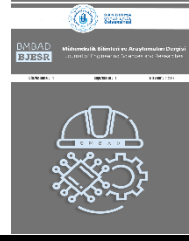




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Soft Switching LED Driver Implementation with ZCS Buck Converter

ZCS Buck Dönüştürücü ile Yumuşak Anahtarlama LED Sürücü Uygulaması

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ABSTRACT

The development of semiconductor technology has led to the widespread adoption of LEDs as a highly efficient and economical lighting system. In order for LED systems to achieve higher efficiency, the driver circuits must also operate with high efficiency. Conventional PWM hard switching power converters used in LED drivers experience excessive heating of their power switches due to switching losses, leading to a reduction in power conversion efficiency. In order to enhance the power conversion efficiency of LED drivers, it is necessary to use solutions that minimize the switching losses. One of these solutions is the use of soft-switching power converters. This paper proposes a half-wave (HW) zero-current switching (ZCS) buck converter as a solution to improve LED driver's efficiency. The switching frequency of the proposed LED driver was varied between 142-200 kHz, and the brightness of the LEDs dimmed under ZCS conditions. A comparison of the effect of MOSFET temperature between the proposed HW-ZCS buck converter and a conventional PWM buck converter-based LED driver has also been made.

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ÖZET

Yarı iletken teknolojisindeki gelişmeler, LED'lerin yüksek verimli ve ekonomik bir aydınlatma sistemi olarak yaygın şekilde kullanılmasına olanak sağlamıştır. LED sistemlerinin daha yüksek verimle çalışabilmesi için sürücü devrelerinin de yüksek verimle çalışması gerekmektedir. LED sürücülerinde kullanılan geleneksel PWM tabanlı sert anahtarlama güç dönüştürücülerinde, anahtarlama kayıpları nedeniyle güç anahtarlarında aşırı ısınma meydana gelmekte ve bu durum güç dönüşüm veriminin azalmasına yol açmaktadır. LED sürücülerinin güç dönüşüm verimini artırmak için anahtarlama kayıplarını en aza indiren çözümlerin kullanılması gerekmektedir. Bu çözümlerden biri yumuşak anahtarlama güç dönüştürücülerin kullanılmasıdır. Bu çalışmada, LED sürücüsünün verimliliğini artırmak amacıyla yarım dalga (HW) sıfır akımda anahtarlama (ZCS) bir buck dönüştürücü önerilmektedir. Önerilen LED sürücüsünün anahtarlama frekansı 142-200 kHz aralığında değiştirilmiş ve LED'lerin parlaklığı ZCS koşulları altında kısılmıştır. Ayrıca, önerilen HW-ZCS buck dönüştürücü ile geleneksel PWM tabanlı buck dönüştürücüye sahip LED sürücüsünün MOSFET gövde sıcaklığı üzerindeki etkileri karşılaştırılmıştır.

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1. INTRODUCTION

LEDs are extensively utilized in a variety of applications, including park and garden lighting, residential and commercial buildings, owing to their ease of integration, compact form factor, and dimmable capability [1]–[3]. Furthermore, their energy efficiency is a major factor contributing to their widespread usage. Unlike conventional lighting bulbs, LEDs require a special driver circuit for their operation. It is important for LEDs to be operated healthily for a long life. Voltage and current fluctuations or surges in the power supply of LEDs negatively affect their lifespan [4]. It is also important for an LED driver to maintain high efficiency while being cost-effective [5]. A constant current (CC) output LED driver provides a suitable solution for ensuring stable luminous flux [1]. The CC operation is possible by current regulator or DC-DC power converter [6], [7].

DC-DC power converters can be divided into two subcategories: isolated and non-isolated power converters [7]. Isolated DC-DC power converters include topologies such as flyback and forward converters, whereas non-isolated DC-DC power converters encompass boost, buck, and buck-boost converters. The main disadvantage of these converters is the switching losses [8]. Conventional PWM converters are alternative applications for LED drivers. PWM hard switching converters have some drawbacks at high frequencies. High power density and efficiency requirements can be achieved with resonant converters [9]. DC-DC power converters need to operate under soft-switching conditions to minimize switching losses and maximize efficiency. For this purpose, zero voltage switching (ZVS) or ZCS can be achieved with ZV or ZC power switch structures in DC-DC converters to achieve soft-switching [10].

Various power converter circuits have been presented for LED drivers [11]. An LED driver operating under ZVS conditions was proposed for automotive applications using an LCL-T resonant power converter [12]. In [13], a self-oscillated Class-E resonant inverter based LED driver circuit with high frequency switching was proposed. In [14], a study was conducted utilizing a switched capacitor to achieve ZCS condition. In [5], power control was realized in a resonant power converter through magnetic control, and an LED driver operating under ZVS conditions was proposed. Further studies utilizing resonant DC-DC power converters have also been conducted [15], [16]. In [17], a soft-switching LED driver system was implemented using a hybrid-controlled Class-E resonant converter.

In this study, HW ZCS buck converter for LED driver application was designed and implemented. The primary objective is to reduce switching losses and develop an LED driver with a reduced number of controlled components. The basic analysis of the HW ZCS buck converter and measurement results obtained with its laboratory application as LED driver are presented. Finally, the power switch body temperature for the ZCS buck converter and the PWM buck converter has been examined.

2. HW-ZCS BUCK LED DRIVER

The proposed HW-ZCS LED driver circuit is presented in Figure 1.

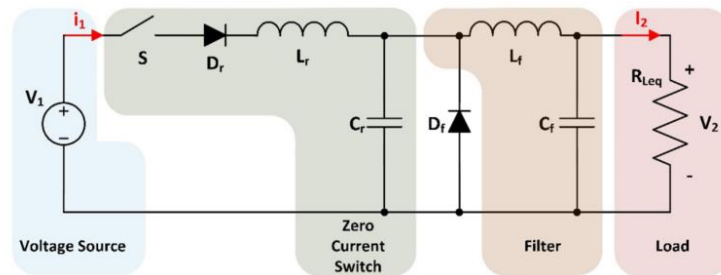


Figure 1. Proposed HW-ZCS Buck LED Driver Circuit.

A HW-ZCS buck converter can be achieved by adding an inductor (L_r) and a capacitor (C_r) to a conventional buck converter, as shown in Figure 1. In this circuit, D_r , L_r , C_r and R_{Leq} represent the blocking diode, resonant inductance, resonant capacitor and load resistance respectively. In the HW-ZCS buck converter, the filter and load circuit can be presented as a constant current source (I_2) as in Figure 2-a [8].

In the analysis, it is assumed that all circuit elements are ideal, the I_2 current is constant and $L_f \ll L_r$. The theoretical waveforms of the HW-ZCS buck converter are presented in Figure 2-b [10].

The normalized load resistance is calculated with Equation 1.

$$r_n = \frac{R_{Leq}}{Z_1} \quad (1)$$

Here Z_1 is the characteristic impedance and is calculated by Equation 2.

$$Z_1 = \sqrt{\frac{L_r}{C_r}} \quad (2)$$

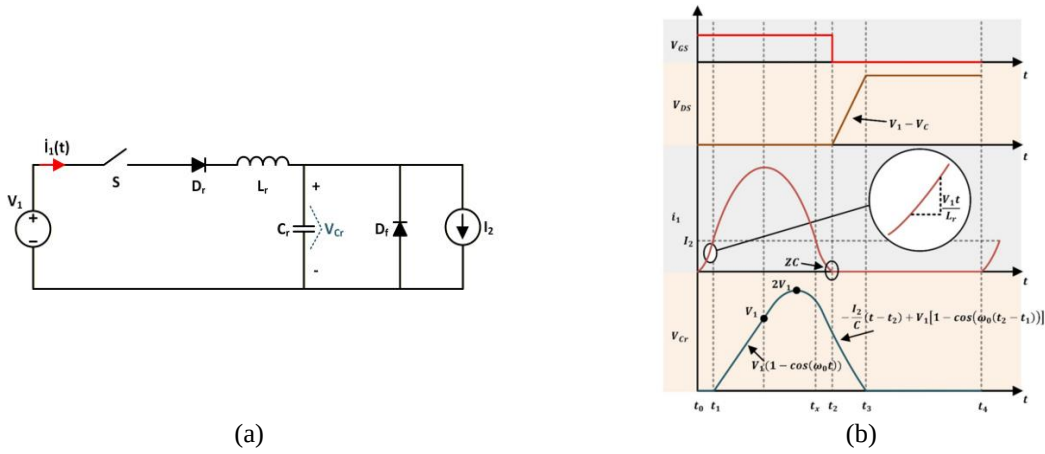


Figure 2. (a) Equivalent circuit of the proposed LED driver, (b) Theoretical waveforms of the HW-ZCS buck converter [10].

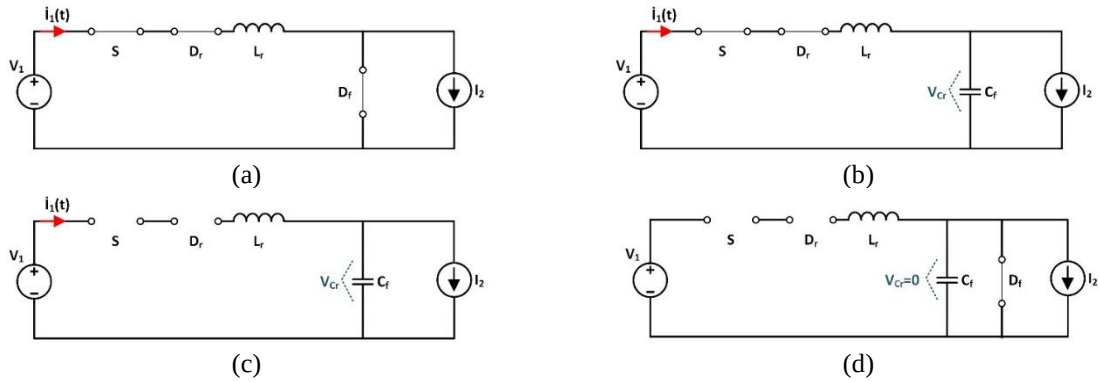


Figure 3. Equivalent circuit of modes, (a) Mode 1, (b) Mode 2, (c) Mode 3 and (d) Mode 4.

2.1. Mode 1 $t_0 < t \leq t_1$

In this mode, switch S is turned on and diode Dr is forward biased as shown in the Figure 3-a. Because of switch current $i_1(t)$ is smaller than output current I_2 , free-wheeling diode Df is forward biased. In this mode, the current flowing through the coil increases linearly at the rate in Eq. 3.

$$i_1(t) = \frac{V_1}{L_r} t \quad (3)$$

The end point of this mode is when i_1 is equal to current I_2 .

2.2. Mode 2 $t_1 < t \leq t_2$

In mode 2, the freewheeling diode is reverse biased. The i_1 current increases and flows through C_r . In this mode, i_1 and v_{Cr} are expressed by [10]:

$$i_1(t) = I_2 + \frac{V_1}{Z_0} \sin(\omega_0 t) \quad (4)$$

$$v_{Cr}(t) = V_1(1 - \cos(\omega_0 t)) \quad (5)$$

ω_0 is the angular resonance frequency and is calculated as follows [18].

$$\omega_0 = \frac{1}{\sqrt{L_r C_r}} \quad (6)$$

In the HW-ZCS buck converter, for ZCS to occur, the turned-off time of the S must take place after the current i_1 reaches zero.

2.3. Mode 3 $t_2 < t \leq t_3$

During this stage i_1 is kept zero and V_{Cr} is decreased linearly. V_{Cr} is expressed by Equation 7 [10].

$$v_{Cr}(t) = -\frac{I_2}{C_r}(t - t_2) + V_1(1 - \cos(\omega_0(t_2 - t_1))) \quad (7)$$

In this mode, the switch terminal voltage (V_{DS}) starts to increase. V_{DS} voltage calculated by Equation 8.

$$V_{DS} = V_1 - V_{Cr} \quad (8)$$

This mode ends when the capacitor voltage reaches to zero.

2.4. Mode 4 $t_3 < t \leq t_4$

In this subinterval, the switch is turned off and diode D_r is reverse biased. Resonant capacitor voltage and switch current are zero. This stage is freewheeling mode. Constant output current I_2 flows through the freewheeling diode. Mode 4 length can be used as a power control variable.

3. DESIGN CRITERIA OF PROPOSED SYSTEM

The proposed converter is designed to operate at 50% and 100% output current, to control the LEDs power under ZCS conditions. The LED array shown in Figure 4 was prepared as the load of HW-ZCS buck converter. Each LED has 2.2 V forward voltage (V_f) and the 350 mA optimum operating current.

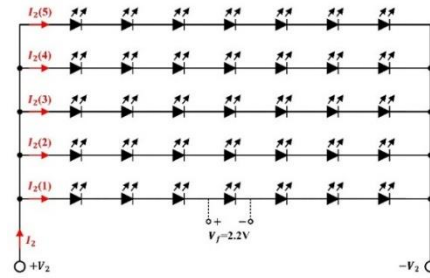


Figure 4. LEDs string.

The time intervals for the designed load can be calculated with the following equations;

$$\alpha = t_1 - t_0 = \frac{I_2 Z_1}{V_1} \quad (9)$$

$$\beta = t_2 - t_1 = \pi + \sin^{-1}\left(\frac{I_2 Z_1}{V_1}\right) \quad (10)$$

$$\gamma = t_3 - t_2 = \frac{V_1}{I_2 Z_1} \left[1 - \sqrt{1 - \left(\frac{I_2 Z_1}{V_1}\right)^2} \right] \quad (11)$$

The minimum switching period can be calculated by Eq. 12.

$$\omega_0 T_s \geq \alpha + \beta + \gamma \quad (12)$$

Maximum switching frequency is related with $\alpha + \beta + \gamma$. The essential condition of the ZC resonant switch to operate under ZCS condition is generated in Eq. 13.

$$I_n < 1 \quad (13)$$

Here, I_n represents normalized current and is calculated as follows;

$$I_n = \frac{I_2 Z_0}{V_1} \quad (14)$$

The conversion ratio (M) is calculated in Eq. 15.

$$M = \frac{I_1}{I_2} = \frac{f_n}{2\pi} \left[\frac{I_n}{2} + \pi + \sin^{-1}(I_n) + \frac{1}{I_n} \left(1 + \sqrt{1 - I_n^2} \right) \right] \quad (15)$$

The resonant components were selected based on the required ZCS condition and acceptable resonant current stress. First, the LED load voltage and current were calculated from the experimentally obtained LED current-voltage characteristic. Then, the input voltage and the conversion ratio were computed by considering the voltage drops and parasitic resistances of the circuit components. Once these design parameters were fixed, the resonant frequency was determined such that the switch current reaches zero during the resonant interval. Finally, the resonant inductance and resonant capacitance were selected according to the angular resonant frequency relation given in Eq. (6). The conversion ratio related to the given load can be calculated as $M=0.743$. Resonant frequency is 310 kHz for given circuit parameters in Table I.

Table I. Circuit parameters

Resonant inductance (L_r)	3.88 μH
Resonant capacitance (C_r)	68 nF
Filter inductance (L_f)	252 μH
Filter capacitance (C_f)	10 μF
Voltage Source (V_i)	24 V

The characteristic impedance is calculated as 7.55 Ω , using the circuit parameters in Table 1. Additionally, $I_2 = 1.75$ A at full load output current, and $I_2 = 0.9$ A at half load output current. Using these current values, the normalized current was calculated as $I_{n\%100} = 0.585$, $I_{n\%50} = 0.301$, respectively. The normalized frequency versus normalized current graph was plotted at different M values and presented in Figure 5.

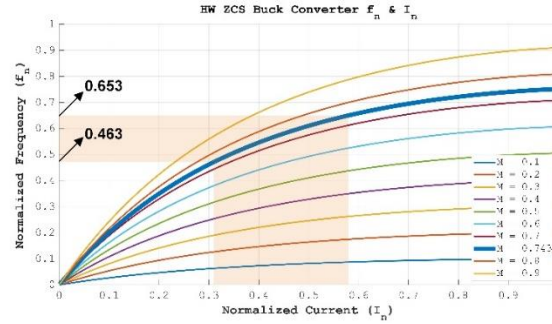


Figure 5. Normalized frequency and normalized current for proposed LED driver

The switching frequency is calculated as $f_s(\%100) = 202.3$ kHz and $f_s(\%50) = 143.4$ kHz from Figure 5. The minimum and maximum duty ratios are also calculated as follows.

$$D_{min} = \frac{\alpha + \beta}{\omega_0 T_s} \quad (16)$$

$$D_{max} = \frac{\alpha + \beta + \delta_x}{\omega_0 T_s} \quad (17)$$

Here, the δ_x time depends on the normalized current value. As a result of these calculations, it is calculated as $D_{min} = 0.452$, $D_{max} = 0.596$ at %100 output current and $D_{min} = 0.276$, $D_{max} = 0.510$ %50 output current.

4. EXPERIMENTAL RESULTS

The experimental studies were carried out by IRFP260 MOSFET, DSB20115PA blocking diode and DSS 16-01A free-wheeling diode. The HW-ZCS Buck LED driver circuit's laboratory prototype is presented in Figure 6. Experimental studies were carried out at 50% and 100% output current, respectively. During the experiments, the duty ratio of the switching signal was kept constant and the power control was performed by frequency modulation. The first experimental studies were carried out 50% output current and 141.9 kHz switching frequency. The measurement result of the V_{GS} and i_1 is shown in Figure 7-a. It is seen that i_1 reaches zero before the switch goes into turn off. Thus, the LED driver operates under ZCS conditions. In addition, i_1 current and V_{Cr} voltage measurements are also presented in Figure 7-b.

The measurement result of the 100% output current is presented in the Figure 7-c. According to this result, it is seen that the MOSFET is switched under ZCS conditions. The duty ratio remained the same but the switching frequency increased to 200 kHz. The measurement results of V_{Cr} voltage and i_1 current under the same current condition are also presented in Figure 7-d. The LED brightness could be dimmed by changing the HW-ZCS Buck power converter frequency between 200 kHz and 142 kHz in the experiments. Comparative results of simulation and experiments are presented in Table II.

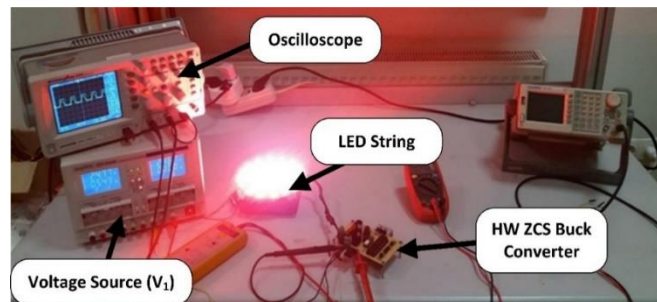


Figure 6. Experimental prototype.

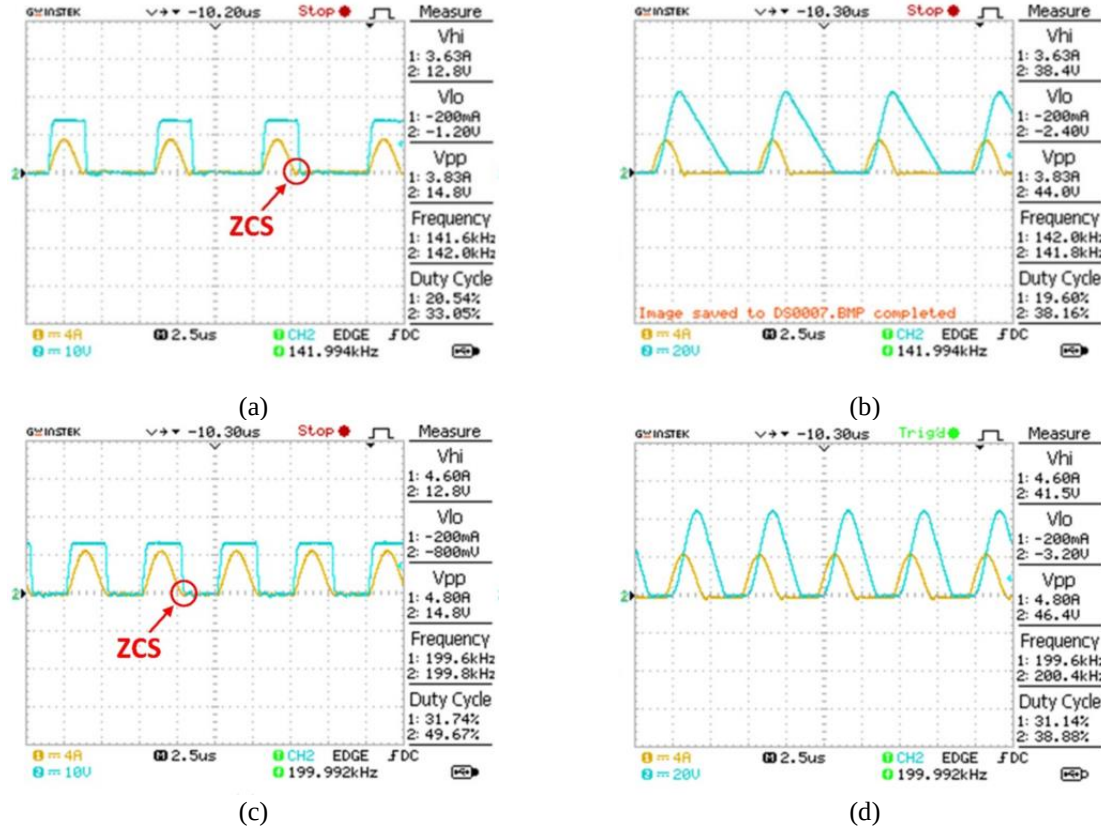


Figure 7. 50 % output current results, (a) V_{GS} and i_L , (b) V_{Cr} and i_L , 100 % output current results, (c) V_{GS} and i_L , (d) V_{Cr} and i_L .

Table II. Simulation and experiment results.

	Parameters	Simulation	Experiment
%100 I_2	f_s	202 kHz	200 kHz
	$i_{L(max)}$	4.77 A	4.71 A
	$V_{Cr(max)}$	45.7 V	46.4 V
	I_2	1.76 A	1.72 A
%50 I_2	f_s	143 kHz	142 kHz
	$i_{L(max)}$	3.90 A	3.83 A
	$V_{Cr(max)}$	45.8 V	44.7 V
	I_2	0.91 A	0.88 A

In order to compare the performance of the proposed HW-ZCS buck converter as an LED driver, experiments were carried out with the conventional PWM buck converter at the same input voltage, operating frequency and load conditions. The experimental results of the conventional buck converter are presented in Figure 8.

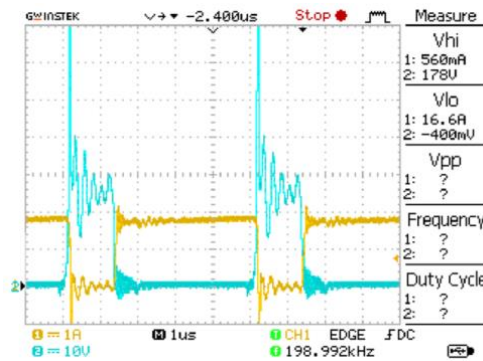


Figure 8. Conventional buck converter experimental result.

In Figure 8, switching losses on the MOSFET and voltage spikes on the VDS caused by hard switching can be observed. The MOSFET temperature was monitored under the same conditions and for the same duration, as shown in Figure 9-a and Figure 9-b.

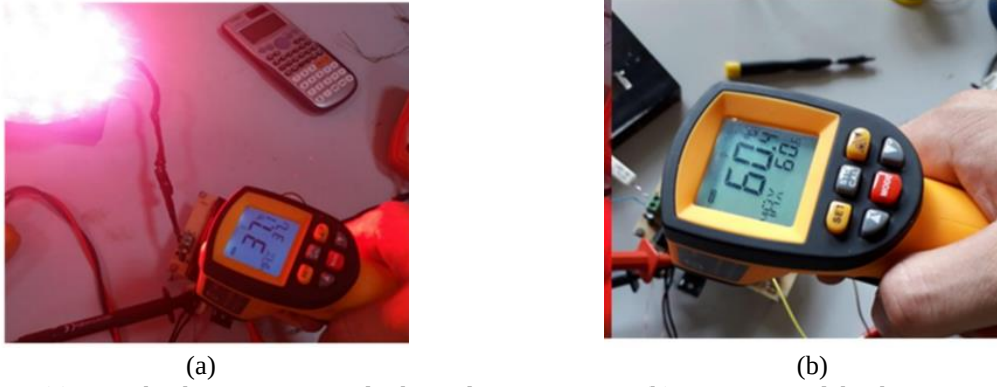


Figure 9. (a) ZCS buck converter result thermal measurement (b) Conventional buck converter thermal measurement.

During this test, the system was operated for 5 minutes. The theoretical switching-loss characteristic and the experimental MOSFET temperature rise after 5 minutes of operation are summarized in Table III.

Table III. Simulation and experiment results.

Converter	Psw	Experimental MOSFET temperature rise after 5 minutes
Conventional Buck Converter	High	35.6 °C
Proposed HW-ZCS Buck Converter	≈ 0	11.6 °C

While the initial MOSFET temperature in the LED driver circuit with HW-ZCS buck converter was 25.5°C, after 5 minutes of operation it was measured at 37.1°C. In the conventional buck converter, the initial temperature was measured as 24.8 °C and the MOSFET temperature was measured as 60.4 °C after 5 minutes of operation. In both LED driver circuits, there is a 23.3 °C difference between the switch temperature rise in tests performed in equal time. As a result, LED driver using a conventional PWM buck converter requires a larger heatsink and cooler fan. In addition, the system efficiency is also reduced due to switching losses.

5. CONCLUSION

A LED driver structure with an HW QR buck converter is proposed in this paper. The analysis of the proposed system is explained operation points for different load conditions and experimental results are presented. In the experiments, it was observed that the proposed LED driver meets the ZCS conditions. The proposed driver is also compared to a conventional PWM buck converter, both were operated for 5 minutes, and the temperature change was monitored. As a result, the PWM buck converter driver results in 23.3 degrees' greater temperature than the proposed soft switching converter. The proposed structure is suitable for low and mid power level LED driver applications. Since the peak value of the resonant current can increase at higher power levels, the current-voltage ratings of the MOSFET, diode, resonant coil and resonant capacitor should be chosen with enough safety margin. Therefore, the resonant current at critical power levels should be considered and limited in the design from the point of view of the element stress.

Author Contributions

Selim ÖNCÜ supervised the study and provided overall guidance throughout the research process. Ali Rıza Derin conducted the theoretical analysis and experimental studies and wrote the manuscript. Kenan ÜNAL conducted the experimental studies.

Declaration of conflicting interests

There is no conflict of interest between the authors.

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