A novel on-chip step-dimmer for low cost AC-powered HV-LED driver

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Abstract: This letter proposes a novel on-chip step-dimmer using an analog dimming method for a high PF AC-powered LED driver. The full AC LED driver can achieve a very high PF and a low THD by using a self-adaptive power processing circuit while delivering a best-in-class dimming performance with the proposed step-dimmer. Under the control of the dimming signal, the dimming voltage is step-adjusted from 1.0 V to 2.5 V, the average LED current can be changed from 40\% to 100\% of the nominal LED current value. To verify the feasibility of the proposed scheme, an 8-string 4.4 W AC-powered LED driver with the proposed step-dimmer was designed and simulated using a 0.35\,\mu m-700 V BCD Magnachip process. The gained results verify that the proposed step-dimmer can maintain a high performance of the AC LED driver under different dimming modes with a PF and a THD around 0.998 and 6\%, respectively.

Keywords: AC-powered LED driver, step-dimmer, analog dimming mode, high voltage LED (HV-LED)

Classification: Integrated circuits

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1 Introduction

In outdoor lighting applications where effects of the flicker at 120/100 Hz from the rectified AC mains can be neglected, AC-powered HV-LED drivers are more attractive than converter-based switch-mode LED drivers since AC LED drivers are simpler in the design as well as lower in cost. Recently, various non-isolated AC-powered LED drivers with multiple LED strings have been introduced, enabling a high power factor (PF), a low total harmonic distortion (THD) as well as lows crest factor [1, 2, 3]. However, the dimming function which is important for a light source that the luminance can be adjusted is not available on these AC LED drivers. Additionally, these AC LED drivers can’t be compatible with phase-cut control technique using triac dimmer as switch-mode LED drivers because of the two main problems: (i) Degrade the PF due to current chopping, (ii) Increase the flicker because of the dead zone of LED current. Another design reported in [4] shows a high PF with a dimming feature; however that design is very complicated in implementing with expensive blocks that degrades its robustness and makes it unsuitable for low cost applications. In [5] N. Ning et al., proposed a self-adaptive power processing circuit (PPC) for AC-powered LED drivers without any control circuit which makes it become one of the most effective, simple and novel designs in order to achieve both of a high PF and a low cost. In this letter, an on-chip step-dimmer using analog dimming method via a simple concept in accompany with the novel self-adaptive PPC reported in [5] is proposed for regulating simultaneously LED brightness as well as maintaining a high PF and a low THD. Compared with the design reported in [4], the proposed design has advantages of lower cost and much simple in design while achieve the same performance.

2 Proposed dimmable AC-direct LED driver with step-dimmer

A - System design configuration: Fig. 1 shows the schematic of the proposed AC LED driver consisting of one bridge, one LED module, one self-adaptive power processing circuit (PPC) based on the design reported in [5], one start-up circuit using an UVLO (under voltage lock out), one low dropout voltage regulator (LDO), and one 2-bit step-dimming circuit. The start-up circuit and the LDO output the voltages $V_{GATE}$ and $V_{DDA}$ to bias the high voltage transistors HM1-HM8, supply power for the dimming circuit as well as for the PPC, respectively. The output of the step-dimmer is connected in series with the PPC to regulate the LED current and brightness. In the PPC, the low voltage components are isolated from the high voltage AC mains by high voltage transistors HM1-HM8. The bias voltage $V_{GATE}$ for the power transistors HM1-HM8 is determined by $V_{TH} + V_{DDA}$ where $V_{TH}$ and $V_{DDA}$ are the threshold voltage of high voltage power transistors HM1-HM8 and...
maximum voltage of the low power components, respectively. As shown in Fig. 1, there is no need of any external passive components such as bulky capacitors, inductors that makes the circuit become simple and increases the reliability.

In order to achieve the highest PF (and lowest THD), the maximum number $N$ of LED string should be used [4]. In this work, a high voltage 30 V/20 mA LED type is utilized with one LED/string, and a 220 V (RMS) of the input voltage $V_{in}$, then 10 LED strings can be adopted since:

$$N = \left( \frac{V_{in}^{\text{RMS}}}{C2} \sqrt{2} \right) / V_{LED}$$  \hspace{1cm} (1)

If the number of LED strings adopts more than 10, then the total equivalent forward voltage drop on all LED strings is in excess of the peak value of the input voltage, whereas if the number of LED strings takes lower than 10 strings, the redundant input voltage would be across the LCRs (linear current regulation) in the PPC, thereby increasing the loss power dissipation on the LCRs as heat. However, considering a margin when the last LED string conducts and an increase of forward voltage of LED strings when the LED current increases, 8 LED strings were chosen as shown in Fig. 1. Fig. 2(a) shows the detailed operation of the PPC with eight modes for a half of operating cycle with each mode for one LCR. Referring to the PPC shown in Fig. 1, the operating principle of this circuit can be fairly easy to understand and is summarized as following: When the input voltage $V_{in}$ increases to a value $V_{LED} < V_{in} < 2V_{LED}$, the LCR1 (which consists of OPA1, MS1 and RS1 to RS8) turns on and conducts the current of LED1 while the other LEDs and other CLR1s are turned off. As the LCR1 turns on, the voltage on the inverting terminal of OPA1 equals to the non-inverting terminal with a value of $V_{dim}$. When the input voltage $V_{in}$ increases to a value $2V_{LED} < V_{in} < 3V_{LED}$, the CLR2 (which consists
of OPA2, MS2 and RS2 to RS7) turns on and conducts the current of LED1 and LED2. As the LCR2 turns on, the voltage on the inverting terminal of OPA2 increases to \( V_{\text{dim}} \) that equals to the voltage of the inverting terminal of OPA1; hence, the voltage drops on RS1 is reduced to zero; and CLR1 is turned off. As the input voltage \( V_{\text{in}} \) increases to higher levels, others LCRs (LCR3 to LCR8) are turned on in a similar way until all LEDs are turned on. This process repeats in the same way in the next cycles.

\[
i_i = \frac{V_{\text{dim}}}{\sum_{j=1}^{8} R_{S_j}}
\]

Since the bias current of the sub-circuits (including start-up circuit, LDO and dimming circuit) is small as compared to the LED current and can be neglected, the input current approximates to the LED current which is the sum of the current elements of LCRs and can be expressed as following:

\[
i_{\text{in}} = i_{\text{LED}} = i_1 + i_2 + \ldots + i_8 = \sum_{i=1}^{8} i_{(i)}
\]

As shown in Fig. 2(a), the PPC provides LED strings with a step-like sinusoidal driving current which follows the ideal sinusoid waveform tightly to obtain a very high power factor (PF) and a low total harmonic distortion (THD). In the other hand, the LED current is insensitive to fluctuations in the AC mains since the LCRs are used, so the flashing phenomenon of the output light is eliminated. A further point of note is that in the proposed design, the power loss is mainly caused by the power losses created from CLRs in the PPC. Since only one LCR turns on at each...
period time, the power loss on LCRs is minimized; hence the high efficiency can be obtained. Because of this, the application of the AC LED driver using PPC topology can be broaden from low power applications to high power applications.

B - Analog dimming method with the proposed step-dimmer: As expressed in Eq. (2), it is easily realized that the LED current is regulated by monitoring the dimming voltage $V_{\text{dim}}$ of LCRs. Additionally, to keep the high PF when the dimming signal is applied; the step-like sinusoidal form of the input current shown in Fig. 2(a) must be maintained. The input current expressed in Eq. (3) can be re-written in details as following:

$$i_{\text{in}} = i_{\text{LED}} = \frac{V_{\text{dim}}}{\sum_{i=1}^{8} \frac{V_{\text{LED}} < V_{\text{in}} < 2V_{\text{LED}}}{RS_i}} + \frac{V_{\text{dim}}}{\sum_{i=1}^{7} \frac{2V_{\text{LED}} < V_{\text{in}} < 3V_{\text{LED}}}{RS_i}} + \ldots \frac{V_{\text{dim}}}{\sum_{i=1}^{1} \frac{V_{\text{in}} > 8V_{\text{LED}}}{RS_i}}$$

As expressed in Eq. (4), it is clear that if all the LED strings are dimmed simultaneously by changing the $V_{\text{dim}}$, the LED current is regulated only in magnitude while the step-like sinusoidal form of the input current is kept. By doing so, the LED brightness is controlled while the high PF and low THD can be maintained. This dimming voltage $V_{\text{dim}}$ is controlled by using a step-dimmer.

Fig. 2(b) illustrates the concept of the proposed step-dimmer which is constructed using only a logic control block and a voltage divider. Depending on the output states of the logic circuit, different levels of the dimming signal can be generated. The realization of the 2-bit step-dimmer is shown in Fig. 1 in which the logic control block is constructed using simple digital cells including a 2-bit-up counter, 6 transmission gates and 2 inverters. To reduce the chip size as well as eliminate the impact of the fabrication process, an integrated voltage divider MOSR1-MOSR5 using a technique reported in [6] was utilized in lieu of a resistor-based voltage divider. The operation of the 2-bit step-dimmer is shown in Fig. 2(c) and can be summarized as following: When an external dimming pulse is applied, the counter counts up to output logic states. These logic states then control the transmission gates which connect the output of the step-dimmer to different positions on the voltage divider. As a result, various levels of the dimming signal $V_{\text{dim}}$ are generated to regulate the LED current (and LED brightness) as expressed in Eq. (4).

The range of dimming depends on the ICMR (input common mode range) of the op-amps in the PPC and the dimming resolution is decided by the resolution of the counter. Theoretically, the LED light can be dimmed from 0 to 100% by using a rail-to-tail op-amp type while the smooth dimming can be enhanced by using the counter with a higher resolution without any difficulties in the design process. It is noticed that a down-dimmer was used in this design as compared with an up/down-
dimmer reported in [4]; however, an bi-directional up/down dimmer can be easily
designed by using a bi-directional up/down counter instead of one-directional up
counter shown Fig. 2(c). A further point to be noticed is that since the analog
dimming method is used, the dimming level is usually limited in a range of 100%
down to 20% because of the change in color at a low forward current flowing in
LEDs. Although the amplitude modulation-based dimming method may cause a
change in color of the output light as compared with digital dimming method using
PWM technique [7]; however, it can be acceptable in most of general outdoor
lighting applications. Finally, the dimming function is controlled in steps make it an
ease of usage.

3 Simulation results

To verify the feasibility of the proposed scheme, the circuit was designed and
simulated using a 0.35 um–700 V BCD process which provides high voltage
devices to be compatible with the commercial AC mains. In order to reduce the
nonlinearity which may cause a reduction of the efficacy in Lumens per Watt if the
operating current of LEDs exceeds the linear range, the full-scale current of LED
was set at 20 mA (peak value) instead of 20 mA (RMS value). The value of $V_{\text{dim}}$ is
generated from the step-dimmer and was chosen in a range of 1.0 V to 2.5 V with a
step of 0.5 V as shown in Fig. 2(b). The start-up circuit was designed to bias the
power transistors HM1-HM8 with a value of 7 V of $V_{\text{GATE}}$ while the LDO was
designed to output a voltage of 5 V. The resistors RS1-RS8 in PPC were set at
500 $\Omega$, 166.67 $\Omega$, 83.33 $\Omega$, 50 $\Omega$, 33.35 $\Omega$, 23.8 $\Omega$, 17.85 $\Omega$, 125 $\Omega$,
respectively, to make the step-like sinusoidal input current waveform fit closely to the ideal
sinusoidal input current as shown in Fig. 2(a).

![Simulation result of the power processing circuit.](image)

Fig. 3 shows the key waveforms the PPC at full dimming level with 2.5 V of
$V_{\text{dim}}$. As seen in Fig. 3(a), the operation of the PPC illustrates a self-adaptive
mechanism without any current glitches between LCRs. Fig. 3(b) and 3(c) show
the input current waveform that is the sum of current elements of LCRs and the waveform of the input current versus the input voltage, respectively. It is clearly seen that the input current $i_{in}$ is in a nearly-sinusoidal form and always in phase with the input voltage $v_{in}$, so a high PF and a low THD are obtained.

![Graph showing input current waveform](image)

**Fig. 4.** Simulation result of AC LED driver when a dimming step is applied. (a) – Operation modes of power processing circuit. (b) – Input voltage and input current.

![Graph showing input voltage and current](image)

**Fig. 5.** Input voltage and input current at different dimming conditions. (a) 40% dimming. (b) 60% dimming load. (c) 80% dimming and (d) 100% dimming.

Fig. 4(a)–(b) shows the operation of the AC LED driver when the dimming signal is applied. It can be seen that the design works well since the input current follows the input voltage as tightly as possible. It is also obvious that the LED current magnitude is proportional to the dimming voltage $V_{dim}$ as expressed in
Eq. (4) while the near-sinusoidal form is maintained. Additionally, there are smooth transitions between different dimming modes without any current glitches which may degrade the PF and efficiency of the design. The full waveforms of the input current versus the input voltage at these dimming modes are shown in the Fig. 5.

The performance of the AC LED driver against the dimming was also calculated to show the robustness of the proposed step-dimmer. Fig. 6 shows the curves of calculated PF and THD against the dimming modes at 25%, 50%, 75% and 100% dimming conditions, respectively. As shown in Fig. 6, there is a slight variation of PF and THD at different dimming modes with $\text{PF} = 0.9984$, $\text{THD} = 5.672\%$ at full dimming mode and $\text{PF} = 0.99776$, $\text{THD} = 6.705\%$ at 25% dimming mode that all comply the IEC 61000-3-2 class C. This small variation is mainly caused by the variation of the forward voltage according to the changing of the forward current on the LED strings which makes the step-like sinusoidal input current vary slightly; however, this variation is very small and can be neglected.

Fig. 6. Simulated PF and THD against dimming modes.

| Refs. | PF    | THD  | Number of LED strings | Power (W) | Circuit structure | Dimming function |
|-------|-------|------|-----------------------|-----------|-------------------|------------------|
| [1]   | 0.99  | >25% | 2                     | 4         | Simple            | N/A              |
| [2]   | 0.97  | >24% | 2                     | 4         | Complex           | N/A              |
| [3]   | >0.99 | <10% | 6                     | 22        | Simple            | N/A              |
| [4]   | >0.998| <5%  | 10                    | 38        | Complex           | Available        |
| This work | >0.997| <7%  | 8                     | 4.4       | Simple            | Available        |

The performance comparison of the proposed design with another AC LED drivers is presented Table I. There are two important points that should be clearly understood in order to make a fair comparison between these works with the proposed design. Firstly, the PF is increased (and THD is decreased) as the number of LED strings increases. Secondly, the power (in Watts) of the works can be customized in the design process without changing the performance of the circuits. For instance, to increase the power in this work, either the dimming voltage can be
increased or the values of resistors RS1-RS8 in the PPC are decreased. As shown in the Table I, the proposed design can gain a very high PF and a low THD as compared with the non-dimmable designs in [1, 2, 3]. In comparison with the dimmable AC LED driver reported in [4], the proposed design owns the similar performance with a more simple circuit structure. Therefore, the proposed design makes itself a dominant solution in the design of low cost AC LED driver for outdoor lighting applications.

4 Conclusion

In this letter, a simple and effective analog dimming method using a step-dimmer for a monolithic AC LED driver has been presented. The dimming range can be flexibly customized according to the resolution of the step-dimmer. The theory analysis of the dimming method was derived, and the simulated results were consistent with it. The proposed scheme was verified with the simulation in the 0.35 um 700 V Magnachip process with very small variations in PF (< 1%) and THD (< 1.5%) at different dimming modes. Besides, the full level of integration and simplicity in design make the proposed dimming circuit in accompanying with the utilized PPC as a compact, reliable and cost-effective solution, thus well suited for use in designing AC LED drivers.

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