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Electronic Ballast for HPS Lamps with Intrinsic Power Regulation over Lamp Life

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ABSTRACT

This paper introduces the electronic ballast for high pressure sodium (HPS) lamps which provides power regulation during the whole lamp life without using a closed-loop power control system, in spite of large variations of lamp characteristics resulting from lamp aging. The structure of the electronic ballast and the parameters of HPS lamps are described. A mathematical model for the ballast is developed and used for the design and analysis of the ballast. A design procedure is presented to design the ballast which provides intrinsic power regulation over the whole lamp life. To improve the technical specifications of the ballast, the practical and standard constraints are considered in the design. According to the design procedure, an electronic ballast for 250-W HPS lamps is designed. All theoretical analyses are verified with the help of a semi-industrial experimental setup. The results validate that the designed ballast provides power regulation during the whole lamp life.

Keywords: Electronic ballast, High pressure sodium, Ballast design

1. Introduction

High Pressure Sodium (HPS) lamps are extensively used for public lighting systems because of their long lifetime and high illumination efficiency. To connect the HPS lamps to the main, an interfacing element is required. This element is called a ballast and it is used to limit a lamp's current due to its negative impedance characteristics [1].

Electronic ballasts have significant advantages with respect to the electromagnetic ballasts. The advantages include higher efficiency and power factor, less total harmonic distortion (THD), longer lamp lifetime and constant lamp power in the presence of source voltage variation [2]. However, the electronic ballasts have not been used extensively due to their low reliability and high price.

Lamp voltage variation due to lamp aging significantly affects lamp power. Lamp power more than the maximum standard level reduces lamp life and lamp power lower than the minimum standard level leads to undesirable luminous output [3-4]. Some of the HPS magnetic ballasts are designed such that lamp aging has a minimal effect on the power delivered to the lamp. However, variation of line voltage significantly affects lamp power in this magnetic ballast [5]. In conventional electronic ballasts, a closed-loop power controller is used to minimize the

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impact of lamp aging on the power delivered to the lamp [6-7]. This increases significantly the complexity and the cost of the electronic ballast.

This paper introduces an electronic ballast which provides intrinsic power regulation during the whole lamp life, without using a closed-loop control system. To improve the technical specifications of the proposed electronic ballast, the design is based on improving five quality indices namely: reliability, lamp lifetime, energy consumption, input current quality, and cost. For this purpose, the practical and standard constrains are considered in the ballast design.

This paper is organized as follows. The structure of the electronic ballast and the parameters of HPS lamp are described in Section 2. The mathematical model for the design and analysis is reviewed in Section 3. The design ballast is presented in Section 4. The design is validate by experimental results in Section 5. Finally, the conclusions are given in Section 6.

2. System Structure

Fig. 1 shows the conventional structure of a high-frequency electronic ballast for HPS lamps. The electronic ballast has two main stages: a power factor corrector (PFC) and an inverter. The PFC is a boost converter which not only improves the power factor but also provides a regulated dc voltage. Proper operation of the PFC improves the input current quality and eliminates the line frequency flickers [8-9]. The electronic ballast also has a class D series resonant inverter circuit located in the output stage.

The firing circuit is used for lamp ignition and has no effect on the steady-state behavior and efficiency of electronic ballast [2]. Thus, the firing circuit is not considered in ballast design and analysis. In some of the electronic ballasts the firing circuit is eliminated using the LCsCp resonant circuit [10]. The proposed design procedure can also be used for designing this kind of electronic ballast.

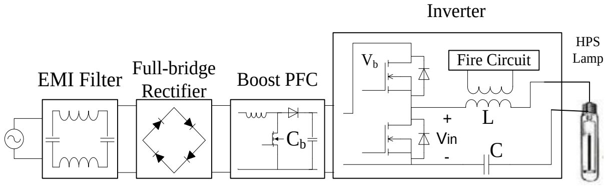

Fig. 1. Electronic ballast structure.

2.1 Lamp Parameters

Fig. 2 shows the trapezoidal diagram of a 250-W HPS lamp based on EN60662 and ANSI C78.42 standards [3-4]. The lamp power changes from minimum to maximum when lamp voltage varies from minimum (for a new lamp) to maximum (for an aged lamp). The blackening of discharge tube and sodium losses result in an increase of the lamp voltage between 2 to 4 V per 1000 h of operation [1]. For a 250-W HPS lamp, at rated power, the lamp voltage varies from 90 to 156 V when aged, Fig. 2.

The lamp voltage variation due to lamp aging significantly affects lamp power. Using a closed-loop power control in the electronic ballasts, the aging effect on lamp power can be eliminated [6-7]. This increases significantly the complexity and cost of the electronic ballast. The electronic ballast proposed in this paper provides a regulated power delivered to the lamp during the whole lamp life without using a close-loop control system.

3. Analysis Methods

The ballast design is based on the power delivered to the lamp. The lamp power is estimated from the steady-state model of the electronic ballast. Fig. 3(a) shows the steady-state equivalent circuit model of the electronic ballast inverter shown in Fig. 1. L and C are series resonant elements of the circuit in Fig. 1. The power delivered to the lamp is estimated using a frequency-domain or time-domain analysis.

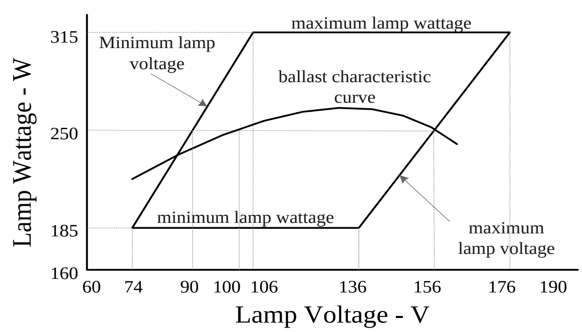

Fig. 2. Trapezoidal diagram for a 250-W HPS lamp.

3.1 Frequency-domain Analysis

Fig. 3(b) shows a steady-state waveform of the inverter input voltage and the lamp current. The inverter has two operation modes. In Mode I, the upper switch is ON and the lower switch is OFF. Thus, the input voltage to the resonant circuit is V_b. In Mode II, the upper switch is OFF and the lower switch is ON and thus, the input voltage to the resonant circuit is zero. Using a sinusoidal approximation for the lamp current, the power delivered to the lamp is [2]

$$P_{lamp} = \frac{2\,V_b^2\,R_{lamp}}{\pi^2\left[\left(L\omega_s - \frac{1}{C\omega_s}\right)^2 + R_{lamp}^2\right]} \tag{1}$$

V_b is the inverter voltage, $\omega_s = 2\pi f_s$, f_s is the switching frequency, L and C are the resonant inductor and capacitor, and R_{lamp} is the lamp resistance. Based on (1), R_{lamp}, V_b, f_s, L and C are parameters that effect the power delivered to the lamp. To design the ballast, the variation ranges of these parameters must be determined. The variation ranges will be specified in Section 4.

3.2 Time-domain Analysis

Equation (1) estimates lamp power approximately and thus is not appropriate for an accurate ballast design. The time-domain analysis provides a more accurate estimation where the lamp power is given by

$$P_{lamp} = R_{lamp}\,I_{lamp\,(rms)}^2 \tag{2}$$

$I_{lamp\,(rms)}$ is the effective value of the lamp current. It is found from the following differential equations which represent a mathematical model of the inverter [11].

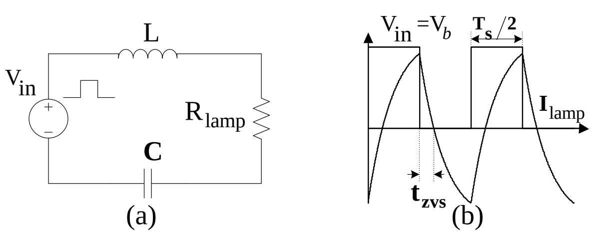

Fig. 3. (a) Steady-state model of the resonant circuit.
(b) Input voltage to the resonant circuit and lamp current.

$$\frac{d^2 v_{c1}}{dt^2} + 2\zeta\omega_r \frac{dv_{c1}}{dt} + \omega_r^2 v_{c1} = \omega_r^2 V_b \quad t \in \left[0 \quad \frac{T_s}{2}\right] \tag{3}$$

$$\frac{d^2 v_{c2}}{dt^2} + 2\zeta\omega_r \frac{dv_{c2}}{dt} + \omega_r^2 v_{c2} = 0 \qquad t \in \left[\frac{T_s}{2} \quad T_s\right] \tag{4}$$

$$i_{Lj} = C\frac{dv_{Cj}}{dx} \qquad j = 1,2 \tag{5}$$

where $\zeta = \frac{R_{lamp}}{2}\sqrt{\frac{C}{L}}$, $\omega_r = \frac{1}{\sqrt{LC}}$, v_{c1} and v_{c2} are the capacitor voltage and i_{L1} and i_{L2} are the inductor currents in Mode I and Mode II. The initial conditions for (3) and (4) are

$$v_{c1}(0) = v_{c2}(T_s) \qquad v_{c1}(T_s/2) = v_{c2}(T_s/2)$$

$$i_{L1}(0) = i_{L2}(T_s) \qquad i_{L1}(T_s/2) = i_{L2}(T_s/2)$$

4. Design Procedure

To design the ballast, the design parameters are explained and then the design algorithm is given. The ballast design method is demonstrated using the 250-W HPS lamp specifications. The selection of this lamp is due to its wide utilization.

4.1 Design parameters

The ballast design is based on lamp power. Thus, the variation ranges of lamp power and effective parameters on lamp power must be specified. To improve the technical specifications of the ballast, the practical and standard constrains are considered in the design.

4.1.1 Lamp Power

According to the standards, lamp power higher than 125% of its rated power reduces the lamp lifetime and lamp power lower than 70% of its rated value leads to undesirable luminous output [3-4]. Therefore, keeping the lamp power close to its rated value leads to a constant luminous flux and increases the lamp life.

4.1.2 Lamp Resistance

According to the trapezoidal diagram shown in Fig. 2, the minimum and maximum values of lamp voltage in rated power for 250-W HPS are 90 V and 156 V. A HPS lamp has a resistive model in high frequency [12]. Therefore, the minimum and maximum values of lamp resistance in rated power are: $R_{lamp\ (min\ )} = 32.4\ \Omega$ and $R_{lamp\ (max\ )} = 97.3\ \Omega$.

4.1.3 Inverter Input voltage

The PFC of the electronic ballast shown in Fig. 1 is a boost converter which has a higher output voltage than input voltage. When the input voltage of PFC is too close to the output voltage, the PFC does not operate properly [8-9]. According to the rated voltage of 220V and considering a 10% over voltage, the peak of maximum voltage is $1.1 \times 220\sqrt{2} = 342\ V$.

In an optimum design, $V_{b(min\ )}$ must be made as small as possible to reduce the cost. For the ballast design, $V_{b(min\ )}$ 360 V is used. For the ballast design, the value of $V_{b(max\ )}$ must be determined. As $V_{b(max\ )}$ increases, the costs and losses will be higher. For the ballast design, $V_{b(max\ )}$ 400 V is used.

4.1.4 Inverter Frequency

To avoid audible noises, the switching frequency must be higher than 25 kHz. In general, various factors such as acoustic resonance, switching losses, lamp specifications, and size of circuit elements are considered in the selection of a maximum switching frequency. The electronic ballast shown in Fig. 1 operates at zero-voltage switching at turn-on. Selecting a proper snubber capacitor, the switching losses at turn-off will be negligible. Thus, the total switching losses for the ballast of Fig. 1 are negligible and do not consider for the selection of maximum frequency. Since an increase in the switching frequency reduces the ballast weight and size, a switching frequency as high as is allowed by the lamp specifications and acoustic resonances is considered. For the ballast design, the highest switching frequency selected is 40 kHz for a 250-W HPS.

4.1.5 Resonance Inductor and Capacitor

The variation ranges of C and L are determined based on the model in Fig. 3(a). Equation (1) can also be rewritten as follows [2]:

$$\frac{\omega_s L}{R_{lamp}} = K + \frac{1}{\omega_s C R_{lamp}} \tag{6}$$

$$K = \sqrt{\frac{2\, V_b^2}{\pi^2\, R_{lamp}\, P_{lamp}} - 1} \tag{7}$$

Fig. 4 shows variations of $\omega_s L / R_{lamp}$ versus $\omega_s C R_{lamp}$ for various amounts of K. For K=0, the area below the curve specifies the operating points that do not fulfill the zero-voltage switching (ZVS) conditions at turn-on [2]. Thus, $\omega_s C R_{lamp}$ must be selected such that resonance happens far away from the area below the curve.

From Fig. 4, it is seen that the value of $\omega_s L / R_{lamp}$ decreases as $\omega_s C R_{lamp}$ increases, In other words, with a larger capacitor a smaller inductor is required. Based on a trade-off between the inductor and capacitor costs, it is found that $\omega_s C R_{lamp}$ should be selected that is more than 2. Additionally, it is realized that increasing $\omega_s C R_{lamp}$ higher than 30 has no effect on the inductance and increases the capacitance only. For the selected HPS lamp power and inverter frequency, the capacitor range is

$$\frac{2}{\omega_s R_{lamp\ (max\ )}} \le C \le \frac{30}{\omega_s R_{lamp\ (min\ )}} \tag{8}$$

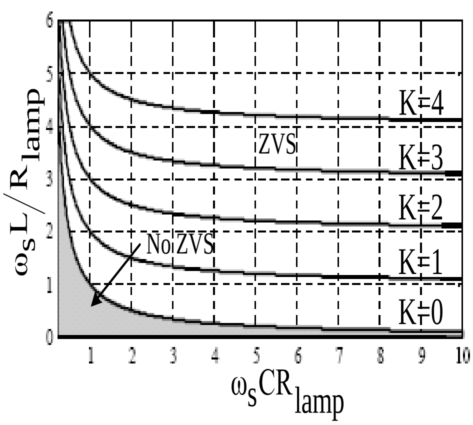

Fig. 4. Variations of $\omega_s L / R_{lamp}$ versus $\omega_s C R_{lamp}$.

From (8), when $f_s = 40\ kHz$, $R_{lamp\ (min)} = 32.4\ \Omega$ and $R_{lamp\ (max)} = 97.3\ \Omega$, then the variation range of the capacitor for a 250-W HPS electronic ballast is: $0.082 \le C \le 3.69\ \mu F$. The standard capacitors that can be used in this ballast are:

$$C \in \begin{bmatrix} 0.082 & 0.10 & 0.15 & 0.22 & 0.27 & 0.33 & 0.39 \\ 0.47 & 0.56 & 0.68 & 0.82 & 1.0 & 1.5 & 2.2 & 3.3 \end{bmatrix} \mu F \qquad (9)$$

The inductor range is specified as follows:

$$L_{min} = \frac{R_{lamp\ (min)}}{\omega_s}\left(K_{min} + \frac{1}{30}\right) \qquad (10)$$

$$L_{max} = \frac{R_{lamp\ (max)}}{\omega_s}\left(K_{max} + \frac{1}{2}\right) \qquad (11)$$

$$K_{min} = \sqrt{\frac{2\, V_{b(min)}^2}{\pi^2\, R_{lamp\ (max)} P_{lamp}} - 1}$$

$$K_{max} = \sqrt{\frac{2\, V_{b(max)}^2}{\pi^2\, R_{lamp\ (min)} P_{lamp}} - 1}$$

From (10)-(11), when $\boldsymbol{f_s = 40\ kHz}$, $\boldsymbol{R_{lamp(min)} = 32.4\ \Omega}$, $\boldsymbol{R_{lamp(max)} = 97.3\ \Omega}$, $\boldsymbol{V_{b(min)} = 360\ V}$, $\boldsymbol{V_{b(max)} = 400\ V}$, and $\boldsymbol{P_{lamp} = 250\ W}$ then the variation range of inductor for 250-W HPS electronic ballast is: $\boldsymbol{41 \le L \le 864\ \mu H}$.

4.2 Design Algorithm

Based on (1), the power delivered to the lamp is a function of:

$$P_{lamp} = f(R_{lamp}, L, V_b, C, f_s) \qquad (12)$$

The optimum values for L, C, V_b, and f_s are determined using the proposed design algorithm. Due to the lack of a power controller, these parameters are fixed at the achieved optimum values. When these parameters are fixed, the lamp power will be a function of lamp resistance, $P_{lamp} = f(R_{lamp})$. The objective of the proposed design algorithm is to determine the optimum values for L, C, V_b, and f_s so that the lamp power has minimum variation when compared with its rated power. Consequently, the aging effect on lamp power is minimized.

As mentioned before, the switching frequency is set at the maximum value. Also, a standard capacitor is selected from (9). These two selections reduce equation (12) to:

$$P_{lamp} = f(R_{lamp}, L, V_b) \qquad (13)$$

In the next step, considering the determined variation ranges and using the least square error (LSE) optimization method, the optimum values for L and V_b are determined such that the SE index shown in equation (14) is minimized. As a result, the lamp power during the whole lamp life has the least error as compared with P_n. In order to increase the accuracy, $P_{lamp}(R_i)$ is calculated by using the time domain analysis.

$$SE = \sum_{i=0}^{n} \left(P_{lamp}(R_i) - P_n\right)^2 \qquad (14)$$

where R_i is the lamp resistance and $R_0 = R_{lamp\ (min)}$ and $R_n = R_{lamp\ (max)}$. It is important to note that R_i is a parameter with a vast variation during lamp lifetime. Proper selection of R_i is very important as it can influence the selection of the optimum value. Therefore, in the following, a method is proposed for obtaining an optimum value for lamp resistance. Assuming that for every 1000 hours of operation, the lamp voltage increases by 3 volts [1], R_{lamp} after each 1000 h can be given as:

$$R_i = \frac{\left(V_{l(min)} + 3i\right)^2}{P_n} \qquad (15)$$

where $0 \le i \le (V_{l(max)} - V_{l(min)})/3$, $V_{l(min)}$ and $V_{l(max)}$ are the minimum and maximum values of lamp voltage in the rated power. According to the trapezoidal diagram shown in Fig. 2 $V_{l(min)} = 90$ and $V_{l(max)} = 156$V for the 250-W HPS lamp. In this case, the time parameter is considered in optimization and lamp power is very close to its rated value during the whole lamp lifetime.

To improve the technical specifications of the ballast, the following conditions are considered in the design algorithm.

- To increase the reliability and reduce the switching losses, the zero-voltage switching at turn-on must be guaranteed. Thus, t_{ZVS} shown in Fig. 3(a) must be higher than $1.0\ \mu S$ during the whole lamp life.
- A Crest Factor (CF) of lamp current over 1.8 for a 250-W HPS decreases the lamp lifetime significantly [3-4]. Thus, the CF of lamp current must be lower than 1.8 during the whole lamp life.

The above procedure is performed for all standard capacitors in (9). If the optimum values are not found, the frequency will be decreased one step and the design procedure will be repeated. Table 1 shows the design results.

4.2.1 Optimum Design Selection

Table 1 shows the possible design choices based on the design algorithm. The First column shows the standard capacitors which can be used for a 250-W HPS electronic ballast. The second and third columns show the corresponding optimum values of the inductor and dc voltage. Based on Table 1, a larger capacitor leads to a smaller inductor. The forth column shows the maximum current of inductor $I_{L(\max)}$, which affects the inductor cost. The fifth column shows the square root of the SE index defined in (14). A smaller $\sqrt{SE}$ results in less impact of lamp aging on the lamp power.

Table 1. Design choices for a 250-W HPS electronic ballast at $f_s = 40\ kHz$.

C (μF)	L_{opt} (μH)	$V_{b(opt)}$ (V)	$I_{L(max)}$ (A)	$\sqrt{SE}$
.082	418	381	3.8	54
0.10	384	381	3.8	54
0.15	329	379	3.9	54
0.22	295	378	4.0	54
0.27	281	377	4.0	54
0.33	272	378	4.0	54
0.39	262	376	4.1	54
0.47	257	377	4.1	53
0.56	250	376	4.1	53
0.68	246	376	4.1	53
0.82	242	376	4.1	53
1.0	237	375	4.1	53
1.5	232	375	4.1	53
2.2	229	375	4.2	53
3.3	227	375	4.2	53

Based on Table 1, $I_{L(max)}$ and $\sqrt{SE}$ are constant for all choices and do not affect the optimum design selection. With a trade-off between the costs of capacitor and inductor, $C = 1.0\ \mu F$ and $L = 237\ \mu H$ are selected. Therefore, to implement a 250-W HPS electronic ballast, the optimum values are:

$$f_s = 40\ kHz \quad C = 1.0\mu F \quad L = 237\mu H \quad V_b = 375V \tag{16}$$

4.3 Design Evaluation

This section evaluates the performances of the designed ballast for a 250-W HPS lamp based on computer simulations. Fig. 5 shows the simulation results. In the computer simulations, the specifications of the 250-W electronic ballast are based on (16), the rated power of the HPS lamp is 250-W. According to section 4.1.B, the variation range of lamp resistance for a 250-W HPS during the lamp lifetime is $32.4 \le R_{lamp} \le 97.3\ \Omega$. Fig. 6(a) shows the power delivered to the lamp versus the lamp resistance. The lamp power is regulated at about 250 W for $32.4 \le R_{lamp} \le 97.3\ \Omega$. Thus, the power delivered to the lamp is close to the rated value during the lamp lifetime. Fig. 5(b) shows the lamp current during the whole lamp life. The solid line shows the effective value of the lamp current and the dashed line shows the peak value of the lamp current. The lamp current is used to

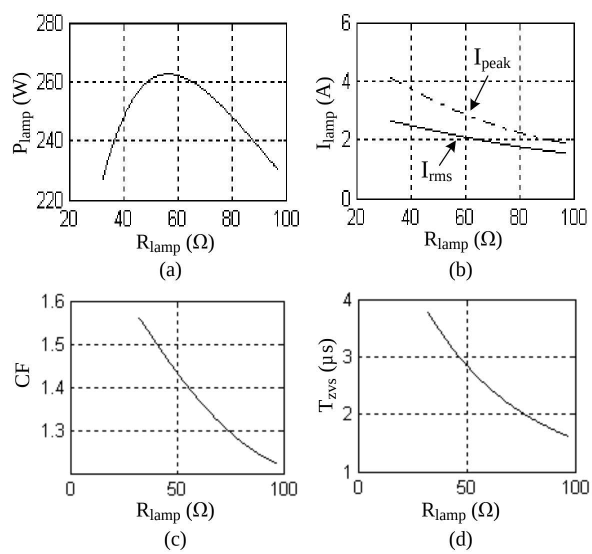

Fig. 5. Performance parameters of the designed ballast. (a) lamp power (b) lamp current (c) CF of lamp current and (d) zero-voltage switching time.

design the inductor and to select the inverter switches. Fig. 5(c) shows the lamp current CF during the lamp lifetime. The lamp current CF is always less than 1.8 which complies with standards [3-4]. Fig 6(d) shows the zero-voltage switching time (t_{ZVS}) during the whole lamp life. The zero-voltage switching time is always more than $1.0\,\mu S$ and thus, the zero-voltage switching at turn-on is guaranteed.

4.4 Design Completion

To complete the design, the inverter switches are selected. To select the inverter-switch, the currents of the inverter-switch under the normal and short-circuit conditions, shown in Table 2, must be determined. $I_{rms\,(max)}$ and $I_{peak\,(max)}$ are the maximum effective value and the maximum peak value of the inverter-switch current, respectively. $I_{SC(rms)}$ and $I_{SC(peak)}$ are the effective and the peak values of the inverter-switch current, respectively, when a short-circuit occurs at the output terminals.

Table 2. Inverter-switch currents.

Lamp current	Value
$I_{rms\,(max)}(A)$	2.6
$I_{peak\,(max)}$(A)	4.1
$I_{SC(rms)}$(A)	3.1
$I_{SC(peak)}(A)$	5.2

Considering $\boldsymbol{V_b = 375\,V}$ and the inverter-switch currents shown in Table II, the selection of IRFP450 is an appropriate choice for the switches of inverter.

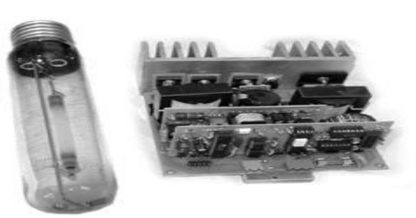

Fig. 6. Implemented semi-industrial electronic ballast.

5. Experimental Results

To examine the performance of the designed ballast, a semi-industrial ballast has been implemented to operate with a 250-W HPS lamp. Fig. 6 shows this electronic ballast. This ballast has many other capabilities, in addition to what was mentioned in this paper.

The performance of the electronic ballast when operating with three 250-W HPS lamps (OSRAM NAV-T) with different lamp aging has been experimentally tested. Fig. 7 shows performance of the designed ballast. Fig. 7(a) to Fig. 7(c) show the instantaneous voltage, power and current of Lamp I to Lamp III, respectively. From Fig. 7(a), the steady-state operating parameters of Lamp I are $V_{lamp} = 90.69\,V_{rms}$, $I_{lamp} = 2.512\,A_{rms}$, and $P_{lamp} = 225.7\,W$. From Fig. 7(b), the steady-state operating parameters of Lamp II are $V_{lamp} = 118.1\,V_{rms}$, $I_{lamp} = 2.138\,A_{rms}$, and $P_{lamp} = 250.4\,W$. From Fig. 7(c), the steady-state operating parameters of Lamp III are $V_{lamp} = 131.7\,V_{rms}$, $I_{lamp} = 1.90\,A_{rms}$, and $P_{lamp} = 248.2\,W$. From the steady-state operating parameters, the high-frequency equivalent resistances of Lamp I to Lamp III are obtained. They are 36 Ω, 55 Ω and 69 Ω respectively. Therefore, Lamp III is aged more than Lamp II and Lamp II is aged more than Lamp I.

Table 3 compares the values of power delivered to Lamp I to Lamp III which are obtained based on experiment and simulation (theory). The second column specifies the lamp that has been tested. The third column shows the high-frequency equivalent resistance obtained from the experiment. The fourth and fifth columns show the steady state lamp voltage and lamp current, respectively. The sixth column shows the power delivered to the lamp. The corresponding experimental and simulated results are close and the differences are mainly due to the inverter losses and the element tolerances that are not considered in the simulation. If a 250-W HPS lamp is aged perfectly, its resistance will be 97.3 Ω. From Fig. 5(a), the power delivered to the lamp with a high-frequency equivalent resistance of 97.3 Ω is similar to amount delivered to the new lamp (Lamp I).

Table 3. Theoretical and experimental results.

Result	Lamp	$R(\Omega)$	$V_l(V)$	$I_{lamp}(A)$	$P_{lamp}(W)$
Exp.	I	36	90.7	2.51	225.7
	II	55	118.1	2.14	250.4
	III	69	131.7	1.90	248.2
Theo.	I	36	92.6	2.57	238.2
	II	55	120.2	2.18	262.5
	III	69	133.4	1.93	257.8

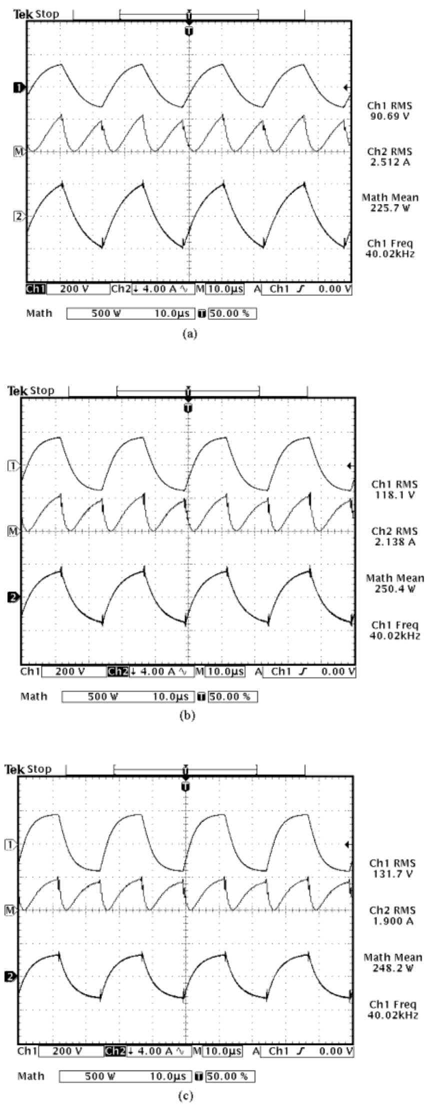

Fig. 7. Performance of the designed ballast based on experiments on (a) Lamp I (b) Lamp II (c) Lamp III (Top) lamp voltage (Bottom) lamp current (Middle) power delivered to the lamp.

6. Conclusions

This paper introduces a design procedure for a HPS electronic ballast. The designed ballast provides power regulation during the whole lifetime of the HPS lamp without using a closed-loop power controller. The ballast design is carried out based on minimum power error and the power regulation is provided intrinsically. Regulating the lamp power intrinsically, keeping the lamp power close to its rated value, and considering the practical and standard constrains in the design improve the technical specifications of the ballast. The electronic ballast for a 250-W HPS lamp was designed and implemented on the basis of the presented design procedure. The computer simulations show that the designed ballast has a desirable performance during the whole lamp life. The experimental tests of the designed ballast show that the power delivered to the lamp is close to the rated value for lamps with different lamp aging.

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