REPETITIVE CONTROL APPLIED TO THE POWER FACTOR CORRECTION USING BOOST CONVERTER

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***Abstract*— This work presents the study and the implementation of a repetitive controller for the power factor correction (PFC) for electronic ballasts, using a boost converter. A quick review of repetitive control is presented followed by the controller design. It can be seen through experimental results that the repetitive control implementation applied to the PFC presents a simple solution and a straightforward implementation with satisfactory results when compared with others techniques, as described in the article.**

***Keywords* - Repetitive Control, THD, PFC, Electronic Ballast.**

I. INTRODUCTION

This work presents the study and implementation of a controller for the power factor correction stage in an electronic ballast with a boost converter used to supply High Pressure Sodium - HPS lamps. These lamps behave as a constant resistance in high frequency operation. Symptomatic energy crisis all over the world have brought to the center of the scene the efficient and rational use of electrical energy, among other forms. Public lighting has a considerable share of the energy consumption. Therefore, the use of long lasting efficient lamps and ballasts has been proposed in this sense.

High intensity discharge lamps (HID) are broadly used in public and industrial environments due to their high light efficiency and long term lifetime as well as a good color reproduction. These lamps, due to their negative resistance characteristic, demand devices which limit their current, avoiding thus their malfunction or disruption. On the other hand, these lamps demand high ignition voltages [1]. Ballasts can be classified in this context in two classes: 1) the Electromagnetic (conventional) ones and 2) the Electronic ones. The first ones are bulky, heavy and present low efficiency, poor power regulation and high sensitivity to oscillations in the feeding line. Generally, these ballasts present low power factor. The electronic ballasts are smaller and lighter than the electromagnetic ones and are capable of controlling the power and light flux in the lamp. They also posses a good power regulation when submitted to oscillation in the line voltage, besides eliminating the stroboscope effect, and can operate in both low and high frequency.

The International Electrotechnical Commission Standard establishes limits for the current harmonics emission in devices (gathered in classes) with current smaller than $16A$ per phase, described in the IEC-61000-3-2 standard. The ballast used in this work is classified as type C and the limits established by the standard are listed in Table I.

TABLE I
IEC-61000-3-2 STANDARD FOR CLASS C EQUIPMENTS.

Harmonic (n)	Standard limit (%)
2	2
3	30*PF
5	10
7	7
9	5
$11 \leqslant n \leqslant 39$	3

obs.: PF (Power Factor) $\simeq 1$.

The main goal for the repetitive control in this work is to reduce the effect of the DC link voltage oscillation in the output (lamp) voltage. These are low frequency oscillations of known spectrum, typically $120Hz$ due to the diode rectifier, which for their repetitive nature, may be easily rejected using repetitive control.

The remaining of this work is organized as follows: Section II, a brief review of the repetitive control and its application in the electronic ballast is presented. Section III deals with the design of the repetitive control associated with a PI control and presents some simulation results. Section IV compares the proposed technique with other two approaches based on experimental results. Finally, in Section V, the conclusions of the work are made.

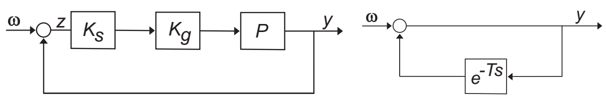
II. REPETITIVE CONTROL: A BRIEF REVIEW

The repetitive control is an appropriate strategy for tracking periodic signals in the presence of disturbances, which, in its most common version, presents itself as a plug-in type control associated with standard feedback compensation. It is based on the Internal Model Principle - IMP and in the decomposition of the control and disturbance signals in Fourier series. According to the IMP [2], in order to achieve tracking error convergence to zero in steady-state it is necessary and sufficient that the generator for the reference signal be included in the closed stable loop. The generator for the reference signal is understood as the linear system (a compensator), which for certain initial condition and null input, generates the reference command as an output.

Based on the IMP, a compensator that generates all the periodic references must be incorporated in the closed loop of the controller in order to track periodic signals of a known period T, in steady-state. If stable, the repetitive control will guarantee zero tracking error without exact knowledge of the plant.

The closed loop dynamics of the repetitive control presents high order and it is very sensitive to high frequency noise and unmodeled dynamics. As mentioned above, it is a plug-in type controller used in combination with state feedback controller such as PI, Adaptive Control, Deadbeat, etc.

Figure 1(a) shows the diagram of a generic feedback control and the additional structure of a repetitive control in continuous time. P is the plant to be controlled, K_s is the standard stabilizing controller and K_g is the command generator used to track a periodic signal w. The output variable y is fed back and compared with the reference, generating the error signal z.



(a) Repetitive Control (K_g) (b) *PSG*

Fig. 1. Block diagram of a) the repetitive control and b) the periodic signal generator (PSG).

A periodic signal generator of period T, with infinite frequency spectrum, is a pure delay of the type e^{-Ts} in feedback, as shown in Figure 1(b). Although suitable for any type of periodic signal, there is no admissible controller K_s capable of stabilizing strictly proper plants P [3]. In order to stabilize systems described by the diagram of Figure 1(a), for strictly proper plants (which constitute physical systems such as the PFP boost converter of the present application) it is necessary that the periodic signal generator be limited somehow in its frequency spectrum. In other words, a pure delay with an infinite spectrum is not stabilizable.

Note that the pure delay in the feedback loop, seen as a transfer function, presents an infinite number of poles, all in the imaginary axes:

$$k_g(s) = \frac{1}{1 - e^{-Ts}} \tag{1}$$

A trade off solution in this case is the inclusion of a low-pass filter coupled to the pure delay as:

$$k_{g_{mod}}(s) = \frac{1}{1 - q(s)e^{-Ts}} \tag{2}$$

This technique, commonly called Modified Repetitive Control - MRC [4], operates the removal of the high frequency poles of the generator rendering the plant stabilizable by the control action $K_s(s)$.

There are several variations of repetitive controllers using the MRC principle. See Figure 2 for an example.

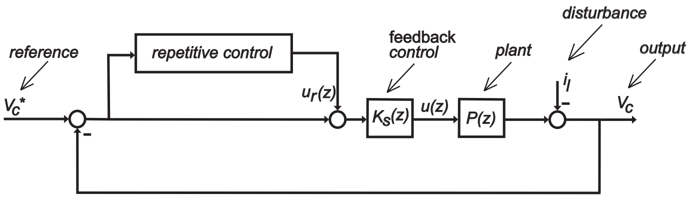


Fig. 2. Block diagram of the repetitive control plug-in and the main stabilizing control.

The $K_s(z)$ block corresponds to the stabilizing controller to be defined, in discrete time. The repetitive control block, $K_g(z)$ [5], is described in discrete time in Figure 3.

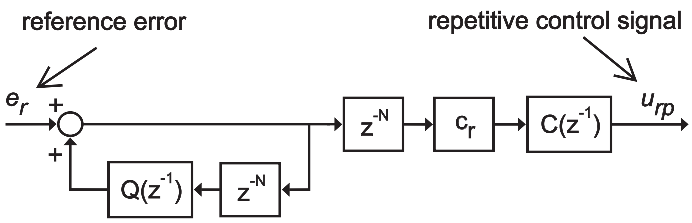


Fig. 3. Block diagram of the repetitive control.

Note that the block z^{-N} delays the input signal (the error $r-y$) of N sampling periods, which correspond to one period of the reference signal. The same z^{-N} block is inserted previous to the filter $C(z^{-1})$ in order to render it causal. In this structure, the blocks $Q(z^{-1})$ and $C(z^{-1})$ are low-pass filters aiming to guarantee stability margins to the close loop system, according to the idea of the Modified Repetitive Control, which is to limit the bandwidth of the periodic signal capable of being tracked by the control. Lets consider two simple possible structures to $Q(z^{-1})$. One is:

$$Q(z^{-1}) = q_r < 1 \tag{3}$$

Other possibility is a second order low-pass filter as:

$$Q(z^{-1}) = \frac{\alpha z + \alpha_0 + \alpha_1 z^{-1}}{2\alpha_1 z + \alpha_0} \tag{4}$$

which has the advantage of attenuating only the high frequencies.

The $C(z^{-1})$ block is also a filter with the purpose of guaranteeing unitary gain and zero phase shift between the controller input and output periodic signals, i.e., $C(z^{-1})G_m(z^{-1}) = 1\angle 0^{o}$ where $G_m(z^{-1}) = \frac{y(z^{-1})}{r(z^{-1})}$. There are at least two possibilities for $C(z^{-1})$. One is:

$$C(z^{-1}) = \frac{1}{G_m(z^{-1})} \tag{5}$$

which implies in obtaining the inverse of the close loop transfer function $G_m(z^{-1})$. Another option, much simpler, is:

$$C(z^{-1}) = z^d \tag{6}$$

where d is determined such that the gain of the output-input signals be unitary and the phase shift as close to zero as possible for the frequency range of interest for the controller.

Finally, c_r is a scalar gain, satisfying $c_r < 1$, and also that guarantees close loop stability of the system consisting of the repetitive and the standard feedback control.

It is appropriate to mention that there are other control approaches using basically the same principles and having very similar structures of this one [6], [7], [8].

Section III below presents a study for the parameters design of the repetitive control described above. The standard feedback control will be a PI controller.

III. Repetitive Control Applied To The PFC Boost Converter

Repetitive control has been applied in UPS (Uninterruptable Power Supply) inverters with success, aiming at the rejection of periodic disturbances due to non linear loads consisting of, for example, a rectifier followed by a capacitor filter and a resistive load.

In the present application, the main objective is to reject the effects of low frequency oscillation in the DC Link due to the ballast input rectifier, in terms of harmonic distortion in the output (lamp) voltage. The boost converter is used, thus, for power factor correction and the input current THD mitigation, using repetitive control.

There are applications of the repetitive control in AC-DC converters using PWM [9], [10]. The main difference between these applications and the one presented here is that the power factor correction in the referred papers is done in the (three phase) rectifier stage which is controlled, whereas in our work the rectifier is uncontrolled and the power factor correction is done by controlling the boost converter. Therefore, the low frequency oscillation of the DC link, caused by the uncontrolled rectifier has also to be rejected by the control of the boost converter.

As described in the precedent section, the repetitive control design aims at a compromise between robustness of the control system as a whole and the rejection of periodic disturbances with a good tracking of the reference signal.

A study of the effect of parameters q_r, defined in Eq. (3), and c_r in the total harmonic distortion was made. First, c_r was kept constant ($c_r = 0.1$) and q_r was varied. Figure 4 shows these results. Notice that smaller q_r corresponds to smaller overall THD values in an almost linear rate for $q_r < 0.8$. For $q_r > 0.8$, the THD increases rapidly.

Figure 5 presents the THD response as c_r varies, for three different values of q_r. It can be seen that the THD does not vary much for values of $q_r < 0.8$. Yet, for $q_r > 0.8$ the THD increases linearly with c_r.

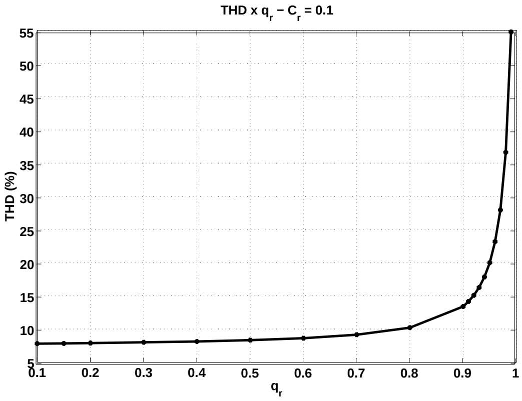


Fig. 4. THD variation as a function of the parameter q_r.

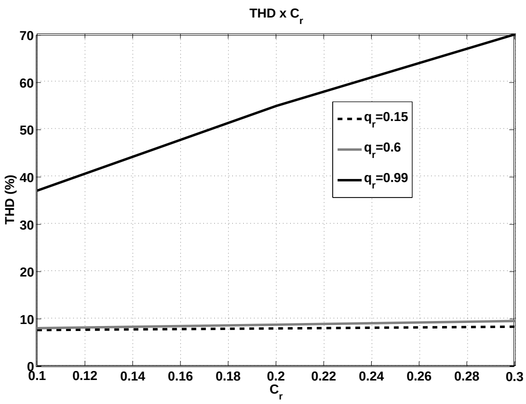


Fig. 5. THD variation as a function of the parameter c_r.

Figures 6 and 7 present the THD and the 3^{rd} harmonic amplitude as a function of the controller gain c_r within interval $(-0.9, 0.3)$. The choice of negative values for c_r is due to the non minimum phase characteristic of the boost converter [12]. It can be seen that, for negative values, the THD and the 3^{rd} harmonic amplitude are smaller than for the positive values. It can also be observed that the effect of the capacitance for two different values: $C_{boost} = 2200\mu F$ and $C_{boost} = 220\mu F$.

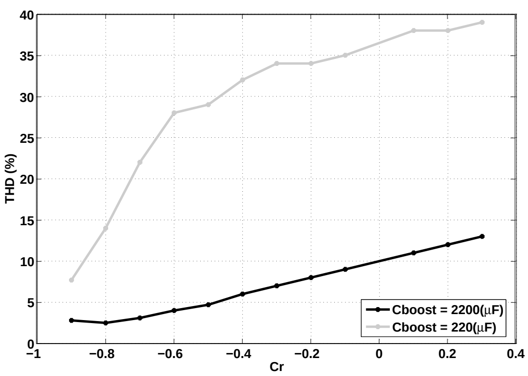


Fig. 6. THD variation as a function of the parameter c_r.

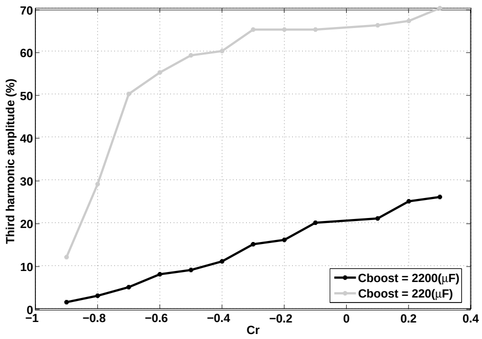


Fig. 7. Third harmonic amplitude for as a function of c_r.

IV. Experimental Results

A boost converter used as a power factor correction stage was implemented in order to obtain a high efficiency ballast. Two different techniques were employed in the boost converter control: the classical approach with current sampling done at the same frequency as the current oscillation and a PI; the second approach uses a repetitive plug-in control added to the main PI control. Both aim at the reduction of the harmonic distortion in the input current.

In order to validate the proposed technique, a boost converter was implemented as a part of an electronic ballast which supplies a HPS-150W GE Lucalox LU150/100/D/40 lamp. The controllers were developed in a Texas Instrument (TMS320F2812) DSP.

The electronic ballast diagram is shown is Figure 8. The characteristics of the ballast are: power: $150W$; boost output voltage, V_o : $250V$; switching frequency, f_s: $24kHz$; line voltage, E: $127Vrms/60Hz$. The boost inductor oscillation current is given as:

$$\triangle i_L = \frac{(V_o - E)E}{L f_s V_o} \tag{7}$$

Equation 8 gives the inductor current average as a function of the input voltage and power:

$$\overline{I_L} = \frac{P\sqrt{2}}{V_{rede}}. \tag{8}$$

Once the reference voltage is a cosine function and the maximum current oscillation corresponds to $E = \frac{V_o}{2}$, the boost inductance as a function of the maximum ripple is given as:

$$L = \frac{V_o}{4 f_s \triangle i_{Lmax} \eta} \tag{9}$$

For a $\triangle i_{Lmax} = 40\%$ of $\overline{I_L}$ and an efficiency, η, of 90%, $L = 3.5mH$.

The repetitive control were made with the number of switching periods per period of the periodic signal, *N=200*.

Note that the parameter d of the filter $C(z^{-1}) = z^d$ is equal 2.

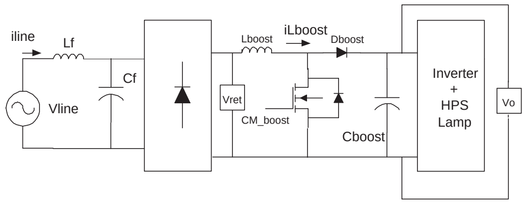


Fig. 8. Diagram of the electronic ballast.

The present section shows a comparison between the proposed repetitive control approach and two other ones: the first one consists on the use of two PIs (one for the voltage and other for the current), sampling the output voltage at the same frequency as for the inductor current, called "classical"approach; the second one uses the same two PIs as the first one but, with a sampling frequency for the voltage of $120Hz$, implemented through a Zero Order Holder - ZOH. The use of the ZOH in this second approach, as well as in the repetitive control, aims at the elimination of the $120Hz$ DC link ripple effect in the output voltage [11]. The advantage of the repetitive control over the ZOH approach is its simplicity and its smaller computational cost.

The ZOH controller, where the DC link voltage is sampled at $120Hz$, presents a THD of 4.13% in simulation [11], [12], which is smaller than the previous one. The inconvenience of such an approach is the determination of the sampling time instant because the correct acquisition of the voltage value is crucial for the output voltage regulation. Once an erroneous sampled value is obtained due to a miscalculated sampling time instant, a static error is inserted in the control. A commonly used technique to determine the sampling time instant is based on the zero crossing of the voltage which is not an easy task to accomplish by software requires extra hardware. Therefore, only the repetitive control was implemented.

Figure 9 presents the block diagram of all the three techniques whereas Table II shows the PI gains K_p and K_i for the same control specifications.

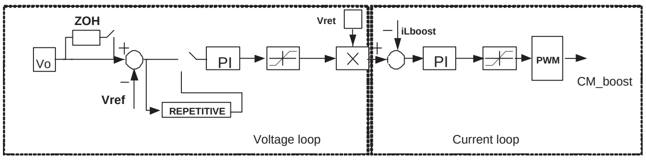


Fig. 9. Block diagram of the implemented controllers.

TABLE II
VALUES OF THE PI GAINS K_p AND K_i.

Type	Voltage		Current	
	K_p	K_i	K_p	K_i
Classical	1,5	75	0,5	1.000
ZOH	1,5	75	0,5	1.000
Repetitive	1,5	75	0,5	1.000

The input voltage was varied of $127V \pm \%15$ and two different values of capacitance were tested in order to evaluate both approaches considered in this study: the classical and repetitive control.

The input voltage variation tests the controller regulation capability were as, the capacitance variation (C_{boost}) evaluates the impact of the voltage ripple in the THD of the input current.

In both tests the same gains for the PI were used. Tables III and IV show the THD as well as the amplitude of each harmonic component for different voltage values, for both capacitance. The power factor and the output power are also shown.

TABLE III
HARMONIC COMPONENTS OF THE REPETITIVE AND CLASSICAL APPROACHES FOR A BOOST CAPACITANCE $C_{boost} = 1500\mu F$.

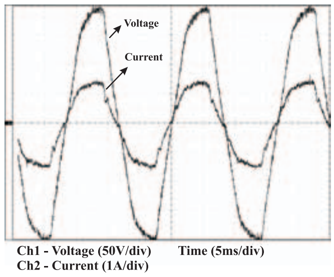
		Classical V_{in} (V)			Repetitive V_{in} (V)	
Harm.	IEC Standard	104	127	147	104	127
n	**%**	**%**	**%**	**%**	**%**	**%**
2	**2**	**0,7**	**1,2**	**1,7**	**0,27**	**0,41**
3	**30*PF**	**4**	**3,8**	**4,5**	**4**	**3,78**
5	**10**	**5,9**	**5,8**	**6,1**	**6**	**5,8**
7	**7**	**0,5**	**1**	**1,3**	**0,7**	**0,89**
9	**5**	**0,55**	**0,7**	**0,8**	**0,87**	**1,04**
11	**3**	**1,2**	**1**	**1,3**	**1,1**	**1,53**
19	**3**	**0,7**	**1,7**	**2,5**	**1,05**	**1,61**
THD (%)		**7,65**	**8,01**	**9,22**	**7,7**	**7,81**
PF		**0,992**	**0,993**	**0,979**	**0,997**	**1**

TABLE IV
HARMONIC COMPONENTS OF THE REPETITIVE AND CLASSICAL APPROACHES FOR A BOOST CAPACITANCE $C_{boost} = 22\mu F$.

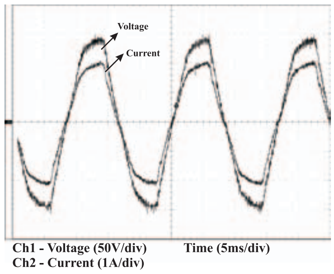
		Classical V_{in} (V)		Repetitive V_{in} (V)	
Harm.	IEC Standard	104	147	104	147
n	**%**	**%**	**%**	**%**	**%**
2	**2**	**1,61**	**0,3**	**0,27**	**0,32**
3	**30*PF**	**2,16**	**20,6**	**4,41**	**4,25**
5	**10**	**5,4**	**8,37**	**6,19**	**6,32**
7	**7**	**0,4**	**1,47**	**1,26**	**1,41**
9	**5**	**0,84**	**1,27**	**0,82**	**0,86**
11	**3**	**1,02**	**1,29**	**1,08**	**1,51**
19	**3**	**0,84**	**1,85**	**0,92**	**2,21**
V_{out} **(V)**		**250,5**	**262**	**250**	**250,1**
THD (%)		**6,5**	**22,64**	**8,06**	**8,91**
PF		**0,997**	**0,92**	**0,997**	**0,987**
P_{out} **(W)**		**152**	**167**	**152**	**148**

Figures 10 and 11 present the current and voltage waveforms for both the classical approach and repetitive control approach.

It can be seen from Table IV, with $C_{boost} = 22\mu F$, for $147V$ at the input, the repetitive control result in a THD 8.91%, much smaller than the value for the classical approach which is 22.64%. This is mainly due to capability of the repetitive control rejecting the 3^{rd} harmonic component.

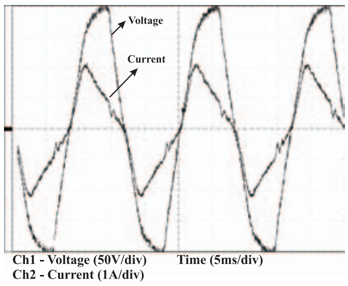


(a) $V_{in} = 146V$.

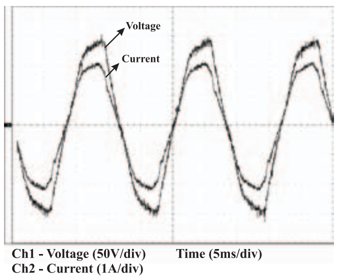


(b) $V_{in} = 104V$.

Fig. 10. Input voltage and current waveforms $(50V/div)$, $(1A/div)$ for $C_{boost} = 22\mu F$ − **Repetitive Control**. Time scale: $5ms/div$.

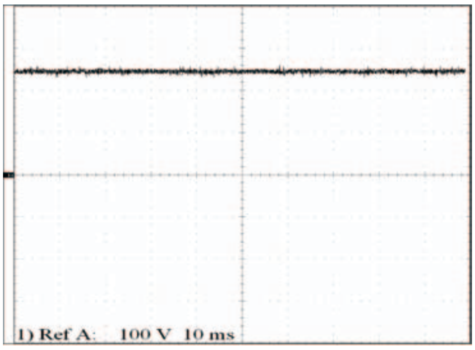


(a) $V_{in} = 146V$.

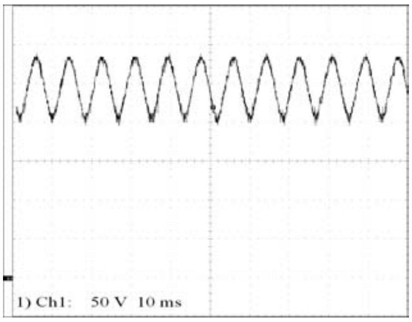


(b) $V_{in} = 104V$.

Fig. 11. Input voltage and current waveforms $(50V/div)$, $(1A/div)$ for $C_{boost} = 22\mu F$ − **Classical control**. Time scale: $5ms/div$.



(a) Output voltage ($100V/div$) waveform of the boost converter. $C_{boost} = 1500\mu F$. Time scale: $10ms/div$.



(b) Output voltage ($50V/div$) waveform of the boost converter. $C_{boost} = 22\mu F$. Time scale: $10ms/div$.

Fig. 12. Output voltage waveforms of the boost converter for $C_{boost} = 1500\mu F$ and $C_{boost} = 22\mu F$. Repetitive control.

Thus, the increase of the output voltage ripple deteriorates the input current when the classical approach is used. This effect is minimized with the repetitive control.

Figure 12(a) shows the voltage waveform at the output of the boost converter (the input of the ballast inverter). Figure 12(b) shows the same voltage waveform when the boost capacitor, $C_{boost} = 22\mu F$. This is the inverter input voltage, which has a $100V$ ripple (peak-to-peak) for an input voltage of $147V$.

It is worth mentioning that the test with a $22\mu F$ capacitor were made in order to emphasize the good rejection capability and the robustness of the repetitive control. Note that the IEC standard are satisfied for a capacitance $C_{boost} = 220\mu F$.

In practice the $22\mu F$ capacitance is not used at the boost output because the voltage ripple at the inverter input would not be tolerable for this application (electronic ballast).

V. Conclusion

The present paper introduces a study and a design method for the power factor correction in electronic ballasts using a boost converter via repetitive control techniques.

The experimental results so far obtained show that other than having a simple structure, appropriate for on-line implementation, the repetitive control show a good harmonic distortion reduction. The THD is smaller than that the standard PI approach. Its advantage with respect to the ZOH approach, which has some drawback and difficulty in its software implementation, is its simplicity.

As can be seen from the experimental results the PI controllers sampled a the same frequency of the current presented a THD of 8.01% which is acceptable by the standards. Nevertheless, the tuning of the PIs is rather involving and complex due to the sensibility of such controller to the fixed point representation of the gains.

The repetitive control presented a THD around 7.81% in experimental results which is better than the classical approach. Nevertheless, it is an extremely simple type of controller, very easy to be implemented via software given that its basic structure can be seen as a delay buffer.

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