A Compact, High-Power-Factor HID Lamp Ballast

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Abstract -- This paper presents a two-stage, high-power-factor electronic ballast for high-intensity-discharging (HID) lamps. The presented ballast is composed of a boundary-conduction-mode (BCM)-operated buck-boost-flyback converter to achieve input current shaping, and a high-frequency (20kHz) combined with low-frequency (200Hz) square-wave-driven half-bridge-type inverter to supply the lamp with low-frequency square-wave sources. The features of the proposed ballast are high power factor (>0.99), low total harmonic distortion (THD) (<13%) of input utility-line current, cost-effectiveness and lack of acoustic resonance. This paper presents the operational principles and experimental results of the proposed ballast for one 70W MH-type HID lamp operating with 110V-rms input AC voltage.

Index Terms-- Electronic Ballast, High-Intensity-Discharging (HID) Lamps, Power Factor

I. INTRODUCTION

High-intensity-discharging (HID) lamps are an attractive lighting source due to high luminous efficacy (>85 lm/W), longer lifetime (>12000 hrs) and good color rendering (the color rendering index R≥85). HID lamps are popularly used in both outdoor and indoor lighting applications [1]. Acoustic resonance is a physical phenomenon that is related to pressure-wave propagation in the discharging tube of the HID lamp. HID lamps operated at high frequencies may cause acoustic resonance [2]. This phenomenon can result in an unstable arc, flickers, extinguishing, or even worse, lamp damage and sometimes lamp explosion. Generally speaking, supplying the HID lamp with a low-frequency, square-wave-operated HID lamp ballast is the most favorable method for eliminating acoustic resonance [3]-[10]. In addition, a power-factor-correction (PFC) function is now generally required for an electronic ballast to comply with regulations such as the IEC 61000-3-2 class C standards. Fig. 1 shows the commercial three-stage HID ballast circuit, which consists of a boost converter for PFC, a buck converter for regulating lamp power, and a full-bridge inverter for supplying the lamp with low-frequency square-wave sources [7]-[9]. However, the disadvantage of the three-stage configuration is its limited circuit efficiency. The previous two-stage HID lamp ballast circuit, shown in Fig. 2, is composed of a PFC AC-DC conversion stage followed by a full-bridge inverter with buck capability [10]. The full-bridge inverter with buck capability includes two power switches that operate at high frequencies to reduce the output DC-bus voltage from the PFC converter to the rated level of lamp voltage, thus regulating the lamp current/power. The inverter’s other two power switches operate at low frequencies in order to provide the square-wave sources. This approach is not cost-effective.

Therefore, this paper demonstrates a high-power-factor, compact, two-stage HID lamp ballast. This new ballast, shown in Fig. 3, consists of a boundary-conduction-mode (BCM)-operated buck-boost-flyback converter with PFC, and a high-frequency and low-frequency square-wave-driven half-bridge inverter, which works in discontinuous-conduction mode (DCM) with the buck capability.

II. ANALYSIS OF THE PROPOSED TWO-Stage HID LAMP BALLAST

The proposed two-stage electronic ballast circuit, shown in Fig. 4, consists of a buck-boost-flyback converter and a high-frequency and low-frequency square-wave-driven half-bridge inverter. The first-stage converter, designed to operate in BCM with variable frequency control as a power factor corrector, is composed of transformer T1 with two windings, power switch S3, two diodes D6 and D8, and two DC-linked capacitors Cf and Ch. The second-stage inverter with buck capability is designed to operate at DCM in order to decrease the output DC-bus voltage from the first stage to the lamp’s rated level of voltage; this attribute regulates the lamp current/power, and supplies the HID lamp with low-frequency square-wave sources. The inverter consists of two power switches S4 and S5, diodes D7 and D9, inductor Lr, capacitors Cr, Cm, Cn as well as the HID lamp and an igniter.
Magnetizing current $I_{Lm}$ linearly decreases with the downslope of $V_{Cb}/L_{m}$ and can be expressed as

$$I_{Lm}(t) = \frac{V_{Cb}}{L_m} (t_2 - t_1). \quad (5)$$

Diode currents $I_{Dh}$ and $I_{Df}$ deliver energy to capacitors $C_b$ and $C_f$ as well as to the equivalent load resistor $R_O$ during the off-time interval. This mode finishes with power switch $S_b$ turning on again at time interval $t_2$.

B. Analysis of Second-Stage Inverter

The second-stage inverter circuit diagram is illustrated in Fig. 7. Fig. 8 shows the conceptual circuit for generating the high-frequency/low-frequency square-wave gate-driving signals $V_{gs1}$ and $V_{gs2}$ by utilizing one NOT logical gate and two AND ones from a high-frequency square-wave input source $V_{high}$ and a low-frequency square-wave input source $V_{low}$. The operational modes and principal waveforms of the second-stage high-frequency/low-frequency square-wave-driven half-bridge inverter are described as follows. and as shown in Fig. 9 and Fig. 10, respectively.

Mode 1 ($t_0$–$t_1$): Power switch $S_1$ turns on at $t_0$ while switch $S_2$ remains off. The equivalent circuit of Mode 1 is shown in Fig. 5 (a). When power switch $S_1$ turns on, inductor $L_{buck}$ is charged by the DC-bus voltage, and the inductor current is linearly increased. The current under this operation mode flows through $S_1$, $L_{buck}$, $R_{Lamp}$, $C$, and $C_b$. The voltage and current across inductor $L_{buck}$ are given by:

$$V_{DS} = |V_{rec}| + V_{Cb}. \quad (4)$$

Fig. 4. The proposed two-stage electronic ballast circuit.

The input utility-line voltage $V_{ac}$ is defined as:

$$V_{ac} = V_n \sin 2\pi ft,$$  \hspace{1cm} (1)

where $V_n$ is the input peak voltage, and $f$ is the utility-line frequency. In order to simplify the analysis, the switching frequency is considered to be much higher than the line frequency. Thus, the sinusoidal input voltage can be considered constant for each switching period.

Mode 1 ($t_0$–$t_1$) - [Fig. 5(a)]: When switch $S_1$ is turned on at $t_0$, the absolute value of the average rectified voltage $|V_{rec}|$ is applied to the magnetic inductance $L_{m}$, and the magnetizing current $I_{Lm}$ linearly increases. Since the buck-boost-flyback converter is designed to operate in BCM in order to achieve high power factor, the magnetizing current’s linear increase is from zero, and can be expressed as

$$I_{Lm}(t) = \frac{|V_{rec}|}{L_m} (t_1 - t_0), \quad (2)$$

where $V_{rec}=2V_n/\pi$ is the average value of the input rectified voltage.

Diodes $D_h$ and $D_f$ are reverse-biased; therefore, no current flows through windings $N_h$ and $N_f$. Current $I_{Lm}$ increases linearly to its peak value according to the following equation:

$$I_{Lm, pk} = \frac{|V_{rec}|}{L_m} DT_s,$$ \hspace{1cm} (3)

where $D$ is the duty cycle of the switch $S_1$, and $T_s$ is the switching period. This mode finishes with switch $S_1$ turning off.

Mode 2 ($t_1$–$t_2$) - [Fig. 5(b)]: When $S_1$ is turned off at $t_1$, $D_h$ and $D_f$ are forward-biased. The identical method is used for specifying the number of primary and secondary turns, which means $N_b=N_f$ and $V_{Cs}=V_{Cf}$. Thus, the drain-to-source voltage $V_{DS}$ is given by

$$V_{DS} = |V_{rec}| + V_{Cb}. \quad (4)$$

Fig. 5. Operation modes of first-stage converter: (a) Mode 1, and (b) Mode 2.
In this interval, capacitor $C$ provides energy to the lamp.

**Mode 4 ($t_5$–$t_6$):** Power switch $S_1$ turns on at $t_5$ while switch $S_1$ remains off. The equivalent circuit of Mode 4 is shown in Fig. 5 (d). When power switch $S_2$ turns on, inductor $L_{buck}$ is charged by the DC-bus voltage, and the inductor current is linearly increased. The current under this operation mode flows through $C_f$, $R_{Lamp}$, $C$, $L_{buck}$, and $S_2$. The voltage and current across inductor $L$ are given by:

$$V_{L_{buck}} = V_{DC} - V_{C_f} - V_{Lamp},$$

and

$$\Delta i_{L_{buck}} = \frac{V_{DC} - V_{C_f} - V_{Lamp} \times DT_s}{L},$$

where $V_{C_f}$ is the voltage across capacitor $C_f$.

**Mode 5 ($t_5$–$t_6$):** Power switch $S_1$ turns off at $t_5$ while switch $S_2$ remains off. The equivalent circuit of Mode 5 is shown in Fig. 5 (e). When switch $S_1$ turns off, the inductor current continues decreasing to zero through diode $D_1$. The current flows through $R_{Lamp}$, $C$, $L_{buck}$, $D_1$, and $C_f$. The voltage and current across inductor $L$ are given by:

$$V_{L_{buck}} = (V_{Lamp} + V_{C_f}),$$

and

$$\Delta i_{L_{buck}} = \frac{-(V_{Lamp} + V_{C_f}) \times (1 - DT_s)}{L}.$$  

**Mode 6 ($t_6$–$t_7$):** The equivalent circuit of Mode 6 is shown in Fig. 5 (f). Power switches $S_1$ and $S_2$ remain off from interval $t_6$ to $t_7$, and the current flows through $R_{Lamp}$ and $C_f$. In this interval, capacitor $C$ provides energy to the lamp.

## III. EXPERIMENTAL RESULTS

A prototype ballast for a 70W HID lamp has been built and tested. The specifications of the experimental HID lamp and key components of the proposed ballast are listed in Table I and Table II, respectively. Fig. 11 and Fig. 12 show inductor current $I_{Lamp}$, its zoom-in waveform, and the DC-bus voltage from the first-stage converter. The measured gate-driving signals of the second-stage inverter’s two power switches and inductor current $I_{L_{buck}}$ are shown in Fig. 13 and Fig. 14, respectively. Fig. 15 and Fig. 16 depict the measured lamp voltage $V_{Lamp}$ and current $I_{Lamp}$ at start-up transient and steady-state periods, respectively. The rms values of lamp voltage and current at steady state are 88 V and 0.8 A, respectively. Fig. 17 presents the photo of the discharging arc inside the HID lamp. Due to the low-frequency square-wave driven ballast, no acoustic resonances occur. The measured input utility-line voltage and current are shown in Fig. 18, and Table III lists the input utility-line current harmonics measured by a power analyzer (Voltelch PM3000) and compared with the IEC 61000-3-2 Class C standards. The measured PF and THD are 0.99 and 13%, respectively. Moreover, the efficiency of the presented ballast is approximately 86%.
Fig. 7. The second-stage circuit diagram.

Fig. 8. Conceptual circuit for generating the high-frequency/low-frequency square-wave gate-driving signals $v_{gs1}$ and $v_{gs2}.$

Fig. 9. Operation modes of second-stage converter.

Fig. 10. Principal waveforms of second-stage converter.
Table I.
SPECIFICATIONS OF THE EXPERIMENTAL HID LAMP.

<table>
<thead>
<tr>
<th>Lamp Type</th>
<th>PHILIPS CDM-T 70W/830</th>
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<tbody>
<tr>
<td>Rated Lamp Voltage</td>
<td>90V</td>
</tr>
<tr>
<td>Rated Lamp Current</td>
<td>0.8A</td>
</tr>
<tr>
<td>Rated Lamp Wattage</td>
<td>70W</td>
</tr>
<tr>
<td>Ignition Voltage</td>
<td>3.5kV</td>
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Table II.
KEY COMPONENTS OF THE PRESENTED BALLAST.

<table>
<thead>
<tr>
<th>Components</th>
<th>Values</th>
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<tr>
<td>Power MOSFET $S_1, S_2$</td>
<td>IRF640 (500V/8A/0.85Ω); IRFP460(500V/20A/0.22Ω)</td>
</tr>
<tr>
<td>Capacitor $C_f, C_b, C_r$</td>
<td>47μF/450V; 680nF/630V</td>
</tr>
<tr>
<td>Diodes $D_f, D_b, D_1, D_2$</td>
<td>BYT56MV(1000V/3A); MUR1560 (600V/15A)</td>
</tr>
<tr>
<td>Magnetic Inductor $L_m, L_r$</td>
<td>0.9mH; 0.54mH</td>
</tr>
<tr>
<td>Switching Frequency of $S_1, S_2$</td>
<td>Low Frequency (200 Hz); High Frequency (20 kHz)</td>
</tr>
</tbody>
</table>

Fig. 11. Measured $I_{Lm}(t)$ and its zoom-in waveform; Time: 2ms/div.

Fig. 12. Measured DC-bus voltage $V_{DC-bus}(200V/div)$; Time: 10ms/div.

Fig. 13. Measured gate-driving signals $V_{GS1}(10V/div)$ and $V_{GS2}(10V/div)$; Time: 2ms/div.

Fig. 14. Measured $I_{Lm}(2A/div)$ and its zoom-in waveform; Time: 1ms/div.

Fig. 15. Measured $V_{Lamp}(50V/div)$ and $I_{Lamp}$ during start-up transient period (2A/div); Time: 5s/div.

Fig. 16. Measured $V_{Lamp}(100V/div)$ and $I_{Lamp}(1A/div)$ at steady-state period; Time: 2ms/div.
Fig. 17. Photo of the discharging arc inside the HID lamp.

Fig. 18. Measured $V'_{ac}$ (50V/div) and $I_{ac}$ (1A/div); Time: 5ms/div.

Table III. MEASURED INPUT UTILITY-LINE CURRENT HARMONICS COMPARED WITH IEC 61000-3-2 CLASS C STANDARDS.

<table>
<thead>
<tr>
<th>Order</th>
<th>IEC 61000-3-2 Class C Standards (%)</th>
<th>Measured (%)</th>
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<tr>
<td>2</td>
<td>2</td>
<td>0.33</td>
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<tr>
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<td>5</td>
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<tr>
<td>7</td>
<td>7</td>
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</tr>
<tr>
<td>11&lt;n&lt;39</td>
<td>3</td>
<td>1.25</td>
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IV. CONCLUSION

This paper has developed a two-stage, high-power-factor high-frequency/low-frequency square-wave-driven HID lamp ballast. Inductor $L_m$ of the first-stage converter is designed to work in boundary-conduction mode to fulfill power-factor-correction functions. The second-stage half-bridge inverter with buck capability, which works in discontinuous-conduction-mode, supplies 20kHz high-frequency combined with 200Hz low-frequency square-wave sources to the HID lamp under stable operation.

A prototype ballast circuit has been built in order to provide a 70W HID lamp with 110V-rms utility-line input voltage. The experimental results have demonstrated high power factor (>0.99), low total harmonics distortion (<13%), acoustic-resonance-free operation of the HID lamp, verifying the functionality of the proposed circuit.

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