A Single Inductor LED Driver Combined with a Cross-Connected Fibonacci-Type Converter and a Buck-Boost Converter

Kei Eguchi1,*, Daigo Nakashima1, Wanglok Do1, Takaaki Ishibashi2, and Ichirou Oota2

1Department of Information Electronics, Fukuoka Institute of Technology, 3-30-1 Wajiro-higashi, Higashi-ku, Fukuoka, Japan
2Department of Electronics Engineering and Computer Science, National Institute of Technology, Kumamoto College, 2659-2 Suya, Koushi-shi, Kumamoto, Japan

Corresponding author: eguti@fit.ac.jp

Abstract. To achieve high voltage gains and high power efficiency, a hybrid light emitting diode (LED) driver with a single inductor is proposed in this paper. Unlike existing LED sink drivers, the proposed driver consists of a cross-connected Fibonacci-type converter and a buck-boost converter. In the proposed driver, the cross-connected Fibonacci-type converter drives the anode terminal of LED strings to realize high voltage gains. On the other hand, the buck-boost converter is connected to the cathode terminal of LED strings to provide output current controllability. Furthermore, the proposed driver achieves a small internal resistance, because these two converter blocks are connected in parallel to an input source. The characteristics of the proposed driver is investigated by theoretical analysis, computer simulations, and breadboard experiments. The obtained results demonstrate that the proposed driver outperforms the conventional LED sink drivers.

1 Introduction

To illuminate light emitting diode (LED) strings, an LED driver using switching converters is a vital component. Among others, many types of LED drivers employing dc/dc converters have been developed in past studies. The LED drivers can be classified into three types, i.e. i) LED driver using inductors such as boost converter [1] and buck-boost converter [2], ii) inductor-less LED driver such as charge pump [3], and iii) hybrid LED driver combining several dc/dc converters. In particular, the hybrid LED driver with a single inductor attracts much attention, because it can provide not only small off-chip components but also high gain and output current controllability. For example, McRae et al. proposed an LED driver [4] with a buck-boost converter and a Fibonacci converter [5], Eguchi et al. suggested an LED sink driver [6] with a buck-boost converter and an SC doubler [7], and Ranjana et al. designed an LED driver [8] with a buck-boost converter and a Cockcroft-Walton circuit [9, 10]. However, the conventional hybrid LED drivers suffer from low power efficiency.

In this paper, a hybrid LED driver with a single inductor is proposed for the realization of high voltage gains and high power efficiency. Unlike existing LED drivers, the proposed driver provides high voltage gains and output current controllability by the cross-connected Fibonacci-type converter [11, 12] and the buck-boost converter, respectively. Furthermore, by connecting these two converter blocks in parallel with an input source, a small internal resistance is achieved by the proposed topology. To
evaluate the performance of the proposed driver, theoretical analysis, computer simulations, and breadboard experiments are performed.

2 Circuit configuration
Fig. 1 describes the circuit configuration of the proposed hybrid LED driver with a single inductor. As it can be seen from Fig. 1, the proposed driver consists of a cross-connected Fibonacci-type converter and a buck-boost converter. In these converter blocks, switches \( S_1 \) and \( S_2 \) are driven by non-overlapped two-phase pulses \( \Phi_1 \) and \( \Phi_2 \), respectively. Unlike the conventional LED drivers [6, 8], the proposed driver does not require series-connection of converter blocks to achieve voltage gains. In the ideal case, the voltages \( 8V_{in} \) and \( -D/(1 - D)\times V_{in} \) are provided to the anode and cathode terminals of LED strings, respectively, where \( D \) denotes a duty cycle of clock pulses. Therefore, the proposed topology realizes smaller internal resistance than the conventional LED drivers with series-connected structure [6, 8]. Furthermore, single inductor topology provides a smaller number of off-chip components. The characteristics of the proposed driver will be clarified theoretically in the following section.

3 Theoretical analysis
By using the four-terminal equivalent model [13], the theoretical analysis of the proposed driver is performed under the conditions that \( i) \) time constant is much bigger than the period of clock pulses \( T \), \( ii) \) parasitic elements of circuit components are negligibly small, and \( iii) \) all switches have the same on-resistance.

![Figure 1. Proposed topology combining a buck-boost converter and a cross-connected Fibonacci converter.](image1)

![Figure 2. Instantaneous equivalent circuits of the proposed driver: (a) state-T1; (b) state-T2.](image2)

First, the equivalent circuit of the cross-connected Fibonacci-type converter is analyzed. Since the instantaneous equivalent circuits of the proposed driver is expressed by Fig. 2, the variation of electric
charges in the I/O terminals of the cross-connected Fibonacci-type converter, $\Delta q_{T_{k,\text{in}}}$ and $\Delta q_{T_{k,\text{op}}}$ ($k = 1, 2$), is expressed as

\[
\text{State-T1: } \Delta q_{T_{1,\text{in}}} = \Delta q_{T_{1,1}} - \Delta q_{T_{1,1}}^{2.1} \\
\text{and } \Delta q_{T_{1,\text{op}}} = \Delta q_{T_{1,1}}^{2.3},
\]

where $\Delta q_{T_{1,1}}^{1.2} = \Delta q_{T_{1,1}}^{2.1} + \Delta q_{T_{1,1}}^{2.2}$

and $\Delta q_{T_{1,1}}^{2.3} = \Delta q_{T_{1,1}}^{1.2} + \Delta q_{T_{1,1}}^{1.3}$.

\[
\text{State-T2: } \Delta q_{T_{2,\text{in}}} = \Delta q_{T_{2,1}}^{2.1} - \Delta q_{T_{2,1}}^{1.1} \\
\text{and } \Delta q_{T_{2,\text{op}}} = \Delta q_{T_{2,1}}^{1.3},
\]

where $\Delta q_{T_{2,1}}^{2.2} = \Delta q_{T_{2,1}}^{1.1} + \Delta q_{T_{2,1}}^{1.2}$

and $\Delta q_{T_{2,1}}^{1.3} = \Delta q_{T_{2,1}}^{2.2} + \Delta q_{T_{2,1}}^{2.3}$.

Furthermore, since the cross-connected Fibonacci-type converter has symmetric structure as shown in Fig. 2, the variation of electric charges in the capacitor $C_{i,j}$, $\Delta q_{T_{k,i}}^{l,j}$ ($(i = 1, 2)$ and $(j = 1, 2, 3)$), satisfies

\[
\Delta q_{T_{1,1}}^{l,j} + \Delta q_{T_{2,1}}^{l,j} = 0, \quad \Delta q_{T_{1,1}}^{l,j} = \Delta q_{T_{2,1}}^{l,j},
\]

\[
\text{and } \Delta q_{T_{2,1}}^{2,j} = \Delta q_{T_{1,1}}^{2,j}
\]

in a steady state condition. Using (1) and (5), the average input current and output currents, $I_{\text{in}}$ and $I_{\text{op}}$, are expressed as

\[
I_{\text{in}} = \frac{\Delta q_{\text{in}}}{T} = \frac{1}{T} \sum_{k=1}^{2} \Delta q_{T_{k,\text{in}}}
\]

and $I_{\text{op}} = \frac{\Delta q_{\text{op}}}{T} = \frac{1}{T} \sum_{k=1}^{2} \Delta q_{T_{k,\text{op}}}$.

Substituting (1)–(5) for (6), we have the relationship between $I_{\text{in}}$ and $I_{\text{op}}$ as

\[
I_{\text{in}} = -8I_{\text{op}} \quad \text{and } \Delta q_{\text{in}} = -8\Delta q_{\text{op}}.
\]

Therefore, the conversion ratio of the cross-connected Fibonacci-type converter is 8.

To obtain the internal resistance $R_{SC}$ of the cross-connected Fibonacci-type converter, energy loss is discussed. The energy loss of the cross-connected Fibonacci-type converter is expressed as

\[
W_T = \sum_{k=1}^{2} W_{T_k} = 2W_{T1},
\]

where $W_{T1} = \frac{2R_{on}}{I_{1}} \left( \Delta q_{T_{1,1}}^{1.1} \right)^2 + \frac{R_{on}}{I_{1}} \left( \Delta q_{T_{1,1}}^{2.1} \right)^2$

\[
+ \frac{R_{on}}{I_{1}} \left( \Delta q_{T_{1,1}}^{1.2} \right)^2 + \frac{2R_{on}}{I_{1}} \left( \Delta q_{T_{1,1}}^{2.2} \right)^2
\]
\[ W_T = 64R_{\text{on}} \left( \frac{\Delta q_{V_{\text{op}}}}{T} \right)^2. \]

In (9), \( R_{\text{on}} \) denotes the on-resistance of switch \( S_k \). Since (9) can be rewritten as

\[ \eta = \frac{R_L}{R_L + 64R_{\text{on}} + \frac{DR_{\text{on}} + (1-D)R_d + R_l}{(1-D)^2}}, \]

and

\[ V_{\text{out}} = \left( \frac{R_L}{R_L + 64R_{\text{on}} + \frac{DR_{\text{on}} + (1-D)R_d + R_l}{(1-D)^2}} \right) V_{\text{in}} \times \frac{R_L}{R_L + 64R_{\text{on}} + \frac{DR_{\text{on}} + (1-D)R_d + R_l}{(1-D)^2}}. \]

**4 Simulation**

By comparing the proposed driver with the conventional hybrid LED drivers, i.e. conventional-1 [6] and conventional-2 [8], the effectiveness of the proposed driver is clarified by simulation program with integrated circuit emphasis (SPICE) simulations. Fig. 3 demonstrates the SPICE simulated results, where the circuit parameters were set to \( V_{\text{in}} = 3.7 \text{ V}, L = 100 \mu\text{H}, C_0 = C_{ij} = 10 \mu\text{F}, T = 1 \mu\text{s}, D = 0.5, \) and \( R_{\text{on}} = 0.1 \Omega \). Due to the difference of driver topologies, the voltage gain of the proposed driver cannot be equal to that of the conventional drivers. As it can be seen from Fig. 3, the proposed driver outperforms the conventional drivers. In the performed simulations, the power efficiency of the
The proposed driver reaches more than 95% when the output power is 4 W and the voltage gain is about 8.6. It is noteworthy that the proposed driver can improve the power efficiency more than 32% from the conventional driver [8] when the output power is 4 W.

![Figure 3](image1.png)

**Figure 3.** Comparison between the proposed driver and conventional drivers: (a) simulated power efficiency; (b) simulated output voltage.

5 Experiment

The experimental circuit of the proposed driver was assembled on a breadboard. In the experimental circuit, the following circuit components were used: photo MOS relays AQW217, Darlington sink driver TD 62004APG, Microcontroller PIC12F629, and diodes 11EQS03L. The measured output voltage of the experimental circuit is demonstrated in Fig. 4, where the experiments were performed under the conditions that \( V_{in} = 3.7 \text{ V} \), \( L = 100 \text{ mH} \), \( C_0 = C_{ij} = 10 \mu\text{F} \), \( f = 800 \text{ Hz} \), and the output load \( R_L = 22 \text{ kΩ} \). As it can be seen from Fig. 4, the experimental circuit generates 29.6 V and 30.7 V for \( D = 0.5 \) and \( D = 0.6 \), respectively. In other words, the voltage gains of Fig. 4a and 4b are 8 and 8.3, respectively. From these results, the validity of the proposed topology can be confirmed, because high voltage gains and output controllability were measured experimentally.

![Figure 4](image2.png)

**Figure 4.** Measured output voltage obtained by the breadboard circuit: (a) \( D = 0.5 \); (b) \( D = 0.6 \).

6 Conclusion

In this paper, a novel hybrid LED driver with a single inductor has been proposed. First, theoretical analysis was performed by assuming a four-terminal equivalent model. In the performed theoretical analysis, the output voltage and power efficiency were derived theoretically. Next, to compare power efficiency and voltage gains, SPICE simulations were conducted between the proposed driver and conventional drivers. In the performed simulations, the proposed driver improved about 32% power efficiency when the output power is 4 W. Finally, the breadboard experiments were conducted concerning the proposed driver. In the performed breadboard tests, the validity of the proposed topology was confirmed, because high voltage gains and output controllability were measured experimentally. A controller design and the IC implementation are left to a future study.
References

[1] H. Kim, C. S. Yoon, D.-K. Jeong, J. Kim, A Single-Inductor, Multiple-Channel Current-Balancing LED Driver for Display Backlight Applications, IEEE Transactions on Industry Applications 50, 4077-4081 (2014).

[2] Y. Lu, Q. Wang, Y. Hong, C. Zheng, Design of high-power buck-boost LED constant current drive circuit, 2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA), 2223-2226, (2016).

[3] L. Avallone, E. Napoli, M. P. Kennedy, Switched Capacitor Charge Pump Voltage-Controlled Current Source, 2018 29th Irish Signals and Systems Conference (ISSC), 1-6 (2018).

[4] T. McRae, A. Prodić, S. Chakraborty, W. McIntyre, A. Aguilar, A Multi-Output Hybrid Divided Power Converter for LED Lighting Applications, 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL), 1-7 (2018).

[5] K. Eguchi, S. Hirata, M. Shimoji, H. Zhu, Design of a Step-Up/Step-Down $k (=2,3, \ldots)$-Fibonacci DC-DC Converter Designed by Switched-Capacitor Techniques, 2012 Fifth International Conference on Intelligent Networks and Intelligent Systems, 170-173 (2012).

[6] K. Eguchi, K. Kuwahara, T. Ishibashi, Analysis of an LED lighting circuit using a hybrid buck-boost converter with high gain, Energy Reports, 6, 250-256 (2020).

[7] M. Shen, A zero voltage switching switched capacitor voltage doubler, 2012 IEEE International Symposium on Industrial Electronics, 131-136 (2012).

[8] M. S. B. Ranjana, R. Alammari, M. Meraj, A. Iqbal, P. Sanjeevikumar, Modified multilevel buck–boost converter with equal voltage across each capacitor: analysis and experimental investigations, IET Power Electronics, 12, 3318-3330 (2019).

[9] K. Eguchi, F. Asadi, A. Shibata, H. Abe, I. Oota, Reduction of Inrush Current in a Shockwave Non-Thermal Food Processing System Using an Exponential Clock Pulse Generator, Sustainability, 12, 6095 (2020).

[10] A. Jaiwanglok, K. Eguchi, K. Smerpitak, A. Julsereewong, Modification of Cockcroft–Walton-Based High-Voltage Multipliers with 220 V and 50 Hz Input for Non-Thermal Food Processing Apparatus, Sustainability, 12, 6330 (2020).

[11] K. Eguchi, R. Rubpongse, A. Shibata, T. Ishibashi, Synthesis and analysis of a cross-connected Fibonacci dc/dc converter with high voltage gain, Energy Reports, 6, 130-136 (2020).

[12] W. Do, H. Bevrani, Q. Shafiee, K. Eguchi, An analytical approach for design of a cross-connected Fibonacci switched capacitor converter, Energies, 13, 431 (2020).

[13] K. Eguchi, W. Do, A. Shibata, Analysis of a High Step-Down DC/DC Converter Topology with a Single Inductor, International Journal of Intelligent Engineering and Systems, 14, 552-565 (2021).