Design and Implementation of Novel Single-Stage Charge-Pump Power Factor Correction Electronic Ballast for Metal Halide Lamp

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Abstract—This paper presents a novel single-stage charge-pump (CP) power-factor-correction (PFC) electronic ballast for the MH lamps driven with the low-frequency square-wave current to avoid the acoustic-resonance problem. In order to achieve high power factor and meet the IEC regulation, the CPPFC technique is applied to the full-bridge inverter of the conventional electronic ballast. Based on the analyses of the operational modes for the proposed electronic ballast, the design criteria of the CP components for the proposed electronic ballast are presented. A prototype circuit for 35-W MH lamp is implemented to confirm the presented design criteria.

Keywords: Charge-pump (CP), power-factor-correction (PFC), single-stage, metal halide lamp, electronic ballast.

I. INTRODUCTION

Recently, the metal halide (MH) lamp has become an attractive lighting source because of its good color rendering, compact size, and high luminous efficiency [1-3]. However, the MH lamp has the phenomenon of acoustic resonance, which causes arc fluctuation, visible flicker, and damage of arc tube [4-7]. In order to avoid the acoustic-resonance problem, driving the MH lamp with low-frequency square waveform current is an excellent solution [7].

The block diagram of the conventional two-stage electronic ballast for the MH lamp is shown in Fig. 1 [8-10]. The first stage, a boost converter, is the power factor correction (PFC) stage, which is used to achieve high power factor and provide a constant DC bus voltage to the second stage. The second stage is a full-bridge inverter, which is utilized to adjust the lamp power and drive the MH lamp with the low-frequency square wave current.

In order to simplify the conventional electronic ballasts and meet the power factor regulations, many single-stage charge-pump power factor correction (CPPFC) schemes for electronic ballasts have been studied and developed [11-15]. The voltage source (VS) CPPFC electronic ballast for fluorescent lamp and the equivalent circuit are shown in Fig. 2(a) and Fig. 2(b), respectively [15]. According to the designs for the parameters of the CP components $C_{in1}$, $C_{in2}$ and $L_X$ in [15], the input current can be shaped into sinusoidal waveform to meet the requirements of high power factor.

In this paper, the CPPFC technique is applied to the full-bridge inverter of the conventional electronic ballast for the single MH lamp. Comparing the conventional electronic ballast, the power switch and the control circuit of the PFC stage can be saved. Consequently, the developed single-stage electronic ballast has potentially cost-effective advantage.

Fig. 1. Block diagram of conventional two-stage electronic ballast for MH lamp [10].

Fig. 2. (a) VS-CPPFC converter and (b) equivalent circuit of VS-CPPFC converter [15].

II. PROPOSED ELECTRONIC BALLAST

Fig. 3 shows the proposed single-stage CPPFC electronic ballast for the MH lamps. In the CPPFC network, the CP components $L_X$, $C_{in1}$ and $C_{in2}$ are utilized to shape the line current into sinusoidal waveform to meet the requirements of IEC 61000-3-2 Class-C Standard. The resonant inductor $L_r$ of the CPPFC network is used to reduce the current stress on the switches $S_{hi}$ and $S_{h2}$ and the diodes $D_{r1}$, $D_{r2}$, $D_{y1}$, and $D_{y2}$. In addition, the resonant inductor $L_e$ is used to improve the input power factor of the electronic ballast.

The key waveforms of the proposed electronic ballast are shown in Fig. 4, where the switches $S_{hi}$ and $S_{h2}$ of the full-bridge inverter are operated with high-frequency pulse width modulation (PWM). In addition, the switches $S_{i1}$ and $S_{i2}$ of the full-bridge inverter are operated complementarily at low-frequency with 50% duty ratio. With the operations of the full-bridge inverter and rectified line voltage, the operational
modes of the electronic ballast can be divided to intervals I, II, III, and IV.

Fig. 5 shows the block diagram of the control circuit for the proposed electronic ballast. The line-voltage sensing circuit is used to detect the line voltage for the MCU. When the sensed signal $v_L(t)$ from the line-voltage sensing circuit reaches zero level, the MCU begins to provide the low-frequency clock signals $V_{g,SL1}$ and $V_{g,SL2}$ with the twice line frequency for the low-frequency half-bridge driver. Furthermore, the MCU also provides the high-frequency clock signal $V_{HF}$ to modulate the operating frequency of the PWM controller.

The current-sensing level-shifting technique [16-17] is employed to achieve the constant lamp power for the proposed electronic ballast. The duty ratio of the signal $V_{PWM}$ can be controlled with the sensed signal $v_{cs}(t)$, which is the sum of the feedback signals $v_{lv}(t)$ and $v_{ic}(t)$. Then, the signal $V_{PWM}$ from the PWM controller is fed into the high-frequency half-bridge driver to generate $V_{g,SH1}$ and $V_{g,SH2}$ by comparing with the signal $V_{g,SL2}$.

III. OPERATIONAL PRINCIPLES

The operational principals of the electronic ballast in Interval-II are analyzed in this paper. The equivalent circuit and the key waveforms of the proposed electronic ballast in Interval-II are shown in Fig. 6 and Fig. 7, respectively. Fig. 8 shows the detailed key waveforms for the duration $T_{a2}$ shown in Fig.7. Within one high-frequency switching cycle, the operational modes in Interval-II include eleven topological stages, as shown in Fig. 9. Referring to the Fig. 7, 8 and 9, the operational principles of the eleven topological stages in interval-II are described as follows.

Mode-1 [$t_0$ ~ $t_1$]: At $t=t_0$, the switch $S_{H2}$ is turned on. The DC-bus voltage $V_{bus}$ is applied to the $C_{in2}$-$R_{lamp}$-$L_1$ network. Therefore, the inductor current $i_{L1}$ increases linearly. Meanwhile, the capacitor $C_{in2}$ discharges to the resonant inductor $L_r$. When the capacitor voltage $v_{Cin2}$ decreases to the rectified line voltage $|V_{AC}|$ at $t_1$, the diode $D_X$ conducts.

Mode-2 [$t_1$ ~ $t_2$]: The CP capacitor $C_{in2}$ is discharged by the net current between the inductor currents $i_{Lr}$ and $i_X$. When the voltage $v_{Cin2}$ across the capacitor $C_{in2}$ reaches zero at $t_2$, the clamping diode $D_{C2}$ conducts.

Mode-3 [$t_2$ ~ $t_3$]: The inductor $L_X$ and the capacitor $C_{in1}$ are charged by the line input current while the voltage level $V_{Cin1}$ is lower than rectifier line voltage $|V_{AC}|$. The capacitor $C_{in1}$ is charged by the inductor current $i_X$ until the voltage $V_{Cin1}$ reaches the DC bus voltage $V_{bus}$.

Mode-4 [$t_3$ ~ $t_4$]: The diodes $D_{y1}$ and $D_{y2}$ conduct at $t_3$. The energy stored in the inductor $L_X$ is released to the bulk capacitor $C_B$. Since the value of rectified line voltage $|V_{AC}|$ is lower than the DC bus voltage $V_{bus}$, the inductor current $i_X$ decreases linearly.

Mode-5 [$t_4$ ~ $t_5$]: The body diode $D_{SH1}$ of the switch $S_{H1}$ conducts while the switch $S_{H2}$ is turned off at $t_4$. The energies stored in the inductors $L_r$ and $L_X$ transfer to the bulk capacitor $C_B$. In addition, the inductor $L_1$ discharges to the capacitor $C_0$ and the resistor $R_{lamp}$. When the inductor current $i_X$ decreases to zero, this mode ends.

Mode-6 [$t_5$ ~ $t_6$]: The energy stored in $L_X$ is released to the bulk capacitor $C_B$ until the inductor current $i_X$ reaches zero.

Mode-7 [$t_6$ ~ $t_7$]: The body diode $D_{SH2}$ of the switch $S_{H2}$ conducts while the switch $S_{H1}$ is turned off at $t_6$. The capacitors $C_{in1}$ discharges to the inductor $L_1$. The inductor current $i_{L1}$ decreases until the negative value of the inductor current $i_{L1}$ equals to the value of the inductor current $i_{L1}$. 

![Fig. 6. Equivalent circuit of proposed electronic ballast in Internal-II.](image-url)
Mode-8 [t7 ~ t8]: Since the voltage level of the capacitor C_{in1} is higher than the lamp voltage V_{lamp}, the CP capacitor C_{in1} discharges to the C_{o}-R_{lamp}-L_{r}-L_{1} network. Therefore, the voltage V_{Cin1} decreases and the inductors currents i_{L1} and i_{Lr} increase. When the voltage V_{Cin1} reaches the rectified line voltage |V_{AC}| at t8, the diode D_{X} conducts.

Mode-9 [t8 ~ t9]: The CP capacitor C_{in1} discharges to the C_{o}-R_{lamp}-L_{1}-L_{r} network. Besides, the inductor L_{X} and capacitors C_{in1}, C_{in2} are charged by the line input current while the voltage level across the capacitors C_{in1}, C_{in2} is lower than rectifier line voltage |V_{AC}|. The capacitor C_{in1} is charged by the difference current between the inductor currents i_{L1} and i_{X} until the voltage V_{Cin1} reaches zero at t9.

Mode-10 [t9 ~ t10]: The inductors L_{r} and L_{1} discharge to the resistor R_{lamp} and capacitor C_{o}. The inductor currents i_{L1} and i_{Lr} decreases linearly. The capacitor C_{in2} is charged by the inductor current i_{X} until the inductor current i_{X} reaches zero at t10.

Mode-11 [t10 ~ t11]: The inductors L_{r} and L_{1} discharge to the capacitor C_{o} and resistor R_{lamp}. When the inductor currents i_{L1} and i_{Lr} reach zero at t11, the switch S_{H2} is turned on and the next high-frequency switching cycle begins.

IV. DESIGN GUIDELINES

In order to simplify the derivation for the expression of the line current, the following assumptions are made:

- Steady-state operation and constant DC bus voltage,
- switches and diodes are ideal components,
- values of CP capacitors C_{in1} and C_{in2} are specified the same,
- resonant inductor L_{r} is neglected,
- i_{L1} during Mode-9 in Interval-Ⅱ are assumed as a constant current source.

The equivalent circuits to represent the conducting paths of the inductor current i_{X} are shown in Fig. 10. And Fig. 11 shows the key waveforms of the equivalent circuits to represent the conducting paths of the inductor current i_{X}. 

![Fig. 7. Key waveforms of proposed electronic ballast in Interval-Ⅱ.](image)

![Fig. 8. Detailed key waveforms of Fig. 7 in duration T_{a2}.](image)

![Fig. 9. Topological stages of proposed electronic ballast in Interval-Ⅱ.](image)
Mode-3 [ta0 ~ ta1]  
According to the equivalent circuit to represent the conducting path of the inductor current $i_X$ during Mode-3 illustrated in Fig. 10(a), the inductor current $i_{X}(t)$ and the capacitor voltage $v_{cin}(t)$ can be obtained, as shown in Equations (1) and (2), respectively.

\[ i_{X}(t) = \frac{\sqrt{V_{ac}}}{Z_{ac}} \sin \left[ \omega_{ac}(t-t_{a1}) \right], \]  

\[ v_{cin}(t) = V_{ac} - \left| V_{ac} \right| \cos \left[ \omega_{ac}(t-t_{a1}) \right], \]  

where

\[ Z_{ac} = \frac{1}{\sqrt{L_{X}C_{ac}}}, \]  

\[ \omega_{ac} = \frac{1}{\sqrt{L_{X}C_{ac}}}. \]

Mode-4 through Mode-5 [ta1 ~ ta2]  
According to the equivalent circuit to represent conducting path of the inductor current $i_X$ during Mode-4 and Mode-5, as shown in Fig. 10(b), the inductor current $i_{X}(t)$ can be obtained, as shown in Equation (3).

\[ i_{X}(t) = \frac{V_{ac}}{Z_{ac}} \frac{1}{2} \left( \left| V_{ac} \right| - \left| V_{ac} \right| \cos \left[ \omega_{ac}(t-t_{a1}) \right] \right). \]  

Mode-9 [ta3 ~ ta4]  
According to the equivalent circuit to represent the conducting path of the inductor current $i_X$ in Mode-9, as shown in Fig. 10(c), the inductor current $i_{X}(t)$ and the capacitor voltages $v_{cin1}$, $v_{cin2}$ can be obtained, as shown in Equations (4), (5), and (6), respectively.

\[ i_{X}(t) = i_{X}(t_{a3}) \cos \left[ \omega_{ac}(t-t_{a3}) \right] \frac{1}{2} \left( \left| V_{ac} \right| - \left| V_{ac} \right| \sin \left[ \omega_{ac}(t-t_{a3}) \right] \right), \]  

\[ v_{cin1}(t) = v_{cin1}(t_{a3}) \sin \left[ \omega_{ac}(t-t_{a3}) \right] \frac{1}{2} \left( \left| V_{ac} \right| + \left| V_{ac} \right| \cos \left[ \omega_{ac}(t-t_{a3}) \right] \right), \]  

\[ v_{cin2}(t) = \frac{1}{2} \left( \left| V_{ac} \right| - \left| V_{ac} \right| \cos \left[ \omega_{ac}(t-t_{a3}) \right] \right). \]  

Mode-10 [ta4 ~ ta5]  
According to the equivalent circuit to conducting path of the inductor current $i_X$ in Mode-10, as shown in Fig. 10(d), the inductor current $i_{X}(t)$ can be obtained, as shown in Equation (7).

\[ i_{X}(t) - i_{X}(t_{a3}) \cos \left[ \omega_{ac}(t-t_{a3}) \right] \frac{1}{2} \left( \left| V_{ac} \right| - \left| V_{ac} \right| \sin \left[ \omega_{ac}(t-t_{a3}) \right] \right) \]  

\[ \frac{\sqrt{V_{ac}}}{Z_{ac}} \sin \left[ \omega_{ac}(t-t_{a3}) \right] \frac{1}{2} \left( \left| V_{ac} \right| + \left| V_{ac} \right| \cos \left[ \omega_{ac}(t-t_{a3}) \right] \right), \]  

where $i_{X}(t)$ and $v_{cin2}(t_{a3})$ are the initial values of the inductor current $i_X$ and the capacitor voltage $v_{cin2}$ at $t_{a3}$, respectively.

\[ i_{X}(t) = \frac{1}{T_{HF}} \int_{t_{a3}}^{t_{a4}} \left[ i_{X}(t) + \frac{1}{2} \int_{t_{a3}}^{t_{a4}} i_{X}(t) \, dt \right] \, dt. \]  

By substituting Equations (1), (3), (4), and (7) into Equation (8), the average line current equation in Interval- II can be rewritten, as shown in Equation (9).

\[ i_{avg} = \frac{1}{T_{HF}} \left[ K_{1} \cdot V_{ac} \cdot K_{2} + K_{3} + K_{4} \right], \]  

where $K_{1} = C_{ac} \cdot (2 - \cos(\omega_{ac}T_{a1}) - \cos(\omega_{ac}T_{a1})), \quad K_{2} = C_{ac} \cdot V_{ac} \cdot \left(2 - \cos(\omega_{ac}T_{a1}) \right), \quad K_{3} = i_{X}(t_{a4}) \sin(\omega_{ac}T_{a1}) \frac{1}{2} \left( \left| V_{ac} \right| - \left| V_{ac} \right| \cos(\omega_{ac}T_{a1}) \right), \quad T_{a1} = t_{a4} - t_{a1}, \quad T_{a1} = t_{a4} - t_{a1}.$
Based on the energy conservation between the input power and output power, Equation (10) can be obtained as follows:

\[
\eta = \frac{P_{in}}{P_{out}} = \frac{V_{in}I_{in}}{V_{out}I_{out}}
\]

where

- \( P_{in} \) is the lamp power,
- \( \eta \) is the conversion efficiency,
- \( V_{in, pk} \) is the peak value of the line voltage, and
- \( I_{in, pk} \) is the peak value of the line current.

Based on Equation (9) and Equation (10), the expression of the CP capacitor \( C_{in1} \) can be derived, as shown in Equation (11).

\[
C_{in1} = \left( 1.23 \times 10^{-1} \cdot K_4 + 111K_4 \right) \cdot \left( 2.3 \times 10^{-1} \cdot K_4 + 6.57 \times 10^{-1} \cdot K_4 + 4 \times 10^{-1} \cdot K_4 \right)
\]

\[
+ 3.28 \times 10^{-1} \cdot K_4 - 2 \times 10^{-1} \cdot K_4 \cdot \frac{500(V_{in, pk} - V_{in})}{\left[ K_4 - 500K_4 \right] V_{in, pk} \cdot \eta}
\]

where

- \( K_4 = \frac{V_{in, pk} \cdot \eta \cdot L_{c, 1}(t_1)(V_{in, pk} - V_{in})}{V_{in, pk}} \),
- \( K_4 = T_{r} \cdot P_{in} \cdot L_{c, 1}(t_1)(V_{in, pk} - V_{in}) \),
- \( K_4 = T_{r} \cdot P_{in} \cdot V_{in} \), and
- \( K_4 = 821 \cdot L_{c, 1}(t_1)(V_{in, pk} - V_{in}) \).

At \( t = \frac{x}{2} \cdot \omega \), Equation (1) can be rewritten as Equation (12) in order to calculate the inductor peak current \( i_{L, pk} \).

\[
i_{L, pk} = \frac{C_{in1} \cdot V_{in, pk}}{L_{c, 1}}
\]

Combining Equations (11) and (12), the expression of the inductance \( L_{c, 1} \) can be derived, as shown in Equation (13).

\[
L_{c, 1} = \frac{\eta \cdot C_{in1} \cdot V_{in, pk}}{4 \cdot P_{in} \cdot K_4}
\]

where

- \( K_4 = \frac{i_{L, pk}}{i_{in, pk}} \).

The specifications for the proposed electronic ballast are listed in Table 1. Plotted from Equation (11), Fig. 12 shows the relationship between the values of the CP capacitors \( C_{in1} \) and \( C_{in2} \) and the DC-bus voltage \( V_{bus} \) with different values of inductor \( L_{c, 1} \). Fig. 12 shows that the DC-bus voltage \( V_{bus} \) increases as the values of the CP capacitors \( C_{in1} \) and \( C_{in2} \) increase.

Plotted from Equation (13), Fig. 13 shows the relationship between the value of inductor \( L_{c, 1} \) versus value of CP capacitors \( C_{in1} \) and \( C_{in2} \) with different value for factor \( K_4 \). According to Fig. 13, the value of inductor \( L_{c, 1} \) increases as the values of the CP capacitors \( C_{in1} \) and \( C_{in2} \) increase.

By applying \( \eta = 0.8 \), \( V_{bus} = 380 \text{V} \), \( K_4 = 5 \), \( i_{L, pk}(t_1) = 0.796 \text{A} \), and the specifications in Table 1 to Equations (11) and (13), the value of the inductor \( L_{c, 1} \) and the value of the inductor \( L_{c, 2} \) can be calculated as \( 4.37 \text{mF} \) and \( 312 \text{μH} \), respectively.

<table>
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<tr>
<th>Specifications</th>
<th>Values</th>
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<tr>
<td>Input AC Voltage ( V_{AC} )</td>
<td>200 \text{Vrms} to 242 \text{Vrms} at 60Hz</td>
</tr>
<tr>
<td>Rated Lamp Voltage ( V_{Lamp} )</td>
<td>88\text{Vrms}</td>
</tr>
<tr>
<td>Rated Lamp Current ( I_{Lamp} )</td>
<td>398\text{mA}</td>
</tr>
<tr>
<td>Rated Lamp Power ( P_{Lamp} )</td>
<td>35\text{W}</td>
</tr>
<tr>
<td>Operating Frequency of LF Leg ( f_L )</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Switching Frequency of HF Leg ( f_H )</td>
<td>50 kHz</td>
</tr>
</tbody>
</table>

**Fig. 12.** Relationship between value of the CP capacitors \( C_{in1}, C_{in2} \) and DC-bus voltage.

**Fig. 13.** Relationship between value of inductor \( L_{c, 1} \) versus value of CP capacitors \( C_{in1}, C_{in2} \) with different factor \( K_4 \).

**V. EXPERIMENTAL RESULTS**

Based on the specifications and the parameters, listed in Tables 1 and 2, respectively, a prototype circuit for 35W MH lamp is implemented to validate the presented design criteria.

Fig. 14 shows the measured waveforms of the input voltage and the input current at 220 \text{Vrms} input voltage. Fig. 15 illustrates the comparison between the measured input current harmonic and the IEC 61000-3-2 Class-C Standard. The measured PF and THD are 0.976 and 16.3%, respectively.

In Fig. 16, the lamp voltage and current waveforms at steady-state are 88.7 \text{Vrms} and 409 mA, respectively. Fig. 17 shows the photo of the shaking-free arc in the MH lamp.
measured efficiency is between 74.4% and 78.9% when the input AC voltage $V_{AC}$ ranges from 200Vrms to 242Vrms. Table 2. Parameters of prototype circuit.

<table>
<thead>
<tr>
<th>Components</th>
<th>Description</th>
<th>Components</th>
<th>Description</th>
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<tbody>
<tr>
<td>$S_{11}, S_{22}$</td>
<td>K2843/600V</td>
<td>$C_{a1}, C_{a2}$</td>
<td>4.4nF</td>
</tr>
<tr>
<td>$S_{m1,m2}$</td>
<td>25K202/5000V</td>
<td>$C_{b}$</td>
<td>47nF</td>
</tr>
<tr>
<td>$L_{x}$</td>
<td>55 μH</td>
<td>$D_{s1}, D_{s2}, D_{r}$</td>
<td>MUR 160/600V</td>
</tr>
<tr>
<td>$L_{r}$</td>
<td>1.2 mH</td>
<td>$D_{r1}, D_{r2}$</td>
<td>MUR 260/600V</td>
</tr>
</tbody>
</table>

Fig. 14. Measured waveforms of input voltage and input current at 220 V$_{rms}$ AC input voltage.

Fig. 15. Measured input current harmonics and IEC 61000-3-2 Class-C Standard.

Fig. 16. Measured waveforms of lamp voltage and lamp current.

Fig. 17. Photo of MH lamp arc.

VI. CONCLUSIONS

A novel single-stage CPPFC electronic ballast for the MH lamp has presented in this paper. Based on the operational principles of the proposed electronic ballast, the design equations for the CP components $L_{x}, C_{in1}$ and $C_{in2}$ have been presented to calculate the parameters of the proposed electronic ballast. A prototype circuit for 35W MH lamp has been designed and implemented. The input current harmonics meet the IEC 61000-3-2 Class-C Standard. The PF is 0.976 and the THD is 16.3%, respectively.

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