

A Systematic Design Approach of Non-Isolated LED Driver Based on Integrated Bridgeless Boost PFC Rectifier and ZVS Class-D Resonant Converter

Chainarin Ekkaravarodome¹,
Kamon Jirasereeamornkul², Non-members, and Yuttana Kumsuwan^{3†}, Member

ABSTRACT

A systematic design approach for a high-power-factor integrated-stage, light-emitting diode (LED) driver for street-lighting applications is presented. The proposed scheme integrates a totem-pole bridgeless boost power-factor correction (PFC) rectifier as a PFC stage and non-isolated zero-voltage switching Class-D resonant converter as a driver stage into an integrated stage by sharing power switches and a DC-bus capacitor. High power factor is inherently achieved by operating the totem-pole bridgeless boost PFC rectifier in discontinuous conduction mode. The proposed systematic design and circuit operation are fully detailed using simplified equivalent circuits, which significantly reduces implementation complexity. This thorough methodology further provides a clear, step-by-step guide for component calculation, loss analysis, and component stress evaluation. The validity of this approach is confirmed by experimental results from a 100-W LED street-lighting driver prototype. Experimental results demonstrate a high power factor of 0.99, a total harmonic distortion of the utility-line current of 11.3%, which fully satisfies the IEC 61000-3-2 Class C standard, and a system efficiency of 80%, confirming the validity and practical feasibility of the proposed design.

Keywords: LED driver, integrated-stage, bridgeless boost PFC rectifier, non-isolated ZVS Class-D resonant converter

1. INTRODUCTION

Currently, the light-emitting diode (LED) represents an outstanding technological advancement in various lighting sectors, such as general, automotive, and street lighting. Due to the LED's advantages over other artificial light sources, including its high luminous efficacy and long lifetime, the component cost is rapidly declining [1]. However, a key limitation is that LEDs cannot be connected directly to the alternating current (AC) utility line because their forward voltage exhibits a slight negative temperature coefficient. Consequently, LEDs must be driven by a stable direct current (DC) source with constant-current control, a function typically realized by a switching-mode DC-DC converter [2]–[5], known as an LED driver [6].

To fully realize the advantages of LEDs, the LED driver powered by the utility line must comply with strict regulations for power quality [1], [6]. Specifically, for solid-state lighting equipment exceeding 5 W, ENERGY STAR requires a high power factor (PF) (0.7 for residential and 0.9 for commercial) and low total harmonic distortion of the utility-line current (THD_i). Furthermore, for lighting equipment over 25 W, the current harmonics injected into the utility line must satisfy the limits specified by the IEC 61000-3-2 Class-C standard.

To meet these requirements, the LED driver consists of two stages: 1) a power-factor correction (PFC) stage and 2) a DC-DC converter with a constant-current control stage, called the driver stage. In recent years, many LED driver topologies have been proposed. Basically, LED driver topology can be divided into two categories: 1) Two-stage topology and 2) Integrated-stage topology. The main advantage of the two-stage LED driver is that one easily obtains high PF and low THD_i, and design method is simple due to the PFC stage and DC-DC converter stage working separately. However, both the PFC stage and driver stage need power switches and control circuits, resulting in relatively complex control, large size, and high costs.

To compromise the size and cost, many an integration version of the two-stage LED drivers called the integrated-stage LED drivers. The integrated-stage LED driver can reduce the power switches and the control circuits by combining the PFC stage and the driver stage

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¹The author is with Department of Instrumentation and Electronics Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand.

²The author is with Department of Electronic and Telecommunication Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand.

³The author is with Department of Electrical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, Thailand.

[†]Corresponding author: yuttana.k@cmu.ac.th

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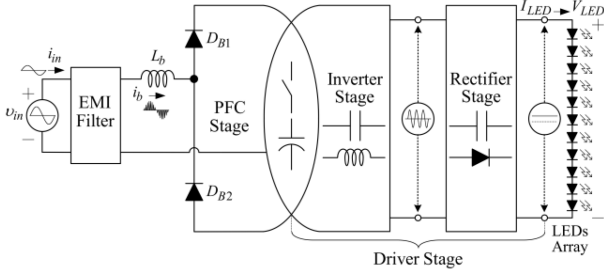


Fig. 1: Circuit diagram of bridgeless non-isolated LED driver with EMI filter.

into one [7], [8]. However, the full-bridge rectifier is an essential component in the input stage of the conventional integrated stage LED driver. This rectifier circuit reduces system efficiency due to increased conduction losses. To overcome this problem, the bridgeless concepts have been introduced, as shown in Fig. 1, and this rectifier can reduce conduction losses by decreasing the number of diodes in the full-bridge rectifier. Therefore, high system efficiency and cost savings can be achieved. Nevertheless, the main drawback of the integrated-stage bridgeless boost PFC rectifier is its increased complexity in both analysis and design [9]–[19].

This paper focuses on the systematic design approach of high PF integrated-stage LED driver for street-lighting applications based on the integration of totem-pole bridgeless boost PFC rectifier as a PFC stage and a non-isolated zero-voltage switching (ZVS) Class-D resonant converter as a driver stage into an integrated-stage by sharing power switches and a DC-bus capacitor.

The developed design approach of the integrated-stage LED driver has the following feature highlights: 1) Design complexity is reduced as simplified equivalent circuits for the inverter and the high-frequency rectifier stages and 2) The design procedure is comprehensively detailed, including component calculation, loss analysis, and component stress evaluation. The validity of this approach is confirmed by experimental results from a 100-W LED street-lighting driver prototype.

2. LED DRIVER STRUCTURE

2.1 Topology Description

Figure 2 presents an integrated-stage LED driver based on the integration of totem-pole bridgeless boost PFC rectifier as the PFC stage and a non-isolated ZVS Class-D resonant converter as the driver stage without an EMI filter. The totem-pole bridgeless boost PFC rectifier, which is designed to be operated in discontinuous conduction mode (DCM) consists of an AC utility-line voltage, a boost inductor L_b and two bridgeless diodes D_{B1} and D_{B2} . The ZVS Class-D resonant converter made of a cascaded Class-D series-resonant inverter and non-isolated zero-current switching (ZCS) Class-D current-driven rectifier consists of two MOSFETs with intrinsic body diodes M_1 and M_2 , a series-resonant circuit L_r and

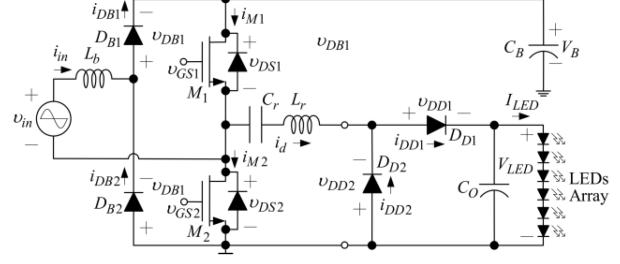


Fig. 2: Bridgeless non-isolated LED driver without EMI filter.

C_r , two diodes D_{D1} , and D_{D2} , an output capacitor C_O , and a DC-bus capacitor C_B stores energy from the PFC stage and provides the DC voltage to the driver stage. In addition, the duty ratios D of M_1 and M_2 are fixed at approximately 0.5. The series-resonant circuit L_r and C_r transforms the MOSFET's square-wave voltage v_{ds2} into a high-frequency current source i_d to drive the ZCS Class-D current-driven rectifier. To simplify the circuit analysis, the following assumptions are made:

- 1) The analysis is performed for the positive half-cycle of the utility-line voltage v_{in} .
- 2) The switching frequency f_s is much higher than the utility-line frequency f_L .
- 3) The capacitances of C_B and C_O are large enough to be modeled as voltage sources.
- 4) The LEDs are modeled as a fixed load resistance R_{LED} in steady state operation.

2.2 Operation Principle in Steady State of Totem-Pole Bridgeless Boost PFC Rectifier

The operation of the totem-pole bridgeless boost PFC rectifier in the DCM during the positive half-cycle of the utility-line voltage v_{in} in one switching cycle and idealized current and voltage waveforms in one line cycle are shown in Figs. 3(a)–(c) and Figs. 4(a)–(d), respectively, which can be divided into three modes:

Mode 1: This mode is shown in Fig. 3(a), the boost inductor L_b stores energy while the M_1 is turned on and M_2 is turned off, allowing utility-line current i_{in} (equals to the boost inductor current i_{Lb}) to flow from the utility-line voltage v_{in} .

Mode 2: With the M_1 is turned off and intrinsic body diode of the M_2 is turned on, the boost inductor L_b discharges its stored energy to the modeled voltage source V_B , as depicted in Fig. 3(b).

Mode 3: With the M_1 and M_2 are turned off, Figure 3(c) shows the totem-pole bridgeless boost PFC rectifier operates in a discontinuous state due to the boost inductor current i_{Lb} is fully discharged. This mode is characterized by a period of no current flow in the PFC stage.

The idealized current and voltage waveforms in one line cycle is shown in Fig. 4. The sinusoidal utility-line voltage v_{in} waveform is presented in Fig. 4(a). Figure 4(b) shows a rectified utility-line voltage $|v_{in}|$ waveform

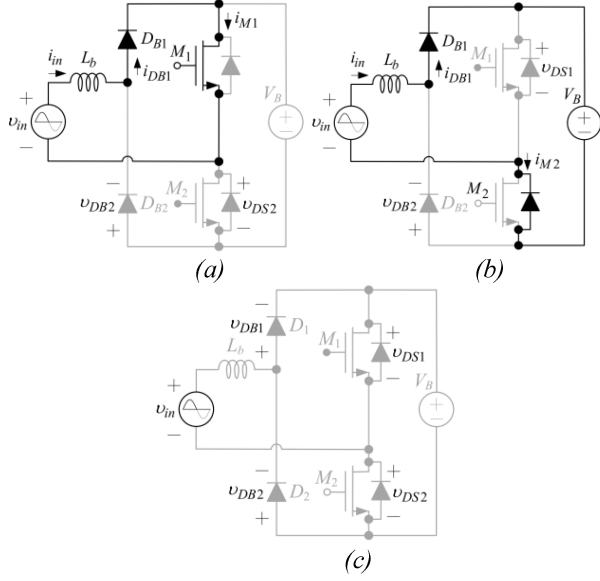


Fig. 3: Operation modes of PFC stage during positive half-cycle of the utility-line voltage v_{in} in one switching cycle. (a) Mode 1: M_1 is turned on and M_2 is turned off, (b) Mode 2: M_1 is turned off and intrinsic body diode of M_2 is turned on, and (c) Mode 3: M_1 and M_2 are turned off.

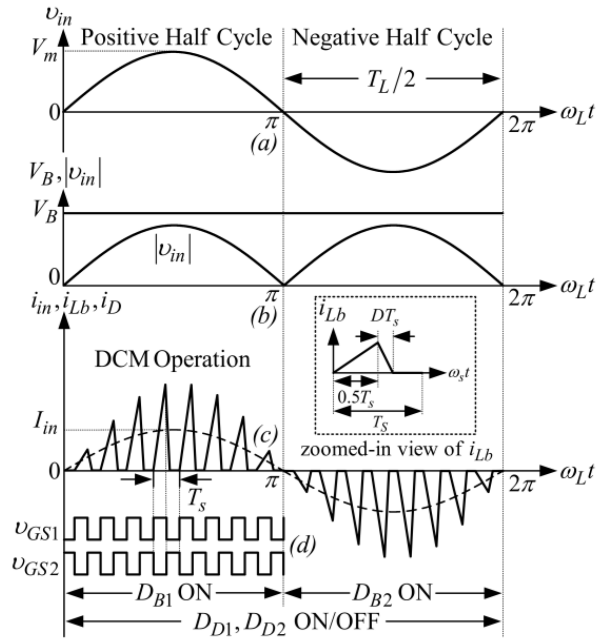


Fig. 4: Idealized current and voltage waveforms in one line cycle. (a) Utility-line voltage v_{in} waveform. (b) Rectified utility-line voltage $|v_{in}|$ versus DC-bus voltage V_B waveforms. (c) Utility-line current i_{in} with and without EMI filter waveforms and (d) Gate-source rectangular-wave voltage waveforms v_{GS1} and v_{GS2} .

versus a DC-bus voltage V_B waveform. Figure 4(c) a utility-line current waveform i_{in} is the filtered average boost inductor current i_{Lb} which is equals to a diode current of the totem-pole bridgeless boost PFC rectifier

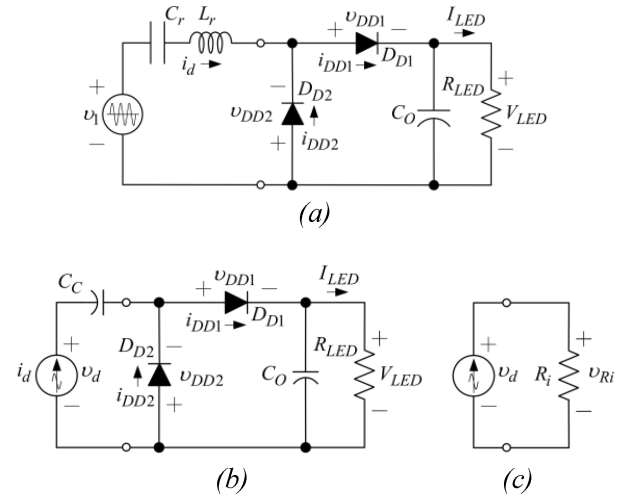


Fig. 5: Non-isolated ZCS Class-D current-driven rectifier. (a) Equivalent circuit of rectifier stage with equivalent fundamental harmonic approximation voltage source, (b) Equivalent circuit of rectifier stage with sine wave current source, and (c) Simplified equivalent circuit of rectifier stage with input impedance.

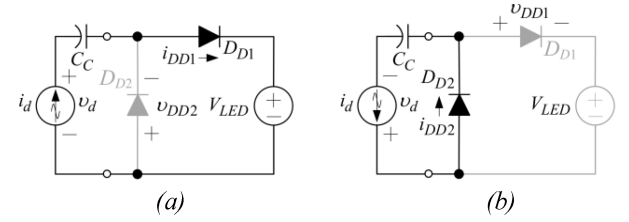


Fig. 6: Simplified equivalent circuit operation modes of rectifier stage. (a) Mode 1: D_{D1} is turned on and D_{D2} is turned off and (b) Mode 2: D_{D1} is turned off and D_{D2} is turned on.

operating in DCM. Figure 4(d) shows nonoverlapping rectangular-wave voltages v_{GS1} and v_{GS2} , that drive the MOSFETs M_1 and M_2 .

2.3 Operation Principle in Steady State of Non-Isolated ZVS Class-D Resonant Converter

The principle of operation of the non-isolated ZVS Class-D converter is shown in Fig. 5. Figure 5(a) illustrates an equivalent circuit of the cascaded inverter stage and rectifier stage with an equivalent coupling capacitor C_C and an equivalent fundamental harmonic approximation voltage source. The series-resonant circuit L_r and C_r transforms the MOSFET's square-wave voltage v_{ds2} into the high-frequency current source i_d to drive the non-isolated ZCS Class-D current-driven rectifier as presented in Fig. 5(b). The input impedance of the non-isolated ZCS Class-D current-driven rectifier is represented by an input resistor R_i as shown in Fig. 5(c).

The operation of the non-isolated ZCS Class-D rectifier and idealized current and voltage waveforms in one switching cycle are shown in Figs. 6(a) and (b) and Fig. 7,

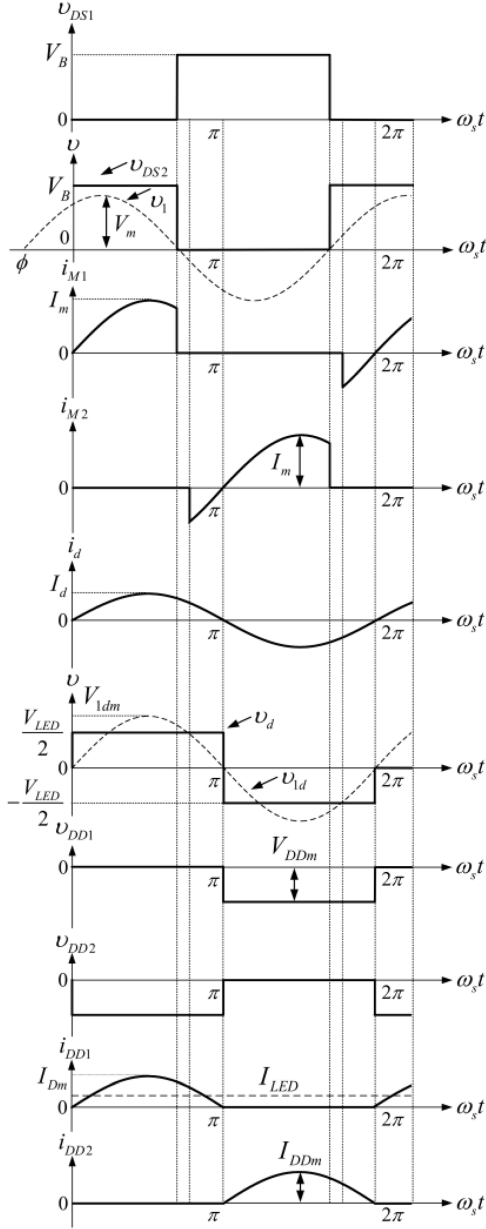


Fig. 7: Idealized current and voltage waveforms in one switching cycle of bridgeless non-isolated LED driver.

respectively, which can be divided into two modes:

Mode 1: With the D_{D1} is turned on and D_{D2} is turned off, the modeled voltage source V_{LED} stores energy while the D_{D1} is turned on and D_{D2} is turned off, as depicted in Fig. 6(a).

Mode 2: With the D_{D1} is turned off and D_{D2} is turned on, the driven current i_d flows through diodes D_{D2} , as depicted in Fig. 6(b). The diodes D_{D1} and D_{D2} begin to turn off when their current reaches zero to reduce turn-off switching loss.

The idealized current and voltage waveforms of the PFC stage and the driver stage during one switching cycle are shown in Fig. 7. The diode currents i_{DD1} and i_{DD2} and diode voltages v_{DD1} and v_{DD2} of the diodes D_{D1} and D_{D2} are operated under ZCS turn-off condition. The MOSFET

currents i_{M1} and i_{M2} and MOSFET voltages v_{M1} and v_{M2} of the MOSFETs M_1 and M_2 are operated under ZVS turn-on condition. As a result, switching losses and switching noise levels are decreased.

3. STEADY STATE ANALYSIS

3.1 PFC Stage

As detailed in [11], [15], inherent PFC is achieved by designing the totem-pole bridgeless boost PFC rectifier to operate in the DCM. The sinusoidal utility-line voltage v_{in} is defined as

$$v_{in} = \sqrt{2}V_{inrms} \sin(\omega_L t), \quad (1)$$

where V_{inrms} and ω_L are the rms value of the sinusoidal input voltage v_{in} and the utility-line angular frequency, respectively. The maximum inductor current i_{Lbm} is obtained as

$$i_{Lbm} = \frac{\sqrt{2}DT_s V_{inrms}}{L_b} \sin \omega_L t, \quad (2)$$

where T_s is the switching period. The maximum duty ratio D that ensures the DCM operation is

$$D \leq 1 - \frac{\sqrt{2}V_{inrms}}{V_B}. \quad (3)$$

The sinusoidal utility-line current i_{in} is equal to the average value of the maximum inductor current i_{Lbm} is obtained as

$$i_{in} = \frac{1}{T_s} \int_0^{T_s} i_{Lbm} dt. \quad (4)$$

The average input power P_{in} is expressed by

$$P_{in} = \frac{1}{T_s} \int_0^{T_s} v_{in} i_{in} dt. \quad (5)$$

From (5), the output power P_{out} is given as

$$P_{out} = \eta P_{in} = \frac{\eta V_B D^2 V_{inrms}^2}{2f_s L_b (V_B - \sqrt{2}V_{inrms})}, \quad (6)$$

where f_s and η are the switching frequency and the system efficiency, respectively.

3.2 Driver Stage

As detailed in [17]–[19]. The ZVS Class-D resonant converter is made of the cascaded Class-D series-resonant inverter and the non-isolated ZCS Class-D current-driven rectifier. Figure 5(a) shows the equivalent circuit of the rectifier stage with an equivalent fundamental harmonic approximation voltage source of the inverter stage. The fundamental component of v_{DS2} is

$$v_1 = V_{1m} \sin(\omega_s t + \phi), \quad (7)$$

where ω_s is the switching angular frequency. The peak fundamental component of v_1 is determined as

$$\begin{aligned} V_{1m} &= \frac{1}{\pi} \int_0^{2\pi} v_{DS2} \sin \omega_s t d\omega_s t, \\ &= \frac{2}{\pi} \int_0^{\pi} \frac{V_B}{2} \sin \omega_s t d\omega_s t, \\ &= \frac{2V_B}{\pi}. \end{aligned} \quad (8)$$

Assume that the non-isolated ZCS Class-D rectifier is driven by an ideal sinusoidal current-source from the inverter stage, from Fig. 5(b), the driven current i_d is defined as

$$i_d = I_{dm} \sin \omega_s t, \quad (9)$$

where I_{dm} is the maximum driven current. The input voltage of the rectifier stage v_d is determined as

$$v_d = \begin{cases} \frac{V_{LED}}{2}, & 0 < \omega_s t < \pi \\ -\frac{V_{LED}}{2}, & \pi < \omega_s t < 2\pi, \end{cases} \quad (10)$$

where V_{LED} is the LEDs voltage. The rms value of the fundamental component of the input voltage of the rectifier stage V_{d1rms} is given as

$$\begin{aligned} V_{d1rms} &= \frac{1}{\pi} \int_0^{2\pi} v_d^2 \sin \omega_s t d\omega_s t, \\ &= \frac{2}{\pi} \int_0^{\pi} \frac{V_{LED}}{2} d\omega_s t, \\ &= \frac{\sqrt{2}V_{LED}}{\pi}. \end{aligned} \quad (11)$$

The input resistance of the non-isolated ZCS Class-D current-driven rectifier R_i is expressed as

$$R_i = \frac{V_{d1m}}{I_{dm}} = \frac{2V_{LED}^2}{\eta_R P_{out} \pi^2}, \quad (12)$$

where $V_{d1m} = \sqrt{2}V_{d1rms}$ is the maximum fundamental component of the input voltage of the rectifier stage. The voltage transfer function of the rectifier stage M_{VR} is obtained as

$$M_{VR} = \frac{V_{LED}}{V_{d1rms}} = \frac{\pi \eta_R}{\sqrt{2}}, \quad (13)$$

where η_R is the rectifier stage efficiency. The loaded quality factor Q_L is given as

$$Q_L = \frac{\sqrt{\frac{\eta_I^2}{\left(\frac{\pi V_{LED}}{\sqrt{2}V_B M_{VR}}\right)^2} - 1}}{\left|\frac{\omega_s}{\omega_o} - \frac{\omega_o}{\omega_s}\right|}, \quad (14)$$

where η_I is the inverter stage efficiency. The current through the diode D_{D1} of the rectifier stage i_{DD1} is

$$i_{DD1} = \begin{cases} I_{dm} \sin \omega_s t, & 0 < \omega_s t < \pi \\ 0, & \pi < \omega_s t < 2\pi \end{cases} \quad (15)$$

and

$$i_{DD2} = \begin{cases} 0, & 0 < \omega_s t < \pi \\ I_{dm} \sin \omega_s t, & \pi < \omega_s t < 2\pi \end{cases} \quad (16)$$

The output current of the LED driver I_{LED} is

$$\begin{aligned} I_{LED} &= \frac{1}{2\pi} \int_0^{2\pi} i_{DD1} d\omega_s t, \\ &= \frac{I_{dm}}{2\pi} \int_0^{\pi} \sin \omega_s t d\omega_s t, \\ &= \frac{I_{dm}}{\pi}. \end{aligned} \quad (17)$$

The output voltage of the LED driver V_{LED} is

$$V_{LED} = I_{LED} R_{LED} = \frac{I_{dm} R_{LED}}{\pi}. \quad (18)$$

4. DESIGN PROCEDURE

4.1 Component Design

The systematic design approach utilizes the totem-pole bridgeless boost PFC rectifier as the PFC stage and the non-isolated ZVS Class-D resonant converter as the driver stage, all while sharing the power switches and the DC-bus capacitor. The design procedures of the proposed LED driver are given as follows:

- 1) First, specify the output voltage V_{LED} and the output power P_{out} , then calculate the load resistance R_{LED} .
- 2) Provide the utility-line rms voltage V_{inrms} and the duty ratio D to calculate the DC-bus voltage V_B .
- 3) Define the switching frequency f_s and expect the system efficiency η to calculate the boost inductance L_b of the PFC stage.
- 4) Calculate the voltage transfer function of the rectifier stage.
- 5) Expect the inverter stage efficiency η_I and select the angular frequency ratio ω_s/ω_o to calculate the loaded quality factor Q_L .
- 6) Expect the rectifier stage efficiency η_R to calculate the input resistance of the non-isolated ZCS Class-D current-driven rectifier R_i .
- 7) Find the resonant inductance L_r and the resonant capacitance C_r .
- 8) Find the maximum switch currents I_{DBm} , I_{DDm} , and I_m .
- 9) Finally, calculate the maximum switch voltages V_{DBm} , V_{DDm} , and V_m .

The design steps for the 100-W LED street-light driver, which uses the totem-pole bridgeless boost PFC rectifier and the non-isolated ZVS Class-D resonant converter is shown in Fig. 8. The specifications of the laboratory prototype are given in Table 1. The fixed load resistance R_{LED} is obtained by

$$R_{LED} = \frac{V_{LED}^2}{P_{out}}. \quad (19)$$

The maximum value of the driven current I_{dm} is obtained as

$$I_{dm} = \frac{\pi P_{out}}{V_{LED}}. \quad (20)$$

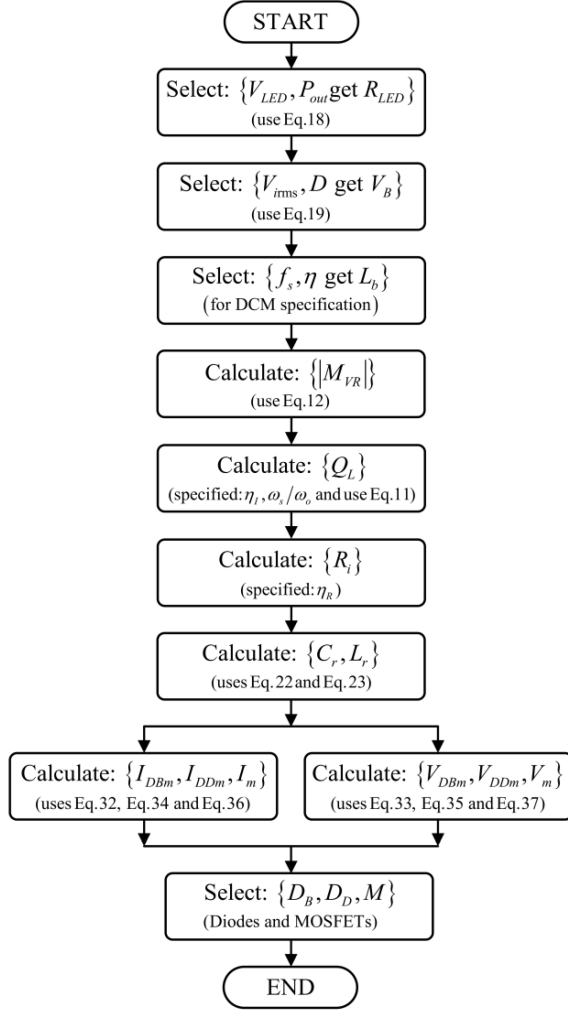


Fig. 8: Design steps for LED driver based on totem-pole bridgeless boost PFC rectifier and non-isolated ZVS Class-D resonant converter.

Table 1: Laboratory Prototype Specifications

Specifications	Value
Utility-line rms voltage V_{inrms}	110 V / 50 Hz
Output voltage V_{LED}	96 V
Output power P_{out}	100 W
Switching frequency f_s	60 kHz
Duty ratio D	0.5
System efficiency η	0.8

The DC-bus voltage V_B is calculated by

$$V_B = \frac{\sqrt{2}V_{inrms}}{1-D}. \quad (21)$$

The boost inductance L_b that ensures the DCM operation is given as

$$L_b = \frac{\eta V_B D^2 V_{inrms}^2}{2f_s P_{out}(V_B - \sqrt{2}V_{inrms})}. \quad (22)$$

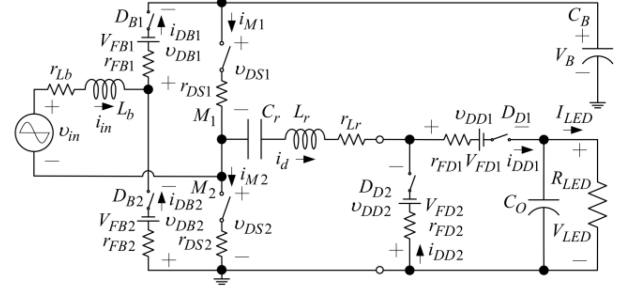


Fig. 9: Equivalent circuit for conduction loss analysis of bridgeless non-isolated LED driver.

The voltage transfer function of the rectifier stage $|M_{VR}|$ and the loaded quality factor Q_L are calculated using (13) and (14), respectively. The input resistance of the non-isolated ZCS Class-D rectifier R_i is obtained as

$$R_i = \frac{2R_{LED}}{\pi^2 \eta_R} \quad (23)$$

The resonant inductance L_r is calculated as

$$L_r = \frac{Q_L R_i}{2\pi \eta_I f_o} \quad (24)$$

The resonant capacitance C_r is expressed as

$$C_r = \frac{\eta_I}{2\pi f_o Q_L R_i} \quad (25)$$

Finally, the DC-bus capacitance C_B and the output capacitance C_O were calculated using the approach described in references [7], [18], [19].

4.2 Conduction Loss Analysis

Figure 9 shows the equivalent circuit used for conduction loss analysis. In this model, the MOSFETs are represented by ideal switches in series with their respective on-resistances r_{DS1} and r_{DS2} . The ESRs of the passive components, namely the EMI filter inductor L_f , the boost inductor L_b , and the resonant inductor L_r , are represented by r_{Lf} , r_{Lb} , and r_{Lr} . Finally, the power diodes are modeled by an ideal switch in series with a constant forward voltage source V_F and an on-resistance r_F . The conduction loss in one bridgeless rectifier diode P_{DB1} or P_{DB2} due to V_{FB} and r_{FB} is found as

$$P_{DB1} = P_{DB2} = \frac{\sqrt{2}V_{FB}P_{out}}{\eta V_{inrms}} + \frac{r_{FB}P_{out}^2}{2\eta^2 V_{inrms}^2} \quad (26)$$

The conduction loss in one ZCS Class-D current-driven rectifier diode P_{DD1} or P_{DD2} due to V_{FD} and r_{FD} is

$$P_{DD1} = P_{DD2} = V_{FD}I_{LED} + \frac{r_{FD}\pi^2 I_{LED}^2}{4} \quad (27)$$

The power dissipated in the ESR of the EMI filter inductor P_{Lf} is

$$P_{Lf} = \frac{r_{Lf} P_{out}^2}{\eta^2 V_{inrms}^2} \quad (28)$$

The power dissipated in the ESR of the boost inductor P_{Lb} is calculated by

$$P_{Lb} = \frac{r_{Lb} P_{out}^2}{\eta^2 V_{inrms}^2} \quad (29)$$

The power dissipated in the ESR of the resonant inductor P_{Lr} is

$$P_{Lr} = \frac{2r_{Lr}\eta_I^2 V_B^2}{\pi^2 R_i^2 \left[1 + Q_L^2 \left(\frac{\omega_s}{\omega_o} - \frac{\omega_o}{\omega_s} \right)^2 \right]} \quad (30)$$

Neglecting switching losses, the conduction loss in each MOSFET P_{DS1} or P_{DS2} is obtained as

$$P_{DS1} = P_{DS2} = I_{DSrms}^2 r_{DS(on)} \quad (31)$$

where

$$\begin{aligned} I_{DSrms} &= \sqrt{I_{inrms}^2 + I_{drms}^2} \\ &= \sqrt{\frac{P_{out}^2}{\eta^2 V_{inrms}^2} + \frac{2r_{Lr}\eta_I^2}{\pi^2 R_i^2 \left(1 + Q_L^2 \left(\frac{\omega_s}{\omega_o} - \frac{\omega_o}{\omega_s} \right)^2 \right)}} \end{aligned} \quad (32)$$

Due to the very small ESR in the capacitors C_f , C_r , C_B , and C_O , the resulting conduction losses are considered minimal and were therefore neglected.

4.3 Component Stresses

The peak voltage across the resonant capacitor C_r and the resonant inductor L_r is designed to be equal

$$V_{Cm} = V_{Lm} = \frac{2V_B Q_L}{\pi} \quad (33)$$

The peak forward current of the bridgeless rectifier diode I_{DBm} is equal to the maximum utility-line current I_{in}

$$I_{DBm} = \frac{\sqrt{2} D V_{inrms}}{f_s L_b} \quad (34)$$

The maximum reverse voltage across the bridgeless rectifier diode V_{DBm} is equal to the DC-bus voltage V_B

$$V_{DBm} = V_B \quad (35)$$

The peak forward current of the ZCS Class-D current-driven rectifier diode I_{DDm} is

$$I_{DDm} = \pi I_{LED} \quad (36)$$

Table 2: Circuit Parameters of Proposed LED Driver.

Symbol	Part Number/Value	Type
PFC Stage		
D_{B1}, D_{B2}	MUR860	Fast-recovery diode
L_b	441 μ H	N87 EE42/21/15
Driver Stage		
D_{D1}, D_{D2}	STPS30150CW	Schottky diode
L_r	618 μ H	N87 EE42/21/15
C_r	15 nF / 1,000 V	Polypropylene
C_O	2,200 μ F / 160 V	Electrolytic
Sharing Stage		
M_1, M_2	IPP60R190C6	SJ MOSFET
C_B	220 μ F / 450 V	Electrolytic
EMI Filter		
L_f	500 μ H	N87 EE20/10/11
C_f	0.3 μ F / 250 V	Polypropylene

The peak reverse voltage across the ZCS Class-D current-driven rectifier diode V_{DDm} is equal to the output voltage V_{LED}

$$V_{DDm} = V_{LED} \quad (37)$$

The maximum MOSFET current I_m occurs at $f_s = f_o$

$$I_m = \frac{\sqrt{2} D V_{inrms}}{f_s L_b} + \frac{\pi P_{out}}{V_{LED}} \quad (38)$$

The peak voltage across each MOSFET V_m is equal to the DC-bus voltage V_B

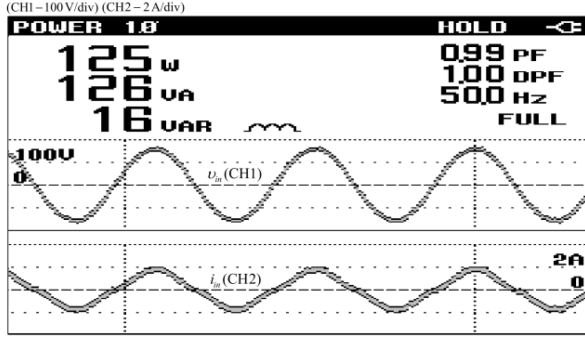
$$V_m = V_B \quad (39)$$

5. EXPERIMENTAL RESULTS

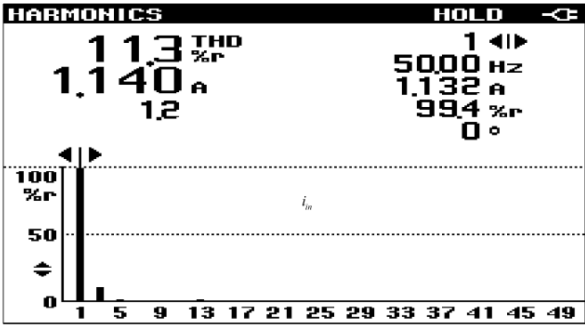
The proposed single-stage converter is intended for LED lighting, where the driver and LEDs are safely enclosed inside an insulated casing. Since users cannot touch any live electrical parts, the non-isolated design has no safety hazards while keeping the system low-cost and compact.

The detail of parameter design is illustrated in Section 2. The proposed 100-W LED street-light driver prototype was constructed using the circuit parameters in Table 2 to verify the theoretical analysis in Section 2. The utility-line voltage was set to 110 Vrms / 50 Hz and output power was set to 100 W.

Figure 10(a) shows the experimental steady-state operating waveforms of the utility-line voltage v_{in} and current i_{in} . The current i_{in} is nearly sinusoidal and in phase with the utility-line voltage v_{in} , yielding a PF of 0.99. Evidently, the measured PF significantly exceeds the U.S. Energy Star program recommendation. As shown in Fig. 10(b), the THD of the input current i_{in} is 11.3%. Furthermore, the input current harmonics of the proposed LED driver remain well below the IEC 61000-3-2 Class-C standard limits.

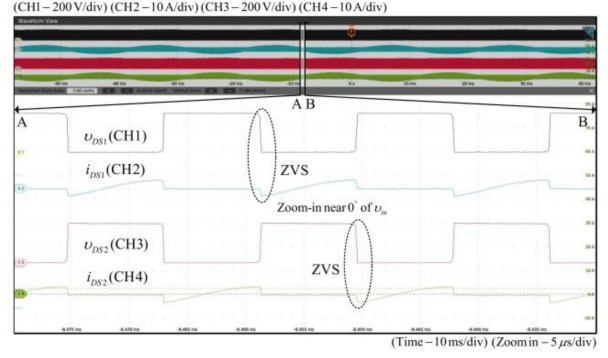


(a)

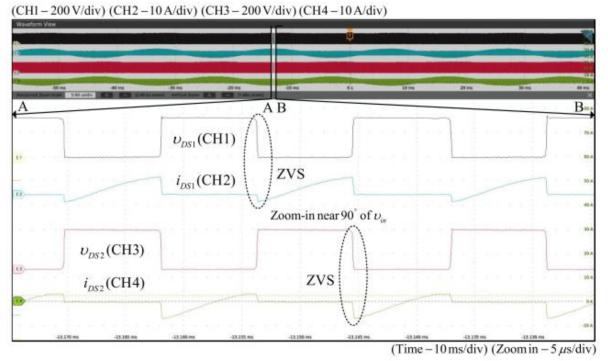


(b)

Fig. 10: Utility-line voltage v_{in} , utility-line current i_{in} , and the corresponding harmonic spectrum of the proposed LED driver. (a) experimental waveforms of the utility-line voltage v_{in} and utility-line current i_{in} and (b) measured THD_i value and individual harmonic content breakdown.



(a)



(b)

Fig. 12: Experimental voltage and current waveforms of MOSFETs M_1 and M_2 of sharing stage. (a) near 0° of v_{in} and (b) near 90° of v_{in} .

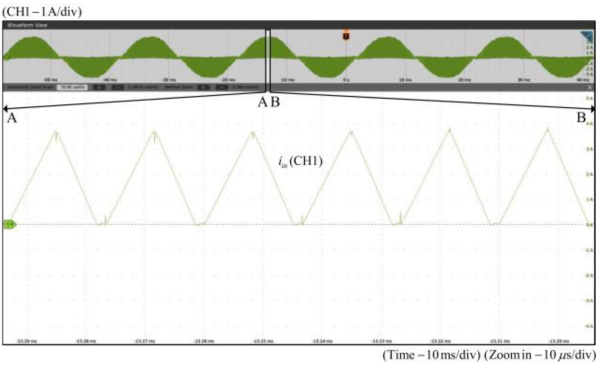


Fig. 11: Experimental boost inductor current i_{Lb} waveforms of PFC stage.

The experimental boost inductor current i_{Lb} is shown in Fig. 11 (top), the bottom waveform provides a zoomed-in view of i_{Lb} near 90 degrees of the utility-line voltage v_{in} . It was evident that the boost inductor i_{Lb} was designed to operate in DCM to achieve PFC.

Figures 12(a) and (b) illustrate the experimental voltage and the current waveforms for MOSFETs M_1 and M_2 of the sharing stage near 0 degrees and 90 degrees of the utility-line voltage v_{in} , respectively. The results show that both MOSFETs turn on with ZVS at a low dv/dt , thereby achieving high efficiency and low switching

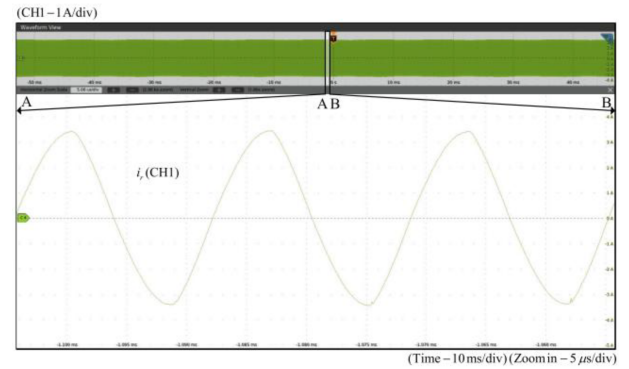


Fig. 13: Experimental waveform of high frequency driven current i_d of inverter stage.

noise.

Figure 13 (top) shows the experimental waveform of the driven current i_d near 90 degrees of the utility-line voltage v_{in} , the bottom waveform provides a zoomed-in view of i_d . It is observed that the driven current i_d magnitude was 3.5 A.

Figure 14 presents the voltage and the current waveforms for the diodes D_{D1} and D_{D2} of the ZCS Class-D current-driven rectifier. The waveforms verify that both diodes achieve the ZCS condition, thereby ensuring high efficiency and minimizing switching noise.

The experimental steady-state operating waveforms

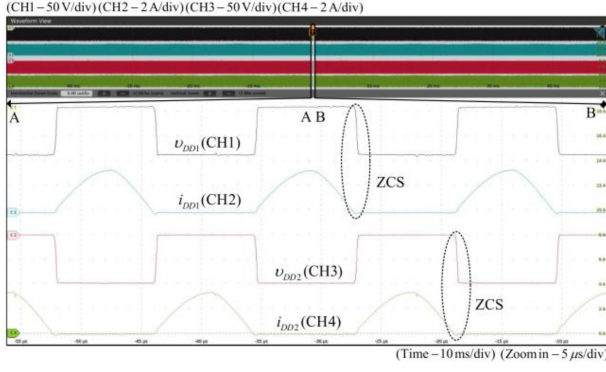


Fig. 14: Experimental voltage and current waveforms of diodes D_{D1} and D_{D2} of rectifier stage.

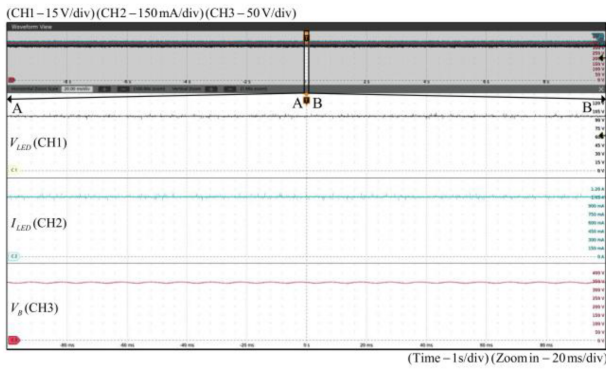


Fig. 15: Experimented waveforms of output voltage V_{LED} , output current I_{LED} , and DC-bus voltage V_B .

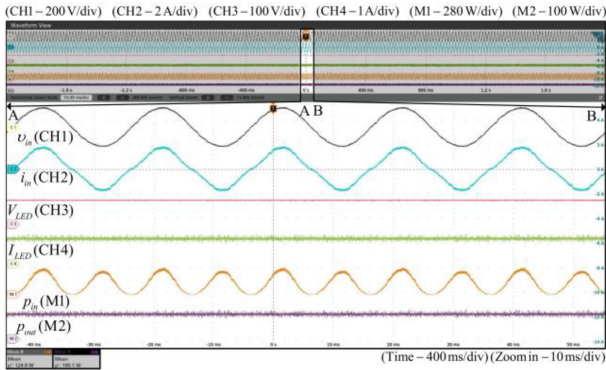


Fig. 16: Experimental waveforms of utility-line voltage v_{in} , utility-line current i_{in} , output voltage V_{LED} , output current I_{LED} , input power p_{in} , and output power P_{out} .

of the LED voltage V_{LED} , LED current I_{LED} , and DC bus voltage V_B are presented in Fig. 15. The resulting LED current I_{LED} complies with the IEEE 1789-2015 standard, which recommends a low-risk flicker percentage of less than 8% at $2f_L = 100$ Hz.

Figure 16 presents the measured utility-line voltage v_{in} and current i_{in} , LED voltage V_{LED} , and LED current I_{LED} , waveforms, along with the calculated input and output power waveforms, including a zoomed-in view at full load with a nominal utility-line voltage v_{in} of

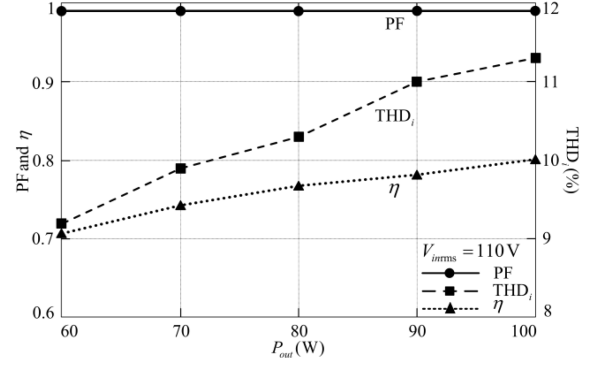


Fig. 17: Measured PF, η , and THD_i versus output power P_{out} at $V_{inrms} = 110$ V.

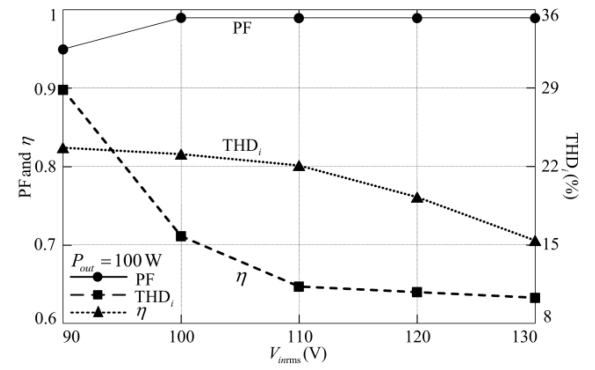


Fig. 18: Measured PF, η , and THD_i versus input voltage v_{in} at $P_{out} = 100$ W.

110 Vrms. The calculated input power P_{in} is approximately 124.9 W, while the achieved output power P_{out} is 100.1 W, resulting in an experimental full-load efficiency of approximately 80%.

Figure 17 shows the measured PF, η , and THD_i plotted against the output power P_{out} at a utility-line voltage v_{in} of 110 Vrms. As illustrated, the proposed LED driver maintains a very high PF across the entire load range. Specifically, the measured PF exceeds 0.99 for all output loads from 60 W to 100 W. Over this load range, the efficiency increases from 70.7% to 80.1%, while the THD_i decreases from 11.3% to 9.2%. Additionally, the ZVS Class-D resonant converter with a half-wave rectifier topology was intentionally selected to achieve a low-cost, low-complexity circuit structure, as it is the only viable topology that operates without requiring a transformer. While the current measured system efficiency is around 80%, higher efficiency can be readily achieved for applications where higher performance is prioritized over circuit simplicity. Specifically, future optimization can be made by adopting a center-tapped rectifier topology, which inherently offers superior efficiency characteristics compared to the half-wave rectifier topology.

Figure 18 shows the measured PF, η , and THD_i plotted against the utility-line voltage v_{in} at a constant output power P_{out} of 100 W. As illustrated, the proposed

LED driver achieves a peak efficiency of approximately 82.4%, which decreases to 70.5% as the input voltage increases from 90 Vrms to 130 Vrms. Meanwhile, the measured PF ranges from 0.95 to 0.99, while the THD_i drops significantly from 28.9% to 10.3%. Figures 17 and 18 demonstrate that the experimental PF well exceeds the U.S. Energy Star program requirements, while the measured THD_i consistently complies with the IEC 61000-3-2 Class-C standard limits.

An SG3525 integrated circuit (IC) is used as a variable-frequency controller, alongside an IR2110 IC as the high-side and low-side gate driver. Although a closed-loop controller is ultimately required for fast dynamic behavior, an open-loop control scheme is implemented in this laboratory prototype to validate the key contributions of the proposed converter. A detailed closed-loop study to predict steady-state and large-signal dynamic characteristics is recommended for future research.

6. CONCLUSION

A systematic design approach for a high-power-factor integrated-stage, LED driver for street-lighting applications was presented. The proposed scheme integrates the totem-pole bridgeless boost PFC rectifier as the PFC stage and the non-isolated ZVS Class-D resonant converter as the driver stage into the integrated stage by sharing the power switches and the DC-bus capacitor. High power factor is inherently achieved by operating the totem-pole bridgeless boost PFC rectifier in DCM.

The proposed systematic design and circuit operation are fully detailed using simplified equivalent circuits, which significantly reduces implementation complexity. This thorough methodology further provides a clear, step-by-step guide for component calculation, loss analysis, and component stress evaluation. To validate the approach, a prototype LED driver operating at a switching frequency of 60 kHz and a 110 Vrms / 50-Hz utility-line voltage was constructed to drive a 100 W LED street-lighting load. The resulting LED driver shown a PF of 0.99 and a THD_i of 11.3%, fully satisfying the IEC 61000-3-2 Class-C standard for lighting equipment, alongside a system efficiency of 80%. Finally, the proposed approach's validity was confirmed through consistent results obtained from experimental verification.

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Chainarin Ekkaravarodome received the B.Ind.Tech. degree in industrial electrical technology from the King Mongkut's Institute of Technology North Bangkok, Bangkok, Thailand, in 2003, and the M.E. and Ph.D. degrees in electrical engineering and energy technology from the King Mongkut's University of Technology Thonburi, Bangkok, in 2005 and 2009, respectively. He is currently an Associate Professor with the Department of Instrumentation and Electronics Engineering,

Faculty of Engineering, King Mongkut's University of Technology North Bangkok. His current research interests include induction heating, LED drivers, power-factor correction circuits, resonant rectifiers, soft-switching power converters, and wireless power transfer.



Kamon Jirasereeamornkul received the B.E. and M.E. degrees in electrical engineering and the Ph.D. degree in electrical and computer engineering from the King Mongkut's University of Technology Thonburi, Bangkok, Thailand, in 1997, 2001, and 2006, respectively. He is currently an Assistant Professor with the Department of Electronic and Telecommunication Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi. His current research interests include induction heating, LED drivers, power-factor-correction circuits, resonant rectifiers, soft-switching power converters, and wireless power transfer.

search interests include induction heating, LED drivers, power-factor-correction circuits, resonant rectifiers, soft-switching power converters, and wireless power transfer.



Yuttana Kumsuwan received the Ph.D. degree in electrical engineering from Chiang Mai University, Chiang Mai, Thailand, in 2007. He is currently a Professor with the Department of Electrical Engineering, Faculty of Engineering, Chiang Mai University. He is the author of more than 100 technical papers (journal articles and conference proceeding papers). His current research interests include renewable energy systems, high-power converters, electric vehicles, and control of power electronics.

power electronics.