Eco-friendly LED illumination using a modified non-inverting Cuk converter for sustainable lighting applications

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ABSTRACT

Light-emitting diodes (LEDs) are essential to current lighting due to their perfect control, long lifespan, great energy efficiency, and environmental friendliness. However, issues like output ripple and uneven brightness could have an impact on both visual comfort and system performance. This research presents the design and implementation of a non-inverting Cuk (NI-Cuk) converter operating in discontinuous conduction mode (DCM), integrated with a valley-fill circuit (Vfc) that reduces voltage and current (V and I) ripple and improves lifetime. The study begins with an analysis of the classic Cuk (CCuk) converter, highlighting its shortcomings, including inverted output polarity and the high current stress across the switching device. A NI-Cuk is proposed to overcome the shortcomings of CCuk, delivering a positive output with higher efficiency. Vfc offers a faster steady-state response, reduces peak loads on components, and reduces losses. To confirm that the design and hardware prototype were developed, and the results are validated with the simulated outcomes. The approach's viability is confirmed by experimental results, and a comparison of CCuk, NI-Cuk, and NI-Cuk with and without Vfc is conducted using voltage regulation, efficiency, and ripple. The results show that the suggested converter assurances are a reliable, effective, and superior power source for LED lighting applications.

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1. INTRODUCTION

LED technology [1] has high efficiency, extended stability, eco-friendly operation, and seamless integration with intelligent control systems in modern lighting. LED is used to convert electrical energy into light [2], resulting in reduced power consumption with reduced cost. These benefits make LEDs the preferred choice for residential and commercial lighting in industries, streetlights, and also automotive applications [3], [4]. But, one of the most critical challenges in LED lighting [5] systems are the occurrence of flicker, which can adversely affect human visual comfort and health. In many LED systems, the driver is a DC-DC converter [6]. However, depending on the converter topology, issues such as [7], [8], increased stress on the switch, inverted output, and noticeable ripple all contribute to flickering and reduced system reliability. Although several DC–DC converter [9], [10] topologies have been reported for LED driving applications, many existing solutions exhibit inherent performance shortcomings. These include noticeable voltage and current ripple, slow dynamic response to input or load disturbances, elevated stress on switching and passive components, and efficiency degradation under practical operating conditions [11], [12]. Certain converters also generate inverted output voltages, requiring additional stages that increase circuit complexity and cost

[13]. Collectively, these limitations lead to flicker, thermal, and electromagnetic issues, reduced LED lifespan, and deterioration of visual comfort, thereby necessitating a more reliable and high-performance driver architecture [14].

To address these challenges, this research work focuses on the hardware implementation of an enhanced positive output Cuk converter-based driver integrated with Vfc. The study begins with the evaluation of a traditional Cuk converter [15] operating at 12 V input, 67% duty cycle, and 30 kHz switching frequency. Although efficient in power conversion, the conventional topology suffers from inherent drawbacks such as output polarity inversion and increased stress on the switching devices. To overcome these drawbacks, a NI-Cuk converter is designed to deliver a positive output voltage (V_o) [16] and improve power conversion efficiency. Even with these enhancements, the NI-Cuk [17] continues to show substantial output ripple and transitory instability during startup and load fluctuations. A Vfc is included in the design to improve performance even more. The reduced Vfc's stress speeds up the process of reaching steady state conditions, greatly minimizes output V and I ripple, minimizes component stress, and improves driver efficiency. The NI-Cuk converter [18], [19] and the Vfc are combined in a new way to create a high-performance topology that is ideal for LED driving applications.

This study focuses on the experimental validation and hardware implementation of the suggested topology. A prototype is created and put through testing with actual supply and load scenarios. Critical performance criteria like efficiency, ripple reduction, switching voltage or current stress, and steady-state responsiveness are all thoroughly evaluated. Based on existing literature, two DC-DC converters [20], [21] are taken into consideration for comparison. The CCuk converter and the NI-Cuk converter. The comparison demonstrates that the suggested solution improves lighting comfort, lifetime, and efficiency. The study provides a reliable and effective solution for modern lighting applications where accuracy, effectiveness, and lifetime are crucial for the hardware design that considers the electrical performances and visual requirements of LED operation [22], [23].

2. NI-CUK CONVERTER WITH VFC

Figure 1 shows the suggested NI-Cuk with Vfc, which is a positive output converter, designed with a single switch [24]–[26] that combines the advantages of the NI converter with enhanced performance. To improve overall system efficiency, this architecture is made to minimize V, I ripple, reduce switching stress, and ensure continuous functioning under a variety of load circumstances.

A different arrangement of diodes and capacitors is used in the creation of Vfc to design the circuit smaller and simpler. The integration of this Vfc increases efficiency, reduced ripple in load V and I. The capacitor repeated charging and discharging in this configuration is managed by the diodes. They are essential in keeping the current flowing only in one way, which stops capacitor C_2 from draining back through capacitor C_3. Consequently, the Vfc guarantees the lifetime of the LED driver with less ripple, more effectiveness, and enhanced power stability [27], [28].

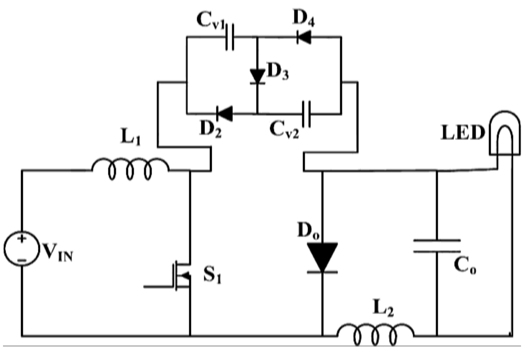


Figure 1. Circuit of NI-Cuk with Vfc

2.1. Working

The NI-Cuk with Vfc offers a reliable and efficient driver for powering LED loads by ensuring better voltage stability and reduced ripple. During mode 1, Inductor L_1 is charged by the source voltage when switch S_1 turns on and enables it to store energy. For continuous LED illumination, inductor L_2 discharges through D_o is depicted in Figure 2. The Vfc capacitors C_{v1} and C_{v2} start charging during this time.

In mode 2, once the switch is turned off, the energy in L_1 is discharged through D_o. The Vfc capacitors discharge simultaneously to support the load. Diode D_3 keeps the circuit's functionality intact and avoids cross-discharging is depicted in Figure 3. This converter is perfect for LED applications since it combines the NI-Cuk and Vfc to provide a positive Vo that matches the input polarity. As a result, the output is extremely steady and flicker-free, offering steady LED brightness and improved dependability [29], [30] under everyday circumstances.

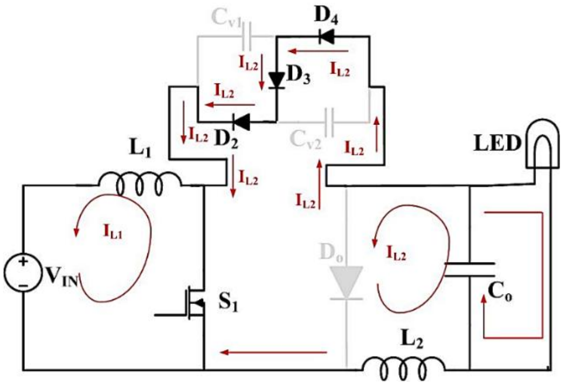


Figure 2. Mode I

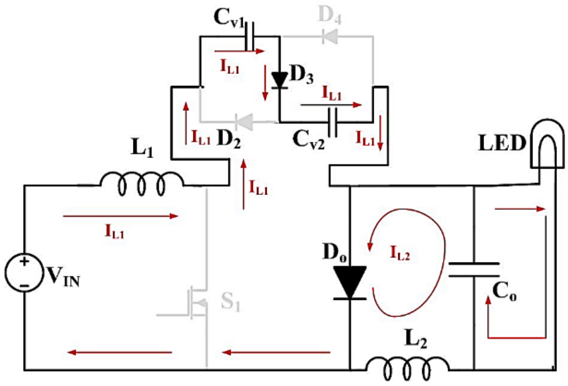


Figure 3. Mode II

2.2. Design of the NI-Cuk converter with Vfc

The specification parameters of NI-Cuk [31], [32] with Vfc is obtained from the design in (1)-(3).

$$D = \frac{V_{out}}{V_{in}+V_{out}} \quad (1)$$

$$L = \frac{(V_{in}(1-D))}{(f\Delta I_L)} \quad (2)$$

$$\Delta I_L = 30 \text{ to } 50\% \text{ of } I_o \quad (3)$$

$$C = \frac{(V_{out}D)}{(\Delta V_{out}f(1-D))} \quad (4)$$

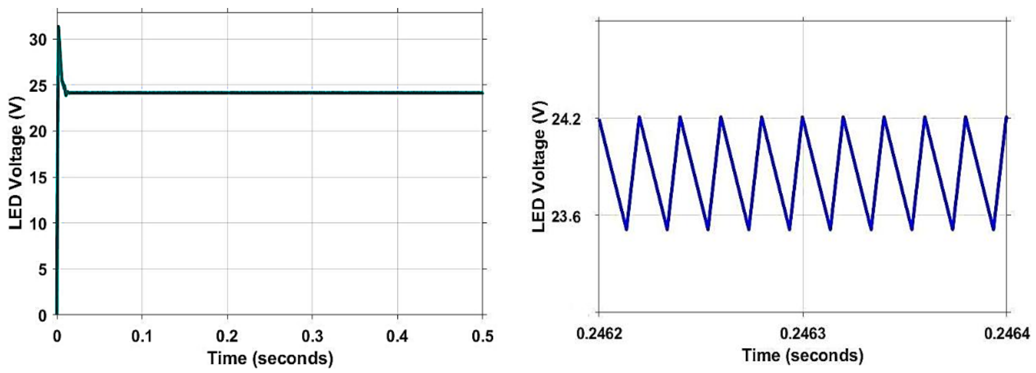
$$\Delta V_{out} = 1 \text{ t0 } 5\% \text{ of } \Delta V_{out} \quad (5)$$

Where D: duty ratio, V_{in}: supply voltage, V_{out}: load voltage, L: inductor value, f: switching frequency, ΔI_L: inductor ripple current, C: filter capacitor, and ΔV_{out}: load ripple.

The values of the inductor, capacitor, and the duty cycle are obtained from the design in (1)-(5) and are presented in Table 1. The LED V and I, their corresponding ripple, are depicted in Figures 4 to 7. Figures 4(a) and 4(b) display the V_o of the NI-Cuk converter with Vfc for driving the LED and is calculated to have a 24 V with a ripple of 1.56%. Figures 5(a) and 5(b) demonstrate the LED current of the NI-Cuk converter with Vfc and is determined to have a 0.42A with a ripple of 1.82%. Figure 6 illustrates the V and I stress on the switch in the NI-Cuk converter with Vfc, recorded as 23 V and 3.6 A, respectively. Figure 7 presents the V and I stress on the diode in the NI-Cuk converter with Vfc, observed to be 22 V and 3 A, respectively.

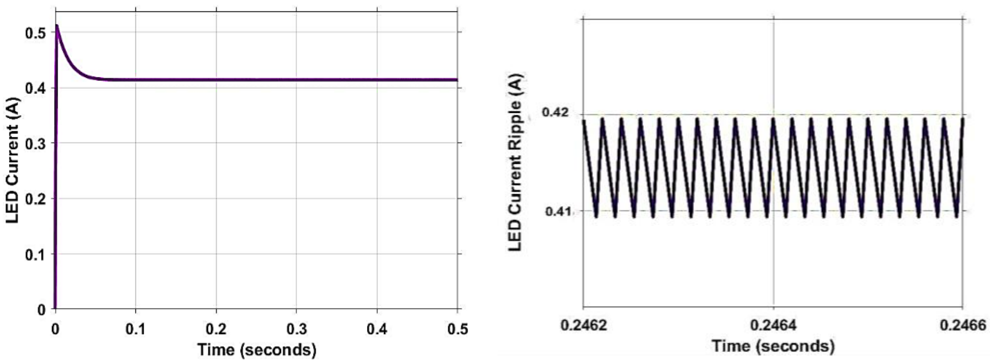
Table 1. NI-Cuk Converter with Vfc design parameters

Parameters	Values
Power	10 W
Input voltage	12 V
Load circuit	0.42 A
Inductor value	314 μH
Capacitance value	9 μF
Switching frequency	30 kHz



(a) (b)

Figure 4. LED voltage of NI-Cuk with Vfc: (a) voltage and (b) voltage ripple



(a) (b)

Figure 5. LED current of NI-Cuk with Vfc: (a) LED current and (b) current ripple of NI-Cuk with Vfc

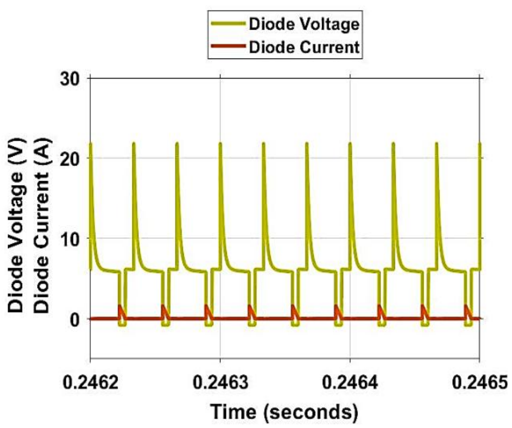


Figure 6. Switch's stress of NI-Cuk with Vfc

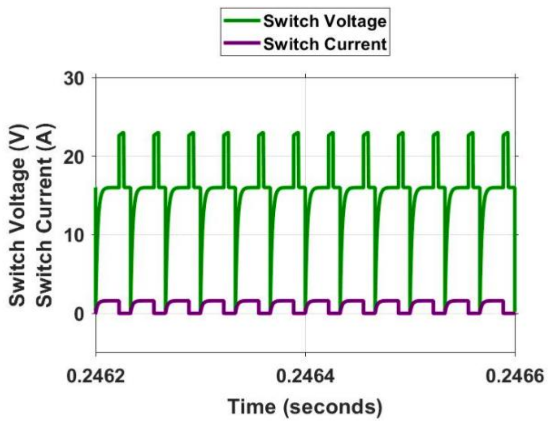


Figure 7. Diode's stress of NI-Cuk with Vfc

3. EXPERIMENTAL IMPLEMENTATION OF NI-Cuk CONVERTER WITH VFC

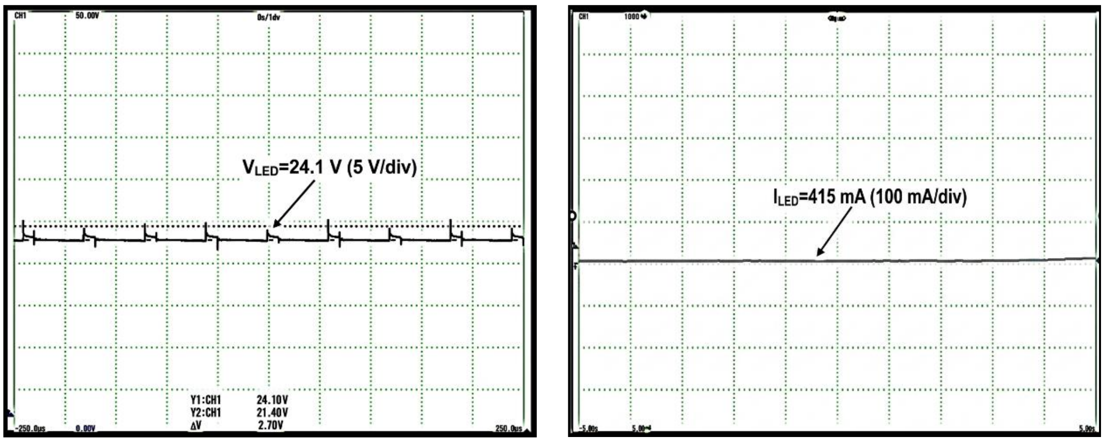
An experimental setup of the recommended NI-Cuk with Vfc was implemented to verify the simulation results. Essential parts like MOSFET, gate driver circuitry, and optocoupler-based isolation were included in the hardware arrangement to provide safe and accurate switching [33]-[35]. The simulation parameters are the same for hardware implementation and are described in Table 1. The experimental performance metrics of NI-Cuk with the Vfc driver are assessed and compared with the simulation metrics. Hardware waveforms are captured using a Yokogawa DL850 Scope Corder for a rated output power of 10 W. These results confirm the effectiveness of the proposed driver [36], demonstrating strong correlation with the simulated performance. A 10W LED can be powered by the NIC with Vfc, with an LED voltage of 24 V, current is about 0.42 A, and 12 V of supply voltage is essential. The experimental prototype of the suggested driver is shown in Figure 8.

The hardware setup for the recommended converter's appropriate waveform is displayed in Figures 9-11. From Figures 9(a) and 9(b), the load voltage is about 24.1 V with the ripple of 1.61%. The load current of the NI-Cuk converter with the Vfc LED driver is about 0.42 A with a ripple of 1.85%. From Figure 10, the stress on the switch in the LED driver is about 21.5 V and 3.4 A. From Figure 11, the stress across the diode is about 18.5 V and 3.7 A. Table 2 displays an extensive comparison of the experimental and simulated results.

Table 2. Comparison of simulation and hardware results

Characteristics	Simulated values	Experimental values
Switch's current (A) and	3.6	3.7
Switch's voltage Stress (V)	23	18.5
Current stress in D_o (A)	3	3.7
Voltage stress across D_o (V)	22	21.5
LED voltage (V_{LED}) (V)	24	24
LED voltage ripple (%)	1.56	1.82
LED current (I_{LED}) (A)	0.42	0.42
LED current ripple (%)	1.61	1.85

Figure 8. Hardware setup of NI-Cuk with Vfc



(a) (b)

Figure 9. LED voltage and current waveforms of NI-Cuk with Vfc: (a) LED voltage and (b) LED current

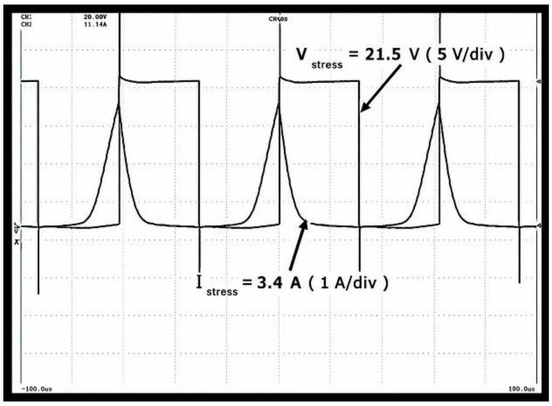


Figure 10. Switch’s stress of NI-Cuk with Vfc

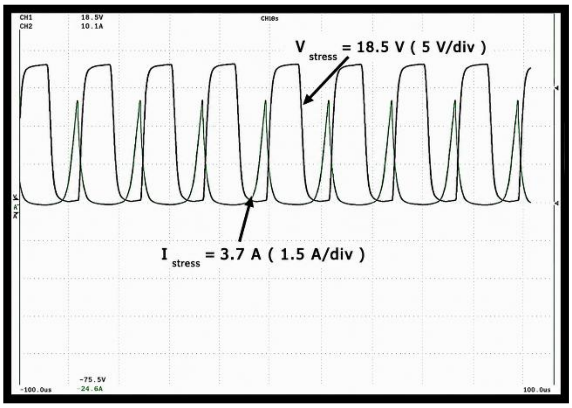


Figure 11. Diode’s stress of NI-Cuk with Vfc

4. COMPARISON OF PERFORMANCE PARAMETERS

In this work, different Cuk converter topologies were explored to find the most suitable option for LED driver applications. The first design used a CCuk converter, which produces -24 V and -0.42 A. To avoid the inverted load voltage and current, a NI-Cuk converter [37] was tested. With better output quality and improved performance, the NI-Cuk with Vfc converter proved to be the best among the three, offering a smooth, reliable, and positive voltage that is ideal for LED lighting applications.

From Table 3, it is clear that the CCuk converters, both the load voltage and current, appear negative. In contrast, for the NI-Cuk converter, the values of V_o and LED current are positive. However, the NI-Cuk converter exhibits higher current and voltage ripple, which are effectively mitigated in the NI-Cuk converter with Vfc. Table 4 depicts that the NI-Cuk with Vfc achieves higher efficiency than both the conventional and the non-inverting Cuk converter. In addition, it has reduced luminous efficacy, flicker index, and stress levels when compared.

Table 3. Performance parameters comparison

Topology/parameter	CUK converter	CUK with Vfc	NI-Cuk	NI-Cuk with Vfc
V_o (V)	-24	-24	24	24
Load current A)	-0.42	-0.42	0.42	0.42
Ripple current (%)	4.7	3.1	3.84	1.82
Ripple voltage (%)	4.83	3.77	3.64	1.56
Switch’s stress	39 V and 4.5 A	29 V and 4.2 A	30 V and 4.1 A	23 V and 3.6 A
Diode’s stress	34 V and 4.8A	28 V and 4.3 A	28 V and 4 A	22 V and 3 A
Losses (W)	1.491	1.223	1.082	0.662
Efficiency (%)	85.2	88	89.2	93.4
Rated power (W)	10	10	10	10

Table 4. Efficiency and flicker index comparison

Topology/parameter	CUK converter	CUK with Vfc	NI-Cuk	NI-Cuk with Vfc
Luminous efficacy (%)	6.06	6.07	6.06	5.3
Flicker index (%)	0.02	0.014	0.017	0.009

5. CONCLUSION

This research examines the hardware implementation of a 10 W, 24 V NI-Cuk with a Vfc for LED lighting. The proposed LED driver achieved a high efficiency of 93.4%. By adding the Vfc, the design reduced V, and I ripple, which helped lower stress on the components and made the output more stable. The measured ripple values were reduced by 1.82% (current) and 1.56% (voltage), meeting the flicker safety limits defined in IEEE Std 1789-2015. This makes the driver suitable for applications where smooth and flicker-free light is important. The design is also cost-effective, making it a practical solution for residential, commercial, and industrial LED systems. Scaling the suggested NI-Cuk LED driver to higher power levels for outdoor and industrial lighting applications may be the subject of future research. To enhance regulation and make smart lighting features possible, digital control and sophisticated dimming techniques can be used. Its applicability in standalone applications can be expanded through integration with energy storage devices and renewable energy sources. Using wide-band-gap technologies like SiC or GaN could improve power density and efficiency even more. Thermal performance and long-term dependability can also be examined.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
B. Lakshmi Praba	✓	✓	✓	✓	✓	✓			✓	✓				
Seyezhai Ramalingam	✓	✓		✓		✓	✓			✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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