ELECTRONIC BALLAST FOR HIGH-PRESSURE SODIUM LAMPS WITH ACOUSTIC RESSONANCE AVOIDANCE

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Abstract – This paper presents the study, design and implementation of some electronic ballasts for high-pressure sodium lamps. Their main feature is the capacity to avoid the phenomenon known as acoustic resonance. Several techniques are discussed to solve the problems related to resonance acoustic detection, and some one of them tested. Besides this, prototype results are presented to confirm the design approach used.

KEYWORDS

Electronic ballast, HID, sodium lamp, acoustic resonance.

I. INTRODUCTION

This paper presents electronic ballasts for high-pressure sodium lamps whose main attribute is the use of a microcontroller to avoid acoustic resonance occurrence.

Three techniques were tested and presented good results. Two first techniques presented are based on spread power spectrum. At the last one, lamp voltage and current are observed during ballast operation to provide necessary information to the microcontroller and based on this information changes converter point operation, if necessary. Beside, microcontroller use allows lamp operation with controlled power even with old lamps, since the arc voltage increases with lamp life.

II. ACOUSTIC RESONANCE

The biggest challenge to develop reliable electronic ballast for high-pressure sodium lamps is overcome the acoustic resonance. This phenomenon created a delay between the electronic techniques used with this sort of lamps and the electronic techniques used in fluorescent lamps.

When a high-pressure discharge lamp is driven by an AC power source, the discharge electric properties depend on ballast frequency. After lamp ignition and arc stabilization, the lamp impedance changes continuously during an AC cycle, if the lamp is operated on mains frequency (50/60Hz). Notwithstanding, its operation with high frequency electronic ballasts can cause the arc instability appearance, kwon as acoustic resonance. The frequency range operation susceptible to acoustic resonance is usually between 1kHz and 300kHz. This happens because the periodic power supply results in gas pressure fluctuation at the same frequency. If this frequency coincides to arc discharge tube frequency resonance, stationary waves are generated and arc is bowed [1], like is shown in Fig 1.

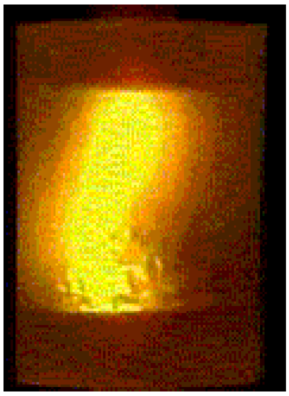

Fig. 1 - Arc path during acoustic resonance occurrence [2].

The gas density oscillations cause several problems, like arc instability, light output fluctuation, color temperature and color point variations. Due to arc path change, they also increase voltage lamp, which may cause arc extinction or, in the worst case, crack the arc tube.

These observations are typical to all kind and power of high-pressure sodium lamps. The biggest variation between several models of lamps is the spectrum resonance distribution that can shift due to mechanical differences. These resonance frequencies are basically determinate by arc tube internal dimensions, electrodes distance, arc tube internal geometry, sound speed and gas pressure [3-5]. Due to high order harmonics occurrence, the high frequency current shape can also be considered an important acoustic resonance excitation factor, since many times electronic ballast deliver a non-sinusoidal lamp current. Based on these factors, several studies already have been presented to try forecasting the acoustic resonance frequency range occurrence and, still according to them, acoustic resonance cannot be eliminated through arc tube shape modifications [6].

At this time is important to say that forecasted stationary waves just will occur if the power at the relevant range frequency were enough strong, which means that power supply should operate the lamp in a critical frequency with a energy level over the minimal limit. The acoustic-resonance-related instabilities are well described theoretically and the respective power input frequency can be calculated [3].

To overcome the acoustic resonance drawback, several methods to avoid the phenomenon were studied. For instance, [5] and [7] proposed a technique that uses some sensors to measure lamp voltage and current to determine the acoustic resonance. According to these approaches, the inverter frequency is varied during the startup process or after arc stabilization, to determine an ideal frequency in a free range.

Another technique proposes a periodical commutation frequency change to avoid stationary wave energy grows up enough to distort arc path [8]. Ideally this should be done in a frequency range where acoustic resonances are not usually observed.

1. Acoustic Resonances Detected

Using a half bridge inverter some experiments has been realized to confirm acoustic resonances critical frequencies with 400W sodium lamps (see table I).

TABLE I

Critical Frequencies [3]

Lamp power	400W	250W	150W
Resonance classification	Power frequency		
Longitudinal	3,0 ~ 3,8	3,8 ~ 4,5	7,75 ~ 8,5
Azimuthall	36,6 ~ 46	37 ~ 48	50 ~60
Radial	83 ~ 87	80 ~ 91	110 ~ 116

During these experiments, four lamps from different manufactures and ages were used, what confirm that the frequency range between 19kHz and 21kHz is extremely susceptible to acoustic resonance excitation, as is shown on Fig 2. This frequency range corresponds to basic azimuthal frequency.

The lamp models used were:

- VIALOX NAVT E40 – Osram;
- SON-T 400W – Philips.

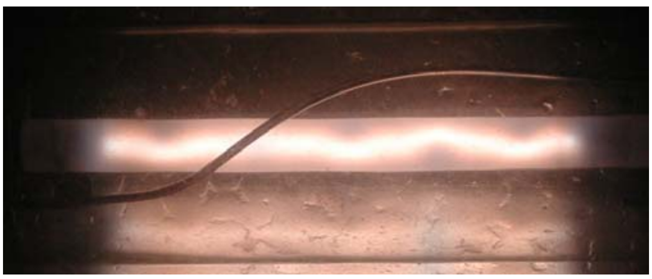

Fig. 2 – Lamp Arc at 20.6kHz.

Fig 3 shows another lamp picture with arc patch distortion around 20kHz frequency range.

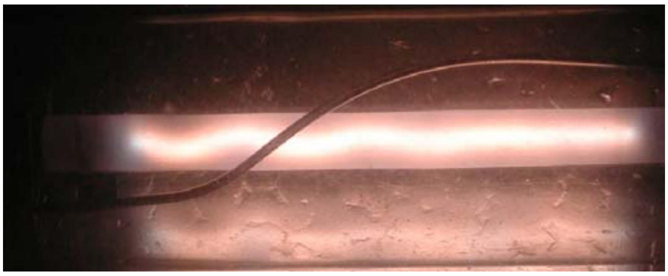

Fig. 3 – Lamp Arc at 20kHz.

The basic radial power range frequency is between 83kHz and 87kHz and because this another frequency range around 42kHz was tested and presented some acoustic resonance, but they were not so much strong as in 20kHz.

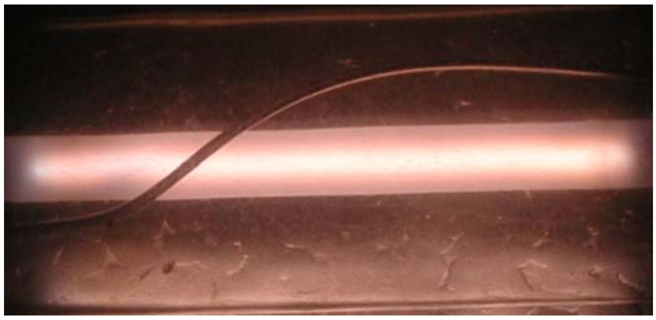

Fig. 4 – Lamp Arc at 42.5kHz.

The basic longitudinal power range frequency was not tested because it is located between 3.0kHz and 3.8kHz, what would take to a very low frequency commutation near 1.6kHz.

Based on these results, the frequency range around 20kHz was chosen to test acoustic resonance avoidance methods.

III. PROTOTYPES

As stated before, three techniques were implemented and their results will be presented now. Once more, a half bridge inverter was used to execute all tests. It fulfills the main role of the electronic ballast:

- Ignite the lamp;
- Supply the lamp after its ignition;
- Avoid acoustic resonance.

As known, a common characteristic to all kinds of discharge lamps is the need to ignite and stabilize the discharge. Ignition involves conversion of the starting gas from a non-conductive into a conductive state. Instead of what happens in mercury lamps, it is impractical to include an auxiliary starting probe within the arc tube in lamps like high-pressure sodium, so the lamp must be ignited with a high-voltage pulse [8] that needs sufficient amplitude and appropriate width and rise time [9]. In low frequency ballasts, this is usually obtained through a separate electronic device, which is part of the control gear circuit. In this paper, the topology used as igniter circuit, is integrated to the inverter.

After studding several different circuits and techniques to ignite the lamp [10] and through the obtained results it was possible to conclude that the technique using the voltage pulse is the best option to the developed prototype, since it presented smaller sensitivity to the parasitic parameters.

Besides, the pulse voltage level can be easily set through the turn ratio used on the ballast inductor.

Fig. 5 presents the inverter with the integrated igniter circuit, which is composed by resistors R1 e R2, diode D1, capacitor C2, spark gap and some turns of main inductor (L1).

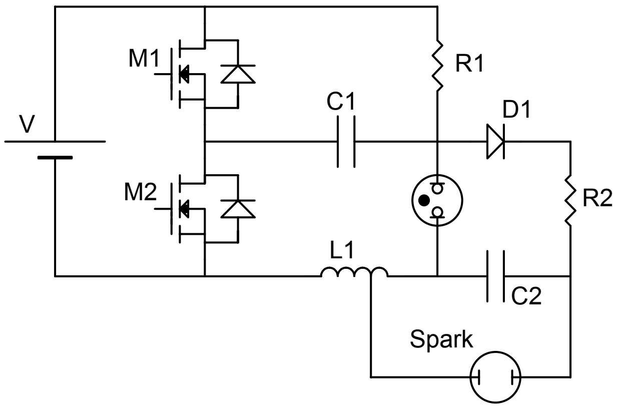

Fig. 5 – High-frequency inverter with integrated igniter circuit.

The half-bridge inverter, using LC filter, was chosen because it can be operated without load and is naturally protected against short circuit. Besides it presents smaller losses conduction when compared to full-bridge inverter and the facility to incorporate ignition circuit. The MOSFET control signals are generated by a microcontroller PIC16F873. An IR2110 makes the connection between the microcontroller and the MOSFET.

The explanation on igniter circuit behavior is given through the waveforms on Fig. 6 where voltage over C2 is presented in channel Ax2 and the lamp voltage is presented in channel Ch2.

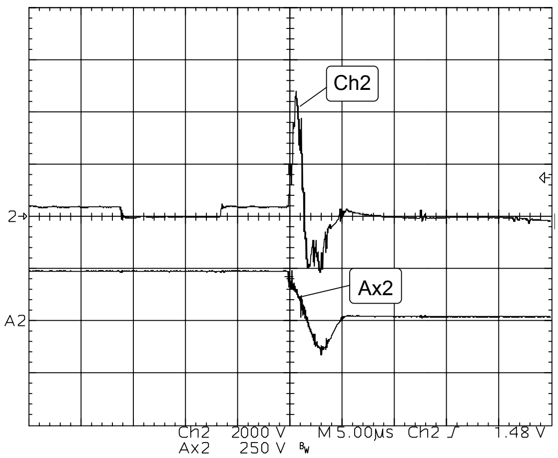

Fig. 6 – Voltages involved in the ignition process.

Its operation can be summarized as: when the circuit is turned on, the lamp is off and its impedance is very high. This way, all voltage supplied by the inverter is applied on it. This voltage is rectified by D1 and charges C2 through R2.

When the voltage over C2 reaches the spark gap breakdown voltage, the energy stored in C2 is applied in a small number of coil turns, generating a high voltage through L1. When the lamp ignites, the voltage on it is much smaller than before and this prevents that the voltage on C2 reaches the spark gap breakdown voltage again.

If the lamp doesn't strike for any reason, the capacitor C2 is recharged and the process is repeated until the converter has been turned off or when the lamp ignites successfully.

1. Frequency Variation [8]

Using a PIC16F873A microcontroller was possible to vary the current lamp frequency in different number of steps and periods. This is considered interesting because this method spreads power spectrum and lamp is operated under minimized power density of individual harmonics.

Due to microcontroller resolution, each step change corresponds to 300Hz frequency change. The number of steps tested varied from two to fifteen and the number of periods between each frequency change varied from two to five.

For instance, when the system operates with two steps at each five periods, this means that inverter starts with 20.6kHz and works during five periods with this frequency, when commutates to 20.9kHz. After more five periods, frequency changes to 21.2kHz. At each five consecutive periods, frequency changes back to 20.9kHz, 20.6kHz, 20.3KHz and 20.0kHz. So, frequency level starts going up again and the process continues with frequency sweeping between 20kHz and 21.2kHz.

The software developed allows choose between lamp operation in normal modulation (50% duty cycle and fixed frequency) or in frequency variation modulation through a switch connected to the microcontroller.

All of testes were realized using 20.6kHz as central frequency at the sweep range and, at all of four different lamps the acoustic resonance were extinguished when the special modulation were applied.

2. Phase Variation

Another tested approach is based on the idea that constant phase variation disturbs the excitation of acoustic resonance; and was initially propose as solution to avoid acoustic resonance in small arc tube lamps, like in metal halide lamps, using a phase jump of 90° [11]. The number of periods between each phase inversion tested varied from five to twenty. Besides, two different phase jumps were tested: 90° and 180°.

Results obtained with four different lamps showed that different number of periods between each phase variation didn't affect the final results, therefore, acoustic resonance was always muddled with any number of periods between each phase jump. On another hand, lamps behavior showed up that phase variation angle, 90° or 180°, interferes in the method performance.

Like in frequency variation prototype, the software developed allows to choose between lamp operation in normal modulation or in phase variation modulation through a switch connected to the microcontroller.

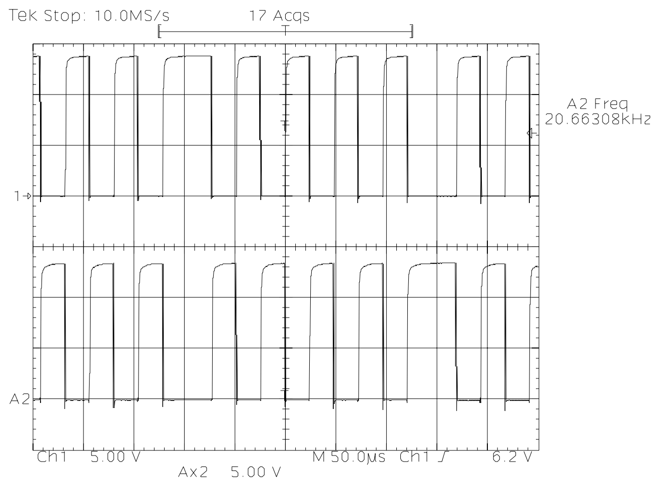

Fig. 7 – Voltages involved in the ignition process.

With inverter operating in normal modulation, all lamps presented strong acoustic resonances, which were totally extinguished when 180° phase jump was applied. At Fig. 7 gate voltages are showed to a 180° phase jump at each five periods.

Fig. 8 shows gate voltage in one of the transistors and current lamp in steady state. It is important to observe that inductor ballast project should take in account a higher current level at each jump phase.

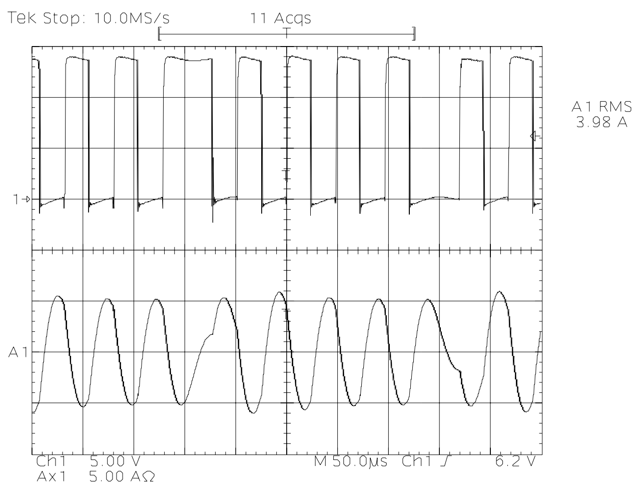

Fig. 8 – Voltages involved in the ignition process.

Instead of what happened with 180° phase jump, the acoustic resonances were not totally extinguished when 90° phase jump was applied in one of the lamps that continued presenting a small curvature in the arc path. However, an important reduction in the acoustic resonance was registered.

In both special modulation presented, when 20.6kHz was used as central frequency, an audible noise was generated. But it can be eliminated with a higher central frequency commutation.

3. Real Time Solution

The last technique used to implement an electronic ballast able to avoid acoustic resonance is classified as real time solution and consists in use a microcontroller that analyzes voltage and current lamp to avoid it.

The program developed can be understood through chart flow showed in Fig. 9.

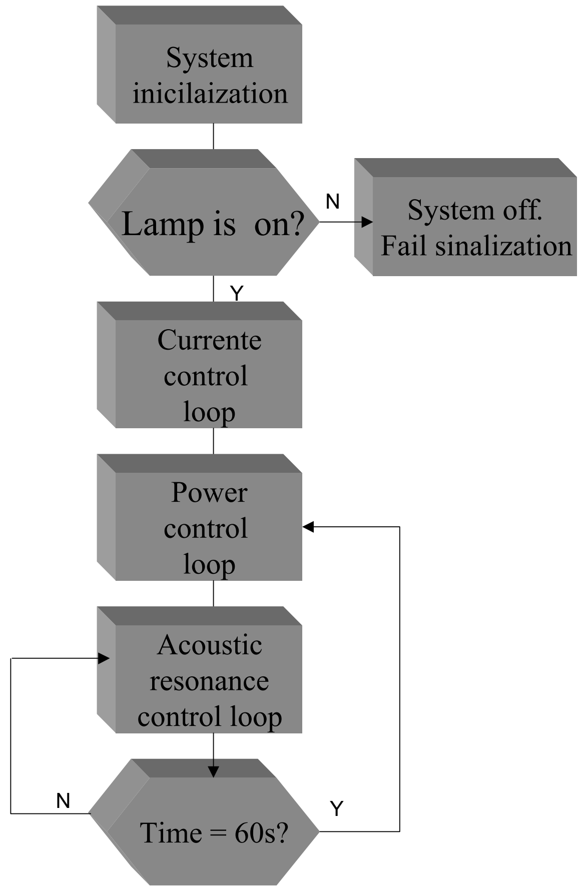

Fig. 9 – Simplified Program Flow Chart.

The main program parts are:

- **System initialization**: when ballast is turned on, microcontroller maintains the power system (inverter and igniter circuit) disabled during 30 seconds. After this time, the system is enabled to start and the inverter is operated with minimum frequency (f_{min}), lower than the nominal frequency. To use a low frequency is especially interesting to facilities lamp ignition e reduces warm up time.
- **Ignition test**: microcontroller maintains power system enabled during 60 seconds, trying to ignite the lamp. If for some reason, the lamp does not strike, power system is disabled again during 60s. The process is repeated 5 times.

If lamp does not strike after fifth tentative, microcontroller disables power system definitively and turns on a LED to indicate the fail.

- **Current control loop**: after lamp strikes, its current is controlled in a level higher than the nominal value, to speed up startup process. Notwithstanding, this value should be lower than 50% higher than nominal value; this way inverter frequency is changed to decrease it. When lamp reaches a maximum startup current, the program follows to the next routine.
- **Power control loop**: frequency inverter operation remains lower than nominal frequency (f_n), till the lamp power reaches 350W. The power is calculated through signals provided for two transducers incorporated to the electronic ballast. After this point, microcontroller acts over the inverter's frequency to stabilize lamp power at the nominal value (400W). Once nominal power is reached, program goes to the next routine that avoids acoustic resonance.
- **Acoustic resonance control loop**: if lamp power is 400W, the sensor's signals are used to calculate lamp impedance. This value is used, through some comparisons, to detect acoustic resonance occurrence. If resonance is detected, frequency inverter is changed in both directions (± 5kHz) to escape from the frequency range where the acoustic resonance occurs. While lamp impedance does not return to its correct value, the frequency inverter stays sweeping between the maximum and minimum frequency values. With lamp working without acoustic resonance detected, at each 60s the program returns to the power control loop to verify if lamp operation conditions changes or if the frequency changes caused by acoustic resonance control loop did not affect lamp power. In this case, inverter's frequency is adjusted once more, and the program goes to acoustic resonance control loop again. If for some reason, the current lamp and/or voltage lamp falls down to zero, this means that there is some problem with the lamp, so the system is disabled and the fail signalization is activated again.

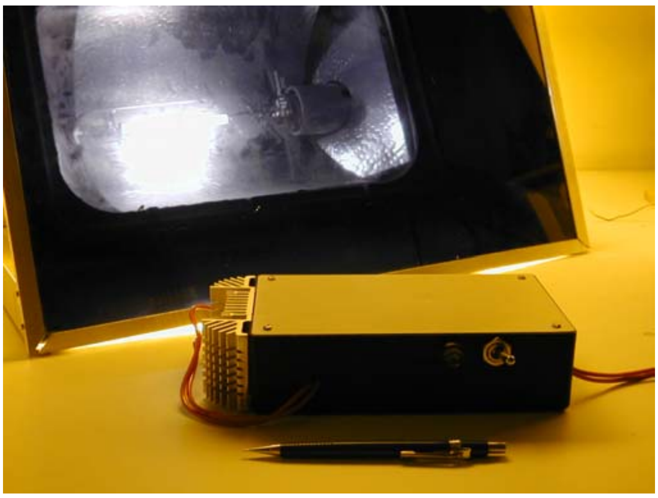

Fig. 10 – Inverter Prototype Picture.

Fig. 10 shows an inverter prototype picture working at nominal power. The invert prototype is inside of a plastic package, but even this way it is possible to notice that it presents a reduced volume.

Results obtained with this approach showed that acoustic resonances like that one presented in Fig.2 and in Fig. 3 are not detected by the developed system because electrical parameters changes are not enough strong to sensitize microcontroller. At Fig. 11 is presented lamp current envelope during resonance occurrence (Fig. 2). It is caused basically by the DC bus voltage ripple.

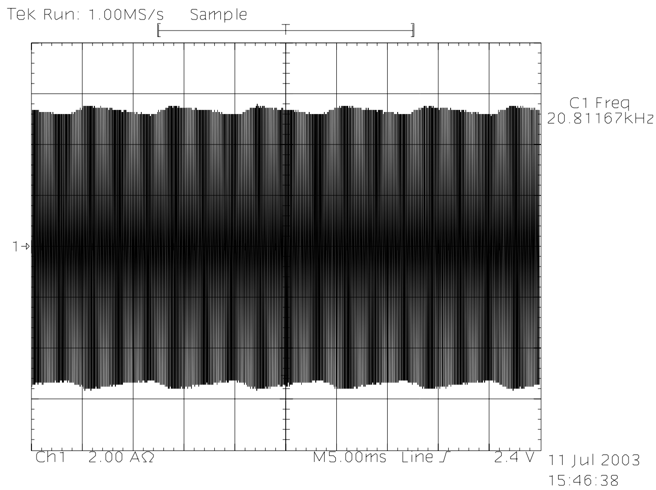

Fig. 11 – Lamp Current Envelop During Acoustic Resonance Occurrence

Just acoustic resonances like that one presented in Fig.12 produces impedances lamp changes enough important to be detected by microcontroller, but even this way, with ballast working inside a hard frequency range like 20kHz, it is not able to extinguish resonances.

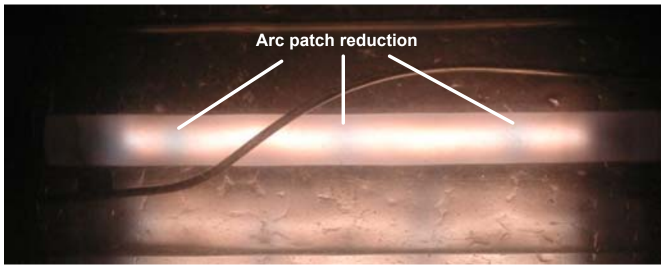

Fig. 12 – Lamp Arc at 20.4kHz.

At this sort of acoustic resonance, when arc path reductions are registered, strong flicker appears and current lamp varies enough to sensitize microcontroller, like is shown at Fig. 13.

This system only presented good results when operated in a frequency range where acoustic resonance concentration is weak.

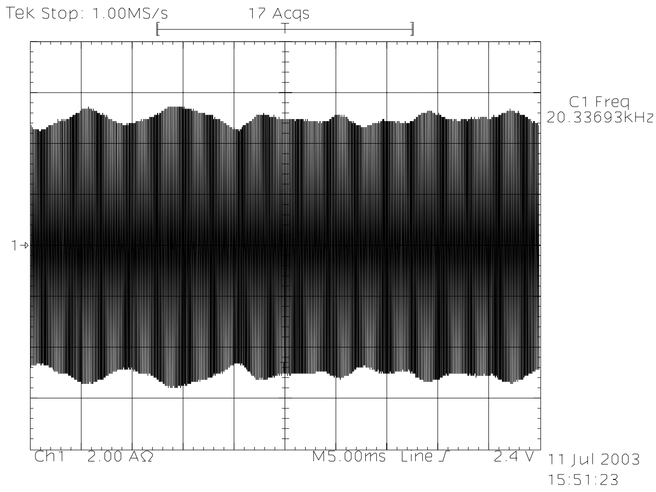

Fig. 13 – Lamp Current Envelop During Acoustic Resonance Occurrence

III. CONCLUSION

A study about topologies able to avoid acoustic resonance in high-pressure sodium lamps operated in high frequency was presented. Three approaches were implemented and their results were discussed. The circuit's heart is a microcontroller that permits to obtain especial commutation techniques and control electrical lamp parameters.

First one is based on the spread spectrum and presented excellent results in all tests realized, extinguishing acoustic resonance in the frequency commutation range around 20kHz. On another hand, tests realized on frequency ranges where acoustic resonance is not usually detected, like 50kHz, showed that technique didn't excite the acoustic resonance phenomenon.

Second approach used is similar to first one and consists in operate the lamp with phase jumps. Two different angles were tested but better results were obtained with 180º. Like it has happened in the first approach, acoustic resonance was extinguished in all realized tests in the frequency commutation range around 20kHz when 180° phase jump modulation was applied.

Some tests with different frequency ranges where acoustic resonance is not usually detected, like 50kHz, showed that technique didn't excite the phenomenon too.

This set of results proves that these special modulations can be reliable used to avoid resonance in a large frequency range. Besides it is possible to state that an interesting design procedure to this kind of electronic ballast is to combine one of these special modulation with a range frequency where theoretically the lamp presents stable behavior.

Finally, a prototype using real time solution was presented. An algorithm specially developed for this application provided good results around 50kHz frequency inverter. On another hand, same results were not obtained in a critical frequency like around 20kHz.

Notwithstanding, through this prototype is possible to control lamp power even with main voltage changes or lamp parameters changes, like arc voltage.

Based on these results is possible to affirm that three techniques can be used in electronic ballast for high-pressure sodium lamps preferentially with frequency commutation that usually do not excite the phenomenon. So, they could be considered as a toll that can ensure a good electronic ballast performance

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