electronics

Article

Power Source Electronic Ballast for Electrodeless Fluorescent Lamps

F. Javier Diaz *, Francisco J. Azcondo, Rosario Casanueva and Christian Brañas

Electronics Technology, Systems and Automation Engineering Department, University of Cantabria, Ave. de los Castros 46, 39005 Santander, Spain; azcondof@unican.es (F.J.A.); casanuer@unican.es (R.C.); branasc@unican.es (C.B.)

* Correspondence: diazrf@unican.es; Tel.: +34-942-201-544

Received: 29 November 2019; Accepted: 25 December 2019; Published: 27 December 2019

Abstract: This paper presents the design, control strategy and experimental results of a two-step, power factor correction stage (PFC) and resonant inverter (RI), electronic ballast proposal to supply 150 W electrodeless fluorescent lamps (EFL). The PFC acts as a controlled power source and provides mid and long-term stability to the system, while the stability of the current through the lamp is achieved with the RI. In addition, the power-mode control requires limitation of the output voltage. The dual operation mode of the PFC (voltage source mode and power source mode) enables an efficient soft resonant ignition and the implementation of simple dimming regulation.

Keywords: electrodeless fluorescent lamps (EFL); electronic ballast; power factor corrector (PFC); resonant converters; light-emitting diode (LED)

1. Introduction

The use of lighting systems represents a large percentage of world energy consumption [1]. For this reason, new lighting technologies continue to be sought that are more efficient and extend useful life so enabling better use of energy resources.

High-intensity discharge lamps (HID), are lamps of great commercial interest, especially in outdoor lighting, due to the good characteristics they have: high energy efficiency, compact size, good color reproduction and a long useful life [2–6].

Currently, LED technology and induction lamps, also known as electrodeless fluorescent lamps (EFL), are replacing traditionally used HID lamps, such as high-pressure sodium (HPS) and metal halide (MH), mainly due to the fact that they have a longer service life [7–9], as shown in Figure 1. EFL lamps are comparable to LED lamps in terms of light output (lm/W), color reproduction, lifetime and scotopic/photopic ratio (S/P ratio). Light sources are assigned an S/P ratio that is a calculation of the scotopic lumens the lamp produces divided by the photopic lumens. If the ratio is 1 the light source performs just as good under scotopic conditions as photopic. The higher this number the better the human eye performs under the light source. Figure 2 shows the S/P ratio for different lamps reported in [7]. However, it should be remarked that electric light sources have strong effects on circadian rhythms in physiology, metabolism, and behavior. For example, recent experimental evidence in humans has shown that the lighting commonly used in typical homes in the evening is enough to delay melatonin onset and weaken its nocturnal peak [10]. Blue light in the range of 450~480 nm has been proved to induce melatonin depression. EFL lamps emit light outside that range, in contrast to the light emitted by an important group of LED lamps. In the LED case, lighting with correlated color temperature below 4000 K contributes to melatonin emission and good sleeping conditions, while LED lighting with correlated color temperature above 4000 K induces melatonin depression and poor sleeping quality.

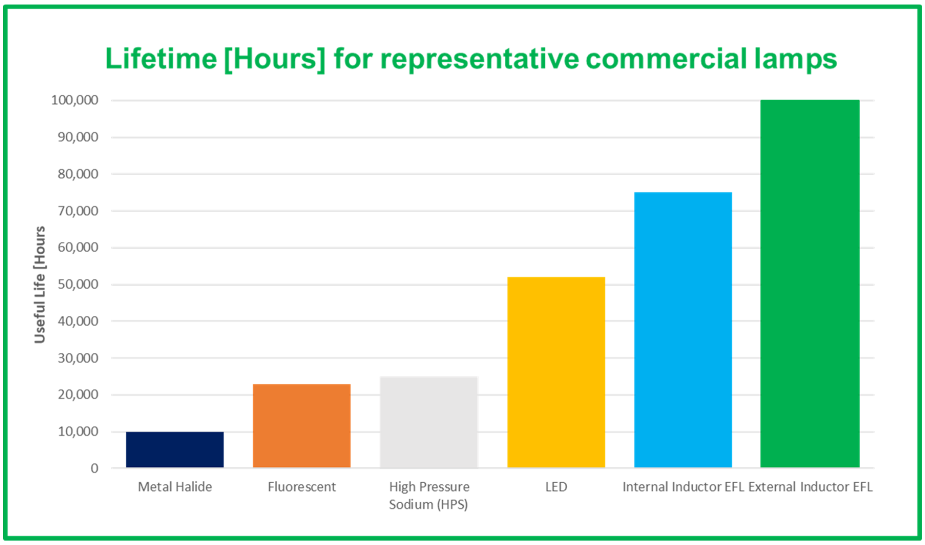

Figure 1. Lifetime, referred to lm/W compared to new lamp, below 50% for representative commercial lamps.

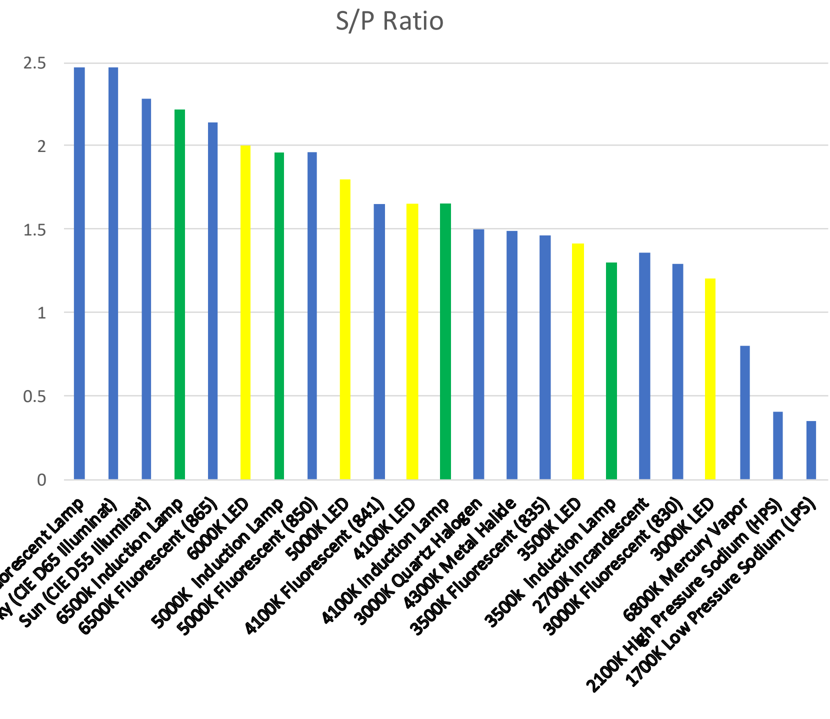

Figure 2. Scotopic/photopic ratio for various light sources. Data from [7].

EFLs are a class of discharge lamps, whose operating principle is known from Tesla's experiments [9]. EFLs, like other discharge lamps, have an incremental negative impedance behavior, making it necessary to use ballast that limits the current through them [9]. The development of power electronics has created compact ballasts for these lamps and made their use widespread. Nowadays they are found in outdoor lighting systems and inside large areas such as airport terminals, markets and industrial plants.

There are two types of EFLs: Lamps with internal excitation coil [9] and operating frequency around 2.65 MHz and those with external excitation coils and an operating frequency around 250 kHz. Resonant inverters provide suitable drive for discharge lamps [11–21]. Their high output impedance stabilizes the lamp power, even without the need to implement a control loop, maintaining high efficiency. In addition, they allow the lamp to be turned on leveraging the high gain of the unloaded resonant circuit.

Industry demands fully controlled electronic ballasts, which comply with the standard, reduce electricity consumption and extend the lamp life. An option to control the lamp power is to modify the frequency or phase of the resonant inverter; however, this can change the operating point and thereby change the performance of the converter and the temperature of the components. In addition, RI control will depend on the switching frequency and resonance [11], which in turn will depend on the aging of the lamp. Another possibility is to control the power or current [2] through the previous stage.

It is common for electronic ballasts driving medium and high-power lamps to have a PFC stage to comply with standard IEC 61000-3-2 class C for electronic lighting equipment [3]. A typical electronic ballast is shown in Figure 3. The control of the power in the lamp, P_{lamp}, can be implemented directly by measuring voltage and current in the lamp, as discussed in [4]. Usually, a boost converter is used as a PFC stage, with which a high-performance unit power factor is obtained. However, to reduce the reactive component in the RI resonant tank and to be able to control P_{lamp} with V_{dc} [5], it is necessary to use a converter such as a PFC that can increase or reduce the input voltage, e.g., a buck-boost converter.

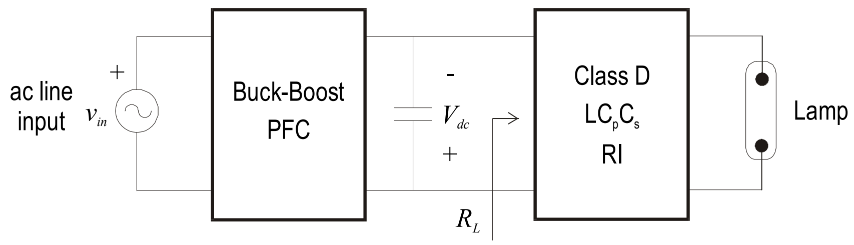

Figure 3. Two-stage electronic ballast structure.

With resonant converters, the over-voltage required to ignite EFL lamps is commonly achieved by setting the switching frequency close to the unloaded resonant frequency, where the voltage gain is the maximum [20]. However, this solution produces high voltage and current stress on the ballast devices and the lamp. An alternative, employed in this work, is the gradual approach of the switching frequency up to the resonant frequency, resulting in the so-called soft ignition, i.e., the excitation energy in the gas increases progressively, so that the ignition is achieved at lower over-voltage, reducing the stress on the components [12].

Reported techniques to dimming EFL lamps are: frequency modulation (FM) [14,17], burst-mode dimming (BMD) [13–15] and bus voltage modulation (BVM) [14,17,20]. In BMD or pulse-width-modulation (PWM) technique, the lamp driving voltage and current are periodically activated and cancelled out by turning on and off the converter. The PWM frequency for dimming purposes, although is much lower than the switching frequency, is high enough to prevent the lamp from a total turn off, so that the PWM modulation effect is the reduction of the average power and the lamp brightness. If the PWM frequency is low, this method may result in flicker perception and health issues.

In this work, a new constant power reduction (CPR) technique is proposed using the concept of power source ballast introduced in [5,6]. In contrast with PWM technique, CPR adjusts P_{lamp} reference in the PFC section with the consequent regulation of the bus voltage. This technique is, therefore, an indirect BVM that uses the lamp power, with closer relation to the lamp light level, as the control variable, avoiding voltage and current spikes that could damage the components of the ballast as well as any flicker effect.

In this paper, P_{lamp} control is achieved from the PFC stage used as a power source, while the RI stage works in open loop at constant switching frequency, behaving as a passive load together with the lamp. A practical case is presented, in which the PFC stage works in the limit between continuous and discontinuous conduction and no more sensors are necessary to implement the power mode control.

The proposed electronic ballast enables the ignition of EFL lamps. In addition, by setting the appropriate power reference according to the lighting needs, the electrical consumption can be reduced. This document is organized as follows: Section 2 describes the characteristics of the EFL lamps. Section 3 analyzes the stages that form the electronic ballast. Next the experimental results are shown in Section 4 and, finally, some conclusions are drawn.

2. Characteristics of Induction or Electrodeless Fluorescent Lamps (EFL)

EFLs are discharge lamps that do not require electrodes to ionize the internal gas of the vacuum tube, which is instead achieved by magnetic elements. They are formed by one or several electromagnetic cores that surround the discharge tube. The ballast excites an electromagnetic field so exciting the internal gas in the discharge tube, which eventually becomes conductive [12–20].

Due to the absence of the electrodes, EFL lamps have a useful life close to 100,000 h, exceeding the operating hours of other technologies, as shown in Figure 1.

There are two commercial versions of EFL lamps: the first ones are characterized by having internal excitation coils and working at frequencies above 2 MHz. Lamps of this type can be found up to 100 W. Higher power EFLs have external excitation coils [9] and their operating frequency is around 250 kHz.

This paper presents a ballast design to supply EFL lamps of this second type, which has two external excitation coils, working at 250 kHz. An image of the lamp used is shown in Figure 4. Some of the most important lamp manufacturers, such as Osram, Sylvania, Philips or General Electric, have their versions of EFL. The cost of a 150 W lamp is around 120€, while a LED array of similar power rating costs around 50€. The initial over cost is compensated by its longer lifetime.

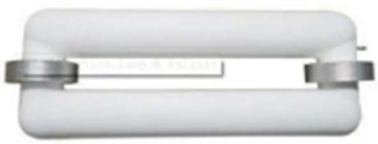

Figure 4. EFL lamp type GS-150W manufactured by Inducled.

A model of the lamp circuit is shown in Figure 5a. In the proposed design, the ballast generates a sinusoidal voltage at 250 kHz, fulfilling the manufacturer's specifications for lamp supply, which is applied across the terminals A and B.

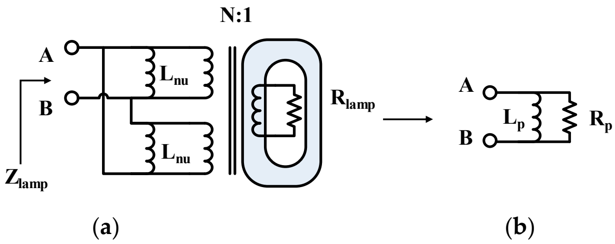

Figure 5. EFL lamp model: (**a**) complete model, and (**b**) simplified model.

A transformer is used for that model, whose primary corresponds to the excitation coils (N turns) and whose secondary represents the vacuum tube [12]. The circuit shown in Figure 5b is used for simplification's sake, including the equivalent resistance of the lamp, R_p, and the equivalent inductance of the magnetic cores, L_p, obtained from Equations (1) and (2), respectively:

$$R_p = \frac{N^2 \cdot R_{lamp}}{4} \quad (1)$$

$$L_p = \frac{L_{nu}}{2} \quad (2)$$

When the EFL lamps are off, they have an equivalent resistance close to an open circuit, it being necessary that the ballast provides a high voltage level, a peak above 1 kV [20], to achieve the ionization of the internal gas of the vacuum tube. Once the arc has been established, the EFLs reach steady state in a short time. The following section describes the proposed ballast solution and the control system used to supply the EFL lamp in its different operating modes.

3. Ballast Stages and Control

Figure 6 shows the scheme of the proposed ballast. In this case, the PFC stage is a buck-boost converter operating in critical conduction mode (CrCM) [6]. The converter is designed to operate connected to the North American and European utility lines: 85–265 Vrms, 50–60 Hz. The maximum output voltage of the PFC is limited to V_{dc} = 400 V, according to the specifications of the RI devices.

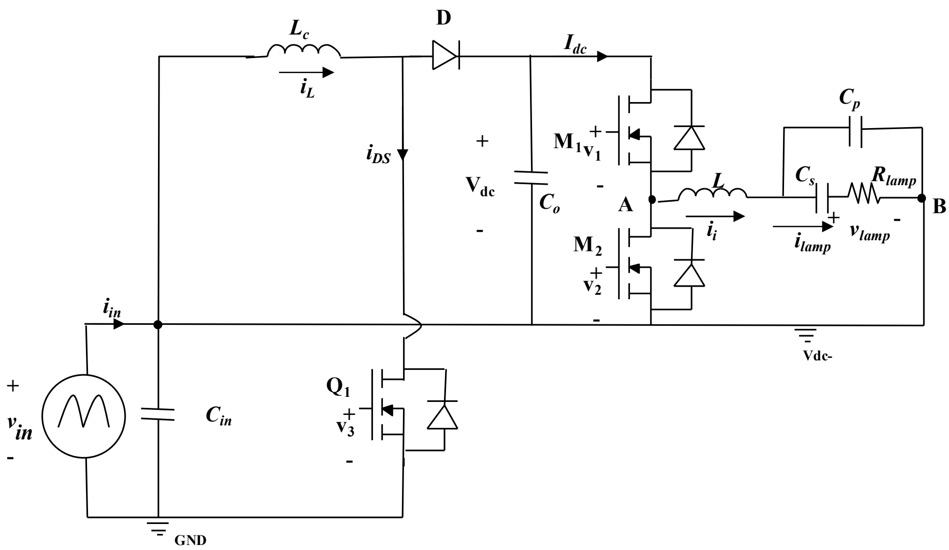

Figure 6. Scheme of the proposed ballast.

A RI Class D LC_pC_s drives the lamp. This converter is designed to achieve the following conditions: (1) operation at constant switching frequency, minimization of the reactive component in the resonant tank at the end of the lamp lifetime, and (2) the voltage variation, V_{dc} in Figure 6, will be the minimum required to keep P_{lamp} constant in steady state, considering the variation of the equivalent resistance, R_{lamp}, during its lifetime [6].

The control of the electronic ballast is carried out with a PIC18F2220 microcontroller, which selects and regulates the operating modes of the ballast. The PFC stage has two different modes of operation: (1) voltage source mode limits V_{dc} to 400 V, to ensure proper ignition and warm-up of the EFL lamp. This mode protects the components of the converter and reduces the time to reach the steady state. (2) power source mode, keeps P_{lamp} constant, allowing the user to modify P_{lamp}, and therefore the luminous flux. The microcontroller generates the control signals of the RI during its two operation modes: (1) defining a soft start-up ignition sequence during the ignition of the lamp and (2) setting a constant frequency during the lamp warm-up and in steady state. This operating frequency is determined by the lamp manufacturer, which in this case is f_s = 250 kHz. In addition, this ballast is equipped with the possibility of regulating the luminous flux [17], either by programmed times, or by external signals.

The control algorithm implemented in the microcontroller and the operation modes of the two stages are summarized in Figure 7, during the ignition and steady state, respectively. The buck-boost converter operates in the CrCM mode as a PFC, with the scheme shown in Figure 8. The microcontroller samples the output and input voltages and input current of the PFC, obtaining V_{dc}_sample, v_{in}_sample and i_{in}_sample, respectively. The measured input power value, P_{in}, is obtained from the product of the input voltage and current samples. The microcontroller selects whether V_{dc_sample} (voltage source mode) or P_{in} (power source mode) is the signal to be regulated, and therefore, compares it with the reference voltage of the controller compensator, in this case V_{ref} = 2.5 V. Thus, the error will be zero when V_{dc} = 400 V in the voltage source mode or $P_{in} = P_{ref}$ in the power source mode, where P_{ref} is the reference:

$$P_{ref} = \frac{P_{lamp}}{\eta_{bal}} \quad (3)$$

where η_{bal} is the full ballast efficiency.

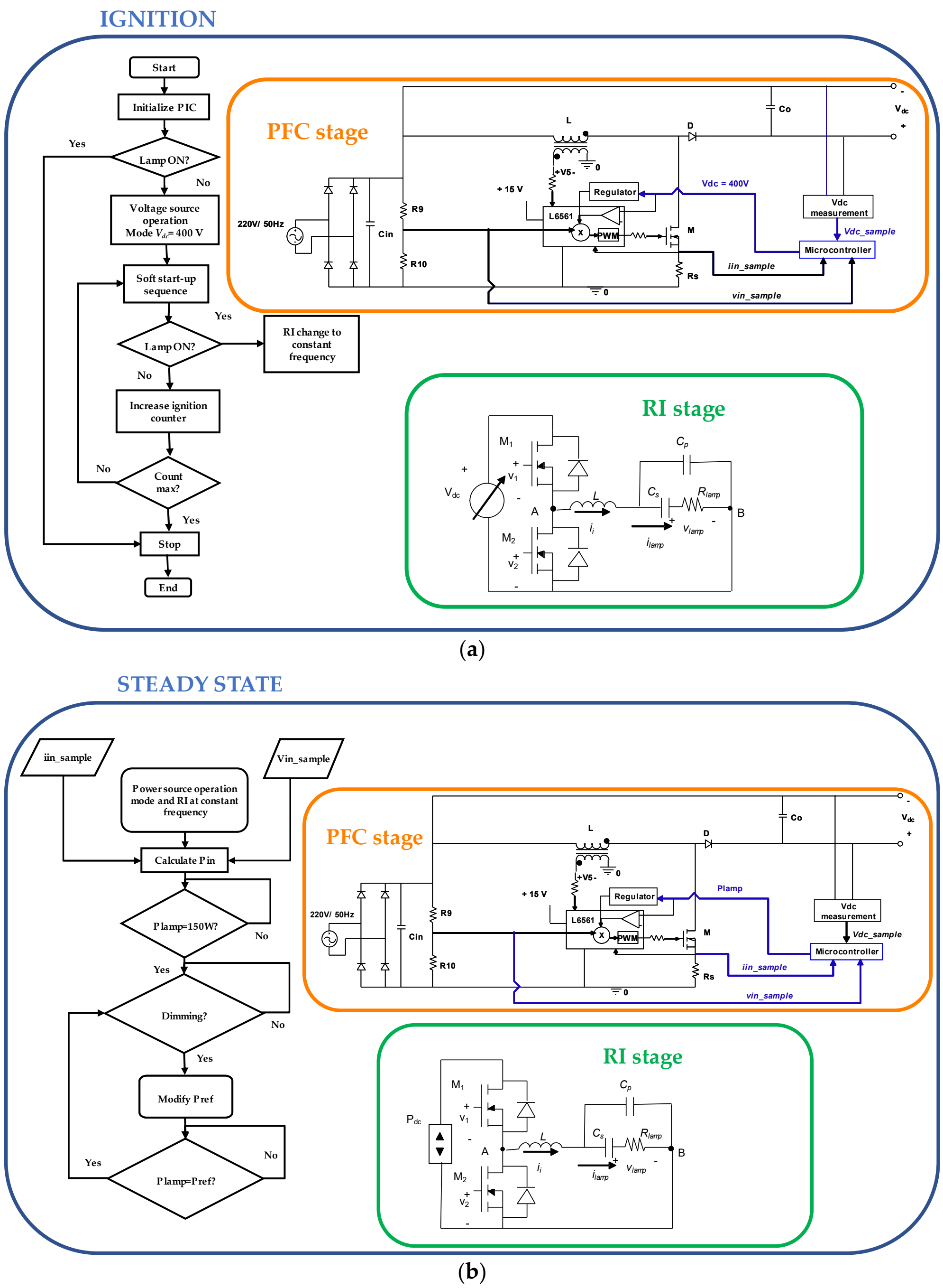

Figure 7. Management of ballast operating modes from the PIC18F2220 microcontroller: (**a**) Ignition and (**b**) during steady state.

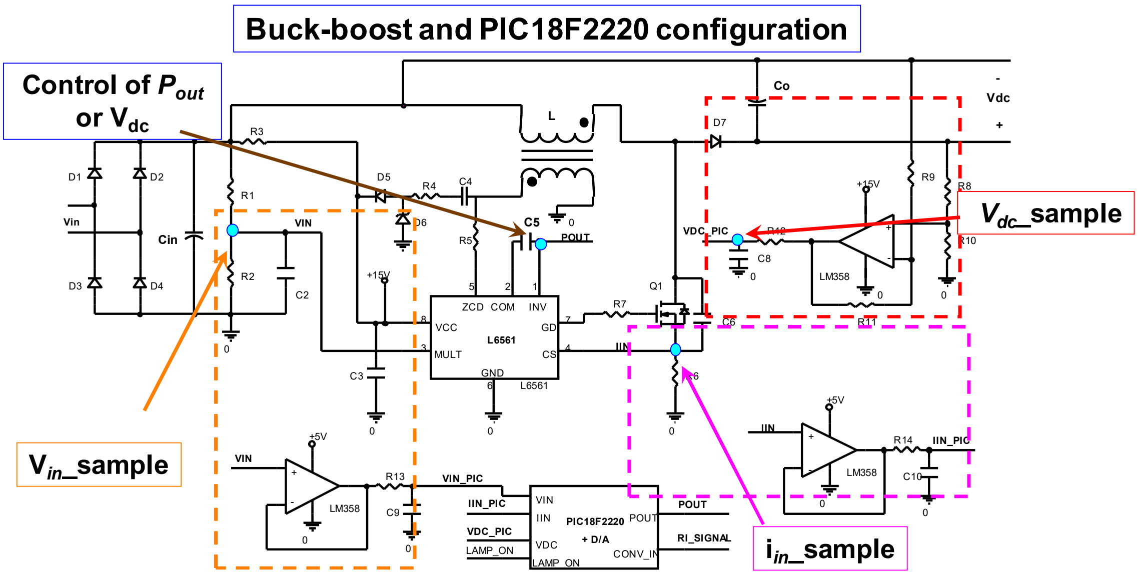

Figure 8. PFC buck-boost controlled by the microcontroller PIC18F2220.

The soft start-up ignition sequence is a frequency sweep from low gain values to a frequency with enough voltage gain for ignition, close to resonance. This method produces a gradual growth of voltage and current during the transient, constituting a safe mode of operation; achieving the lighting of the lamp with a lower level of voltage than other methods [12,20]. During the start-up and warm-up time of the lamp V_{dc} and P_{lamp} follow the curves shown in Figure 9. The PFC stage begins operating as a limited voltage source at V_{dc} = 400 V and remains in this mode until P_{lamp} = 150 W. When the power reaches this value, the ballast changes to work in power source mode. In steady state, V_{dc} is adjusted to keep P_{lamp} constant and the microcontroller modifies the value of P_{ref} for dimming.

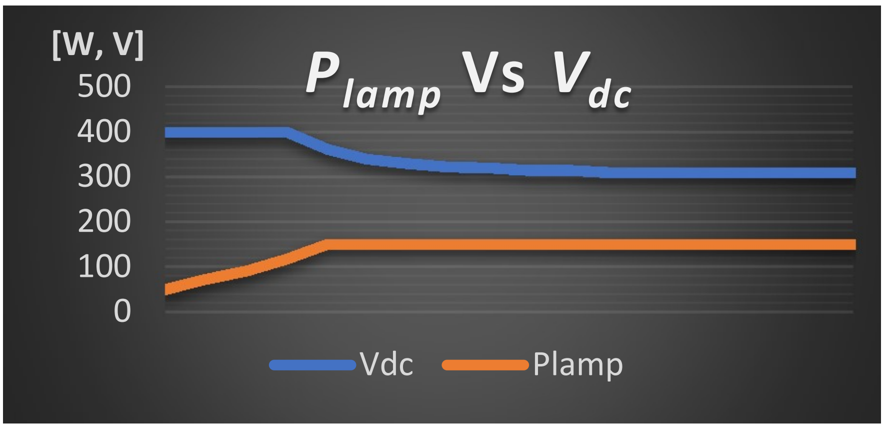

Figure 9. P_{lamp} and V_{dc} during the start-up and warm-up time of the lamp.

The control scheme of the RI is shown in Figure 10. The microcontroller generates the RI control signal, *RI_SIGNAL*, adjusting it to the operating mode. Initially, when the lamp is turned off, the microcontroller generates a soft start-up sequence until the microcontroller detects that the lamp turns on with the signal *LAMP_ON_INV* and changes the RI operation mode to constant frequency f_s = 250 kHz until the lamp reaches its nominal power, following the curves shown in Figure 9.

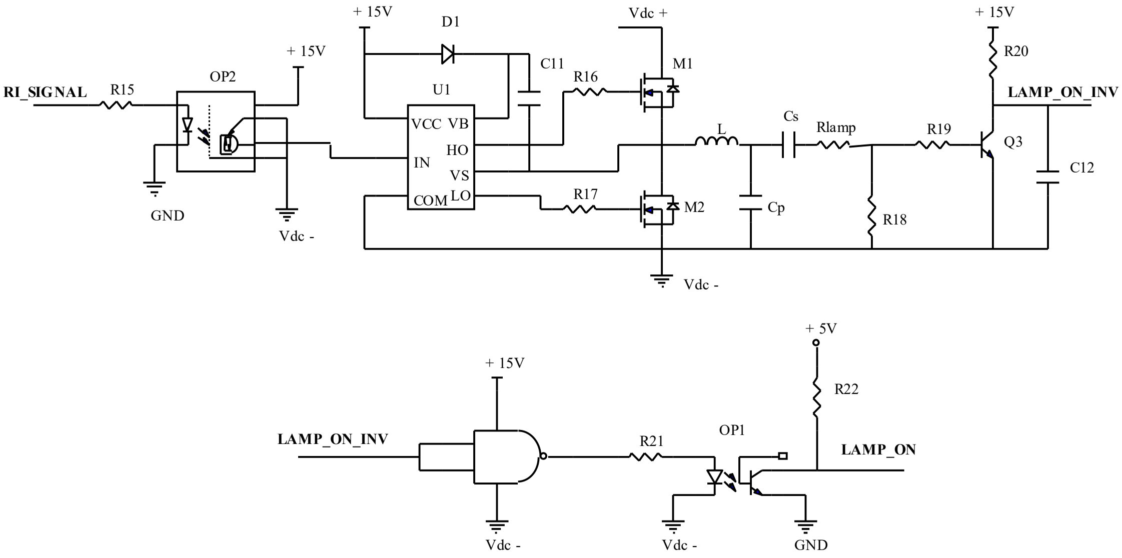

Figure 10. Management of ballast operating modes from the PIC18F2220 microcontroller.

The deviation of the resonance frequency due to the magnetization inductances of the lamp is shown in the simulation of the lighting of the lamp in Figure 11.

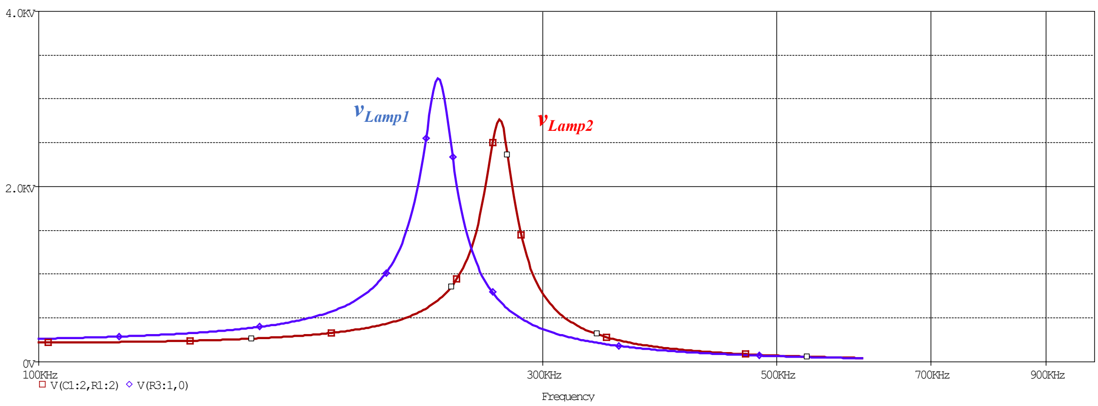

Figure 11. RI output voltage during the start-up of the EFL lamp: v_{lamp1}, considering only a resistive load and v_{lamp2}, considering the LR model (Inductance-resistance) of the lamp.

4. Experimental Results

In other gas discharge lamps, the parts with the shortest life are the electrodes, limiting lamp lifespan severely. The electrical parameters of EFLs do not vary excessively with aging, so R_{lamp} increases more slowly than in other discharge lamps [12–20].

Table 1 summarizes the electrical parameters of the external inductance EFL lamp (Inducled, Valencia, Spain) GS-150W type. This lamp, shown in Figure 4, sets a steady-state voltage, $V_{RMSlamp}$ = 180 V, at, $I_{RMSlamp}$ = 0.8 A. The value of V_{dc} for a new lamp is calculated for the RI design to achieve a constant P_{lamp} during the life of the lamp while minimizing the variation of V_{dc} [6]. The LC_pC_s resonant circuit is designed to have virtually zero current lag at the end of its useful life [5], ensuring ZVS mode; for this lamp with the switching frequency, f_s = 250 kHz, V_{dc} = 340 V, $L = Z_p/\omega_p$ = 134 µH, $C_p = 1/\omega_p Z_p$ = 3.33 nF and C_s = 33 nF, with the parallel impedance of Z_p = 300 Ω. For a new lamp, the quality factor is set to Q_{pN} = 0.8, and this design guarantees operation under these conditions during $\Delta Q_p/Q_{pN}$ = 2. Therefore, ZVS operation mode is guaranteed during the whole useful lifetime. The lamp ignites at a frequency close to $\omega_p = 2\pi$ (270 kHz). Table 2 summarizes the resonant inverter parameters.

Table 1. Electrical parameters of the EFL lamp used.

Parameter	Value
RMS Lamp voltage $V_{RMSlamp}$	180 V
RMS Lamp current $I_{RMSlamp}$	0.8 A
Lamp Power P_{lamp}	150 W
Lamp equivalent resistance R_{lamp}	230 Ω

Table 2. Resonant Inverter parameters.

Parameter	Value
Switching frequency f_s	250 kHz
Resonant parallel capacitor C_p	3.33 nF
Resonant series capacitor C_s	33 nF
Resonant inductor L	134 µH
Power switches M_1, M_2	IRF840LC

The PFC components of Figure 6 are: L_c = 1.2 mH, C_o = 68 µF, C_{in} = 1 µF. Assuming a ballast efficiency η_{bal} = 90%, the ballast input power target is P_{in} = 170 W in steady state. The PFC operates in voltage source mode, V_{dc} = 400 V, until P_{in} = P_{ref} = 170 W and then it changes to power source mode. The measured efficiency of the PFC is η_{PFC} = 94%. The main parameters of the PFC stage and ballast efficiencies are summarized in Tables 3 and 4, respectively.

Table 3. PFC stage parameters.

Parameter	Value
Inductor L_c	1.2 mH
Output capacitor C_o	68 µF
Input capacitor C_{in}	1 µF
Controller	L6561
Power switch Q_1	STW9NB90
Diode D	STTA1212

In addition, Table 5 shows the comparison of the EFL lamps ignition among the ballast in references [12,20], commercial solution of Inducled and the one proposed in this paper. Similarly, Table 6 informs of the dimming capability, where the commercial solution is not included since it does not allow dimming.

Table 4. Efficiency and ballast parameters.

Parameter	Value
RMS Input utility-line voltage V_{AC}	85–265 V
Microcontroller	PIC18F2220
PFC efficiency η_{PFC}	94%
RI efficiency η_{RI}	95%
Ballast efficiency η_{bal}	90%

Table 5. Comparison of the EFL lamps ignition: proposed ballast, commercial solution of Inducled and ballasts in [12,20].

Item	Proposed Ballast	Commercial Ballast	Ballast in [12]	Ballast in [20]
Lamp voltage v_{lamp}	<800 V	>1 kV	>800 V	>1.6 kV
Lamp current i_{lamp}	<1 A	>10 A	<1 A	>3 A
Lamp Power P_{lamp}	150 W	150 W	40 W	100 W

Table 6. Comparison of the EFL lamps dimming: proposed ballast and ballasts in [12,20].

Item	Proposed Ballast	Ballast in [12]	Ballast in [20]
Method	CPR	BMD	BV
Lamp current spikes	no	yes	yes
Lamp voltage spikes	no	yes	yes

The measurement setup is shown in Figure 12, along with the EFL lamp and the laboratory prototype.

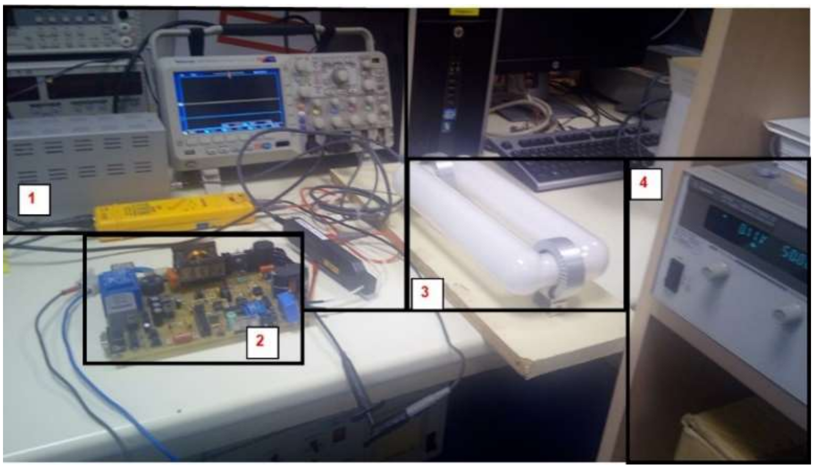

Figure 12. Measurement setup: (**1**) oscilloscope and probes, (**2**) electronic ballast prototype, (**3**) EFL lamp and (**4**) AC power source.

Figures 13 and 14 show a capture of the lamp voltage (v_{lamp}) and current (i_{lamp}) during the ignition process with the proposed design and a commercial ballast, respectively. It is verified that the lamp ignition with the proposed ballast occurs at lower voltage and current levels than in the commercial alternative and others [20]. Figure 15 shows the lamp waveforms (v_{lamp}, i_{lamp}, p_{lamp}) during the steady-state operation at nominal power, P_{lamp} = 150 W. The measured rms lamp voltage and current are 172 V and 0.875 A, respectively. Figure 16 shows the same waveforms during dimming operation until P_{lamp} = 110 W. The measured rms lamp voltage and current are 195 V and 0.616 A, respectively.

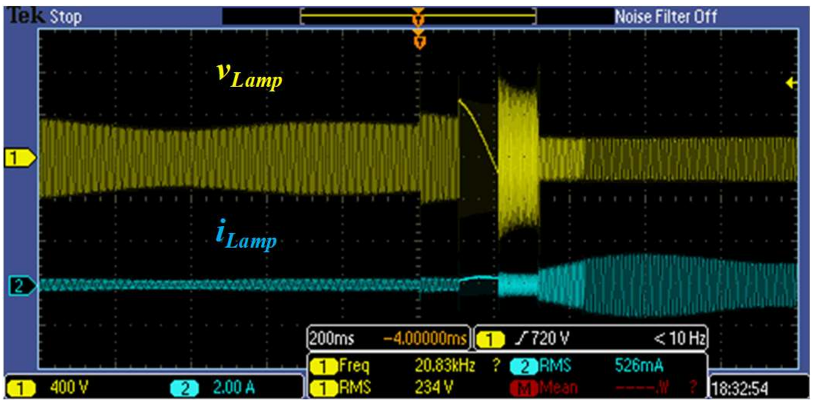

Figure 13. EFL Lamp voltage (v_{lamp}) and current (i_{lamp}) during the ignition transient.

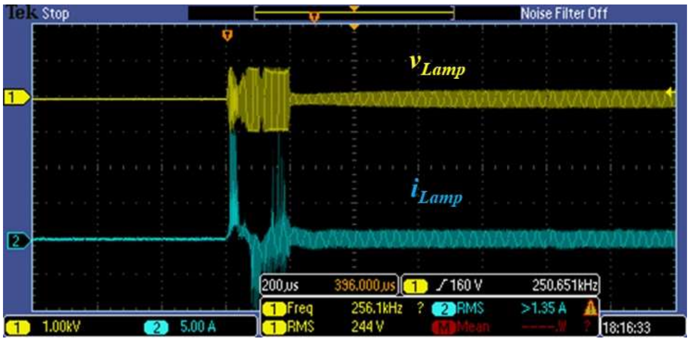

Figure 14. EFL Lamp voltage (v_{lamp}) and current (i_{lamp}) during the commercial lamp ignition transient.

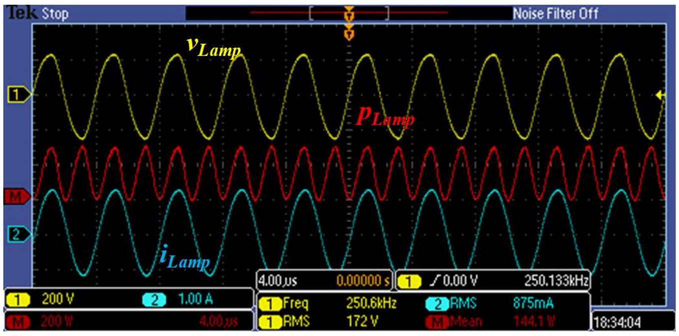

Figure 15. EFL lamp voltage (v_{lamp}), current (i_{lamp}) and power (p_{lamp}) operating in steady state.

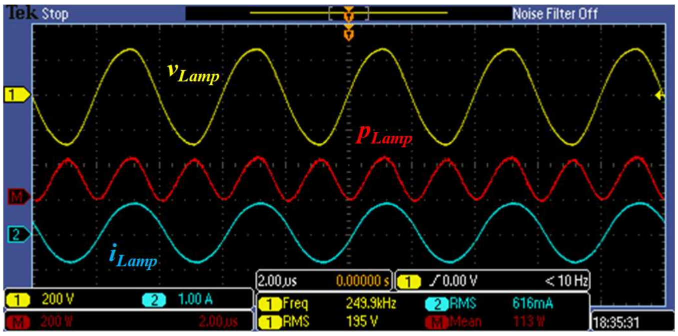

Figure 16. EFL lamp voltage (v_{lamp}), current (i_{lamp}) and power (p_{lamp}) during the dimming operation.

5. Conclusions

A two-stage electronic ballast controlled in power source mode and limited in voltage for EFL lamps has been presented. The cost of lighting using EFL lamps is clearly greater than using LEDs. However, their use is justified when robustness and performance factors such as useful life, light efficiency in terms of lm/W ratio, color reproduction and S/P ratio are an important specification. They are especially suitable in outdoor applications, where LED-based solutions may result in a negative biological impact.

The soft start-up ignition sequence is a preferable solution than other methods for EFL lamps because it reduces the voltage and current levels necessary for ignition, protecting the components of the power source and the lamp. Comparison with other reported solutions reveals that the proposal produces lower voltage and current stress.

Power mode electronic ballast with ignition and warm-up voltage limitation has proved to be a robust solution to drive EFL lamps with high efficiency and low EMI, as soft switching occurs during the whole lifetime. Power-mode with dimming capabilities prevents the aging acceleration caused by lamp overdriving, and excessive power consumption. This makes this lamp a suitable alternative to LEDs, especially in outdoor lighting.

Author Contributions: Conceptualization, F.J.D. and F.J.A.; methodology, F.J.D. and F.J.A.; validation, F.J.D.; investigation, F.J.D.; writing—original draft preparation, F.J.D.; writing—review and editing, F.J.A., R.C. and C.B.; supervision, F.J.D.; project administration, F.J.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been supported by the Spanish Ministry of Science and Innovation and the EU through the projects CICYT-FEDER-TEC2014-52316-R: "Estimation and Optimal Control for Energy Conversion with Digital Devices, ECOTRENDD" and RTI2018-095138-B-C31 PEGIA: "Power Electronics for the Grid and Industry Applications".

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IEA (International Energy Agency). Energy Efficiency Indicators Highlights 2017. Available online: https://www.iea.org/publications/freepublications/publication/energy-efficiency-indicators-highlights-2017.html (accessed on 7 October 2019).
2. Dupuis, P.; Bolsens, B.; van den Keybus, J.; Driesen, J.; Belmans, R. A versatile power source for HID lamps. In Proceedings of the 40th IAS Annual Meeting. Conference Record of the 2005 IEEE Industry Applications Conference, Hong Kong, China, 2–6 October 2005; pp. 1188–1192. [CrossRef]
3. IEC. *Limits for Harmonic Current Emissions (Equipment Input Current ≤ 16 A per Phase)*, 1st ed.; IEC 61 000-3-2; International Standard: Geneva, Switzerland, 2018. Available online: https://webstore.iec.ch/publication/28164 (accessed on 25 December 2019).
4. Cardesín, J.; Alonso, J.M.; López-Corominas, E.; Calleja, A.J.; Ribas, J.; Rico-Secades, M.; García, J. Small-Signal Analysis of a Low-Cost Power Control for LCC Series-Parallel Inverters With Resonant Current Mode Control for HID Lamps. *IEEE Trans. Power Electron.* **2005**, *20*, 1205–1212. [CrossRef]
5. Azcondo, F.J.; Brañas, C.; Casanueva, R.; Bracho, S. Power mode controlled power factor corrector for electronic ballast. *IEEE Trans. Ind. Electron.* **2005**, *52*, 56–65. [CrossRef]
6. Azcondo, F.J.; Diaz, F.J.; Branas, C.; Casanueva, R. Microcontroller Power Mode Stabilized Power Factor Correction Stage for High Intensity Discharge Lamp Electronic Ballast. *IEEE Trans. Power Electron.* **2007**, *22*, 845–853. [CrossRef]
7. Roberts, M. The Science behind Magnetic Induction Lighting. Available online: https://www.induluxtech.com/Library.html (accessed on 7 October 2019).
8. Da Silva, M.F.; Fraytag, J.; Chagas, N.B.; Schlittler, M.E.; Dallas Costa, M.A.; Pinto, R.A.; Seidel, A.R.; do Prado, R.N. Single-stage high-power-factor dimmable lighting system for electrodeless fluorescent lamp. In Proceedings of the 2011 IEEE International Symposium on Industrial Electronics, Gdansk, Poland, 27–30 June 2011; pp. 390–395. [CrossRef]
9. Da Silva, M.F.; Chagas, N.B.; Schlittler, M.E.; Fraytag, J.; Marchesan, T.B.; Bisogno, F.E.; Alonso, J.M.; Do Prado, R.N. Electric Equivalent Model for Induction Electrodeless Fluorescent Lamps. *IEEE Trans. Power Electron.* **2013**, *28*, 3603–3613. [CrossRef]
10. Tang, S.; Guo, Y.; Hao, W.; Huang, S.; Wei, K.; Wen, R.; Cai, J.; Luo, A. Lighting Illuminance Influence on Blue Light Induced Melatonin Depression. In Proceedings of the 2018 15th China International Forum on Solid State Lighting: International Forum on Wide Bandgap Semiconductors China (SSLChina: IFWS), Shenzhen, China, 23–25 October 2018; pp. 1–4. [CrossRef]
11. Vorperian, V. Approximate small-signal analysis of the series and the parallel resonant converters. *IEEE Trans. Power Electron.* **1989**, *4*, 15–24. [CrossRef]
12. Lin, C.H.; Wang, C.M.; Lee, L.C.; Ou-Yang, T. Design and implementation of electronic ballast for electrodeless fluorescent lamp with primary-side control. In Proceedings of the 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Seoul, Korea, 1–5 June 2015; pp. 2365–2368. [CrossRef]
13. Fraytag, J.; Seidel, A.R.; Alonso, J.M.; Do Prado, R.N.; Da Silva, M.F. Digital control applied to single-stage high-power-factor EFL ballast with burst-mode dimming. In Proceedings of the 2015 IEEE 24th International Symposium on Industrial Electronics (ISIE), Buzios, Brazil, 3–5 June 2015; pp. 1178–1183. [CrossRef]
14. Fraytag, J.; Schlittler, M.E.; Dalla Costa, M.A.; Seidel, A.R.; Alonso, J.M.; Do Prado, R.N.; Da Silva, M.F. A Comparative Performance Investigation of Single-Stage Dimmable Electronic Ballasts for Electrodeless Fluorescent Lamp Applications. *IEEE Trans. Power Electron.* **2015**, *30*, 2239–2252. [CrossRef]

15. Kido, H.; Makimura, S.; Masumoto, S. A study of electronic ballast for electrodeless fluorescent lamps with dimming capabilities. In Proceedings of the 36th IAS Annual Meeting, Conference Record of the 2001 IEEE Industry Applications Conference (Cat. No.01CH37248), Chicago, IL, USA, 30 September–4 October 2001; pp. 889–894. [CrossRef]
16. Ben-Yaakov, S.; Shvartsas, M.; Lester, J. A behavioral SPICE compatible model of an electrodeless fluorescent lamp. In Proceedings of the 17th APEC Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.02CH37335), Dallas, TX, USA, 10–14 March 2002; pp. 948–954. [CrossRef]
17. Jang, T.E.; Kim, H.J.; Kim, H. Dimming Control Characteristics of Electrodeless Fluorescent Lamps. *IEEE Trans. Ind. Electron.* **2009**, *56*, 93–100. [CrossRef]
18. Rodríguez-Benítez, O.M.; Ponce-Silva, M.; Aquí-Tapia, J.A.; Cortés-García, C. Resonant Half-Bridge Current-Inverter (RHBCI) used as Power Supply for Induction Lamps with High-Power-Factor and without Electrolytic Capacitors. In Proceedings of the 14th International Conference on Power Electronics (CIEP), Cholula, Mexico, 24–26 October 2018; pp. 56–61. [CrossRef]
19. Chagas, N.B.; Rosa, V.; Da Silva, M.F.; Do Prado, R.N. A study of electrodeless fluorescent lamp's cores of ferrite N87 and IP12E. In Proceedings of the 2015 IEEE Industry Applications Society Annual Meeting, Addison, TX, USA, 18–22 October 2015; pp. 1–6. [CrossRef]
20. Da Silva, M.F.; Fraytag, J.; Schlittler, M.E.; Bandeira, T.; Da Silva, M.F.; Alonso, J.M.; Do Prado, R.N. Analysis and Design of a Single-Stage High-Power-Factor Dimmable Electronic Ballast for Electrodeless Fluorescent Lamp. *IEEE Trans. Ind. Electron.* **2013**, *60*, 3081–3091. [CrossRef]
21. Miyazaki, H.; Shoji, H.; Namura, Y. High-frequency class-D converter driving with feedback capacitors for electrodeless fluorescent lamps. *IEEE Trans. Ind. Appl.* **2000**, *36*, 1033–1038. [CrossRef]