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COMPARISON OF DC-DC SEPIC, CUK AND FLYBACK CONVERTERS BASED LED DRIVERS

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ABSTRACT

This paper presents the comparison of LED driver topologies that include SEPIC, CUK and FLYBACK DC-DC converters. Both topologies are designed for 8W power and operated in discontinuous conduction mode (DCM) with 88 kHz switching frequency. Furthermore, inductors of SEPIC and CUK converters are wounded as coupled. Applications are realized by using SG3524 integrated circuit for open loop and PIC16F877 microcontroller for closed loop. Besides, ACS712 current sensor used to limit maximum LED current for closed loop applications. Finally, SEPIC, CUK and FLYBACK DC-DC LED drivers are compared with respect to LED current, LED voltage, input voltage and current. Also, advantages and disadvantages of all topologies are concluded.

Keywords: CUK, FLYBACK, LED driver, SEPIC

1. INTRODUCTION

Using power LEDs in illumination has been so popular lately due to the high efficiency feature with respect to other illumination methods such as fluorescent, incandescent and metal halide bulbs. But, to operate power LEDs with different illumination levels, variable DC power is required. This DC power can be supplied by using DC-DC converters. Basic DC-DC converters are buck, boost and buck-boost converters. In buck-boost converter, output voltage can be lower or higher than input voltage. So, buck-boost DC-DC converter using as a LED driver is more attractive. Furthermore, SEPIC, CUK and FLYBACK DC-DC converters are also buck-boost derived topologies and for low power, it is better to operate those converters in DCM.

In literature, some studies are conducted this topic as follows. Design and analysis of SEPIC, CUK and FLYBACK DC-DC converters are given in [1–8]. In [9, 10], CUK DC-DC converter based LED driver are presented. SEPIC DC-DC converter based LED drivers are also given in [11,12] for road vehicles and general application. In references [13–16], FLYBACK DC-DC converter based LED drivers are also proposed as the single and multi-output drivers. AC-DC and DC-DC converters that are buck, boost, buck-boost, FLYBACK and half bridge are reviewed as a LED driver in [17]. In [18], comparison is made for buck-boost, SEPIC and CUK DC-DC converters based LED drivers. Another comparison is also made in [19] for buck and FLYBACK converter based LED drivers.

In this paper, comparison of SEPIC, CUK and FLYBACK LED driver topologies are presented. Both topologies are connected to DC power supply over an input filter and designed for 8W power with 88 kHz switching frequency. Besides, open loop operation is realized by SG3524 IC and closed loop operation is carried out by PIC16F877, and ACS712 current sensor not to exceed maximum current limit. Furthermore, LED voltage, LED current, input side inductor voltage and current, input voltage and current are measured for all topologies.

The article has the following structure: power LED current-voltage characteristic and electrical circuit model are included in section 2, LED driver

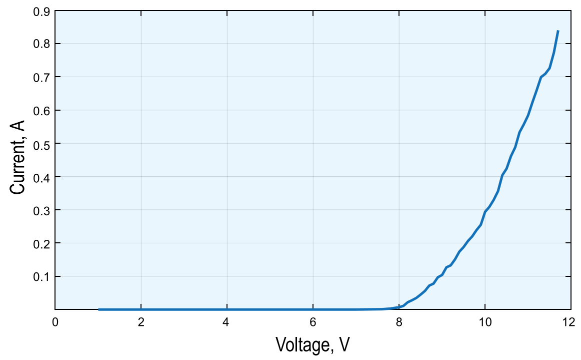


Fig. 1. Voltage-current characteristic of power LED

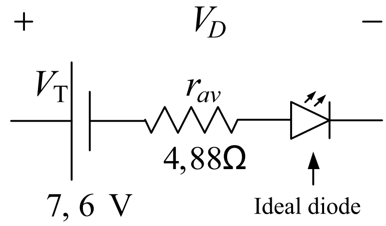


Fig. 2. Electrical equivalent model of power LED

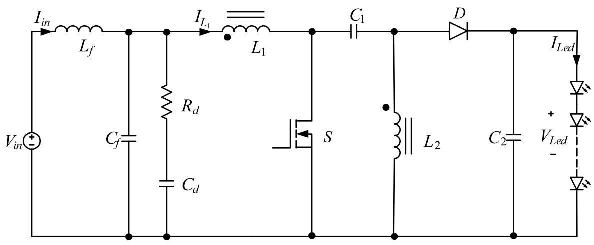


Fig. 3. SEPIC DC-DC Converter

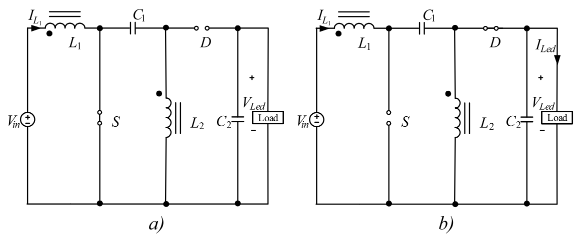


Fig. 4. Switching state: a) on, b) off

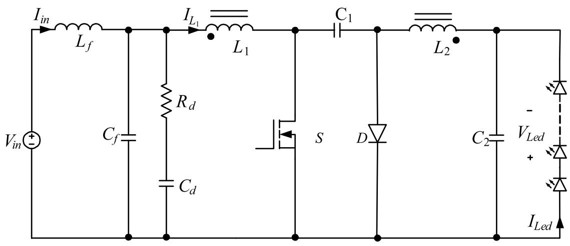


Fig. 5. CUK DC-DC converter

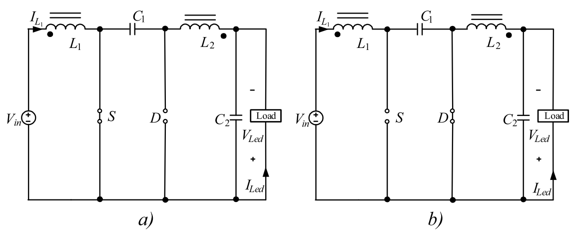


Fig. 6. Switching state: a) on, b) off

topologies applied are introduced in section 3, applications of LED drivers are presented in section 4, measurement results are given in section 5, and conclusions are done in section 6.

2. POWER LED

In this chapter, current-voltage characteristics and electrical circuit model of power LED that are used for this study are derived by using Fluke 15B and Fluke 17B as in [20, 21].

Fig. 1. shows voltage-current characteristic of power LED. The characteristic is obtained by increasing voltage of power LED and plotting voltages versus current. It is seen from the figure that LED voltage and current has exponential relation and LED current increase extremely after LED turns on. Also, LED voltage doesn't change much after and up to 0.8 A current [20, 21].

Electrical circuit model of power LED is derived by using Fig. 1 and presented in Fig. 2. It is understood by this model that threshold voltage and resistance of power LED are 7.6 V and 4.88 Ω respectively as in [20, 21].

3. LED DRIVER

In this chapter, DC-DC SEPIC, CUK and FLYBACK converter based LED drivers are introduced. Both drivers are connected to DC supply over an input filter. All these topologies can be operated buck-boost principle that means output voltage can be lower or higher than input voltage. Furthermore, input filter is used in order to have current with low noise because of the DCM operating condition and high frequency switching. In SEPIC and CUK converter inductors can be wound as coupled, also FLYBACK converter uses high frequency transformer that works as an inductor.

3.1. SEPIC DC-DC Converter

Fig. 3. shows the SEPIC DC-DC converter that is connected to DC supply by using input filter and this converter has two inductors that are wounded as coupled and two capacitors. Besides, output voltage is the same polarity with the input voltage.

In Fig. 4 circuit of SEPIC converter is shown by switching states. To understand operation of SEPIC

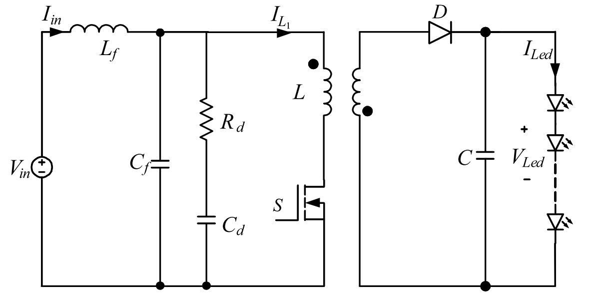
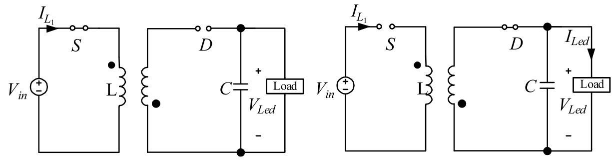


Fig. 7. FLYBACK DC-DC converter



a) b)

Fig. 8. Switching state: a) on, b) off

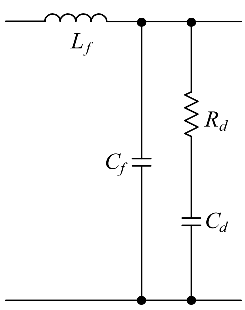


Fig. 9. Input LC series damped filter

converter and design of passive elements, converter should be analyzed with respect to switch on and off position. When S is turned on, L_1 is energized by power source and L_2 is energized by C_1, C_2 feeds the load. When S is turned off, C_1 is charged by power source and L_1, while currents of L_1 and L_2 flowing through D and load, C_2 is also charged [2, 3].

SEPIC converter can supply power to load with lower or higher voltage with respect to input voltage and output voltage is with the same polarity of input voltage. Passive elements in SEPIC converter can be chosen by using equations (1–3) as in [2, 3]. In these equations, L_{1min}, L_{2min} are the maximum inductor values for DCM operation, D is the duty cycle, V_{in} is the input voltage, f_{sw} is the switching frequency, ΔI_L is inductor current ripple, ΔV_{C1} is C_1 voltage ripple, I_{out} is the output current, and V_{ripple} is ripple on C_2.

$$L_{1min} = L_{2min} = D.{V_{in}} \big/ {\Delta I_L . f_{sw}}. \quad (1)$$

$$C_2 \geq {I_{out}.D} \big/ {V_{ripple} . f_{sw}}. \quad (2)$$

$$C_1 = {I_{out}.D} \big/ {\Delta V_{C_1} . f_{sw}}. \quad (3)$$

3.2. CUK DC-DC Converter

Fig. 5. shows CUK DC-DC converter circuit that has also two inductors and two capacitors. Furthermore, inductors in CUK converter are also wounded as coupled that means on the same core.

Circuits of CUK converter with respect to switch states are shown in Fig. 6. When S is turned on, L_1 is energized by power source, and C_1 discharges over C_2, load and L_2. When S is turned off, C_1 is charged by power source and L_1, also L_2 currents flows through D, load and C_2 [1, 8].

CUK converter also supplies power with lower or higher voltage with respect to input voltage. However, output voltage polarity of CUK converter is reverse polarity with input voltage.

Passive elements in CUK converter can be chosen by using equations (4, 6) as in SEPIC converter [1, 8]. In these equations, L_{1min}, L_{2min} are the maximum inductor values for DCM operation, D is duty cycle, V_{in} is input voltage, f_{sw} is switching frequency, ΔI_L is inductor current ripple, ΔV_{C1} is C_1 voltage ripple, I_{out} is output current, and V_{ripple} is ripple on C_2.

$$L_{1min} = L_{2min} = D.{V_{in}} \big/ {\Delta I_L \cdot f_{sw}}. \quad (4)$$

$$C_2 \geq {I_{out}.D} \big/ {V_{ripple} \cdot f_{sw}} \quad (5)$$

$$C_1 = {I_{out}.D} \big/ {\Delta V_{C_1} \cdot f_{sw}} \quad (6)$$

3.3. FLYBACK DC-DC Converter

Fig. 7. shows the FLYBACK converter circuit that has a high frequency transformer and a capacitor is connected to input supply by input filter. Furthermore, transformer of FLYBACK converter operates as an inductor.

Switch states of FLYBACK converter are shown in Fig. 8. When S is turned on, primary winding of transformer is energized by power source and C feeds load. When S is turned off, energy on primary winding is transferred to secondary winding and over D secondary current flows through load and C [1, 4–7].

Passive elements in FLYBACK converter can be chosen by using equations (7, 8) as in [1, 4–7]. In these equations, L_{mmax} is the maximum magnetization inductance value for DCM operation, D is the duty cycle, R_{Lmin} is the minimum load, f_{sw} is the switching frequency, C_{min} is the minimum output capacitor, V_{cpp} is voltage ripple on C, I_{omax} is the maximum output current, n is the transformer's turn ratio.

$$L_{m(max)} = {n^2 R_{Lmin} (1\text{-}D)^2} \Big/ {2.f_{sw}}. \tag{7}$$

$$C_{min} = {I_{omax}.D} \Big/ {f_{sw}.V_{cpp}}. \tag{8}$$

3.4. Input Filter

Fig. 9. shows the input filter circuit that is used with SEPIC, CUK and FLYBACK converters. This filter is called as LC series damped type input filter. In this paper, all of the converters are operated in DCM mode therefore, without using an input filter, supply current will be discontinuous. In order to have continuous supply current and to reduce high frequency noise LC series damped type input filter is used.

Passive elements in input filter can be chosen by using equations (9–12) as in [22, 23]. In these equations, f_f is the cutoff frequency of filter, L_f is filter inductor, C_f is filter capacitor, R_0 is the characteristic impedance of un-damped filter, R_d is the damping resistance, C_d is the damping capacitor, a is ratio between C_d and C_f. After calculations, values of L_f, C_f, R_d and C_d are found as 160μH, 10μF, 2.47Ω and 40μF respectively and used in all LED drivers.

$$f_f = 1 \Big/ 2\pi\sqrt{L_f C_f}. \tag{9}$$

$$R_0 = \sqrt{L_f \big/ C_f}. \tag{10}$$

$$R_d = R_0 \sqrt{(2+a)(4+3a) \Big/ 2a^2(4+a)}. \tag{11}$$

$$a = C_d \big/ C_f. \tag{12}$$

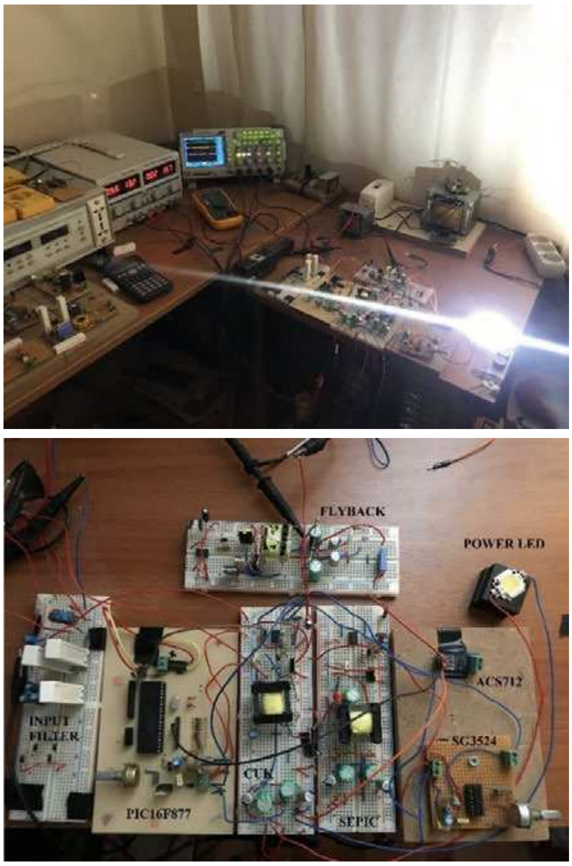


Fig. 10. Experimental setup

4. APPLICATION

In this chapter, applications of SEPIC, CUK and FLYBACK LED drivers are realized. Fig. 10. shows the experimental setup. Both converters are connected to input supply over LC input filter. Furthermore, as a load COB power LED having characteristics in Fig. 1 is connected. In applications, TPS2024B oscilloscope, A622 current probe, FLUKE15B, 17B multi-meters are used. Open and closed loop applications are conducted by SG3524 IC and PIC16F877 microcontroller.

4.1. SEPIC DC-DC CONVERTER

In Fig. 11, application circuit of SEPIC based LED driver is shown. It is understood that open loop operation is realized by SG3524 IC and closed operation by PIC16F877 and ACS712. Besides, IRFZ44N MOSFET, TC4427 MOSFET driver, Schottky diode 1N5822 are included in the application circuit. Furthermore, L_1, L_2 are 18 μH, C_1 is the 10 μF and C_2 is 460 μF [2,3, 24–29].

The duty cycle can be changed by the potentiometer connected to SG3524, PIC16F877 and PWM

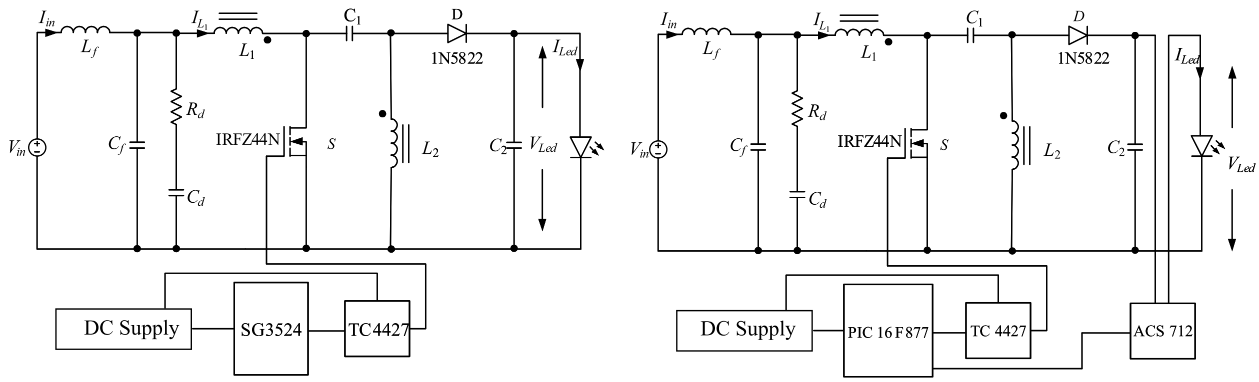


Fig. 11. Application circuit of SEPIC converter

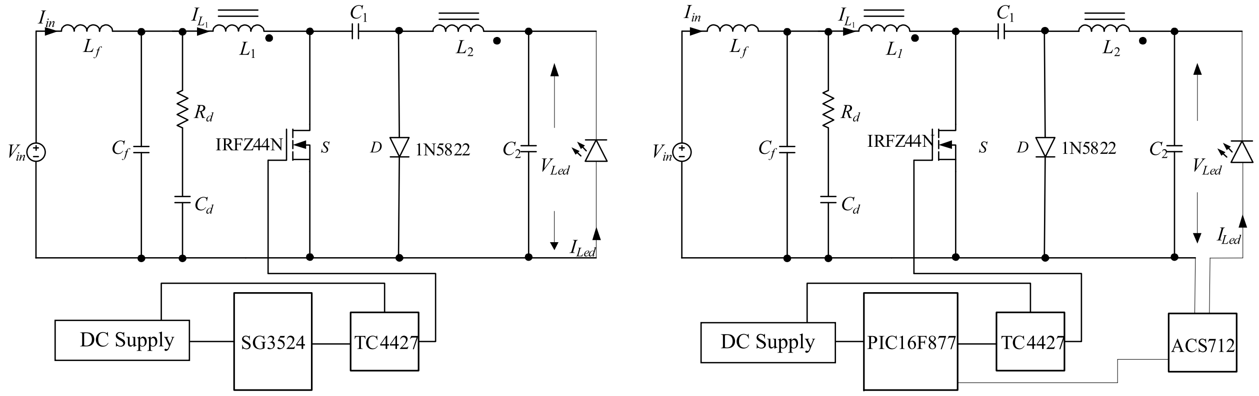


Fig. 12. Application circuit CUK converter

frequency is set to 88 kHz. To reduce high frequency noise and avoid discontinuous supply current *LC* filter is used. Besides, passive elements are used after calculations in equations (1–3).

4.2. CUK DC-DC Converter

Fig. 12. shows the application circuit of CUK converter based LED driver. This application is also realized by open and closed loop algorithm. Furthermore, SG3524 IC or PIC16F877 used for PWM signals, IRFZ44N MOSFET, TC4427 MOSFET driver, Schottky diode 1N5822 are used in the application circuit. Furthermore, L_1, L_2 are 18 μH, C_1 is 10 μF and C_2 is 460 μF [8, 24–29].

The duty cycle can also be changed by the potentiometer connected to SG3524 or PIC16F877 and PWM frequency is again used as 88 kHz. By using equations (4–6), passive elements are chosen.

4.3. FLYBACK DC-DC Converter

Fig. 13 shows the application circuit of FLYBACK converter based LED driver. This application is also realized by open and closed loop algorithm. Furthermore, SG3524 IC or PIC16F877 is used for PWM signals and IRFZ44N MOSFET, TC4427 MOSFET driver, Schottky diode 1N5822 are used in the application circuit. Also, primary and secondary windings of transformer are 18 μH and *C* is equal to 460 μF [4–7, 24–29].

The duty cycle can also be changed by the potentiometer connected to SG3524, PIC16F877 and PWM frequency is again used as 88 kHz. By using equations (7–9), passive elements are chosen.

5. MEASUREMENT RESULTS

LED voltages (V_{LED}), LED currents (I_{LED}), input voltages (V_{in}), input currents (I_{in}), PWM signals, current and voltage of input side inductors (V_{L1}), (I_{L1}) are measured by using TPS2024B oscilloscope and A622 current probe for each LED drivers.

5.1. SEPIC DC-DC Converter

In Fig.14, SEPIC DC-DC Converter characteristics are shown which are getting with help from 1 to 4 oscilloscope channels respectively. LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current

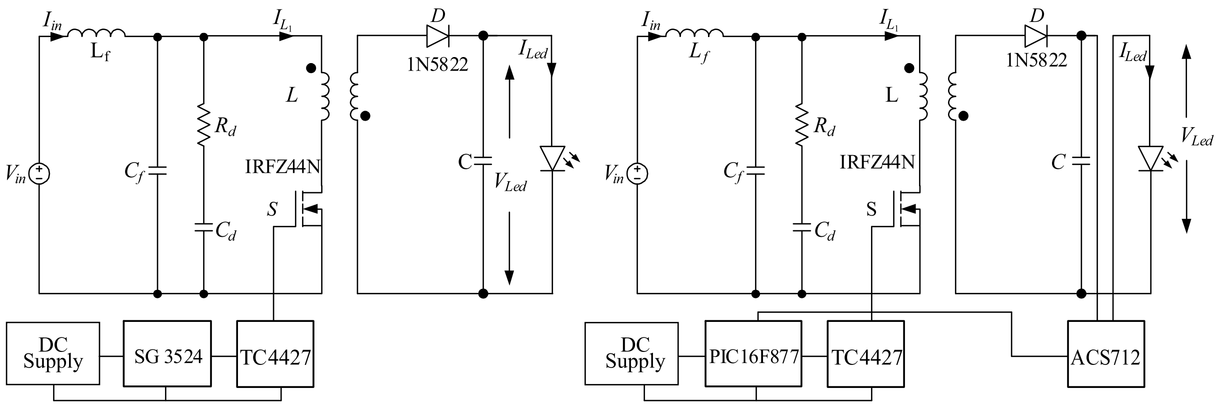


Fig. 13. Application circuit FLYBACK converter

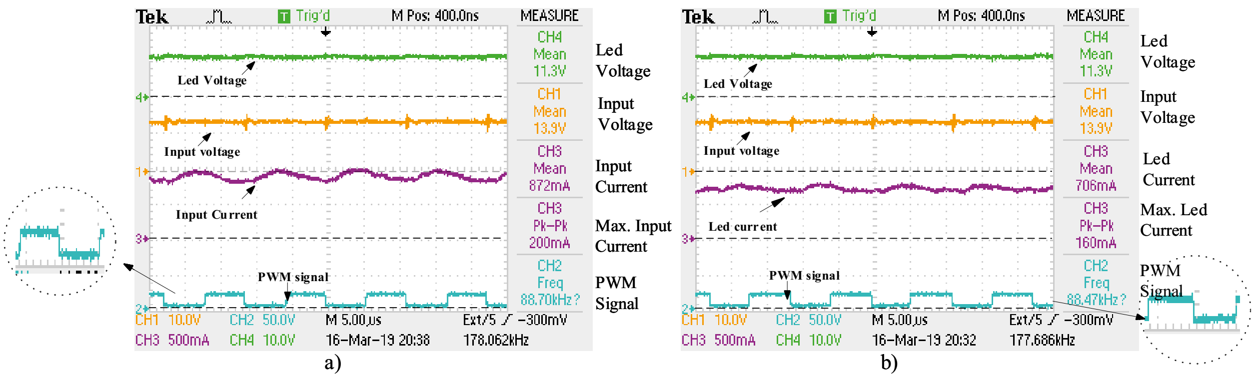


Fig. 14. SEPIC converter: a – LED voltage (V_{LED}), input voltage (V_{in}) and current (I_{in}), PWM signal; b – LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}), PWM signal

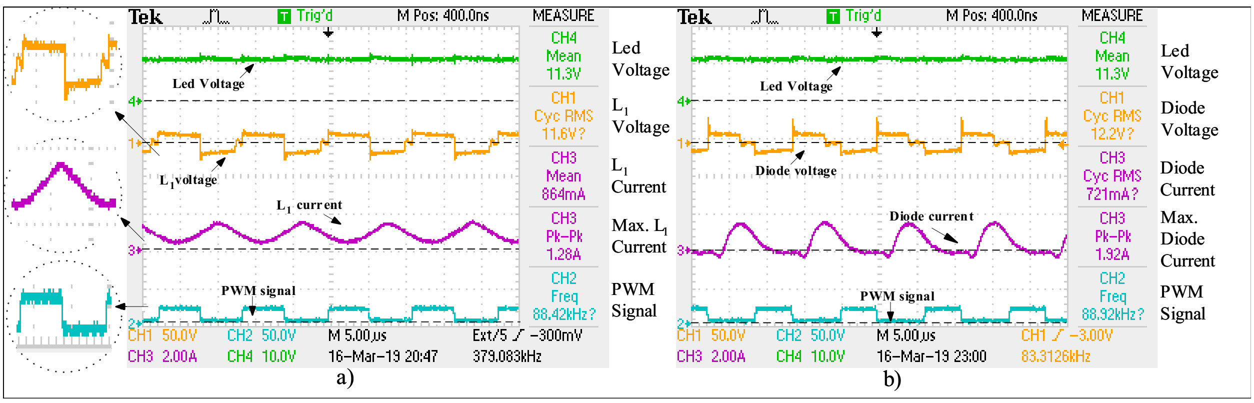


Fig. 15. SEPIC converter: a – LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current (I_{L1}), PWM signal; b – SEPIC converter input voltage (V_{in}), diode voltage and current, PWM signal

(I_{L1}), PWM signal and LED voltage (V_{LED}), diode voltage and diode current, PWM signal are shown in Fig. 15 a, b respectively. Although, L_1 current (I_{L1}) shown in Fig. 15a is continuous, in DCM operation of SEPIC converter L_1 current swings from a constant current level instead of zero as in [30]. So, diode current shown in Fig. 15 b proves the DCM operation, diode current decreases to zero and increase from zero current. As a result, it is understood that SEPIC converter is operated in DCM with 11.3V LED voltage.

5.2. CUK DC-DC converter

In Fig. 16 CUK DC-DC converter characteristics are presented: a – LED voltage (V_{LED}), input voltage (V_{in}), input current (I_{in}), PWM signal and in b – LED voltage (V_{LED}), input voltage (V_{in}), LED

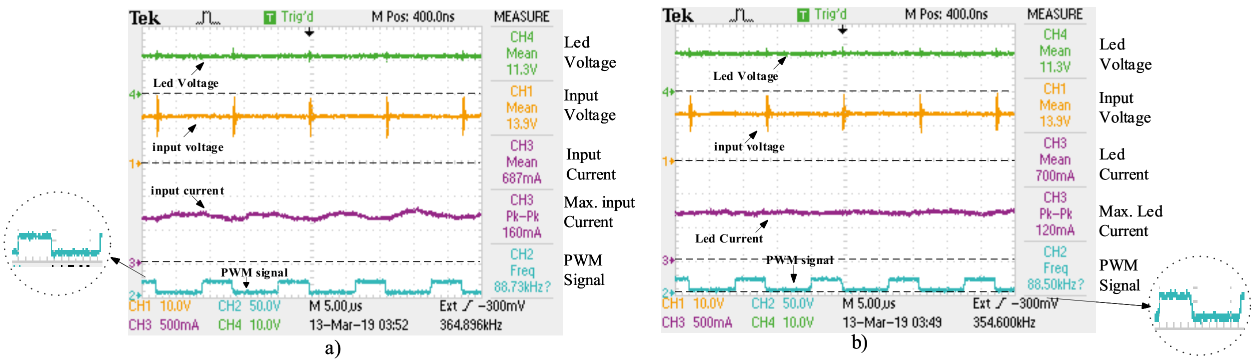


Fig. 16. CUK converter, LED voltage (V_{LED}), input voltage (V_{in}) and current (I_{in}), PWM signal –a; CUK converter, LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}), PWM signal – b

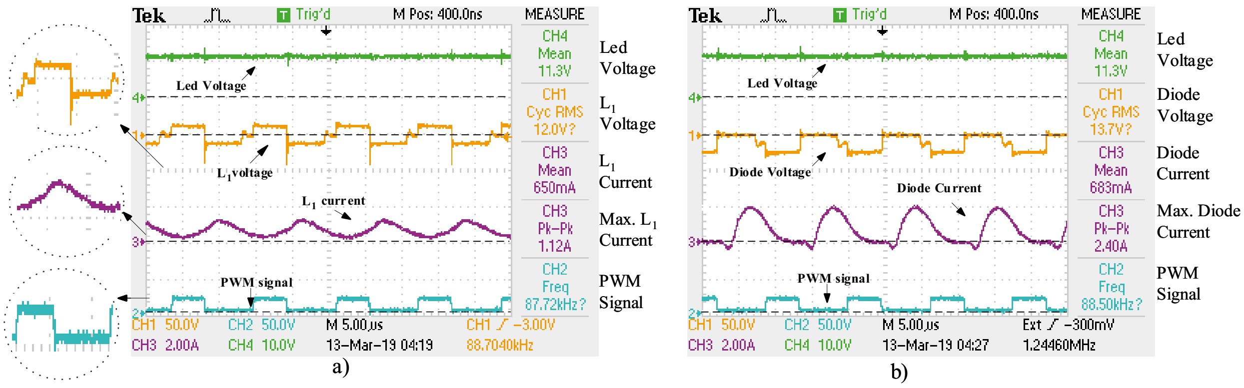


Fig. 17. CUK converter, LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current (I_{L1}), PWM signal – a; CUK converter input voltage (V_{in}), diode voltage and current, PWM signal – b

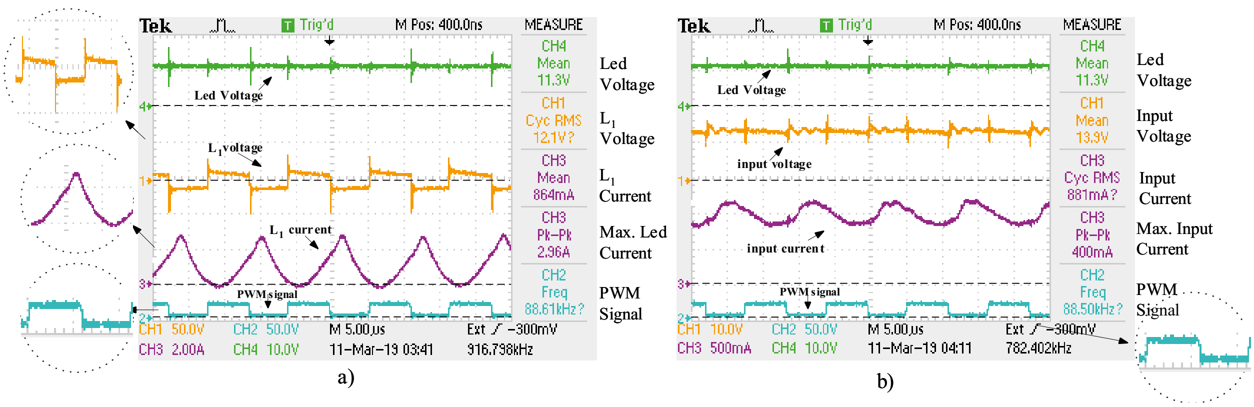


Fig. 18. FLYBACK converter, LED voltage (V_{LED}), primary voltage (V_{L1}) and current (I_{L1}), PWM signal- a; FLYBACK converter, LED voltage (V_{LED}), input voltage and current, PWM signal – b

current (I_{LED}), PWM signal are shown by 1 to 4 oscilloscope channels respectively. It is seen that by using input filter continuous supply current is obtained and efficiency is around 83 % at 8W output power.

In Fig. 17, LED voltage (V_{LED}), input side inductor voltage (V_{L1}) and current (I_{L1}), PWM signal and LED voltage (V_{LED}), diode voltage and current, PWM signal are shown a) and b) respectively. As described in SEPIC converter, in DCM operation of CUK converter L_1 current swings from a constant current level instead of zero as in [30]. So, diode current shown in Fig. 17 b) proves the DCM operation, diode current decreases to zero and increase from zero current. As a result, it is understood that SEPIC converter is operated in DCM with 11.3V LED voltage.

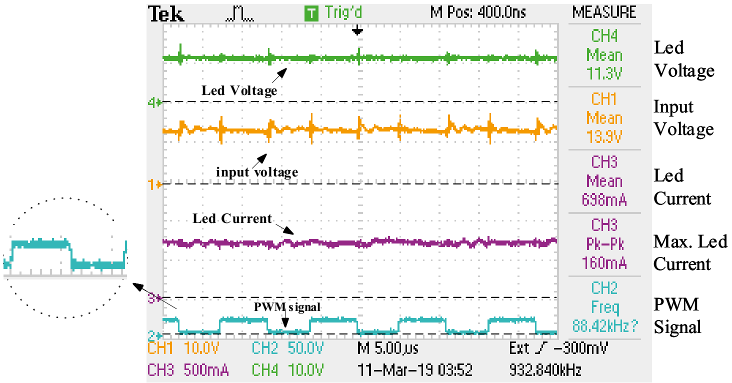


Fig. 19. FLYBACK converter, LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}), PWM signal

5.3. FLYBACK DC-DC converter

In Fig. 18 FLYBACK DC-DC converter characteristics are shown by 1 to 4 channels, respectively: LED voltage (V_{LED}), primary voltage (V_{L1}) and current (I_{L1}), PWM. It is seen that, FLYBACK converter is operated in DCM with 11.3V LED voltage. In Fig. 18.b LED voltage (V_{LED}), input supply voltage (V_{in}), supply current (I_{in}) and PWM signal is also shown by 1 to 4 channels, respectively. It is seen that by using input filter continuous supply current is obtained.

In Fig. 19 LED voltage (V_{LED}), input voltage (V_{in}), LED current (I_{LED}) and PWM signal are shown. It can be calculated that efficiency is obtained around 65 % at 8W power.

6. CONCLUSIONS

This paper compares DC-DC SEPIC, CUK and FLYBACK converter based LED drivers. All converters are operated at DCM, both open and closed loop applications are conducted. Also, LED current is measured by ACS712 current sensor in order to limit maximum LED current to prevent damage on power LEDs. By means of the applications, LED current, LED voltage, input current, input voltage and input side inductor voltage and current are measured.

By using the same input filter, SEPIC, CUK and FLYBACK LED drivers have 0.1A, 0.08 A and 0.2 A input current oscillations. Also SEPIC LED driver does not disturb input voltage like other drivers. Furthermore, SEPIC, CUK and FLYBACK LED drivers provides current to power LEDs with 80 mA, 60 mA and 80 mA current oscillations, respectively. Besides, power LED voltage is smooth in SEPIC and CUK LED drivers but in FLYBACK LED driver, it has small pulsations. Besides, CUK converter gives better efficiency that SEPIC and FLYBACK converter.

It is observed by the application results, CUK and SEPIC LED drivers have similar characteristics but CUK converter gives better results. On the other hand, SEPIC converter gives the same polarity output voltage with input voltage that is reverse in CUK LED driver. So, if the voltage polarity is matters using SEPIC converter is a better solution. However, FLYBACK LED driver has an electrical isolation because of its high frequency transformer. When isolation is required, FLYBACK LED driver can also be used.

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