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Close loop digital control implemented in a microcontroller and used to eliminate acoustic resonances in HID lamps

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Abstract

A closed loop digital control to eliminate acoustic resonances (AR) in the electronic ballast for high intensity discharge lamps is proposed in this paper. The system senses the AR intensity and a microcontroller compares this signal with a reference level in order to apply different frequency modulation patterns to reduce the AR intensity below the reference level value. The use of different frequency modulation patterns allows avoiding the AR intensity due to changes in the lamp eigenfrequencies, ambient temperature and the lamp aging.

1 Introduction

Acoustic resonance (AR) is one of the main problems to be solved in the electronic ballast design for high intensity discharge (HID) lamps. It is characteristic when the HID lamps are operated at frequencies above 10 kHz and appears when the lamp power at an eigenfrequency exceeds a threshold value [1]. Some problems caused by this phenomenon are: emitted light fluctuations (flicker), color temperature changes, lamp voltage variation and, in the worst case, a discharge tube cracking and ballast damage. This phenomenon depends on several parameters like pressure and type of the lamp filling gas, geometric dimensions discharge tube, ambient temperature, etc. As consequence, the lamp eigenfrequencies vary with operation temperature, aging, and the lamp type.

Several solutions have been proposed to solve this problem, including: 1) lamp operation at non-eigenfrequencies [2], 2) lamp feeding with voltage and current square wave forms [3,4], 3) voltage and lamp current with frequency modulation [5], and (4) superimposing the third harmonic to the lamp voltage [6]. Lamp eigenfrequencies depend on the lamp type, the ambient temperature, and the lamp aging, so that the first solution is not reliable. The same problem is presented in the third solution, because if the modulated frequency reaches an eigenfrequency, AR will not be eliminated. The second solution implies application of a low frequency DC power to the lamp so that any acoustic resonance could be presented. This requires, however, a two stage circuit: the first one for lamp stabilization, the second one an inverter for generating lamp supply voltage, furthermore electronic ballast operation is in a hard switching mode. The fourth solution also tries to apply a DC lamp power and operates with sinusoidal waveforms in a soft switching mode, but the circuit is complex because two resonant tanks are needed: the first one for the fundamental and the second one for the third harmonic.

In this paper, frequency modulation is used to avoid AR caused by the uncertainty in the lamp eigenfrequencies at which acoustic resonance may appear. Different modulation frequency patterns with several modulation index values are applied to the lamp until the AR intensity is reduced to non-critical values avoiding flicker or lamp damage. In this way, the resultant circuit is a conventional resonant electronic ballast with soft switching mode operation, where no extra resonant tanks are necessary. In order to simplify the electronic ballast and to reduce the components, a microcontroller is used to generate different switching patterns according to the AR intensity signal.

This paper is organized as follows: Section 2 presents the proposed method for the closed loop digital control, the algorithm description, and its implementation in a microcontroller. Experimental results for several HID lamps are included in Section 3, and, finally, conclusions are presented in Section 4.

2 Closed loop method description

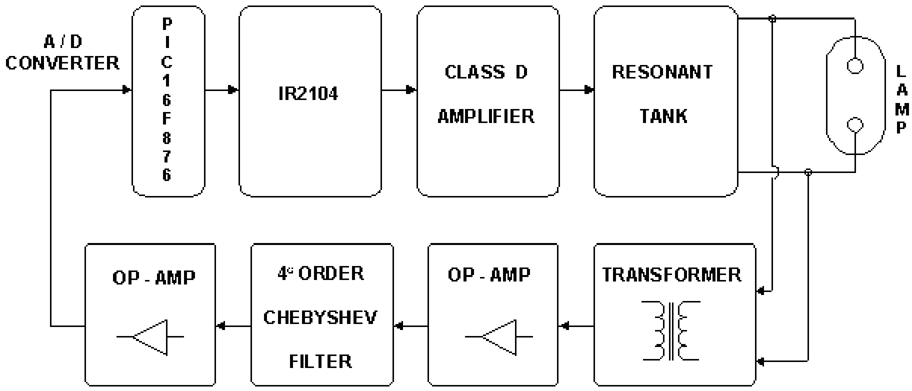


Figure 1: Proposed closed loop control method.

Figure 1 shows the closed loop circuit. The detailed description of each stage given below.

2.1 Electronic ballast

The electronic ballast consists of a resonant inverter (class D amplifier plus a LCC resonant tank) working in soft switching mode. The circuit is designed for operating at eigenfrequency at which AR is presented in the lamp. LCC resonant tank is designed for the maximum gain voltage condition [7].

AR is detected in the lamp voltage using a transformer, this signal is filtered by a fourth order Chebyshev filter in order to eliminate all components with frequencies above 100 Hz, in this way only the AR components are obtained. Then AR signal is adjusted by an op-amp and applied to the microcontroller A/D converter. The digital signal is compared with an internal reference level. If the AR intensity is greater than the reference level, a first frequency modulation pattern is applied to eliminate the acoustic resonance; if the AR intensity remains high, the modulation index (m) is increased. If the AR remains above the reference level even after several modulating increases, the frequency modulation pattern is changed until AR intensity becomes lower than the reference value. Different frequency modulating patterns are generated by the microcontroller in order to control the class D amplifier by means of the IR2104 driver.

2.2 Acoustic resonance sensing circuit

In a typical electronic ballast, when AR occurs, the lamp current has three frequency components: a) a high frequency one caused by the resonant inverter frequency operation, b) a 100 – 120 Hz frequency component due to the power factor correction output voltage stage and c) a very low frequency component due to the AR in the lamp (1 – 10 Hz). If higher frequency components are eliminated, it is possible to detect the AR effect in the lamp current [8]. In this way, AR is detected in the lamp voltage using a transformer, this signal is filtered by a fourth order Chebyshev filter in order to eliminate all components with frequencies above 100 Hz, in this way only AR components are obtained. Then AR signal is rectified by diodes and then is adjusted by an op-amp to be applied to the microcontroller A/D converter.

2.3 Frequency modulation patterns

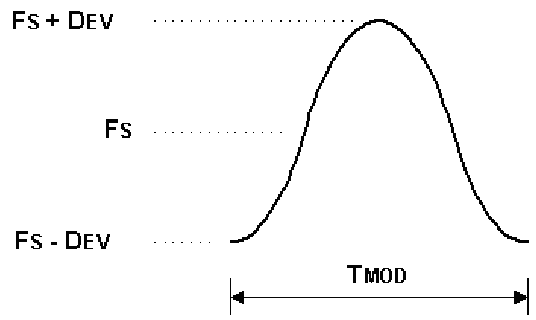


Figure 2: Sinusoidal frequency modulated waveform.

The control method objective is to generate a PWM signal with 50% of duty cycle in which the frequency could be modulated by a modulating signal, that can be sinusoidal, saw-tooth or another one. This process can be explained using a sinusoidal waveform shown in Fig. 2. Fs is the central frequency and corresponds to the operation frequency when no modulation is applied. *Dev* represents the frequency deviation form the central to the maximum and minimum values; *Tmod* represents the time period in which one cycle of the frequency variation will be made. The signal shown in Fig.

2 can be expressed by the equation:

$$Fout = Dev \sin\left[\frac{\pi}{2}\left(\frac{t}{90} - 1\right)\right] + Fs. \quad (1)$$

Due to necessity to generate this waveform with a microcontroller, the expression must be digitized:

$$Fout = Dev \sin\left[\frac{\pi}{2}\left(\frac{n}{90} - 1\right)\right] + Fs \quad (2)$$

where

$Fout$ is the frequency generated by the microcontroller,
Fs is the central frequency with no modulation,
Dev is the maximum frequency deviation.

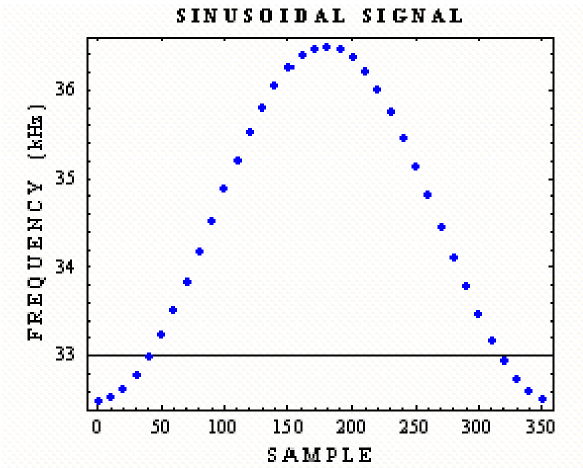


Figure 3: Discrete sinusoidal frequency modulated waveform.

Discreet waveform for Fs = 35 kHz with Dev = 2 kHz is showed in Fig. 3. When the $Fout$ frequency values are known, then it is necessary to calculate the value that must be loaded in the PIC16F876 $PR2$ register in order to generate this frequency value. Expression (3) relates $Fout$ with the value of $PR2$.

$$PR2 = \frac{Fclock}{4\ Fout} - 1 \quad (3)$$

where $PR2$ is the $PR2$ register value, $Fclock$ is the microcontroller clock frequency, and $Fout$ is the output frequency.

From Fig. 3 one can obtain a table for specific values of Fs and Dev. With this table it is possible to calculate the data that must be loaded in $PR2$ in order to generate the corresponding Fout. With a similar procedure, equations for triangular and saw-tooth can be obtained. The corresponding expressions are resumed in Table 1.

Waveform	Equation
Sinusoidal	$Fout = Dev \sin\left[\frac{\pi}{2}\left(\frac{n}{90} - 1\right)\right] + Fs;\ 0 \leq \text{n} < 360$
Triangular	$Fout = Dev\left(\frac{n}{90} - 1\right) + Fs;\quad 0 \leq \text{n} < 180$ $Fout = Dev\left(3 - \frac{n}{90}\right) + Fs;\quad 180 \leq \text{n} < 360$
Saw-tooth	$Fout = Dev\left(\frac{n}{180} - 1\right) + Fs;\quad 0 \leq \text{n} < 360$

Table 1. Discrete modulated waveforms equations.

Here:

Fs is the central frequency,

Dev is the maximum frequency deviation,

n is integer and positive number.

The modulation index (m) is defined as [9]:

$$M = \frac{2\ Dev}{Fmod} \tag{4}$$

where:

Dev is the maximum frequency deviation,

$Fmod$ is the modulating signal frequency.

2.4 Proposed control algorithm

The proposed control algorithm is shown in Fig. 4. The first block configures all registers, the AD converter, and all PIC timers. Then the switching frequency is generated for lamp ignition and its value corresponds to the eigenfrequency in which AR is present during lamp operation. For evaluation purposes, the circuit operates without frequency modulation until an external interruption is activated; when it happens, the microcontroller generates the first frequency modulation pattern to avoid the AR.

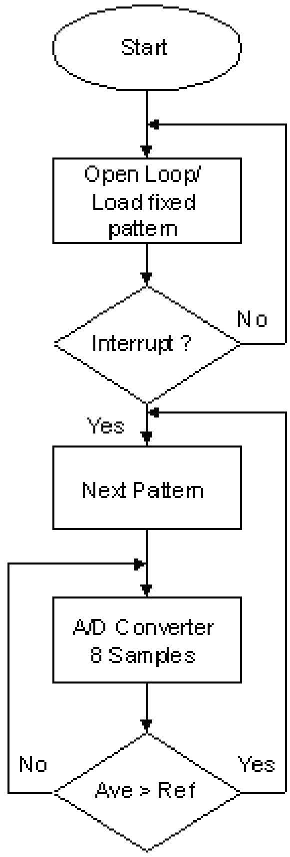


Figure 4: Proposed control algorithm.

In order to avoid noise or mistakes in the AR processing signal, the microcontroller takes a group of eight samples each time when AR signal is sensed, and obtains their average value. When this calculation is finished, TMR0 is programmed to establish the period in which the next group of samples will be obtained. Then the AR signal average value is compared with the internal referenceand, and, if the average is greater than the internal reference value, the microcontroller increases the modulation index in order to reduce the AR intensity. If the AR intensity is still greater than the reference, then the microcontroller changes the frequency patterns until AR is eliminated.

The program will change different modulation patterns in a circular way (as can be seen in Fig. 5) until the AR samples average value becomes lower

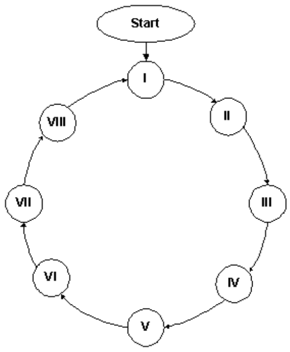


Figure 5: Modulation frequency patterns sequence.

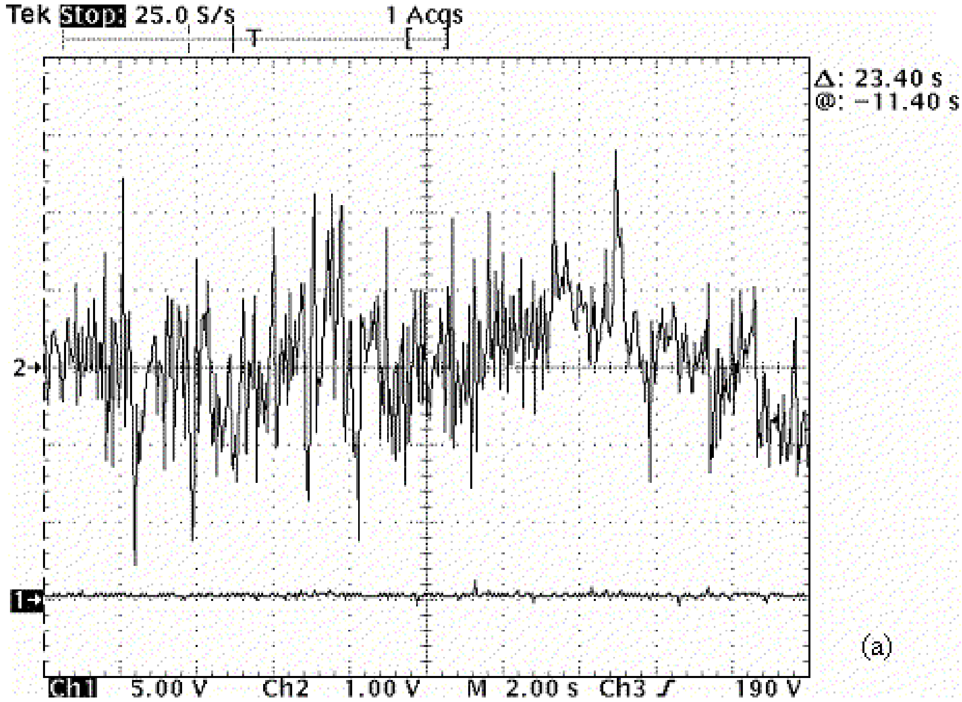
than the internal reference.

3 Experimental results

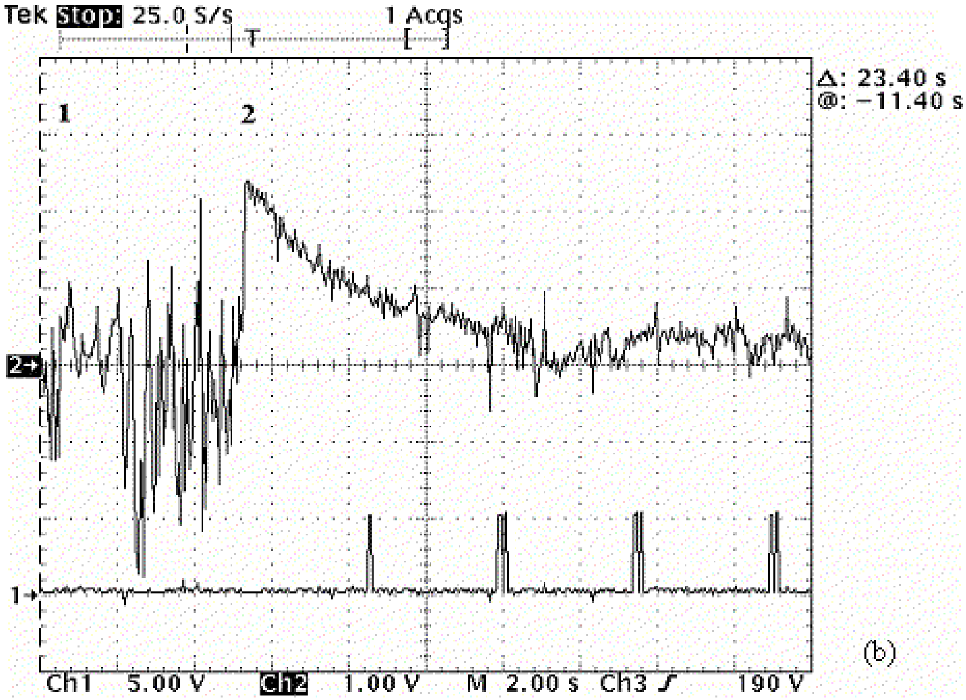
The control method was probed in several kinds of HID lamps: mercury, sodium, and metal halide lamps. Experimental results are presented in Figs. 6 to 9. In all of them two signals are presented: the AR intensity signal (upper channel) and the ADC signal that indicates when the microcontroller takes the AR signal samples group (lower channel). From the samples group average value the microcontroller changes the modulating frequency pattern when it is necessary, so that in the upper trace it is possible to see when AR is eliminated by the frequency modulation pattern. Experimental results for different kind of lamps are given below.

3.1 H38JA-100W mercury lamp

The experimental results for this lamp are shown in Fig. 6 for 35 kHz central frequency. Fig. 6a shows the AR intensity signal waveform when no modulation is applied. In Fig. 6b, the circuit operates in the open loop mode between 1 and 2. At time 2, an interruption is applied to the microcontroller and it applies the first modulating pattern to eliminate the AR in the lamp. As a result, AR intensity diminishes but if the AR signal is greater than the reference level, the next frequency modulated pattern is applied four seconds later. At this moment, TMR0 is programmed to obtain next samples group every 4 seconds. Fig 6c shows the condition when AR is eliminated and the lamp is stabilized.


Tek Stop: 25.0 S/s
1 Acqs
T
Δ: 23.40 s
@: −11.40 s
2→
1→
Ch1 5.00 V
Ch2 1.00 V
M 2.00 s
Ch3 ∫
190 V

(a)


Tek Stop: 25.0 S/s
1 Acqs
T
Δ: 23.40 s
@: −11.40 s
1
2
2→
1→
Ch1 5.00 V
Ch2 1.00 V
M 2.00 s
Ch3 ∫
190 V

(b)

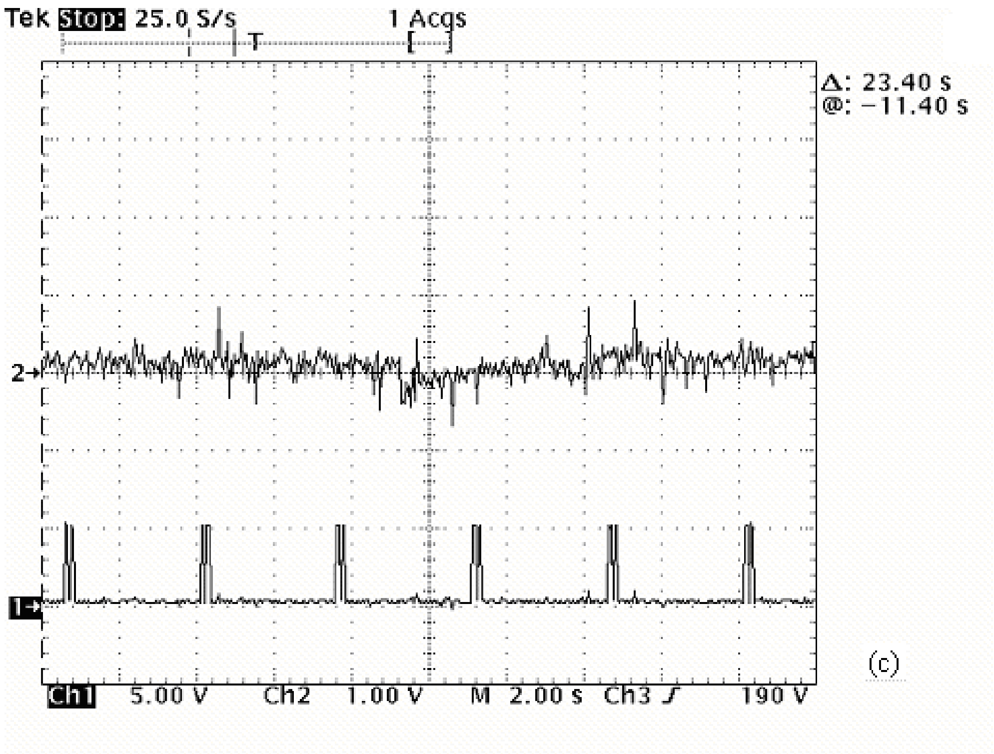
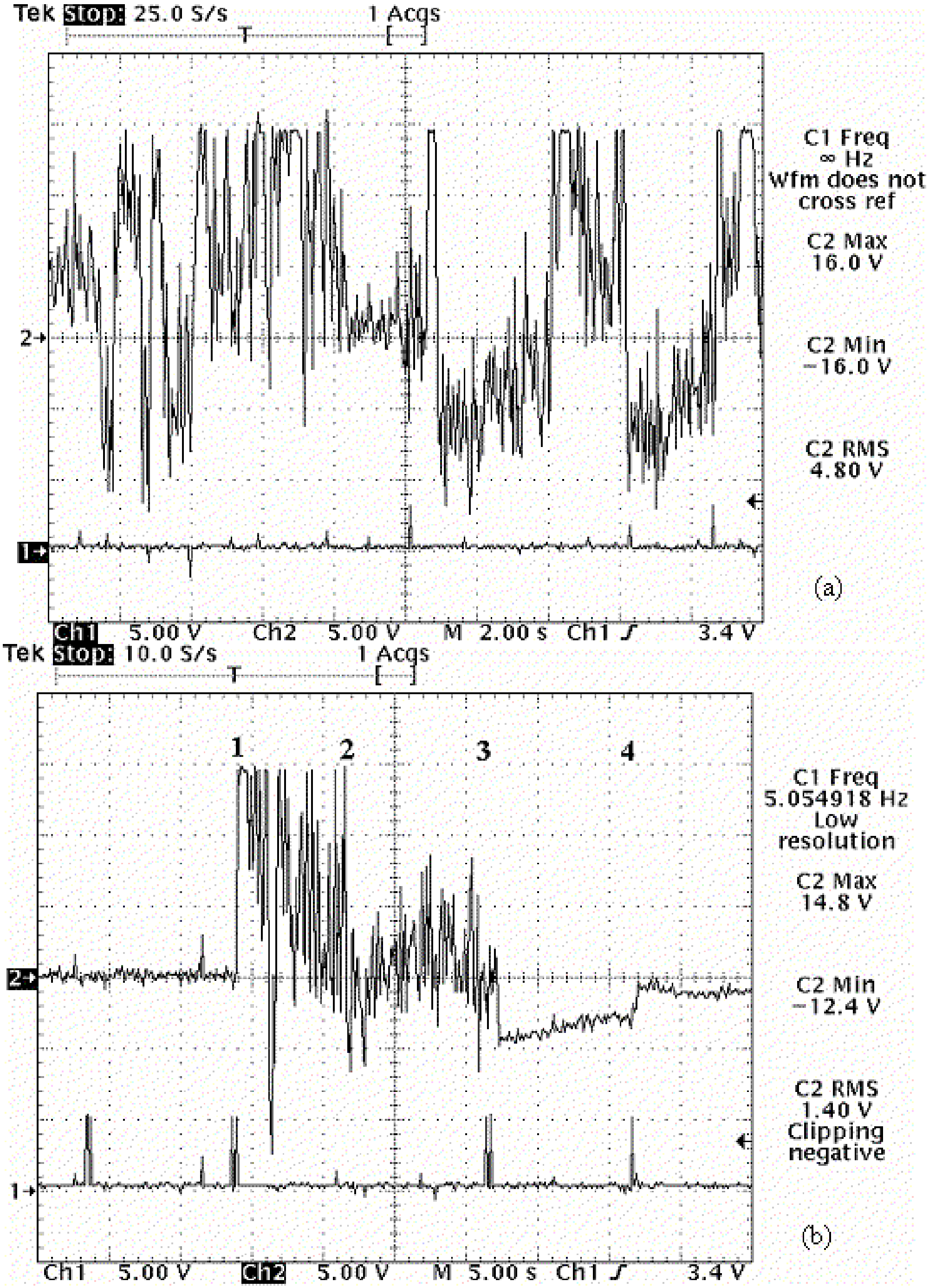


Figure 6: H38JA – 100W mercury lamp results.

3.2 HQI/TS150W metal halide lamp

The experimental results for a 150W metal halide lamp are shown in Fig. 7. In a general way, AR intensity in metal halide lamps is very high with respect to other kinds of lamps, as can be seen in Fig 7a. In Fig. 7b the circuit operates in the closed loop mode, and the AR eliminated in the lamp before time 1; at this time the microcontroller stops the frequency modulation, the ballast operates at the central frequency, and AR appears again. At time 2 an interruption occurs, and the first modulation pattern is applied, so that the AR intensity diminishes. Ten seconds later, the AR signal remains higher than reference level and the second pattern is applied. The third pattern is applied between times 3 – 4 and, finally, at time 4, AR is eliminated and the lamp is stabilized.


Tek Stop: 25.0 S/s
1 Acqs
C1 Freq
∞ Hz
Wfm does not cross ref
C2 Max
16.0 V
C2 Min
−16.0 V
C2 RMS
4.80 V
(a)
Ch1 5.00 V Ch2 5.00 V M 2.00 s Ch1 ∫ 3.4 V
Tek Stop: 10.0 S/s
1 Acqs
1
2
3
4
C1 Freq
5.054918 Hz
Low resolution
C2 Max
14.8 V
C2 Min
−12.4 V
C2 RMS
1.40 V
Clipping negative
(b)
Ch1 5.00 V Ch2 5.00 V M 5.00 s Ch1 ∫ 3.4 V

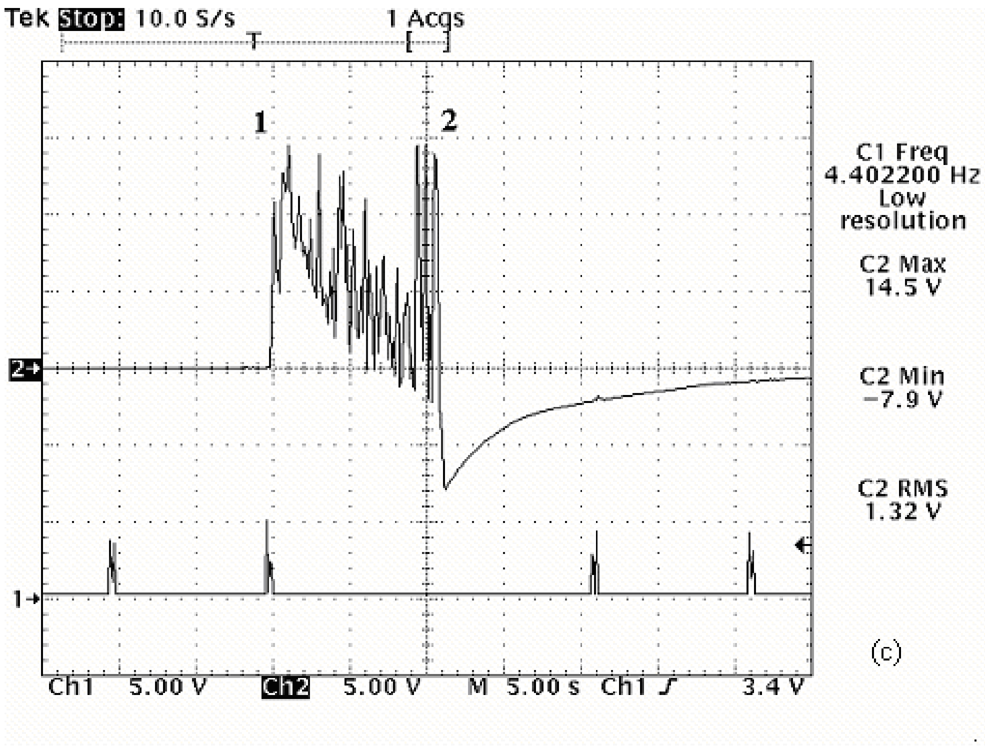


Figure 7: 150W metal halide lamp results.

In this kind of lamp, the microcontroller takes samples every ten seconds, this time is different for every kind of lamp. Fig. 7c shows a similar operation, but the AR is eliminated in a faster way showing the control method effectiveness.

3.3 LU-52/100W sodium lamp

High-pressure sodium lamps were also tested using the central frequency 28 kHz. As can be seen in Fig. 8a, the AR intensity is lower than in metal halide lamps, and when the modulation pattern is applied, the AR is eliminated as can be seen in Fig. 8b. In this case, the AD converter signal is not presented in the graphs.

These kinds of lamps are very sensitive to a damage caused by AR, and AR is not so frequent as in metal halide lamps.

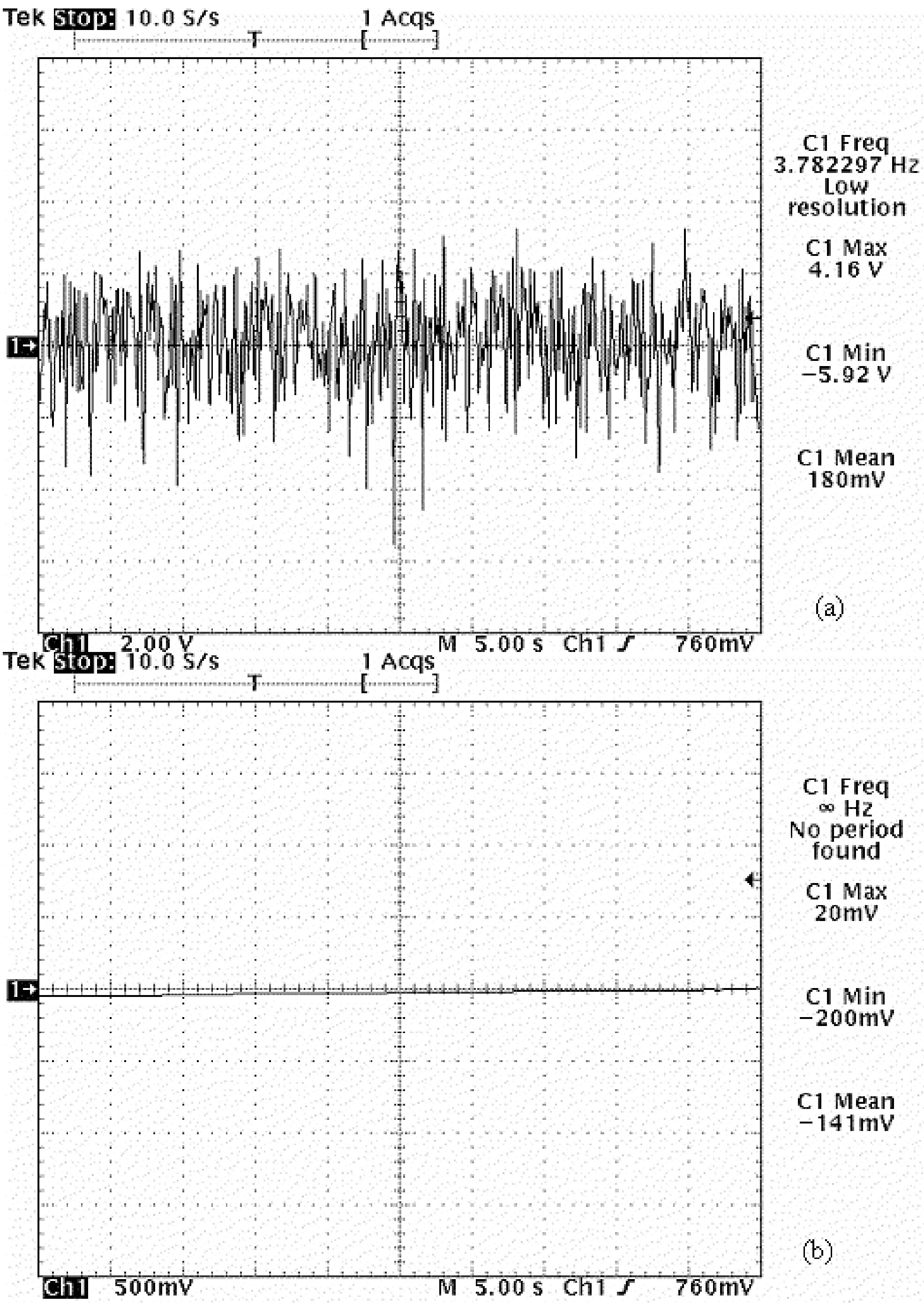
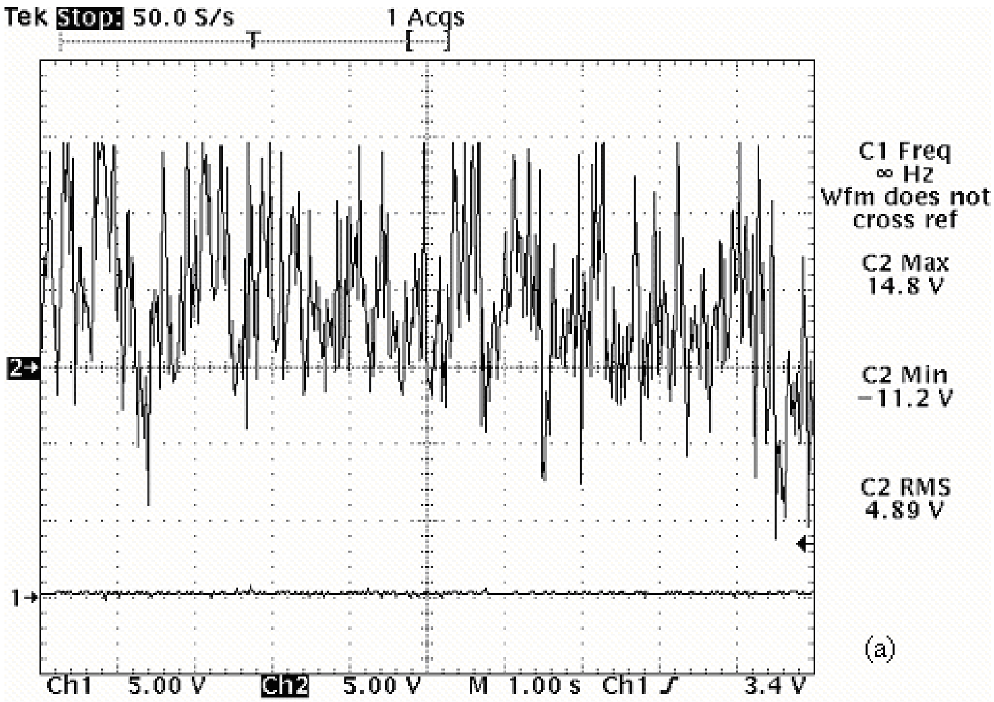


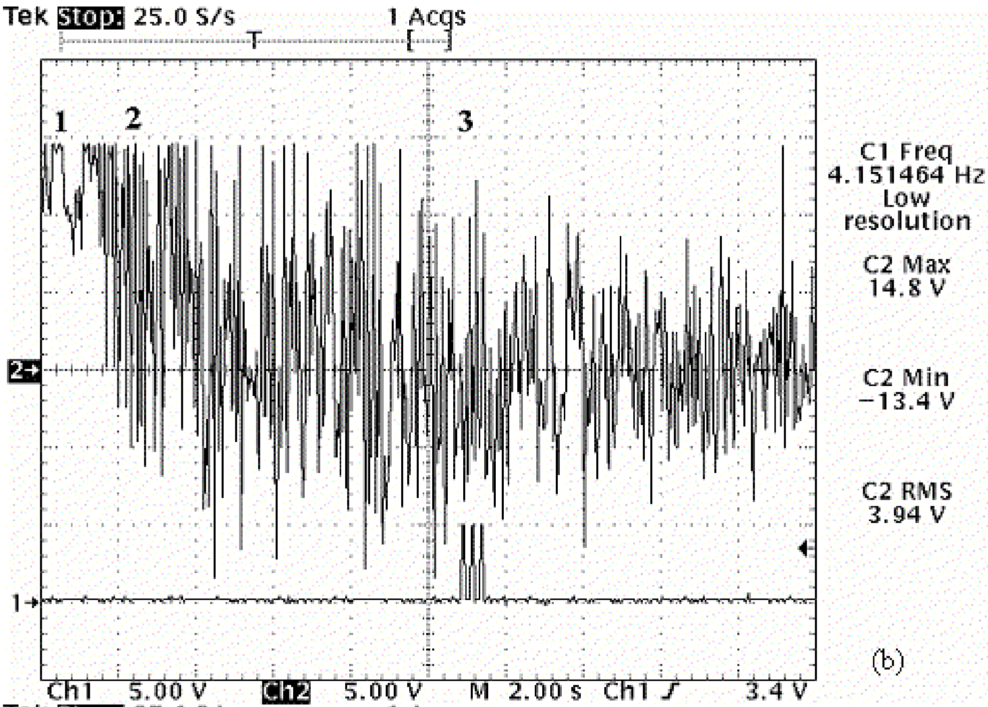
Figure 8: LU-52/100W high pressure sodium lamp results.

3.4 CDMR-70W/830 metal halide lamp

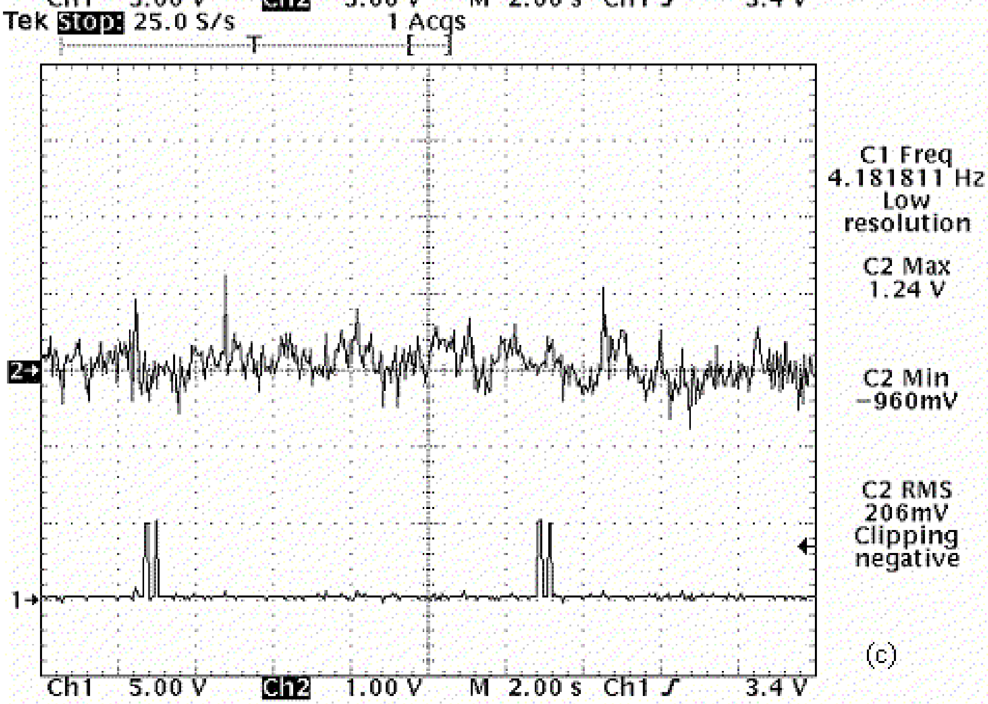
In this case, the central frequency is 35 kHz. As can be seen in Fig. 9a, the AR intensity is very high compared with the high-pressure sodium lamps. In a particular case, this kind of lamp presented the slowest dynamics in order to eliminate the AR in the lamp, which can be seen in Fig. 9b: at time 2 the first modulation pattern is applied and the second one is applied at time 3; the AR intensity diminishes in a slow way. After 5 minutes of operation, the lamp was stabilized, as shown in Fig. 9c. Once the AR has been eliminated, if a perturbation is presented and AR appears again, the control eliminates the AR in a faster way. In this case, the AR signal sample group is taken every 10 seconds.



(a)


Tek Stop: 25.0 S/s 1 Acqs
1
2
3
C1 Freq
4.151464 Hz
Low
resolution
C2 Max
14.8 V
C2 Min
−13.4 V
C2 RMS
3.94 V
Ch1 5.00 V Ch2 5.00 V M 2.00 s Ch1 ʃ 3.4 V

(b)


Tek Stop: 25.0 S/s 1 Acqs
C1 Freq
4.181811 Hz
Low
resolution
C2 Max
1.24 V
C2 Min
−960mV
C2 RMS
206mV
Clipping
negative
Ch1 5.00 V Ch2 1.00 V M 2.00 s Ch1 ʃ 3.4 V

(c)

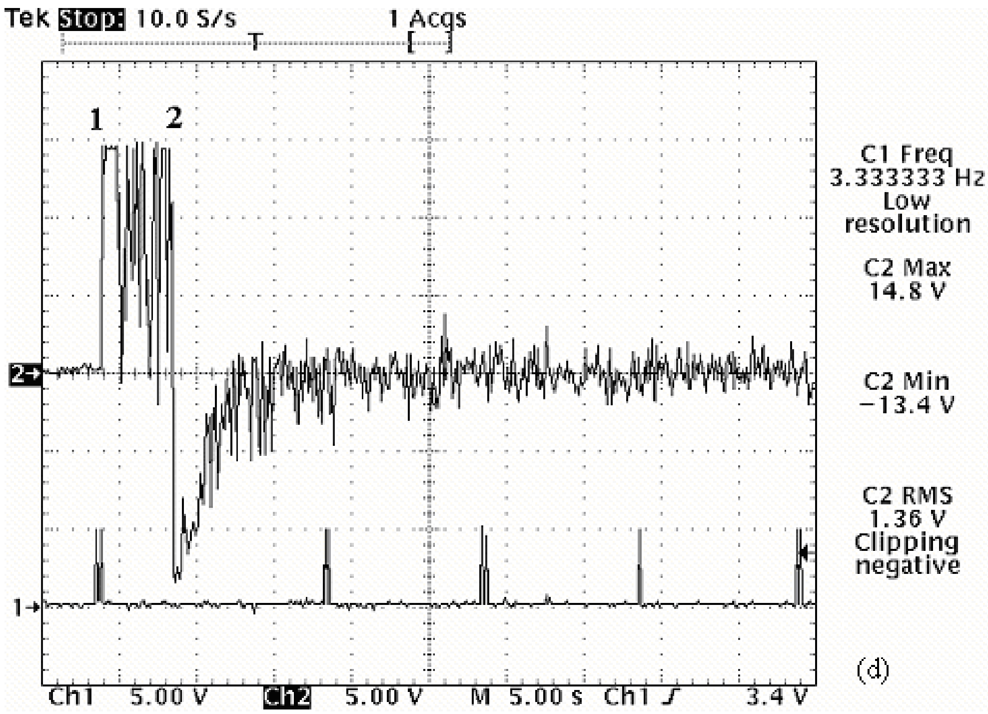


Figure 9: CDMR-70W/830 lamp results.

4 Conclusions

A closed loop digital control to eliminate AR in resonant electronic ballast for HID lamps has been proposed in this paper. AR is detected by filtering frequency components above 100 Hz, and only very low frequencies correspond to AR signal. This signal is introduced to the PIC microcontroller ADC which generates a 50% duty cycle frequency-modulated PWM signal with a triangular, saw-tooth, or sine modulating waveform. A class D amplifier is driven by an IR2104 driver using the microcontroller control signal, so that the control implementation is very simple, and a low cost microcontroller is necessary.

The proposed control method was tested in a 100W high-pressure sodium lamps, 100W mercury lamp, and metal halide lamps of 150 and 70W power from different manufacturers. Every kind of lamp requires different stabilization time when modulating pattern is applied, so it is important to determinate the period in which the AD converter must take the samples group for changing the modulating pattern, if required.

AR filtering was made with a 4th order Chebyshev active filter but it is possible to include this filter inside the microcontroller using a digital filter, resulting in a further simplification of the electronic ballast, component number, and final cost.

The complete electronic ballast results in a more simple solution to AR in HID lamps than feeding the lamp with square waveforms or the use of a conventional resonant electronic ballast to obtain a higher efficiency due to the soft switching; the lowest efficiency measure corresponds to 70W lamp and is equal to 96%.

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References

[1] J.J. de Groot and J.A.J.M Van Vliet, *The High Pressure Sodium Lamp* (MacMillan Education, London, 1986).

[2] R. Redl and J.D. Paul, IEEE Applied Power Electronic Conference, APEC'99, p.486 (1999).

[3] M. Ponce, A. López, J. Correa, J. Arau, and M. Alonso, IEEE Applied Power Electronics Conference and Exposition, APEC'01, p.658 (2001).

[4] M. Shen, Z. Qian, and F.Z. Peng, IEEE Trans. on Industry Applications **39**, 424 (2003).

[5] L. Laskai, P. Enjeti, and I.J. Pitel, IEEE Trans. on Industry Applications **34**, 597 (1998).

[6] M. Alonso *et. al.*, IEEE Power Electronics Specialists Conference, PESC'02, p.1483 (2002).

[7] J. Correa, M. Ponce, J. Arau, and M. Alonso, IEEE Power Electronics Specialist Conference, PESC'01, p.114 (2001).

[8] J. Zhou, L. Ma, and Z. Qian. IEEE Applied Power Electronics Conference, APEC'99, p.480 (1999).

[9] R. Schoenbeck, *Electronic Communications: Modulation and Transmission*, p.169-199 (Maxwell McMillan, 2nd ed. 1992).