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Line voltage compensation technology for AC-direct multiple-string LED drivers

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Abstract: An AC-mains voltage compensation technology for variable load multiple-string LED drivers is presented. By forming a closed loop control of the multiple reference voltages and by introducing an external compensation resistor, the output luminance is well compensated in case of line voltage variations. The proposed technology along with the accompanied AC-direct multiple-string LED driver were integrated in an 1 µm trench-isolated BCD process and tested with a three-string prototype. With very few external components used, the line regulation character of the LED driver is highly optimized by the proposed technology. The experimental results show that within 15% AC-mains voltage tolerance, the output luminance deviation is restrained to 2.0% (1.5%) under 10 W, 110 V/AC (220 V/AC), 50 Hz conditions.

Keywords: LED, AC driver, line regulation, multi-string LED

Classification: Electron devices, circuits, and systems

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1 Introduction

LED can offer 270% more luminance than a fluorescent bulb of the same power, and is regarded as the most promising light source for the next generation [1, 2]. Various attempts have been made to increase the power factor (PF) and eliminate expensive and relatively short-lived components such as magnetic transformer and electrolytic capacitor [3]. Among these attempts, AC-direct multiple-string LED driver technology stands out [4, 5]. Due to its properties of low lost, high PF and high efficiency, the technology has been widely implemented in commercial lamps. Based on the topology, several improvements have been found in the literature, in [6], [7], and [8], soft self-commutating technology is introduced instead of hard switching for lower THD. In [9], single reference and twin-switch topology is implemented for better noise rejection and adjustable current ratio.

However, in conventional AC-direct multiple string LED drivers, represented by [6], [7] and [9], the current regulation level is fixed. The LED driver described in [10] proposed a variable current level, but only for dimming functions. Unlike the switched mode power supply (SMPS) solutions designed for universal AC input [11, 12], one of the major flaws for the AC-direct multiple-string LED driver is the luminance variation due to the AC-mains voltage tolerance. The root mean square (RMS) value of the AC-mains voltage changes slowly and periodically, which has great impact on the input power of the traditional AC-direct LED driver, resulting in different luminance output. In this letter, a line voltage compensation technology for AC-direct multiple-string LED driver is proposed. By forming a feedback loop control of the multiple reference voltages and by using a compensation resistor, the output luminance can be well constrained in case of a deviated AC-mains voltage.

2 Principle of proposed technology

As shown in Fig. 1, the block diagram outside the dashed box illustrates a typical three-string AC-direct LED driver topology, similar topologies can be found in various commercial AC-direct LED lamps.

The detailed working principle of the circuitry can be found in [8]. The block diagram of the proposed line voltage compensation method is shown inside the dashed box. The structure consists of a bandgap reference, an integrator, an operational amplifier (OP4), a compensating resistor R_{comp}, a capacitor C_{comp}, a buffer (BUF), and a set of resistor divider ($R_{d1\sim3}$). The voltage across R_{sense} is denoted as V_{sense}, which is generated by current of two branches, one branch flows

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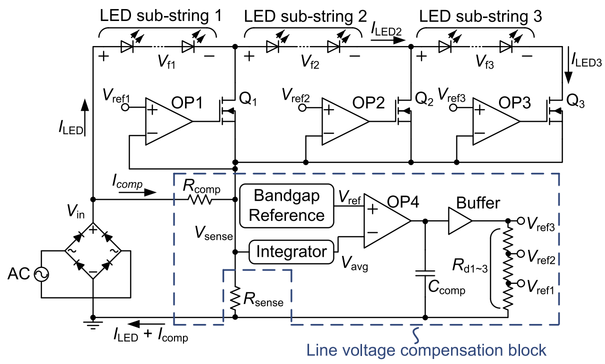

Fig. 1. Block diagram of proposed line voltage compensation technology.

through LED strings, denoted as I_{LED}, the other branch flows through R_{comp}, denoted as I_{comp}. Considering that V_{sense} is negligible compared to the rectified input voltage V_{in}, I_{LED} can thus be derived as

$$V_{\text{sense}} = \left(\frac{V_{\text{in}}}{R_{\text{comp}}} + I_{\text{LED}}\right) \cdot R_{\text{sense}} \tag{1}$$

The integrated signal of V_{sense}, denoted as V_{avg}, is sent to the negative input terminal of OP4. The positive input signal of OP4 is a zero temperature coefficient voltage reference V_{ref}. C_{comp} is introduced to generate a dominant pole, thus compressing the bandwidth of the system to 10 Hz~20 Hz, in order to properly respond to the signal of V_{sense} (approx. 100 Hz). The buffer acts as a voltage follower, generating multiple references $V_{\text{ref1}} \sim V_{\text{ref3}}$. The constant multiple references in the conventional drivers are replaced by variable references $V_{\text{ref1}} \sim V_{\text{ref3}}$ generated according to the averaged current of LED sub-string 1, forming a negative feedback loop.

The forward voltages of each LED sub-string are indicated by $V_{\text{f1}} \sim V_{\text{f3}}$, respectively, which are independent from input voltage variations. Therefore, a larger RMS value of the AC-mains voltage will inevitably cause an earlier turn-on, and a later turn-off of the each LED sub-string, resulting in a larger I_{LED} duty cycle within each half-wave cycle of the input voltage, as illustrated in Fig. 2. Note that the duty cycle variation becomes larger when the V_{f} of an LED string gets higher, the relationship holds for increased or decreased AC-mains voltages, e.g., $|\Delta d_1| > |\Delta d_2| > |\Delta d_3|$ in Fig. 2.

The normal I_{LED} curve under normal V_{in} is marked with blue triangles, while the uncompensated I_{LED} curve under 115% V_{in} is marked with red circles. The D_1, D_2 and D_3 represents the turn on duty cycle of Q_1, Q_2, and Q_3 within one half-wave cycle, respectively. Neglecting the transition periods of transistors Q_1 Q_3, the output power can be approximated as

$$P_{\text{out}} \approx \frac{V_{\text{f1}}(D_1 V_{\text{ref1}} + D_2 V_{\text{ref2}} + D_3 V_{\text{ref3}})}{R_{\text{sense}}} + \frac{V_{\text{f2}}(D_2 V_{\text{ref2}} + D_3 V_{\text{ref3}})}{R_{\text{sense}}} + \frac{V_{\text{f3}} D_3 V_{\text{ref3}}}{R_{\text{sense}}} \tag{2}$$

In response to higher AC-mains voltage, D_1, D_2 and D_3 in (2) will increase to αD_1, βD_2 and γD_3, respectively, resulting in a larger P_{out} if the new duty cycles are substituted in (2). Note that $1 < \alpha < \beta < \gamma$ in this case. For a lower AC-mains voltage, $\gamma < \beta < \alpha < 1$ according to the previous discussion on Fig. 2.

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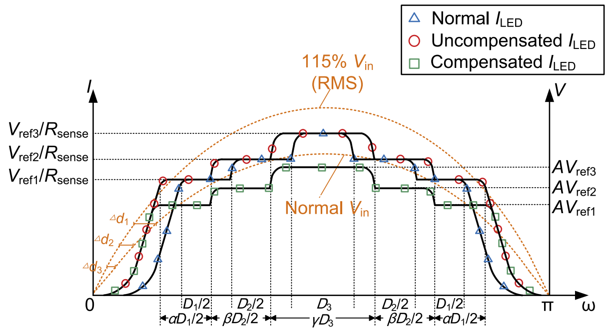

Fig. 2. The normal, uncompensated and compensated I_{LED} waveforms.

The 1st, 2nd and 3rd terms in (2) represents the power of LED sub-string 1, 2 and 3 respectively. The I_{comp} branch in Fig. 1 is disconnected temporarily to simplify the analysis. As V_{avg} solely represents the current flows through LED sub-string 1, by regulating multiple references from $V_{ref1} \sim V_{ref3}$ to $A \cdot V_{ref1} \sim A \cdot V_{ref3}$, respectively, where A is the compensation factor,

$$A = \frac{D_1 V_{ref1} + D_2 V_{ref2} + D_3 V_{ref3}}{\alpha D_1 V_{ref1} + \beta D_2 V_{ref2} + \gamma D_3 V_{ref3}} \tag{3}$$

The feedback loop stabilizes the power of the LED sub-string 1 automatically, and helps to compensate the power of the other two LED sub-strings as derived in the 2nd and 3rd terms of (2).

However, A is not enough to fully compensate the power increment of LED sub-string 2 and 3. For example, the proper compensation factor A' to accurately compensate the power of LED sub-string 2, or the 2nd term of (2) should be:

$$A' = \frac{D_2 V_{ref2} + D_3 V_{ref3}}{\beta D_2 V_{ref2} + \gamma D_3 V_{ref3}} \tag{4}$$

And that

$$A - A' = \frac{\gamma + \beta - 2\alpha}{(\alpha D_1 V_{ref1} + \beta D_2 V_{ref2} + \gamma D_3 V_{ref3})(\beta D_2 V_{ref2} + \gamma D_3 V_{ref3})} \tag{5}$$

For higher AC-mains voltage, $A > A'$, while for lower AC-mains voltage, $A < A'$, which means under compensation will occur when the system multiplies the 2nd and 3rd terms of (2) by A. By connecting R_{comp} to the upper terminal of R_{sense}, a small current proportional to V_{in} is introduced to restrain I_{LED} further. The inhibition level of the I_{LED} is inversely proportional to the RMS value of V_{in}, the under compensation can thus be balanced. The value of R_{comp} is selected by experimental approach.

3 Experimental results of the technology

The proposed technology, along with the accompanied AC-direct multiple-string LED driver are fabricated with an 1 µm trench-isolated BCD process based upon silicon on insulator (SOI) technology for better noise immunity. The die photograph and the distribution of each block is shown in Fig. 3.

With the integration of three UHV LDMOS devices (Q1 ~ Q3 in Fig. 1), the chip size is 1.4 mm × 2.5 mm. The relatively larger C_{comp} and integration capacitors are designed off-chip. Key parameters of the prototype is shown in Table I.

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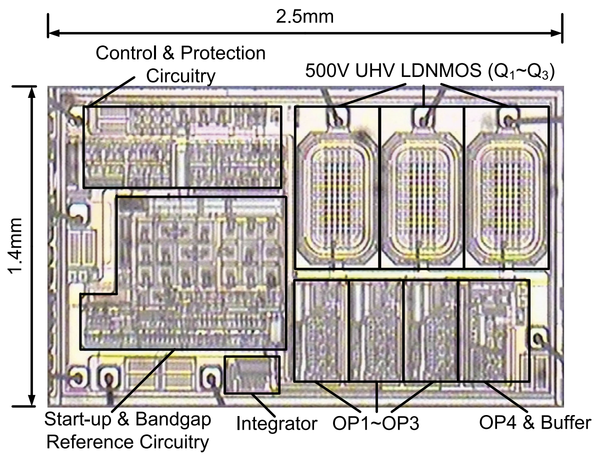

Fig. 3. Micrograph of fabricated LED driver with proposed technology.

Table I. Key parameters of proposed prototype

Parameter	Definition	Value
V_{ref}	reference voltage	1.0 V
$Prop.V_{\mathrm{ref1\sim3}}$	$V_{\mathrm{ref1}} : V_{\mathrm{ref2}} : V_{\mathrm{ref3}}$	0.8 : 0.9 : 1
$R_{\mathrm{sense,220V/AC}}$	current sensing resistance for 220, 110 V/AC	14, 7 Ω
$nLED_{\mathrm{sub\text{-}string1\sim3}}$	LED number in sub-string 1~3	58 : 12 : 12 pcs
C_{int}	integration capacitance	4.7 µF
C_{comp}	compensation capacitance	10 µF
R_{comp}	compensation resistance 220, 110 V/AC	330 k, 470 k Ω

The measured I_{LED} waveforms under 220 V/AC with ±15% voltage deviation conditions are shown in Fig. 4.

The IC is also tested with 50 Hz, 110 V/AC and 220 V/AC under 10 W input power conditions. The output luminance variation under 110 V/AC and 220 V/AC with 15% voltage deviation conditions is shown in Fig. 5.

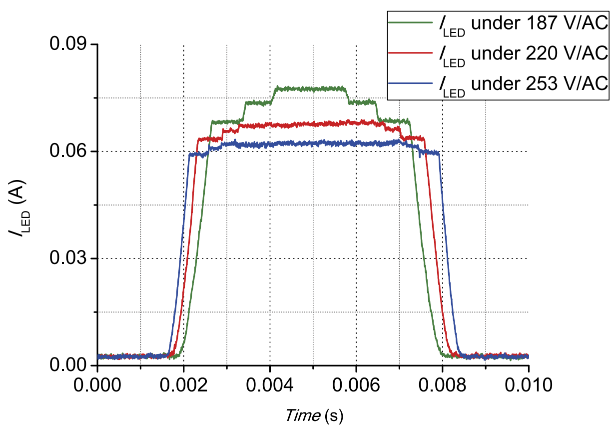

Fig. 4. Tested I_{LED} under 220 V/AC 15% variations.

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Less than 2.0% and 1.5% luminance variation under 110 ± 15% V/AC and 220 ± 15% V/AC conditions is obtained, respectively, demonstrating that the technology proposed is highly effective in stabilizing the output luminance in case of AC input variations.

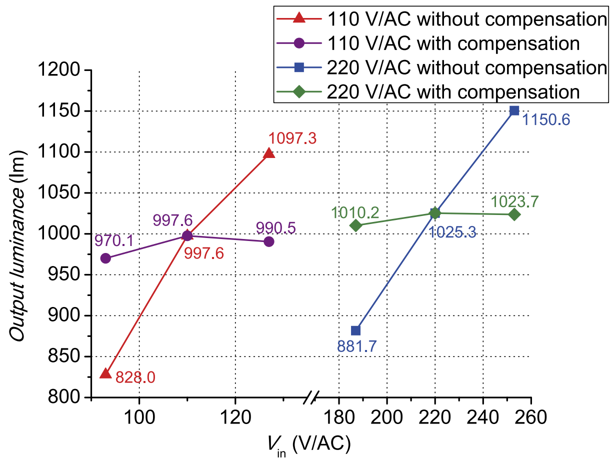

Fig. 5. Luminance variation test results.

4 Conclusion

A line voltage compensation technology for AC-direct multiple-string LED drivers is shown in this letter. By forming a closed loop control of the multiple reference voltages and by introducing an external compensation resistor, the output luminance can be well compensated in case of line voltage variations. A three-string, AC-direct LED driver with the presented structure is designed and fabricated in an 1 µm trench-isolated BCD process based upon SOI technology. The experimental results show that the output luminance variation is less than 2.0% (1.5%) under 110 V/AC (220 V/AC) ±15% conditions. The proposed technology can also be implemented in other soft self-commutating LED driver topologies, including the structures described in [7], [9] and [10].

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