Design of a TRIAC Dimmable LED Driver Chip with a Wide Tuning Range and Two-Stage Uniform Dimming
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Abstract

A TRIAC dimmable LED driver with a wide tuning range and a two-stage uniform dimming scheme is proposed in this paper. To solve the restricted dimming range problem caused by the limited conduction ratio of TRIAC dimmers, a conduction ratio compensation technique is introduced, which can increase the output current up to the rated output current when the TRIAC dimmer turns to the maximum conduction ratio. For further optimization, a two-stage uniform dimming diagram with a rapid dimming curve and a slow dimming curve is designed to make the LED driver regulated visually uniform in the whole adjustable range of the TRIAC dimmer. The proposed control chip is fabricated in a TSMC 0.35μm 5V/650V CMOS/LDMOS process, and verified on a 21V/500mA circuit prototype. The test results show that, in the 90V/60Hz~132V/60Hz ac input range, the voltage linear regulation is 2.6%, the power factor is 99.5% and the efficiency is 83%. Moreover, in the dimming mode, the dimming rate is less than 1% when the maximum dimming current is 516mA and the minimum dimming current is only about 5mA.

Key words: Constant output current, LED driver, Wide tuning range, TRIAC dimmer, Two-stage uniform dimming

I. INTRODUCTION

High brightness (HB) LEDs have become increasingly popular in the lighting market since they have higher luminous efficiency, less energy consumption and longer life expectancy than traditional incandescent lamp bulbs [1]-[3]. However, there are various aspects that require attention when it comes to applying LEDs for general lighting. One such aspect is related to the dimming control of HB LEDs, especially the LEDs drivers’ compatibility with a TRIAC dimmer, which means the driver should be specially designed to avoid potential issues such as flicker, audible noise, improper dimming function, limited dimming scope etc. [4], [5]. However, the present situation of the technology that allows LED drivers to perform wide range dimming is still imperfect [6]. In [7], an extra dummy load is parallel connected to a TRIAC dimmer, to make the LED match the dimmer. The conduction angle of the TRIAC dimmer ranges from 30° to 150°, and the dimming ratio is about 10%. However, this method is only suitable for the half-bridge topology and the extra dummy load decreases the system efficiency. In [8], an additional CFL ballast circuit is added, so that the current flowing through the LED can be regulated by the conduction angle of the TRIAC dimmer. However, the use of an additional CFL ballast circuit increases the power consumption of the circuit and reduces the system efficiency. In [9], power factor correction was introduced to make the input current track the input voltage. Therefore, the LED drivers can exhibit behavior that is similar to incandescent lamps and be compatible with the TRIAC dimmers. However, since the conduction angle of the TRIAC dimmer is limited, the dimming range of the output current is also limited without any offset. In [10], by introducing a LC input filter and a changing switched capacitor, the power of the LED is controlled by the Triac dimmer and the system has a high linear adjustment rate. However, in the dimming process, the minimum power of the LED load is only about 20~30% of the maximum power, and the dimming range is narrow. Therefore, it is necessary to research the compatibility of the
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... dimming controller and the TRIAC dimmer to expand the scope of the dimming.

On the other hand, it has been extensively studied on how to achieve satisfactory light since the quality and correlated color temperature (CCT) of light has an impact on human comfort and productivity. In [11], a control method based on an estimator of the luminous flux emitted by a LED is proposed to obtain the enhanced full linear dimming control of the device. In [12], a scheme for controlling the luminosity and CCT of a bi-color LED lamp by utilizing closed-loop control with feedback from a color sensor is presented. The study in [13] is primarily targeted at achieving accurate dimming and CCT control of bi-color variable CCT LED lamps, through the use of a nonlinear empirical LED model that accounts for the thermal interdependence of the two color sources and the actual imperfections of LEDs. All of these studies aim at improving the comfort of human eyes when exposed to light.

There is a difference between actual brightness and observed brightness. This difference leads to the fact that the sensitivity of an eye to changes in brightness is affected by the initial brightness value. For example, in the process of changing from dark to bright, if the actual brightness increases linearly, the observed brightness increases quickly at first, but very slowly later. Based on the above characteristics of the human eye, uniform dimming is another important performance characteristic for a high quality light source.

Up to now, no published work claims to achieve a wide dimming ratio and uniform dimming at the same time. A novel dimming control circuit is proposed in this paper. By introducing conduction compensation technology, the dimming current rises to the rated current when the conduction angle reaches the maximum and declines nearly to zero when the conduction angle reaches the minimum. Consequently, the output current is no longer restricted by the limited conduction angle, and the dimming range can be greatly enlarged. Meanwhile, since eyes are insensitive to large current LED lighting and sensitive to small current LED lighting, the two-stage uniform dimming design is proposed based on a previous design. Namely, a two-stage dimming curve consisting of rapid and slow dimming curves is designed to make the LED brightness vary fairly uniformly with the conduction angle. The detailed operation principle for the proposed dimming circuit is illustrated in Section II. Then, design considerations of the key circuits are presented in Section III. Section IV shows some experimental results, while Section V concludes the paper.

II. OPERATION PRINCIPLE

A. System Overview

A system diagram of the proposed wide tuning range and two-stage uniform dimming AC-DC LED driver is shown in Fig. 1. It consists of a bridge rectifier BD, TRIAC dimmer, primary-side sense resistor \( R_{CS} \), RCD snubber circuit, freewheel diode \( D_{o} \), output capacitor \( C_o \), power MOSFET \( M_1 \) and the control IC. The control IC is mainly composed of an \( I_{OUT} \) estimation circuit, constant current (CC) module, power factor correction (PFC) module and the proposed dimming control circuit. A conduction ratio detection circuit (CRDC), conduction ratio compensation circuit (CRCC) and pull-down current control circuit (PCCC) form the proposed dimming control circuit, which can guarantee an output current constant with a wide tuning range. With two-stage dimming optimization, the proposed dimming control circuit is developed and the output current shows two-stage uniform dimming characteristics.

In the control IC, as shown in Fig. 1, the \( I_{OUT} \) estimation circuit samples the voltage of the primary-side sense resistor and exports \( V_{CAL} \), which indicates output current value. Meanwhile, \( V_{CAL} \) is processed in the CC to make the output current constant. \( I_{OUT} \) is achieved from the proposed dimming control circuit. \( V_{COMP} \) is obtained from the CC, which disposes of the pull-down current. The PFC module manages \( V_{COMP} \) and \( V_{FB} \) from the auxiliary winding. The driving signal \( DRV \), and the signal \( T_{ON} \) and \( T_{OFF} \) can be acquired in the normal condition. In order to regulate the output current by the TRIAC, the proposed dimming control circuit generates a pull-down current controlled by the TRIAC dimmer to the CC. As a result, the output current can be regulated by the TRIAC dimmer. The detail principle of the constant current and the dimming are explained below.

B. Principle of Constant Current

The proposed controller operates in the boundary conduction mode (BCM) and the output current is estimated by the \( I_{OUT} \) estimation block. Steady state waveforms of the sensed primary-side signals for the output current estimation are shown in Fig. 2. According to Fig. 1, \( DRV \) is the driving voltage of the power MOSFET \( M_1 \). When the DRV is a high voltage, the power MOSFET is switch-ON and this period is called \( T_{ON} \). Similarly, \( T_{OFF} \) is the switch-OFF period during a switching cycle. \( I_P \) is the primary-side instantaneous current. \( I_S \) is the secondary-side instantaneous current.

When the system works in the stable state, the output current can be expressed as Eq (1).

\[
I_{OUT} = \frac{1}{2} \cdot \frac{I_S}{T_{ON} + T_{OFF}}
\]  

(1)

In Eq (1), \( I_{OUT} \) is the output current, and \( I_S \) is the peak current of the secondary-side instantaneous current in a switching cycle. \( T_{ON} \) and \( T_{OFF} \) are the turn-on time and turn-off time, respectively.

\( V_{CS} \) is the sensing voltage of the primary-side sense resistor. \( V_{CAL} \) is the output of the \( I_{OUT} \) estimation module, which calculates \( V_{CS} \) with \( T_{ON} \) and \( T_{OFF} \). Therefore, \( V_{CAL} \) can be
obtained by Eq (2).

\[ V_{\text{CAL}} = \frac{V_{\text{CS,P}} \cdot T_{\text{OFF}}}{T_{\text{ON}} + T_{\text{OFF}}} \]  (2)

According to the relationship of the transformer ampere-turns, there is:

\[ I_{\text{SP}} = \frac{N_p}{N_S} \cdot I_{\text{PP}} = \frac{N_p}{N_S} \cdot \frac{V_{\text{CS,P}}}{R_{\text{CS}}} \]  (3)

Where, \( N_p \) and \( N_S \) are the turns of the primary-side winding and secondary-side winding, respectively. \( I_{\text{PP}} \) and \( V_{\text{CS,P}} \) denote the peak value of \( I_p \) and \( V_{\text{CS}} \). \( R_{\text{CS}} \) is the value of the primary-side sense resistor. The average output current \( I_{\text{OUT}} \) can be given as:

\[ I_{\text{OUT}} = \frac{1}{2} \cdot \frac{N_S}{N_p} \cdot \frac{V_{\text{CAL}}}{R_{\text{CS}}} \]  (4)

In Eq (4), the output current \( I_{\text{OUT}} \) is determined by \( N_p, N_S, R_{\text{CS}} \) and \( V_{\text{CAL}} \).

Fig. 3 shows the constant current control circuit. The amplifier, NMOS and resistor comprise the voltage-to-current converter. Therefore, the current \( I_{\text{REF}} \) and \( I_2 \) are converted by the reference voltage \( V_{\text{REF}} \) and the estimated output current signal \( V_{\text{CAL}} \), respectively. \( \text{COMP} \) is connected to the external compensation capacitance, and the current \( I_2, I_{\text{REF}} \) and \( I_{\text{pull}} \) meet Kirchhoff’s current law.

\[ I_{\text{REF}} = I_2 + I_{\text{pull}} = \frac{V_{\text{CAL}}}{R_2} + I_{\text{pull}} \]  (5)

In Eq (5), \( I_{\text{REF}} \) is the reference current, \( I_2 \) is converted by \( V_{\text{CAL}} \) and \( V_{\text{CAL}} \) comes from the \( I_{\text{OUT}} \) estimation circuit. \( R_2 \) is the converted resistor, and \( I_{\text{pull}} \) is the pull-down current from the proposed dimming control circuit.

In accordance to Eq (4) and (5), the output current \( I_{\text{OUT}} \) can be derived as:

\[ I_{\text{OUT}} = \frac{1}{2} \cdot \frac{N_S}{N_p} \cdot \frac{R_2}{R_{\text{CS}}} (I_{\text{REF}} - I_{\text{pull}}) \]  (6)

In Eq (6), \( R_{\text{CS}} \) is the primary-side sense resistor. Eq (6) shows that \( I_{\text{OUT}} \) varies with \( I_{\text{pull}} \), which is controlled by the conduction angle of the TRIAC dimmer. Therefore, \( I_{\text{OUT}} \) can be regulated by the conduction angle. In addition, \( I_{\text{OUT}} \) is kept constant when the conduction angle is fixed. The rated output current \( I_{\text{RC}} \) is an output current without a TRIAC dimmer and...
The conduction ratio

\[
I_{\text{pull}} = K \cdot I_{\text{REF}} \cdot D_{\text{TRI+25\%}}
\]

In Eq (8), \(I_{\text{pull}}\) is the pull-down current from the proposed dimming control circuit, \(I_{\text{REF}}\) is the reference current, \(K\) is the pull coefficient of the PCCC, which is controlled by the reference voltage and resistor, and \(D_{\text{TRI+25\%}}\) is the duty cycle of \(\text{TRI+25\%}\) coming from the CRCC. In order to make the output current go down to zero when \(D\) comes to its minimum value 20\%, according to Eq (6) and (8), the pull coefficient \(K\) of the PCCC can be determined by Eq (9).

\[
I_{\text{REF}} = K \cdot I_{\text{REF}} \cdot (1 - (20\% + 25\%))
\]

In Eq (9), \(I_{\text{REF}}\) is the reference current, and \(K\) must be set as 1.78.

Combining Eq (6), (7) and (8) with \(K=1.78\), the output current can be rewritten as:

\[
I_{\text{out}} = 1.78 \cdot D \cdot I_{\text{RC}} - 0.33 \cdot I_{\text{RC}}
\]

Eq (10) shows that the output current \(I_{\text{out}}\) is linear to the conduction ratio \(D\), and \(I_{\text{RC}}\) is the rated output current.

When the conduction ratio \(D\) varies from 20\% to 75\%, the output current \(I_{\text{out}}\) can be regulated from zero to \(I_{\text{RC}}\).

The theoretical dimmer outline of the traditional dimming control circuit and the proposed dimming control circuit is shown in Fig. 5. Traditionally, the output current is directly controlled by the conduction ratio \(D\) without any conduction ratio compensation or optimization of the pull coefficient \(K\). Therefore, the output current range is always restricted by the limited conduction ratio \(D\), as shown by Scheme T in Fig. 5. The proposed dimming control circuit can manage the maximum output current up to \(I_{\text{RC}}\) when \(D\) is above 75\%, and the minimum output current down to zero when \(D\) is less than 20\%. Therefore, the proposed control circuit can manage the wide tuning range.

D. Two-Stage Uniform Dimming Principle

The proposed wide tuning range and two-stage uniform dimming control circuit is developed from a previous design and its diagram is given in Fig. 6. With the rapid dimming curve \(l_1\) and the slow dimming curve \(l_2\), the output current can be regulated relatively uniform in the whole adjustable range, since eyes are sensitive to small current LED lighting but not to large current LED lighting. In addition, the dimming curves \(l_1\) and \(l_2\) are selected by the switch circuit. Compared with TRI\_REF whose duty cycle is 50\%, rapid dimming \(l_1\) is chosen when \(D\) is larger than 50\%, and slow dimming \(l_2\) is selected when \(D\) is smaller than 50\%.

The rapid dimming curve \(l_1\) consists of the CRDC, CRCC and PCCC, and its pull coefficient \(K_1\) is 2.5. Similar to the wide tuning range design, the CRDC detects the conduction angle \(D\). The CRCC adds an extra 25\% duty cycle to the TRI and then inverts it to the output signal TRI+25\% . The pull-down current \(I_{\text{pull}}\) of \(l_1\) is generated from PCCC(\(K_1=2.5\)) and then inverts it to the output signal TRI+25\% .
and meets Eq (11).

\[ I_{pull1} = D_{TRI+25}\% \cdot K_1 \cdot I_{REF} = 2.5 \cdot (1 - D - 25\%) \cdot I_{REF} \]  

(11)

In Eq (11), \( D_{TRI+25\%} \) is the duty cycle of \( \overline{TRI+25\%} \) from the CRCC, and \( K_1 \) is the pull coefficient of the PCCC in \( l_1, D \) is the conduction ratio.

The slow dimming curve \( l_2 \) is composed of the CRDC, INV and PCCC with the pull coefficient \( K_2=1.25 \). The INV is an inverter to reverse the TRI to obtain \( \overline{TRI} \). The pull-down current \( I_{pull2} \) is generated from the PCCC (\( K_2=1.25 \)) and satisfies:

\[ I_{pull2} = D_{TRI} \cdot K_2 \cdot I_{REF} = 1.25 \cdot (1 - D) \cdot I_{REF} \]  

(12)

In Eq (12), \( D_{TRI} \) is the duty cycle of \( \overline{TRI} \) coming from the INV, and \( K_2 \) is the pull coefficient of the PCCC in \( l_2, D \) is the conduction ratio.

Through the switch circuit, the pull-down current \( I_{pull} \) can be switched between \( I_{pull1} \) and \( I_{pull2} \) according to the conduction ratio \( D \), and \( I_{pull} \) can be expressed as:

\[
I_{pull} = \begin{cases} 
2.5 \cdot [1 - (D + 0.25)] \cdot I_{REF} ; (0.5 < D < 0.75) \\
1.25 \cdot (1 - D) \cdot I_{REF} ; (0.2 < D < 0.5) \\
I_{REF} ; (0 < D < 0.2) \\
0 ; (0.75 < D < 1)
\end{cases}
\]  

(13)

In Eq (13), \( I_{pull} \) is the pull-down current of the proposed dimming control circuit, \( I_{REF} \) is reference current and \( D \) is conduction ratio of the TRIAC dimmer.

According to Eq (6), (7) and (13), the output current \( I_{OUT} \) can be rewritten as:

\[
I_{OUT} = \begin{cases} 
2.5 \cdot D \cdot I_{RC} - 0.875 \cdot I_{RC} ; (0.5 < D < 0.75) \\
1.25 \cdot D \cdot I_{RC} - 0.25 \cdot I_{RC} ; (0.2 < D < 0.5) \\
I_{RC} ; (0.75 < D < 1) \\
0 ; (0 < D < 0.2)
\end{cases}
\]  

(14)

In Eq (14), \( I_{OUT} \) is the output current, \( I_{RC} \) is the rated output current, and \( D \) is the conduction ratio.

Based on Eq (14), a theoretical output diagram of the wide tuning range and the two-stage uniform dimming design is presented in Fig. 7.

In Fig. 7, when the adjustment of the TRIAC dimming conduction angle is between 20% and 75%, the current flowing through the LED can be adjusted between zero and the rated output current. When the conduction angle is greater than 50%, the LED output current with the conduction angle changes quickly into the fast dimming mode; when the conduction angle is less than 50%, the LED output current with the conduction angle changes slowly into the slow dimming mode. The output current can be adjusted from zero to the rated current value throughout the active range of the TRIAC dimmer, and the brightness of the LEDs observed by the human eye remains relatively uniform throughout the dimming interval. 50% is the result of multiple tests and brightness verifications, which is the experience value. When selecting 50% as the critical point of the slow and fast current regulation, it is possible to realize the best characteristics of uniform dimming. Therefore, with two-stage dimming optimization, the proposed control circuit can manage a wide tuning range and two-stage uniform dimming.

III. DESIGN CONSIDERATIONS OF THE KEY CIRCUITS

In order to achieve the proposed wide tuning range and two-stage uniform dimming characteristic, key circuits of the developed dimming control circuit are discussed in detail.
A. Conduction Ratio Compensation Circuit (CRCC)

The CRCC is the core circuit to improve the dimming range of the output current. By imposing an extra compensation to the detected conducted ratio, the weakness where the maximum conduction ratio cannot reach 100% can be avoided, and the maximum output current can reach rated output current.

In order to achieve an extra 25% compensation for D, a conduction ratio compensation circuit is designed in Fig. 8, which contains a sample and hold (S/H) module, resistor divider, comparator, one-shot and charging/discharging circuit composed of M1~M5, C1 and M6. The one-shot is a monostable trigger, outputting a narrow pulse signal at the falling edge of the input signal during each cycle. A high precision cascade current mirror consists of M2~M5, C1 and M6 discharges C1 rapidly when the reset signal is high. The S/H is composed of the transmission gate T1, holding capacitance C2, amplifier, M7 and R1, R2 is three times R1 in value, and resistor divider is formed.

Fig. 9 shows key operation waveforms of the conduction ratio compensation circuit. The TRI is the detected conduction ratio signal coming from the CRDC. In addition, a narrow pulse signal sample and reset can be achieved by the TRI and sample, respectively. The current I_charge charges the capacitance C1, and Vc increases linearly in every cycle. When the signal reset is active, Vc must be dropped to zero. Before the signal reset, the peak voltage VCP of Vc is sampled and held by a signal sample in the S/H. Processed by the resistor divider, VCP/4 can be achieved and compared with Vc. As a result, a 25% extra compensation signal POR_25% is achieved. With a logical gate, the signal TRI+25% after compensation can be obtained, as can the signal TRI+25% as shown in Fig. 9.

B. Switch Circuit

The switch circuit is designed to identify whether D is larger than 50%. Therefore, a switch reference signal TRI_REF with a 50% duty ratio and the same period as the TRI must be introduced. The circuit to generate the switch reference signal TRI_REF is similar to the conduction ratio compensation circuit. With the resistor ratio of the resistor divider in the CRCC replacing 3/1 with 1/1, VCP/2 is compared with Vc and switch reference signal TRI_REF, the duty ratio of which is 50%.

The switch circuit is shown in Fig. 10. The TRI is the detected conduction ratio signal. TRI_REF is the switch reference signal and TRI+25% is the output of the CRCC. D1 is triggered by the falling edge of the clock, and the switch circuit outputs TRI_C and TRI_P. When D is larger than 50%, TRI_C=1, and the rapid dimming curve is selected. Namely, the PCCC, the pull coefficient K1 of which is 2.5, is selected and TRI_P is TRI+25%. Otherwise, when D is less than 50%, TRI_C=0, and the slow dimming curve is chosen. Namely, the pull coefficient K2 of the PCCC is 1.25 and TRI_P is the TRI. As a result, the dimming curve can be switched between l1 and l2.

From Fig. 11, when D is larger than 50%, TRI_REF is in
Fig. 10. Design implementation of the switch circuit.

Fig. 11. Key operation waveforms of the switch circuit.

In Fig. 13 and the die size K. When -0 K in V NMOS -K -K -K. At to I. As a -PCCC R -Vnt is -K ng the value of the pull resistor, the V1 25% TRI+25% TRI+25% TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI TRI 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Design of a TRIAC Dimmable LED Driver Chip with a Wide Tuning Range

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**TABLE I**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC input voltage</td>
<td>$V_{IN}$</td>
<td>90–132Vac (RMS)</td>
</tr>
<tr>
<td>Output current</td>
<td>$I_{OUT}$</td>
<td>500mA</td>
</tr>
<tr>
<td>Output voltage</td>
<td>$V_{OUT}$</td>
<td>21V</td>
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<td>BD1</td>
<td>MB6S</td>
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<tr>
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<td>EE6</td>
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<tr>
<td>Transformer Turns-ratio</td>
<td>$N_p : N_S : N_A$</td>
<td>157/31/37</td>
</tr>
<tr>
<td>Power MOSFET</td>
<td>$Q_1$</td>
<td>AP03N70</td>
</tr>
<tr>
<td>Output capacitor</td>
<td>$C_o$</td>
<td>470μF/35V</td>
</tr>
<tr>
<td>Primary-side current sense resistor</td>
<td>$R_{CS}$</td>
<td>2Ω</td>
</tr>
</tbody>
</table>

---

to 99.6% at 100Vac input. The measured efficiency of the prototype at no dimming conduction is shown in Fig. 17. The maximum efficiency is 83% at 132Vac input, and the minimum efficiency is above 75% in seven 3W-LEDs.

Fig. 18 shows the measured input current and rectified bus voltage $V_T$ at different conduction ratios. The TRIAC dimmer

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Fig. 17. Measured efficiency versus the ac input voltage.

\[ V_{\text{IN}} = 110 \text{V} \]
\[ D = 75\% = D_{\text{max}} \]
\[ I_{\text{OUT}} = 516 \text{mA} \]

(a)

Fig. 18. Measured steady waveforms under 110Vac and 60Hz at:

(a) \( D = 75\% \); (b) \( D = 50\% \); (c) \( D = 30\% \).

\[ V_{\text{IN}} = 110 \text{V} \]
\[ I_{\text{OUT}} = 185 \text{mA} \]
\[ D = 50\% \]

(b)

\[ V_{\text{IN}} = 110 \text{V} \]
\[ I_{\text{OUT}} = 90 \text{mA} \]
\[ D = 30\% \]

(c)

Fig. 19. Measured output current waveforms under 110Vac and 60Hz at: (a) \( D = 75\% \); (b) \( D = 50\% \); (c) \( D = 30\% \).

\[ V_{\text{IN}} = 110 \text{V} \]
\[ I_{\text{IN}} \]
\[ D = 50\% \]

(b)

\[ V_{\text{IN}} = 110 \text{V} \]
\[ I_{\text{IN}} \]
\[ D = 30\% \]

(c)

Fig. 20. Measured output current versus the conduction ratio.

range, the dimming outline consists of a rapid dimming curve and a slow dimming curve. Therefore, the dimming outline exerts a wide tuning range and two-stage uniform dimming characteristics.

Finally, Table II shows a performance comparison with prior studies. From Table II, it is shown that the maximum output current \( I_{\text{MAX}} \) of the proposed TRIAC dimming driver is up to the rated output current \( I_{\text{RC}} \) and that the current ratio which is the ratio of \( I_{\text{MAX}} \) and \( I_{\text{RC}} \) is about 100%. In addition, its minimum dimming current \( I_{\text{MIN}} \) is only 5mA, and the dimming ratio which is the ratio of \( I_{\text{MIN}} \) and \( I_{\text{MAX}} \) is less than 1%.
TABLE II
COMPARISON BETWEEN THE PROPOSED METHOD AND PRIOR STUDIES

<table>
<thead>
<tr>
<th></th>
<th>This work</th>
<th>[15]</th>
<th>[16]</th>
<th>[14]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>FLYBAC</td>
<td>FLYBAC</td>
<td>FLYBAC</td>
<td>FLYBAC</td>
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<tr>
<td>Working mode</td>
<td>BCM</td>
<td>BCM</td>
<td>-</td>
<td>BCM</td>
</tr>
<tr>
<td>Rated load</td>
<td>21V/0.5A</td>
<td>27V/0.5A</td>
<td>24V/0.3A</td>
<td>28V/0.5A</td>
</tr>
<tr>
<td>Conduction ratio (D)</td>
<td>10%−85%</td>
<td>19%−78%</td>
<td>4%−92%</td>
<td>12%−89%</td>
</tr>
<tr>
<td>Efficiency (\eta)</td>
<td>83%</td>
<td>87.5%</td>
<td>80%</td>
<td>87%</td>
</tr>
<tr>
<td>Power factor PF</td>
<td>0.995</td>
<td>0.985</td>
<td>-</td>
<td>0.99</td>
</tr>
<tr>
<td>Rated current (I_{BC})</td>
<td>510mA</td>
<td>475mA</td>
<td>300mA</td>
<td>-</td>
</tr>
<tr>
<td>Maximum dimming current (I_{\text{MAX}})</td>
<td>516mA</td>
<td>370mA</td>
<td>270mA</td>
<td>550mA</td>
</tr>
<tr>
<td>Minimum dimming current (I_{\text{MIN}})</td>
<td>5mA</td>
<td>50mA</td>
<td>13mA</td>
<td>50mA</td>
</tr>
<tr>
<td>Current ratio (I_{\text{MAX}}/I_{\text{BC}})</td>
<td>=100%</td>
<td>=78%</td>
<td>=90%</td>
<td>-</td>
</tr>
<tr>
<td>Dimming ratio (I_{\text{MIN}}/I_{\text{MAX}})</td>
<td>1%</td>
<td>13%</td>
<td>4%</td>
<td>9%</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS
This paper proposes a TRIAC controlled AC-DC LED driver chip with a wide tuning range and two-stage uniform dimming. When compared with prior designs, the dimming range is no longer restricted by the limited conduction ratio of TRIAC dimmers and the LED lights change more uniformly with the TRIAC dimmer. A theoretical analysis and key circuits are illustrated in this paper. The proposed control chip is fabricated in a TSMC 0.35μm 5V/650V CMOS/LDMOS process, and verified in a 21V/500mA circuit prototype. The test results show that, in 90V/60Hz−132V/60Hz ac input range, the voltage linear regulation is 2.6\%, the power factor is 99.5\%, and the efficiency is 83\%. Moreover, in the dimming mode, the maximum dimming current is 516mA, with the corresponding rated current 510mA, the minimum dimming current is almost zero, and the dimming rate is less than 1\%. Therefore, the proposed control chip has a promising application in TRIAC-dimmable LED drivers.

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REFERENCES

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