A Single-stage LED Driver with Voltage Doubler Rectifier

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ABSTRACT

In this paper, a configuration of a single-stage AC-DC converter and a high voltage resonant controller IC L6598 for LED street light driver is discussed. The converter is obtained by integrating two boost circuits and a half-bridge LLC resonant circuit. A voltage double rectifier circuit is adopted as output to lower the voltage stress on transformer and the associated core. The two boost circuits work in boundary conduction mode (BCM) to achieve the power factor correction (PFC). The converter works in soft-switching mode allowing the power switches to operate in zero-voltage-switching (ZVS) and the output diodes to operate in zero-current-switching (ZCS). This reduces the switching losses and enhances the efficiency. The converter features lower voltage stress on the power switches and the bus voltage is reduced to slightly higher than the peak input voltage. Therefore, the converter can perform well under high-input-voltage. Here, the DC bus and the output filter capacitances are greatly reduced. So, electrolytic capacitor-less converter can be realized for a long lifetime LED driver. Simulation results from PSpice are presented for a 100-W prototype.

Keywords: LED driver, boost circuit, LLC, power factor correction, street lighting, voltage doubler

INTRODUCTION

Recently, light-emitting diode (LED) has become popular for street lighting due to its energy savings capacity and low maintenance costs. Switching from incandescent lights to LEDs can also help reduce greenhouse gas emissions from power plants in addition to providing better light quality and eliminating mercury waste disposal (“Energy Efficient,” 2013).

An appropriate converter that can support a wide range of universal input ac voltages is desirable. Therefore, AC-DC conversion stage is a compulsory to drive the system powered from ac source. Switching converter is usually chosen due to its economical driving solutions, but the conventional AC-
DC switching converters have poor performances in PF and harmonic distortion. In order to achieve input current shaping, an additional PFC stage is added in front of the converters. In spite of its good performance, these two-stage converters are usually expensive, bigger in size and energy inefficient compared to the single-stage converters. To simplify the circuit and improve the reliability of the system, single-stage AC-DC converters were proposed (Gacio et al., 2011; Lin et al., 2006; Lu et al., 2008). PFC circuit and the DC-DC converter were integrated into one stage by sharing one or more switches. However, the integrated switch was subjected to high voltage stress and operated in hard switching which decreases the circuit efficiency.

A single-stage LLC resonant converter has the advantage of soft-switching characteristics and can achieve high efficiency. However, the single-stage PFC converters based on half-bridge resonant structure (Chen et al., 2012; Kang et al., 2002; Lai & Shyu, 2007) continued to maintain a high bus voltage twice the input peak voltage. On the contrary, the converter in Seok & Kwon, 2001 demonstrated a lower bus voltage, and less voltage stress on the switching devices. Wang et al. (2010) proposed a single-stage LED driver which comprises an interleaving boost circuit and half-bridge LLC resonant circuit. The two boost circuits work in DCM to obtain PFC function. With proper switching frequency, the primary-side switches operate in ZVS and the secondary-side diodes operate in ZCS. Cheng and Yen (2011) implemented the same topology and reduced one capacitor at the input side. Later, Wang et al. (2015) improved the topology by replacing the two boost inductors with a single inductor that was shared by the two boost circuits. Both boost circuits worked in BCM. However, the driver is more complex and larger in terms of its size since it uses pulse transformer for the driving circuit.

In this paper, the configuration of a single-stage LED driver proposed in Wang et al., 2015 and a resonant controller ICL658 is used to design a 100-W prototype for application under 240-V AC input. Since the voltage divider capacitors can fulfill the same role, the driver eliminated the DC input filter capacitor after the input bridge rectifier. By employing the output-voltage doubler rectifier on the secondary side, a higher voltage conversion ratio is obtained with a lower turn ratio transformer. The reduced turn ratio increases the overall efficiency. The transformer size also can be decreased. Here, the output voltage is shared by two output filter capacitors. So, a smaller capacitance with lower voltage rating capacitor can be used. Since, the DC bus and the output filter capacitance are incredibly downsized; film type capacitor can be utilized. Hence, a longer life span for the LED driver can be achieved.

Structure of the proposed circuit

Figure 1 shows the proposed configuration of LED driver with a resonant controller and a control circuit. The driver consists of a full-bridge rectifier, two voltage divider capacitors $C_1$ and $C_2$, two boost diodes $D_1$ and $D_2$, a boost inductor $L_b$, two power switches $S_1$ and $S_2$, a bus voltage capacitor $C_{bus}$, a resonant capacitor $C_r$, a transformer with resonant inductor $L_r$ and magnetizing inductor $L_m$, two output diodes $D_{r1}$ and $D_{r2}$, two output capacitors $C_{r1}$ and $C_{r2}$ and LED street light module. Here, $C_{S1}$ and $C_{S2}$ are the parasitic capacitors, while $D_{S1}$ and $D_{S2}$ are the parasitic diodes of switches $S_1$ and $S_2$. Two boost circuits are obtained by integrating the switches of half-bridge LLC resonant circuit. $C_{bus}$, $D_{r1}$, $L_r$, $S_1$, and $D_{S2}$ constitute one boost circuit, whereas $C_{bus}$, $D_{r2}$, $L_m$, $S_2$, and $D_{S1}$ constitute another boost circuit. $C_{bus}$ and $L_b$ are shared by the two boost
circuits. A high voltage resonant controller IC manufactured by ST Microelectronics, L6598 would be used to drive the two switches alternately with a certain dead time and switching duty cycle nearly 0.5. The dead time provided between the conduction of the high-side switch and low-side switch will allows the switches to turn on with ZVS. The auxiliary voltage $V_{aux}$ supply a constant voltage to the resonant controller for driving the switches.

**Principle of the operation**

This driver has ten operational modes in a single switching period. The steady state operating waveforms of the driver are demonstrated in Figure 2. In the following, the descriptions for the operational modes are elaborated.

**Mode 1 ($t_0 - t_1$):** At time $t_0$, switch $S_2$ is already turned off. Resonant current $i_r$ flows in opposite direction through switch $S_1$ to discharges parasitic capacitor $C_{S1}$. Hence, drain-source voltage $V_{DS1}$ decreases to zero and parasitic diode $D_{S1}$ is turned on. During this time, boost inductor $L_b$ discharges energy via $D_{S1}$, $C_{bus}$, $D_2$, and $C_2$. On the secondary side, diode $D_{r1}$ is turned on and current $i_{Dr1}$ increases. So, the voltage across magnetizing inductor $L_m$ is clamped by output voltage. Resonant inductor $L_r$ and resonant capacitor $C_r$ form a resonant tank. Afterward, gate signal $V_{GS1}$ arrives to turn on $S_1$ in ZVS. At the end of this mode, $i_r$ becomes zero.

**Mode 2 ($t_1 - t_2$):** Within this time interval, resonant current $i_r$ flows in positive direction and increases with sinusoidal shape.

**Mode 3 ($t_2 - t_3$):** At time $t_2$, parasitic diode $D_{S1}$ is turned off. Resonant current $i_r$ flows through $C_{bus}$ and $S_1$. Magnetizing current $i_m$ continues to decrease linearly. At the end of this mode, boost inductor $L_b$ is completely discharged until current $i_{Lb}$ becomes zero.

![Figure 1. The proposed configuration of LED driver with a resonant controller and a control circuit](image-url)
Mode 4 ($t_3 - t_4$): At time $t_3$, $C_1$ charges $L_b$ via $D_1$ and $S_1$. Magnetizing current $i_m$ becomes zero, then changes its flow to positive direction and continues to increase linearly to the maximum value. Resonant current $i_r$ also increases until reaching the peak value then decreases until the value is equal to $i_m$. The difference current between $i_r$ and $i_m$ flows through the primary winding of the transformer and power is supplied to the load. Here, diode current $i_{Dr1}$ increases to the peak value and then decreases to zero.

Mode 5 ($t_4 - t_5$): At time $t_4$, diode $D_{r1}$ is turned off in ZCS. The secondary side circuit is separated from the primary side circuit. So, the voltage across $L_m$ is no longer clamped by output voltage. Hence, $L_m$ involves in the resonant tank with $L_r$ and $C_r$. At this time, $i_r$ and $i_m$ are equal. The current continues to flow through $C_{bus}$ and $S_1$. At the end of this mode, switch $S_1$ is turned off. Parasitic capacitor $C_{SI}$ is charged and drain-source voltage $V_{DS1}$ increases to bus voltage. Boost inductor $L_b$ is fully charged and $i_{Lb}$ reaches peak value.

Mode 6 ($t_5 - t_6$): At time $t_5$, resonant current $i_r$ flows through switch $S_2$ and discharges parasitic capacitor $C_{S2}$. Hence, drain-source voltage $V_{DS2}$ decreases to zero and parasitic diode $D_{S2}$ is turned on. During this time, boost inductor $L_b$ discharges energy via $C_1$, $D_1$, $C_{bus}$, and $D_{S2}$. On the secondary side, diode $D_{r2}$ is turned on and current $i_{Dr2}$ increases. So, the voltage across $L_m$ is clamped by output voltage. Resonant inductor $L_r$ and resonant capacitor $C_r$ form a resonant tank. Afterward, gate signal $V_{GS2}$ arrives to turn on $S_2$ in ZVS. At the end of this mode, $i_r$ decreases to zero.

Figure 2. The steady state operating waveforms of the driver.
Mode 7 ($t_6 - t_7$): During this mode, resonant current $i_r$ flows in negative direction and increases with sinusoidal shape.

Mode 8 ($t_7 - t_8$): At time $t_7$, parasitic diode $D_{S2}$ is turned off. Resonant current $i_r$ flows through $S_2$. Magnetizing current $i_m$ continues to decrease linearly. At the end of this mode, boost inductor $L_b$ is completely discharged until current $i_{Lb}$ becomes zero.

Mode 9 ($t_8 - t_9$): At time $t_8$, $C_2$ charges $L_b$ via $S_2$ and $D_2$. Magnetizing current $i_m$ becomes zero, then changes its flow to negative direction and continues to increase linearly to the maximum value. Resonant current $i_r$ also increases until reaching the peak value then decreases until the value is equal to $i_m$. The difference current between $i_r$ and $i_m$ flows through the primary winding of the transformer and power is supplied to the load. Here, diode current $i_{D2}$ increases to the peak value and then decreases to zero.

Mode 10 ($t_9 - t_{10}$): At time $t_9$, diode $D_{r2}$ is turned off in ZCS. The secondary side circuit is separated from the primary side circuit. So, the voltage of $L_m$ is no longer clamped by output voltage. Hence, $L_m$ involves in the resonant tank with $L_r$ and $C_r$. At this time, $i_r$ and $i_m$ is equal. The current continues to flow through switch $S_2$. At the end of this mode, switch $S_2$ is turned off. Parasitic capacitor $C_{S2}$ is charged and drain-source voltage $V_{DS2}$ increases to bus voltage. Boost inductor $L_b$ is fully charged and $i_{Lb}$ reaches peak value.

From the waveforms, the boost inductor current $i_{Lb}$ is naturally in BCM state. The two boost circuits charge and discharge the energy to boost inductor $L_b$ alternately in one switching period.

The switch is turned on when the drain-source voltage is zero. During this time, the parasitic diode carries reverse current before the switch conducts forward current. Hence, there are no turn on switching losses exist in the switches. Furthermore, when the switch is turned off, the parasitic capacitor will be charged and the drain-source voltage increases. At the same time, the parasitic capacitor of the opposite switch will be discharged and the energy stored is returned to the dc source. Here, capacitive loss is eliminated. This help to erase the turn off switching losses. Thus, the switches operate alternately with ZVS.

On the secondary side, output diodes are turned off with ZCS. Then, the secondary side is separated from the primary side and the output filter capacitors will supply energy to the LEDs.

**Design consideration**

A prototype of an LED driver is designed for application under 240-V AC input. Here, the LED street light module consists of six strings with two LEDs per string. The LED has steady state rated performance of 26.5V/320mA. The switching frequency $f_s$ of LLC resonant circuit must satisfy the range $f_m < f_s < f_r$ for the switches to work in ZVS and the secondary side diodes to work in ZCS. Here, the switching frequency is set to $0.9 f_r$. A large value of $L_m$ is used to obtain a lower bus voltage in variation of the load. The utilized components for the driver are shown in detail in Table 1.
Simulation result

In this paper, a 100-W prototype with 53V output for an LED street light module is simulated using PSpice. Figure 3 shows the waveforms of the input voltage $v_{in}$ and input current $i_{in}$. The input current is in phase with the input voltage, so the PFC function is obtained. The sinusoidal waveform without shape distortion portray that the current consist of fundamental component, so a low current THD can be estimated.

![Figure 3. The waveforms of the input voltage $v_{in}$ and input current $i_{in}$](image)

Table 1
Component list

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Divider Capacitor</td>
<td>$C_1, C_2$</td>
<td>330nF</td>
</tr>
<tr>
<td>Boost Inductor</td>
<td>$L_b$</td>
<td>200uH</td>
</tr>
<tr>
<td>Resonant Capacitor</td>
<td>$C_r$</td>
<td>10nF</td>
</tr>
<tr>
<td>Leakage Inductor</td>
<td>$L_r$</td>
<td>110uH</td>
</tr>
<tr>
<td>Magnetizing Inductor</td>
<td>$L_m$</td>
<td>990uH</td>
</tr>
<tr>
<td>Bus Capacitor</td>
<td>$C_{bus}$</td>
<td>90uF</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>$C_{r1, r2}$</td>
<td>47uF</td>
</tr>
</tbody>
</table>

Figure 4 shows the waveforms of $V_{DS1}$, $V_{GS1}$ and $I_{DS1}$. The switch gate voltage $V_{GS1}$ comes after the switch drain-source voltage $V_{DS1}$ turned to zero. During this time, the switch conducts reverse current. This is demonstrating that the switches work in ZVS mode. Figure 5 shows the waveforms of the switch drain-source voltage $V_{DS1}$ and diode current $i_{Dr1}$. The diode current slowly decreases to zero and there is a short time it to keep it at zero value, which shows that the secondary side diodes turn off in ZCS mode.
Figure 4. The waveforms of the switch drain-source voltage $V_{DS1}$, switch gate voltage $V_{GS1}$ and switch current $I_{DS1}$.

Figure 5. The waveforms of the switch drain-source voltage $V_{DS1}$ and output diode current $i_{Dr1}$.

Figure 6 shows the waveforms of $V_{DS1}$, $i_r$, $i_{Dr1}$ and $i_{La}$ in 100-W full-load stage. The resonant current $i_r$ has a step shape and the diode current $i_{Dr1}$ works in ZCS. The switching frequency is 141 kHz.

Figure 7 shows the waveforms of output voltage $V_o$ and output current $I_o$. The voltage is 53 V, and the current is 1.9 A, hence, the output power is approximately 100 W. The voltage ripple is lower than 1 V, while the current ripple is lower than 100 mA, which is an acceptable value to drive the LEDs without flicker.
CONCLUSION

A 100-W single-stage LED driver based on two boost circuits and a half-bridge type LLC resonant circuit is simulated under 240-V AC input. The boost circuits share a single inductor that operate in BCM to obtain the PFC. Input voltage is divided by two capacitors, so the voltage stress of the switches is reduced by half and the driver is suitable for high-input-voltage condition. The value of the magnetizing inductor is selected to be high so that the bus voltage is low in variation of the power. Both switches work with soft-switching characteristics in order to achieve a high conversion efficiency. Simulation results showed that the bus voltage was about 400V, which is higher than the input peak voltage. Here, ideal elements were selected, thus, the switches or components losses were not considered throughout the simulation.
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REFERENCES


