A Study on LED Retrofit Solutions for Low-Voltage Halogen Cycle Lamps

J. Marcos Alonso, *Senior Member, IEEE*, David Gacio, *Student Member, IEEE*, Antonio J. Calleja, *Member, IEEE*, Javier Ribas, *Member, IEEE*, and Emilio López Corominas, *Member, IEEE*

***Abstract*—In this paper, a study on LED retrofit solutions for low-voltage halogen cycle lamps is conducted. In the first part of this paper, a lamp based on a LED array is designed to operate in substitution of a 12-V/50-W halogen lamp, for lighting fixtures in which these lamps are supplied using a line transformer. The design includes the selection of an adequate LED array in terms of lumen output and color temperature and the calculation of the necessary heatsink to assure the correct operation of the LED lamp within the selected temperature range. In the second part of this paper, a passive converter based on a bridge rectifier and a limiting resistance is studied and tested in the laboratory. Next, an active solution based on a buck–boost converter operating in discontinuous conduction mode is designed and experimentally evaluated. Finally, a comparison in terms of input power factor, input current harmonic content, LED current ripple, LED current regulation, efficiency, and photometric characteristics is carried out.**

***Index Terms*—Active driver, buck–boost converter, LED lamps, low-voltage halogen lamps, passive driver, retrofitting.**

I. Introduction

LOW-VOLTAGE halogen cycle lamps are an evolution of conventional incandescent lamps in which a halogen gas is added to reduce the filament evaporation. These lamps also incorporate a thick filament that provides increased resistance to current flow, generating a greater luminous intensity than line-voltage lamps of the same wattage. Thus, a great amount of light can be generated from a very small area, making these lamps a very good choice for many lighting applications [1]. However, they are still quite inefficient, with a luminous efficacy ranging from 10 to 18 lm/W. In fact, some recent benchmark tests have given an average value among different manufactures of only 13 lm/W [2].

With the advent of LED technology, many companies are starting to develop and commercialize retrofit solutions for low-voltage halogen lamps and fluorescent lamps, trying to match their characteristics in terms of size, color temperature, and color rendition [3]–[5]. This trend has been stimulated by LED good features regarding luminous efficacy and life expectancy, which provide an opportunity to obtain high energy savings and low payback times. Still, many LED lamps that are nowadays present in the market claiming for halogen lamp replacement are far from giving the same lumen output as their halogen counterparts.

In this paper, a study on LED retrofit solutions for low-voltage halogen cycle lamps is carried out. Two solutions are investigated for retrofitting a 12-V/50-W halogen lamp, for lighting fixtures in which these lamps are supplied using a line transformer. First, a passive solution is investigated, and its main advantages and disadvantages are highlighted. Second, an electronic solution based on a buck–boost converter operating in closed loop is presented and evaluated experimentally. In Section II, the design of the LED lamp is presented. Section III shows the analysis, design, and experimental results regarding the selected passive solution. Section IV deals with the proposed active solution based on the buck–boost converter, showing the important design equations and the experimental results obtained from a laboratory prototype. In Section V, photometric measurements from different alternatives are presented and compared. Finally, the conclusions are given in Section VI.

II. Design of the LED Lamp

Low-voltage halogen lamps present a color temperature ranging typically from 2900 K to 3000 K, and their luminous efficacy is between 10 and 20 lm/W. Therefore, for a 50-W lamp, the expected total luminous flux will be between 500 and 900 lm, with a typical value of 650 lm. Taking these data into account, a Bridgelux LED array BXRA-W0802 has been selected in this project to replace the halogen lamp. The main characteristics of this array are shown in Table I [6]. As can be seen, it can generate a luminous flux up to 800 lm at a case temperature of 60 °C. Thus, in the present design, the target case temperature will be 60 °C to assure sufficient light output, compatible with halogen lamps.

Fig. 1 shows the voltage–current characteristic of the LED array for two different operating temperatures. The first one at 25 °C junction temperature was obtained from the manufacturer's datasheet. The second one was measured in the laboratory by applying small duty-cycle current pulses so that the junction and case temperatures are maintained constant during the test at approximately 69 °C and 60 °C, respectively. From these experiments, the obtained value for the forward voltage

Manuscript received June 30, 2011; revised December 29, 2011 and March 20, 2012; accepted March 20, 2012. Date of publication July 23, 2012; date of current version September 14, 2012. Paper 2011-ILDC-337.R2, presented at the 2011 IEEE Industry Applications Society Annual Meeting, Orlando, FL, October 9–13, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Industrial Lighting and Display Committee of the IEEE Industry Applications Society.

The authors are with the Department of Electrical and Electronics Engineering, Universidad de Oviedo, 33204 Gijón, Spain (e-mail: marcos@uniovi.es; gacio@ate.uniovi.es; calleja@uniovi.es; ribas@uniovi.es; elopezc@uniovi.es).

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Digital Object Identifier 10.1109/TIA.2012.2209852

TABLE I
CHARACTERISTICS OF LED ARRAY BXRA-W802 AS STATED IN THE MANUFACTURER'S DATASHEET

Operating Current and Typical Voltage, T_j=25ºC	1050 mA 12.2 V
Typical Luminous Flux, T_j=25 ºC	930 lm
Typical Luminous Flux, T_{case} = 60 ºC	800 lm
Typical Color Temperature	3000 K
Typical Thermal Resistance, junction-to-case, T_j=25ºC	0.7 ºC/W
Typical Temperature Coefficient of Forward Voltage	-4 to -12 mV/ºC

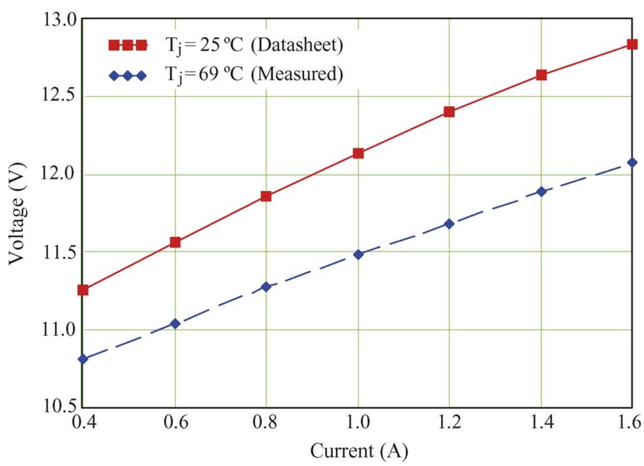

Fig. 1. Voltage–current characteristic of the LED array BXRA-W802.

coefficient at nominal current was -14.4 mV/°C, which is similar to the values specified by the manufacturer (Table I).

The next step in the design of the LED lamp is to determine the necessary heatsink that will maintain the LED array operating at the proper temperature. As stated before, the target case temperature is 60 °C in order to maintain a minimum luminous flux. The case temperature T_{case} can be estimated as follows:

$$T_{\text{case}} = T_a + P_{\text{LED}}(R_{\theta ch} + R_{\theta h}) \quad (1)$$

where T_a is the ambient temperature, P_{LED} is the power transformed into heat by the LED array, $R_{\theta ch}$ is the case-to-heatsink thermal resistance, and $R_{\theta h}$ is the heatsink thermal resistance.

For $R_{\theta ch}$, a conservative value of 0.15 °C/W may be assumed when using thermal grease in the assembling [7]. From [6], the array heat dissipation can be estimated as 85% of the total input power. Thus, since the LED power at nominal conditions is 12.2 W, the power transformed into heat will be 10.4 W. Assuming a maximum ambient temperature of 35 °C, the necessary heatsink thermal resistance for a case temperature of 60 °C can be calculated from (1), obtaining 2.2 °C/W. In the presented prototype, a Fischer Electronic heatsink with a length of 50 mm has been selected, which presents a thermal resistance of 1.9 °C/W, as stated in the manufacturer's datasheet. Fig. 2 shows the characteristics of this heatsink and the assembly of the LED array.

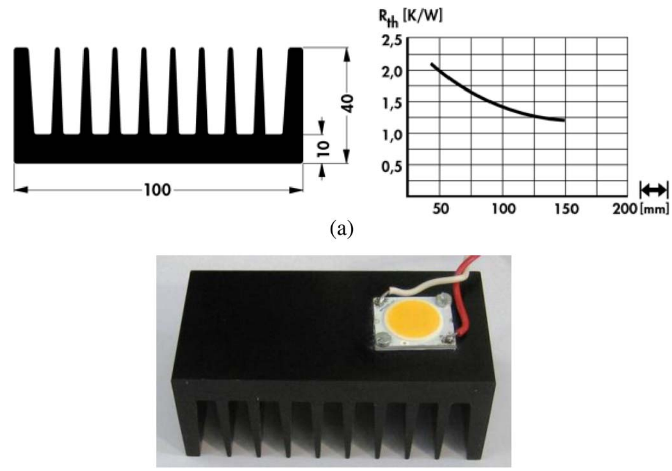

Fig. 2. (a) Characteristics of the heatsink selected for the experiments. (b) LED array mounted on the heatsink.

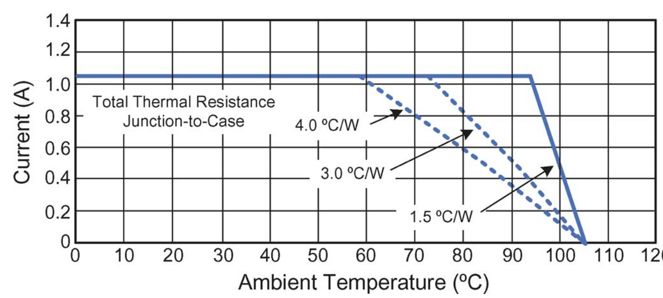

Fig. 3. Derating curves for the LED array BXRA-W802.

Another important point is the maximum current that the LED array can withstand, which depends on the ambient temperature and on the total thermal resistance from junction to case. The derating curves for the BXRA-W802 array are shown in Fig. 3, as given by the manufacturer. In the present design, the total junction to ambient thermal resistance is $0.7 + 0.15 + 1.9 = 2.75$ °C/W. Therefore, as can be seen in Fig. 3, a maximum current rating of 1.05 A can be maintained up to 73 °C ambient temperature, even for a thermal resistance of 3 °C/W. Since the expected maximum ambient temperature in the present design is 35 °C, a maximum current of 1.05 A can be supplied to the array without any damage.

As a final step in the lamp design, Fig. 4 shows the normalized luminous flux of the LED array as a function of the junction temperature. As it is well known, LED light output decreases when the operating temperature increases. In this design, the maximum expected junction temperature can be calculated with the following expression:

$$T_j = T_{\text{case}} + P_{\text{LED}} R_{\theta jc} \quad (2)$$

where $R_{\theta jc}$ is the junction-to-case thermal resistance, which, in this case, is 0.85 °C/W. Then, for a case temperature of 60 °C and a heating power of 10.4 W, a junction temperature

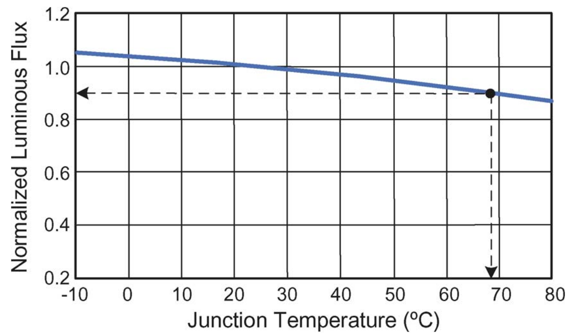

Fig. 4. Typical light output versus junction temperature characteristic for the LED Array BXRA-W802.

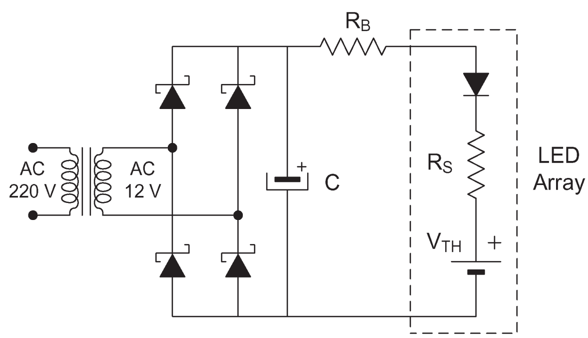

Fig. 5. Passive circuit to supply the LED array with resistive current limitation.

of 68.8 °C is obtained from (2). Using Fig. 4, the normalized luminous flux at this operating point will be 0.9. Since the typical lumen output is 930 lm, the expected luminous flux at maximum operating temperature will be 837 lm.

III. Passive Solution

A. Description and Analysis

In this section, a low-cost passive solution able to drive the LED lamp will be presented and evaluated. The LED lamp is intended to be supplied from a 220-V/50-Hz main voltage using a standard step-down transformer that generates an output of 11.5 V_{rms}/50 Hz with a maximum output current of 3.95 A_{rms}.

Fig. 5 shows the passive circuit employed to supply the LED lamp. A full-wave rectifier with a filter capacitance is used to generate a low ripple dc voltage. The current through the LED array is then limited by using a series resistance. Schottky diodes are employed in the rectifier to minimize voltage drop and losses. As shown in Fig. 5, the LED array is modeled by means of its series resistance and threshold voltage, R_S and V_{TH}, respectively. The model parameters can easily be calculated from the voltage–current characteristic shown in Fig. 1. The values obtained for operation at nominal current at 25 °C and 69 °C junction temperatures are shown in Table II.

Assuming that a low-output current ripple is pursued, an analysis of the circuit shown in Fig. 5 gives the following equation for the LED average current I_{LED}:

$$I_{\mathrm{LED}} = \frac{V_m - V_{TH}}{R_B + R_S + R_E} \tag{3}$$

TABLE II
Equivalent Series Voltage and Resistance of the LED Array BXRA-W802 at Rating Current

	$T_j = 25$ °C	$T_j = 69$ °C ($T_c = 60$ °C)
R_S (Ω)	1.35	1.03
V_{TH} (V)	10.78	10.44

where V_m is the peak line voltage, R_B is the resistance used to limit the LED current, and R_E is an effective resistance that depends on the filter capacitance C as follows:

$$R_E = \frac{1}{4fC} \tag{4}$$

where f is the mains frequency.

It is also important to determine the peak-to-peak ripple current through the LED array, namely, ΔI_{LED}. The analysis of the circuit gives the following:

$$\Delta I_{\mathrm{LED}} = \frac{2 I_{\mathrm{LED}} R_E}{R_B + R_S}. \tag{5}$$

Using (3)–(5), the values of R_B and C can be calculated for a given average and ripple currents through the LED array. As stated in [8], a peak-to-peak ripple current up to 50% will not degrade the LED luminous efficiency. Therefore, the selected design conditions are $I_{\mathrm{LED}} = 1.0$ A and $\Delta I_{\mathrm{LED}} = 0.5$ A_{pp}. The calculated values for the series resistance and the filter capacitance are $R_B = 3.2\ \Omega$ and $C = 4700\ \mu$F.

This circuit is very simple, reliable, and cost effective. However, it suffers from two main drawbacks. The first one is that the LED current changes when the line voltage and/or the LED threshold voltage change. This effect can be evaluated by taking derivatives in (3):

$$\frac{dI_{\mathrm{LED}}}{dV_m} = \frac{1}{R_T} \tag{6}$$

$$\frac{dI_{\mathrm{LED}}}{dV_{TH}} = \frac{-1}{R_T} \tag{7}$$

where R_T is the total effective resistance given by

$$R_T = R_B + R_{\mathrm{LED}} + R_E. \tag{8}$$

In the present design, $R_T \approx 5\ \Omega$, which gives a variation of 0.2 A/V. If the input voltage changes by 1 V, the current will vary by 0.2 A with the same sign. On the other hand, if the LED threshold voltage increases by 1 V due to thermal effects, the LED current will decrease by 0.2 A and vice versa. The variations in the LED current could be lowered by selecting a higher value of the series resistance R_B; however, this would decrease the efficiency. Another possibility would be to use a higher value of the filter capacitance, thus increasing the value of the effective resistance R_E, but this would require a capacitor of larger volume and size.

The second disadvantage of the passive solution is the efficiency decrease due to the use of a resistance as a limiting

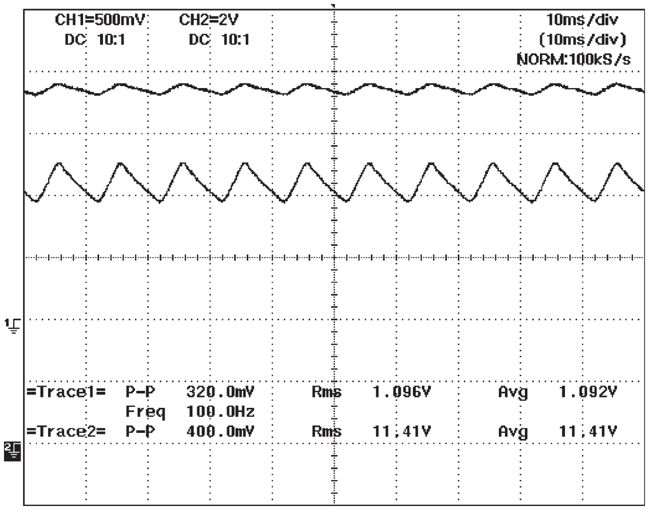

Fig. 6. Voltage and current waveforms for the LED lamp when operating with the passive solution at 220-V line voltage. Top (trace 2): LED lamp voltage, 2 V/div. Bottom (trace 1): LED lamp current, 0.5 A/div. Horizontal Scale: 10 ms/div.

device. Neglecting the output current ripple, the efficiency can be estimated as follows:

$$\eta = \frac{P_{\mathrm{LED}}}{P_B + 4P_D + P_{\mathrm{LED}}} = \frac{I_{\mathrm{LED}}^2 R_S + I_{\mathrm{LED}} V_{\mathrm{TH}}}{I_{\mathrm{LED}}^2 (R_B + R_S) + (V_{\mathrm{TH}} + 2V_\gamma) I_{\mathrm{LED}}} \tag{9}$$

where P_{LED} is the total power delivered to the LED array, P_D is the power in each Schottky diode, P_B is the power consumed by the series resistance R_B, and V_γ is the forward voltage of the Schottky diodes. In the present design, the LED power is 11.5 W, the power in R_B is 3.2 W, and the Schottky diodes have a forward voltage of 0.4 V, giving a total power in the bridge rectifier of 0.8 W. Therefore, the expected efficiency is 74.2%. It must be noted that this is only the efficiency of the retrofit converter. The total efficiency from mains to lamp must have into account the efficiency of the transformer. Since the transformer does not operate at its maximum power rating, its efficiency will be low, typically 70%. Therefore, the total expected efficiency of the passive retrofit solution will be around 50%.

B. Experimental Results

The transformer used in the experiments is a KNOBEL 50-KTr/12, with a voltage transformation ratio of 230 V/ 11.5 V. The transformer was characterized using an impedance analyzer HP4284 and also performing open- and short-circuit loss measurements. The following parameters were obtained: magnetizing inductance $L_M = 2.97$ H, core loss equivalent resistance $R_M = 10.5$ kΩ, leakage inductance seen from the primary side $L_{k1} = 82.4$ mH, and series resistance seen from the primary side $R_{s1} = 127$ Ω. Fig. 6 shows the voltage and current waveforms in the LED lamp at 220-V line voltage. The measured peak-to-peak voltage ripple is 0.4 V, which is quite similar to the value obtained from the theoretical design. The measured peak-to-peak current ripple is 0.32 A, which is slightly different from the expected value because the latter

TABLE III
MEASURED LAMP ELECTRICAL PARAMETERS AND EFFICIENCY FOR THE PASSIVE SOLUTION

Line Voltage (Vrms)	Line Power (W)	LED Lamp Voltage (V)	LED Lamp Current (A)	LED Lamp Power (W)	Efficiency (%)
200	14.7	11.1	0.65	7.2	49.2
210	17.8	11.3	0.77	8.7	48.8
220	21.2	11.4	0.91	10.4	49.0
230	24.9	11.6	1.04	12.0	48.2
240	28.9	11.7	1.17	13.7	47.2

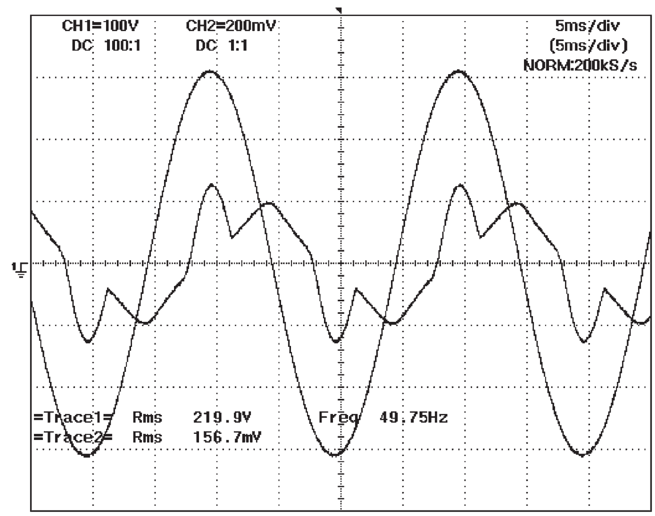

Fig. 7. Line voltage and current for the passive solution at 220-V line voltage. 100 V/div, 200 mA/div, and 5 ms/div.

depends on the lamp series resistance, which, in turn, depends on the particular lamp and operating temperature. In this case, as can be seen from Fig. 6, the equivalent series resistance is $0.4\ \mathrm{V}/0.32\ \mathrm{A} = 1.25\ \Omega$, instead of the expected value of 1.0 Ω given in Table II.

Table III shows the electrical measurements made on the prototype for line-voltage variations in the range 200–240 $\mathrm{V_{rms}}$. As can be seen, the line-voltage variations affect the LED lamp power. Approximately, a 10% change in line voltage causes a 20% variation in lamp power. The efficiency of the whole system, including the transformer, is around 50%, as expected from the theoretical analysis. Nevertheless, the reduction in power compared to the halogen lamp is significant since the input power at nominal line voltage is 20.5 W, which is less than 50% of the halogen lamp consumption. The experimental results related to the luminous flux will be presented in a later section.

In regard to the current harmonic injection to the line and the line power factor (PF), Fig. 7 shows the line voltage and current of the complete arrangement, including the line transformer. The presence of the transformer softens the current waveform, improving PF and decreasing harmonic content. Table IV shows the PF and the current total harmonic distortion (THD) within the voltage range under study. Fig. 8 shows the line current harmonic contents compared to IEC61000-3-2 [10]. In this case, the input power is less than 25 W; therefore, the limits that can be considered are those of class D, which provide a maximum value in milliamperes per watt for each harmonic. As can be seen, the limits are well fulfilled with this solution.

TABLE IV
MEASURED PF AND LINE CURRENT THD FOR THE PASSIVE SOLUTION

Line Voltage (Vrms)	Power Factor	Line Current THD (%)
200	0.56	38.7
210	0.57	39.9
220	0.59	40.6
230	0.59	41.0
240	0.60	41.2

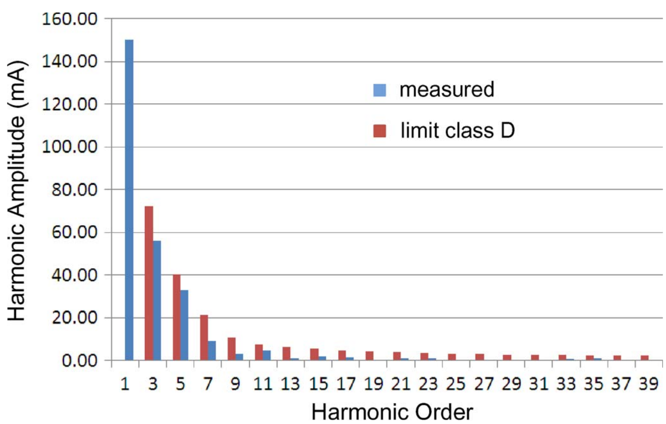

Fig. 8. Measured line current harmonic content for the passive solution at 220 V and comparison with the standard IEC61000-3-2 limits.

IV. Active Solution

A. Description and Analysis

An active solution is investigated in this section as an alternative to the passive solution presented previously. Given the similarity between the transformer output voltage (12 V_{rms}) and the LED lamp voltage (11.5 V) and taking into account that the converter should be as cost effective as possible, the best choice is to use a buck–boost converter operating in discontinuous conduction mode (DCM). In this way, a near-unity input PF can be achieved, assuring IEC61000-3-2 standard fulfillment.

Fig. 9 shows the diagram of the buck–boost converter studied for the active retrofit solution. The converter employs a single inductor, which is simpler than the two coupled inductors used in a flyback converter. The difficulty here is that the load is floating, thus slightly complicating the implementation of closed-loop and protection circuitry. Nevertheless, these drawbacks can be solved by using low-cost optocouplers, as shown later.

It is well known that this converter operating in DCM exhibits a triangular input current waveform with a peak value proportional to the instantaneous line voltage. Thus, the average low-frequency input current is also sinusoidal and proportional to the line voltage. As conclusion, the converter behaves as resistance from the point of view of the line, whose value is the following [9]:

$$R_I = \frac{2L_O f_s}{D^2} \tag{10}$$

where L_O is the converter inductance, f_S is the switching frequency, and D is the duty cycle of the power switch. By

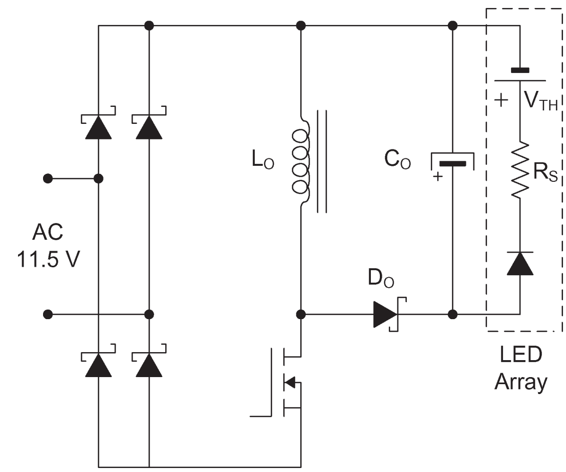

Fig. 9. Electric diagram of the buck–boost converter studied for the active retrofit solution.

equaling input and output powers, the mean LED lamp current I_{LED} can be calculated as follows:

$$I_{\mathrm{LED}} = \frac{1}{\sqrt{2}} \frac{V_m}{\sqrt{R_I R_{\mathrm{LED}}}} \tag{11}$$

where R_{LED} is the effective LED lamp resistance given by the total LED lamp voltage (V_{LED}) over the LED lamp current.

As commented in previous sections, an important design parameter is the low-frequency ripple current through the LED lamp. This can be calculated from the low-frequency component in the current of the output diode D_O, with its amplitude being equal to the average value given by (11). Then, neglecting the voltage ripple across the LED lamp, which is usually very low, the following expression is obtained for the peak-to-peak amplitude of the low-frequency LED lamp current:

$$\Delta I_{\mathrm{LED}} = \frac{V_m^2}{4\pi f R_I V_{\mathrm{LED}} R_S C_O}. \tag{12}$$

Using (10)–(12), the values of the converter inductance L_O and capacitance C_O can be calculated for a given LED average and ripple current.

In order to diminish the size as much as possible, the laboratory prototype was designed to operate at a switching frequency of 115 kHz. Then, for a given LED lamp mean current equal to 1 A, using (11), a value of the converter input resistance $R_I = 11.5\ \Omega$ is obtained. From that, using (10) and selecting a duty cycle of 40% at nominal operation, the required value for the converter inductance is calculated as $L_O = 8\ \mu$H. The selected output capacitor for the converter was the same with the one employed in the passive solution $C_O = 4700\ \mu$F. Thus, using (12), the LED lamp current ripple can be calculated. For example, for operating at $T_j = 60\ ^\circ$C, using the value given in Table II for the LED lamp series resistance, a peak-to-peak ripple current of 0.7 A is obtained. This represents a 40% increase in the ripple current compared to the passive solution for the same capacitor, which is a disadvantage for the active solution. If the same current ripple as that in the passive solution (0.5 A) is required, a capacitance of 6800 μF would be necessary.

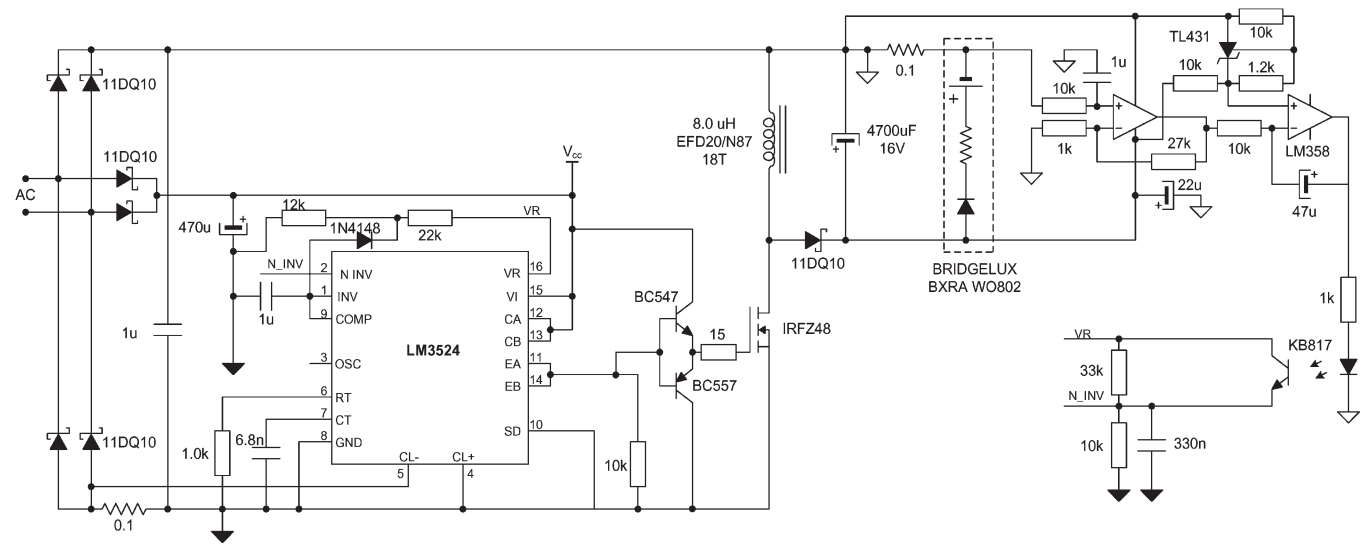

Fig. 10. Electric diagram of the laboratory prototype for the active solution.

In order to solve the problem of having different voltage references for the input and output sections, the sensing and compensating circuitry was referenced to the output section, and a low-cost KB817 optocoupler was used to isolate the control signal generated by the compensator output. The complete electrical diagram of the laboratory prototype for the active solution is shown in Fig. 10. As can be seen, the LED lamp current is measured using a series resistance and then filtered and compared with a reference level implemented with the TL431. A proportional–integral compensator is implemented using the LM358. Then, the optocoupler sends the signal to the input of the control circuit LM3524. The duty cycle is both limited at maximum and minimum levels using the corresponding circuitry. An overcurrent protection is implemented using a series resistance and the LM3524 built-in circuitry (pins CL+ and CL−).

B. Experimental Results

Fig. 11 shows the voltage and current waveforms in the LED lamp when operating with the active solution at 220-V line voltage. The measured low-frequency ripples were 0.61 V and 0.54 A for the lamp voltage and lamp current, respectively, which are very similar to those expected from the theoretical design. In this case, the measured equivalent series resistance of the lamp as obtained from Fig. 11 is $0.61\ \mathrm{V}/0.54\ \mathrm{A} = 1.13\ \Omega$.

Table V shows the electrical parameters measured on the active prototype for different line voltages. It must be noted that the converter operates in closed loop. Therefore, as can be seen in the results shown in Table V, the lamp current is maintained constant for the different line voltages. As long as the lamp series resistance and voltage are constant, the lamp power is also regulated, as can be seen in Table V. Most of the lamp power is consumed by its equivalent series voltage source, whose value does not vary excessively with temperature. For this reason, even though the lamp current is the parameter being regulated, the lamp power is expected to be maintained quite independent of the temperature. This lamp power regulation is one of the main advantages of the active solution versus the passive one.

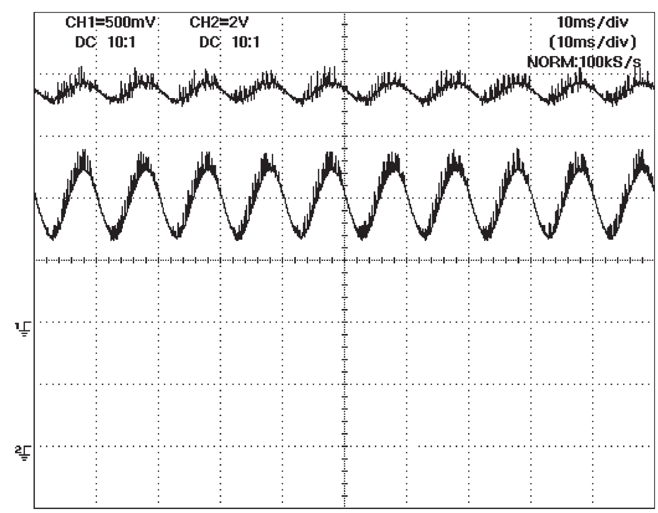

Fig. 11. Voltage and current waveforms for the LED lamp when operating with the active solution at 220-V line voltage. Top (trace 2): LED lamp voltage, 2 V/div. Bottom (trace 1): LED lamp current, 0.5 A/div. Horizontal Scale: 10 ms/div.

TABLE V
MEASURED LAMP ELECTRICAL PARAMETERS AND EFFICIENCY FOR THE ACTIVE SOLUTION

Line Voltage (Vrms)	Line Power (W)	LED Lamp Voltage (V)	LED Lamp Current (A)	LED Lamp Power (W)	Efficiency (%)
200	21.9	11.47	1.09	12.5	57.1
210	22.0	11.47	1.09	12.5	56.8
220	22.2	11.47	1.09	12.5	56.3
230	22.5	11.47	1.09	12.5	55.6
240	22.9	11.47	1.09	12.5	54.6

The total efficiency measured from line to lamp, including the line transformer, is shown in Table V. The efficiency is around 7% higher in the active solution than in the passive one.

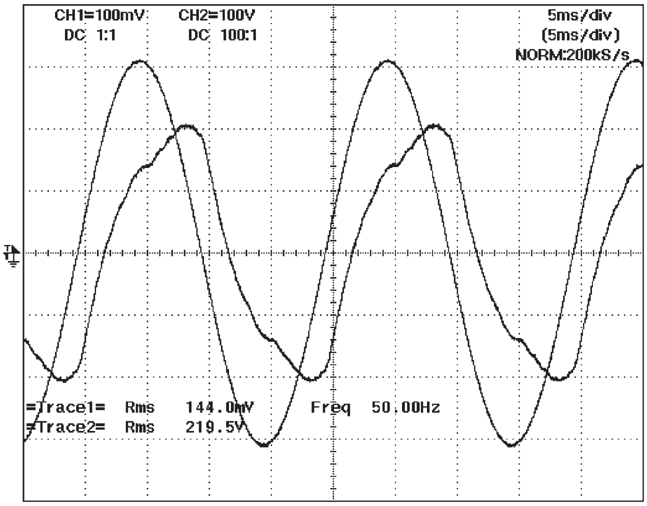

Fig. 12. Line voltage and current for the active solution at 220-V line voltage. 200 mA/div, 100 V/div, and 5 ms/div.

TABLE VI
MEASURED PF AND LINE CURRENT THD FOR THE ACTIVE SOLUTION

Line Voltage (Vrms)	Power Factor	Line Current THD (%)
200	0.78	16.0
210	0.73	15.5
220	0.68	16.2
230	0.62	17.5
240	0.57	19.5

The line voltage and current for the active solution are shown in Fig. 12. As can be seen, even though the buck–boost converter behaves as a resistance, the current at the input of the transformer is not purely resistive. This is due to the behavior of the line transformer. The magnetizing and leakage inductances and the winding capacitances of the line transformer form a low-pass filter that modified the input current, as can be seen in Fig. 12.

The PF and line current THD are shown in Table VI. The PF is similar to that in the passive solution, but the current distortion is much lower, as is verified from the waveform shown in Fig. 12. The low PF is mainly due to the lagging phase of the input current.

The harmonic content of the line current for the active solution compared to the IEC61000-3-2 standard is shown in Fig. 13. It is verified that the standard is well fulfilled by the developed prototype.

V. PHOTOMETRIC RESULTS

The luminous output of the retrofit solutions investigated in this paper has been measured in the laboratory using a 2-m integrating sphere from Labsphere with a J18 Tektronix photometer. For comparison purposes, the luminous output of two 12-V/50-W halogen lamps made by General Electric and Philips and a 7-W LED lamp by Philips was also measured. The results are shown in Table VII. All the lamps were aged for at least 100 h prior to measurement.

The halogen lamps used as reference were an MR16 12-V/50-W by General Electric and a 12-V/50-W Philips Capsuline.

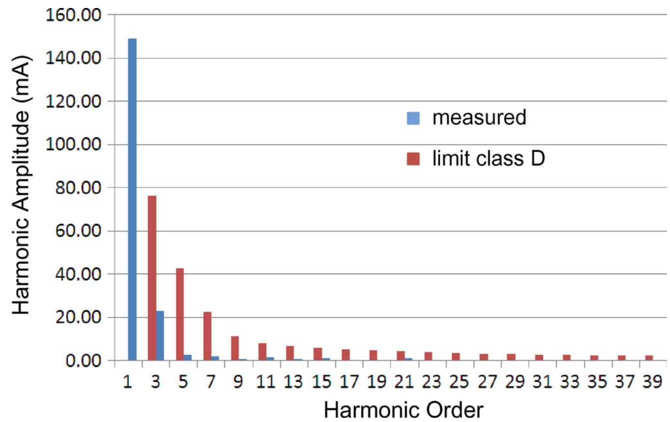

Fig. 13. Measured line current harmonic content for the active solution at 220 V and comparison with the standard IEC61000-3-2 limits.

TABLE VII
PHOTOMETRIC MEASUREMENTS FOR DIFFERENT LAMPS AND LABORATORY PROTOTYPES

Halogen Lamp: General Electric MR16 12 V/50 W			
Line Voltage (Vrms)	Line Power (W)	Luminous Flux (lm)	Efficacy (lm/W)
200	47.7	528	11.1
210	51.6	626	12.1
220	56.0	764	13.6
230	60.0	884	14.7
240	64.1	1021	15.9
Halogen Lamp: Philips Capsuline 12 V/50 W			
Line Voltage (Vrms)	Line Power (W)	Luminous Flux (lm)	Efficacy (lm/W)
200	48.2	506	10.5
210	52.1	604	11.6
220	56.2	722	12.8
230	60.4	843	14.0
240	64.6	970	15.0
LED Lamp: Philips LED Spot 220 V/7 W			
Line Voltage (Vrms)	Line Power (W)	Luminous Flux (lm)	Efficacy (lm/W)
200	5.6	107	19.1
210	6.3	130	20.6
220	6.9	150	21.7
230	7.3	167	22.9
LED Lamp: Prototype Passive Solution			
Line Voltage (Vrms)	Line Power (W)	Luminous Flux (lm)	Efficacy (lm/W)
200	14.3	566	39.6
210	17.4	669	38.4
220	20.6	783	38.0
230	24.2	884	36.5
240	28.1	965	34.3
LED Lamp: Prototype Active Solution			
Line Voltage (Vrms)	Line Power (W)	Luminous Flux (lm)	Efficacy (lm/W)
200	22.1	834	37.7
210	22.2	834	37.6
220	22.4	834	37.2
230	22.6	834	36.9
240	23.0	834	36.3

As shown in Table VII, the MR16 lamp provides a luminous output ranging from 528 to 1021 lm, with a nominal value at 220 V of 764 lm. Its luminous efficacy at nominal operation is 13.6 lm/W, which is within the expected range found in the literature. The Philips Capsuline lamp gave a luminous output between 506 and 970 lm, with an efficacy ranging from 10.5 to 15 lm/W. The nominal values at 220 V were 722 lm and 12.8 lm/W, respectively, which are also within the expected range. As can be seen, in both cases, there is no output regulation against line-voltage variations. It can roughly be said that a 10% line-voltage variation provides a 15% lamp power change and 30% variation in the luminous flux.

The Philips LED Spot provides a luminous output much lower than the halogen lamps. The luminous output ranges from 107 to 167 lm, with a luminous efficacy ranging from 19.1 to 22.9 lm/W. The nominal luminous efficacy at 220 V is 21.7 lm, which represents a 70% increase compared to the halogen lamps. As can be seen, the lamp power is not regulated against line voltage. Approximately, a 10% line-voltage variation generates a 30% light output change. This lamp is intended to operate with phase cut dimmers, so it is understandable that it does not provide power regulation.

As regards to the proposed passive solution, the luminous output ranges from 566 to 965 lm, quite matching that of the halogen lamps. Moreover, the efficiency is much higher, ranging from 34 to 39 lm/W. In this solution, the lamp power is not regulated against line-voltage variations. Thus, a 10% line-voltage change produces approximately a 30% change in lamp power and light output. At the nominal operation point, the luminous output is 783 lm with an efficacy of 38 lm/W. Thus, the passive solution achieves the same luminous output, consuming only 20.6 W, which represents a 63% reduction in the lamp power rating. For an 8-h operation per day, the yearly energy saving is 100 kWh approximately.

Finally, Table VII shows the results obtained from the active solution presented in this paper. As can be seen, the light output is regulated to 834-lm output. This guarantees higher luminous flux than that obtained from the halogen lamps. The lamp input power is 22 W approximately in the whole voltage range, giving a 34-W energy saving, which is 61% less energy consumption compared to the halogen lamp. The luminous efficacy is around 37 lm/W. It is worth noting that, despite the higher efficiency of the active solution, the measured efficacies in lumens per watt were nearly the same in both converters. This is probably due to slightly different operating conditions of the LED lamp with each converter. The lamp current ripple was slightly lower in the passive solution than in the active one, 0.32 against 0.54 A, respectively, what could make the lamp more inefficient under the active converter operation. Therefore, it is reasonable to expect that, for exactly equal operating conditions, the efficacy would be also higher for the active solution in the same amount as it is in the converter efficiency.

VI. Discussion

In this section, a discussion is carried out comparing both developed solutions in terms of light output, cost effectiveness, reliability, efficiency, PF/THD/electromagnetic interference (EMI), lamp power regulation, light quality, and dimming.

1) *Light output*. Both solutions can supply the lamp with similar waveforms in terms of average value and current ripple. Therefore, the light generated by the LED lamp reached the expected value in both solutions, around 800 lm in both designs.
2) *Cost effectiveness*. The passive solution is clearly less complex, and it requires lower number components. Consequently, a significant lower cost is expected for the passive solution compared to the active one. This is one of the strong points in favor of the passive solution.
3) *Reliability*. The passive solution does not incorporate any electrostatic-discharge-sensitive components such as integrated circuits, bipolar transistors, MOSFETs, and voltage regulators. Therefore, it is expected that this solution will be more reliable than the active one. In both solutions, the most restrictive component in terms of life span is the electrolytic capacitor required to smooth the lamp current. One solution to this problem could be building the lamp in such a manner that the user could easily change the electrolytic capacitor when damaged, as it is commonly done in fluorescent fixtures with the glow starter.
4) *Efficiency*. The efficiency obtained for the active solution was around 7% higher than that of the passive solution. This is one of the strong points for the active solution. It makes a better use of the energy, and it could pay for the higher cost in the long term.
5) *PF/THD/EMI*. It has been found that both solutions can comply with the IEC standard, and therefore, both of them could be employed. The results are slightly better for the active solution, where a PF of around 0.7 was measured compared to 0.6 for the passive solution. However, the current THD was quite higher for the passive solution, with a value of around 41% against 16% for the active solution. In regard to the EMI, it is expected that the active solution would require a larger EMI filter than the passive one due to the injection of high-frequency harmonics, whereas they are not present in the passive converter.
6) *Lamp power regulation*. The active solution provides lamp power regulation against line voltage and lamp characteristic fluctuations. This is important because it assures a nearly constant lamp power operation and assures longer lamp life. In the passive solution, the lamp can operate at a power higher than the nominal value, thus increasing the lamp temperature and decreasing its life.
7) *Light quality*. The active solution provides better light quality compared to the passive one. Since the lamp current is regulated in closed loop, the lamp power remains nearly constant, and it does not fluctuate when line-voltage oscillations appear due to instabilities in the grid. Light fluctuations can be quite annoying in some applications.
8) *Dimming*. In the active solution, the lamp current can be controlled by changing the compensator reference, thus providing dimming functionality. This is another important advantage compared with the passive solution because it allows the user to adapt the light output to the required value for each situation, thus providing additional energy saving.

VII. Summary and Conclusion

In this paper, a study on LED retrofit solutions to substitute existing low-voltage halogen lamps has been carried out. A LED array has been selected to build a LED lamp compatible with the halogen lamps in terms of luminous output and color temperature. The design of the lamp included the selection of the LED array, the determination of the maximum operating temperature to assure sufficient light output, and the calculation of the heatsink thermal resistance necessary to assure the correct operation of the lamp within the whole temperature range. Derating curves were taking into account to assure that the lamp will be able to be supplied with the necessary current level. Also, the variation of the luminous flux against LED case temperature was taken into account.

In the second part of this paper, a passive solution based on a full diode rectifier, a filter capacitance, and a limiting resistance is evaluated. This solution is very cost effective and ensures light output matching that of the halogen lamps and energy saving up to 63%. The passive solution was analyzed, and some important points regarding its design and behavior were presented. One disadvantage of the passive solution is that it cannot regulate the lamp power against line-voltage variations. Therefore, line-voltage oscillations will produce lamp brightness fluctuations that can be annoying in some circumstances.

In the third part of this paper, an active solution based on a buck–boost converter operating in DCM was presented. The important design equations were highlighted and employed to justify the developed laboratory prototype. One of the important advantages found for the active solution was the 7% higher efficiency obtained compared to that of the passive solution. Other advantages that can be highlighted are a higher PF, a lower line current harmonic content, and lamp power regulation against line voltage and lamp characteristic variations. Also, alike the passive solution, a similar light output compared to the halogen lamps has been achieved. An important additional advantage of the active solution is that dimming can easily be implemented by using a variable reference voltage at the regulator input.

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J. Marcos Alonso (S’94–M’98–SM’03) received the M.Sc. and Ph.D. degrees in electrical engineering from the Universidad de Oviedo, Gijón, Spain, in 1990 and 1994, respectively.

From 1990 to 1999, he was an Assistant Professor in the Department of Electrical and Electronics Engineering, Universidad de Oviedo, where he was an Associate Professor from 1999 to 2007 and has been a Full Professor since 2007. He was the Advisor for six Ph.D. theses in the field of power electronics. He is the primary author of more than 70 journal and international conference papers on power and industrial electronics and has coauthored more than 200. He is the holder of six Spanish patents with one under review. His research interests include high-frequency electronic ballasts, LED power supplies, discharge lamp modeling, power converters for ozone generation and other electrostatic applications, power factor correction topologies, and high-frequency switching converters in general.

Dr. Alonso has been awarded by a national funding for the Intensification of Research Activity for the period 2008–2012. He was a recipient of the Early Career Award of the IEEE Industrial Electronics Society in 2006, the Best Paper Award of the 2009 IEEE International Symposium on Industrial Electronics, the Second Prize Paper Award of the 2005 IEEE Industry Applications Society Meeting, Production and Application of Light Committee, and the IEEE Industrial Electronics Society Meritorious Paper Award in 1996. He is an active member of IEEE, where he usually collaborates as a TRANSACTIONS Paper Reviewer, a Conference Session Chairman, and a Session Organizer, among other positions. Since October 2002, he has served as an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS in the field of Lighting Applications. He has served as a Guest Editor for the Special Issue on Lighting Applications, published in the IEEE TRANSACTIONS ON POWER ELECTRONICS in May 2007 and as a Co-Guest Editor for a Special Section on Modern Ballast Technology and Lighting Applications published in the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS in April 2012. He is also a member of the European Power Electronics Association, and he belongs to the International Steering Committee of the European Conference on Power Electronics and Applications (EPE), where he usually collaborates as a Topic Cochair.

David Gacio (S’08) was born in Gijon, Spain, in 1983. He received the M.Sc. degree in electrical engineering from the Universidad de Oviedo, Gijón, in 2007, where he has been working toward the Ph.D. degree in the Department of Electrical and Electronics Engineering since July 2008. His Ph.D. thesis is being developed in the field of solid-state lighting.

Since March 2008, he has been a Lecturer and a Researcher in the Department of Electrical and Electronics Engineering, Universidad de Oviedo. He is the primary author or coauthor of 23 international conference papers and eight journal papers on power and industrial electronics. His research interests include power factor correction topologies, electronic ballasts, power converter modeling, LED modeling, and solid-state lighting in general.

Mr. Gacio collaborates as an IEEE TRANSACTIONS Paper Reviewer. He was a recipient of the Best Paper Award at the 2009 IEEE International Symposium on Industrial Electronics.

Antonio J. Calleja (S’96–A’98–M’04) was born in Leon, Spain, in 1964. He received the B.Sc., M.Sc., and Ph.D. degrees from the Universidad de Oviedo, Gijón, Spain, in 1987, 1995, and 2000, respectively.

He is currently with the Universidad de Oviedo, where he was an Assistant Professor from 1995 to 2001 and has been an Associate Professor since 2002. His research interests include high-frequency electronic ballast, discharge lamp modeling, power factor correction topologies, industrial control systems, and low-power inverter grid connection topologies.

Javier Ribas (S'97–M'04) was born in Milwaukee, WI, in 1971. He received the M.Sc. and Ph.D. degrees from the Universidad de Oviedo, Gijón, Spain, in 1995 and 2001, respectively.

Since 1996, he has been with the Universidad de Oviedo, where he was an Assistant Professor and has been an Associate Professor since 2002. His current research interests include dc/dc converters, electronic lighting systems, switching power supplies, inverters, and high-power-factor rectifiers.

Emilio López Corominas (M'97) was born in Oviedo, Spain, in 1965. He received the M.Sc. and Ph.D. degrees in electrical engineering from the Universidad de Oviedo, Gijón, Spain, in 1992 and 1999, respectively.

From 1993 to 2001, he was an Assistant Professor in the Department of Electrical and Electronics Engineering, Universidad de Oviedo, where he has been an Associate Professor since 2001. His research interests include electronic systems for lighting and renewable-energy systems, high-frequency electronic ballasts, discharge lamp modeling, electronic drivers for high-brightness LEDs, high-frequency switching converters, power factor correction converters, industrial control systems, and digital control for power electronics.