An Efficient Buck/Buck-Boost Reconfigurable LED Driver Employing SIN^2 Reference

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***Abstract*— An efficient buck/buck-boost reconfigurable LED driver based on peak current control is introduced. The driver supports pulse-width modulation (PWM) and pulse-frequency modulation (PFM) operations. The use of a combination of rectified sin and sin^2 functions in the reference is introduced for the purpose of improving the power factor (PF) and total harmonic distortion (THD) of buck and buck-boost converters. The optimal reference waveform shape for buck and buck/boost modes can be set externally. The design ensures that the peak of the inductor current maintains a constant level that is invariant for different ac line voltages. The LED driver has been implemented in a 130-nm CMOS process. PF and THD are improved when the proposed reference is employed, and the peak PF and lowest THD values are 0.995/0.983/0.996 and 7.8/6.2/3.5% for the buck (PWM), buck (PFM), and buck-boost (PFM) cases, respectively. The corresponding peak efficiency for the three cases is 88/92/91%, respectively.**

***Index Terms*— Buck-boost converter, buck converter, LED, LED driver, power factor correction (PFC), pulse frequency modulation (PFM), pulse-width modulation (PWM), total harmonic distortion (THD).**

I. Introduction

LIGHT emitting diodes (LED) are becoming a commonly used light source for general-purpose applications because of their long lifetime and high efficiency compared to fluorescent and incandescent lamps. Fluorescent lamps had gained popularity compared to incandescent lamps due to their better efficiency before high-performance LED devices became available. However, LED technology has dramatically improved the performance beyond that offered by fluorescent lamps, in both the lifetime and efficiency [1]. High-brightness and high-efficiency LEDs are now widely used in lighting solutions [2]–[10] and liquid crystal display backlight solutions [11]–[13]. Owing to high efficiency, and a wide range of options with regards to form factors and light colors, LED lighting is also a key part of emerging smart-home technologies.

A key design challenge for LED technology arises from the requirement for an efficient driver. For efficient transmission of energy from a source to a load, it is desirable to maximize the real power delivered by the ac line voltage (V_{ac}) while minimizing root-mean-square (RMS) current. Power factor (PF), which is defined as the ratio of real power to apparent power supplied to the entire converter, is a metric that determines how efficiently electrical power is being transferred to the load. To achieve a high PF from an ac line voltage V_{ac}, the phase of the ac line current (I_{ac}) has to be aligned with V_{ac}. Furthermore, the shape of the waveform has to follow a sinusoidal form. Total harmonic distortion (THD) of I_{ac} is another important consideration. A high THD is not acceptable since it can cause interference in the operation of other electronic systems and also shorten the life span of the equipment [14].

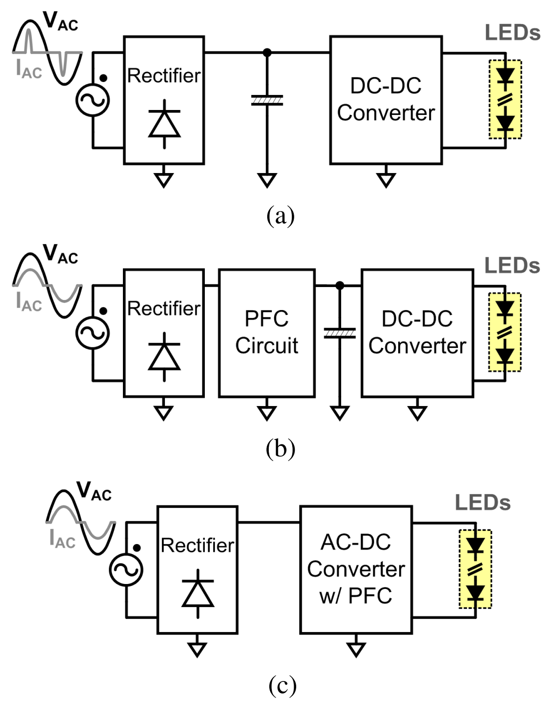

Fig. 1. LED drivers. (a) Dc–dc converter. (b) Dc–dc converter with PFC circuit. (c) Ac–dc converter with PFC.

Inductor-based switching-type dc-to-dc converters are widely used in off-the-shelf LED lamp drivers and are shown in Fig. 1(a) and (b). The dc-to-dc converter can be a buck converter, which can step down the voltage from the input to the output, or it can be a buck-boost or flyback converter that can step down or step up the voltage from the input to the output. In order to design a simple and low-cost LED driver, the dc-to-dc converter can use dc supply from the rectified ac input by filtering the ac ripple with a large capacitor [Fig. 1(a)]. However, this approach leads to significant reactive power due to different shapes of the supply voltage and the current flowing in the ac line, which lowers the PF. The PF can be improved by the use of a controller-based

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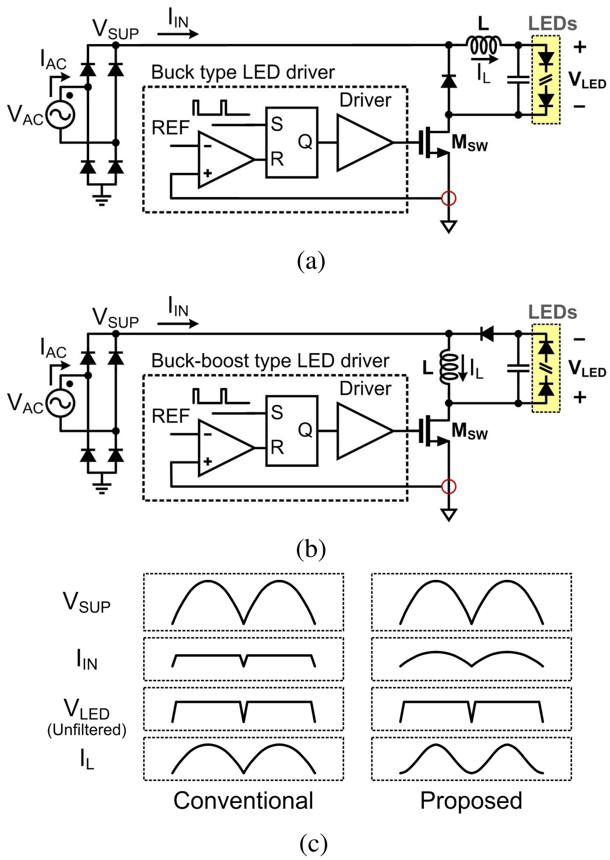


Fig. 2. Ac–dc converter for LED drivers. (a) Buck type. (b) Buck-boost type. (c) Input voltage, input current, LED voltage, and inductor current waveforms.

active [15], [16] or valley-fill passive [17] PF correction (PFC) circuits, in combination with a dc-to-dc converter [2]–[5] to drive LEDs, as shown in Fig. 1(b). However, these approaches may increase the manufacturing cost and the power consumption because of the requirement for additional PFC circuits with multiple peripheral components.

Recently, LED drivers that can directly drive LEDs from an ac outlet source [Fig. 1(c)] and perform PFC have been demonstrated using ac-to-dc conversion [6]–[10]. AC-to-DC converters are also based on inductor-based switching regulators and employ a basic architecture that is almost identical to a dc-to-dc converter. However, unlike a dc-to-dc converter, a rectified ac signal, instead of a dc supply, is applied to the load, and the time-varying signal is used as the reference signal for the regulator control loop. ac-to-dc converters have been implemented using a non-isolated single-stage buck converter [6], [7], [10] and an isolated transformer-based flyback converter [8], [9]. A non-isolated driver offers benefits of efficiency and low cost, while the isolated type is also attractive due to better safety. These designs perform PFC and exhibit low THD by directly driving the load from the rectified ac source.

Conventional ac-to-dc LED drivers [6]–[9] employ a rectified sine-wave reference ($|\sin(\phi)|$) to control the inductor current. The shape and the phase of the ac input current is determined primarily by the inductor current. By comparing the sensed inductor current to the reference, the inductor current is forced to follow the shape of the reference, which has a rectified sine-waveform. If the phase of rectified sine-wave reference is aligned with the ac input voltage, then the the input current is also aligned with the input voltage, which helps to improve the PF.

In this paper, an efficient LED driver based on peak current control is described, which uses a $|\sin(\phi)|$ as well as a $\sin^2(\phi)$ term in I_L for both buck and buck-boost converters. The proposed reference control can improve the PF as well as the THD compared to a design that uses a rectified sinusoidal reference because not only the phase but also the shape of the input current follows the ac input voltage. The buck and buck-boost converters require different reference shapes to achieve the best performance. The proposed driver can be reconfigured to provide the desired reference shape for each converter. In addition, the design ensures that the peak of the inductor current maintains a constant level that is invariant for different ac line voltages.

This paper is organized as follows. Section II describes efficient PFC methods using a $|\sin(\phi)|$ as well as a $\sin^2(\phi)$ reference for buck and buck-boost converters. Section III describes the complete architecture with the proposed reference generation circuits. Section IV describes measurement results, and the conclusion follows in Section V.

II. Power Factor Correction for Buck/Buck-Boost Converters

In order to transmit energy efficiently from an ac power source to a load, and minimize losses, the average power needs to be maximized while the RMS current and voltage need to be minimized. PF is a metric that determines how efficiently electrical power is transferred to a load and it is expressed as

$$\mathrm{PF} = \frac{P_{\mathrm{IN}}}{V_{\mathrm{RMS}} \cdot I_{\mathrm{RMS}}} \tag{1}$$

where V_{RMS} is the RMS voltage of the source, I_{RMS} is the RMS current provided by the source, and P_{IN} is the average input power that feeds into the entire converter. To achieve a high PF, the phase of the ac input current needs to be aligned with that of the ac input voltage, and the shape of the ac input current has to follow the sinusoidal shape of the ac input voltage. Hence, the maximum PF that can be obtained is unity and is observed for resistive loads.

In conventional ac-to-dc LED drivers, a rectified sinusoidal reference is used in order to align the ac input current with the ac input voltage and enhance the PF. However, this is not the best reference shape in terms of PF and THD performance. Unlike a conventional rectified sinusoidal reference, an optimized reference signal that contains a $\sin^2$ factor is proposed here to maximize the PF and minimize THD in buck and buck-boost converters for ac-to-dc conversion. The $\sin^2$ factor makes the shape of the ac input current that follows the ac input voltage and improves the distortion of the input current. Buck and buck-boost type LED drivers that employ direct ac-to-dc conversion are shown in Fig. 2. The driver controls the active switch (M_{SW}) by comparing the sensed inductor current (I_L) to the reference signal and forces the shape of the inductor current to follow that of the reference signal.

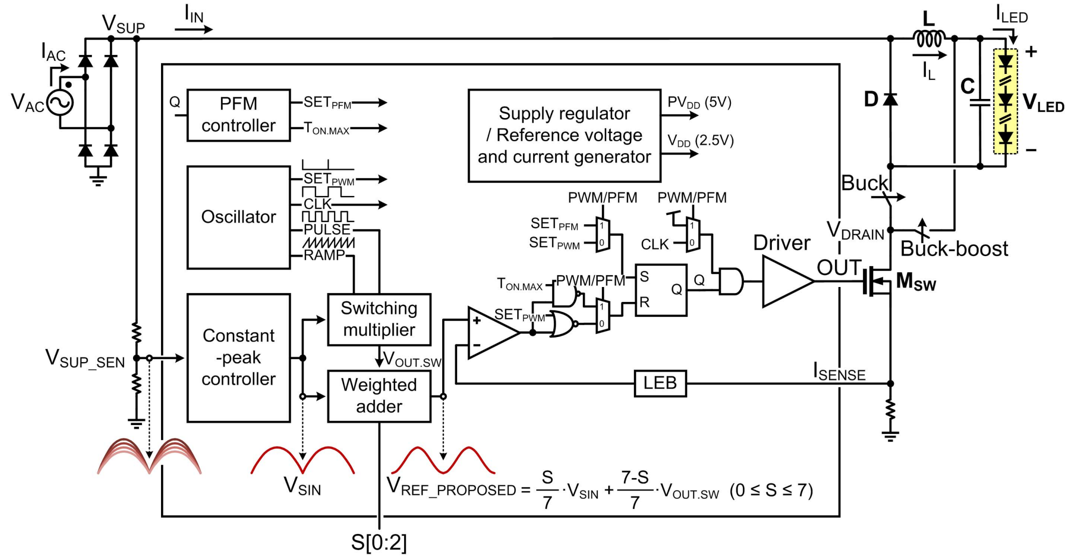


Fig. 3. Architecture of the proposed LED driver.

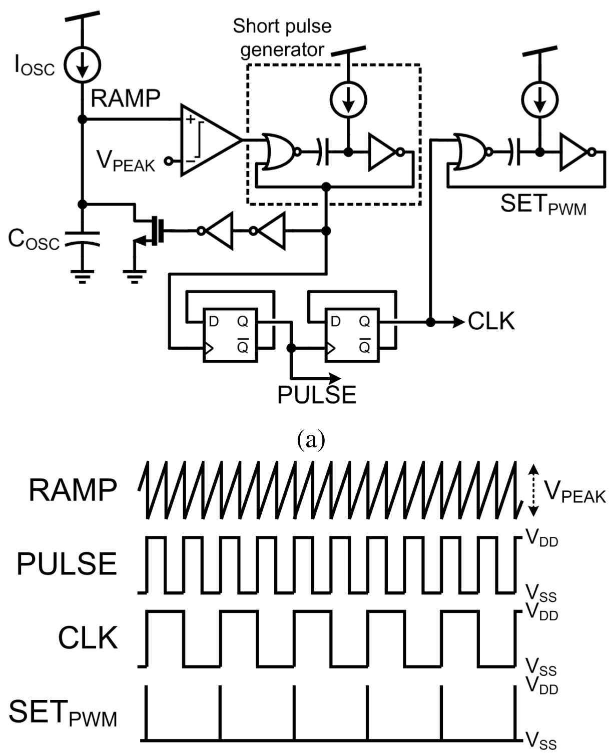


Fig. 4. Oscillator. (a) Block diagram. (b) Timing diagram.

A. Buck Converter

Fig. 2(a) shows a buck type LED driver using ac-to-dc conversion. The buck converter is a switching topology that lowers the input supply voltage V_{SUP} to the output LED voltage V_{LED}. The duty-cycle (D) determines the ratio between the input voltage and the output voltage, which can be expressed as below

$$V_{\text{LED}.B} = D \times V_{\text{SUP}} \tag{2}$$

where $V_{\text{LED}.B}$ is the output LED voltage of the buck converter.

In a buck converter, the output current flows continuously when the converter is operating in continuous conduction mode (CCM) because the inductor is always connected to the output voltage. Thus, a relatively small capacitor can be used at the output voltage, for reducing the voltage ripple across the LEDs.

The input current (I_{IN}) of a buck converter only flows when the switch is in the ON-state. Thus, I_{IN} is given by the product of the duty-cycle (D) and the inductor current (I_L). The duty-cycle is determined by $V_{\text{LED}}/V_{\text{SUP}}$, where V_{LED} is the forward voltage of the LED string and V_{SUP} is the rectified ac input voltage. V_{SUP} can be represented as $V_{\text{ac.PEAK}} \times |\sin(\phi)|$, where ϕ is the angle of the ac input voltage phasor that varies from 0 to 2π and $V_{\text{ac.PEAK}}$ is the peak voltage of V_{SUP}. Thus, I_{IN} can be represented as below

$$I_{\text{IN}.B} = D \times I_L = \frac{V_{\text{LED}}}{V_{\text{SUP}}} \times I_L = \frac{V_{\text{LED}}}{V_{\text{ac.PEAK}} \cdot |\sin(\phi)|} \times I_L \tag{3}$$

where $I_{\text{IN}.B}$ is the input current of the buck converter.

In order to achieve a high PF and low THD, it can be observed from (3) that $I_{\text{IN}.B}$ needs to have a rectified sinusoidal form $|\sin(\phi)|$. However, if V_{LED} is assumed to be a dc voltage, and I_L follows the rectified sine-wave shape of the reference, then $I_{\text{IN}.B}$ will be a dc level. The dc form of $I_{\text{IN}.B}$ will degrade the PF and also increases the THD. On the other hand, if I_L has a $\sin^2(\phi)$ shape, instead of the rectified sine-wave shape, a rectified sinusoidal form of $I_{\text{IN}.B}$ can be achieved.

B. Buck-Boost Converter

Fig. 2(b) shows a buck-boost type LED driver. Unlike a buck converter, the output voltage of the buck-boost converter can step up as well as step down the output voltage relative to the input. The relationship between the input voltage and output voltage can be expressed as below

$$V_{\text{LED.BB}} = \frac{D}{1-D} \times V_{\text{SUP}} \tag{4}$$

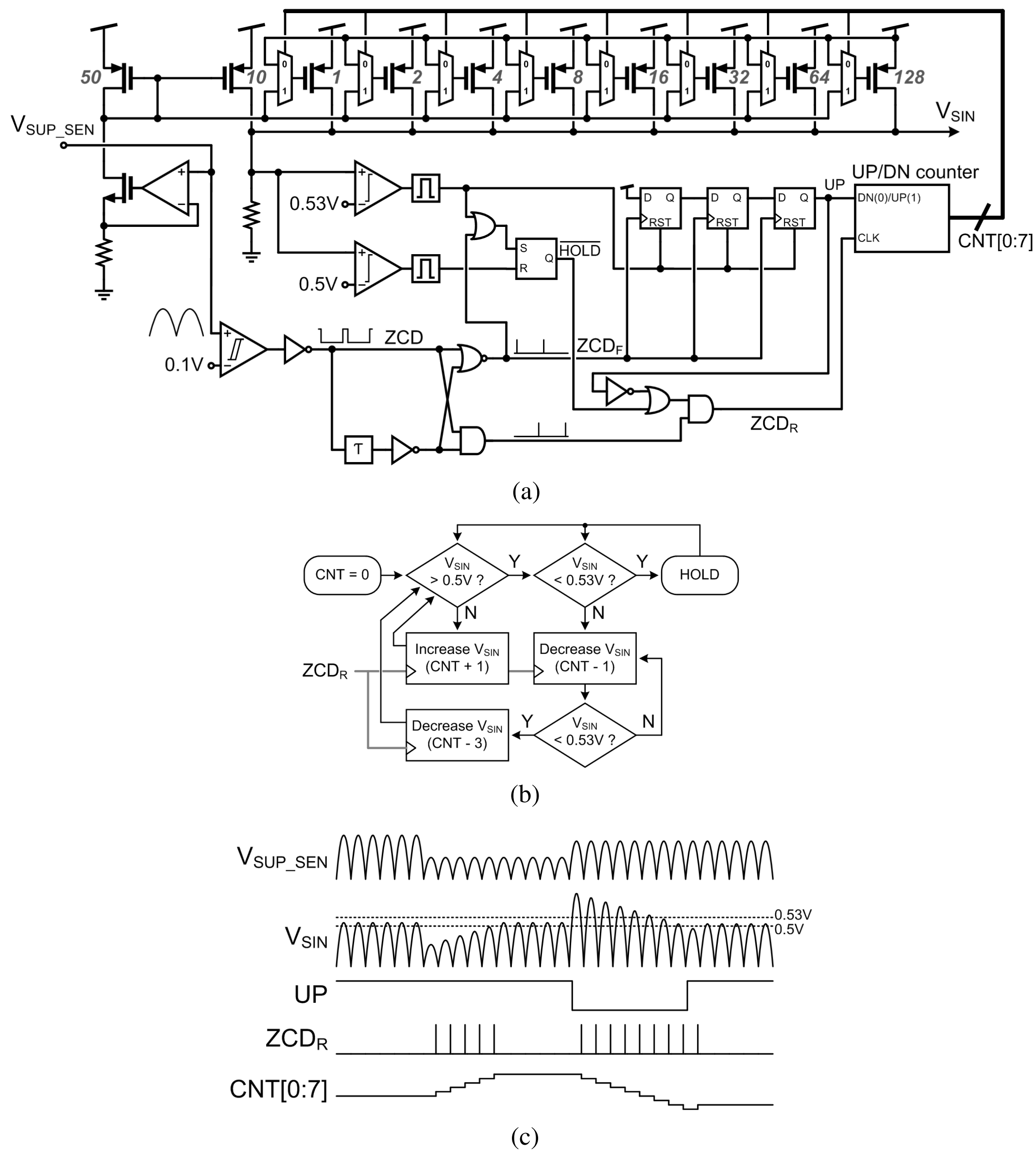


Fig. 5. Constant-peak controller. (a) Block diagram. (b) Flowchart. (c) Timing diagram.

where $V_{\text{LED.BB}}$ is the output LED voltage of the buck-boost converter and D is the duty-cycle of the waveform applied to the switch M_{SW}.

In a buck-boost converter, the inductor is connected to the input when the switch is in the ON-state, and it is connected to the output when the switch is in the OFF-state. Therefore, the current only flows into the LED when the switch is OFF. A large capacitor is thus required at the output, across the LED, to filter the discontinuous output current.

The input current in a buck-boost converter ($I_{\text{IN.BB}}$) is also given by the product of the duty-cycle (D) and inductor current (I_L), where the duty-cycle is $V_{\text{LED}}/(V_{\text{LED}} + V_{\text{SUP}})$. Thus, $I_{\text{IN.BB}}$ can be represented as below

$$I_{\text{IN.BB}} = D \times I_L = \frac{V_{\text{LED}}}{V_{\text{LED}} + V_{\text{SUP}}} \times I_L = \frac{V_{\text{LED}}}{V_{\text{LED}} + V_{\text{ac.PEAK}} \cdot |\sin(\phi)|} \times I_L. \tag{5}$$

In this case, if V_{LED} is assumed to be a dc voltage, I_L has to be of the form of $|\sin(\phi)| + V_{\text{ac.PEAK}}/V_{\text{LED}} \times \sin^2(\phi)$ in order to obtain a rectified sinusoidal $I_{\text{IN.BB}}$. If V_{LED} is small compared with $V_{\text{ac.PEAK}}$ due to the use of a small number of LEDs, the desired form of I_L is close to $\sin^2(\phi)$. Increasing the number of LEDs will increase the $|\sin(\phi)|$ factor in the form of I_L.

In general, the desired inductor current has to be in the form of $\alpha \times |\sin(\phi)| + (1-\alpha) \times \sin^2(\phi)$ $(0 \leq \alpha \leq 1)$. The coefficient α will be 0 in the case of buck converters such that I_L has to have a $\sin^2$ shape. In buck-boost converters, α can be shown to be $V_{\text{LED}}/(V_{\text{LED}} + V_{\text{ac.PEAK}})$, which implies that α will increase as the number of LEDs increases.

Fig. 2(c) depicts the waveforms of the input voltage, input current, LED voltage, and inductor current in conventional and proposed references. In a practical design, V_{LED} is determined by the I–V characteristic of the LEDs, which typically follows an exponential relationship. Thus, V_{LED} holds a relatively

TABLE I
OPERATION MODES OF PROPOSED DRIVER

Mode	Operation	Max. duty-cycle
PWM	43 kHz fixed switching frequency	50 %
PFM	Constant OFF-time (~13μs)	80 %

constant dc value with a small variation in response to the shape of I_L, when it is fully turned-on. However, this variation is sufficiently small compared to dc value such that its impact on performance is negligible.

III. COMPLETE LED DRIVER ARCHITECTURE

Fig. 3 shows the architecture of the proposed LED driver. The driver is designed to provide pulse-width modulation (PWM) and pulse-frequency modulation (PFM) operation. Table I describes the operating modes of the proposed driver. In the PWM mode, the output of the driver switches at a fixed frequency of 43 kHz. A relatively low switching frequency that is less than 50 kHz is chosen to achieve a higher efficiency; however, the converter still operates in CCM since the input voltage increases for a given inductor size in this mode. The maximum duty-cycle is limited to 50% in order to avoid sub-harmonic oscillation without additional slope compensation circuits. In the PFM mode, the driver operates with constant OFF-time control. Once the sensed inductor current I_{SENSE} exceeds the reference level $V_{\mathrm{REF\_PROPOSED}}$, the output maintains a low level with a set OFF-time of 13 μs. The duty-cycle can exceed 50% here, since constant OFF-time control does not suffer from sub-harmonic oscillation; however, the maximum duty-cycle is limited to 80%. This is the case because the voltage gain ($V_{\mathrm{IN}}/V_{\mathrm{OUT}}$) can be reduced at a high duty-cycle by non-idealities such as parasitic resistance in the inductor. The PWM mode is used for the buck converter, and the PFM mode is used for buck and buck-boost converters. To generate the desired reference voltage of the form $\alpha \times |\sin(\phi)| + (1-\alpha) \times \sin^2(\phi)$ $(0 \leq \alpha \leq 1)$, for both buck and buck-boost converters, the constant peak of the two references that provide $|\sin(\phi)|$ and $\sin^2(\phi)$ is generated from the sensed voltage ($V_{\mathrm{SUP\_SEN}}$), while the ratio α is adjusted by a weighted adder. Thus, the proposed driver can be reconfigured as a buck and a buck-boost converter, because the ratio α can be set externally based on the type of converter and the number of LEDs.

A. Oscillator

Fig. 4 shows the block diagram and timing diagram of the oscillator. A relaxation-mode oscillator is employed, and it generates the necessary timing and control signals for the architecture. The capacitor C_{OSC} is charged by the current source I_{OSC} and generates a RAMP signal. When the RAMP signal exceeds V_{PEAK} (0.5 V), a short pulse is generated at the rising edge of the output of the comparator. This short pulse resets the capacitor and is also applied to a frequency divider to generate the PULSE signal, which has a 50% duty-cycle.

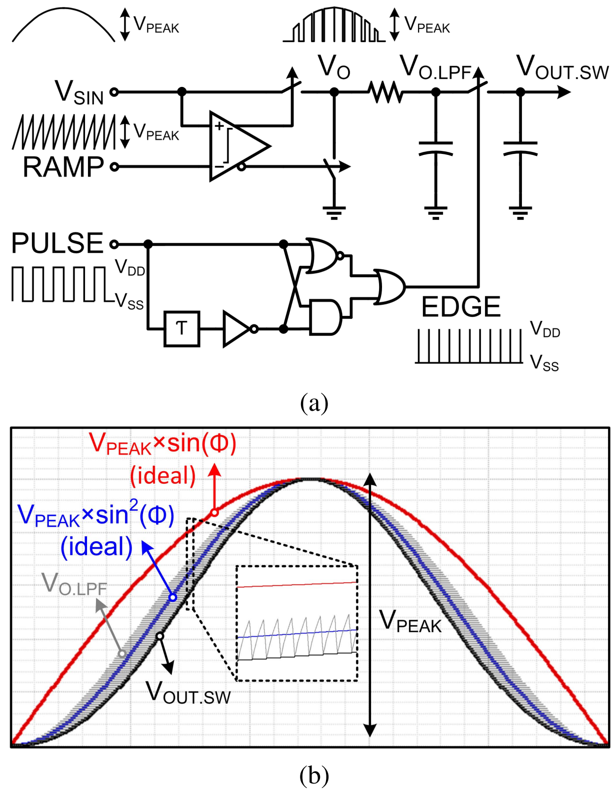


Fig. 6. Switching multiplier. (a) Block diagram. (b) Simulation result.

The signal PULSE is divided by 2 again and generates the CLK signal that has a frequency of approximately 43 kHz.

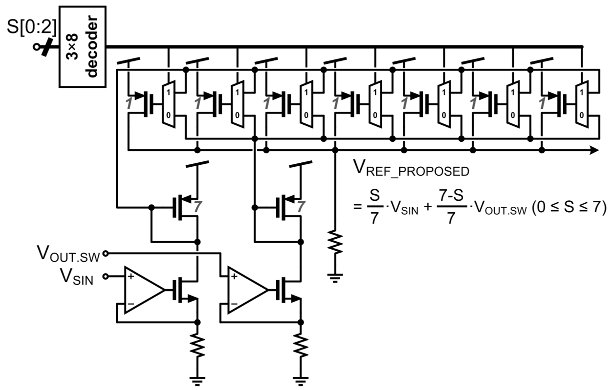
In the PWM operation, the CLK signal functions as the main operating clock, and the output is set to high at every cycle of the CLK signal using $\mathrm{SET_{PWM}}$. The PULSE and RAMP signals are used in the switching multiplier to provide a waveform $V_{\mathrm{OUT.SW}}$ that is used for generating the $\sin^2$ reference.

B. Constant Peak Controller

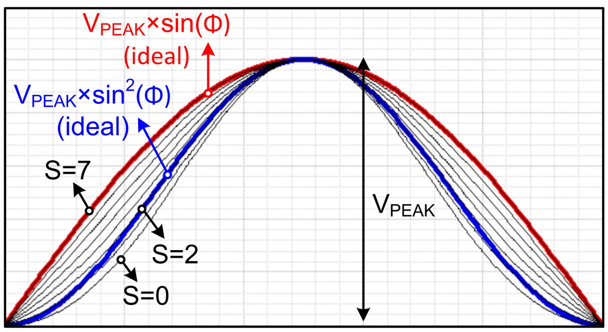
If the rectified sinusoidal reference is derived from the rectified ac input voltage V_{SUP}, then the reference can vary in response to ac line voltage variation and, in turn, vary the inductor current. This will cause the output power of the LEDs to vary. Thus, a constant reference level is essential for maintaining a constant output power, regardless of the ac line voltage.

A rectified sinusoidal reference with a constant peak level can be implemented using a current digital-to-analog converter (DAC) and an updown counter [8]. In this approach, the peak level of the reference continuously tracks a given threshold level to maintain a constant peak amplitude. However, when the peak amplitude reaches the given threshold and approaches steady state, it still toggles around the threshold level.

A constant peak level without toggling in the steady state is proposed here, by employing a hysteresis range for safe operation, as shown in Fig. 5. $V_{\mathrm{SUP\_SEN}}$, which is an attenuated version of the supply voltage V_{SUP}, is applied to the controller. The amplitude of V_{SIN} starts from 1/5th of $V_{\mathrm{SUP\_SEN}}$. Two comparators compare V_{SIN} with 0.5 and 0.53 V to



(a)



(b)

Fig. 7. Weighted adder. (a) Block diagram. (b) Simulation result.

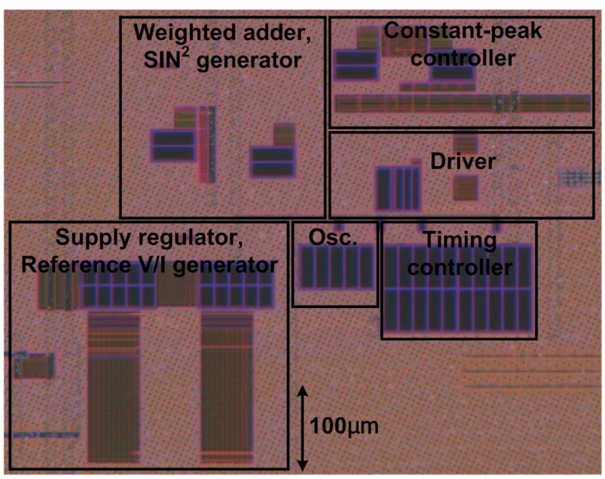
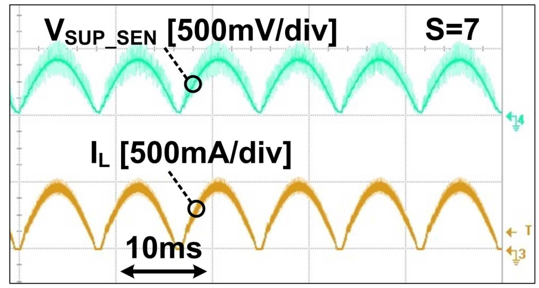


Fig. 8. Chip microphotograph.

determine the peak of V_{SIN}. Until the peak of V_{SIN} reaches 0.5 V, the amplitude of V_{SIN} is increased gradually in every cycle of $V_{\mathrm{SUP\_SEN}}$. When V_{SIN} exceeds 0.5 V, the current DAC maintains its amplitude by holding the output of the counter. If the peak of V_{SIN} decreases below 0.5 V due to V_{ac} variation, the DAC starts to increase the amplitude again until the peak of V_{SIN} reaches 0.5 V. If the peak of V_{SIN} exceeds 0.53 V due to V_{ac} variation, the DAC starts to decrease the amplitude of V_{SIN}. Once V_{SIN} crosses 0.53 V, the DAC decreases the level by three additional bits, which ensures that the peak of V_{SIN} is located around 0.5 V. Therefore, V_{SIN} can be expressed as $V_{\mathrm{PEAK}} \times |\sin(\phi)|$, where V_{PEAK} is set to 0.5 V by the design.



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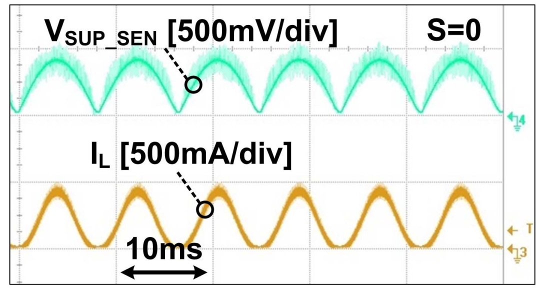
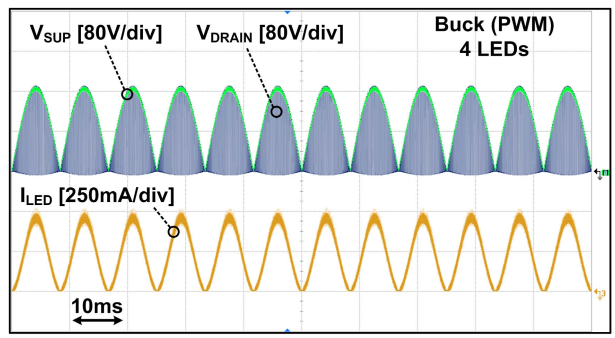


(b)

Fig. 9. Measured waveform of $V_{\mathrm{SUP\_SEN}}$ and inductor current I_L. (a) $S = 7$. (b) $S = 0$.



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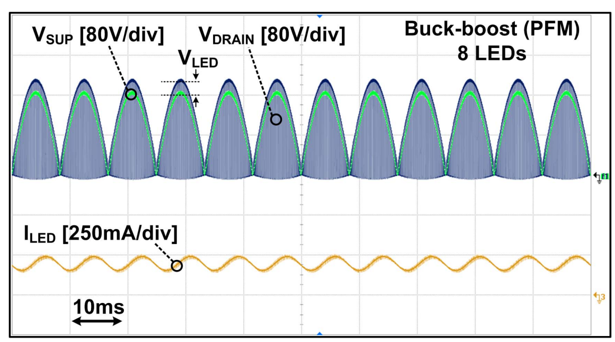
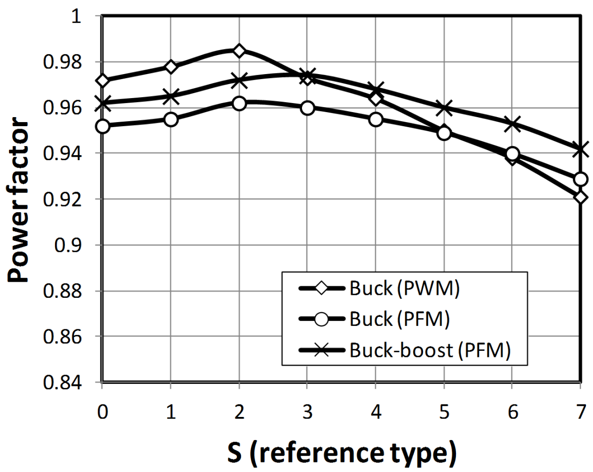


(b)

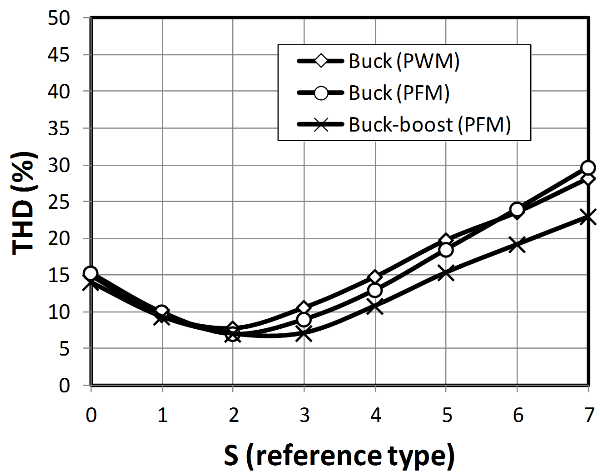
Fig. 10. Measured waveforms. (a) Buck converter (PWM). (b) Buck-boost converter (PFM).

C. Reference Generator

To obtain the desired reference signal that has to be in the form of $\alpha \times |\sin(\phi)| + (1-\alpha) \times \sin^2(\phi)$ $(0 \le \alpha \le 1)$, a switching multiplier and a weighted adder based on a current mirror are proposed. The switching multiplier is used to generate a sin^2 shaped waveform with a constant peak of V_{PEAK}, as depicted



(a)



(b)

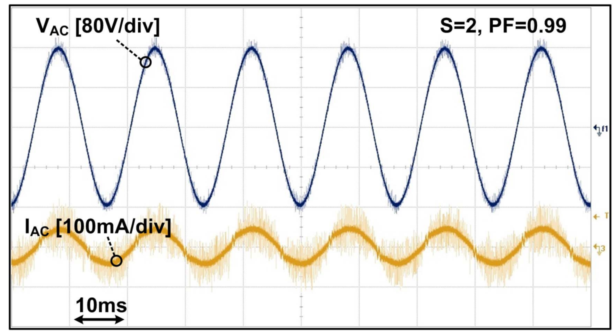
Fig. 11. Measured results for different types of reference signal with 4 LEDs. (a) Power factor. (b) THD.

in Fig. 6. The reference V_{SIN} ($= V_{\text{PEAK}} \times |\sin(\phi)|$), which has a constant peak amplitude (V_{PEAK}) set by the constant peak controller, is applied to the switching multiplier. V_{SIN} is switched using a PWM signal that has a duty-cycle that is controlled by comparing V_{SIN} and a RAMP signal. The RAMP signal has the same peak amplitude V_{PEAK} that is generated by the oscillator. Therefore, the duty-cycle can be represented by $V_{\text{SIN}}/V_{\text{PEAK}}$. After low-pass filtering, the PWM output of switching multiplier is thus given by $V_{\text{SIN}} \times V_{\text{SIN}}/V_{\text{PEAK}}$, that is, $V_{\text{PEAK}} \times \sin^2(\phi)$. The ripple voltage on the output is removed by employing a sample-and-hold circuit. Even though the average value of the low-pass-filtered output ($V_{O.\text{LPF}}$) is consistent with $V_{\text{PEAK}} \times \sin^2(\phi)$, the output of the sample-and-hold circuit ($V_{\text{OUT.SW}}$) is observed to be slightly narrower than this shape [Fig. 6(b)]. The instantaneous waveform of $V_{O.\text{LPF}}$ consists of a sequence of triangular ramps corresponding to the sequence of pulses observed at V_O, due to the action of the LPF. The sample-and-hold circuit samples $V_{O.\text{LPF}}$ at the lowest value of the ripple arising from the triangular output shape, leading to the above narrowing.

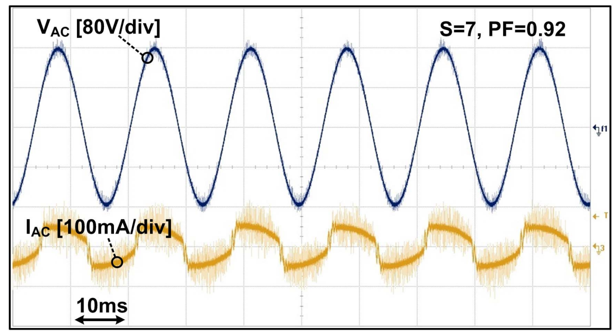
A weighted adder is used to combine the V_{SIN} and $V_{\text{OUT.SW}}$ terms to generate the desired reference shape for buck as well as buck-boost converters, using a 3-bit reference control signal (S) as shown in Fig. 7. The V_{SIN} and $V_{\text{OUT.SW}}$ references are converted to current information and applied to the current-weighted adder. The reference control signal S can be controlled externally. By changing the current mirror ratio of V_{SIN} and $V_{\text{OUT.SW}}$ through S, the proposed reference signal ($V_{\text{REF\_PROPOSED}}$) can be generated with the following form:

$$V_{\text{REF\_PROPOSED}} = \frac{S}{7} \times V_{\text{SIN}} + \frac{(7-S)}{7} \times V_{\text{OUT.SW}} \quad (6)$$

where S can vary from 0 to 7. Fig. 7(b) shows the simulation results with different values of S. $V_{\text{REF\_PROPOSED}}$ is closest to $V_{\text{PEAK}} \times \sin^2(\phi)$ when $S = 2$ since $V_{\text{OUT.SW}}$ is narrower than $V_{\text{PEAK}} \times \sin^2(\phi)$ due to the sample-and-hold circuit, while it is equal to V_{SIN} ($= V_{\text{PEAK}} \times |\sin(\phi)|$) when $S = 7$, which is the same as the reference signal used in prior implementations [6]–[8]. Therefore, the coefficient of α in $\alpha \times |\sin(\phi)| + (1-\alpha) \times \sin^2(\phi)$ can be set between 0 to 1 in fractional steps by changing the S from 2 to 7 in the weighted adder.



(a)

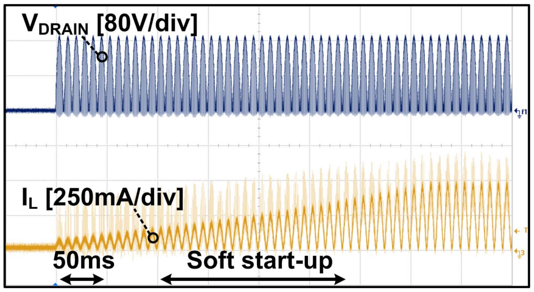


(b)

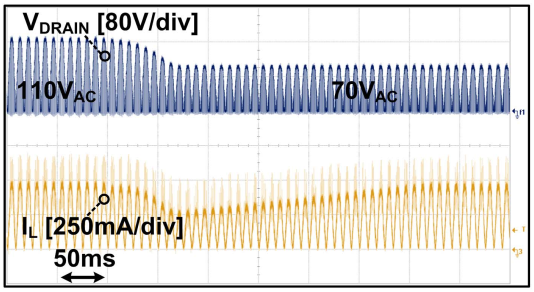
Fig. 12. Measured ac line voltage (V_{ac}) and line current (I_{ac}) waveform of buck converter (PWM). (a) $S = 2$ (proposed). (v) $S = 7$ (conventional).

IV. Measurement Results

The above design has been implemented in a 130-nm CMOS process (Fig. 8). A 400-V N-channel power MOSFET and a 400-V diode are used for the switches. A supply voltage of 5.5 V is applied to the driver externally. A 4.7-mH inductor is employed in the converter. The reference control signal (S) can be controlled externally. The driver can be configured as a buck converter as well as a buck-boost converter. A 22-nF ceramic capacitor and a 330-μF aluminum capacitor are used across the LED output in the buck converter and the buck-boost converter, respectively. The buck-boost converter



(a)



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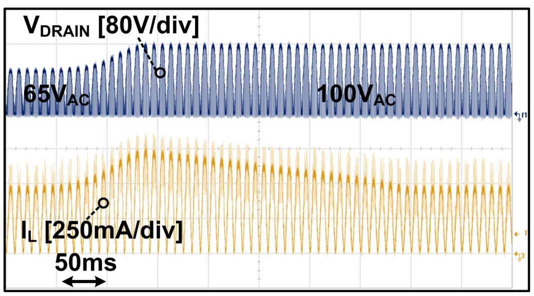
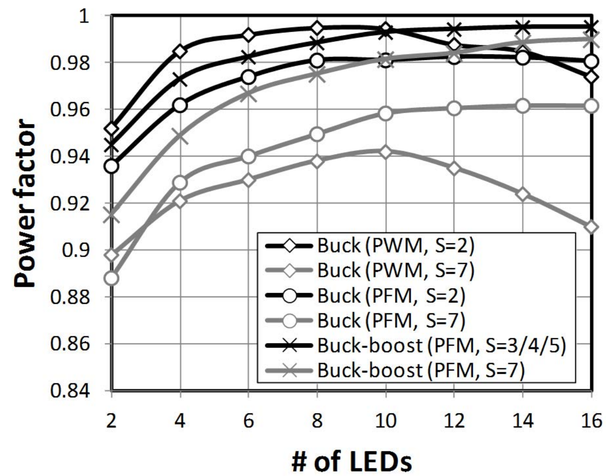
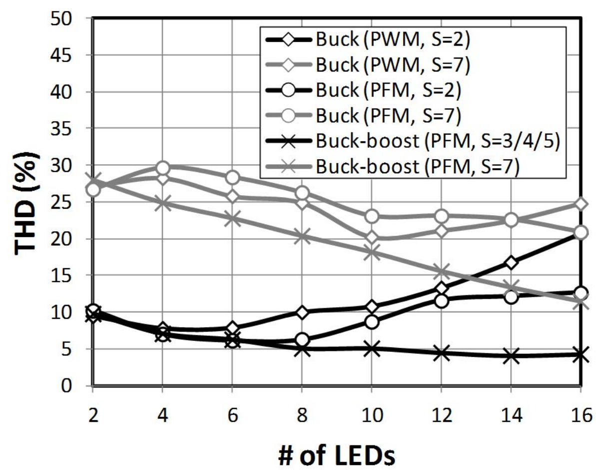


(c)

Fig. 13. Measured waveform of drain voltage (V_{DRAIN}) and inductor current (I_L) in buck converter (PWM). (a) Soft startup. (b) AC line voltage transition from 110V$_{\mathrm{AC}}$ to 70V$_{\mathrm{AC}}$. (c) AC line voltage transition from 65V$_{\mathrm{AC}}$ to 100V$_{\mathrm{AC}}$.



(a)



(b)

Fig. 14. Measurement results for different number of LEDs. S = 3/4/5 is used for 2-8/10-14/16 LEDs, respectively, in buck-boost converter. (a) PF. (b) THD.

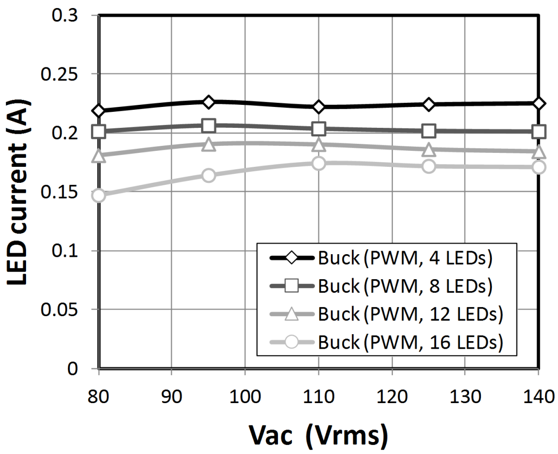
requires a large output capacitor for filtering, since the output of the buck-boost converter switches in every cycle, while the output of the buck converter does not. The operating mode can be changed between PWM and PFM (Table I). The PWM mode is used in the buck converter, and the PFM mode is used in the buck and buck-boost converters.

To verify the operation of the proposed reference signal, the inductor current is measured, since it is proportional to the shape of the reference signal. Fig. 9 shows the measured $V_{\mathrm{SUP\_SEN}}$ and the inductor current. $V_{\mathrm{SUP\_SEN}}$ follows the shape of a rectified sinusoid because it is directly sensed from the rectified ac input. I_L follows V_{SIN} reference, which has the $|\sin(\phi)|$ form when $S = 7$ and follows the $V_{\mathrm{OUT.SW}}$ reference that corresponds to the lowest ripple voltage points at the output of the low-pass filter when $S = 0$ [Fig. 6(b)]. The shape of I_L can be varied between V_{SIN} and $V_{\mathrm{OUT.SW}}$ by changing S.

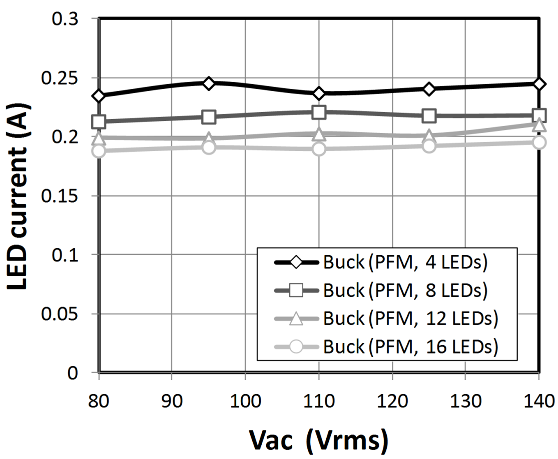
Fig. 10 shows the measured waveform of the buck converter in the PWM mode and the buck-boost converter in the PFM mode. The drain voltage switches between $V_{\mathrm{SUP}} + V_D$ and GND in the buck converter, while it switches between $V_{\mathrm{SUP}} + V_{\mathrm{LED}} + V_D$ and GND in the buck-boost converter. V_D is the forward-bias voltage of the power diode switch. The LED current (I_{LED}) is averaged in the buck-boost converter because a large output capacitor is used to low-pass filter the switching output voltage in this mode.

Fig. 11 shows the measured PF and THD for various settings of S. The measurement employs four LEDs. In a buck converter (PWM and PFM), the highest PF and lowest THD are achieved when $S = 2$, because, the proposed reference is closest to the $V_{\mathrm{PEAK}} \times \sin^2(\phi)$ when $S = 2$, as shown in Fig. 7(b). In a buck-boost converter, $S = 3$ shows the best performance because the desired I_L of the buck-boost design already contains the $|\sin(\phi)|$ term. Fig. 12 depicts the ac line voltage and the corresponding current waveform in the buck converter (PWM) with four LEDs when $S = 2$ and $S = 7$. By employing the proposed reference signal, the harmonic components are significantly reduced for $S = 2$ compared with $S = 7$, due to which the PF is increased from 0.92 to 0.99, and THD is reduced from 28.3% to 7.8%.

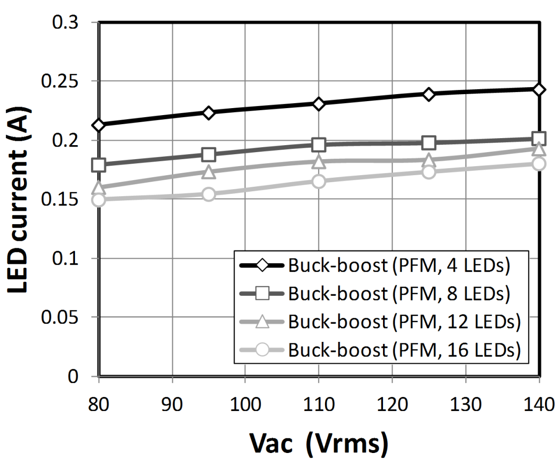
To verify the operation of the constant peak reference controller, the drain voltage of M_{SW} and I_L are measured (Fig. 13). When V_{ac} is applied, I_L starts to increase



(a)



(b)



(c)

Fig. 15. Measured LED current versus ac voltage variation. (a) Buck converter (PWM). (b) Buck converter (PFM). (c) Buck-boost converter (PFM).

gradually through a soft startup function and maintains a constant peak current of 0.5 A. I_L is observed with an abruptly varying V_{ac}. Even if V_{ac} varies, I_L is observed to maintain a constant peak current level, due to the use of the proposed constant-peak controller.

PF and THD are measured by varying the number of LEDs from 2 to 16 when $V_{\mathrm{ac}} = 110V_{\mathrm{RMS}}$. Two different types of

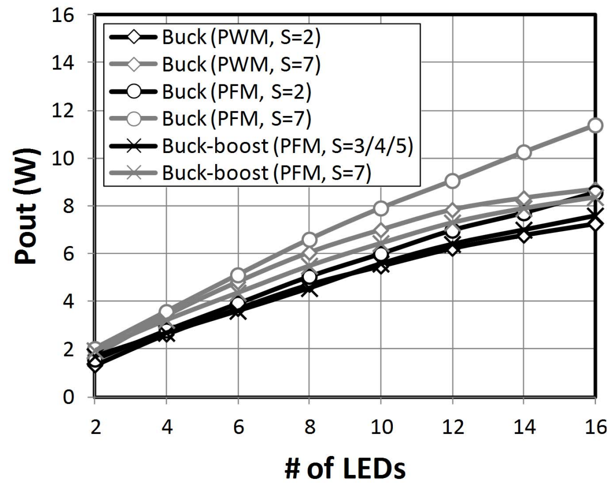
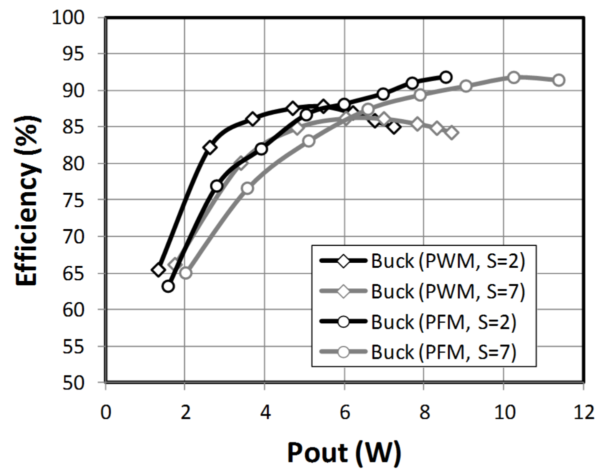
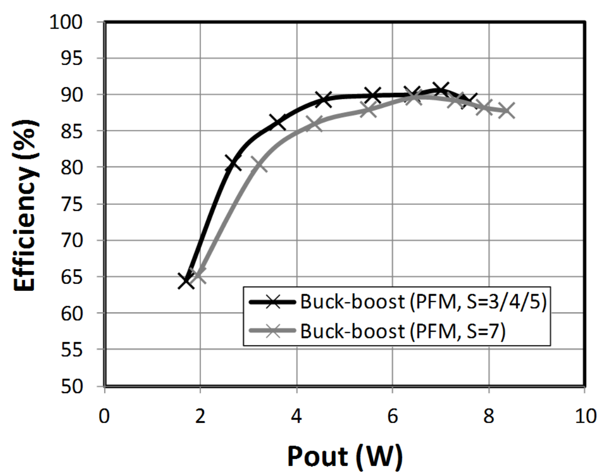


Fig. 16. Measured LED output power for different number of LEDs.



(a)



(b)

Fig. 17. Measured efficiency versus P_{OUT}. (a) Buck converter. (b) Buck-boost converter.

references are used to compare the performance of the proposed reference and the conventional reference ($S = 7$; V_{SIN}) (Fig. 14). $S = 2$ is used in the buck converter regardless of the number of LEDs, while $S = 3/4/5$ values are used for

TABLE II
PERFORMANCE COMPARISON

	[6]	[7]	[8]*	[10]	This Work					
Topology	Non-isolated Buck	Quasi-resonant Non-isolated Buck	Flyback	Non-isolated Buck	Non-isolated Buck				Non-isolated Buck-boost	
Power Switch	On-chip Power MOSFET	Off-chip GaN FET	Off-chip Power MOSFET	Off-chip Power MOSFET	Off-chip Power MOSFET					
Control (F_{SW})	PWM (43 kHz)	Burst Mode Control (11 MHz)	CRM (N/A)	Sine-ref. Band Control (N/A)	PWM (43kHz)		PFM (T_{OFF}=13μs)		PFM (T_{OFF}=13μs)	
					S=7 **Conventional**	S=2 **Proposed**	S=7 **Conventional**	S=2 **Proposed**	S=7 **Conventional**	S=3/4/5 **Proposed**
# of LEDs	5-16	20	5-11	10-36	2-16					
Output Power	2.5-7W	7-22W	6-12W	5-14W	1.8-8.7W	1.3-7.3W	2-11.4W	1.6-8.6W	1.9-8.4W	1.7-7.6W
PF	0.96-0.98 ($110V_{AC}$) 0.82-0.95 ($220V_{AC}$)	0.78-0.95 ($110V_{AC}$)	0.937-0.98 ($220V_{AC}$)	0.95-0.99 ($220V_{AC}$)	0.9-0.94 ($110V_{AC}$)	0.95-0.995 ($110V_{AC}$)	0.89-0.962 ($110V_{AC}$)	0.94-0.983 ($110V_{AC}$)	0.92-0.992 ($110V_{AC}$)	0.95-0.996 ($110V_{AC}$)
Lowest THD	19% ($110V_{AC}$) 14% ($220V_{AC}$)	N/A	N/A	N/A	20.2% ($110V_{AC}$)	7.8% ($110V_{AC}$)	21% ($110V_{AC}$)	6.2% ($110V_{AC}$)	8.2% ($110V_{AC}$)	3.5% ($110V_{AC}$)
Peak Efficiency	88%	89.4%	83%	90.7%	86.2%	87.8%	91.8%	91.8%	89.6%	90.6%
Line Regulation (# of LEDs)	N/A	N/A	< ±2% @ 180-260V_{AC} (8 LEDs)	±2.36% @ 90-260V_{AC} (N/A)	-	±1.25% @ 80-140V_{AC} (8 LEDs)	-	±1.84% @ 80-140V_{AC} (8 LEDs)	-	±5.89% @ 80-140V_{AC} (8 LEDs)

* The performance of the design referred to as Type 3 in [8] is shown here, as it achieves the maximum PF.

the buck-boost converter for 2-8/10-14/16 LEDs, respectively, because the desired form of the inductor current has to be changed as a function of the number of LEDs as explained in Section II-B. I_L has to be close to $|\sin(\phi)|$ as the number of LEDs is increased. PF and THD are both observed to improve when the proposed reference is employed. The peak PF and lowest THD are 0.995/0.983/0.996 and 7.8/6.2/3.5% for buck (PWM), buck (PFM), and buck-boost (PFM) cases, respectively. Since the buck converter only allows step-down conversion, the PF and THD are degraded when the number of LEDs is increased, especially in the PWM mode, due to the limited maximum duty-cycle. In the buck-boost converter, PF and THD are improved significantly when the number of LEDs is small because the shape of the desired inductor current is close to $\sin^2$.

Fig. 15 shows the LED current (I_{LED}) as V_{ac} is varied from 80 V_{RMS} to 140 V_{RMS} with the different number of LEDs using the proposed reference. As noted above, the buck converter employs S=2, and the buck-boost converter uses $S = 3/4/5$, based on the given number of LEDs that have been used in PF and THD measurements. The average LED current level in the buck converter as well as the buck-boost converter is reduced when the number of LEDs increases because the ripple current is increased. I_{LED} of the buck converter (PWM, PFM) deviates by less than ±3% due to V_{ac} variation, regardless of the number of LEDs, except for the case of 16 LEDs at low V_{ac} in the buck converter (PWM). A large number of LEDs cannot be driven properly with low V_{ac}, because the duty-cycle is limited to 50% in the buck converter (PWM). I_{LED} of the buck-boost converter increases almost linearly with V_{ac}, because the output load current of the buck-boost design varies as $(1 - D)\times\ I_L$, where the duty-cycle (D) decreases as V_{ac} is increased.

Fig. 16 shows the measured LED output power (P_{OUT}) as a function of the different number of LEDs. P_{OUT} using the proposed reference is lower than that achieved using a conventional reference for the same number of LEDs, because I_L in the proposed reference has a narrower shape, which leads to lower I_{LED} than the conventional case. However, this is not a limitation, because P_{OUT} in the proposed case can be made larger using a higher reference peak level for a given number of LEDs. Fig. 17 shows the measured efficiency. The efficiency is improved for a given P_{OUT} with the proposed reference using a larger V_{LED}, with more LEDs. The PWM mode has a higher efficiency than the PFM mode at the same P_{OUT} due to reduced switching. The peak efficiency is 88/92/91% for the buck with PWM, buck with PFM, and buck-boost (PFM) cases, respectively, which includes the driver current consumption of 280 μA with PWM and 330 μA with PFM. Table II summarizes the performance using conventional as well as proposed references and provides a comparison with prior work.

V. CONCLUSION

An efficient LED driver that supports PWM and PFM operation is demonstrated. The driver can be reconfigured to operate as a buck and a buck-boost converter, while using an optimal reference waveform shape for each mode that can be set externally. Rectified sin as well as $\sin^2$ functions are employed in the reference signal to improve the PF and THD of the buck and buck-boost converters. The design ensures that the peak of the inductor current maintains a constant level that is invariant for different ac line voltages. The use of the desired reference waveform is shown to improve key performance metrics including the PF and the THD in both modes of operation, relative to conventional topologies.

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