# A Si ngl e－St age LED Driver Based on ZCDS Cl ass－E Current－Driven Rectifier as a PFC for Street－Li ght ing Appl i cations 

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# A Single-Stage LED Driver based on ZCDS Class-E Current-Driven Rectifier as a PFC for Street-Lighting Applications 

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Abstract-This paper presents a light-emitting diode (LED) driver for street-lighting applications that uses a resonant rectifier as a power-factor corrector (PFC). The PFC semi-stage is based on a zero-current and zero-derivative-switching (ZCDS) Class-E current-driven rectifier, and the LED driver semi-stage is based on a zero-voltage-switching (ZVS) Class-D $L L C$ resonant converter that is integrated into a singlestage topology. To increase the conduction angle of the bridge-rectifier diodes current and to decrease the current harmonics that are injected in the utility line, the ZCDS Class-E rectifier is placed between the bridge-rectifier and a DC-link capacitor. The ZCDS Class-E rectifier is driven by a high-frequency current source, which is obtained from a square-wave output voltage of the ZVS Class-D LLC resonant converter using a matching network. Additionally, the proposed converter has a soft-switching characteristic that reduces switching losses and switching noise. A prototype for a 150-W LED street light has been developed and tested to evaluate the performance of the proposed approach. The proposed LED driver had a high efficiency ( $>91 \%$ ), a high PF $\left(>0.99\right.$ ), and a low $\operatorname{THD}_{i}(<8 \%)$ under variation of the utility-line input voltage from $180 \sim 250 \mathrm{~V}_{\text {rms }}$. These experimental results demonstrate the feasibility of the proposed LED scheme.

Index Terms-Street-lighting system, LED driver, power-factor correction, soft-switching techniques, Class-E current-driven rectifier.

## Footnote

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## I. Introduction

The conventional light sources for street-lighting systems that are using gas discharge lamps, such as high-pressure sodium vapor lamps and metal halide lamps, will inevitably be replaced by high-brightness light-emitting diodes (HB-LEDs) for the next generation of lighting applications. This replacement is due to the attractive characteristics of the latter source, including its high efficacy, good color-rendering index, long lifespan, ecological friendliness, and low price. HB-LEDs do not require high-striking voltage during starting and hot restarting. Table I shows some comparisons of the high-pressure sodium vapor lamps, metal halide lamps, and HB-LEDs for street-lighting systems. Typically, the rated lamp power of a commercialized LED street light lies between 60 W to 240 W [1]. An LED also requires a driving circuit called an LED driver to operate, which is similar to the ballast for the gas-discharge lamps. The main function of the LED driver is to convert a high-voltage alternating current (AC) from the utility line into a low-voltage direct current (DC) with constant-current control.

The generic implementation of a two-stage LED driver and a single-stage LED driver are presented in Fig. 1(a) and (b), respectively. Commonly, LED drivers for HB-LED employ two-stage topologies, which consist of a PFC stage and a DC-DC converter stage with constant-current control, as presented by many researchers [2]-[10]. These topologies are relatively easy to design because each part is separated. However, many power switches and control circuits in each stage are required, which leads to high costs and large size. Therefore, the two-stage topologies are suitable for high-power applications. To overcome these problems, single-stage topologies in which a PFC semi-stage and a DC-DC converter semi-stage are integrated into one as has been proposed by many researchers in recent years [11]-[39]. All the existing

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single-stage topologies can be classified based on the number of their power switches: usually a single switch or two switches. The main advantage of single-stage single-switch topologies [11]-[21] is a low cost. Additionally, these topologies are usually chosen for low-power applications, such as residential and commercial applications, due to the high-voltage stress. Single-stage two-switch topologies are usually suitable for medium-power applications. Nevertheless, the single-stage two-switch topologies [22]-[39] are chosen when system efficiency, the total harmonic distortion of the utility-line input current and a low DC-link voltage stress are the main design targets.

Some single-stage two-switch topologies have been proposed and based on resonant rectifiers, such as a PFC semi-stage [34]-[39]. The high-power-factor and the low-line current harmonic are achieved using the output characteristics of the resonant rectifier, which is placed between the front-end bridge-rectifier and a DC-voltage link. The various kinds of resonant rectifiers that are used as a power-factor corrector can be divided into two categories, as illustrated in Fig. 2. The first group is the zero-voltage-switching (ZVS) topologies, which can be further divided into two sub-groups: the Class-E- based topology, such as a Class-E current-driven rectifier that is used as a power-factor corrector (CECS-RPFC) [34]; and the Class-DE-based topology, such as a Class-DE current-driven rectifier that is used as a power-factor corrector (CDECS-RPFC) [35]-[37]. These ZVS rectifiers are operated under zero-voltage and zeroderivative switching (ZVDS) conditions. Despite their low-line current harmonic contents and high power-factor, the ZVS groups have a main problem of high-conduction losses in the power switches near the zero-crossing of the utility-line input voltage; this conduction loss leads to relatively low-system efficiency. The second group is the zero-current-switching (ZCS) topologies, which can be further divided into two sub-groups: the Class-D-based topology, such as a Class-D current-driven rectifier that is used as a power-factor corrector (CDCS-RPFC) [38], [39], which has a high system efficiency and a high total harmonic distortion (THD) of the utility-line input current; and the Class-E-based topology, which is the scheme proposed in this paper.

This paper presents a new topology of the RPFC family in which a ZCDS Class-E current-driven rectifier is used as a power-factor corrector (CECS-RPFC) of a single-stage LED street-light driver. The system efficiency, switching noise, and utility-line input current harmonic can be improved when compared with the previously reported ZVS-RPFC and ZCS-RPFC topologies. The step-by-step design procedures, power loss analysis, experimental validation of theory, and performance comparison are given.

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II. Structure of Proposed LED Driver

## A. Resonant Rectifier for Power-Factor Correction Concept

Fig. 3 depicts a conceptual diagram with key waveforms of the resonant rectifier as a power-factor corrector based on a ZCDS Class-E current-driven rectifier. The ZCDS Class-E current-driven rectifier is placed between the bridge-rectifier, and the DC-link capacitor is driven by a high-frequency current source. Additionally, a part of the ZCDS Class-E current-driven rectifier performs the function of a pass device across which the voltage difference $v_{O}$ that is dropped. To increase the current conduction angle of the bridge-rectifier diodes and to decrease the current harmonics injected in the utility-line input, the DClink voltage $V_{B}$ should be higher than the peak of the rectified utility-line input voltage $\left|v_{\text {in }}\right|$, and the output voltage of the ZCDS Class-E current-driven rectifier $v_{O}$ should be high near the zero crossing of the utility-line input voltage and low near the peak of the utility-line input voltage. The analysis and design of the proposed single-stage LED driver that is based on a ZCDS-CECS-RPFC is carried out under the following assumptions to simplify the analysis:

1) the power MOSFETs and the power diodes form an ideal switch whose on-state voltage equals zero, off-state is modeled by an infinite resistance, and switching time equals zero. However, their parasitic capacitor and anti-parallel diode of the power MOSFETs are considered as a function of the ZVS operation.
2) the passive components are linear and do not have parasitic components except for a transformer at the load matching network, which uses the transformer parasitic elements as resonant components.
3) the DC-filter capacitors are large enough that their voltages are approximately constant over one switching cycle and the $L C$ input filter is not present in the circuit.
4) in the steady state, the LED is considered as a load resistor with a fixed resistance.

## B. Circuit Description

The circuit diagram of the proposed single-stage LED driver of an LED street light with an output voltage and current controller is shown in Fig. 4. The presented single-stage LED driver consists of a bridge-rectifier $D_{1}-D_{2}-D_{3}-D_{4}$, a differential-mode electromagnetic interference (EMI) filter $L_{f}-C_{f}$, which is inserted on the DC side and serves as a filter to prevent the high-frequency current of the PFC semi-stage entering the bridge rectifier. Hence, the bridge-rectifier can use standard-recovery diodes. The ZCDS Class-E current-driven rectifier for the PFC contains a fast-recovery diode $D_{E}$ and a high-frequency transformer $T_{1}$ as an isolating device and a part of the matching network. A series-resonant circuit $L_{d c}-C_{d}$

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serves the function of high-frequency current shaping, which is fed by a square-wave output voltage $v_{p}$ from the ZVS Class-D $L L C$ resonant converter and is converted into a high-frequency current source $i_{d p}$ to drive the ZCDS Class-E current-driven rectifier. A DC-link capacitor $C_{B}$ is charged by the PFC semistage and can be regarded as a voltage source that supplies the LED driver semi-stage [40]-[45]. The ZVS Class-D $L L C$ resonant converter consists of a matching network $C_{r}-L_{r}-L_{m D}$, which must present an inductive load to ensure ZVS operation; a center-tapped transformer $T_{2}$ with a turns ratio of $N_{p}: N_{s 1}: N_{s 2}=$ $n_{L L C}: 1: 1$, full-wave center-tapped rectifier $D_{D 1}-D_{D 2}$, and an output capacitor $C_{O}$. The transformer $T_{2}$ is also an isolation device and a part of matching network, where $L_{m D}$ is the magnetizing inductance, and $L_{r}$ is the transformer leakage inductance. A pair of bidirectional switches $M_{1}-M_{2}$ is operated with a duty ratio of approximately 0.5 . Each switch is comprised of a transistor and an anti-parallel diode. The metal-oxidesemiconductor field-effect transistors (MOSFETs) are preferred devices because their body diodes can be used for operation above resonance. A dual control loop of a constant voltage (CV) and a constant current (CC) controller, part number SEA05 (STMicroelectronics), is used to detect the output voltage through the resistive voltage divider and the output current through the current sensing resistor. The output signal of the CV/CC controller is fed into a variable-frequency controller with gate driver part number L6599 (STMicroelectronics) via the photocoupler, part number PC851 (Sharp Microelectronics).

## C. Operating Principle

The operation principle of the ZCDS Class-E current-driven rectifier in the PFC semi-stage is described by an equivalent circuit presented in Fig. 5(a). The two standard-recovery diodes $D_{1}$ and $D_{4}$ of the bridge-rectifier conduct during the positive half-cycle of the utility-line input voltage $v_{i n}=V_{i n} \sin \omega_{L} t$, where $\omega_{L}$ is a line angular frequency. The two standard-recovery diodes $D_{2}$ and $D_{3}$ conduct during the negative utility-line input half-cycle. The model of the positive utility-line input voltage rectifier output is a full-wave rectified sinusoidal voltage source $\left|v_{i n}\right|=V_{i n}\left|\sin \omega_{L} t\right|$. For simplicity sake, the fundamentalcomponent approximation is used in the analysis of the rectifier with adequate accuracy. An inductance $L_{m E}$ is a reflected magnetizing inductance from the primary side to the secondary side of the transformer $T_{1}$. To simplify the design procedure, assume that the transformer $T_{1}$ is ideal. Therefore, the transformer turns ratio is $n_{P F C}=N_{p} / N_{s}=\sqrt{L_{p} / L_{s}}$, where $N_{p}$ and $N_{s}$ are the winding numbers of the turns of the primary $L_{p}$ and the secondary $L_{s}$ inductors, respectively. If the inductance $L_{m E}$ is large enough, then the current is approximately constant over one switching cycle and is equal to $I_{O}$, as depicted in Fig. 5(b). A highfrequency voltage source $v_{p}$ and a series inductor $L_{d p}$ on the primary side of the transformer $T_{1}$ are reflected to the secondary side as a voltage source $v_{s}$ and an inductor $L_{d s}$, as illustrated in Fig. 5(c).

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The high-frequency voltage source $v_{s}$ and a series inductor $L_{d s}$ is converted into a high-frequency current source $i_{d s}$ to drive the ZCDS Class-E current-driven rectifier, as shown Fig. 5(d). The current waveform of the matching network that drives the ZCDS Class-E current-driven rectifier is assumed to be a sine-wave $i_{d s}=I_{d s} \sin \left(\omega_{s} t+\phi\right)$, where $\omega_{S}$ is the switching angular frequency. In this circuit, the DC-link voltage source $V_{B}$ and the full-wave rectified sinusoidal voltage source $\left|v_{i n}\right|$ are connected in series. Hence, these voltage sources can be combined into one voltage source $v_{O}=V_{B}-\left|v_{i n}\right|$, as shown in Fig. 5(e). The output voltage of the ZCDS Class-E current-driven rectifier is forced by the voltage source $v_{O}=$ $V_{B}-\left|v_{i n}\right|$. This voltage leads to a varying load resistance $R_{L}$ of the ZCDS Class-E current-driven rectifier. The equivalent circuit of the ZCDS Class-E current-driven rectifier for the PFC during the negative utility-line input half-cycle is similar to the equivalent circuit during the positive utility-line input halfcycle. Accordingly, the explanations are omitted. The important characteristic of the proposed ZCDS-CECS-RPFC is that the duty ratio $D_{e}$ of the diode $D_{E}$ in the ZCDS Class-E current-driven rectifier depends on the load resistance $R_{L}$. If the load resistance $R_{L}$ of the ZCDS-CECS-RPFC is increased, while its high-frequency driving current is kept relatively constant, the output voltage $v_{O}$ of the ZCDS-CECSRPFC increases, and the diode duty ratio $D_{e}$ is reduced. In other words, if the output voltage $v_{O}$ of the ZCDS-CECS-RPFC is forced to a higher voltage than the nominal value, the diode duty ratio $D_{e}$ of the ZCDS Class-E current-driven rectifier is automatically reduced. The average diode current automatically decreases as the output voltage $v_{O}$ increases. Therefore, the output characteristics of the ZCDS Class-E current-driven rectifier with a varying load resistance roughly matches the output characteristics to achieve the proper operation of the power-factor correction, as presented in Fig. 3.

The operating modes in one switching cycle of the equivalent circuit of the ZCDS-CECS-RPFC during the positive and negative utility-line input half-cycles are given in Table II. When the diode $D_{E}$ is turned on, the diode forward current $i_{E}$ equals the difference of the high-frequency current source $i_{d s}$ and the inductor current $i_{L E}$. The derivative of the diode forward current is zero at turn-on, and its absolute value reaches zero at turn-off. When the diode $D_{E}$ is turned off, the diode reverse voltage $v_{E}$ equals the difference of the output voltage $v_{O}$ and the inductor voltage $v_{L E}$. The diode reverse voltage $v_{E}$ has a step change at turn-off and a low absolute value of the derivative at turn-on. Therefore, the diode current $i_{E}$ and diode voltage $v_{E}$ of diode $D_{E}$ are operated under the ZCS and ZCDS conditions $i_{E}(0)=0$ and $d i_{E}\left(\omega_{S} t\right) /\left.d\left(\omega_{S} t\right)\right|_{\omega s t=0}=0$. In this case, switching losses and the switching noise level are reduced. The formulas further explaining these conditions can be found in reference [46].

Fig. 6 shows conceptual waveforms of the proposed single-stage LED driver. Figs. 6(a) and (b) show the sinusoidal utility-line input voltage $v_{i n}$ and the rectified utility-line input voltage $\left|v_{i n}\right|$ waveforms. The

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combined voltage $V_{B}-\left|v_{i n}\right|$ waveform is depicted in Fig. 6(c). If an instantaneous value of the utility-line input voltage $v_{i n}$ is positive and low near a zero crossing, the output voltage of the CECS-RPFC $v_{O}=V_{B}-$ $\left|v_{i n}\right|$ is high, and the diode duty ratio $D_{e}$ of the ZCDS-CECS-RPFC diode current $i_{E}$ is low. Consequently, the average value of the rectifier diode current $\left|i_{i n}\right|$ over one switching cycle is low. Similarly, if an instantaneous value of the utility-line input voltage $v_{i n}$ is positive and high near a peak, the output voltage of the CECS-RPFC $v_{O}=V_{B}-\left|v_{i n}\right|$ is low, and the diode duty ratio $D_{e}$ of the ZCDS-CECSRPFC diode current $i_{E}$ is high. Accordingly, the average value of the rectifier diode current $\left|i_{i n}\right|$ over one switching cycle is high. The amplitude of the high-frequency current source $i_{d p}$ depends on the output voltage $v_{O}$ of the ZCDS-CECS-RPFC. Thus, the waveform of the high-frequency current source $i_{d p}$, which is shown in Fig. 6(d), is high near the peak of the utility-line input voltage and low near the zero crossing of the utility-line input voltage in order to achieve a high-power-factor and low utility-line input current harmonics. Fig. 6(e) depicts the current $i_{s}$ waveform of square-wave output voltage source at midpoint of the ZVS Class-D $L L C$ resonant converter. Fig. 6(f) presents the rectifier diode current $i_{E}$ of the ZCDS-CECS-RPFC. A conduction angle modulation of the bridge-rectifier diode current waveform without the EMI filter over the line frequency $f_{L}$ and the line current $i_{i n}$ waveform are shown in Fig. $6(\mathrm{~g})$. The negative utility-line input half-cycle is similar to the conceptual waveforms during the positive utility-line input half-cycle; hence, the descriptions are not presented.

If the switching frequency $f_{S}$ is much higher than the line frequency $f_{L}$, then the high-frequency current source $i_{d s}$ is approximately constant for one switching cycle and equals the output current $i_{O}$ of the ZCDS-CECS-RPFC. The key current and voltage waveforms in one switching cycle of the proposed single-stage LED driver are shown in Fig. 7. A detailed analysis of the complete operation of the ZVS Class-D $L L C$ resonant converter, including the six stages, can be found in references [40]-[45].

## D. Circuit Analysis

The principle of operation of the proposed single-stage LED driver is explained by the equivalent circuit that is shown in Fig. 8(a). The input impedance of the ZCDS Class-E current-driven rectifier is represented by a series combination of an input resistor $R_{i p}$ and the input inductor $L_{i p}$, which is reflected from the secondary side of the transformer $T_{1}$. Additionally, the matching network $C_{r}-L_{r}-L_{m D}$, the centertapped transformer $T_{2}$ with turns ratio of $n_{L L C}: 1: 1$, the full-wave center-tapped rectifier diodes $D_{D 1}-D_{D 2}$, the output filter capacitor $C_{O}$, and the street-lighting LEDs are transformed into the AC-equivalent circuit $C_{r}-L_{r}-L_{m D}-R_{p}$, as presented in Fig. 8(b). The series inductor circuit $L_{i p}-L_{d p}$ is replaced by an equivalent inductor $L_{i d p}=L_{i p}+L_{d p}$. The MOSFETs are modeled by switches with on-resistances $r_{D S 1}$ and $r_{D S 2}$. The

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resistance $r_{L d t}$ represents the equivalent winding resistances of the inductors $L_{d p}$ with the transformer $T_{1}$ and the resistance $r_{L r t}$ represents the equivalent winding resistance of the transformer $T_{2}$. Therefore, the equivalent circuits of the ZVS Class-D $L L C$ resonant converter are modeled by a square-wave voltage source $v_{D S 2}$ with an equivalent resistor $r_{S}=\left(r_{D S 1}+r_{D S 2}\right) / 2 \approx r_{D S}$ and are loaded by two series circuits $r_{L d t}-C_{d^{-}}$ $L_{i d p}-R_{i p}$ and $r_{L r t}-C_{r}-L_{r m}-R_{s}$ as depicted in Fig. 8(c).

An equivalent circuit of the PFC semi-stage with an equivalent sine-wave voltage source is presented in Fig. 9(a). The high-frequency voltage source at midpoint of the ZVS Class-D $L L C$ resonant converter through a matching network are reflected from the primary side to the secondary side of the transformer $T_{1}$, as depicted in Fig. 9(b). The model of the proposed LED street-light driver can be divided into two parts: a simplified circuit of the ZCDS-CECS-RPFC and an equivalent circuit of the ZVS Class-D LLC resonant converter semi-stage, as depicted in Figs. 9(c) and (d), respectively. From Fig. 9(b), the minimum value of the load resistance $R_{L \min }$ occurs at the minimum output voltage $v_{O \min }$ as does the maximum output current $i_{O \max }$. The minimum load resistance of the ZCDS-CECS-RPFC $R_{L \min }$ is obtained as

$$
\begin{equation*}
R_{L \min }=\frac{v_{O \min }}{i_{O \max }}=\frac{V_{B}-V_{i n}}{I_{i n}}, \tag{1}
\end{equation*}
$$

where $I_{O \max }=I_{i n}$ is the output current flowing though the output voltage source $v_{O}$. Moreover, the output voltage $v_{O}$, the output current $i_{O}$, and the load resistance $R_{L}$ of the ZCDS-CECS-RPFC vary with time at the frequency $2 f_{L}$. From [46], the maximum duty ratio $D_{e \max }$ of the diode $D_{E}$ of the ZCDS Class-E currentdriven rectifier depends on the normalized load resistance $R_{L \min } / \omega_{S} L_{E}$ and can be written as

$$
\begin{align*}
\frac{R_{L \min }}{\omega_{S} L_{E}}= & \frac{2 \pi}{1-2 \pi^{2} D_{e \max }^{2}-\cos 2 \pi D_{e \max }}  \tag{2}\\
& +\frac{\left(\sin 2 \pi D_{e \max }-2 \pi D_{e \max }\right)^{2}}{1-\cos 2 \pi D_{e \max }}
\end{align*}
$$

The input power of the proposed single-stage LED driver is calculated as

$$
\begin{equation*}
P_{\text {in }}=\frac{V_{\text {in }} I_{\text {in }}}{2}=\frac{V_{\text {in }} I_{O \max }}{2} \tag{3}
\end{equation*}
$$

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Substituting this equation into (1) provides the relationship between the maximum duty ratio $D_{\text {emax }}$ and the normalized load resistance of the ZCDS Class-E current-driven rectifier, as follows:

$$
\begin{equation*}
\frac{R_{L \min }}{\omega_{S} L_{E}}=\frac{\left(\frac{V_{B}}{V_{\text {in }}}-1\right) V_{i n}^{2}}{2 P_{\text {in }} \omega_{S} L_{E}} . \tag{4}
\end{equation*}
$$

Combining (2) and (4), a voltage ratio between the DC-link voltage and the amplitude of the utility-line input voltage $V_{B} / V_{i n}$ of the ZCDS Class-E current-driven rectifier for the power-factor correction is

$$
\begin{align*}
\frac{V_{B}}{V_{i n}}= & \frac{4 \pi \omega_{S} L_{E}}{\left(1-2 \pi^{2} D_{e \max }^{2}-\cos 2 \pi D_{e \max }\right.}+1  \tag{5}\\
& \left.+\frac{\left(\sin 2 \pi D_{e \max }-2 \pi D_{e \max }\right)^{2}}{1-\cos 2 \pi D_{e \max }}\right) R_{L \min }
\end{align*}
$$

The voltage ratio $V_{B} / V_{i n}$ was obtained from a simulation of the ZCDS Class-E current-driven rectifier at fixed values of the amplitude of the utility-line input voltage $V_{i n}=311 \mathrm{~V}$, the switching frequency $f_{S}=55$ $\mathrm{kH}_{z}$, and the parallel inductance $L_{E}=2.4 \mathrm{mH}$. Hence, the voltage ratio $V_{B} / V_{i n}$ is a function of the maximum duty ratio $D_{\text {emax }}$ of the ZCDS Class-E current-driven rectifier as illustrated in Fig. 10. The duty ratio $D_{e}=D_{e m i n}=0$ at the no-load condition, and the duty ratio $D_{e}=D_{e m a x}$ at the full-load condition. The numerical values of the ZCDS Class-E current-driven rectifier for the PFC parameters at selected maximum duty ratio values $D_{\text {emax }}$ are given in Table III.

## III. Design Procedure

The design of the proposed single-stage driver for the LED street-light modules can be divided into two parts: the PFC semi-stage and the driver semi-stage. The design steps of the PFC semi-stage are illustrated in Fig. 11, and the design procedures of the PFC semi-stage based on the ZCDS-CECS-RPFC are given as follows:

1) a near-sinusoidal utility-line input current was assumed, and an expected efficiency $\eta$ was estimated. The amplitude of the utility-line input current $I_{i n}$, which is the maximum output current $I_{O_{\text {max }}}$ of the ZCDS-CECS-RPFC, was obtained for a given input power $P_{i n}$, output power $P_{\text {out }}$, and rms value of the utility-line input voltage $V_{i r r m s}$.

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2) select the maximum duty ratio $D_{\text {emax }}$ from Table III according to the tradeoffs regarding the ratio of the DC-link voltage and the amplitude of the utility-line input voltage $V_{B} / V_{i n}$. If a low value of the maximum duty ratio $D_{\text {emax }}$ is selected, a low-total harmonic distortion of the line current $\left(\mathrm{THD}_{i}\right)$ is achieved, but the main switches have high-voltage stresses. If a high value of the maximum duty ratio $D_{\text {emax }}$ is used, a high $\mathrm{THD}_{i}$ occurs, but the main switches have low-voltage stresses.
3) determine the DC-link voltage $V_{B}$ from the specified utility-line input voltage $V_{i n}$ and add to a calculated the minimum load resistance $R_{L \min }$ of the ZCDS-CECS-RPFC.
4) find the parallel inductor $L_{E}$ of the classic ZCDS Class-E rectifier, which is obtained from the normalized load resistance $R_{L \min } / \omega_{S} L_{E}$ at the same line as that of the chosen $D_{\text {emax }}$ value in Table III.
5) find the full-load input impedance of the ZCDS Class-E current-driven rectifier $Z_{i s f}$, which consists of the input resistance $R_{i s f}$ and the input reactance $X_{i s f}$ from Table III at the same line as that of the chosen $D_{\text {emax }}$ value. The input resistance $R_{i s}$ and input reactance $X_{i s}$ are plotted versus $D_{e}$, as shown in Figs. 12 and 13, respectively.
6) find the amplitude of the equivalent voltage source $v_{e q}$ at the full-load condition.
7) calculate the amplitude of the driving current at full-load $I_{\text {eqf }}$.
8) find the no-load input impedance of the ZCDS Class-E current-driven rectifier $Z_{i s n}$, which consists of the input resistance $R_{i s n}$ and input reactance $X_{i s n}$.
9) find the amplitude of the equivalent voltage source $v_{e q}$ at the no-load condition.
10) calculate the amplitude of the driving current at the no-load condition $I_{\text {eqn }}$.
11) calculate the turn ratio $n_{P F C}$ of the transformer $T_{1}$.
12) find the value of the inductance $L_{d}$ from the results of procedures 5 to 11 , with the assumption that the series inductance $L_{d p}$ equals the primary inductance $L_{p}$ of the transformer $T_{1}$.
13) find the value of inductance $L_{d p}$ and add an additional inductance $L_{c}$ to $L_{d p}$ to cancel the reactance of the capacitance $C_{d}$.

## A. PFC Semi-Stage Design

The single-stage LED driver for a $150-\mathrm{W}$ LED street light was designed to handle a line rms voltage $V_{i n r m s}$ of 220 V and a line frequency $f_{L}$ of $50 \mathrm{H}_{z}$. It was assumed that the total efficiency $\eta$ equaled 0.92 and the LED driver drew a sine-wave utility-line input current. The input power is obtained by

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$$
\begin{equation*}
P_{\text {in }}=\frac{P_{\text {out }}}{\eta} \tag{6}
\end{equation*}
$$

The amplitude of the utility-line input current $I_{i n}$, which is the maximum output current $I_{O \max }$ of the ZCDS-CECS-RPFC, is given by

$$
\begin{equation*}
I_{\text {in }}=I_{O \max }=\frac{\sqrt{2} P_{\text {in }}}{V_{\text {in } \mathrm{rms}}} \tag{7}
\end{equation*}
$$

The maximum duty ratio $D_{e m a x}=0.9$ was used because it gives the best compromise between the $\mathrm{THD}_{i}$ and reasonable value of the voltage stress of the power switches $M_{1}-M_{2}$. From Table III, we achieved the following: $V_{B} / V_{i n}=1.0932$, the amplitude of the utility-line input voltage $V_{i n}=\sqrt{2} V_{i n \mathrm{rms}} \approx 311 \mathrm{~V}$ and the DC-link voltage $V_{B} \approx 340 \mathrm{~V}$. Substitute these values into equation (1) to obtain the full-load resistance of the ZCDS-CECS-RPFC, which is $R_{L \min }$. The parallel inductance $L_{E}$ of the ZCDS Class-E current-driven rectifier can be obtained from the normalized load resistance $R_{L \min } / \omega_{S} L_{E}$ at the same line as that of the chosen $D_{\text {emax }}$ value in Table III.

$$
\begin{equation*}
L_{E}=\frac{R_{L \min }}{0.0334 \omega_{S}}, \tag{8}
\end{equation*}
$$

where the switching frequency $f_{S}=55 \mathrm{kH}_{\mathrm{Z}}$. At the full-load condition, the input impedance of the ZCDS Class-E current-driven rectifier is as follows:

$$
\begin{equation*}
Z_{i s f}=R_{i s f}+j X_{i s f} \tag{9}
\end{equation*}
$$

where

$$
\begin{equation*}
R_{i s f}=0.0560 \omega_{S} L_{E} \tag{10}
\end{equation*}
$$

and

$$
\begin{equation*}
X_{i s f}=0.0228 \omega_{S} L_{E} \tag{11}
\end{equation*}
$$

The amplitude of the driving current at full-load condition $I_{\text {eqf }}$ is calculated from

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$$
\begin{equation*}
I_{e q f}=\sqrt{\frac{2 I_{O \max }\left(V_{B}-V_{\text {in }}\right)}{R_{i s f}}} \tag{12}
\end{equation*}
$$

The amplitude of the equivalent voltage source $V_{e q}$ at the full-load condition is given by

$$
\begin{equation*}
V_{e q}=I_{e q f} \sqrt{R_{i s f}^{2}+\left(\omega_{S} L_{i s f}+\omega_{S} L_{e q}\right)^{2}} \tag{13}
\end{equation*}
$$

At the no-load condition, the input impedance of the ZCDS Class-E current-driven rectifier is

$$
\begin{equation*}
Z_{i s n}=R_{i s n}+j X_{i s n} \tag{14}
\end{equation*}
$$

The inductance $L_{i s n}$ equals the inductance $L_{E}$. The amplitude of the driving current under the no-load condition $I_{\text {eqn }}$ is obtained by

$$
\begin{equation*}
I_{e q n}=\frac{V_{B}}{\left|j \omega_{S} L_{E}\right|} \tag{15}
\end{equation*}
$$

The amplitude of the equivalent voltage source $V_{e q}$ under the no-load condition is calculated by

$$
\begin{equation*}
V_{e q}=I_{e q n}\left|j \omega_{S} L_{e q}+j \omega_{S} L_{i s n}\right| \tag{16}
\end{equation*}
$$

The values of $V_{e q}$ and $L_{e q}$ are obtained by solving (13) and (16). The turn ratio $n_{P F C}$ of the transformer $T_{1}$ is determined by

$$
\begin{equation*}
n_{P F C}=\frac{\pi V_{e q}}{V_{B}} \tag{17}
\end{equation*}
$$

To simplify the design procedure, assume that the series inductance $L_{d p}$ equals the primary inductance $L_{p}$ of the transformer $T_{1}$. Consequently, the driven inductance $L_{d p}$ is given by

$$
\begin{equation*}
L_{d p}=\frac{2 L_{e q}}{n_{P F C}^{2}} \tag{18}
\end{equation*}
$$

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For a finite value of a capacitance $C_{d}$, an additional $L_{c}$ can be added to the inductance $L_{d p}$ to compensate for the reactance of a capacitance $C_{d}$. The value of the additional inductance $L_{c}$ is determined by

$$
\begin{equation*}
L_{c}=\frac{1}{\omega_{S}^{2} C_{d}} \tag{19}
\end{equation*}
$$

Therefore, the total inductance $L_{d c}$ is

$$
\begin{equation*}
L_{d c}=L_{d p}+L_{c} \tag{20}
\end{equation*}
$$

To achieve a ripple voltage of less than $1 \%$, the value of the DC-link capacitor is determined by

$$
\begin{equation*}
C_{B}=\frac{P_{\text {in }}}{0.02 V_{B}^{2} \omega_{L}} \tag{21}
\end{equation*}
$$

Normally, the DC-link capacitance $C_{B}$ and the output capacitance $C_{O}$ should be larger to accommodate a high LED current ripple, which may influence the lighting quality [47]. If low capacitances are selected, a high LED current ripple occurs. Alternatively, if high capacitances are used, a low LED current ripple occurs. For long lifespan applications, high-temperature electrolytic capacitors are adequate for the DClink capacitor $C_{B}$ and the output capacitor $C_{O}$ for low cost LED drivers and are widely used in the market. According to the lifespan estimation method of the electrolytic capacitor [48]-[50], the lifespan of the high temperature electrolytic capacitors doubles for every $10^{\circ} \mathrm{C}$ decrease of the operating temperature below the rated level.

## B. Losses Analysis

The circuit losses of the presented single-stage LED driver for an LED street light can be divided into five major components, which are the power diodes, the power MOSFETs, the inductors, the transformers, and the sensing resistor. The simple equivalent circuit for a conduction loss analysis is shown in Fig. 8(b). For The bridge-rectifier $D_{1}-D_{4}$ was built using standard recovery diodes. The average value of the input rectifier diode currents $i_{D 1}-i_{D 4}$ equals the average value of the half-wave rectified utilityline input current. Thus, the diode losses in one diode of the bridge-rectifier diode are calculated from

$$
\begin{equation*}
P_{D B}=\frac{V_{F D B} I_{i n}}{\pi}+\frac{I_{i n}^{2} R_{F D B}}{4}, \tag{22}
\end{equation*}
$$

where $V_{F D B}$ is the diode threshold voltage, and $R_{F D B}$ is the diode forward resistance of the bridge-rectifier diode. The ZCDS Class-E current-driven rectifier was built using a silicon carbide Schottky diode $D_{E}$. The power loss in the diode $D_{E}$ is determined using

$$
\begin{equation*}
P_{D E}=\frac{2 V_{F D E} I_{i n}}{\pi}+\frac{I_{i n}^{2} R_{F D E}}{2} \tag{23}
\end{equation*}
$$

where $V_{F D E}$ is the diode threshold voltage, and $R_{F D E}$ is the diode forward resistance of the ZCDS Class-E current-driven rectifier diode. The full-wave center-tapped rectifier of the ZVS Class-D $L L C$ resonant converter was built using two silicon Schottky diodes $D_{D 1}-D_{D 2}$. The conduction losses in each diode are obtained using

$$
\begin{equation*}
P_{D D}=\frac{V_{F D D} I_{L E D}}{2}+\frac{\pi I_{L E D}^{2} R_{F D D}}{16}, \tag{24}
\end{equation*}
$$

where $V_{F D D}$ is the diode-threshold voltage, and $R_{F D D}$ is the diode forward resistance of these silicon Schottky diodes. For the power switches $M_{1}$ and $M_{2}$, the turn-on switching losses are both zero; thus, the losses of the power switches are composed of the conduction losses and turn-off switching losses, which can be determined using

$$
\begin{equation*}
P_{D S}=I_{s \mathrm{rms}}^{2} r_{D S(\mathrm{on})}+\left(\frac{V_{B} I_{M} t_{r}}{3 T_{S}}+\frac{V_{B} I_{M} t_{f}}{2 T_{S}}\right), \tag{25}
\end{equation*}
$$

where $r_{D S(\text { on })}$ represents the resistance when the power MOSFET is turned on and $t_{r}$ and $t_{f}$ are the switchvoltage rise time and switch-current fall time of the power switches $M_{1}$ and $M_{2}$ during turn-off, respectively. The rms values of the drain current of the power MOSFET is determined by

$$
\begin{equation*}
I_{s \mathrm{rms}}=\sqrt{I_{d p \mathrm{rms}}^{2}+I_{r \mathrm{rms}}^{2}} \tag{26}
\end{equation*}
$$

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The rms value of the driving current $I_{d p r m s}$ of the ZCDS-CECS-RPFC can be obtained using the principle of double side band amplitude modulation (DSB-AM) with a carrier signal [51] and is given by

$$
\begin{equation*}
I_{d p \mathrm{rms}}=\frac{n_{P F C}\left(I_{e q f}+2 I_{e q n}\right) \sqrt{2+m^{2}}}{4} \tag{27}
\end{equation*}
$$

where $m$ is the ratio between the modulated and unmodulated carrier amplitudes. In the case of the ZCDS-CECS-RPFC, the modulation index $m=0.33$. From Fig. 8(c) the rms values of the drain current of the power MOSFETs are the sum of the rms values of the driving current $i_{d p}$ and the resonant current $i_{r}$. The rms value of the resonant current in the ZVS Class-D $L L C$ resonant converter semi-stage $I_{r \mathrm{rms}}$ [44], [45] can be obtained as

$$
\begin{equation*}
I_{r \mathrm{rms}}=\frac{1}{\eta_{c}} \sqrt{\left(\frac{\pi I_{L E D}}{n_{L L C} \sqrt{8}}\right)^{2}+\left(\frac{n_{L L C}\left(V_{L E D}+V_{F D D}\right)}{4 \sqrt{2} f_{S} M_{V}\left(L_{m D}-L_{r}\right)}\right)^{2}} \tag{28}
\end{equation*}
$$

It was assumed that the ZVS Class-D $L L C$ resonant converter efficiency $\eta_{c}=0.95$, the turn ratio of the transformer $T_{2} n_{L L C}=6$, and the DC to DC voltage transfer function $M_{V}=1.12$. The losses of the magnetic components can be separated into the core loss and the copper loss. Therefore, the core losses in the EMI filter inductor $L_{f}$, the series inductor $L_{d c}$, and the transformers $T_{1}, T_{2}$ can be obtained using the improved generalized Steinmetz equation [52]-[54]

$$
\begin{gather*}
P_{\text {core }}=\frac{1}{T_{S}} \int_{0}^{T_{S}}\left(\frac{k}{(2 \pi)^{\alpha-1} \int_{0}^{2 \pi}|\cos \theta|^{\alpha} 2^{\beta-\alpha} d \theta},\right.  \tag{29}\\
\\
\left.\left|\frac{d B}{d t}\right|^{\alpha}(\Delta B)^{\beta-\alpha} d t\right)
\end{gather*}
$$

where $k$ is a core loss coefficient, $\alpha$ is a frequency exponent, $\beta$ is a core loss exponent, and $B$ is a peak to peak value of an induction sinusoidal waveform. The copper resistance of the EMI filter inductor is $r_{L f}$ and the rms value of the current flowing through the winding of the EMI filter inductor $i_{L f}$ equals the rms value of the full-wave rectified utility-line input current. Hence, the copper loss in the EMI filter inductor is calculated by

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$$
\begin{equation*}
P_{r L f}=\frac{I_{i n}^{2} r_{L f}}{2} \tag{30}
\end{equation*}
$$

The copper loss in the series inductor $P_{r L d c}$ is obtained by

$$
\begin{equation*}
P_{r L d c}=I_{d p \mathrm{rms}}^{2} r_{L d c}, \tag{31}
\end{equation*}
$$

where $r_{L d c}$ represented the equivalent series resistance (ESR) of the series inductor $L_{d c}$. The copper losses of the transformer $T_{1}$ can be divided into the primary side and the secondary side. The copper loss in the winding of the primary side $r_{p T 1}$ of the transformer $T_{1}$ is calculated by

$$
\begin{equation*}
P_{r p T 1}=\stackrel{2}{I_{d p \mathrm{rms}} r_{p T 1}} \tag{32}
\end{equation*}
$$

The rms value of the current flowing through the winding of the secondary side $r_{s T 1}$ of the transformer $T_{1}$ equals the rms value of the full-wave rectified utility-line input current. Therefore, the copper loss in the winding of the secondary side $r_{s T 1}$ of the transformer $T_{1}$ is given by

$$
\begin{equation*}
P_{r s T 1}=\frac{I_{i n}^{2} r_{s T 1}}{2} \tag{33}
\end{equation*}
$$

The copper loss in the winding of the primary side $r_{p T 2}$ of the transformer $T_{2}$ is calculated from

$$
\begin{equation*}
P_{r p T 2}=I_{r \mathrm{rms}}^{2} r_{p T 2} \tag{34}
\end{equation*}
$$

The copper loss in the winding of the secondary side $r_{s T 2}$ of the transformer $T_{2}$ is given by

$$
\begin{equation*}
P_{r s T 2}=\frac{r_{s T 2} \pi^{2} I_{L E D}^{2}}{16} \tag{35}
\end{equation*}
$$

By using Ohm's law, the current sensing resistor $R_{\text {sense }}$ can be expressed as

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$$
\begin{equation*}
R_{\text {sense }}=\frac{V_{c s t h}}{I_{L E D \max }} \tag{36}
\end{equation*}
$$

where $V_{\text {csth }}$ is the current sense threshold, and $I_{L E D \max }$ is the maximum output current. Therefore, the power loss of the current sensing resistor $R_{\text {sense }}$ can be calculated by

$$
\begin{equation*}
P_{\text {Rsense }}=I_{L E D \max }^{2} R_{\text {sense }} \tag{37}
\end{equation*}
$$

The total loss of the proposed single-stage LED driver $P_{l}$ is given by

$$
\begin{align*}
P_{l}= & 2 P_{D B}+P_{D E}+2 P_{D D}+2 P_{D S}+P_{\text {core }}+P_{r L f}  \tag{38}\\
& +P_{r L d c}+P_{r p T 1}+P_{r s T 1}+P_{r p T 2}+P_{r s T 2}+P_{\text {Rsense }}
\end{align*}
$$

The efficiency of the presented single-stage LED driver $\eta$ is given by

$$
\begin{equation*}
\eta=\frac{P_{\text {out }}}{P_{\text {in }}} \times 100 \%=\frac{P_{\text {out }}}{P_{\text {out }}+P_{l}} \times 100 \% \tag{39}
\end{equation*}
$$

The $150-\mathrm{W}$ LED street-light driver is constructed from 3 modules of the $50-\mathrm{W} / 32-\mathrm{V}$ LED module connected in parallel, as shown in Fig. 9(d). The design of the ZVS Class-D $L L C$ resonant converter can be found in references [40]-[45], and the design of the EMI filter can be found in reference [55].

## IV. Experimental Results

To verify the theoretical analysis, the prototype of the proposed single-stage LED driver was built using the prototype parameters obtained from the design procedure given previously and listed in Table IV. The prototype of the proposed single-stage LED driver based on the ZCDS-CECS-RPFC is depicted in Fig. 14. The utility-line input voltage is set to $220 \mathrm{~V}_{\mathrm{rms}}$ with a frequency $f_{L}$ of $50 \mathrm{H}_{\mathrm{z}}$. The measured waveforms of the utility-line input voltage $v_{i n}$ and the current $i_{i n}$ at full power are displayed in Fig. 15. The shape of utility-line input current is sinusoidal and in phase with the utility-line input voltage. At the rated output power of 150 W , the input power that was measured using a power analyzer model 43B (FLUKE) was 164 W , and the PF was 0.99 . The $\mathrm{THD}_{i}$ was $7.9 \%$, as shown in Fig. 16 .

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To measure the key circuit waveforms, a mixed signal oscilloscope (model DL2024), a differential probe (model 700924), and a current probe (model 701932) that were manufactured by YOKOGAWA were employed. The measured waveform of the driving current $i_{d p}$ with a zoomed-in view near the peak of the utility-line input voltage is shown in Fig. 17. It can be seen that the amplitude of the driving current $i_{d p}$ near the zero crossing of the utility-line input voltage is low. As a result, the current stresses of the power MOSFETs have been significantly reduced when compared to the ZVDS-CECS-RPFC [34] and ZVDS-CDECS-RPFC [35] topologies.

The switch voltage $v_{E}$ and the switch current $i_{E}$ waveforms of $D_{E}$ of the ZCDS Class-E current-driven rectifier at 60 degrees of the utility-line input voltage are shown in Fig. 18. The result shows that the diode $D_{E}$ turns on at zero $d i / d t$ and low $d v / d t$, which allows the high-efficiency and low-switching noise to be captured.

Figs. 19(a) and (b) present the measured waveforms of the diode voltage $v_{E}$ and the diode current $i_{E}$ of the ZCDS-CECS-RPFC near the peak and the zero-crossing of the utility-line input voltage, respectively. The experimental results of the rectified utility-line input voltage $\left|v_{i n}\right|$, the combined voltage waveform $v_{O}=V_{B}-\left|v_{\text {in }}\right|$, and the rectified utility-line input current $\left|i_{i n}\right|$ are shown in Fig. 20. As expected, the current of the diode $D_{E}$ increased, and the combined voltage $v_{O}$ decreased as the instantaneous utility-line input voltage increased; conversely, the current of the diode $D_{E}$ decreased, and the combined voltage $v_{O}$ increased as the instantaneous utility-line input voltage decreased. These waveforms roughly match the required waveforms illustrated in Fig. 6. Figs. 21(a) and (b) illustrate the experimental waveforms of the switch voltage and the switch current of the power MOSFETs $M_{1}$ and $M_{2}$ near the peak and the zerocrossing of the utility-line input voltage, respectively. The maximum voltage stresses of switch $M_{1}$ and $M_{2}$ were both approximately 340 V , and ZVS can be achieved.

Fig. 22 presents the experimental waveforms of the utility-line input voltage (Ch1), the utility-line input current (Ch2), the input power (Math1), het output voltage (Ch3), the output current (Ch4) and the output power (Math2). The input power $P_{i n}$ was 164.372 W , and the output power $P_{\text {out }}$ was 150.285 W . Hence, the measured system efficiency of the single-stage LED driver $\eta$ under the full output power and a fixed value of the utility-line input voltage $V_{i n \mathrm{rms}}=220 \mathrm{~V}$ was approximately $91.4 \%$. As expected, the proposed topology is more efficient because the ZVDS-CECS-RPFC [34] and ZVDS-CDECS-RPFC [35] topologies had more high-current stress in the PFC semi-stage. It can be observed that the measured LED current ripple was approximately $18 \%$ of $I_{L E D}$. According to [47], this value is well below the acceptable limits of flicker and the perception of stroboscopic effects.

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Figs. 23(a) and (b) depict the measured system PF and $\mathrm{THD}_{i}$ of the proposed topology under the utility-line input voltage range of $180 \mathrm{~V}_{\mathrm{rms}}$ to $250 \mathrm{~V}_{\mathrm{rms}}$ at $P_{\text {out }}=150 \mathrm{~W}$ and the different output power range of 60 W to 150 W at $v_{\text {in }}=220 \mathrm{~V}_{\mathrm{rms}}$, respectively. It can be observed that the PF is always higher than 0.97 , and the $\mathrm{THD}_{i}$ is lower than $20 \%$. Table V shows the measured utility-line input-current harmonic contents, under the two-level output powers of 60 W and 150 W , compared with the IEC 61000-3-2 Class-C at the nominal utility-line input voltage of $220 \mathrm{~V}_{\mathrm{rms}}$. The results completely meet the power-factor requirement and the utility-line input current harmonic contents of the lighting equipment standard IEC 61000-3-2 Class-C.

The main losses come from the conduction losses in the PFC semi-stage elements, such as the ESR of the series inductor $L_{d c}$, the copper resistance of the transformer $T_{1}$ and the power switches $M_{1}$ and $M_{2}$. It can be seen that the system efficiency has been reduced when operated from the low utility-line input voltage because the higher driving current $i_{d}$. Therefore, the proposed single-stage LED driver based on the ZCDS-CECS-RPFC has to be designed with only $\pm 15 \%$ of the standard utility-line input voltages of $220 \mathrm{~V}_{\mathrm{rms}}$ or $110 \mathrm{~V}_{\mathrm{rms}}$, respectively, and is not suitable for universal-line voltages, which are in the range of $90 \mathrm{~V}_{\mathrm{rms}}$ to $265 \mathrm{~V}_{\mathrm{rms}}$. The system efficiency when the utility-line input voltage changes from $180 \mathrm{~V}_{\mathrm{rms}}$ to $250 \mathrm{~V}_{\mathrm{rms}}$ at full-load and the output power varies from 60 W to 150 W at $220 \mathrm{~V}_{\mathrm{rms}}$ is illustrated in Figs. 24(a) and (b), respectively.

Additionally, Table VI shows the component count and key performance comparison of the ZVDS-CECS-RPFC [34], the ZVDS-CDECS-RPFC [35], the ZCS-CDCS-RPFC [38], and the proposed ZCDS-CECS-RPFC. The proposed LED driver has a good system efficiency compared with the previous ZVSRPFC topologies and a low $\mathrm{THD}_{i}$ when compared with the previous ZCS-RPFC topologies. The comparative study of the proposed ZCDS-CECS-RPFC with the previously LED street-light drivers that employ two-stage topologies is depicted in Table VII. It can be seen that the two-stage LED drivers have many power switches and controller ICs for each stage, which leads to high costs, complexity and large sizes.

## V. Discussion of the Effect of Junction Capacitance of the ZCDS-CECS-RPFC Diode

To achieve the low-total harmonic distortion of the utility-line input current, the utility-line input current $i_{i n}$ near the zero-crossing of the utility-line input voltage must equal zero. The utility-line input current $i_{i n}$ cannot reach zero near the utility-line input voltage $v_{i n}$, due to the junction capacitance effect of the ZCDS Class-E current-driven rectifier diode $D_{E}$, as shown in Fig. 25(a). In this circuit, the

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equivalent circuit cannot be modeled by a series combination of the inductor $L_{d s}$ with the input impedance of the ZCDS Class-E current-driven rectifier. In a first simplified approach, the voltage source $v_{O}$ appears as a short circuit to the high-frequency AC component and the junction capacitor $C_{j}$ is interchangeable. Therefore, the input impedance of the ZCDS Class-E current-driven rectifier with the parasitic capacitance effect can be modeled by the parallel $L_{s p}-R_{s p}$ or the series $L_{s s}-R_{s s}$ with the junction capacitor $C_{j}$ as presented in Figs. 25(b) and (c), respectively. It is well known that the voltage transfer function of the $L L C$ resonant inverter is more than 1 [43]. Thus, near the zero-crossing of the utility-line input voltage $v_{i n}$, the $D_{E}$ can conduct current because the voltage at its anode is more positive than the voltage at its cathode. As a result, the utility-line input current $i_{i n}$ cannot reach zero. Accordingly, a diode with a small $C_{j}$ is preferred.

## VI. Conclusion

This paper has proposed a circuit of a single-stage LED driver for street-lighting applications. The LED driver combines a modified zero-current and zero-derivative-switching Class-E current-driven rectifier as a power-factor correction semi-stage with a zero-voltage-switching Class-D $L L C$ resonant converter as a driver semi-stage into one power-conversion stage. A 150-W experimental prototype LED driver has been developed and tested with the utility-line input voltages ranging from 180~250 $\mathrm{V}_{\text {rms }} / 50$ $\mathrm{H}_{\mathrm{z}}$. The experimental results of the single-stage LED driver prototype had a high PF (0.99), a low $\mathrm{THD}_{i}$ (7.9\%), and high system efficiency $(91.4 \%)$ at rated load condition. The $\mathrm{THD}_{i}$ of the proposed LED driver was lower than the ZCS-RPFC topologies, while the system efficiency was higher than that of the ZVS-RPFC topologies, due to the reduced current stresses in the power MOSFETs near the zero-crossing of the utility-line input voltage. The power MOSFETs can be operated under the ZVS condition and the diode in the PFC semi-stage turns on at zero $d i / d t$ and low $d v / d t$. Therefore, a low-switching noise level can be achieved.

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Figure captions
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(a)

(b)

Fig. 1.


Fig. 2.


Fig. 3.


Fig. 4.

(a)

(c)

(b)

(d)

(e)

Fig. 5.


Fig. 6.


Fig. 7.

(a)

(b)

(c)

Fig. 8.

(a)

(c)

(b)

(d)

Fig. 9.


Fig. 10.


Fig. 11.


Fig. 12.


Fig. 13.


Fig. 14.


Fig. 15.


Fig. 16.


Fig. 17.


Fig. 18.


Fig. 19.


Fig. 20.


Fig. 21.


Fig. 22.


Fig. 23.

(a)

(b)

Fig. 24.

(a)

(b)

(c)

Fig. 25.

TABLE I

| Items | High-Pressure <br> Sodium <br> Vapor Lamp | Metal <br> Halide Lamp | HB-LED |
| :--- | :---: | :---: | :---: |
|  | OSRAM | OSRAM | GENESIS |
| Model | NAV-T | HQI-E | LED Module |
|  | 150 W | 150 W | $3 \times 50 \mathrm{~W}$ |
| Nominal Wattage | 150 W | 150 W | 150 W |
| Efficacy | $115 \mathrm{~lm} / \mathrm{W}$ | $831 \mathrm{~m} / \mathrm{W}$ | $90 \mathrm{~lm} / \mathrm{W}$ |
| Luminous Flux | $17,500 \mathrm{~lm}$ | $12,500 \mathrm{~lm}$ | $14,000 \mathrm{~lm}$ |
| Color Rendering Index | 25 | 88 | 70 |
| Color Temperature | $2,000 \mathrm{~K}$ | $4,200 \mathrm{~K}$ | $6,000 \mathrm{~K}$ |
| Light Appearance | Warm White | Cool White | Daylight |
| Lifespan | $>2,400$ hours | $>6,000$ hours | $>50,000$ hours |

TABLE II


## TABLE III

| $D_{\text {emax }}$ | $V_{B} / V_{\text {in }}$ | $R_{L \text { min }} /$ <br> $\omega_{S} L_{E}$ | $R_{i s} /$ <br> $\omega_{S} L_{E}$ | $X_{i s} /$ <br> $\omega_{S} L_{E}$ | $R_{i s} / R_{L \text { min }}$ | $L_{i s} / L_{E}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0 | $\infty$ | $\infty$ | 0 | 1 | 0 | 1 |
| 0.1 | $8.01 \times 10^{3}$ | 2865.3 | 0.0007 | 0.999 | $0.0002 \times 10^{-3}$ | 0.999 |
| 0.2 | 481.620 | 171.88 | 0.0097 | 0.996 | $0.0566 \times 10^{-3}$ | 0.996 |
| 0.3 | 89.390 | 31.611 | 0.4190 | 0.976 | $1.3260 \times 10^{-3}$ | 0.976 |
| 0.4 | 26.091 | 8.9734 | 0.1045 | 0.915 | $11.650 \times 10^{-3}$ | 0.915 |
| 0.5 | 9.7845 | 3.1416 | 0.1836 | 0.788 | $58.440 \times 10^{-3}$ | 0.788 |
| 0.6 | 4.3786 | 1.2083 | 0.2433 | 0.590 | $201.40 \times 10^{-3}$ | 0.590 |
| 0.7 | 2.3017 | 0.4655 | 0.2427 | 0.354 | $521.40 \times 10^{-3}$ | 0.354 |
| 0.8 | 1.4418 | 0.1580 | 0.1669 | 0.142 | $1056.5 \times 10^{-3}$ | 0.142 |
| 0.9 | 1.0933 | 0.0334 | 0.0560 | 0.022 | $1678.8 \times 10^{-3}$ | 0.022 |
| 1 | 1 | 0 | 0 | 0 | $2000.0 \times 10^{-3}$ | 0 |

TABLE IV

| Symbol | Part Number or Value | Type |
| :---: | :---: | :---: |
| Bridge-Rectifier and EMI Filter |  |  |
| $D_{1}-D_{4}$ | 1N5395 | Standard-Recovery Diode |
| $L_{f}$ | 5 mH | N87 EE32/16/9 |
| $C_{f}$ | $680 \mathrm{nF} / 400 \mathrm{~V}$ | Polypropylene |
| PFC Stage |  |  |
| $D_{E}$ | GB10MPS17 | Silicon Carbide Schottky Diode |
| $T_{1}$ | $L_{p}=92 \mu \mathrm{H}, L_{s}=2.5 \mathrm{mH}$ | N87 EE42/21/15 |
| $L_{d c}$ | $340 \mu \mathrm{H}$ | N87 EE42/21/15 |
| $C_{d}$ | $33 \mathrm{nF} / 1,000 \mathrm{~V}$ | Polypropylene |
| Driver Stage |  |  |
| $M_{1}-M_{2}$ | IRFP460 | N-Channel MOSFET |
| $D_{D 1}-D_{D 2}$ | STPS40H100CW | Silicon Schottky Diode |
| $T_{2}$ | $L_{r}=270 \mu \mathrm{H}, L_{m D}=1.4 \mathrm{mH}$ | N87 EE42/21/20 |
| $C_{r}$ | $30 \mathrm{nF} / 1,000 \mathrm{~V}$ | Polypropylene |
| $\mathrm{Co}_{0}$ | $100 \mu \mathrm{~F} / 50 \mathrm{~V}$ | Electrolytic |
| $C_{B}$ | $240 \mu \mathrm{~F} / 400 \mathrm{~V}$ | 2 Parallel Connected of $120 \mu \mathrm{~F}$ Electrolytic Capacitors |
| LEDs | $50 \mathrm{~W} / 32 \mathrm{~V}$ | 3 Parallel Connected of LED Street-Light Modules |
| Control Stage |  |  |
| $U_{1}$ | L6599 | High-Voltage |
| ${ }_{1}$ | L6599 | Resonant Controller |
| $U_{2}$ | PC851 | Photocoupler |
| $U_{3}$ | SAE05 | CV/CC Controller |

TABLE V

| Harmonic <br> Number <br> $(\mathrm{n})$ | IEC 61000-3-2 <br> Class-C <br> $(\%)$ | Experimental <br> Result at <br> $P_{\text {out }}=60 \mathrm{~W}(\%)$ | Experimental <br> Result at <br> $P_{\text {out }}=$ |
| :---: | :---: | :---: | :---: |
| 2 | 2 | $0.150 \mathrm{~W}(\%)$ |  |

## TABLE VI

| Circuit Topology | ZVDS-CECS <br> $[34]$ | ZVDS-CDECS <br> $[35]$ | ZCS-CDCS <br> $[38]$ | ZCDS-CECS <br> (proposed) |
| :--- | :---: | :---: | :---: | :---: |
| AC Line Voltage (Vrms) | 120 | 220 | 220 | 220 |
| Max. Output Power (W) | 32 | 36 | 34 | 150 |
| Voltage Ratio $V_{B} / V_{\text {in }}$ | 1.27 | 1.051 | 1.1 | 1.093 |
| Power Factor | 0.99 | 0.99 | 0.98 | 0.99 |
| Line Current THD (\%) | 12.6 | 1.3 | 20 | 7.9 |
| Efficiency (\%) | 88.3 | 90 | 93.5 | 91.4 |
| Normalized Driving Current | 3.87 | 6.36 | 0 | 0.39 |
| $I_{\text {eqn }} / I_{\text {in }}$ at Zero-Crossing of $v_{\text {in }}$ |  |  |  |  |
| Normalized Diode | 3.61 | 6.36 | 3.14 | 2.08 |
| Current Stress $I_{D} / I_{\text {in }}$ |  |  |  |  |
| Normalized Diode | 2 | 1 | 1 | 2 |
| Voltage Stress $V_{D} / V_{B}$ | 1 | 2 | 2 | 1 |
| Diode | 1 | 1 | 1 | 1 |
| Inductor | 2 | 3 | 1 | 1 |
| Capacitor | 1 | 0 | 0 | 1 |
| Transformer | 5 |  | 4 | 4 |
| Component Count |  |  |  |  |

TABLE VII

| Item | Two-Stage <br> $[3]$ | Two-Stage <br> $[8]$ | Two-Stage <br> $[9]$ | Single-Stage <br> (proposed) |
| :--- | :---: | :---: | :---: | :---: |
| AC Line Voltage ( $\mathrm{V}_{\text {rms }}$ ) | 120 | $90 \sim 264$ | 220 | $180 \sim 250$ |
| Output Voltage (V) | 95 | 43 | 27 | 32 |
| DC-Bus Voltage (V) | 400 | $\mathrm{~N} / \mathrm{A}$ | 400 | 340 |
| Max. Output Power (W) | 40 | 150 | 100 | 150 |
| PF | $\mathrm{N} / \mathrm{A}$ | 0.98 | $\mathrm{~N} / \mathrm{A}$ | 0.99 |
| $\mathrm{THD}(\%)$ | $\mathrm{N} / \mathrm{A}$ | 16 | $\mathrm{~N} / \mathrm{A}$ | 7.9 |
| $\eta(\%)$ | 91.5 | 89.9 | 94.5 | 91.4 |
| Power Switch | 3 | 3 | 3 | 2 |
| Diode | 7 | 7 | 7 | 7 |
| Capacitor | 5 | 4 | 5 | 5 |
| Inductor | 3 | 3 | 4 | 2 |
|  |  | 1 | 1 | 1 |
| Transformer | (with $L_{m}$ and $L_{r}$ ) | (with $L_{m}$ ) | (with $L_{m}$ ) | (with $L_{m E}$, |
|  | 2 | 2 | 2 | $L_{m D}$ and $L_{r}$ ) |
| Controller | 21 | 20 | 22 | 1 |
| Component Count |  |  |  | 19 |


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