

Single-Stage AC/DC Single-Inductor Multiple-Output LED Drivers

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Abstract— Various AC/DC LED driver topologies have been proposed to meet the challenges of achieving a compact, efficient, low-cost and robust multi-string LED lighting system. These LED drivers typically employ a two-stage topology to realize the functions of AC/DC rectification and independent current control of each LED string. The choice of having two stage conversions involves additional hardware components and a more complicated controller design process. Such two-stage topologies suffer from a higher system cost, increased power loss, and large form factor. In this paper, a single-stage AC/DC single-inductor multiple-output (SIMO) LED driver is proposed. It uses only one single inductor and $N+1$ active power switches (N being the number of LED strings) with reduced component count and smaller form factor. The proposed driver can achieve both functions of AC/DC rectification with a high power factor and precise independent current control of each individual LED string simultaneously. A prototype of an AC/DC single-inductor triple-output (SITO) LED driver is constructed for verification. Experimental results corroborate that precise and independent current regulation of each individual LED string is achievable with the proposed driver. A power factor of above 0.99 and a peak efficiency of 89% at 30 W rated output power are attainable.

Index Terms— Single-inductor multiple-output (SIMO), color control, lighting system, LED, power factor control.

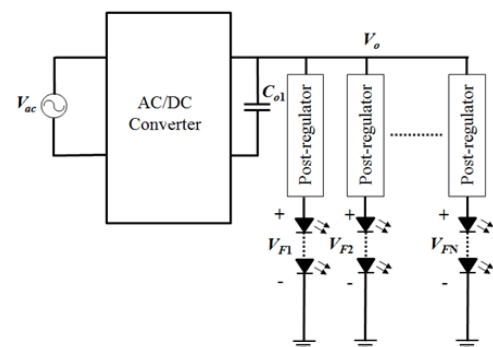
I. INTRODUCTION

Light-emitting-diodes (LED) are increasingly gaining acceptance in lighting industry with a growing list of applications, such as general, decorative and display lighting applications [1]–[6]. The four major factors supporting their popularity are (i) preponderant long lifetime; (ii) mercury free

and environmental friendly; (iii) high luminous efficiency; and (iv) flexibility to perform color mixing and dimming control [7]–[11]. Depending on the specific application requirements, the LED can either be arranged in series as a single string (or a single LED chip), or in parallel forming a multi-string structure (for medium and high power applications). Many LED drivers achieving small form factor and low cost have been proposed for the single LED chip/string applications [12]–[14]. However, achieving a compact and low-cost LED driver design is challenging for applications where multiple parallel LED strings are needed. This is because extra functionalities such as current balancing, individual string current regulation, or open/short circuit fault protection are typically demanded in such multi-string LED systems.

For instance, in high power applications, such as streetlight and large-scale LCD panels, current sharing between strings is crucial for providing an evenly distributed light output and heat. Most importantly, if the current imbalance causes one or more LED strings to exceed their rated current values, the lifetime of the LED strings will be drastically reduced [15]–[19]. In color mixing applications, such as RGB LED lamp and LED-backlit LCD display, fast and precise current control of the red, green and blue LEDs should be guaranteed [20]–[22]. Basically, these functionalities, i.e., current sharing, individual string regulations, and/or open/short circuit fault protection, can be simultaneously achieved if each of the string current is regulated independently. In this way, current sharing can be simply realized by assigning a common current reference for all strings, while individual current regulation is accomplished by assigning a different reference command for each string.

Several solutions for driving multi-string LED systems with independent current control have been proposed. They can be broadly classified into two types, as shown in Fig. 1(a) and (b).



(a)

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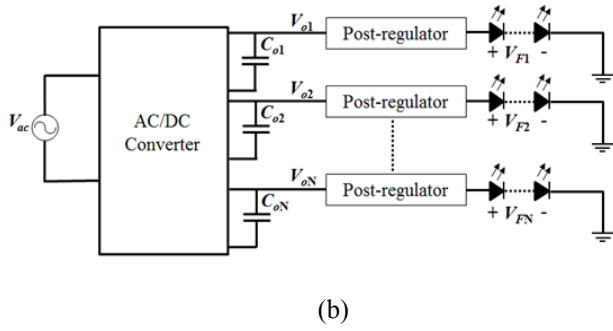


Fig. 1. Conventional multi-string LED systems of which the AC/DC stage generates (a) a common output bus voltage and (b) a separate output voltage for each individual LED string.

Their major difference lies in the circuit architecture of the AC/DC stage, which is required to enable an AC voltage input and/or perform power factor correction (PFC) function. Fig. 1(a) shows an AC/DC stage which generates a single common output bus V_o that is shared by all the LED strings [14], [23]–[26], whereas Fig. 1(b) shows an AC/DC stage which assigns a separate output voltage for each LED string [15], [27], [28]. To realize independent current regulation of each LED string, the output of the AC/DC pre-regulation stage must be cascaded with an additional post-regulator for each LED string, which regulates the current of the string to which it is connected. There are generally two types of post-regulators: linear type [23], [24], [28] and DC/DC converter type [14], [15], [25].

The linear type of post-regulators gives the simplest hardware configuration, but might incur severe power loss if improperly designed [23]. On the other hand, the DC/DC converter type of post-regulators is ideally lossless. However, each DC/DC post-regulator introduces additional switches and passive component such as inductor to the system. This inevitably leads to a higher system cost and larger form factor that grows as the number of LED strings increases. Therefore, there is always tradeoff between efficiency and the system's cost and size whenever a post-regulator is used. Another problem with the two-stage configuration is that two sets of controllers (one for the AC/DC stage and the other for the post-regulators) are required, which complicates the system design. Additionally, a two-stage structure requires the use of DC-link capacitor(s) (typically electrolytic capacitors (E-Cap)) (C_{o1} for Fig. 1(a), and C_{o1} – C_{oN} for Fig. 1(b)). If the DC-link voltage is high, it is hard to select a proper capacitor that has a long lifetime. The use of short lifetime capacitors in the LED drivers reduces the reliability of the LED driver [29], [30].

In view of the aforementioned issues, in this paper, a single-stage AC/DC single-inductor-multiple-output (SIMO) LED driver for multi-string LED applications, which can simultaneously achieve PFC and independent current regulation of each LED string, is proposed. The system architecture of the proposed single-stage SIMO driver is illustrated in Fig. 3, in which the functions of a PFC stage and a conventional DC/DC SIMO topology are integrated into a single stage. Therefore, the need for a post-regulator stage is eliminated. As the name suggests, only one inductor is needed. The total number of switches is also reduced as compared with the conventional two-stage solution using DC/DC type of

post-regulators. Therefore, the proposed LED driver is compact and cost-effective. In addition, it requires only one controller to regulate the switching sequence of all the power and output switches. This is made possible by time-multiplexing the control signals of each string. Moreover, by enabling one-stage operation, the intermediate high-voltage E-Cap is eliminated. It enables the use of low-voltage, long-lifetime capacitors which extends the operating life of the proposed LED driver.

In order to perform a power loss analysis, a non-ideal circuit simulation model, which includes the parasitic resistance, inductance and capacitance for the major components, has been created for the proposed single-stage AC/DC SIMO LED driver topology as well as the two prior arts, namely the conventional two-stage AC/DC LED driver (with three post-regulators) [14], [23]–[26] and the two-stage AC/DC SIMO LED driver [39], [40] for comparison purpose. Based on the simulation results, the total power loss and the power efficiency in each of the three topologies have been compared and tabulated in Table I.

TABLE I. COMPARISON OF THE SIMULATED POWER LOSS AND POWER EFFICIENCY OF THE PROPOSED SINGLE-STAGE AC/DC SIMO LED DRIVER AGAINST THE CONVENTIONAL TWO-STAGE AC/DC LED DRIVER [14], [23]–[26] AND THE TWO-STAGE AC/DC SIMO LED DRIVER. [39], [40].

Main power loss contributor	Conventional two-stage LED driver		Two-stage SIMO LED driver		Proposed single-stage SIMO LED driver	
	Conduction Loss (W)	Switching Loss (W)	Conduction Loss (W)	Switching Loss (W)	Conduction Loss (W)	Switching Loss (W)
Buck switch (Stage 1)	0.11642	0.07636	0.02564	0.22622	0.0063	0.1524
Buck switch (Stage 2)	0.030324	0.701	0.0343	0.67		
Output switch	0.0077175	1.17	0.0077175	0.0785	0.0077175	0.09
Freewheeling diode (Stage 1)	0.76039		0.37826		1.13875	
Freewheeling diode (Stage 2)	1.09414		1.035125			
Branch diode	1.3125		0.81073		1.33575	
Full-bridge diode	0.5244		0.4352		0.2072	
EMI filter inductor	0.0172		0.0136		0.003562	
Inductor (Stage 1)	0.00248		0.001513			
Inductor (Stage 2)	0.036		0.00605			
Sub-total	3.9015715	1.94736	2.7481355	0.97472	2.7184795	0.2424
Total power loss		5.8489315		3.7228555		2.9608795
Power efficiency (%)		83.68		88.96		91.02

To summarize, the proposed single-stage AC/DC SIMO LED driver results in the smallest total power loss, compared with the prior arts. Specifically, the proposed single-stage AC/DC SIMO driver results in a 32 % reduction in the total power loss, compared with the conventional two-stage driver using three post-regulators and about 18 % reduction in the total power loss, compared with the two-stage SIMO. On the other hand, the simulated power efficiency of the proposed SIMO driver is around 91 %, compared with 83.68 % from the conventional two-stage driver and 88.96 % from the two-stage SIMO. The proposed single-stage SIMO driver can achieve higher power conversion efficiency due to the use of only one buck switch as well as one freewheeling diode in the power stage. As a further improvement in power efficiency of the proposed driver, we can consider replacing the freewheeling diode in the power stage with a low-side MOSFET having a small $R_{ds(on)}$ as in a synchronous buck converter configuration.

II. AC/DC SINGLE-INDUCTOR MULTIPLE-OUTPUT LED DRIVERS

A. Existing AC/DC SIMO LED Driver

There is growing interest in using DC/DC SIMO converters for multi-string LED applications due to their reduced cost and smaller form factor. A single-inductor dual-output (SIDO) converter with time-multiplexing control scheme operating in DCM is first reported in [31], [32]. Extending from SIDO, a DC/DC SIMO parallel string LED driver operating in DCM is recently reported in [33]-[38]. All of these reported SIMO converters *can only* realize DC/DC conversion, and a stable DC input is typically required. To accommodate an AC voltage input, e.g. a 110 V, 60 Hz AC mains, a DC/DC SIMO LED driver is often cascaded behind an AC/DC front-end stage [39], [40], as shown in Fig. 2, again forming a two-stage configuration, which is similar to that given in Fig. 1.

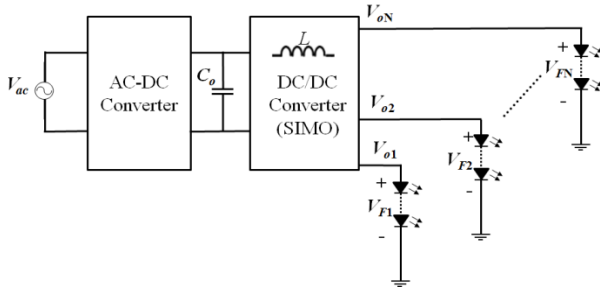


Fig. 2. System architecture of the existing two-stage AC/DC SIMO LED driver.

In [39], the AC/DC front-stage is simply a diode bridge rectifier with a large capacitor. An unregulated DC voltage is produced without performing any PFC. Such a configuration is only useful for low-power LED applications, of which the PF requirement is less stringent [41], [42]. Also, the SIMO converter in [40] is operating in continuous conduction mode (CCM) and suffers from cross-regulation issues. Therefore, individual current regulation of LED strings is unviable, and only current sharing function is performed. On the other hand, in [40], a boost PFC converter is implemented as the AC/DC front-stage converter, providing a well-regulated DC voltage and a high PF. Nevertheless, by employing a two-stage configuration, these existing AC/DC SIMO LED drivers inherently have similar demerits as those described in Fig. 1.

B. Proposed Single-Stage AC/DC SIMO LED Driver

Fig. 3 shows the configuration of the proposed single-stage SIMO LED driver.

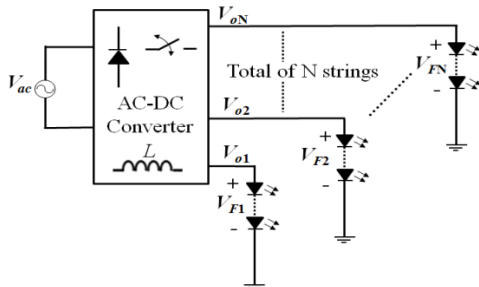


Fig. 3. System architecture of the proposed single-stage AC/DC SIMO LED driving system.

Unlike existing AC/DC SIMO LED drivers that are configured as shown in Fig. 2, the proposed AC/DC SIMO LED driver can directly drive multiple LED strings off an AC voltage source in a single stage, without an intermediate DC-link. Both PFC and independent regulation of string currents are simultaneously viable. This is possible through proper component integration of a PFC stage and a DC/DC SIMO converter. For example, if a DCM buck converter is adopted for the PFC stage (Fig. 4(a)), and a buck-type DC/DC SIMO is selected for the SIMO stage (Fig. 4(b)), by integrating their main power switch S_a and S_a' , freewheeling diode D_a and D_a' , and inductor L and L' , a single-stage buck-type AC/DC SIMO driver can be obtained as shown in Fig. 4(c).

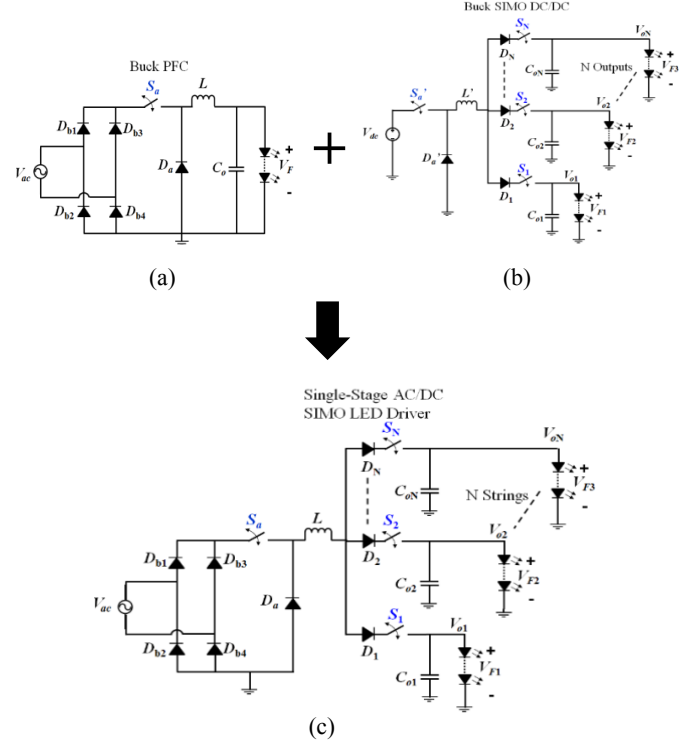


Fig. 4. Derivation of a buck-type single-stage AC/DC SIMO LED driver. (a) A DCM buck PFC converter. (b) A buck-type DC/DC SIMO converter. (c) The derived buck-type single-stage AC/DC SIMO LED driver.

By employing a time-multiplexing control scheme, at any instance in time, the LED driver depicted in Fig. 4(c) can be operated to act as a single-input single-output DCM buck converter. Since a DCM buck converter is naturally an emulated resistor at low frequencies [43], the averaged input current of the LED driver over each switching period is inherently proportional to the line voltage. As a result, the original DC/DC SIMO converter can be readily turned into a single-stage AC/DC SIMO driver integrated with PFC function through minor hardware modifications including the addition of the front-end diode rectifier. In contrast to all previous methods that are two-staged-based, the driver in Fig. 3 and Fig. 4(c) requires no E-Cap between the diode bridge and the SIMO stage. Clearly, the removal of a short lifetime high voltage E-Cap extends the operating lifetime of the proposed LED driver. Also, by operating the proposed SIMO driver in DCM,

cross-regulation can virtually be eliminated as the individual LED strings are fully decoupled from one another.

III. OPERATING PRINCIPLES OF THE PROPOSED SINGLE-STAGE AC/DC SIMO LED DRIVER

A. Operating Modes

A single-inductor triple-output (SITO) AC/DC buck converter as shown in Fig. 5 is used for the sake of our discussions.

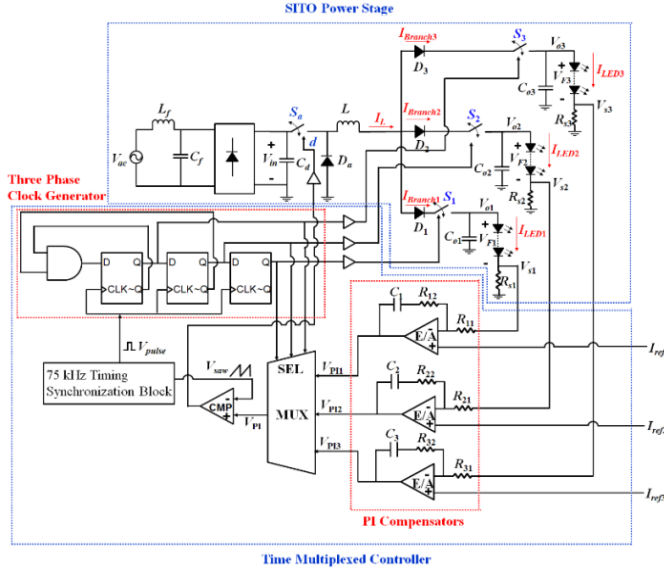


Fig. 5. Complete circuit diagram with three LED strings.

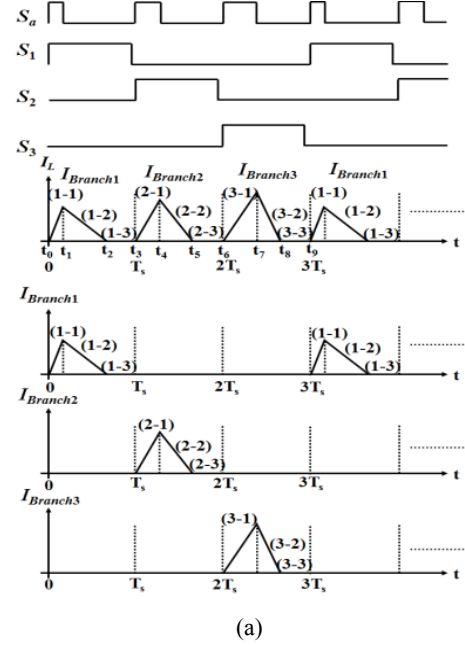
As shown in Fig. 5, a total of four switches, i.e., one main switch S_a and three output switches S_1 – S_3 , are used in this converter. L_f and C_f forms the input EMI filter, C_d is the high-frequency filter capacitor, D_a is the freewheeling diode, and L is the main inductor. D_i is the branch diode in the i^{th} LED string for preventing reverse flow of the branch current. C_{oi} and R_{si} are the output capacitor and sensing resistor of the i^{th} LED string. The AC input voltage is V_{ac} , the input voltage to the buck converter is represented by V_{in} and the three output voltages are V_{o1} – V_{o3} . I_L is the inductor current and $I_{branch1}$ – $I_{branch3}$ are the branch currents that flows through the respective output switches. The ideal waveforms of S_a , S_1 – S_3 , I_L , and $I_{branch1}$ – $I_{branch3}$ are shown in Fig. 6(a), where T_s represents the switching period of the main switch S_a .

It can be seen that the proposed AC/DC SIMO converter operates in DCM where I_L always returns to zero at the end of each switching cycle. Fig. 6(b) depicts the control sequence of the SITO AC/DC converter under normal operations. In three switching cycles (0 – $3T_s$), there are a total of nine control sequences which can be categorized into the following three distinctive modes of operation.

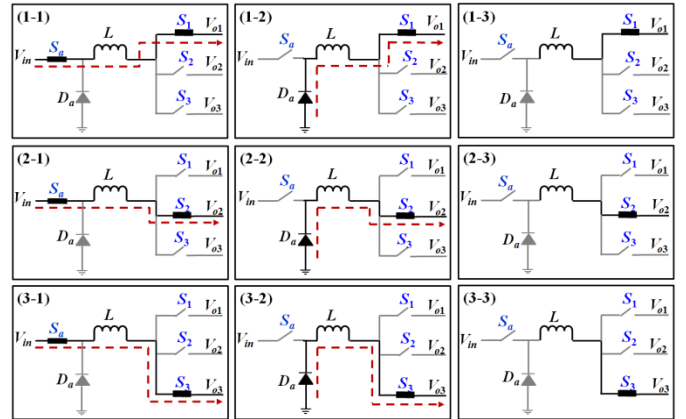
- **Mode 1** (t_0 – t_1): Main switch S_a is ON and freewheeling diode D_a is OFF. The inductor current I_L increases at a rate of $(V_{in}-V_{o1})/L$. The output switch S_1 is ON and S_2 and S_3 are OFF since only the first output is enabled. This corresponds to (1–1), (2–1), and (3–1) in Fig. 6(b).
- **Mode 2** (t_1 – t_2): S_a is OFF and D_a is ON. I_L decreases linearly at a rate of V_{o1}/L . At t_2 , I_L drops to 0 and Mode 2 ends. This

corresponds to (1–2), (2–2), and (3–2) in Fig. 6(b).

- **Mode 3** (t_2 – t_3): Both S_a and D_a are OFF. I_L remains at zero during this idle period. In order to reduce the switching loss, for example, S_1 can be turned off with zero-current switching (ZCS) and S_2 can be turned on with ZCS during this interval. This corresponds to (1–3), (2–3), and (3–3) in Fig. 6(b).



(a)



(b)

Fig. 6. (a) Timing diagram of the main switch S_a and output switches S_1 – S_3 , inductor current I_L and branch currents $I_{branch1}$ – $I_{branch3}$ and (b) control sequence of the proposed AC/DC SITO LED driver.

The same process is repeated in the next two switching periods for the second and third output in which S_1 is OFF and S_2 , S_3 take turns to be ON. The energy is transferred from the inductor to the three outputs in a time-interleaved manner. The same control sequence can also be scaled conveniently to N outputs, where N is the total number of LED strings. The output switch corresponding to each LED string, namely S_1 , S_2 , ..., S_N , is ON only during one of the N switching cycles. The output switch is OFF during the remaining $(N-1)$ switching cycles.

B. Control Schemes

The control circuit of the proposed AC/DC SITO buck LED driver is a specialized time multiplexed controller as shown in Fig. 5. According to the operating principles described in Section A, the on-instant of S_a should be synchronized with respective output switches S_1 – S_3 . The synchronization is realized by the 75 kHz time synchronization block. A more detailed explanation will be given in Section C. The averaged current of each LED string is controlled by the respective control loop that compares the current-sense voltage V_{si} (which is equal to the LED current amplified by 10 times) to a reference I_{refi} . The error signal V_{Eai} is compensated by a PI compensator and modulated by a PWM modulator to give the on-time duty ratio d_i and command S_a . The signals that are provided by the three phase clock generator are used to command S_1 – S_3 and select one of the three channels of the MUX. In practice, there will be a total of three feedback loops, one for each LED string. The three PI controllers take turns to use the analog comparator, which means that in any instance, the circuit effectively has only one set of PI controller in operation. In addition, with reference to [43], by operating the system in DCM, the load is essentially an emulated resistor connected to the converter input. Although the emulated resistor, which is determined by the duty cycle d_i , is different in three LED strings, in any instance only one emulated resistor will be connected to the converter input, which means that the PFC can be achieved. Fig. 7 shows the timing diagram of the time-multiplexed PWM control using three distinct-colored LEDs to represent different loading conditions among the three LED strings.

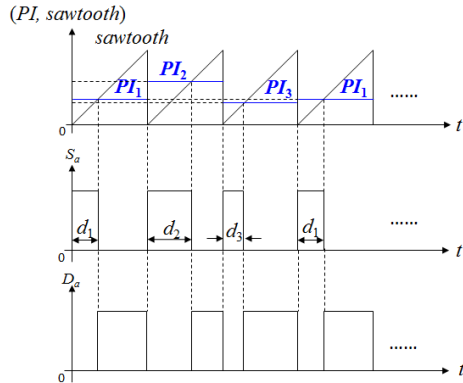


Fig. 7. Timing diagrams for different PWM duty ratios using three distinct-colored LEDs.

Note that for different loading conditions and/or with different current reference command, the PI outputs are different and thus the PWM duty ratios for each string are different. In order to minimize the hardware resources, the outputs of the PI compensators are time-multiplexed together while sharing a common PWM modulator. This enables the subsequent logic elements beyond the PI compensators to be time shared among all the SITO outputs. In the SITO topology, the use of time-interleaving control with multiple energizing phases means that each of the LED string is independently driven and is decoupled from the other strings with minimal cross-interference. The current in each individual LED string

can be controlled separately by assigning a unique current reference in each LED string. It can be expected that, with different loading conditions and current reference commands, the inductor current I_L for respective string will have different (rising and falling) slopes and durations. This phenomenon is shown in Fig. 6(a) and is verified later by experimental measurement. In addition, current balancing, which is a special case of independent current control, can be realized by using the same current reference signal across all the LED strings without the need for additional post-regulator circuits.

C. 75 kHz Timing Synchronization Block

The timing of S_a and S_1 – S_3 is synchronized using a 555 timer operating in monostable state. The detailed 75 kHz timing synchronization block is illustrated in Fig. 8.

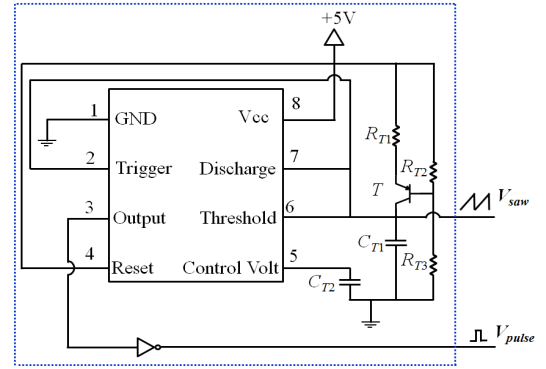


Fig. 8. 555 timer operating in monostable state to generate linear ramp V_{saw} and pulse train V_{pulse} .

The bias voltage of the BJT T is set by R_{T2} and R_{T3} , and R_{T1} serves to limit the current flowing through T to charge up capacitor C_{T1} . The voltage across C_{T1} is

$$V_{CT1} = \frac{Q}{C_{T1}} = \frac{I_T}{C_{T1}} t, \quad (1)$$

where Q is the charge of C_{T1} , and I_T is the current through the BJT. Under the given configuration, the 555 timer operates to generate a linear ramp V_{saw} at pin 6. The output pin 3 generates a trigger pulse which dips every time C_{T1} is discharged. By inverting this trigger pulse, a pulse train V_{pulse} , which is synchronized with V_{saw} , is obtained. V_{saw} is fed to the PWM comparator and V_{pulse} is used to generate the three phase clock to enable the SITO operation.

IV. PARAMETER DESIGN OF THE SIMO LED DRIVER

A. Inductor Design

To minimize the size of the inductor and simplify the controller design for PFC, the converter should be operated in DCM. Also, the current ripple in the inductor L should be limited to reduce the current stress of the power switches. Thus, the buck main inductor should neither be too large nor too small.



Fig. 9. An equivalent LED model which comprises of an ideal diode D_{LED} , small signal resistor R_{LED} and threshold voltage V_{th} .

Fig. 9 shows an equivalent LED model, which comprises a series connection of an ideal diode D_{LED} , a resistor R_{LED} and a threshold voltage V_{th} . Based on this model, the parameters of the red (R), green (G), and blue (B) LEDs [44] used in the experiments are tabulated in Table II.

TABLE II. PARAMETERS OF THE RGB LEDs.

Type	Luxeon Rebel Red	Luxeon Rebel Green	Luxeon Rebel Blue
Equivalent Resistance R_{LED} (Ω)	4	6	6
Rated Current I_{LED} (mA)	350	350	350
Threshold Voltage V_{th} (V)	0.7	0.8	0.85
Forward Voltage V_F (V)	2.1	2.9	2.95
Rated Power P_{LED} (W)	0.735	1.015	1.0325

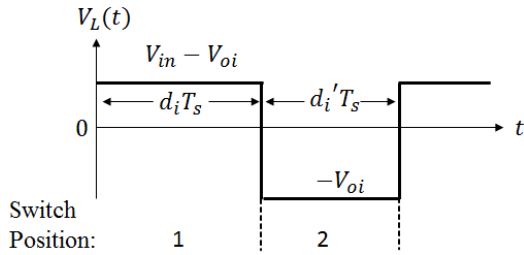


Fig. 10. Inductor voltage waveform of a buck converter in CCM operation.

Fig. 10 shows the inductor voltage waveform of a buck converter in CCM at steady state. Using inductor volt-second balance,

$$(V_{in} - V_{oi})d_i T_s - V_{oi}(1 - d_i)T_s = 0, \quad (2)$$

where V_{in} is the input voltage of the buck converter, V_{oi} is the output voltage of the i^{th} LED string, as described in Fig. 5, and d_i is the duty ratio of the i^{th} LED string as shown in Fig. 7. The output voltage of the i^{th} LED string is

$$V_{oi} = d_i V_{in}. \quad (3)$$

In the first switching interval, the increasing rate of inductor current I_{Li} is

$$\frac{dI_{Li}}{dt} = \frac{V_{Li}(t)}{L_i} = \frac{V_{in} - V_{oi}}{L_i}, \quad (4)$$

where L_i is the inductance when the i^{th} string is considered. The peak-to-average current ripple is defined as

$$\Delta I_{Li,pa} = \frac{V_{in} - V_{oi}}{2L_i} d_i T_s. \quad (5)$$

In steady-state condition, the DC component of the buck capacitor current should be zero. Therefore, the DC component of the buck inductor current is

$$I_{Li} = I_{LEDi} = \frac{V_{oi} - WV_{thi}}{WR_{LEDi}}, \quad (6)$$

where W is the number of LEDs in one string, and I_{LEDi} , V_{thi} and R_{LEDi} are respectively the rated LED current, the LED threshold voltage, and the LED equivalent resistance in the i^{th} string. If the system operates in DCM, then $I_{Li} < \Delta I_{Li}$, where ΔI_{Li} represents the maximum inductor current ripple when the buck converter operates in boundary conduction mode (BCM), i.e.,

$$\frac{V_{oi} - WV_{thi}}{WR_{LEDi}} < \frac{V_{in} - V_{oi}}{2L_i} d_i T_s. \quad (7)$$

where $d_i = V_{oi}/V_{in}$ in BCM. Hence, the minimum value of L_i is

$$L_{i_min} = \frac{(V_{in} - V_{oi})WR_{LEDi}}{2(V_{oi} - WV_{thi})} d_i T_s = \frac{(V_{in} - V_{oi})WR_{LEDi}}{2(V_{oi} - WV_{thi})} \frac{V_{oi}}{V_{in}} T_s, \quad (8)$$

and the upper boundary of the main inductance is given by

$$L < \min\{L_{i_min}\}, \quad i = 1, 2, 3, \dots, W. \quad (9)$$

On the other hand, the lower boundary can be obtained by considering the maximum allowable inductor current ripple ΔI_{L_max} using

$$\Delta I_{Li} = \frac{V_{in} - V_{oi}}{L_i} d_i T_s \leq \Delta I_{L_max}. \quad (10)$$

In DCM operation, we have

$$\frac{V_{rms}^2}{R_{e_i}(d_i)} = P_{LEDi}, \quad (11)$$

where V_{rms} is the RMS value of V_{in} , $R_{e_i}(d)$ is the equivalent resistance emulated by the DCM buck converter for the i^{th} LED string given by [43]

$$R_{e_i}(d_i) = \frac{2L_i}{d_i^2 T_s}, \quad (12)$$

and P_{LEDi} is the power consumed by the LED load in the i^{th} string given by

$$P_{LEDi} = WV_{Fi} I_{LEDi}, \quad (13)$$

where V_{Fi} is the forward voltage of LED in the i^{th} string. From (11) and (12), the duty cycle d_i can be represented by

$$d_i = \sqrt{\frac{2L_i}{R_{e-i}(d_i)T_s}} = \sqrt{\frac{2L_i P_{LEDi}}{V_{rms}^2 T_s}}. \quad (14)$$

By substituting (14) into (10), the maximum value of L_i is

$$L_{i_max} = \left(\frac{V_{in} - V_{oi}}{\Delta V_{L_max}} \right)^2 \frac{2P_{LEDi} T_s}{V_{rms}^2}, \quad (15)$$

and the lower boundary of the main inductance is given by

$$L \geq \max \{L_{i_max}\}, \quad i = 1, 2, 3, \dots, W. \quad (16)$$

B. Output Capacitor Design

For each LED string, an output capacitor C_{oi} is separately required. The design of the capacitors can be performed independently since the operation of each string is decoupled. The design approach is the same as that for a DC-link capacitor in conventional AC/DC rectifying systems since the employed output capacitors have to perform the same functions of AC energy storage and switching frequency filtering. This is different from that of the DC/DC SIMO LED driver in which the output capacitor is designed to handle only switching ripples.

If $\Delta V_i = kV_{oi}$, where V_{oi} is the average output voltage in string i , ΔV_i is the peak output voltage ripple, and k is the ripple factor that defines the allowable peak voltage ripple, then with reference to [43], the lower limit for C_{oi} is

$$C_{oi} \geq \frac{P_{LEDi}}{kV_{oi}^2} \times \frac{T_{ac}}{2\pi}, \quad (17)$$

where $T_{ac} = 1/(60 \text{ Hz})$.

C. Small-Signal Analysis and Controller Design

Due to the time-multiplex arrangement of the three controllers, only one output is effective at any instance. Therefore, the controller can be designed independently. Take one string as an example. Fig. 11 shows the small-signal block diagram of one string. Essentially, the controlled power plant is a buck converter operating in DCM. A straight-forward way to determine the low frequency small-signal control-to-output transfer function of the buck converter in the i^{th} string, denoted by $G_{Buck-i}(s)$, is to let the main inductance L tend to zero. With reference to [43], $G_{Buck-i}(s)$ is given by

$$G_{Buck-i}(s) = \left. \frac{\hat{i}_{oi}}{\hat{d}_i} \right|_{\hat{v}_g=0} = \frac{\frac{2V_{oi}}{d_i} \times \frac{1-M_i}{2-M_i} \times \frac{1}{WR_{LEDi}}}{1 + \frac{s}{2-M_i} \times \frac{1}{(1-M_i)WR_{LEDi}C_{oi}}}, \quad (18)$$

where M_i is the DCM conversion ratio of the i^{th} LED string given by

$$M_i = \frac{V_{oi}}{V_{in}} = \frac{2}{1 + \sqrt{1 + \frac{8L_i}{WR_{LEDi}d_i^2 T_s}}}. \quad (19)$$

A simple PI controller is used as the compensator. In Fig. 11, which shows the small-signal control block diagram, the transfer function of the compensator of the i^{th} LED string is given by

$$G_{ci}(s) = \frac{sk_{p-i} + k_{int-i}}{s}, \quad (20)$$

where k_{p-i} is the proportional gain and k_{int-i} is the integral gain. Here, V_M is the amplitude of the sawtooth carrier waveform and $H_i(s)$ is the sensing gain for the i^{th} string. The output of PI compensator $\hat{v}_{ci}$ is fed into the PWM modulator with a gain of $1/V_M$ in order to generate a duty ratio $\hat{d}_i$. The averaged current in each LED string is determined by the corresponding current reference value $I_{refi}(s)$.

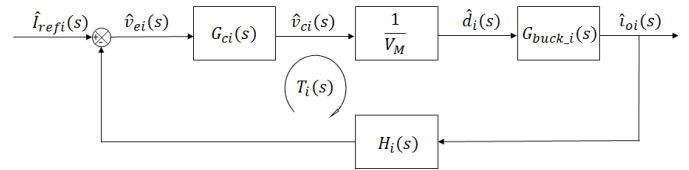


Fig. 11. Small-signal block diagram of the i^{th} string in the proposed closed-loop SIMO converter.

The loop gain $T_i(s)$ of the system can be represented as

$$T_i(s) = G_{ci}(s) \times \frac{1}{V_M} \times G_{Buck-i}(s) \times H_i(s). \quad (21)$$

By substituting (18) and (20) to (21), the loop gain becomes

$$T_i(s) = \frac{sk_{p-i} + k_{int-i}}{s} \times \frac{\frac{2V_{oi}}{d_i} \times \frac{1-M_i}{2-M_i} \times \frac{1}{WR_{LEDi}}}{1 + \frac{s}{2-M_i} \times \frac{1}{(1-M_i)WR_{LEDi}C_{oi}}} \times \frac{1}{V_M} \times H_i(s). \quad (22)$$

D. Design Example

The design parameters given in Table III are adopted for illustrative purpose. By substituting the values into (8), the upper limits of the inductance for the three different LED strings can be found as $L_{1_min} = 254 \mu\text{H}$, $L_{2_min} = 336 \mu\text{H}$, $L_{3_min} = 341 \mu\text{H}$. According to (9), the upper limit of inductance will be $L < 254 \mu\text{H}$.

Next, by substituting the same design parameters into (15), the lower limit of inductance for the three LED strings can be found as $L_{1_max} = 3.52 \mu\text{H}$, $L_{2_max} = 4.48 \mu\text{H}$, $L_{3_max} = 4.53 \mu\text{H}$. From (16), the lower limit of inductance is found as $L \geq 4.53 \mu\text{H}$. Therefore, the range of inductance is $4.53 \mu\text{H} \leq L \leq 254 \mu\text{H}$. In order to minimize the size of the main inductor to achieve a smaller overall form factor of the proposed LED

driver, L is selected to be $5 \mu H$. However, for a practical design, more design margins of L are recommended to compensate for the operating transient, component tolerances, etc. Then, by referring to (17), the lower limits of C_{oi} for the three LED strings are $C_{o1} \geq 902 \mu F$, $C_{o2} \geq 653 \mu F$, $C_{o3} \geq 642 \mu F$. For illustration purpose, C_{o1} , C_{o2} , and C_{o3} are all chosen to be $1000 \mu F$.

To demonstrate the controller design, string 1 (red LEDs) is chosen as an example. The input voltage V_{in} has a peak value of $110\sqrt{2} V$. With reference to Table II, it is desired to supply a regulated output voltage $V_{o1} = 14.7 V$ and LED current $I_{LED1} = 350 mA$. The first step is to determine the feedback gain $H_1(s)$. A 1Ω resistor R_{s1} is used as the current sensing resistor. The voltage of R_{s1} will then be amplified by a factor of $p = 10$ using proportional amplifier, and compared with current reference I_{ref1} . Hence, we have

$$H_1(s) = R_{s1}p = 10. \quad (23)$$

By substituting the related parameters listed in Table III into (21), the open-loop transfer function of the system before compensation (when $G_{c1}(s) = 1$) can therefore be written as

$$T_{u1}(s) = \frac{1}{V_M} \times G_{Buck_1}(s) \times H_1(s) = \frac{56}{\frac{s}{75} + 1}. \quad (24)$$

By setting $|T_{u1}(j\omega)| = 1$, the cross-over frequency f_{cu1} of the uncompensated loop gain $T_{u1}(s)$ can be obtained as $f_{cu1} = 0.668 kHz$. The desired cross-over frequency of the loop gain after compensation $T_1(s)$ is chosen to be $f_{c1} = (1/10) \times f_o = 2.5 kHz$, where f_o is the output switch frequency. From (24) at $2.5 kHz$, the magnitude of $T_{u1}(s)$ is

$$|T_{u1}(j \times 2\pi \times 2.5k)| = \left| \frac{56}{\frac{j \times 2\pi \times 2.5k}{75} + 1} \right| = -11.46 dB. \quad (25)$$

From (20), to obtain a unity loop gain at $2.5 kHz$, the compensator should have a $2.5 kHz$ gain of $11.46 dB$, which means that

$$|G_{c1}(j \times 2\pi \times 2.5k)| = \left| \frac{j \times 2\pi \times 2.5k \times k_{p_1} + k_{int_1}}{j \times 2\pi \times 2.5k} \right| = 11.46 dB. \quad (26)$$

By choosing $k_{p_1} = 3.5$, k_{int_1} can be calculated as $k_{int_1} = 20755$. Thus, the compensator transfer function $G_{c1}(s)$ is

$$G_{c1}(s) = \frac{sk_{p_1} + k_{int_1}}{s} = 3.5 + \frac{20755}{s}. \quad (27)$$

Based on (24) and (27), the Bode plots of the open-loop gain before and after compensation as well as the compensator transfer function $G_{c1}(s)$ can be plotted as shown in Fig. 12. From the figure, the phase margin is 70° , which indicates that the system is stable.

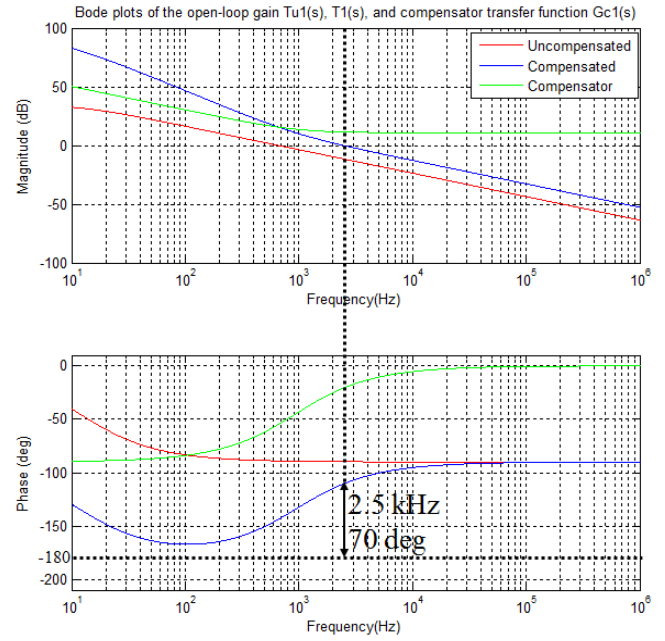


Fig. 12. Bode plots of loop gain $T_1(s)$ before and after compensation as well as the compensator transfer function $G_{c1}(s)$.

V. EXPERIMENTAL VERIFICATION

A hardware prototype of the proposed single-stage AC/DC single-inductor three-output (SITO) LED driver has been constructed. Fig. 13 shows a photo of the prototype.

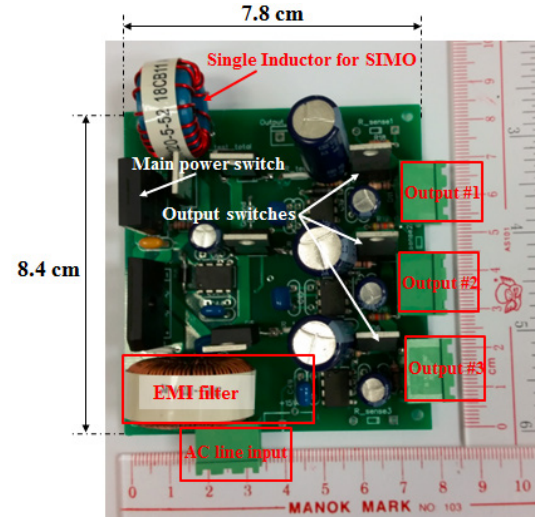


Fig. 13. Hardware prototype of the proposed single-stage AC/DC single-inductor three-output (SITO) LED driver.

Experiment verifications are performed based on the hardware prototype shown in Fig. 13 and the design specifications provided in Table III.

TABLE III. DESIGN SPECIFICATIONS.

Design Parameter	Value	Design Parameter	Value
Input voltage V_{ac}	110 V	Rated LED Current I_{LED}	350 mA
EMI Filter (L_f, C_f)	1 mH, 0.1 μ F	Voltage Ripple Factor k	7%
Filter Capacitor C_d	0.1 μ F	Sensing Resistor R_s	1 Ω
Main Switch Frequency f_s	75 kHz	Power Inductor L	5 μ H
Max. Current Ripple Δi_{Lmax}	8 A	Cross-over Frequency f_c	2.5 kHz
Output Capacitor (C_{o1}, C_{o2}, C_{o3})	1000 μ F	Same-colored LED	String 1: 7 Blue LEDs
			String 2: 7 Blue LEDs
			String 3: 7 Blue LEDs
Rated Output Voltage (V_{o1}, V_{o2}, V_{o3})	String 1: 14.7 V	Distinct-colored LED	String 1: 7 Red LEDs
	String 2: 20.3 V		String 2: 7 Green LEDs
	String 3: 20.7 V		String 3: 7 Blue LEDs

Table IV shows a list of components used in the experiment. The experiments involve two types of LED loads. In the first scenario, same-colored LEDs are used for the three strings, that is, each string consists of 7 blue LEDs. In the second scenario, distinct-colored LEDs are used for the three strings, that is seven red LEDs are assigned to the first string, seven green LEDs for the second string, and seven blue LEDs for the third string. Note that the current in the three strings in either scenario can be controlled independently to be identical or different.

TABLE IV. COMPONENT LIST.

Component	Model no.	Component	Model no.
Diode Bridge Rectifier	GBU10G-BP	MUX	CD74HC4051E
Main Switch (S_a)	IPW50R280CE	Comparator	AD8561ANZ
MOSFET Gate Driver	IRS2101PBF	Oscillator	LM555CN/NOPB
Freewheeling and Branch Diodes	MUR1540G	Operational Amplifier	OP340PA
Output Switches (S_1, S_2, S_3)	IRFI4227PbF	Output Capacitor (C_{o1}, C_{o2}, C_{o3})	UPX1V102MHD (long lifetime)

A. Circuit Operating Principle

Fig. 14 shows the AC line voltage and input current waveforms using a 110 V 60 Hz AC source and same-colored LEDs as the load. It can be seen that the AC line voltage and the input current are essentially in phase and the power factor is measured as 0.99, thereby verifying the functionality of PFC.

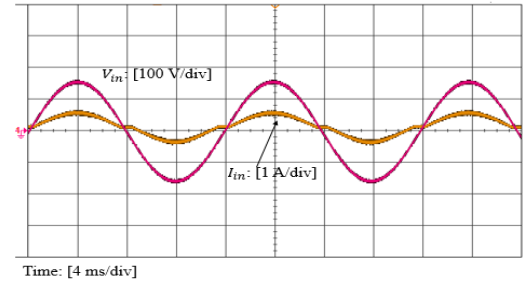


Fig. 14. Measured waveforms of the AC line input voltage and current for 30 W output power using same-colored LEDs with a common current reference of 350 mA.

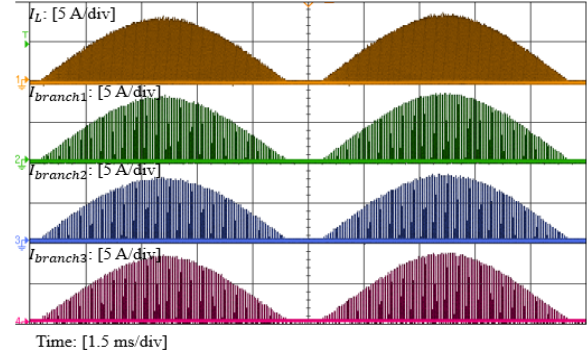
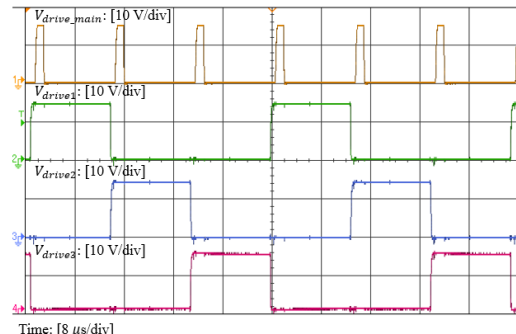


Fig. 15. Measured waveforms of I_L and $I_{branch1}$ – $I_{branch3}$ employing same-colored LEDs with identical LED current of 350 mA.

Fig. 15 shows the full view of the inductor current I_L and the three branch currents $I_{branch1}$ – $I_{branch3}$ with same-colored LEDs and a common 350 mA reference current. The maximum current in each LED string peaks at around 7.5 A which falls within the design specification limit (i.e., $\Delta i_{Lmax} = 8$ A). Figs. 16 to 18 show the close-up view of I_L and $I_{branch1}$ – $I_{branch3}$, and the corresponding driving signals of main switch V_{drive_main} and output switches V_{drive_1} – V_{drive_3} under different conditions. From Fig. 16, same-colored LEDs with a 350 mA common reference command are used. It shows that (i) the duty cycles of the PWM signal that drives the main switch S_a are similar for different LED strings; and (ii) the peak values of $I_{branch1}$ – $I_{branch3}$ are the same. Also, S_a is ON in every switching cycle, but the output switch S_i (where $i = 1, 2, 3$) is ON in every three switching cycles. Consequently, I_L ramps up and down in each switching cycle but the branch current $I_{branchi}$ of each LED string appears every three switching cycles. In other words, I_L is assigned to each of the three LED strings in a round-robin fashion. The experimental results verify the functionality of the SIMO topology and the time-multiplexed control method.



(a)

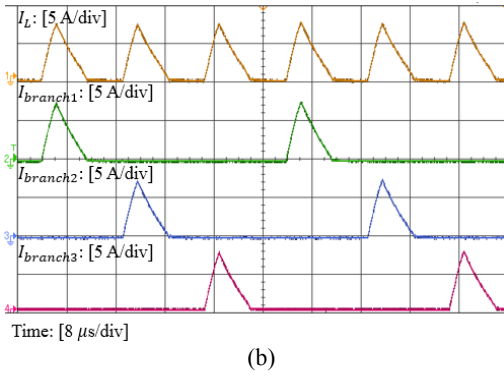


Fig. 16. Close-up view of (a) driving signals of main switch S_a and output switches S_1 – S_3 and (b) the corresponding I_L and $I_{branch1}$ – $I_{branch3}$ with same-colored LEDs and a common 350 mA reference command.

Fig. 17 shows the “distinct-colored LEDs” scenario with a 350 mA common reference. It is important to note that the PWM duty ratio corresponding to each of the three LED strings is different. Also, the peak value of the branch current $I_{branchi}$ (also the peak inductor current) is also distinct among the three LED strings. On the other hand, Fig. 18 shows the “same-colored LEDs” scenario with different reference values. Similar to Fig. 17, the duty cycle of the PWM signal which drives S_a and the peak values of $I_{branchi}$ in three LED strings are different in every switching cycle.

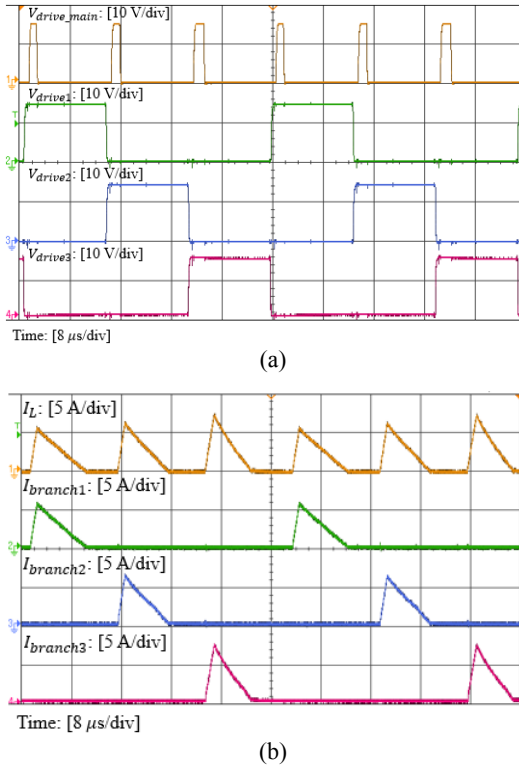


Fig. 17. Close-up view of (a) driving signals of main switch S_a and output switches S_1 – S_3 and (b) the corresponding I_L and $I_{branch1}$ – $I_{branch3}$ with distinct-colored LEDs and a common 350 mA reference command.

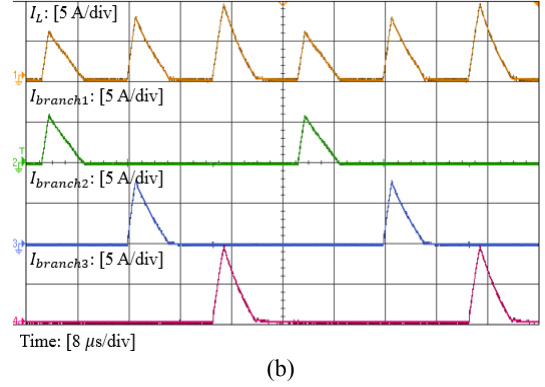
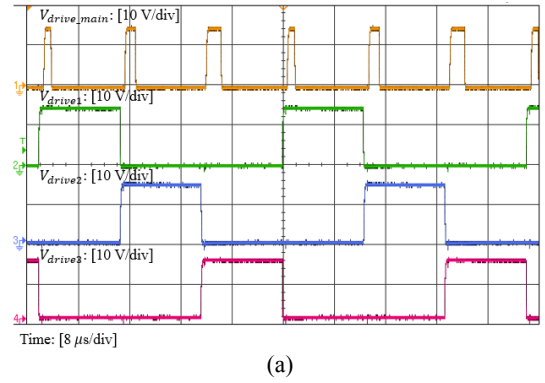
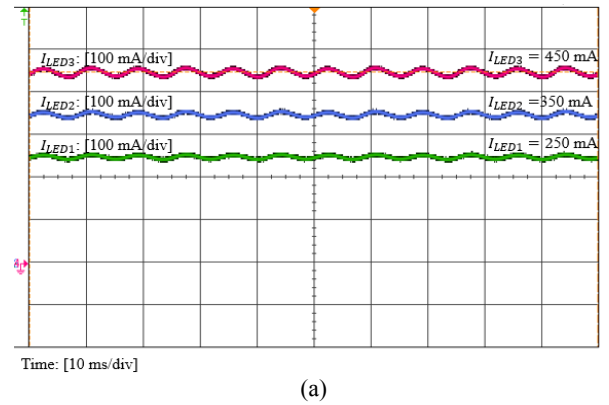


Fig. 18. Close-up view of (a) driving signals of main switch S_a and output switches S_1 – S_3 and (b) the corresponding I_L and $I_{branch1}$ – $I_{branch3}$ using same-colored LEDs and with distinct reference current values (i.e., 250 mA, 350 mA, 450 mA) across the three LED strings.

B. Current Balancing and Steady State Independent Current Regulation

The averaged current in each of the three individual LED strings can be independently adjusted for the purpose of color-mixing and dimming. Also, in order to achieve brightness uniformity, current balancing of different LED strings is required. The waveforms for these two scenarios are illustrated in Fig. 19.



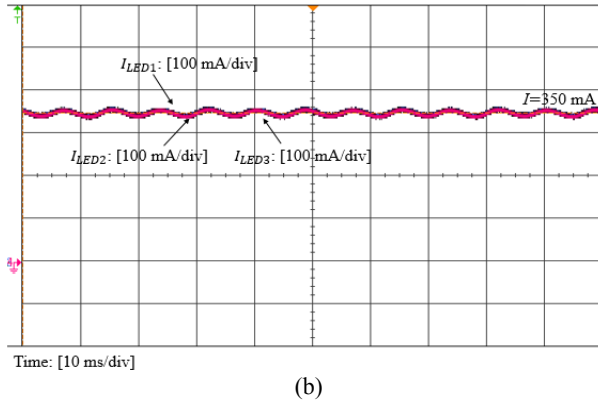


Fig. 19. Output current waveforms of the three LED strings using same-colored LEDs and with (a) 250 mA, 350 mA, 450 mA individual current control and (b) 350 mA current balancing condition.

Fig. 19(a) shows the individual current control of output currents I_{LED1} – I_{LED3} in each LED string in steady-state condition. It shows that the average current values in the first, second and third LED string are 250 mA, 350 mA and 450 mA, respectively, due to different current references being applied to each LED string. Fig. 19 (b) shows the current balancing of I_{LED1} – I_{LED3} in each LED string. The average current values in each of the three LED strings are identical ($I_{LEDi} = 350$ mA) with a peak-to-peak ripple within 10% of I_{LEDi} . This demonstrates the current balancing capability of the proposed driver.

C. Independent Current Control without Cross-Regulation

In order to further demonstrate the independent current control capability of the proposed AC/DC LED driver, the reference command I_{ref3} for String 3 is step changed from 3.5 V (350 mA) to 2.5 V (250 mA) and then back to 3.5 V (350 mA) shown in Fig. 20, corresponding to 100% to 70% load interchange. The current references of the other two strings $I_{ref1,2}$ are kept constant at 350 mA. As shown, the rising and falling transition times are both around 25 ms and there is no observable cross-regulation issue for the three LED strings.

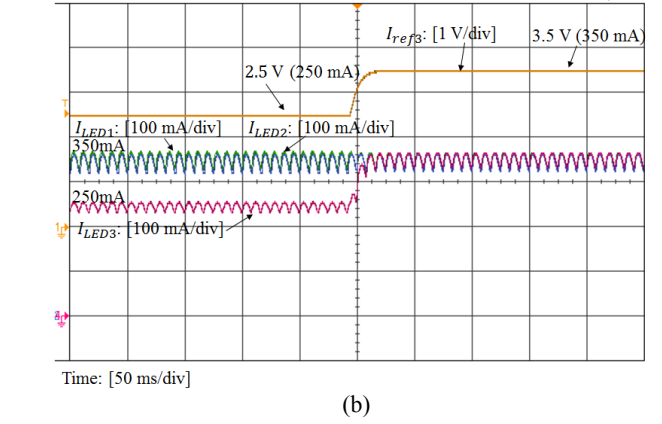
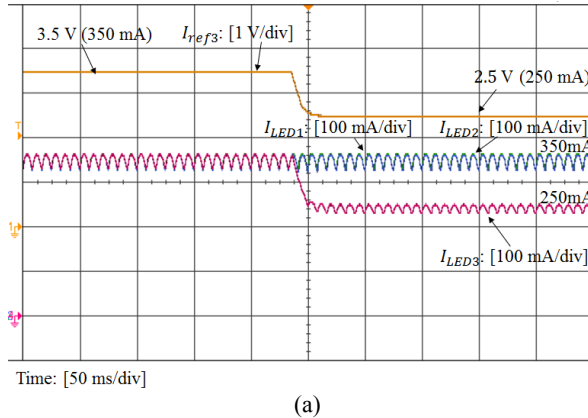


Fig. 20. Transient current waveforms and reference control command for (a) 350 mA to 250 mA in LED string 3 and (b) 250 mA to 350 mA in LED string 3.

D. Measured Efficiency and Performance

The measured power conversion efficiency, power factor and total harmonic distortion (THD) versus output power are respectively shown in Fig. 21–23.

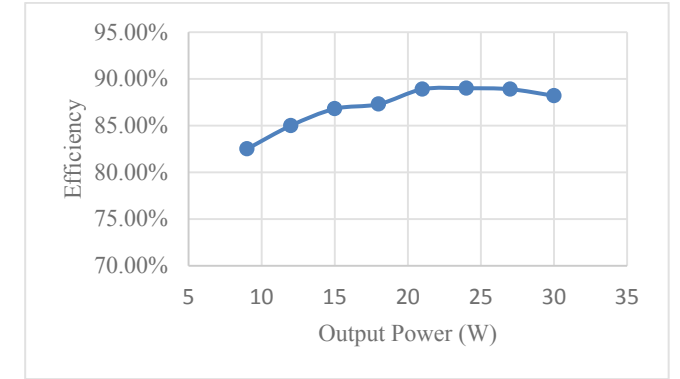


Fig. 21. Measured power efficiency versus the output power.

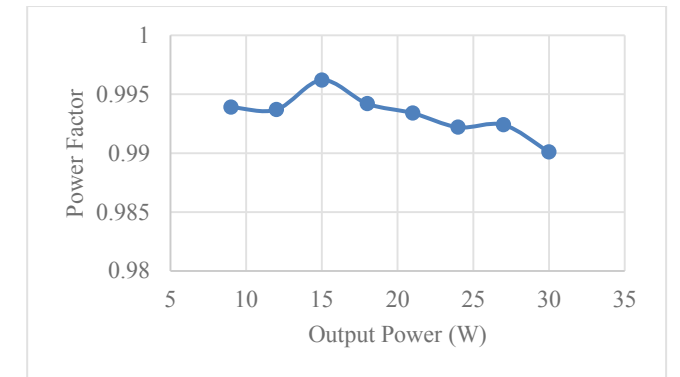


Fig. 22. Power factor measurements versus the output power.

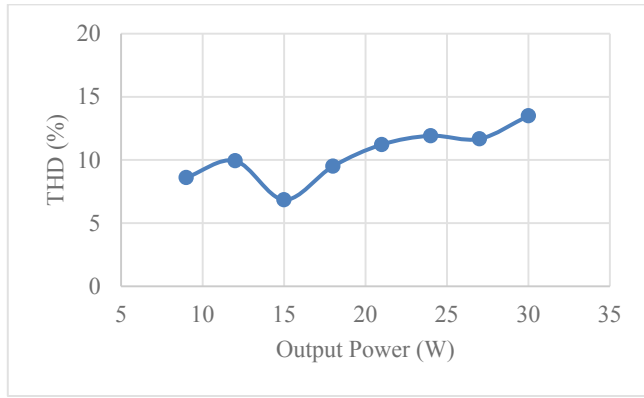
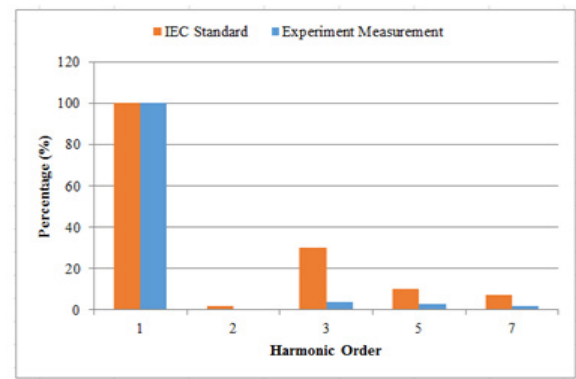


Fig. 23. Measured THD versus the output power.

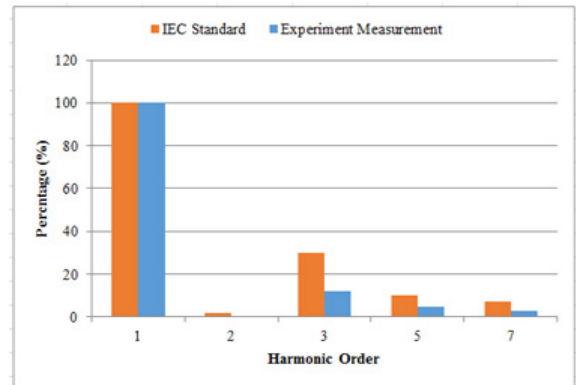
From Fig. 21, it can be seen that as the output power increases, the efficiency of the proposed AC/DC SIMO LED driver also increases and peaks at 89% (including driver's loss) at around 21 W. Fig. 22 shows the variations of the power factor across different values of the output power. The measured power factor peaks at 0.996 and the corresponding THD is measured to be 7%, as shown in Fig. 22 and 23. The measured input current also conforms to Class C of the IEC1000-3-2 standard [45], as will be discussed shortly. It should be noted that with an increasing number of LEDs connected in series or with an increased output power (i.e., the output voltage becomes larger) at a given AC line input voltage, the power factor (PF) could potentially drop below 0.99 due to the larger distortion in the AC line input current I_{in} at the zero-crossing point, where there is a short interval when the current is not conducting. The duration of this non-conducting interval of I_{in} is directly related to the output DC voltage. That is, the larger the output voltage, the longer this interval will be. Hence, when either more LEDs are connected in series or the output power increases (i.e., higher output DC voltage), both THD and PF performance will be degraded. From the above analysis, the proposed LED driver can be designed based on the rated output power so that the power factor can be maintained to be no less than 0.99 over the entire dimming range.

E. IEC1000-3-2 Standard Compliance

The harmonic currents of the proposed LED driver, which belongs to the Class C Equipment under the IEC1000-3-2 standard [45], are measured and compared against the corresponding harmonic current limit in accordance with the IEC 1000-3-2 standard. Fig. 24(a) shows the measured harmonic currents against the harmonic current limits at a 30 W rated output power. Likewise, Fig. 24(b) shows the measured harmonic currents against the harmonic current limits at a 3 W output power (i.e. 10 % of the rated output power). The experimental results clearly show that all the measured harmonic currents fall within their corresponding maximum harmonic current limit as defined by the IEC1000-3-2 standard [45].



(a)



(b)

Fig. 24. Comparison of the measured harmonic currents versus their corresponding maximum harmonic current limits defined by the IEC1000-3-2 standard at (a) 30 W rated output power; (b) 3 W output power (i.e., 10 % rated output power).

V. CONCLUSIONS

This paper proposes an AC/DC SIMO LED driver which integrates the power factor correction (PFC) pre-regulation and LED current regulation into a single-stage converter. Unlike the existing two-stage driver topologies, the intermediate DC-link stage is eliminated in the proposed single-stage topology. This enables the use of low-voltage, long-lifetime capacitors in the proposed LED driver. In addition, the proposed driver employs only one single inductor to drive multiple independent LED strings. It can achieve fully-independent current control in each LED string with no noticeable cross-regulation. The major benefits of the proposed single-stage LED driver include a lower component count, reduced BOM cost, simplified control scheme, and ease of implementation. The experimental results demonstrate the effectiveness of the proposed single-inductor three-output (SITO) LED driver in attaining precise and independent current regulation across the three individual LED strings. It enables flexible color-mixing and wide-range dimming for high-quality lighting applications.

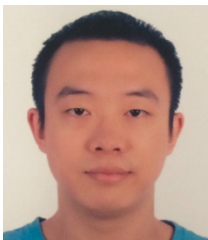
ACKNOWLEDGMENT

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