage (PFC) is used to provide HPF to the electronic ballast. However, it is used, in this work, an indirect frequency changer to achieve this characteristic and to supply high frequency to the lamp, which implies, as a consequence, in a low frequency (voltage source frequency) modulation. This output characteristic applied in HPS lamps will be discussed. Following, two different modulation strategies are proposed to improve the input and output current characteristics. Finally, experimental results of a prototype for 250W HPS lamps are discussed.**

***Keywords* – Electronic ballast, indirect frequency changer, power factor correction and HPS lamp.**

I. INTRODUCTION

High pressure sodium lamps have become an attractive lighting source for their high luminous efficacy and long life, among 24.000 to 32.000 hours.

However, HPS lamps have negative impedance characteristic. This fact does not allow connecting it directly to the line source. So it is necessary an element that limits the lamp current. This element is called ballast [1].

Traditionally electromagnetic ballasts are been used in this application, but this elements have some problems: high volume and weight; poor regulation, audible noise and low power factor [2].

Focused in improving those characteristics electronic ballasts for HPS lamps have been received great attention in recent year. Electronic ballasts operate in high frequency, allowing reduction of the volume and weight and avoiding audible noise if the switching frequency is high enough. Besides, this kind of ballasts permit to control the power delivered to the load.

This last characteristic is the mainly advantage of the electronic ballast, since it is possible to save energy if the converter is capable of control the power on the lamp without a considerable loss of efficiency. The electronic ballast has a higher initial cost than electromagnetic ballasts, however, in the long run it is more economic because of the energy saving.

Unluckily operating HPS lamps in high frequency can generate a serious problem: acoustic resonance. This is undesirable because it can generate light output variation, arc instability and it might even crack the arc tube. Another problem is the cataphoresis caused when the HPS lamp is fed by current with a DC level.

Another concern is the power quality of the input current of the electronic ballast [3]. Traditionally to provide HPF to this ballasts it is used a PFC stage [4] (Fig. 1 (b)) [5] (Fig. 1 (a)), but this extra stage decrease efficiency and increase cost. Thus, with the objective of improving these characteristics others electronic ballasts without this PFC stage have been proposed [6] [7] [8] [9].

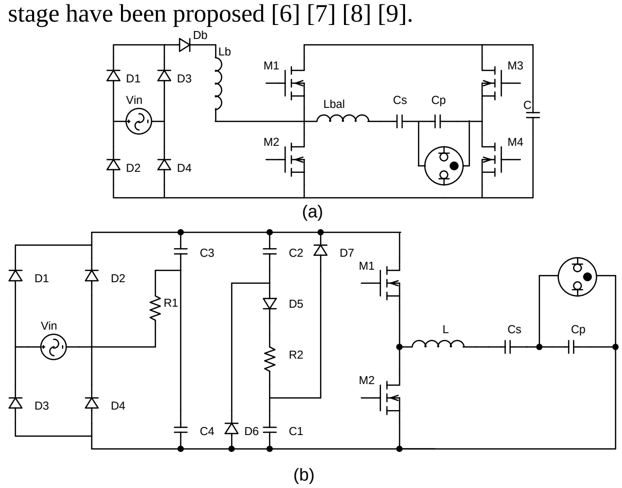

Fig. 1 Electronic ballast proposed by: (a) Ferrero [5] (b) Brañas [4].

This paper will present electronic ballast based on an indirect frequency changer. The mainly idea is achieve HPF using full bridge diode rectifier with a low value output capacitor connected to a full bridge inverter. Fig. 2 shows the ballast block diagram. This structure will apply on the load high frequency current modulated in low frequency [6] [7] [8].

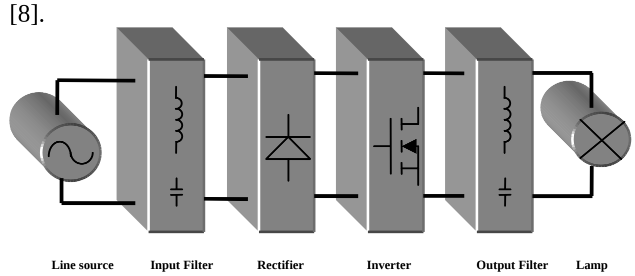

Fig. 2 Indirect frequency changer block diagram.

Additionally it will be presented two high frequency modulations strategies for the voltage inverter used to improve the input and output current characteristic. Also will be discussed two possible output filters.

Finally, experimental results will be presented to prove that the proposed solution is suitable to achieve the requirements demanded.

II. INDIRECTY FREQUENCY CHANGER

The main characteristics of the present electronic ballast based on an indirect frequency changer are the absence of a PFC stage, the low frequency output current behavior and the power control capability. These characteristics can decrease volume, weight and costs and increase efficiency in comparison with others electronics ballasts. Besides, the capacity of controlling the power on the lamp makes this structure more attractive than electromagnetic ballast.

A circuit diagram of the indirect frequency changer used as electronic ballast is show in Fig. 3. The structure is composed by an input filter to improve the input current, the full bridge diodes rectifier with the low value Cb capacitor allowing HPF, the high frequency inverter and the output filter.

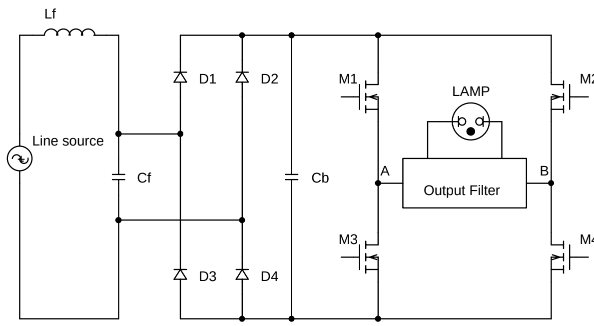

Fig. 3 Indirect frequency changer circuit diagram.

A. Input Stage

The input stage is composed by the input filter and the full bridge diodes rectifier. The input filter has the function of adjust the harmonic levels of the current added to line source by the inverter, in this case is used a low-pass filter implemented by an L-C. The rectifier has high power factor due to the low capacitance value of the output capacitor. The bus capacitor is used only to supply energy to the inverter in the zero crossing of the line voltage source.

To verify the efficiency of the proposed circuit simulation results are presented in the sequence. Fig. 4 presents the circuit used in the simulation. It can be noted that the load is resistive. The input current and the voltage in the bus capacitor Cb are show in Fig. 5. It can be seen that the current has a sinusoidal form, which guarantee the HPF of the structure.

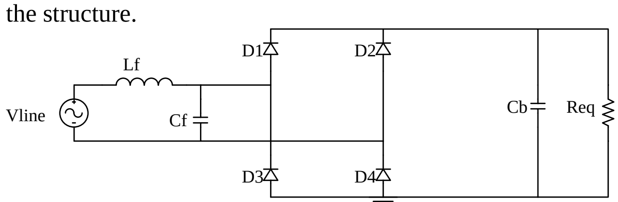

Fig. 4 Input stage circuit simulated.

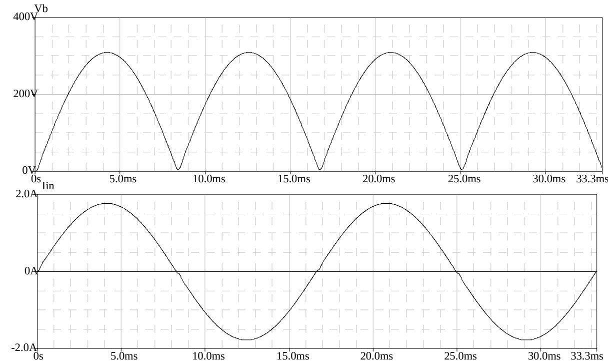

Fig. 5 Input current and Cb voltage.

B. Inverter

The inverter should operate at high frequency and supply AC current to the HPS lamp. To achieve these requirements was chosen the voltage full bridge inverter shown in Fig. 3. Despite of using a traditional half bridge, the full bridge was chosen because with this topology it is possible to apply on the load the maximum value of voltage from the input, that allows to supply nominal power to the lamp. Another advantage of this topology is the capability of soft switching operation.

C. Output Filter

HPS lamps have negative impedance characteristics, then it is necessary an element to limit the current in the lamp. The filter utilized in the output of the inverter should stabilize the voltage and current on the lamp, control the current at zero crossing of the voltage line source, provide ignition pulse to start the lamp and allow inverter soft switching operation. To accomplish the requirements two topologies are used: resonant filter (LC) (Fig. 6) and series resonant filter (LCsCp) (Fig. 7).

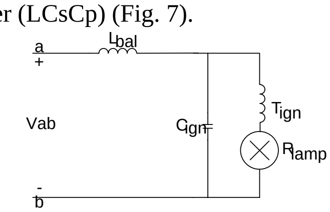

Fig. 6 Resonant filter – LC.

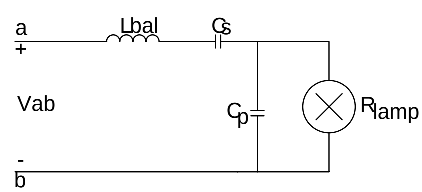

Fig. 7 Series resonant filter – LCsCp.

III. MODULATION STRATEGIES

For each of the output filter used one modulation strategy was developed. This was necessary to improve the input current form and to decrease the re-ignition time of the HPS lamp at half-cycle of the period of the input voltage. The purpose of both modulation is to warm up the lamp in the zero crossing of the voltage line source and, then, decreasing the re-ignition time.

A. Frequency Modulation

The first modulation implemented was the frequency modulation [6]. The idea is simple: apply a variation in the switching frequency in a semi period of the voltage line source. Fig. 8 presents the modulation function utilized, it can be noted that the switching frequency vary from 27kHz to 42kHz. These limits were used to achieve the nominal power on the lamp.

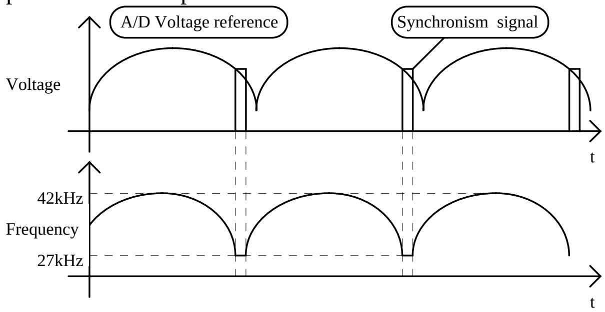

Fig. 8 Frequency modulation function.

The motivation to decrease the switching frequency near to the zero crossing of the input voltage is to supply higher power to the lamp making the re-ignition time lower. This strategy will be used with the resonant filter LC.

B. Modified Sinusoidal Pulse Width PWM Modulation

In this modulation strategy to warm up the lamp in desired moments will be used a duty cycle variation in a semi period of the input voltage. The objective is to use the sinusoidal pulse width PWM modulation, however, some modification must to be introduced to obtain the desired characteristics: the larger pulse will be placed near to the zero crossing of the voltage source [7]. To eliminate DC component in the lamp current the drive signal of the switches M1/M4 and M2/M3 will be inverted in each semi period of the line source. This is necessary to avoid the cataphoresis phenomenon.

For that reason the reference signal is modified. Fig. 9 shows the pulse width variation, the modified reference signal used, the comparison triangular signal and the drive signal for the switches M1/M4. The switching frequency is fixed and in this example is lower than the frequency really employed.

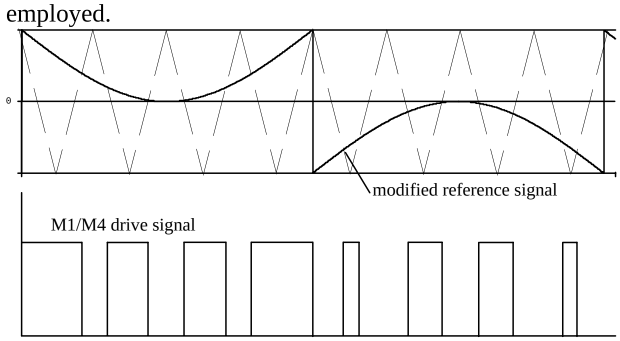

Fig. 9 Modified sinusoidal pulse width PWM modulation.

IV. EXPERIMENTAL RESULTS

A. Resonant Output Filter

The first prototype implemented employs the resonant filter LC. The frequency modulation was used to improve the input and output current characteristics. It was used a microcontroller PIC16F873 from Microchip to generate the drive signals for the switches. This allows an easily implementation of the modulation presented above. The ballast parameters are: 220V input voltage; switching frequency vary from 27kHz to 42kHz; L_{bal} = 363μH; C_{ign} = 94nF; T_{ign} = 100μH; Cb = 1μF. Fig. 10 presents the circuit implemented in laboratory. In this figure can be seen that the high voltage pulse is applied in the lamp by T_{ign} when S_{disc} is commanded to conduct. This pulse is about 3.5kV.

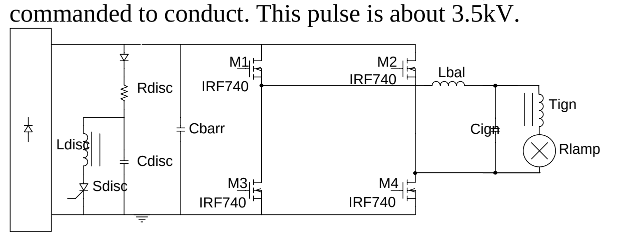

Fig. 10 Circuit implemented in laboratory.

Lamp voltage and current are shown in Fig. 11. It is clearly the low frequency behavior of the lamp. This is caused by the characteristic of the presented ballast.

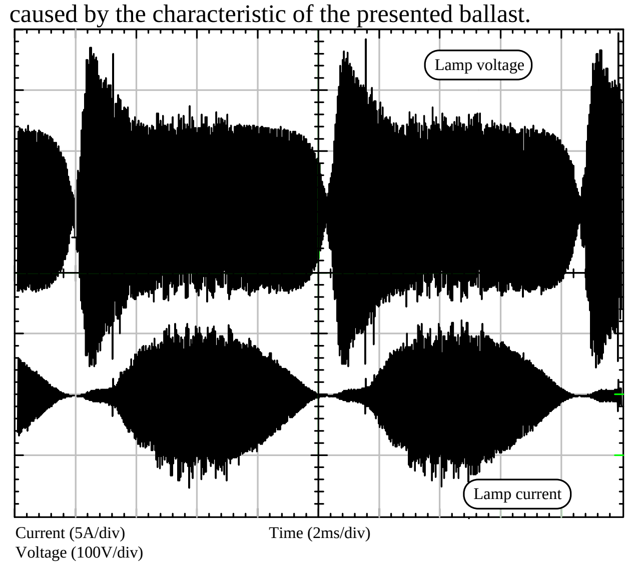

Fig. 11 Lamp voltage and current in low frequency.

Lamp voltage and current in high frequency are shown in Fig. 12. In this figure can be noted that the lamp current presents resistive characteristics in that condition.

The voltage reference signal and the synchronism signal are shown in Fig. 13. These signals are necessary to synchronism the drive signal from the microcontroller with the input voltage source.

The input voltage and current are shown in Fig. 15. It can be seen that the presented electronic ballast achieve HPF. This can be proved by the harmonic analysis of the input current presented in Fig. 14. Besides, Table 1 presents the mainly parameters obtained by the experimental prototype.

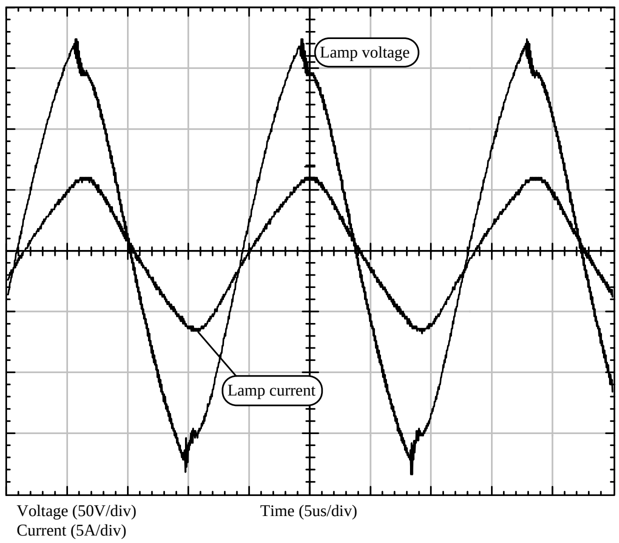

Fig. 12 Lamp voltage and current in high frequency.

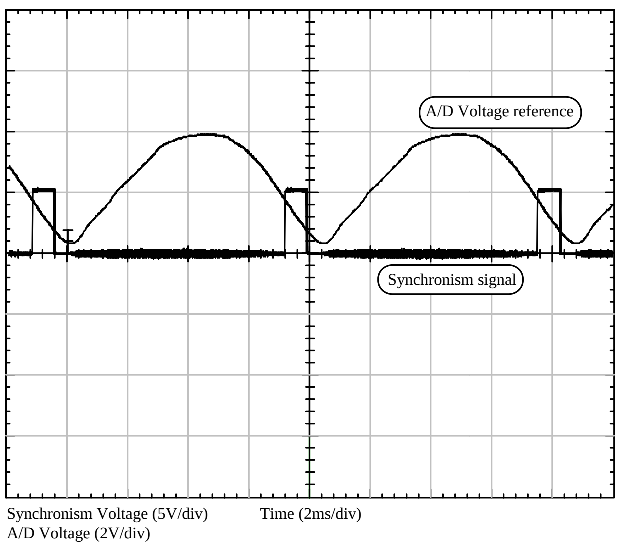

Fig. 13 Voltage reference and synchronism signal.

TABLE I
Input and output data

	Active Power	Voltage	Current	Power Factor
Input	252W	220V	1.88A	0.965
Lamp	231W	107.4V	2.99A	

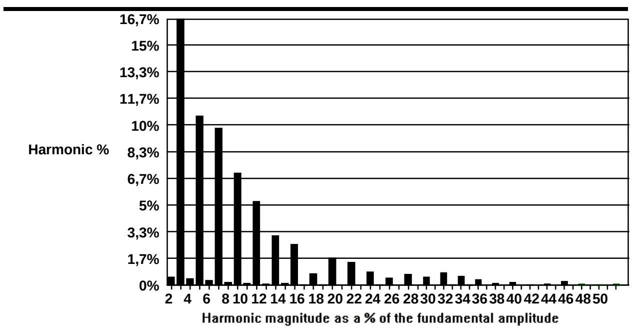

Fig. 14 Harmonic analysis of the input current.

The efficiency of the prototype is 91.6%. The HPF has been obtained in this structure, however, some lamps that have been tested presented acoustic resonance. This fact occurs because the amplitude modulation is not capable of avoid this phenomenon. Another problem is the difficulty to control the power on the load with the lamp ageing, and this occurs because of the modulation used.

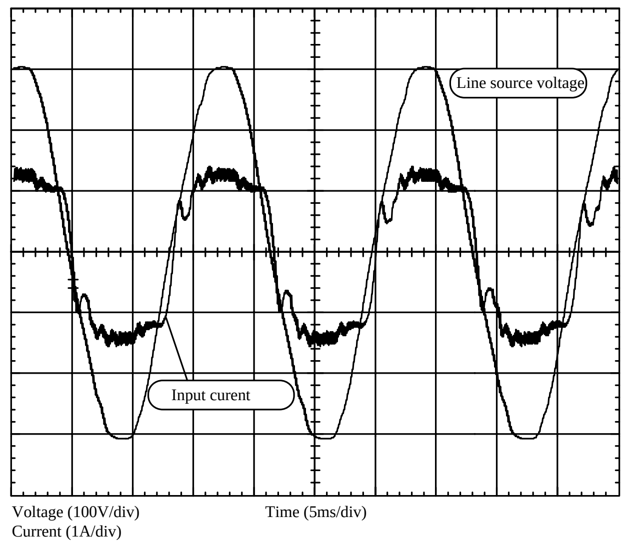

Fig. 15 Input current and voltage.

B. Series Resonant Filter

Other prototype was implemented using now the series resonant filter LCsCp. With this output filter the modulation applied was the modified sinusoidal pulse width PWM modulation. It was used a microcontroller PIC16F873 from Microchip to generate the drive signal for the switches. The ballast parameters are: 220V input voltage; switching frequency of 40kHz; L_{bal} = 217μH; Cs = 1μF; Cp = 72nF. Fig. 16 presents the circuit implemented in laboratory. In this figure one can be noted that the high pulse auxiliary circuit was removed. This output filter is capable of apply a high pulse in the lamp if the switching frequency is modified to a value narrow of its resonance frequency [10]. However, a control methodology for the lamp ignition must be implemented using the microcontroller to protect the structure in the case of a lamp ignition fault. The first step is to detect the zero crossing of the input voltage source, then, 3.5ms after this the switching frequency is changed to a value near to the resonance frequency. The zero detection and the delay are necessary to apply the high voltage pulse when the input voltage is higher than 90% from the nominal value. The resonance switching frequency is applied during 1ms. This is a safe period where the voltage in the lamp will increase to a value capable of starting the lamp, but not dangerous to damage the structure.

Fig. 17 shows lamp voltage and current. Again it can be noted the low frequency characteristic of them. In comparison with the other implementation this one improved the current characteristic as the time that the lamp current is low. The time taken to the lamp re-ignition is important because it is the interval where the input current is more distorted, Fig. 18 shows this fact.

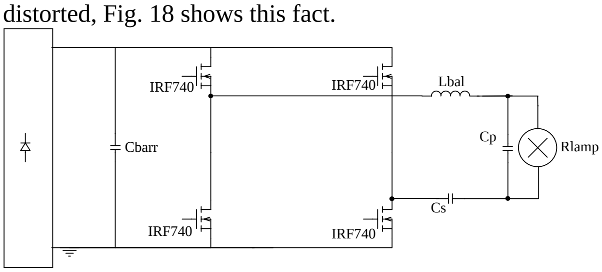

Fig. 16 Circuit implemented in laboratory.

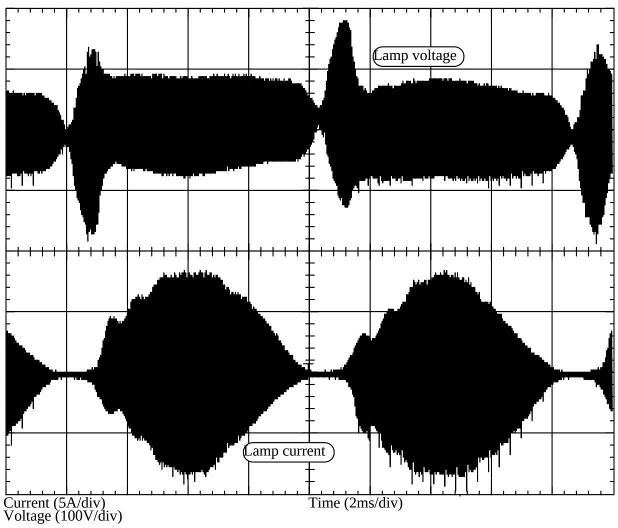

Fig. 17 Lamp voltage and current in low frequency.

Lamp voltage and current in high frequency are shown in Fig. 19. In this figure can been noted, again, the resistive characteristic of the lamp current in that condition.

Input current and voltage are shown in Fig. 21. It can be noted a small current peak, caused by the lamp re-ignition. The harmonic analysis of the input current is presented in Fig. 20. In this figure one can be noted that the harmonic content has improved in comparison with the other implementation.

Table 2 presents the mainly parameters obtained by the experimental prototype. The efficiency of the prototype is 92%. The HPF has been achieved in this structure and it is about 0.978.

In this prototype the acoustic resonance was not observed. A factor that contributed to this is the characteristic of the modulation implemented. The pulse width modulation can spread the harmonic content of the lamp power. And if the values of some harmonic components are low enough the acoustic resonance can be avoided [11] [12].

Another concern is the lamp current characteristic where the crest factor is about 2. In fluorescent lamp this would be a problem. However, recently studies show that in high frequency operation the high crest factor is not a concern to the HPS lamp [13]. In fact, the electrode erosion, in this condition, is lower than obtained in the low frequency line operation. For low power lamps there are a strategy that can improve the crest factor [14], on the other hand, this strategy is not applicable in these 250W lamps, because the elements to store the energy are to large.

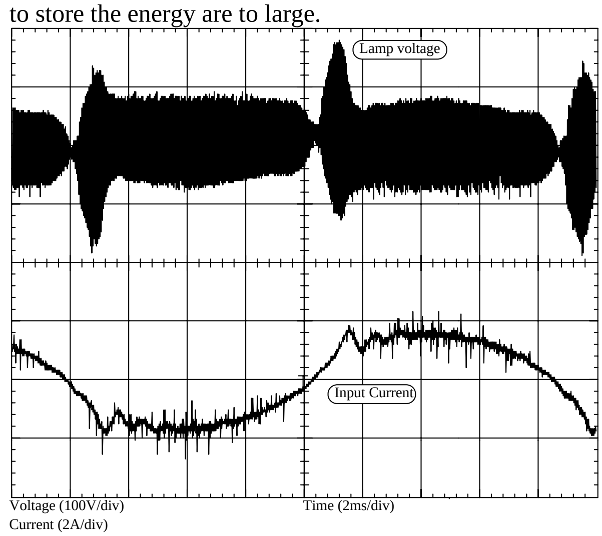

Fig. 18 Lamp voltage and input current.

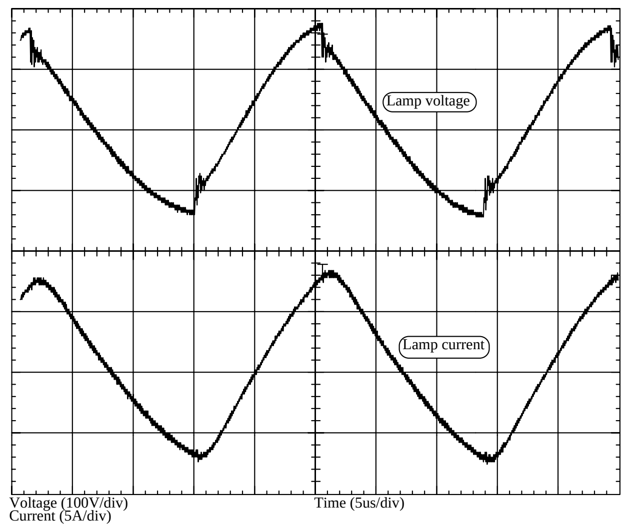

Fig. 19 Lamp voltage and current in high frequency.

TABLE 2
Input and output data

	Active Power	Voltage	Current	Power Factor
Input	285W	222V	1.27A	0.978
Lamp	262W	104V	3.48A	

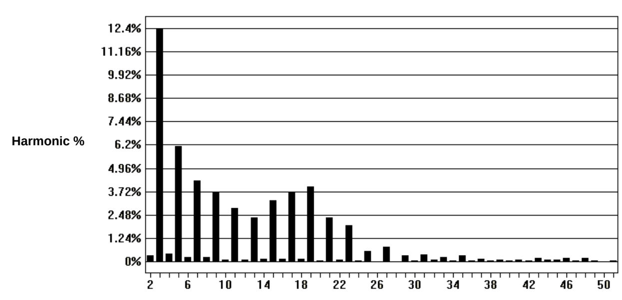

Fig. 20 Harmonic analysis of the input current, LC filter.

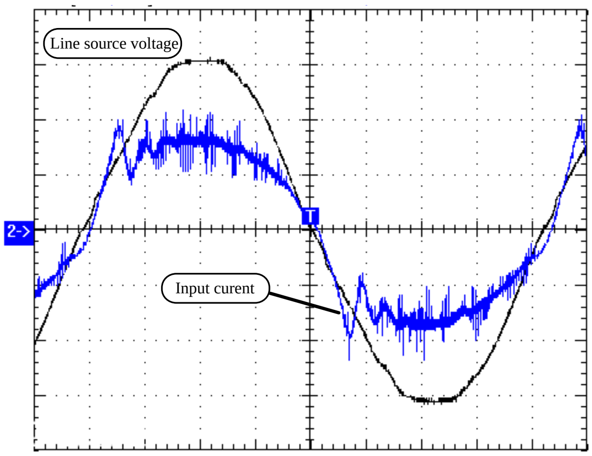

Fig. 21 Input current and voltage.

Fig. 22 shows voltage and current in switch M1. It can be noted the soft switching commutation of the electronic ballast. This is possible because of the current characteristic of the series resonant filter.

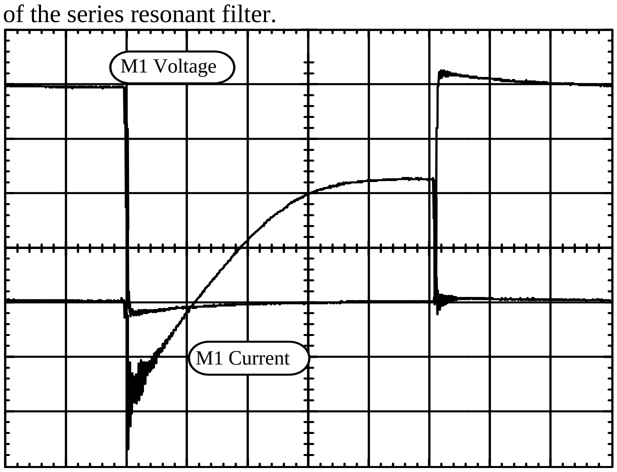

Fig. 22 M1 voltage and current.

V. CONCLUSION

An electronic ballast using an indirect frequency changer to achieve HPF for HPS lamps was analyzed. With the purpose of improve the quality of input and output current two modulation strategies were proposed. Both presented good results in the structures applied.

Both output filters presented HPF. However, the pulse width modulation using the series resonant LCsCp filter presented best results. Other advantage is the capacity of improving the possibility of avoiding the acoustic resonance, but this characteristic should be investigated. Another concern, the crest factor, might not be a problem to the HPS lamp in high frequency operation. However, the crest factor can be decreased using an appropriated filter, but this strategy normally is used in low power lamps. The dimming control is possible and also the regulation of the lamp power.

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REFERENCES

[1] Groot, J. J. and Vliet, J. A. J. M. Van, *The high pressure sodium lamp.* London, U.K.: Mac Millan Educational, 1986.N.

[2] Blanco, C., Alonso, M., López, E., Calleja, A. and Rico, M.: “A single stage fluorescent lamp ballast with high power factor”, *IEEE-APEC, 1996,* pp. 616-627.

[3] European Standard EN 61000-3-2 “Limits for harmonic current emissions”, April 1999.

[4] Brañas, C., Azcondo, F. J. and Bracho, S., “Evaluation of an electronic ballast for HID lamps with passive power factor correction”, *IECON 02*, Vol. 1, pp: 317-376, 2002.

[5] Ferrero, F. J., Rico, M., Alonso, J. M., Blanco, C. and Ribas, J., “Analysis and design of an AC/AC resonant converter as a high pressure sodium lamp ballast.” *IECON’98*, Vol. 2, pp: 947-952, 1998.

[6] Wuerges, S. A., *Electronic ballast for a 250W high pressure sodium lamp without an active power factor correction stage (In Portuguese)*, Dissertation (Master in Electrical Engineering), Florianópolis, 2004. UFSC.

[7] Sincero, G. C. R., *A 250W high pressure sodium lamp high power factor electronic ballast using an AC chopper (In Portuguese)*, Dissertation (Master in Electrical Engineering), Florianópolis, 2005, UFSC.

[8] Reis, F. S. dos, Canalli, V. M. et al., “Low Cost High Power Factor Electronic Ballast For High Pressure Sodium Lamps”. Joinville, 2004. *Induscon’04*, October 2004, pp. 1000 – 1005.

[9] Licitra, C., Malesani, L., Spiazzi, G., Tenti. P. and Testa, A., “Single-ended soft-swithcing electronic ballast with unity power factor”, *Proc. of IEEE-IAS Ann. Meet.*, 1991, pp. 953-958.

[10] Pereira, E. I., Nascimento, C. B., Perin, A. J.: “Electronic ballast for fluorescent lamps with the PFC stage integrated with the resonant inverter”, *35th Annual IEEE Power Electron. Specialists Conference*, vol. 5, pp. 4050-4056, June 2004.

[11] Faehnrich, H. and Rasch, E., “Electronic Ballast for Metal Halide Lamps”, *Journal of Illuminating Engineering Society*, Summer 1988, pp. 191-140.

[12] Laskai, L., Enjeti, P. N. and Pitel, I. J., “White-noise modulation of high-frequency high-intensity discharge lamp ballast”, *IEEE Transactions on Industry Applications*, Vol. 34, pp. 597 - 605

[13] Kaiser, W., Correa, A. F. and Marques, R. P., “Electrode Erosion in Pulse Operated High-Pressure-Sodium Lamps”. *Industry Applications Conference, 2004. 39th IAS Annual Meeting. Conference Record of the 2004 IEEE*, Vol. 2, pp. 1362 – 1367.

[14] Malesani, L., Rossetto, L., Spiazzi, G. and Tenti, P., “High efficiency electronic lamp ballast with unity power factor” *Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting*, Vol. 1, pp. 681-688.