A Switching Capacitor Control in Single-Stage AC-DC Reconfigurable RGB-LED Driver

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***Abstract*—A single-stage ac-dc LED driver operating in discontinuous conduction mode is presented to realize ac-dc rectification with high power factor and current regulation of red, green, blue (RGB) LEDs in this paper. The features of single-stage architecture reduce component cost and lower circuit size. A switching capacitor control is employed to hop the output voltage instantly for precisely adjusting LED currents. The voltage difference between the green/blue and red LEDs is automatically reflected on a hopping capacitor while the fast hopping scheme can rapidly regulate the output voltage level. The experimental results demonstrate the fast hopping scheme of the ac-dc LED driver and the capability in current regulation.**

Keywords: LED driver, AC-DC converter, switching capacitor, power factor (PF).

I. Introduction

Due to long lifetime, low power consumption, and environmental protection, the light-emitting diode (LED) has become an attractive light source in the indoor/outdoor applications. LED luminance is proportional to its flowing forward current, so it is suitable to employ a current control to adjust the brightness of LEDs. For LCD panels, there are two groups of LED backlights. One is white-LED backlight, and the other is red, green, and blue (RGB)-LED backlight. For white-LED backlight, the color filters pass only 33% of the light, leading to large power dissipation in the backlight module [1]. To decrease power dissipation by removing color filters, RGB LEDs combined with the field-sequential color (FSC) control scheme are employed. Consequently, red, green, and blue light sources can be generated directly. Based on the FSC operation scheme, RGB LEDs become on sequentially, leading to small total power consumption. Moreover, RGB-LED light sources offer a good saturation and better color gamut compared with white-LED light source. RGB LEDs adopt distinct materials to cause different conducting voltages even passing through the identical current. Commonly, a red LED has a smaller conducting voltage than a green or blue LED.

Based on the Energy Star regulations, the power factors (PFs) of residential lighting and commercial lighting provided by the power grid directly should be larger than 0.7 and 0.9. The low-frequency harmonics of the line current should also meet the IEC 61000-3-2. Hence, an ac-dc LED driver requires power factor correction (PFC) to conform with the rules. Fig. 1(a) shows a conventional two-stage RGB-LED driver, which is composed of an ac-dc PFC converter and a dc-dc converter [2]. Because the dc-dc converter can generate a fixed current for RGB LED strings, the PFC converter can employ a relatively small capacitance C_{out1} and acquire high PF. Nevertheless, the two-stage architecture requires more components, resulting in larger cost and system board. To decrease component cost and form factor, a single-stage RGB-LED driver presented in Fig. 1(b) is adopted. However, a large capacitance C_{out} is needed to adjust the power difference between the ac input source and dc output load [3].

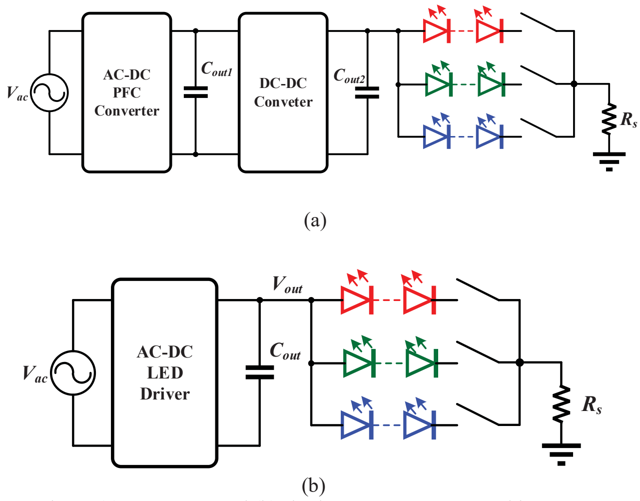


Fig. 1. (a) Two-stage and (b) single-stage RGB-LED architectures.

Based on the FSC control, RGB LEDs become on sequentially and alternately. In a sequential color display, one frame of data consists of RGB sub-frames [4]. For Fig. 1(b), V_{out} provides power for RGB-LED strings. Fig. 2 shows the output voltage fluctuation of the single-stage ac-dc LED architecture with FSC control, where the total conducting voltage of the green/blue LEDs is higher and the output voltage ripple is insignificant. The hopping response of V_{out} is restrained by the narrow bandwidth of ac-dc driver and the large C_{out}; therefore, inappropriate output levels offer to the RGB LEDs. Consequently, it leads to much smaller and larger currents flowing into the green/blue and red LEDs, respectively, and increasing current harmonics. Hence, the single-stage architecture with FSC control demands the short rising time t_r and short falling time t_f.

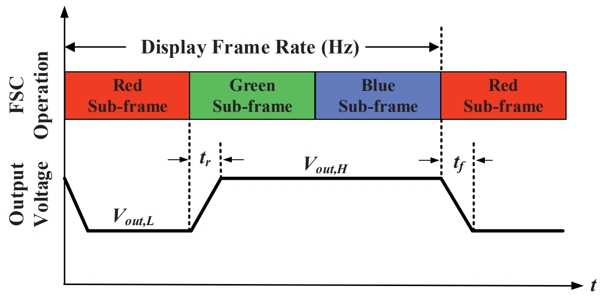


Fig. 2. Output voltage fluctuation of a single-stage ac-dc LED architecture with FSC operation.

A switching capacitor control in a single-stage ac-dc RGB-LED driver is presented in this paper. The buck architecture is adopted due to low cost and high efficiency. To obtain high PF with a simple control, the buck ac-dc LED driver is designed in the discontinuous conduction mode (DCM). With the switching capacitor control, the output voltage can hop between $V_{out,L}$ and $V_{out,H,}$ immediately. As a result, the LED currents are adjusted well and the overall power efficiency is improved. In Section II, the presented single-stage ac-dc RGB-LED driver is illustrated and its implementation is described. Section III and IV discuss experimental results and conclusions, respectively.

II. Single-Stage AC-DC Reconfigurable RGB-LED Driver

A. System Architecture

Fig. 3 shows the switching capacitor control in ac-dc RGB-LED driver, where the functions of a switching capacitor circuit and an ac-dc conversion are combined into a single stage. The on/off condition of switches S_a to S_d is decided by the color sequence signal *Color*. To regulate the current flowing through the RGB LEDs, the feedback signal V_{fb} is adopted and then transfer to a digital controller. Sequentially, pulse width modulation (PWM) and frequency compensation are performed by the digital controller. Then, through the gate driver, S_m is regulated by the gate signal V_{gm}. The switching capacitor circuit is utilized to immediately hop between two distinct levels of output voltage. By using the current control, the average current through LED strings is managed by the compensator. To ensure the hopping scheme smoothly, two compensators are adopted: one is for the green/blue LEDs and the other is for the red LEDs. As result, the proposed ac-dc LED driver achieves fast hooping response and high efficiency concurrently.

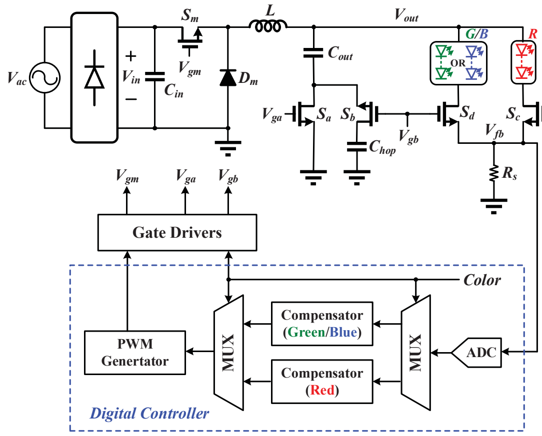


Fig. 3. Presented single-stage ac-dc LED driver.

B. Operation Principle of Switching Capacitor Control in AC-DC Converter

To realize high PF with a simple control, the presented LED driver operates in DCM. The average input current of the LED driver and the ac input voltage are proportional because the buck converter with DCM operation at low frequencies imitates resistance. Fig. 4 illustrates the operation of output voltage hopping scheme, where the output voltage ripple is ignored.

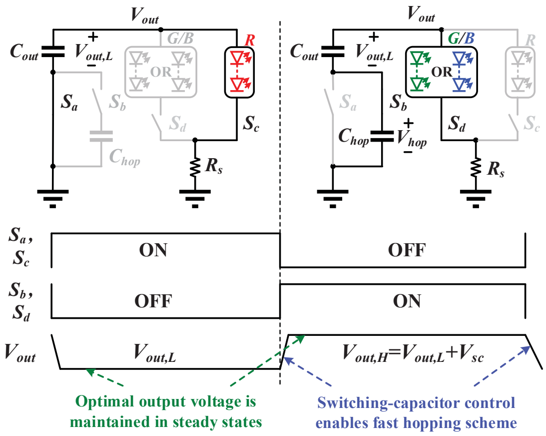


Fig. 4. Operation of the output voltage hopping scheme.

S_a and S_c become on while S_b and S_d become off when the red LEDs are enabled. Since C_{out} links between ground and V_{out}, the output voltage is set as $V_{out,L}$. When the green/blue LEDs are enabled, S_b and S_d are on and S_a and S_c are off, leading to a series connection between C_{out} and C_{hop}. If V_{hop} equals to the conducting voltage difference ΔV_{LED} between the green/blue and red LEDs, V_{out} can be instantly boosted by

ΔV_{LED}. The hopping response is no longer constrained by the narrow bandwidth of the LED driver. Thus, the output voltage is set as $V_{out,H}$ (= $V_{out,L}$ + V_{hop}) to power the GB-LED string. When the red LEDs becomes on, S_a is turned on and S_b is turned off. Then, C_{out} disconnects from C_{hop}, and then the output voltage is changed to $V_{out,L}$ again.

It is critical to ensure that V_{hop} on C_{hop} is exactly equal to ΔV_{LED} between red and green/blue LEDs. V_{hop} across C_{hop} during the start-up process is shown in Fig. 5. For simplicity, the V_{out} ripple is neglected. When the ac-dc LED driver gets started, V_{out} begins from zero. Assuming the red LEDs is enabled first, the output voltage level is adjusted to $V_{out,L1}$ with the routine regulation of RGB-LED driver. V_{hop} is zero because C_{hop} is separated from the LED driver. When green/blue LEDs are enabled, C_{out} and C_{hop} are linked in series first. Subsequently, the output voltage level gradually raised from $V_{out,L1}$ to $V_{out,H1}$. The incremental value of V_{hop} for one step-up procedure can be formulated as

$$V_{hop,1} = V_{hop,0} + \frac{C_{out}}{C_{out} + C_{hop}}\left(V_{out,H1} - V_{out,L1} - V_{hop,0}\right) \tag{1}$$

where $V_{hop,0}$ means the beginning value of V_{hop}. When red LEDs are enabled, C_{hop} is separated from C_{out} first, leading to V_{out} stepping down by V_{hop} rapidly. Then the ac-dc LED driver adjusts the output voltage approaching $V_{out,L2}$. V_{hop} is kept constant during this cycle because of separating from the proposed LED driver. Afterwards, V_{hop} is raised continuously by the switching capacitor control. V_{hop} can be written in (2) after n times step-up procedure.

$$V_{hop,n} = V_{hop,n-1} + \frac{C_{out}}{C_{out} + C_{hop}}\left(V_{out,Hn} - V_{out,Ln} - V_{hop,n-1}\right) \tag{2}$$

Once $V_{out,Hn}$ and $V_{out,Ln}$ approach their final values $V_{out,H}$ and $V_{out,L}$, respectively, V_{hop} on C_{hop} will be the same ΔV_{LED} between the green/blue and red LEDs at the end of the start-up procedure. As a result, the output voltage jumps between $V_{out,L}$ and $V_{out,H}$ instantly according to the color control signal, without waiting for the routine operation of the ac-dc LED driver. It should be noted that any ΔV_{LED} variation will be automatically revealed on the V_{hop} change according to the switching capacitor control.

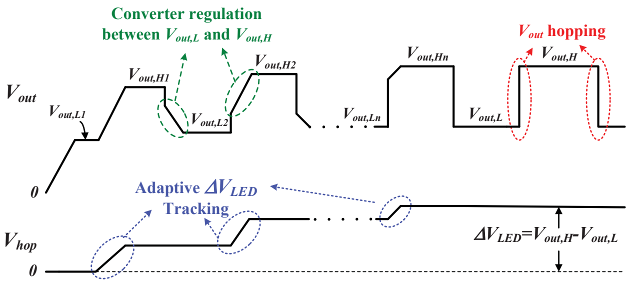


Fig. 5. V_{out} and V_{hop} during the start-up procedure.

C. Control Arrangement

According to the operation of the switching capacitor control, only single LED string is connected to the buck converter in any instance. The distinct LED strings cause the difference in the compensator output, resulting in slow hopping response of the output voltage. Thus, one compensator is for the green/blue LEDs and the other is for the red LEDs as illustrated in Fig. 3. To share gate drivers, a PWM generator, and, a common ADC, two multiplexers are employed. By setting the reference signals in the compensators identical, the current balance of GB-LED and R-LED strings can be fulfilled. With switching capacitor control, the PWM operation for the RGB-LED strings are shown in Fig. 6. For GB-LED string, the compensator output $V_{ea,GB}$ is higher due to bigger conducting voltage, so its PWM duty ratio of main switch S_a is larger. Similarly, for R-LED string, since the compensator output $V_{ea,R}$ is lower, its PWM duty ratio is smaller.

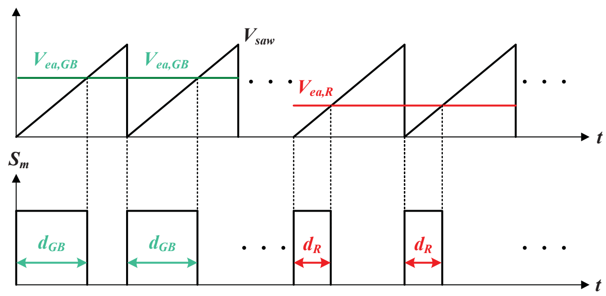


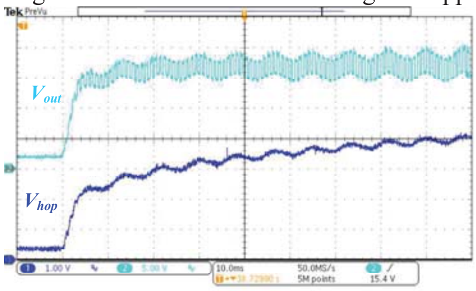
Fig. 6. PWM operation with switching capacitor control.

III. Experimental Results

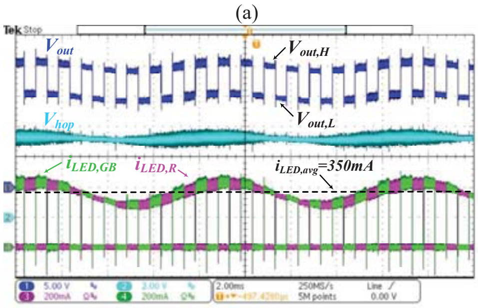
To demonstrate the circuit validity of switching capacitor control, a prototype of ac-dc LED driver is designed with maximum output current of 350 mA, ac input voltage of 110 V_{rms}, and output voltage of 10-20 V. The switching frequency and frequency of color sequence signal *Color* are set as 100 kHz and 1 kHz, respectively. The input filter capacitance is 0.1 μF. The inductance is 40 μH, while the output and hopping capacitance are 1000 μF and 3000 μF, respectively. The green/blue and red LED strings are adopted and every LED string consists of six LEDs.

The measured waveforms V_{out} and V_{hop} of the presented LED driver during the start-up procedure is shown in Fig. 7(a). Since the green/blue and red LEDs become on sequentially, the magnitude of V_{hop} continuously increases during the start-up procedure. The measured waveforms for normal operation of presented LED driver are shown in 7(b). After the start-up procedure, V_{hop} is about 5 V across C_{hop}. The V_{hop} level is identical to voltage difference between the green/blue and red LEDs. When green/blue and red LEDs are turned alternately and sequentially, V_{out} instantly jumps between $V_{out,H}$ and $V_{out,L}$, unconstrained by the driver bandwidth. Furthermore, the average current $i_{LED,avg}$ through

LED strings are maintained constant during the hopping state.



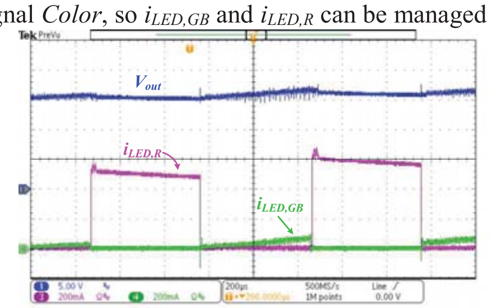
(a)



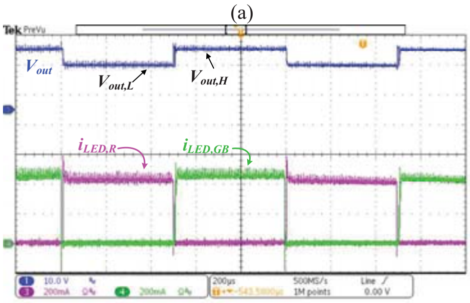
(b)

Fig. 7. Experimental waveforms of the presented LED driver for (a) start-up procedure and (b) normal operation.

When green/blue and red LEDs are turned sequentially, the experimental waveforms with and without the switching capacitor control are shown in Fig. 8. The transient response of the LED driver without switching capacitor control is slow, so V_{out} is adjusted to be smaller than the conducting voltage of green/blue LEDs but larger than the conducting voltage of red LEDs. Hence, $i_{LED,GB}$ and $i_{LED,R}$ become much lower and higher, respectively. Thanks to the switching capacitor control, V_{out} immediately hops between $V_{out,H}$ and $V_{out,L}$ based on signal *Color*, so $i_{LED,GB}$ and $i_{LED,R}$ can be managed well.



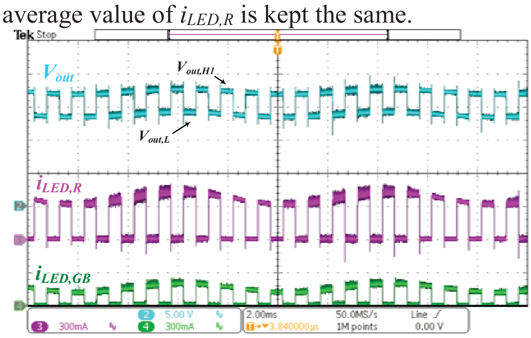
(a)



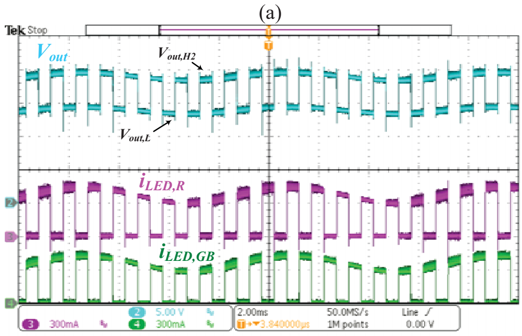
(b)

Fig. 8. Experimental waveforms (a) without and (b) with the switching capacitor control.

Fig. 9 shows the experimental waveforms of the proposed LED driver when the average value of $i_{LED,GB}$ changes from 150 mA to 350 mA. When the average value of $i_{LED,GB}$ is 150 mA in Fig. 9(a), the V_{hop} level ($=V_{out,H1}-V_{out,L}$) is smaller. In Fig. 9(b), the V_{hop} level ($=V_{out,H2}-V_{out,L}$) becomes larger while the average value of $i_{LED,GB}$ changes to 350 mA. From Fig. 9, the average value of $i_{LED,R}$ is kept the same.



(a)



(b)

Fig. 9. Experimental waveforms when $i_{LED,GB}$ is (a) 150 mA and (b) 350 mA.

IV. CONCLUSION

The switching capacitor control in single-stage ac-dc LED driver is presented for reducing component cost and circuit size. To obtain high PF with simple control, the ac-dc driver operates in DCM. Thanks to the switching capacitor control, the output voltage can hop instantly for precisely adjusting LED currents. The hopping capacitor automatically stores the voltage difference between the green/blue and red LEDs. The measured results demonstrate the fast hopping scheme of the ac-dc LED driver and the capability in current regulation.

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REFERENCES

[1] P.-J. Liu and K.-L. Peng, "Adaptive Driving Bus Voltage and Energy Recycling Control Schemes for Low-Power AC-DC RGB-LED Drivers," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 7741-7748, Oct. 2017.

[2] C.-C. Chen, C.-Y. Wu, Y.-M. Chen, and T.-F. Wu, "Sequential Color

LED Backlight Driving System for LCD Panels," *IEEE Trans. on Power Electron.*, vol. 22, no. 3, pp. 5097-5107, May 2007.
[3] P. Athalye, M. Harris, and G. Negley, "A two-stage LED driver for highperformance high-voltage LED fixtures," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2012, pp. 2385-2391.
[4] A. Yohso and K. Ukai, "How color break-up occurs in the human visual system: Mechanism of color break-up phenomenon," in *Proc. SID, Dig. 25.2*, 2005, pp. 1223-1228.