energies

MDPI

Article

A Single-Stage High Power Factor Power Supply for Providing an LED Street-Light Lamp Featuring Soft-Switching and Bluetooth Wireless Dimming Capability

Chun-An Cheng *, **Hung-Liang Cheng**, **Chien-Hsuan Chang**, **En-Chih Chang**, **Wei-Shiang Hung**, **Chin-Chih Lai** and **Long-Fu Lan**

Department of Electrical Engineering, I-Shou University, Kaohsiung City 84001, Taiwan; hlcheng@isu.edu.tw (H.-L.C.); chchang@isu.edu.tw (C.-H.C.); enchihchang@isu.edu.tw (E.-C.C.); isu10601014m@cloud.isu.edu.tw (W.-S.H.); isu10501001m@cloud.isu.edu.tw (C.-C.L.); isu10601018a@cloud.isu.edu.tw (L.-F.L.)

* Correspondence: cacheng@isu.edu.tw; Tel.: +886-7-657-7711 (ext. 6619)

Abstract: Light-emitting diode (LED) has the characteristics of environmental protection and energy saving, having become the lighting source of a new generation of street-light lamps. The traditional two-stage power supply for providing an LED street-light lamp is composed of an AC-DC converter with a power-factor-correction (PFC) function at the front stage and a DC-DC converter at the rear stage. The two-stage power supply for an LED street-light lamp has a large number of electronic components and costs, and the circuit efficiency is not high. Therefore, this paper presents a novel single-stage high power factor AC-DC power supply for providing an LED street-light lamp featuring soft-switching and Bluetooth wireless dimming capability through using smart tablets or smartphones to remote control the output power of the LED street-light lamp for achieving energy-saving benefits. The proposed AC-DC LED power supply integrates an interleaved buck converter circuit with coupled inductors and a half-bridge LLC resonant converter circuit into a single-stage power conversion circuit. Moreover, the coupled inductor of the interleaved buck converter circuit is designed to operate in the discontinuous conduction mode, which can naturally achieve PFC. In addition, the two power switches in the novel LED power supply have zero-voltage switching (ZVS) characteristics, which can reduce the switching losses of the power switches. The two output diodes have the characteristics of zero-current switching (ZCS), which can reduce the conduction losses of the power diodes. This paper developed a single-stage prototype circuit for providing an 144 W (36 V/4 A)-rated LED street-light lamp. According to the experimental results of the prototype circuit with an AC input voltage of 110 volts, the presented single-stage LED power supply offers high power factor (PF > 0.99), low input-current total harmonic distortion factor (THD < 3%), and high efficiency (>89%). In addition, this paper used the built-in Bluetooth wireless communication function of a smart tablet or smart phone to fulfill remote dimming control. By changing the duty ratio of the control signal, we could realize remote dimming control of 20% to 100% of the output LED street-light lamp power.

Keywords: Bluetooth; converter; light-emitting diode (LED); power factor correction (PFC); power supply; street-light; wireless dimming

Citation: Cheng, C.-A.; Cheng, H.-L.; Chang, C.-H.; Chang, E.-C.; Hung, W.-S.; Lai, C.-C.; Lan, L.-F. A Single-Stage High Power Factor Power Supply for Providing an LED Street-Light Lamp Featuring Soft-Switching and Bluetooth Wireless Dimming Capability. *Energies* **2021**, *14*, 477. https://doi.org/10.3390/en14020477

Received: 7 December 2020
Accepted: 14 January 2021
Published: 18 January 2021

1. Introduction

The street-light lamps widely installed on roads, streets, parks, squares, public places, and decorative outdoor lighting areas have the function of providing night lighting, being are usually lit at night or in the dark and extinguished in the early morning. The traditional street lighting source is a high-pressure mercury lamp featuring low installation cost. However, it has the disadvantages of poor luminous efficiency and high energy consumption, as well as the problems of mercury pollution and being difficult to start up in low-temperature circumstances. In recent years, high-pressure mercury lamps have been replaced by light-emitting diode (LED) street-lights with their attractive characteristics of environmental protection and energy-saving [1,2]. For instance, comparing an LED street-light lamp with a high-pressure mercury one under approximately the same output luminous flux, the LED version has a 50% lower power consumption (120 W vs. 250 W), a 50% higher lighting efficacy (110 lm/W vs. 52 lm/W), and a longer average lifetime (50,000 h vs. 24,000 h) [3,4]. Generally, the power supply circuit of LED street-light lamps uses AC mains as the input power. The first stage is an AC-DC power converter with power factor correction (PFC) function and the second stage is a DC-DC power converter to provide the rated DC voltage and current required by the LED street-light lamp [5–8]. The traditional two-stage AC-DC high power factor power supply (HPFPS) for providing an LED street-light lamp includes an AC-DC boost converter as the first-stage circuit featuring PFC and a DC-DC half-bridge LLC resonant (HB-LLCR) converter as the second-stage circuit to supply the LED street-light lamp with rated power. Figure 1 shows the two-stage AC-DC power supply for providing an LED street-light lamp that consists of a boost converter with PFC and a HB-LLRC converter [8]. In their respective studies, [9–18] developed and implemented the integration of the first-stage AC-DC converter and the second-stage DC-DC converter into a single-stage LED power supply, which is characterized by improved circuit efficiency and reduction in the number of circuit components. An existing single-stage HPFPS for furnishing an LED street-light lamp merging with an interleaved boost converter and a HB-LLC converter was developed in [18], as depicted in Figure 2. The AC-DC power supplies as shown in Figures 1 and 2 for providing an LED street-light lamp are based on boost-type power conversion in the front-part circuit, and the voltage stresses of the DC-link capacitor and power switches are high.

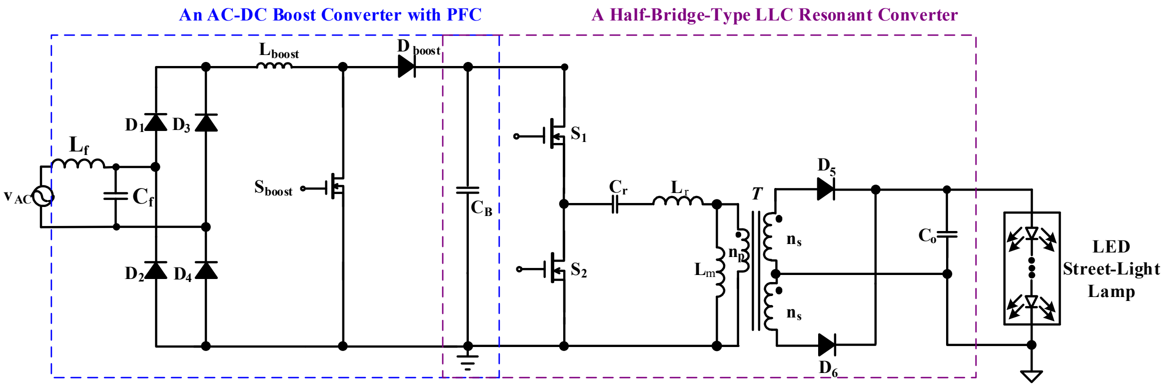


Figure 1. Traditional two-stage AC-DC power supply for providing a light-emitting diode (LED) street-light lamp [8].

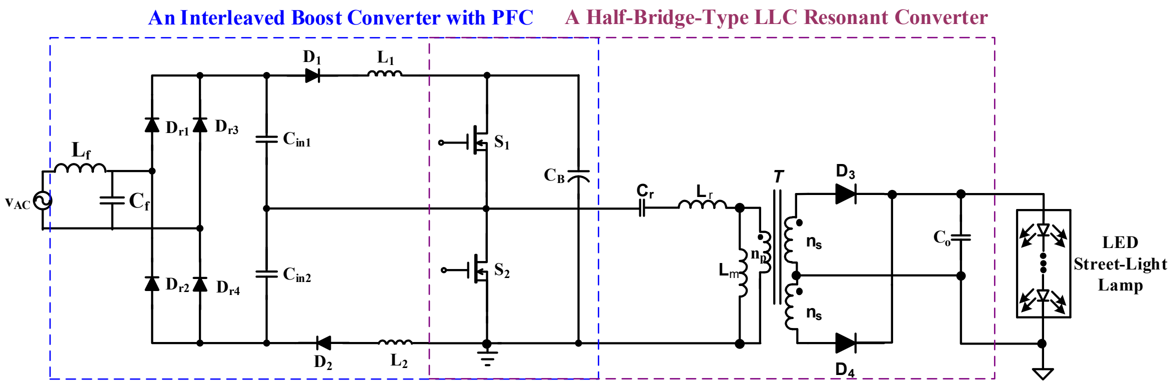


Figure 2. An existing single-stage AC-DC power supply with power factor correction (PFC) for providing an LED street-light lamp [18].

In order to lower voltage stresses of the DC-link capacitor as well as the power switches, this paper presents a single-stage AC-DC HPFPS based on buck-type power conversion in the front-part circuit for providing an LED street-light lamp. In addition, the following will illustrate an energy-saving design example for outdoor lighting applications that can be applied to provide dimming control of the power supply for LED street-light lamps [19]. During the period from six to twelve o'clock in the evening, let the LED street-light power supply produce 100% of the rated power to provide sufficient night lighting for the general public and passersby. After twelve o'clock in the morning, the output power of the LED street-light lamp can be reduced to 80% of the rated value. After two o'clock in the morning, the output power of the LED street-light lamp can be decreased to 60% of the rated value. After four o'clock in the morning, the demand for night lighting gradually decreases, and thus the output power of the LED street-light lamp can be reduced to 40% or 20% of the rated value. The power supply for the LED street-light lamp can be turned off during the period from six in the morning to six in the evening. The LED street-light power supply with dimming capability is suitable to adjust the output power in the above scheme in order to achieve the effect of energy saving and power saving [15,20,21]. Therefore, this paper developed a Bluetooth wireless dimming capability using a smart device (tablet or mobile phone) to carry out remote dimming control of the output power of the LED street-light lamp.

2. Description and Circuit Analysis of the Proposed Single-Stage Power Supply for Providing an LED Street-Light Lamp

This paper proposes a single-stage AC-DC HPFPS based on buck-type power conversion in the front-part circuit, as shown in Figure 3, for providing an LED street-light lamp; it integrates an AC-DC interleaved buck converter with PFC (including an inductor (L_f), a capacitor (C_f), a full-bridge rectifier (D_{r1}, D_{r2}, D_{r3}, and D_{r4}), two coupled inductors (L_{B1} and L_{B2}; L_{B3} and L_{B4}), four diodes (D_{B1}, D_{B2}, D_{B3}, and D_{B4}), two switches (S_1 and S_2) as well as a DC-link capacitor (C_{DC}), a DC-DC HB-LLCR converter (including switches (S_1 and S_2a), a DC-link capacitor (C_{DC}), a resonant inductor (L_r), a resonant capacitor (C_r), a center-tapped transformer (T) along with a magnetizing inductor (L_m) and two output windings, two output diodes (D_1 nd D_2), an output capacitor (C_o), and the LED street-light lamp) into single-stage AC-DC power conversion circuit [22].

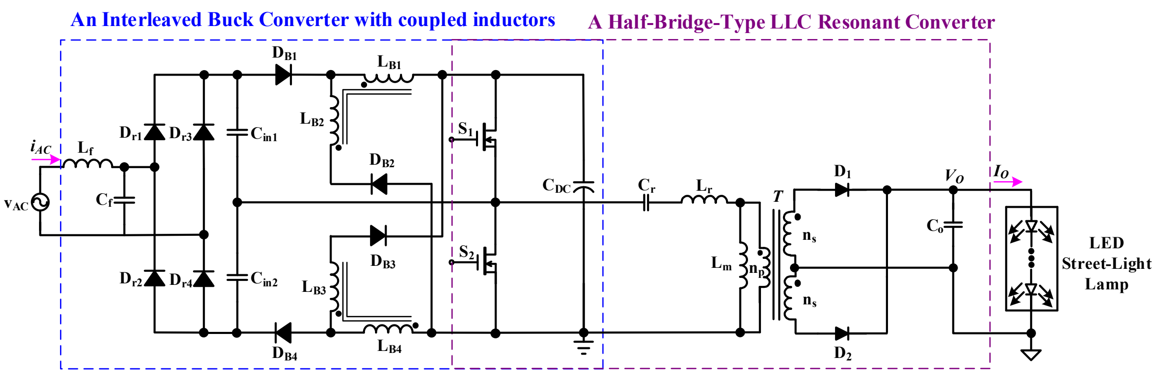


Figure 3. The proposed single-stage AC-DC power supply with PFC for providing an LED street-lighting lamp [22].

In order to facilitate the descriptions of the operation modes in the proposed LED power supply, we made the following assumptions during circuit analysis.

- The input AC mains voltage can be regarded as a fixed level in each high-frequency switching cycle, because its switching frequency is much greater than that one of the utility line.
- The rectified equivalent voltage sources V_{REC1} and V_{REC2} are respectively expressed as the voltage on capacitors C_{in1} and C_{in2} after the AC mains voltage is passed through the inductor L_f, the capacitor C_f, and the full-bridge rectifier.

- The power switches S_1 and S_2 work complementarily, taking into account their essential diodes and parasitic capacitors.
- The forward-biased voltage drops and equivalent resistors of diodes (D_1, D_2, D_{o1}, D_{o2}, D_{o3}, and D_{o4}) are ignored.
- The equivalent series resistors of all capacitors are neglected.
- Two coupled inductors (L_{B1} and L_{B2}; L_{B3} and L_{B4}) are arranged to work in discontinuous conduction mode (DCM).

Figure 4 displays the equivalent circuit diagram of the proposed single-stage AC-DC power supply for providing an LED street-light lamp.

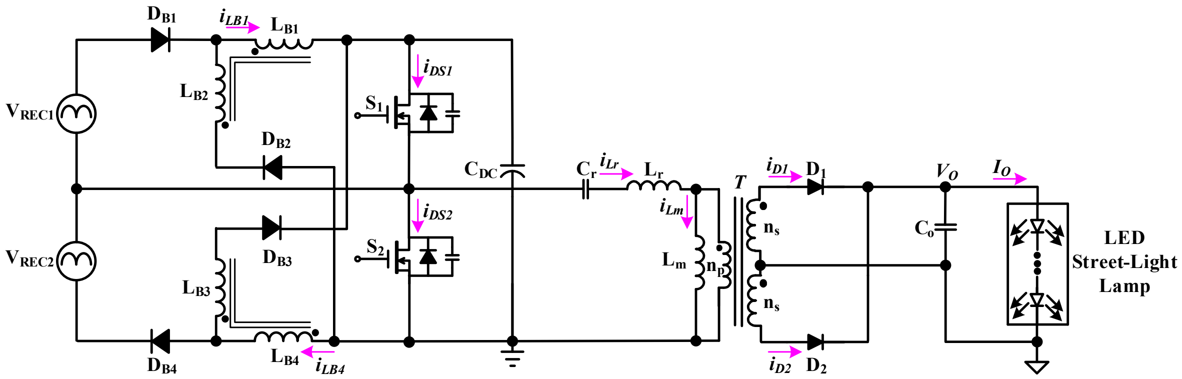
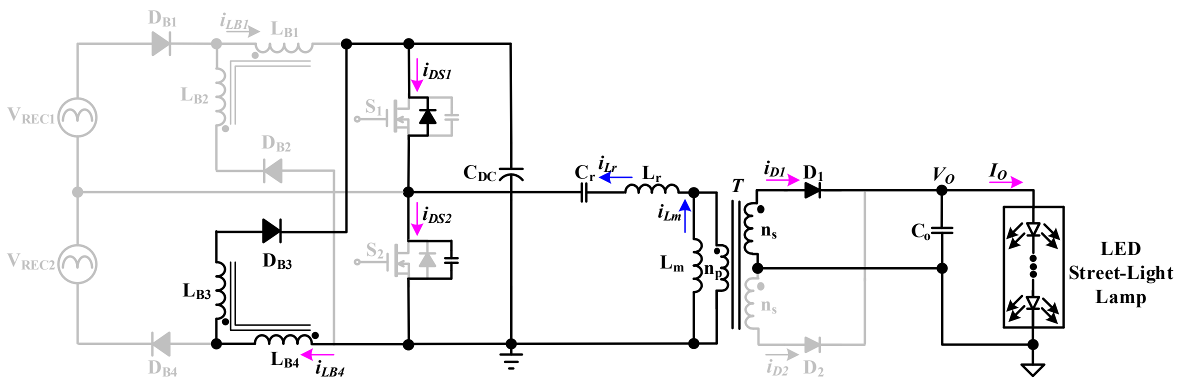


Figure 4. Equivalent circuit diagram of the proposed single-stage AC-DC power supply for providing an LED street-light lamp.

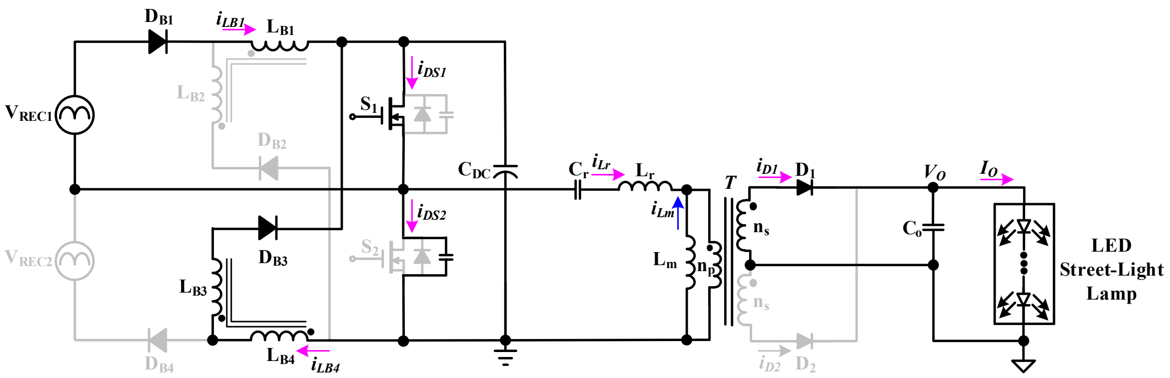
The operational modes and theoretical waveforms of the presented LED power supply are shown in Figures 5 and 6, respectively, and the circuit analysis along with the operating of the LED power supply is described and discussed in detail below.

Mode 1 (the equivalent circuit as shown in Figure 5a): suppose that in the previous mode, the energy stored in the parasitic capacitor of the power switch S_1 is released, so that the switch voltage v_{DS1} drops to zero, causing the essential diode of the switch S_1 to be turned on at time t_0. The resonant inductor L_r and the magnetizing inductor L_m offer energy to the parasitic capacitor of the power switch S_2 and the DC-link capacitor C_{DC} and the resonant capacitor C_r by way of the essential diode of the switch S_1, and offer energy to the output capacitor C_o and the LED street-light lamp via the transformer T and the output diode D_1. Since the diode D_{B3} is forward-biased and turned on in the previous mode, the coupled inductors L_{B3} and L_{B4} offer energy to the DC-link capacitor C_{DC} by means of the diode D_{B3}. When the current i_{Lr} of the resonant inductor L_r is decreased to zero, this mode finishes.

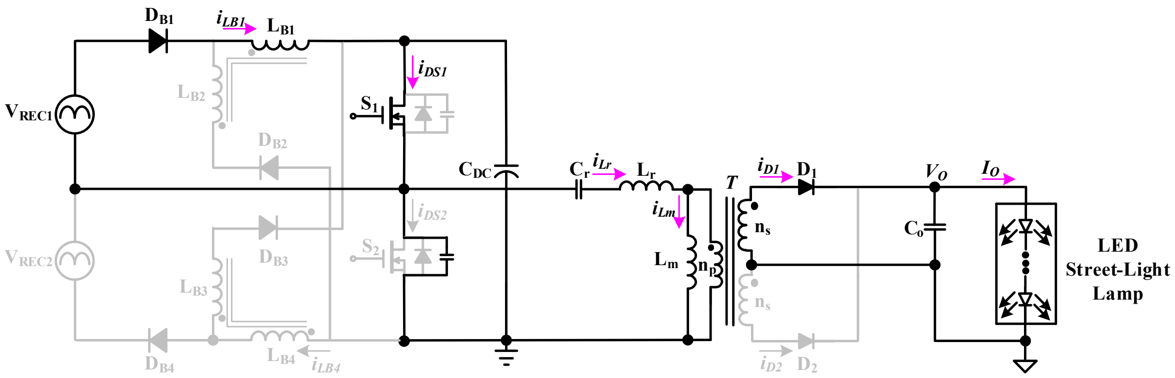


(**a**) *Mode 1* ($t_0 \leq t < t_1$)

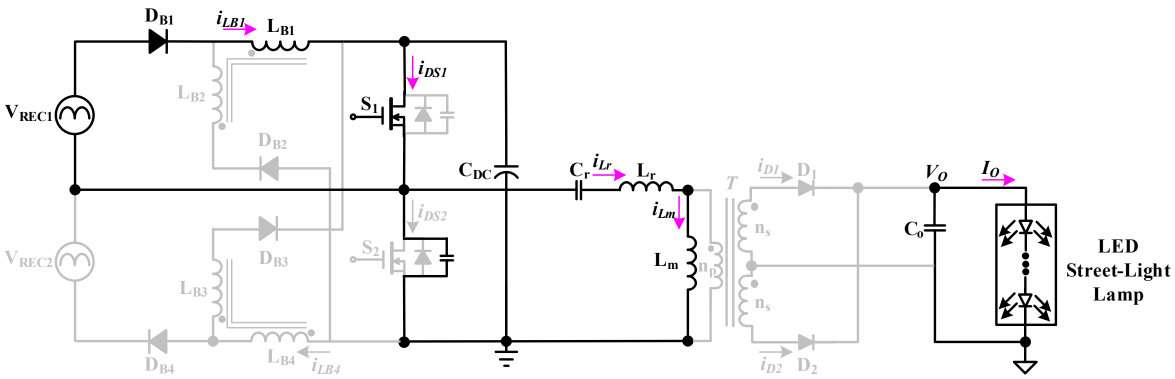
Figure 5. *Cont.*



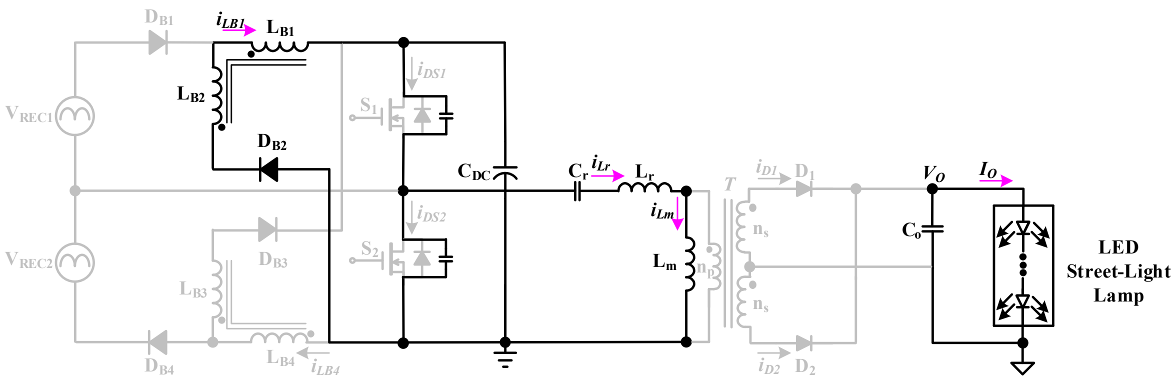
(**b**) *Mode 2* ($t_1 \le t < t_2$)



(**c**) *Mode 3* ($t_2 \le t < t_3$)

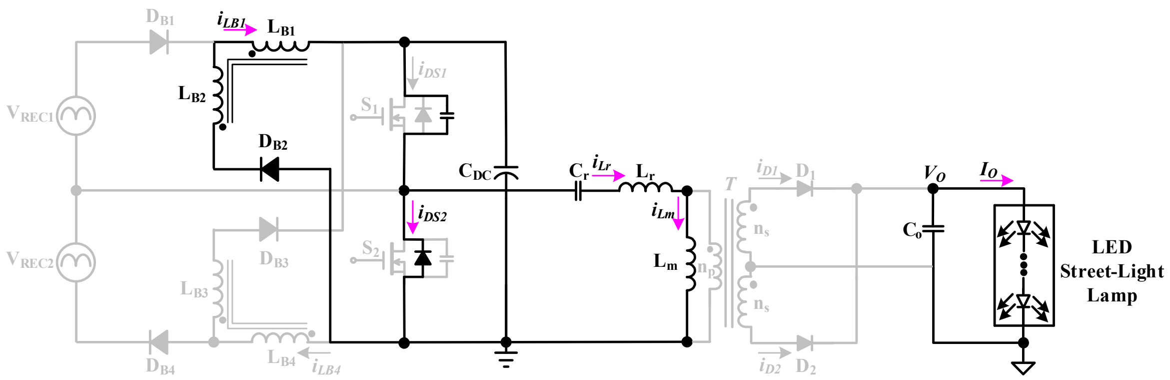


(**d**) *Mode 4* ($t_3 \le t < t_4$)

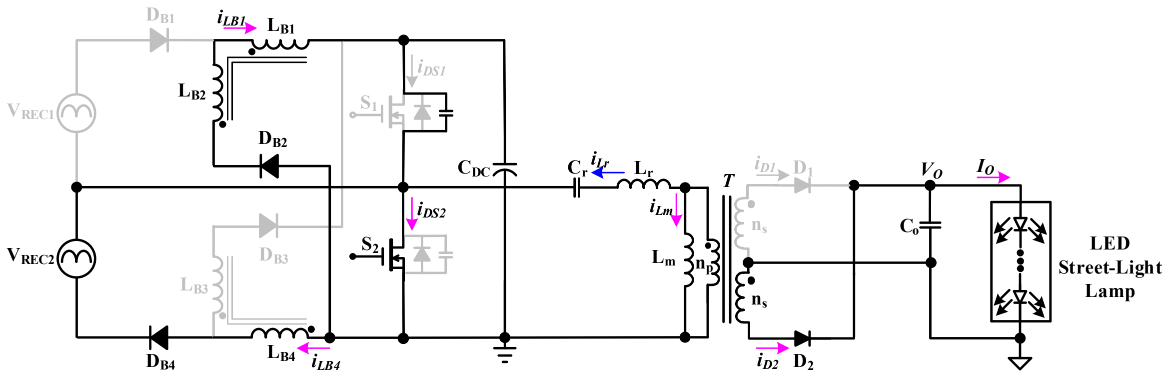


(**e**) *Mode 5* ($t_4 \le t < t_5$)

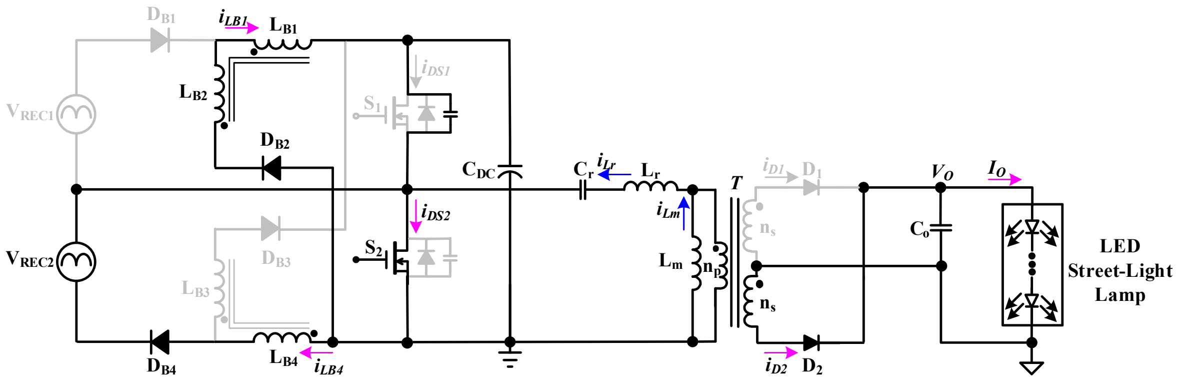
Figure 5. *Cont.*



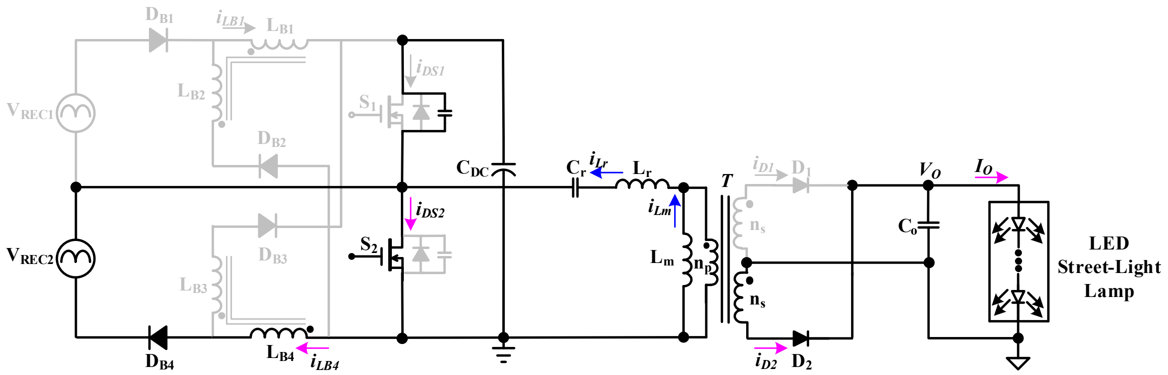
(**f**) *Mode 6* ($t_5 \le t < t_6$)



(**g**) *Mode 7* ($t_5 \le t < t_6$)

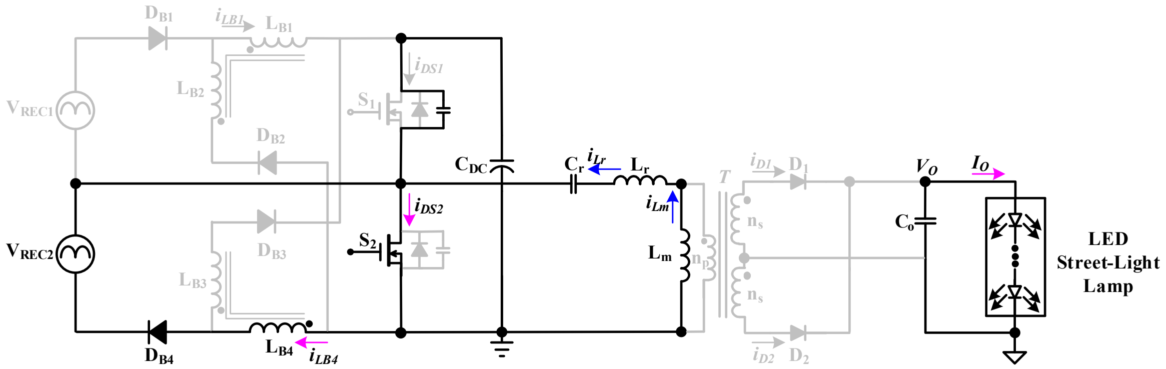


(**h**) *Mode 8* ($t_5 \le t < t_6$)

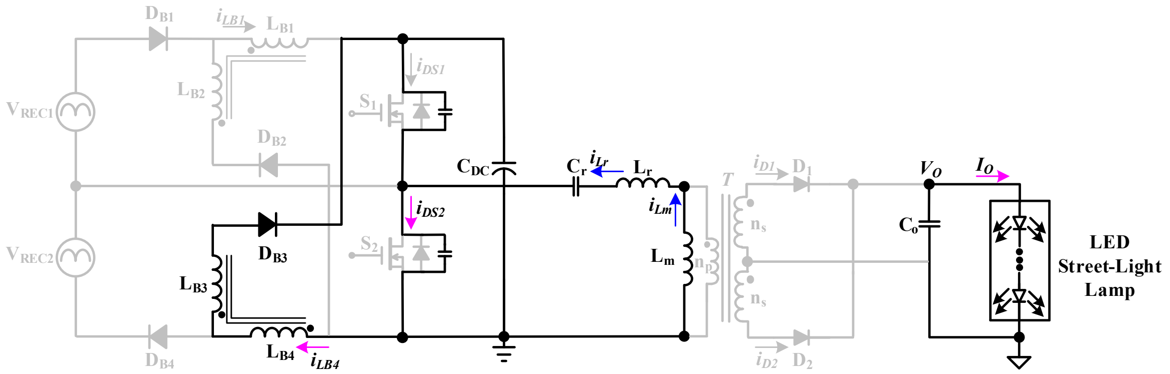


(**i**) *Mode 9* ($t_5 \le t < t_6$)

Figure 5. *Cont.*



(**j**) *Mode 10* ($t_5 \leq t < t_6$)



(**k**) *Mode 11* ($t_5 \leq t < t_6$)

Figure 5. Operation modes of the presented AC-DC power supply for providing an LED street-light lamp.

Mode 2 (the equivalent circuit as shown in Figure 5b): at time t_1, the power switch S_1 is driven and turned on, and has the characteristics of zero-voltage switching (ZVS). The rectified equivalent voltage source V_{REC1} offers energy to the coupled inductor L_{B1} by way of the diode D_{B1} and the switch S_1, and the coupled inductor current i_{LB1} rises linearly. In addition, the diode D_{B2} is reversely biased and cannot be turned on. The DC-link capacitor C_{DC}, the resonant capacitor C_r, and the magnetizing inductor L_m offer energy to the resonant inductor L_r via the switch S_1, and offer energy to the output capacitor C_o and the LED street-light lamp by means of the transformer T and the output diode D_1. The DC-link capacitor C_{DC} offers energy to the parasitic capacitor of the power switch S_2 by way of the switch S_1. The coupled inductors L_{B3} and L_{B4} continuously offer energy to the DC-link capacitor C_{DC} by means of the diode D_{B3}. When the coupled inductor current i_{LB4} drops to zero, this mode completes.

Mode 3 (the equivalent circuit as shown in Figure 5c): the rectified equivalent voltage source V_{REC1} keeps on providing energy to the inductor L_{B1} by way of the diode D_{B1} and the switch S_1, and the inductor current i_{LB1} goes on increasing linearly. The DC-link capacitor C_{DC} and the resonant capacitor C_r continuously offer energy to the resonant inductor L_r and the magnetizing inductor L_m by means of the switch S_1, and supply energy to the output capacitor C_o and the LED street-light lamp by way of the transformer T and the output diode D_1. The DC-link capacitor C_{DC} continuously offers energy to the parasitic capacitor of the power switch S_2 by means of the switch S_1. When the diode current i_{D1} drops to zero at time t_3, this mode ends.

Mode 4 (the equivalent circuit as shown in Figure 5d): the rectified equivalent voltage source V_{REC1} holds on providing energy to the inductor L_{B1} by way of the diode D_{B1} and the switch S_1, and the inductor current i_{LB1} keeps on rising linearly. The DC-link capacitor C_{DC} and the resonant capacitor C_r continuously offer energy to the resonant inductor L_r and the magnetizing inductor L_m through the switch S_1. The DC-link capacitor C_{DC} continuously supplies energy from the switch S_1 to the parasitic capacitor of the power switch S_2. The capacitor C_o provides energy to the LED street-light lamp. When switch S_1 is turned off at time t_4, this mode completes.

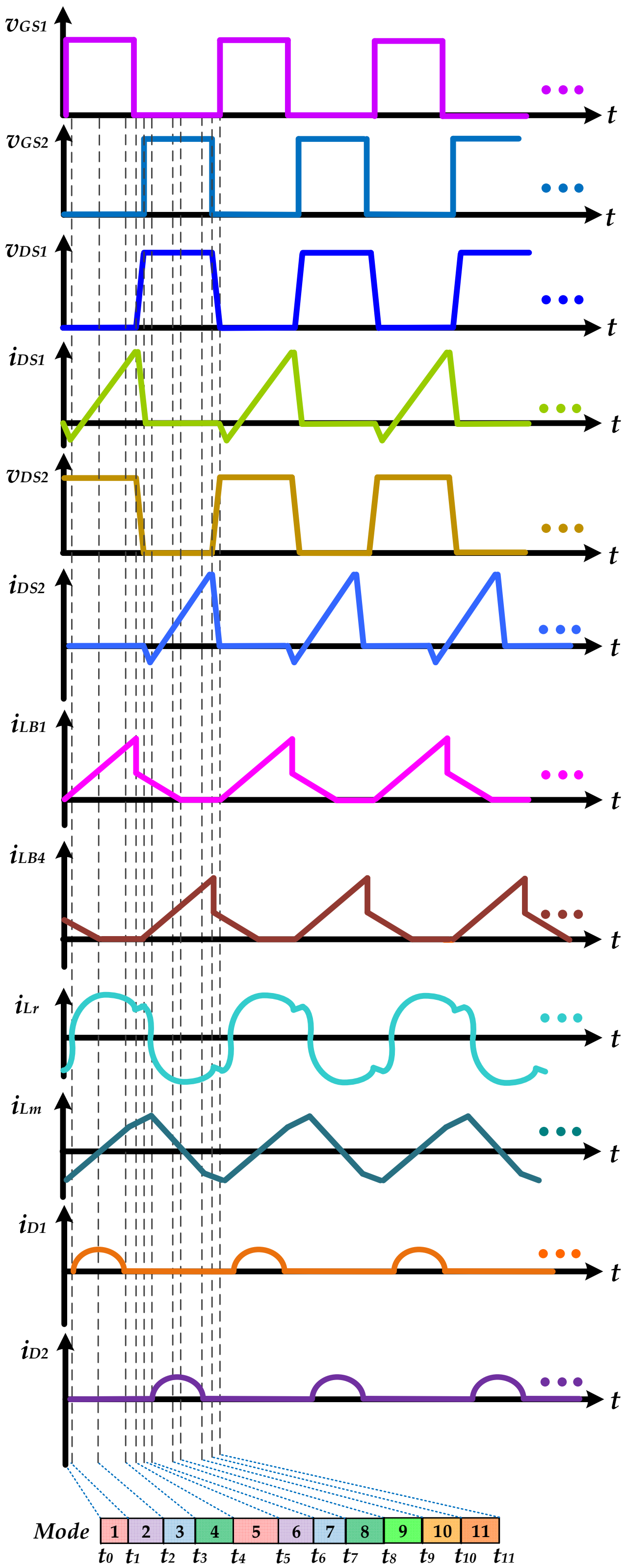


Figure 6. Theoretical waveforms of the presented AC-DC power supply for providing an LED street-light lamp.

Mode 5 (the equivalent circuit as shown in Figure 5e): when the switch S_1 is turned off, the diode D_{B2} is turned on for being forward-biased, and the coupled inductors L_{B1} and L_{B2} offer energy to the DC-link capacitor C_{DC} by way of the diode D_{B2}, and the inductor current i_{LB1} decreases linearly. The DC-link capacitor C_{DC} and the parasitic capacitor of the power switch S_2 offer energy to the parasitic capacitor of the power switch S_1, the resonant capacitor C_r, the resonant inductor L_r and the magnetizing inductor L_m. The capacitor C_o continuously supplies energy to the LED street-light lamp. When the switching voltage v_{DS2} drops to zero at time t_5, this mode completes.

Mode 6 (the equivalent circuit as shown in Figure 5f): since in the previous mode, the energy stored in the parasitic capacitor of the switch S_2 is released, the switch voltage v_{DS2} drops to zero, which causes the essential diode of the switch S_2 to conduct. The coupled inductors L_{B1} and L_{B2} go on offering energy to the DC-link capacitor C_{DC} by way of the diode D_{B2}, and the inductor current i_{LB1} keeps on showing a linear decrease. The DC-link capacitor C_{DC}, the resonant inductor L_r, and the magnetizing inductor L_m continuously supply energy to the resonant capacitor C_r and the parasitic capacitor of the power switch S_1 by means of the essential diode of the switch S_2, and the magnetizing inductor current i_{Lm} decreases linearly. The output capacitor C_o holds on providing energy to the LED street-light lamp. When the switch S_2 is turned on, this mode ends.

Mode 7 (the equivalent circuit as shown in Figure 5g): the power switch S_2 is driven and turned on, and has the characteristics of ZVS. The rectified equivalent voltage source V_{REC2} offers energy to the inductor L_{B4} by way of the diode D_{B4} and the switch S_2, and the inductor current i_{LB4} rises linearly. In addition, the diode D_{B3} is reversely biased and cannot be turned on. The coupled inductors L_{B1} and L_{B2} continuously provide energy to the DC-link capacitor C_{DC} by means of the diode D_{B2}, and the inductor current i_{LB1} goes on showing a linear decrease. The DC-link capacitor C_{DC} offers energy to the parasitic capacitor of the switch S_1 by way of the power switch S_2. The resonant capacitor C_r and the magnetizing inductor L_m offer energy to the resonant inductor L_r, the output capacitor C_o, and the LED street-light lamp by means of the switch S_2, the transformer T, and the diode D_2, and the magnetizing inductor current i_{Lm} keeps on showing a linear decrease. When the magnetizing inductor current i_{Lm} reaches zero at time t_7, this mode ends.

Mode 8 (the equivalent circuit as shown in Figure 5h): the rectified equivalent voltage source V_{REC2} keeps on offering energy to the inductor L_{B4} by way of the diode D_{B4} and the switch S_2, and the inductor current i_{LB4} keeps on rising linearly. The coupled inductors L_{B1} and L_{B2} go on providing energy to the DC-link capacitor C_{DC} by way of the diode D_{B2}, and the inductor current i_{LB1} goes on showing a linear decrease. The DC-link capacitor C_{DC} continuously supplies energy to the parasitic capacitor of the switch S_1 by means of the power switch S_2. The resonant capacitor C_r offers energy to the resonant inductor L_r, the magnetizing inductor L_m, the output capacitor C_o, and the LED street-light lamp by way of the switch S_2, the transformer T and the diode D_2. When the coupled inductor current i_{LB1} drops to zero, this mode completes.

Mode 9 (the equivalent circuit as shown in Figure 5i): the rectified equivalent voltage source V_{REC2} holds on providing energy to the inductor L_{B4} by way of the diode D_{B4} and the switch S_2, and the inductor current i_{LB4} keeps on rising linearly. The DC-link capacitor C_{DC} continuously provides energy to the parasitic capacitor of the switch S_1 by means of the power switch S_2. The resonant capacitor C_r continuously supplies energy to the resonant inductor L_r, magnetizing inductor L_m, output capacitor C_o, and the LED street-light lamp by way of the switch S_2, the transformer T, and the diode D_2. When the diode current i_{D2} drops to zero at time t_9, this mode completes.

Mode 10 (the equivalent circuit as shown in Figure 5j): the rectified equivalent voltage source V_{REC2} continuously supplies energy to the inductor L_{B4} by means of the diode D_{B4} and the switch S_2, and the inductor current i_{LB4} continues to show a linear increase. The DC-link capacitor C_{DC} continuously offers energy to the parasitic capacitor of the switch S_1 by way of the power switch S_2. The resonant capacitor C_r continuously offers energy to the resonant inductor L_r and the magnetizing inductor L_m by means of the switch S_2. The output capacitor C_o offers energy to the LED street-light lamp. When switch S_2 is turned off at time t_{10}, this mode completes.

Mode 11 (the equivalent circuit as shown in Figure 5k): when the switch S_2 is turned off, the diode D_{B3} is forwardly biased and turned on, and the coupled inductors L_{B3} and L_{B4} offer energy to the DC-link capacitor C_{DC} by way of the diode D_{B3}, and the inductor current i_{LB4} presents a linear decrease. The parasitic capacitor of the power switch S_1 and the resonant capacitor C_r provide energy to the resonant inductor L_r, the magnetizing inductor L_m, and the DC-link capacitor C_{DC}. The output capacitor C_o continues to provide energy to the LED street-light lamp. When the voltage v_{DS1} of the parasitic capacitor of the switch S_1 drops to zero at time t_{11}, this mode completes. After that, the circuit returns to operate *Mode 1*.

3. Design Considerations in the Presented Single-Stage AC-DC Power Supply for Providing an LED Street-Light Lamp

3.1. Design of the Coupled Inductors

The input utility-line voltage can be expressed by

$$v_{AC}(t) = \sqrt{2}v_{AC-rms}\sin(2\pi f_{AC}t) \quad (1)$$

where $v_{AC\text{-}rms}$ and f_{AC} are the root mean square (rms) value and the frequency of the input utility-line voltage, respectively. Figure 7 shows the theoretical waveforms of the coupled inductors' currents i_{LB1} and i_{LB4} along with the input utility-line current i_{AC} at the positive half-cycle. The peak value of the coupled inductor current i_{LB1} is obtained as

$$i_{LB1-pk}(t) = \frac{\left|\sqrt{2}v_{AC-rms}\sin(2\pi f_{AC}t)\right|}{2L_{B1}f_S}duty \quad (2)$$

where f_S and *duty* are the switching frequency and the duty cycle of the gate-driving signals of two power switches, respectively. In each switching period, the input mains current $i_{AC}(t)$ is equal to two times average level of the coupled-inductor current $i_{LB1-pk}(t)$, and can be represented by

$$i_{AC}(t) = \frac{2}{T_S}\int_0^{T_S} i_{LB1-pk}(t)dt = \frac{\sqrt{2}v_{AC-rms}\sin(2\pi f_{AC}t)}{L_{B1}f_S}duty^2 \quad (3)$$

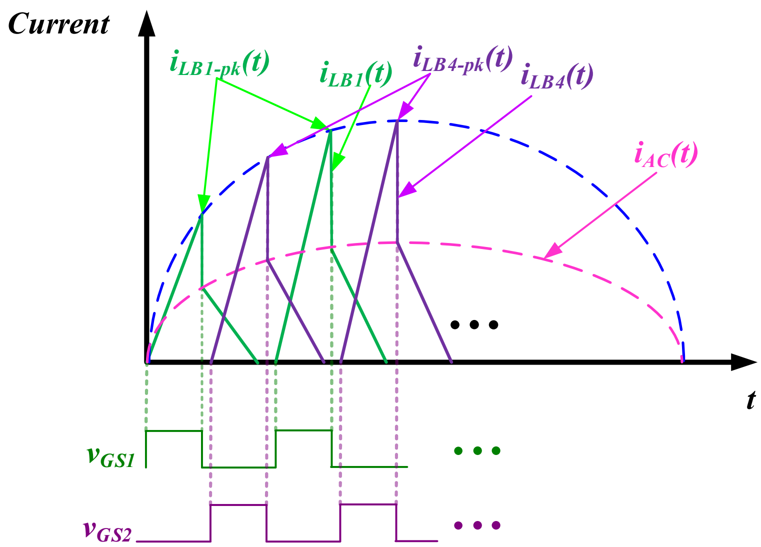


Figure 7. Theoretical waveforms of the coupled inductors currents i_{LB1} and i_{LB4} along with the input utility-line current i_{AC} at the positive half-cycle.

Combining (1) with (3), the average input power P_{IN} is indicated by

$$P_{IN} = \frac{1}{T_S}\int_0^{T_S} v_{AC}(t)\cdot i_{AC}(t)dt = \frac{{v_{AC-rms}}^2}{L_{B1}f_S}duty^2 \quad (4)$$

The relationship between the rated-output LED power P_o and the input power P_{in} is given by

$$P_O = P_{IN}\cdot\eta = \frac{\eta {v_{AC-rms}}^2}{L_{B1}f_S}duty^2 \quad (5)$$

where η is the estimated circuit efficiency of the LED power supply.

Rearranging (5), the mathematical expression for designing the coupled inductor L_{B1} is indicated by

$$L_{B1} = \frac{\eta {v_{AC-rms}}^2}{P_{lamp}f_S}duty^2 \quad (6)$$

With a η of 0.9, a $v_{AC\text{-}rms}$ of 110 V, a D of 0.5, a P_o of 144 W, and a switching frequency f_S of 100 kHz, the inductance of the coupled inductor L_{B1} is calculated as

$$L_{B1} = \frac{\eta {v_{AC-rms}}^2}{P_{lamp}f_S}duty^2 = \frac{0.9\cdot 110^2}{144\cdot 100k}0.5^2 = 189.06\ \mu\text{H}$$

In addition, in the prototype circuit, the coupled inductor L_{B1} is selected to be 180 μH, with the coupled inductors L_{B2}, L_{B3}, and L_{B4} having the same values as L_{B1}.

3.2. Design of the LLC Resonant Network

According to the design equations of the LLC resonant network as shown in [23], the inductor L_r can be expressed by

$$L_r = \frac{Q_r R_{eq}}{2\pi f_{r1}} \quad (7)$$

where Q_r is the quality factor, R_{eq} is represented as the equivalent output resistance referring to the primary side of the transformer T, and f_{r1} is the main resonant frequency of the LLC resonant network.

The magnetic inductor L_m is given by

$$L_m = AL_r \quad (8)$$

where A is the inductance ratio. The resonant capacitor C_r is described as

$$C_r = \frac{1}{(2\pi f_{r1})^2 L_r} \quad (9)$$

With an f_{r1} of 100 kHz, an R_{eq} of 182.4 Ω, an A of 5, and a Q_r of 0.3, the parameters of the LLC resonant network are respectively calculated as

$$L_r = \frac{Q_r R_{eq}}{2\pi f_{r1}} = \frac{0.3\cdot 182.4}{2\pi\cdot 100k} = 87.09\ \mu\text{H}$$

$$L_m = AL_r = 5\cdot 87.09\mu = 435.45\ \mu\text{H}$$

and

$$C_r = \frac{1}{(2\pi f_{r1})^2 L_r} = \frac{1}{(2\pi\cdot 100k)^2\cdot 87.09\mu} = 29.09\ \text{nF}$$

In addition, the inductors L_r and L_m, and capacitor C_r are selected as 90 μH, 450 μH, and 22 nF, respectively.

4. Experimental Results of the Prototype AC-DC Power Supply for Providing an LED Street-Light Lamp

Table 1 shows the specifications of the experimental LED street-light lamp, with this paper completing the development of a single-stage prototype power supply for providing an 144 W (36 V/4 A)-rated LED street-light lamp suitable for an AC input utility-line voltage of 110 V. Table 2 presents the utilized circuit components in the proposed single-stage AC-DC power supply for providing an LED street-light lamp.

Table 1. Specifications of the experimental LED street-light lamp.

Parameter	Value
Input utility-line voltage v_{AC}	110 V (rms)
Input utility-line frequency f_{AC}	60 Hz
Rated LED power	144 W
Rated LED voltage	36 V
Rated LED current	4 A

Table 2. Circuit components utilized in the presented AC-DC power supply for supplying an LED street-light lamp.

Parameter	Value
Capacitors (C_{in1}, C_{in2})	330 nF
Coupled inductors (L_{B1} and L_{B2}; L_{B3} and L_{B4})	179 µH
Diodes (D_{B1}, D_{B2}, D_{B3}, D_{B4})	MUR460
Power switches (S_1, S_2)	STP20NM60
DC-link capacitor C_{DC}	220 µF/450 V
Magnetizing inductor L_m	450 µH
Resonant inductor L_r	90 µH
Resonant capacitor C_r	22 nF
Diodes (D_1, D_2)	MBR30H100CT
Output capacitor C_o	2200 µF/63 V

Figure 8 demonstrates experimental waveforms of coupled inductor currents i_{LB1} and i_{LB4}. Figure 9 presents the experimental waveforms of the power switch voltage v_{DS2} and the resonant inductor current i_{Lr}. From the waveform, it is known that the voltage waveform leads the current waveform, and thus the resonant network has the characteristics of an inductive load. Figure 10 demonstrates the experimental waveforms of the power switch voltage v_{DS1} and current i_{DS1}. It can be seen that ZVS was achieved on the power switch, which can reduce the switching losses of the power switch. Figure 11 presents the experimental waveforms of the power switch voltage v_{DS1} and the diode current i_{D1}. The waveform diagram shows that the output diode had the characteristic of zero-current switching (ZCS), which can reduce the conduction loss of the power diode. Figure 12 presents the experimental waveform of the DC-link voltage V_{DC}, with the average level of the DC-link voltage being 228.7 V. Figure 13 demonstrates the experimental waveforms of the output voltage V_O and the output current I_O. The average levels of the output voltage and current were approximately 36 V and 4 A, respectively.

Figure 14 shows the experimental waveforms of the input AC mains voltage v_{AC} and current i_{AC}. It can be seen from the figure that the input AC mains current followed the input AC mains voltage and that the phases of the two waveforms were the same, which resulted in a high power factor. Figure 15 demonstrates the comparisons between the measured harmonics of each order of the input AC mains current and the IEC 61000-3-2 Class C standard values through using a power analyzer (Tektronix PA 4000) at an AC input voltage of 110 V. It can be seen from the figure that the measured harmonics of each order of the input AC mains current met the requirements of the specification. The measured power factor and total harmonic distortion factor of the input AC utility-line current were 0.9992 and 2.2954%, respectively. In addition, the measured efficiency of the prototype LED power supply circuit was 89.53%.

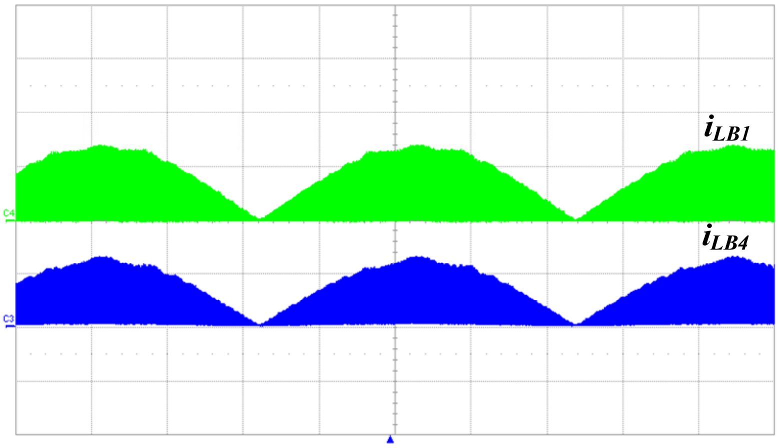


Figure 8. Experimental waveforms of the coupled-inductor currents i_{LB1} (5 A/div) and i_{LB4} (5 A/div); time scale: 2 ms/div.

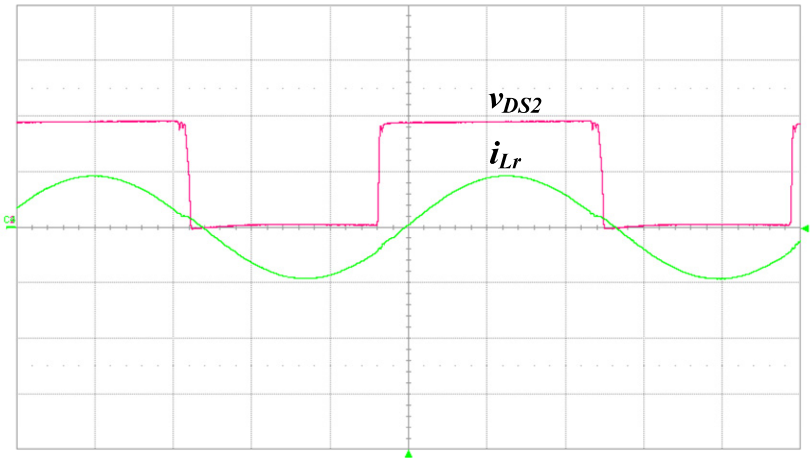


Figure 9. Experimental waveforms of the switch voltage v_{DS2} (100 V/div) and the resonant inductor current i_{Lr} (2 A/div); time scale: 2 μs/div.

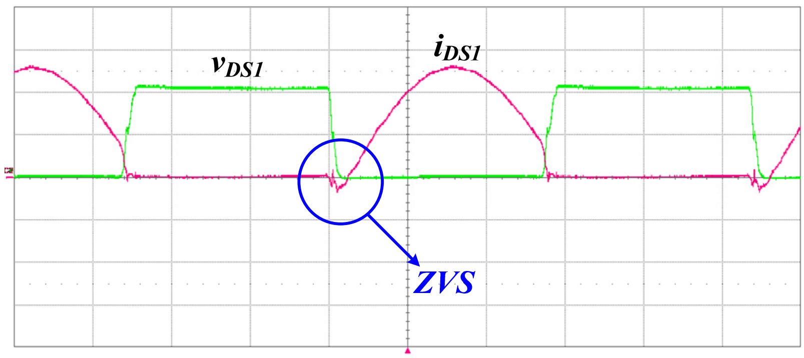


Figure 10. Experimental waveforms of the switch voltage v_{DS1} (100 V/div) and the switch current i_{DS1} (1 A/div); time scale: 2 μs/div.

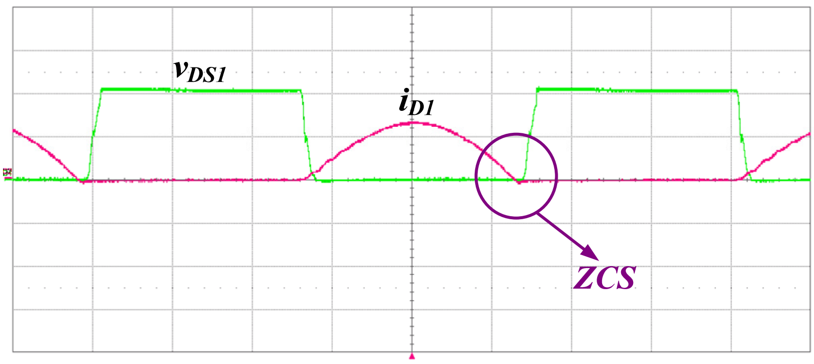


Figure 11. Experimental waveforms of the switch voltage v_{DS1} (100 V/div) and the output diode current i_{D1} (5 A/div); time scale: 2 µs/div.

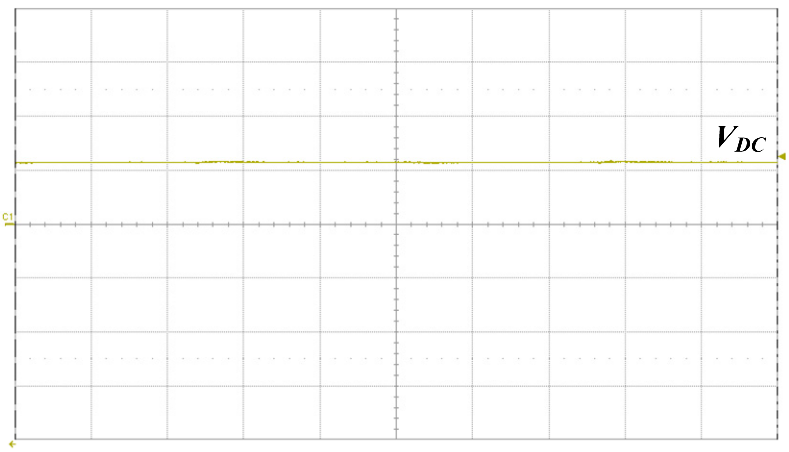


Figure 12. Experimental waveform of the DC-link voltage V_{DC} (200 V/div); time scale: 2 µs/div.

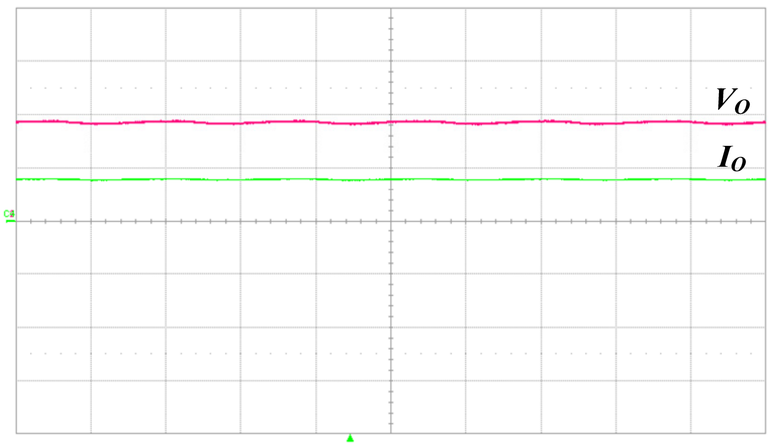


Figure 13. Experimental waveforms of the output LED voltage V_O (20 V/div) and the output LED current I_O (5 A/div); time scale: 5 ms/div.

Table 3 shows the experimental results of the output LED voltage and output LED current ripples for the presented LED power supply at an input AC mains voltage of 110 V. It is observed that the experimental voltage and current ripple factors were less than 4% and 2%, respectively. Figure 16 is a photo of the proposed single-stage prototype power supply circuit that lights up the LED street-light lamp provided with an AC power source. Furthermore, Table 4 shows comparisons between the existing single-stage AC-DC LED power supply in reference [18] and the proposed one. It can be seen that the presented power supply possessed lower input AC mains current total harmonic distortion (THD) and better circuit efficiency in comparison to reference [18].

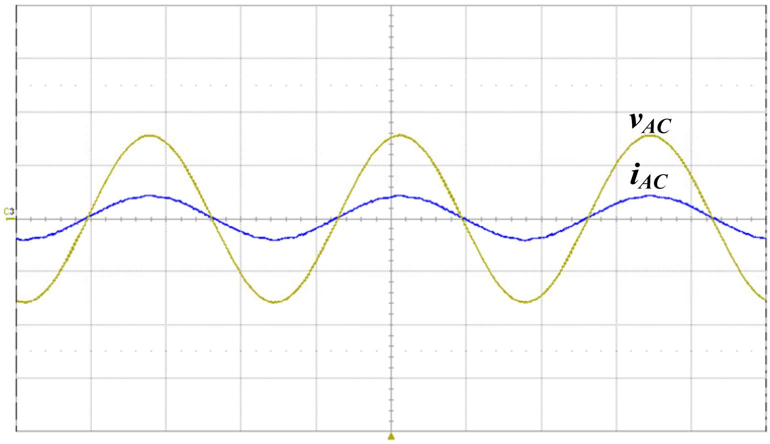


Figure 14. Experimental waveforms of the input AC mains voltage v_{AC} (100 V/div) and the AC mains current i_{AC} (5 A/div); time scale: 5 ms/div.

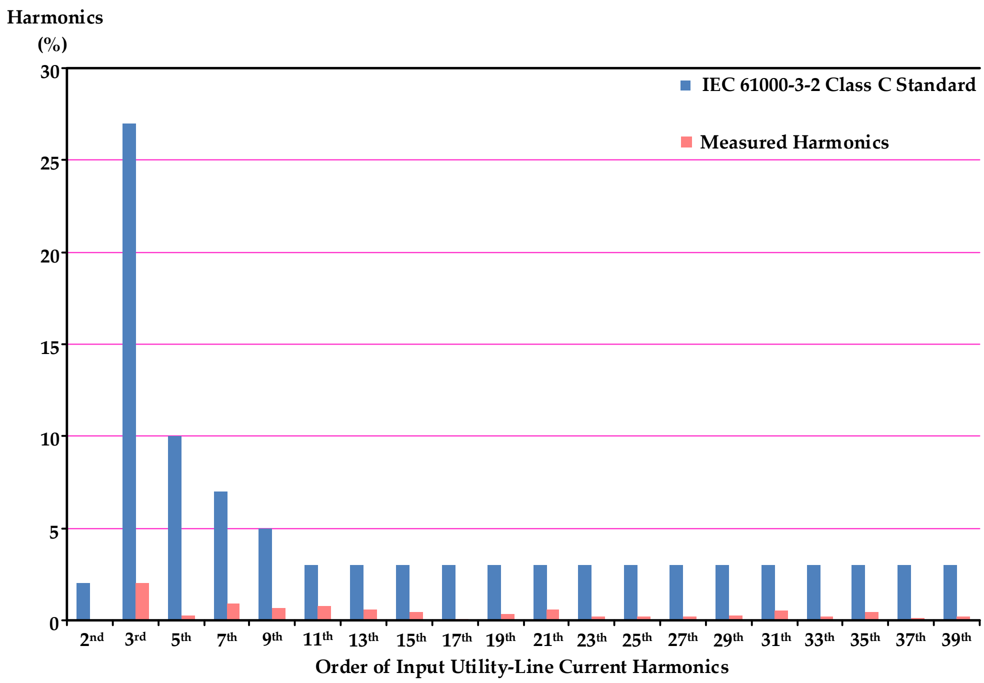


Figure 15. Measured harmonics of each order of the input AC mains current compared with the IEC 61000-3-2 Class C standard values.

Table 3. Experimental results of the output LED voltage and output LED current ripples of the presented AC-DC LED power supply at an input AC mains voltage of 110 V.

Parameter	Value
Average level of output LED voltage	36.03 V
Peak-to-peak level of output LED voltage	1.3 V
Voltage ripple factor	3.61%
Average level of output LED current	3.938 A
Peak-to-peak level of output LED current	67 mA
Current ripple factor	1.7%

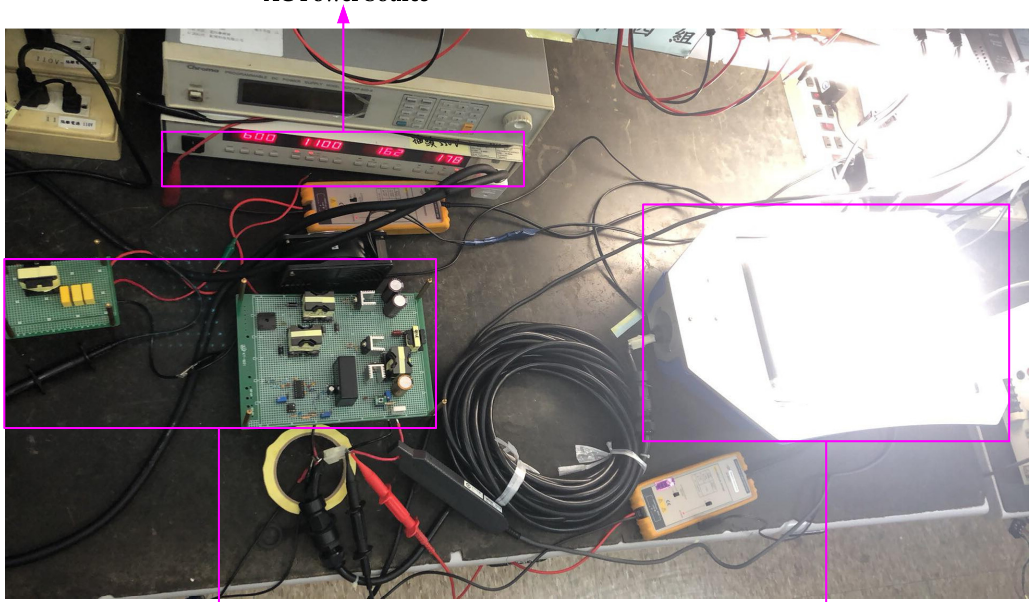


Figure 16. An overhead photograph of the proposed AC-DC power supply providing the LED street-light lamp with an input AC mains voltage of 110 V.

Table 4. Comparisons between the existing single-stage AC-DC LED power supply in [18] and the presented version in this paper.

Item	Existing AC-DC LED Power Supply in Reference [18]	Presented AC-DC LED Power Supply
Circuit topology	Integration of interleaved boost converter and HB-LLCR converter	Integration of interleaved buck converter with coupled-inductors and HB-LLCR converter
Number of required power switches	2	2
Number of required diodes	8	10
Number of required capacitors	6	6
Number of required magnetic components	5	5
Input utility-line voltage	110 V	110 V
Output power	144 W (36 V/4 A)	144 W (36 V/4 A)
Measured power factor	>0.99	>0.99
Measured current THD	<10%	<3%
Measured circuit efficiency	>88%	>89.5%

5. Bluetooth Wireless Dimming Tests of the Prototype AC-DC Power Supply for Providing an LED Street-Light Lamp

Figure 17 shows the architecture diagram of the proposed AC-DC power supply, which uses Bluetooth wireless communication technology to achieve the function of remote digital dimming control of the LED street-light lamp. In the wireless dimming control scheme of the LED street-light power supply circuit, the dimming control command sent by the administrator through the smart device (for example a smart tablet, a smart pad, or a smartphone) is sent to the microcontroller (Arduino NANO) via the Bluetooth wireless communication using a Bluetooth communication module (the model name is HC-05). Then, the dimming control signal from the microcontroller is sent to the power switch S_{dim}, which is connected in series with the LED street-light lamp and that is responsible for dimming control. By changing the duty ratio of the digital dimming control signal (from 100% to 20%) fed into the power switch S_{dim}, we can achieve the process of dimming and controlling the LED street-light lamp at 100% to 20% of the rated output power using Bluetooth wireless communication.

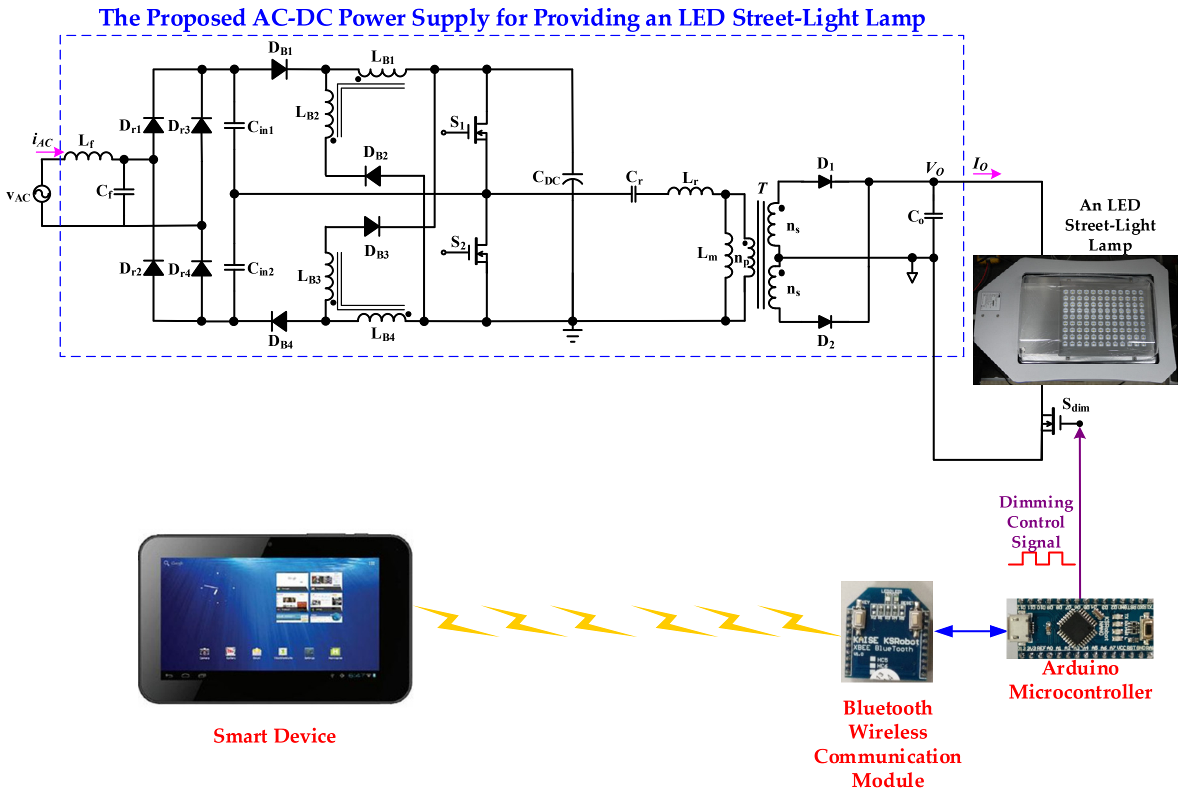


Figure 17. The architecture diagram of the proposed AC-DC power supply for providing an LED street-light lamp with Bluetooth wireless dimming capability.

Table 5 demonstrates the measured output current I_O of the LED street-light lamp when the duty ratio of the dimming control signal ranged from 20% to 100%. The measured output LED street-light lamp currents were 0.591 A, 1.063 A, 1.378 A, 1.811 A, 2.127 A, 2.914 A, 3.347 A, 3.702 A and 3.938 A when the duty ratio of the dimming control signal was at 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%, respectively. Moreover, the normalized value of the output LED street-light lamp current, $I_{O,\,normalized}$, is defined as the measured LED current divided by the rated one during the dimming process. By utilizing the measured data as shown in Table 5, the graph in Figure 18 shows the relationship between the duty ratio of the dimming control signal and the normalized output LED current $I_{O,\,normalized}$. Additionally, the minimum value of the normalized output LED current was 0.1471, while the duty ratio of the dimming control signal was 20%.

Table 5. The measured output LED current at different duty ratios of the dimming control signal during the Bluetooth wireless dimming process.

Duty Ratio of the Dimming Control Signal	Measured Output LED Current I_O
20%	0.591 A
30%	1.063 A
40%	1.378 A
50%	1.811 A
60%	2.127 A
70%	2.914 A
80%	3.347 A
90%	3.702 A
100%	3.938 A

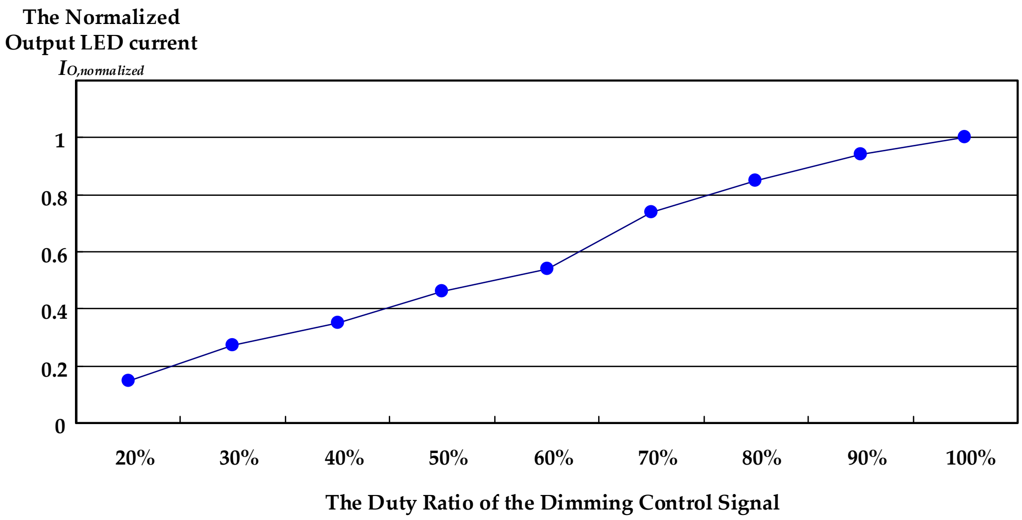


Figure 18. The relationship between the duty ratio of dimming control signal and the normalized output LED current $I_{O,\ normalized}$.

6. Conclusions

Compared with high-pressure mercury lamps, LEDs have the advantages of long service life, high lighting efficiency, and low power consumption, having become a new generation of street light sources. This paper proposed and analyzed a single-stage AC-DC power supply, combining an interleaved buck converter with coupled inductors and an HB-LLCR converter for providing an LED street-light lamp with features of high power factor and soft-switching. A prototype power supply for providing a 144 W-rated LED street-light lamp was successfully implemented and tested. In addition, this paper developed Bluetooth dimming applications for smart tablets or smart phones, having the function of remote wireless dimming to control the output power of the LED street-light lamp, achieving energy-saving benefits. Satisfactory experimental results acquired from the prototype LED power supply demonstrated that a high power-factor (>0.99), a low utility-line current THD (<3%), a high circuit efficiency (>89%), ZVS on power switches, ZCS on power diodes, and Bluetooth wireless dimming control at 20–100% of rated output power.

Author Contributions: C.-A.C. and H.-L.C. conceived and invented the LED power supply circuit. C.-H.C. and E.-C.C. carried out the circuit simulations and designed the circuit parameters. W.-S.H. implemented the prototype LED power supply and measured experimental results. C.-C.L. and L.-F.L. accomplished Bluetooth wireless dimming tests of the LED power supply. C.-A.C. prepared and submitted the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to express their appreciation for grant support from the Ministry of Science and Technology (MOST) of Taiwan under its grant with reference numbers MOST 107-2221-E-214-009, MOST 109-2221-E-214-011, and MOST 109-3116-F-006-020-CC1.

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

References

1. Brañas, C.; Azcondo, F.; Alonso, J.M. Solid-state lighting: A system review. *IEEE Ind. Electron. Mag.* **2013**, *7*, 6–14. [CrossRef]
2. Almeida, P.S.; Camponogara, D.; Costa, M.A.D.; Braga, H.A.C.; Alonso, J.M. Matching LED and driver life spans: A review of different techniques. *IEEE Ind. Electron. Mag.* **2015**, *9*, 36–47. [CrossRef]
3. Specifications of OSRAM HQL 250W E40. Available online: https://www.any-lamp.com/osram-hql-250w-e40 (accessed on 30 December 2020).
4. Datasheet of LEDENVO^{TM} LED Street Light. OSRAM. 2016. Available online: http://ls.osram.com.cn/pdf/EN_LEDENVO_Street_Light_Datasheet_v1p2_20160926.pdf (accessed on 30 December 2020).
5. Wang, Y.; Guan, Y.; Xu, D.; Wang, W. A CLCL resonant DC/DC converter for two-stage LED driver system. *IEEE Trans. Ind. Electron.* **2016**, *63*, 2883–2891. [CrossRef]
6. Arias, M.; Lamar, D.G.; Linera, F.F.; Balocco, D.; Diallo, A.A.; Sebastian, J. Design of a soft-switching asymmetrical half-bridge converter as second stage of an LED driver for street lighting application. *IEEE Trans. Power Electron.* **2012**, *27*, 1608–1621. [CrossRef]
7. Wang, Y.; Guan, Y.; Liang, X.; Wang, W.; Xu, D. Two-stage LED street lighting system based on a novel single-stage AC/DC converter. *IET Power Electron.* **2014**, *7*, 1374–1383. [CrossRef]
8. Naraharisetti, K.; Green, P.B. Design of 200 W Boost PFC Plus HB LLC Resonant Converter with IR1155, IRS27952 and IR11688. *Application Note*, Infineon. Available online: http://www.infineon.com (accessed on 30 December 2020).
9. Camponogara, D.; Ferreira, G.F.; Campos, A.; Dalla Costa, M.A.; Garcia, J. Offline LED driver for street lighting with an optimized cascade structure. *IEEE Trans. Ind. Appl.* **2013**, *49*, 2437–2443. [CrossRef]
10. Arias, M.; Lamar, D.G.; Sebastian, J.; Balocco, D.; Diallo, A. High-efficiency LED driver without electrolytic capacitor for street lighting. *IEEE Trans. Ind. Appl.* **2013**, *49*, 127–137. [CrossRef]
11. Cheng, C.A.; Cheng, H.L.; Chung, T.Y. A novel single-stage high-power-factor LED street-lighting driver with coupled inductors. *IEEE Trans. Ind. Appl.* **2014**, *50*, 3037–3045. [CrossRef]
12. Cheng, H.L.; Lin, C.W. Design and implementation of a high power-factor LED driver with zero-voltage switching-on characteristics. *IEEE Trans. Power Electron.* **2014**, *29*, 4949–4958. [CrossRef]
13. Cheng, C.A.; Chang, C.H.; Chung, T.Y.; Yang, F.L. Design and implementation of a single-stage driver for supplying an LED street-lighting module with power factor corrections. *IEEE Trans. Power Electron.* **2015**, *30*, 956–966. [CrossRef]
14. Wang, Y.; Guan, Y.; Ren, K.; Wang, W.; Xu, D. A single-stage LED driver based on DCM boost circuit and LLC converter for street lighting system. *IEEE Trans. Ind. Electron.* **2015**, *62*, 5446–5457. [CrossRef]
15. Cheng, C.A.; Chung, T.Y. A single-stage LED streetlight driver with PFC and digital-PWM-dimming capability. *Int. J. Circuit Theory Appl.* **2016**, *44*, 1942–1958. [CrossRef]
16. Luo, Q.; Huang, J.; He, Q.; Ma, K.; Zhou, L. Analysis and design of a single-stage isolated AC-DC LED driver with a voltage doubler rectifier. *IEEE Trans. Ind. Electron.* **2017**, *64*, 5807–5817. [CrossRef]
17. Cheng, C.-A.; Chang, C.-H.; Cheng, H.-L.; Tseng, C.-H.; Chung, T.-Y. A single-stage high-power-factor light-emitting diode (LED) driver with coupled inductors for streetlight applications. *Appl. Sci.* **2017**, *7*, 167. [CrossRef]
18. Cheng, C.A.; Cheng, H.L.; Chang, C.H.; Yang, F.L.; Chung, T.Y. A single-stage LED driver for street-lighting applications with interleaving PFC feature. In Proceedings of the IEEE International Symposium on Next-Generation Electronics, Kaohsiung, Taiwan, 25–26 February 2013; pp. 150–152.
19. "Technical Application Guide—POWERTRONIC," OSRAM. January 2013, pp. 1–42. Available online: http://www.osram.com/media/resource/hires/334206/technical-guide---powertronic-for-hid-lamps-gb.pdf (accessed on 30 December 2020).
20. Bellido-Outeiriño, F.J.; Quiles-Latorre, F.J.; Moreno-Moreno, C.D.; Flores-Arias, J.M.; Moreno-García, I.; Ortiz-López, M. Streetlight control system based on wireless communication over DALI protocol. *Sensors* **2016**, *16*, 597. [CrossRef] [PubMed]
21. Elejoste, P.; Angulo, I.; Perallos, A.; Chertudi, A.; Zuazola, I.J.G.; Moreno, A.; Azpilicueta, L.; Astrain, J.J.; Falcone, F.; Villadangos, J. An easy to deploy street light control system based on wireless communication and LED technology. *Sensors* **2013**, *13*, 6492–6523. [CrossRef] [PubMed]
22. Cheng, C.A.; Cheng, H.L.; Chang, C.H.; Chang, E.C.; Hung, W.S.; Lan, L.F. A novel single-stage high-power-factor LED power supply with soft-switching feature for streetlight applications. In Proceedings of the IEEE International Symposium on Computer, Consumer and Control (IS3C2020), Taichung, Taiwan, 13–16 November 2020; pp. 1–3.
23. Cheng, C.A.; Chang, C.H.; Cheng, H.L.; Chang, E.C.; Chung, T.Y.; Chang, M.T. A single-stage LED streetlight driver with soft-switching and interleaved PFC features. *Electronics* **2019**, *8*, 911. [CrossRef]