The Development of an LED Lighting Circuit Using High Gain Buck-Boost Converters

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***Abstract*—This paper presents an LED driver using high gain buck-boost converters. By combining a traditional buck-boost converter and a Switched-Capacitor (SC) DC-DC converter with flying capacitors, the proposed driver can achieve the following features: 1) High voltage gain realized by cascade connection, 2) controllability of conversion ratio owing to the hybrid topology, and 3) small volume with only one inductor. The characteristics of the proposed driver, such as output voltage and power efficiency, were investigated by Simulation Program with Integrated Circuit Emphasis (SPICE) simulations. Furthermore, the feasibility of the proposed driver was confirmed by experiments. The simulation and experiment show the effectiveness of the proposed driver.**

***Index Terms*—DC-DC converters, buck-boost converters, backlight, backlight of LED**

I. Introduction

In recent years, Light Emitting Diodes (LEDs) have been used as one solution for backlighting. The backlight is a light source installed on the back of the liquid crystal display. The voltage required for LED to emit light "forward voltage" depends on the bandgap of the LED used. Therefore, in order to cause the LED to emit light, it is necessary to transform the input voltage to a high voltage. Also, to avoid the complexity of the current control of LEDs, long strings of LEDs are commonly used in LED devices. Therefore, it is necessary to give a larger voltage to the LED.

To drive LEDs effectively, several types of switching converter topologies have been proposed in past studies. The converter topologies of the LED drivers can be divided into three types: inductor-based converter topology [1]-[8], capacitor-based converter topology [9]-[17], and hybrid topology combined with two power converters [17]-[21]. The LED driver with inductor-based converter topologies, such as buck-boost type [1], hybrid input buck-boost type [2], boost type [3]-[5], tapped-inductor boost type [6], interleaved flyback type [7], and LLC [8], can achieve simple circuit configuration. However, the LED driver with inductor-based converter topology suffers from high switching loss in the LED device with long LED strings, because the switching loss has a relation with the output voltage.

The LED driver with capacitor-based converter topologies, such as negative charge pump type [9], three-mode charge pump type [10], series-parallel type [11], [12], Fibonacci type [13]-[15], and Dickson type [16], [17], can achieve less passive components, because the capacitor-based converter topology does not use a magnetic material. Therefore, it can be lightweight, downsized, and can realize highly efficient transformation. However, the LED driver with capacitor-based converter topologies suffers from poor regulation, because it is difficult to change the conversion ratio according to the state of the input voltage.

The LED driver with hybrid topologies, such as boost type combined with LLC [18], boost type combined with buck type [19], flyback type combined with class-E DC-DC cell, and Fibonacci type combined with buck-boost type [20], can achieve high voltage gain by combining two power converters. Among others, by combining a Fibonacci-type capacitor-based converter and a buck-boost type inductor-based converter, McRae *et al*.'s converter [21] can achieve the voltage conversion by using only one inductor. Therefore, small passive component area and controllability of conversion ratio can be realized by McRae et al.'s converter. In [21], long strings of LEDs were driven by adding the output voltage of the Fibonacci converter to that of the buck-boost converter. Therefore, in the point of voltage gain, there is a room for improvement.

In this paper, an LED driver using high gain buck-boost converters is proposed for energy harvesting applications. In the proposed converter, the output voltage of the traditional buck-boost converter is doubled by a switched-capacitor (SC) DC-DC converter with flying capacitors [22], [23]. Furthermore, owing to the hybrid topology with only one inductor, the proposed converter can provide small passive component area and

Manuscript received October 5, 2018; revised April 10, 2019; accepted May 1, 2019.
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doi: 10.18178/ijeetc.8.5.262-267

controllability of conversion ratio by changing the duty ratio of switches. By developing a converter with a wide boost range, it is possible to realize an LED lighting circuit by energy harvesting using micro energy as an input voltage.

The rest of this paper is organized as follows. In Section 2, the circuit configuration of the proposed LED driver is presented. In Section 3, we simulated the proposed LED driver using the circuit simulation program (SPICE). Experimental conditions and results of the proposed circuit are shown in Section 4. Finally, conclusion and future work are drawn in Section 5.

II. Circuit Configuration

A. Conventional Converter Used in LED Drivers

Fig. 1 illustrates the circuit configuration of a conventional buck-boost converter. As Fig. 1 shows, this is an inductor-based converter, where the output voltage is a negative output by generating the buck electromotive force of the coil. The output is given as shown in equation (1):

$$V_{out} = V_L = -\frac{d}{(1-d)}V_{in} \tag{1}$$

where V_L is the voltage of the inductor L and the duty ratio of the switch is set to d. As you can see from Equation (1), the buck boost converter can perform both step-down and step-up by adjusting the duty ratio d of the switch.

The cathode of the LED is driven by the negative output of the buck-boost converter to light the LED. If the output voltage can be raised, the boost ratio can be increased.

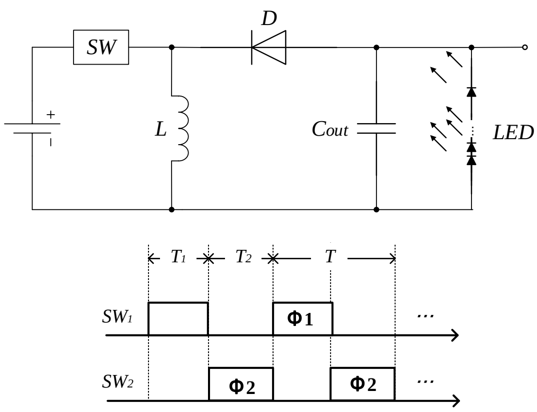


Fig. 1. Buck-boost converter

B. Proposed Converter Used in LED Drivers

The proposal of this research is to develop an LED light emitting circuit using a high gain buck-boost converter. Specifically, we develop a circuit that can adjust high boost ratio and duty ratio of switch.

Fig. 2 shows the circuit configuration of the proposed converter. The proposed converter is alternately controlled by switch 1 (S_1) and switch (S_2). A part of the proposed converter of Fig. 2 has the same structure as the conventional converter of Fig. 1. The proposed converter connects the capacitor C_2 in series with the inductor L of the conventional converter. The newly connected series capacitor C_2 is charged with the same value as the inductor L by using the flying capacitor C_1. So, twice the charge of the output capacitor of the conventional converter is accumulated in the output capacitor of the proposed converter. The representation of the output voltage in the proposed converter is represented by

$$V_{out} = 2V_L = -2\frac{d}{(1-d)}V_{in} \tag{2}$$

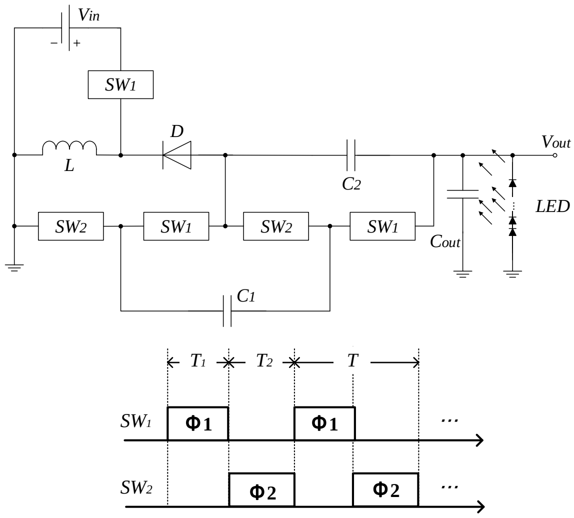
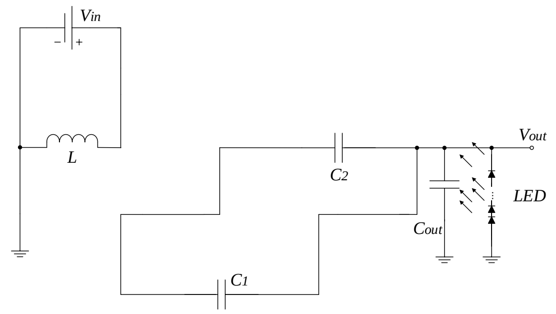
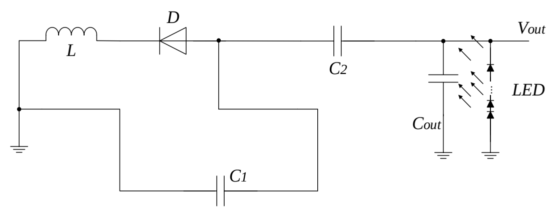


Fig. 2. Proposed converter



(a)



(b)

Fig. 3. Instantaneous equivalent circuits: (a) State 1 and (b) State 2

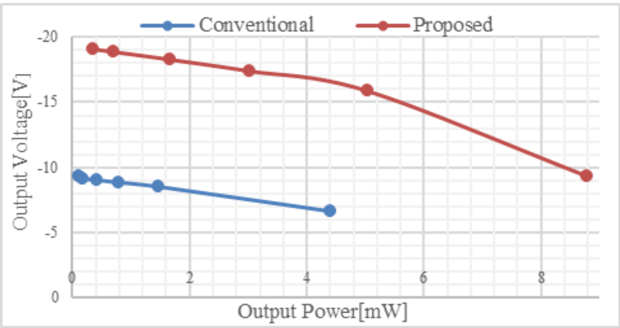
Fig. 3 shows the ON and OFF conditions of the switches in State 1 (T_1) and State 2 (T_2). The proposed converter first turns ON the switch 1 (S_1) and charges the inductor. (State 1/T_1: Fig. 3 (a)). Thereafter, the switch 2 (S_2) is turned on, and the inductor discharges the capacitor C_1 by the induced current. (State 2/T_2: Fig. 3 (b)). The switch 1 (S_1) is turned ON again to charge the inductor. Along with this, since the capacitor C_1 is connected in parallel with C_2, the capacitor C_2, is charged with a value equivalent to C_1. (State $1/T_1$: Fig. 3 (a)). Therefore, the output capacitor C_{out} is charged with the voltage of L and C_2, and $2V_L$ is output. The proposed converter obtains twice the output of the conventional converter by repeating the state 1 (T_1) and the state 2 (T_2).

III. Simulation

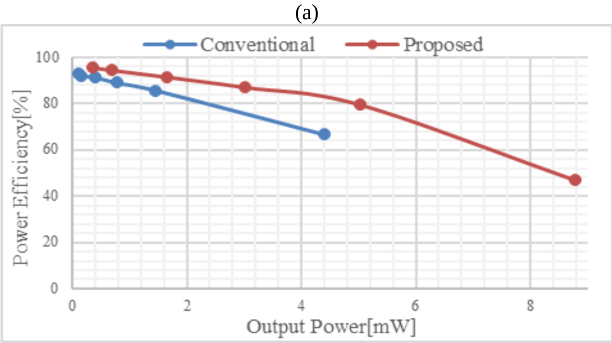
In LTSPICE simulations, the characteristics of the proposed LED lighting circuit were compared with that of the conventional LED lighting circuit.

The SPICE simulations of conventional converter were conducted under conditions that V_{in}=10 V, L=10 mH, C_{out}=10 μF, T=10 μs and T_1=T_2=5 μs. At this time, simulation was performed while changing the value of R_{out} from 10 Ω to 1 kΩ. Similarly, in the SPICE simulations of proposed converter were conducted under conditions that V_{in}=10 V, L=1 mH, C_1=C_2=5 μF, C_{out}=10 μF T=10 μs and T_1=T_2=5 μs. At this time, simulation was performed while changing the value of R_{out} from 10 Ω to 1kΩ.

Fig. 4 shows the results of the simulation. Fig. 4 (a) shows the relationship between output power and output voltage. According to Fig. 4 (a), when the output power is 4 W, the output voltage of the conventional converter is −7 V, and the output voltage of the proposed converter is −17 V. From this fact, it can be confirmed that the proposed converter achieves the boost ratio nearly twice that of the conventional converter.



(a)



(b)

Fig. 4. The result of simulation: (a) Output voltage and (b) power efficiency

Fig. 4 (b) shows the relationship between the output power and the power efficiency. Similarly, for an output power of 4 W, it can be seen that the proposed converter has a power efficiency of 85% and the conventional converter has a 70% variation efficiency. From this result, it can be seen that the proposed converter improved the power efficiency by 15%. From the above two results, it was confirmed by simulation that the boost rate of the converter was increased and the power efficiency was improved.

IV. Experiment

A. Conventional Buck-Boost Converter

In the experiments, we focused on the verification of the circuit topology. Therefore, the experimental circuit was built with commercially available ICs on bread board. Concretely, the experimental circuit of the conventional converter was built photo-MOS relay AQW217, Darlington sink driver TD62004 APG, microcontroller PIC, and diode 1N4007 on a bread board, where V_{in}=10 V, L=100 mH, C_{out}=10 μF, R_{out}=51 kΩ, T=10 ms and T_1=T_2=5 ms.

Fig. 5 shows the switching cycle of the conventional converter. As explained in the experimental conditions, circuit switching is done for 5ms in State 1 and State 2. Therefore, the duty ratio of the switch is 50%. Fig. 6 shows an experiment screen of a conventional converter. Input voltage and output voltage were measured. From Fig. 6, the output −9.82 V was measured against the input voltage of 10.01 V. From Table I, the measurement result with respect to the ideal value was an absolute error of 1.8%, and the result close to the ideal value was measured.

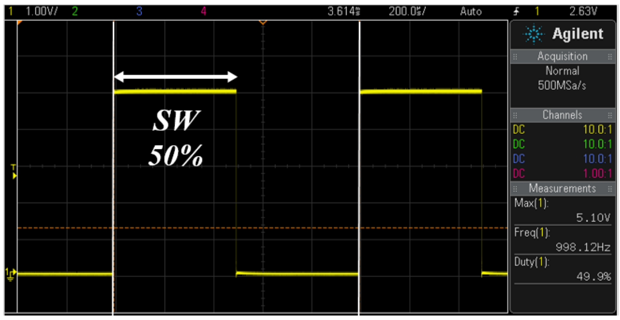


Fig. 5. Measure clock pulses
(Conventional converter, Switch duty ratio: 50%)

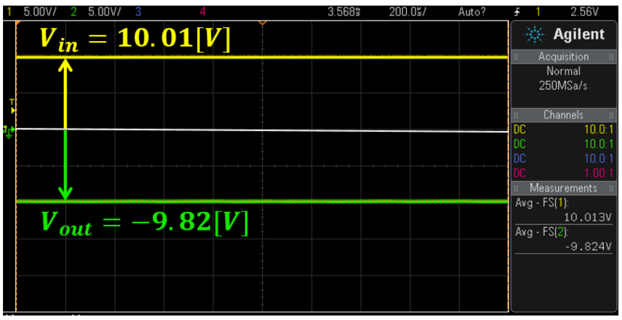


Fig. 6. Measure output voltages
(Conventional converter, Switch duty ratio: 50%)

TABLE I. The Result of Experiment

Converter type	Duty ratio [%]	Ideal value [V]	Experiment value [V]
Conventional	50	−10.00	−9.82
	30	−4.29	−3.58
Proposed	50	−20.00	−19.81
	30	−8.57	−8.56

Next, change the condition of the switch of the conventional converter and confirm that the step-up ratio of the converter changes. The measurement was performed by changing the duty ratio of the switch from 50% (Fig. 5) to 30% (Fig. 7).

Fig. 8 shows an experiment screen of a conventional converter. Input voltage and output voltage were measured. From Fig. 8, the output −3.58 V was measured against the input voltage of 10.03 V.

From Table I, the measurement result with respect to the ideal value was an absolute error of 16.55%.

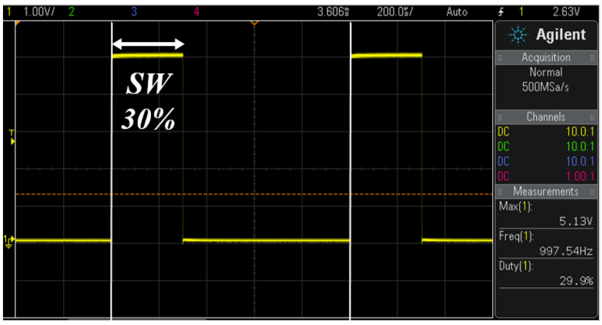


Fig. 7. Measure clock pulses
(Conventional converter, Switch duty ratio: 30%)

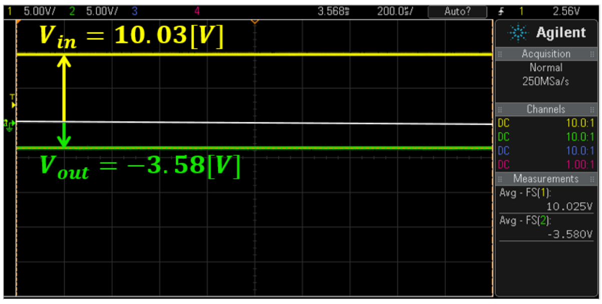


Fig. 8. Measure output voltages
(Conventional converter, Switch duty ratio: 30%)

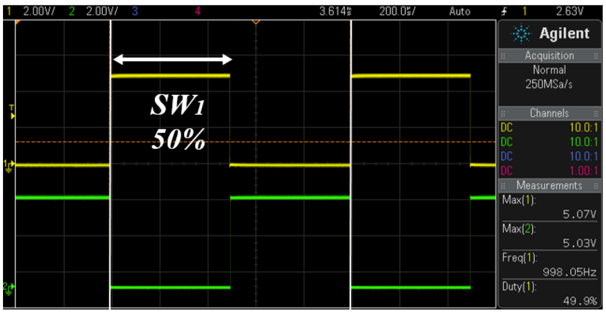


Fig. 9. Measure clock pulses
(Proposed converter, Switch duty ratio: 50%)

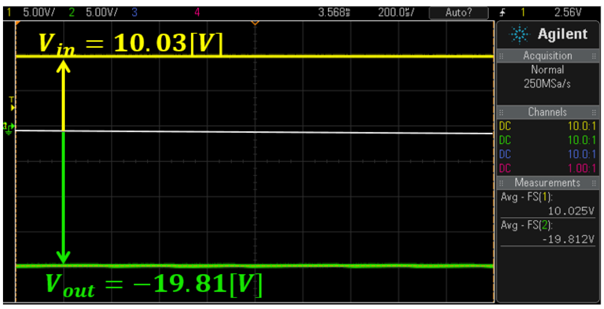


Fig. 10. Measure output voltages
(Proposed converter, Switch duty ratio: 50%)

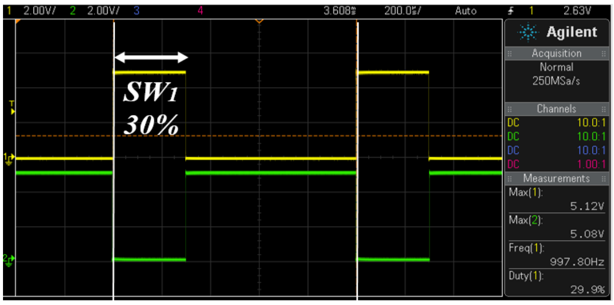


Fig. 11. Measure clock pulses
(Proposed converter, Switch duty ratio: 30%)

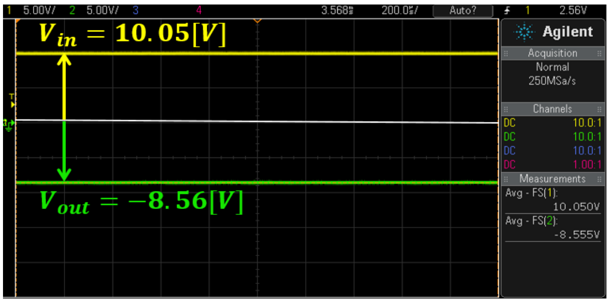


Fig. 12. Measure output voltages
(Proposed converter, Switch duty ratio: 30%)

B. Proposed Converter

The experimental circuit was built on a pan board with a commercially available IC. Specifically, the experimental circuit of the proposed converter is composed of a photo MOS relay AQW 217, a Darlington sink driver TD 62004 APG, a microcontroller PIC, a diode 1 N 4007 (on a pan board with V_{in}=10 V, L=100 mH, C_{out}=10 µF, R_{out}=51k Ω, T=10 ms, T_1=T_2=5 ms.

Fig. 9 shows the switching cycle of the proposed converter. As explained in the proposed conditions, circuit switching is done for 5 ms in state 1 and state 2. Therefore, the duty ratio of the switch is 50%. Fig. 10 shows an experiment screen of a proposed converter. Input voltage and output voltage were measured. From Fig. 10, the output −19.81V was measured against the input voltage of 10.03V.

From Table I, the measurement result with respect to the ideal value was an absolute error of 0.94%, and the result close to the ideal value was measured.

Next, change the condition of the switch of the proposed converter and confirm that the step-up ratio of the converter changes. The measurement was performed by changing the duty ratio of the switch from 50% (Fig. to 30% (Fig. 11).

Fig. 12 shows an experiment screen of a proposed converter. Input voltage and output voltage were measured. From Fig. 12, the output −8.56 V was measured against the input voltage of 10.05 V. From Table I, the measurement result with respect to the ideal value was an absolute error of 0.12%, and the result close to the ideal value was measured.

V. Conclusion

An LED lighting circuit using high gain buck boost converters has been proposed in this paper. The results of this work are as follows:

1. Experimental results when the duty ratio of the switch is 50% show that the output voltage of the conventional converter is −9.88 V and the proposed converter is −19.81 V. Therefore, the output voltage of the proposed converter can be doubled compared with the conventional converter.
2. Experimental results indicate that the boost ratio can be modified by changing a duty ratio of switches.
3. It was confirmed by simulations that the power efficiency was improved by 15%.
4. Even when the value of the input voltage is small, necessary driving voltage can be supplied for LED lighting systems.

The IC implementation of the proposed LED driver is left to a future study.

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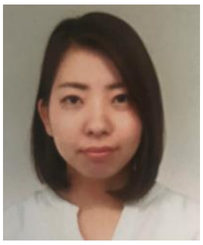

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