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A New Current Mirror Balancing Circuit for AC-LED Lighting

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ABSTRACT This paper proposes a new current balancing method for alternating current (AC) - light emitting diodes (LED). The proposed method uses the bi-directional current mirror circuit with negative feedback that consists of two reference currents, n+1 NPN transistors, n+1 PNP transistors, and 2(n+1) resistors for n pairs of anti-parallel LED strings. It can balance the LED currents in multiple AC-LED strings regardless of the polarity of the AC source while reducing the differences in LED currents caused by the early effect. In addition, the proposed circuit can achieve LED current balancing even in the variations of parameters among the transistors due to the negative feedback operation. Simulations and experiments were performed to verify the effectiveness of the proposed circuit. The balancing operation of the proposed circuit was simulated at low (50/60 Hz) and high (60 kHz) frequencies. In addition, open/short protection, power factor, and efficiency of an LED driver using the proposed circuit were analyzed and compared with a basic mirror circuit. For the experiments, a prototype was built and tested for 5W LED lighting consisting of three pairs of anti-parallel LED strings. The maximum LED current difference Δi_{LED} was reduced from 45 mA to 4 mA by the balancing operation of the proposed circuit.

INDEX TERMS AC-LED, current mirror circuit, current balancing, multiple LED strings, early effect.

I. INTRODUCTION

AC indirect and direct LED divers have been used in LED lighting applications. An AC indirect LED driver requires a power factor correction and a converter. The use of power conversion circuits increases the cost and size of a lighting device and reduces the power efficiency of a lighting system, instead of meeting the power factor and flicker recommendations [1], [2]. On the other hand, an AC direct LED driver is directly connected to an AC line voltage of $110V_{AC}/220V_{AC}$ without using circuits [3]. As a result, it has advantageous in efficiency, size, and cost, but may suffer from flicker and power factor issues. The change in brightness of AC-LEDs causes the flicker problem that has a harmful effect on the human body, which is especially important in indoor lighting applications such as offices, schools, hospitals, etc. The report described in IEEE Standard PAR1789 states on the biological effects of flicker and provides strong recommendations

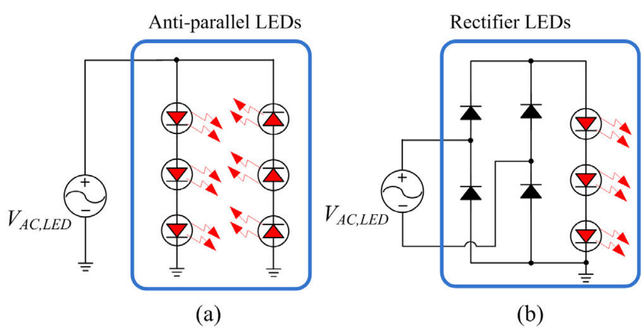

FIGURE 1. Two conventional arrangements of AC-LEDs for AC-direct LED driver: (a) Anti-parallel string configuration (anti-parallel LEDs) and (b) Bridge-rectifier configuration (rectifier LEDs).

for flicker index [4], [5]. Most AC direct LED drivers for indoor lighting applications should meet these recommendations [6], [7]. On the other hand, the negative impact and complaints of flicker can be very small in outdoor environments such as streets and parking lots [8], [9]. Therefore, many LED drivers for outdoor LED applications are still being used

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without considering the flicker problem. Along with flicker, power factor is a very important index for LED lamps. The Energy Star Program and EU regulation 1194/2012 define the power factor requirement according to the LED lamp power [10], [11]. Since the AC direct LED driver does not use a power factor correction, it requires designs and methods to meet these requirements [7].

There are two conventional arrangements of AC-LEDs for AC-direct LED driver, which are shown in Fig. 1 [3]. The anti-parallel string configuration consists of pairs of anti-parallel LED strings. A pair of anti-parallel LED strings consist of two LED strings connected in parallel (Fig. 1(a)). The number of LEDs which are serially connected in a LED string is equal to that in the other LED string, while the directions of the LEDs are the opposite of each other. Each LED string can be driven by the AC source without the rectifier diodes, but it can only be operated during the half AC line cycle. The rectifier LED configuration (Fig. 1(b)) consists of rectifier diodes and LEDs. It can be operated during the entire AC line cycle because the rectifier diodes convert AC to DC. However, due to the diodes, the cost of the circuit increases and the power efficiency decreases [3], [12].

In lighting applications requiring high brightness, such as street lighting, factory lighting, and traffic lighting, LEDs must be connected in a multistring in order to produce the required level of brightness. The most preferred method for a multistring of LEDs is series-parallel connection. For the series-parallel connection, several or dozens of LEDs are connected in series to form a single LED string, and these strings are connected in parallel. However, LED current imbalance occurs between LED strings due to the manufacturing tolerance and different operating temperatures of LEDs. This leads to a non-uniform distribution of light and poor lighting quality [12].

Many current balancing methods have been studied to improve the current imbalances between LED strings [6], [12]–[19]. The linear current regulator (Fig. 2(a)) is a conventional method for balancing LED currents between LED strings connected in parallel. It consists of an Op-amp, a resistor, and a BJT, and is required for each LED string. Due to the negative feedback control using the semiconductor devices (an Op-amp and a BJT), the linear current regulator can achieve accurate current balancing. However, it requires an independent power source for Op-amps and can only be applied to DC LEDs and rectifier LEDs [13], [14]. Another balancing method using semiconductor devices is current mirror circuit (Fig. 2(b)). It has low cost and small size, because it consists of only NPN transistors that do not need an independent power source. However, as the number of LED strings increases, its accuracy for the LED current balancing decreases. In order to improve this accuracy degradation, an NPN transistor with high current gain (β) should be used for a balancing circuit. In addition, it can only be applied to the DC LEDs and rectifier LEDs in common with the linear current regulator, and has a limit of balancing accuracy due to the early effect [15], [16].

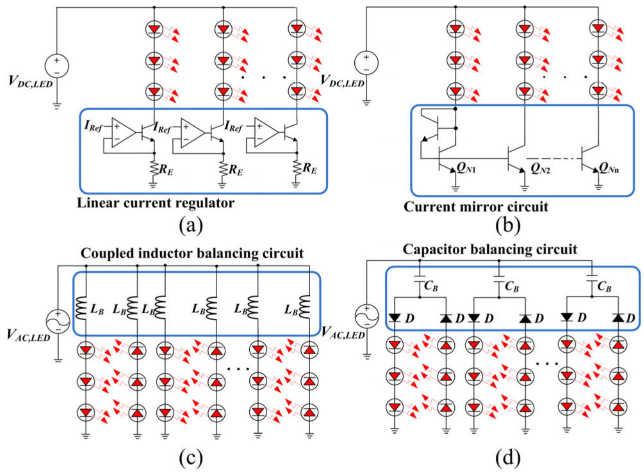

FIGURE 2. **Current balancing methods for multiple LED strings: (a) linear current regulator, (b) current mirror circuit, (c) coupled inductor balancing circuit, and (d) capacitor balancing circuit.**

Balancing methods using reactive components (Fig. 2(c) and (d)) have been proposed to improve the current imbalances between parallel connected LED strings, regardless of the arrangements of AC-LEDs. Since these balancing methods use coupled inductors and capacitors, they cause little power dissipation for LED current balancing, unlike the balancing method using semiconductor devices [6], [17]–[19]. The coupled inductor balancing circuit (Fig. 2(c)) requires coupled inductors for the current balancing of the multiple LED strings. The main disadvantage of this method is that it is not a suitable method for a LED driver with a large number of LED strings, because the couple inductors are generally more expensive and larger than other elements such as semiconductors and capacitors [6], [17]. The capacitor balancing circuit (Fig. 2(d)) uses capacitors with the same impedance for the current balancing of LED strings. The current of each LED string is controlled by the impedance of the capacitor. Since capacitors are smaller and less expensive than coupled inductors, it can be applied to the LED driver with a large number of LED strings. However, it is designed based on half or full bridge converters and uses a resonant tank to reduce a reactance due to capacitors. This complicates the design and control of LED driver circuits [18], [19].

As mentioned above, the balancing method using semiconductor devices causes power dissipation even though they have high current balancing accuracy. In addition, it cannot be applied to anti-parallel LED strings. On the other hand, the balancing method using reactive components rarely causes power dissipation and can be used regardless of the arrangements of AC-LEDs. However, it complicates design and control of LED driver circuits and is not easy to apply to a large number of LED strings. In order to solve these problems, a new balancing method using semiconductor devices is proposed in this paper. The proposed method uses the bidirectional current mirror circuit with negative feedback consisting of two reference currents, NPN transistors, PNP

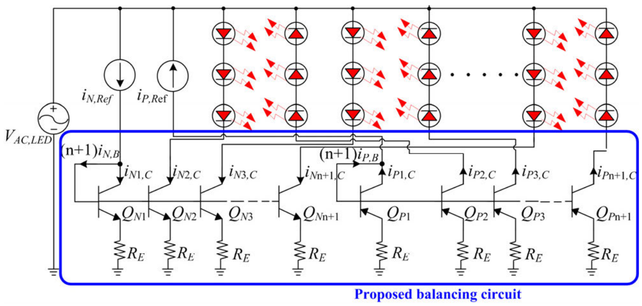

FIGURE 3. Proposed balancing circuit.

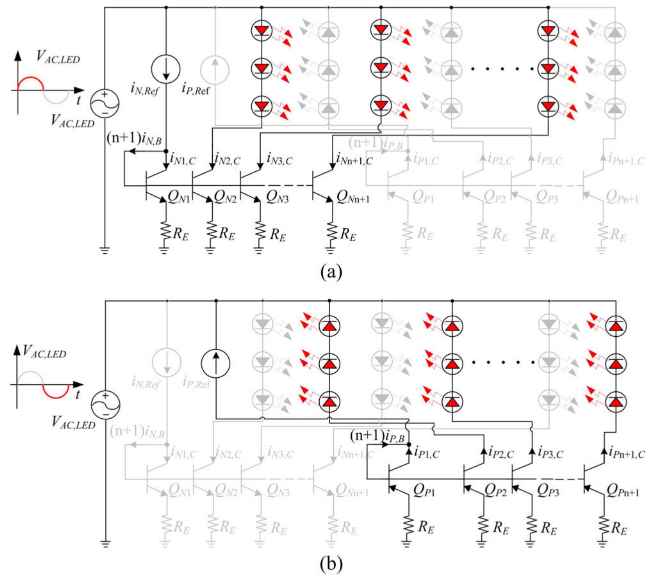

FIGURE 4. Operating modes of the proposed balancing circuit: (a) mode 1 [$V_{AC,LED} \geq 0$] and (b) mode 2 [$V_{AC,LED} < 0$].

transistors, and resistors for the multiple anti-parallel LED strings. Due to the current mirror operation with negative feedback, it can achieve accurate current balancing and have a small size. In addition, it can be used for both the AC indirect LED driver and AC direct LED driver. Various simulations and experiments were performed to verify the operation and effectiveness of the proposed balancing method. This paper is organized as follows. The circuit structure, operation principle and power loss analysis of the proposed balancing method are explained in Section II. The comparison of balancing circuits is given in Section III. The simulation and experiment results are described in Section IV and Section V, respectively. Finally, a conclusion is given in Section VI.

II. PROPOSED CURRENT BALANCING CIRCUIT

As described above, LED current imbalance occurs between multiple LED strings. This leads to a non-uniform distribution of light and poor lighting quality. A new bi-directional current mirror circuit with negative feedback (Fig. 3) is proposed in order to improve the LED current imbalance in multiple anti-parallel LED strings connected in parallel. It can balance the LED currents in multiple AC-LED strings regardless of the polarity of the AC source while reducing the differences in LED currents caused by the early effect. In addition, the proposed circuit can achieve LED current balancing even in the variations of parameters among the transistors due to the negative feedback operation.

A. CIRCUIT STRUCTURE

The proposed balancing circuit consists of two reference currents ($i_{N,Ref}$ and $i_{P,Ref}$), n+1 NPN transistors (Q_Ns), n+1 PNP transistors (Q_Ps), and 2(n+1) resistors (R_Es) for LED current balancing in n pairs of anti-parallel LED strings. BJTs (Q_Ns and Q_Ps) perform the current mirror operation and resistors (R_Es) form the negative feedback loop reducing the differences in the LED currents caused by the early effect.

As shown in Fig. 3, in the LED strings on odd lines, the anode of the LED at the top of each LED string is connected to $V_{AC,LED}$, and the cathode of the LED at the bottom of each LED string is connected to the NPN transistor (Q_N). In order to perform the current mirror operation for all LED strings on the odd lines, the reference current ($i_{N,Ref}$) is connected to the NPN transistor (Q_{N1}). Then the collector and base of Q_{N1} are tied together, and the bases of all NPN transistors are tied together. By contrast, in the LED strings on even lines, the cathode of the LED at the top of each LED string is connected to $V_{AC,\ LED}$, and the anode of the LED at the bottom of each LED string is connected to the PNP transistor (Q_P). For the current mirror operation among all LED strings on the even lines, the reference current ($i_{P,Ref}$) is connected to the PNP transistor (Q_{P1}). Then the collector and base of Q_{P1} are tied together, and the bases of all PNP transistors are tied together. To balance all LED currents in multiple anti-parallel LED strings, the two reference currents ($i_{N,Ref}$ and $i_{P,Ref}$) have the same magnitude but in opposite directions. In addition, for negative feedback operation, resistors (R_Es) are connected in series with the BJTs (Q_N or Q_P), respectively.

B. OPERATION PRINCIPLES

The proposed bi-directional current mirror circuit has two operation modes: When the LED driving voltage $V_{AC,LED} \geq 0$, the NPN transistors perform the current mirror operation to balance the LED currents (mode 1). Conversely, when $V_{AC,LED} < 0$, the PNP transistors perform the current mirror operation to balance the LED currents (mode 2). As a result, the proposed balancing circuit can balance the LED currents in multiple anti-parallel LED strings, regardless of the polarity of $V_{AC,LED}$. The operating mode of the proposed balancing circuit was analyzed under the following assumptions: 1) the BJTs for the current mirror operation are operated in the active region. 2) All of the NPN transistors are matched and have the same current gain (β_N). 3) All of the PNP transistors are matched and have the same current gain (β_P).

Mode 1 [Fig. 4(a), $V_{AC,LED} \geq 0$]: When $V_{AC,LED} \geq 0$, the reference current ($i_{N,Ref}$) and LED strings on odd lines are turned on, but the reference current ($i_{P,Ref}$) and LED strings on even lines are turned off. Meanwhile, the NPN transistors (Q_Ns) perform the current mirror operation because they are working in the active region (see Fig. 4(a)). If the emitter resistors (R_Es) are zero, all of the NPN transistors (Q_Ns) have the same base-emitter voltage (V_{BE}). If the NPN transistors with the same V_{BE} are matched, their base currents are equal. Therefore, $i_{N,Ref}$ is given by

$$i_{N,Ref} = i_{N1,C} + (\mathrm{n}+1)\, i_{N,B} \tag{1}$$

where $i_{N,Ref}$ is the reference current for the LED strings on the odd lines, $i_{N1,C}$ is the collector current of Q_{N1}, n is the number of the LED strings on odd lines, and $i_{N,B}$ is the base current of Q_N.

Because $i_{N1,C} = \beta_N i_{N,B}$, equation (1) can be expressed as

$$i_{N,\mathrm{Ref}} = \beta_N i_{N,B} + (\mathrm{n}+1)\, i_{N,B} = (\beta_N + \mathrm{n}+1)\, i_{N,B} \tag{2}$$

where β_N is the current gain of an NPN transistor.

Assuming that all of the NPN transistors have infinite early voltage (V_A), their collector currents ($i_{N,C}$s) satisfy the following relation:

$$i_{N1,C} = i_{N2,C} = i_{N3,C} = \cdots = \beta_N i_{N,B}. \tag{3}$$

From equations (2) and (3),

$$i_{N1,C} = i_{N2,C} = i_{N3,C} = \cdots = \frac{\beta_N i_{N,Ref}}{(\beta_N + n + 1)}. \tag{4}$$

Equation (4) shows that the LED currents in the LED strings on the odd lines are all the same, except for the LED current ($i_{N,Ref}$) in LED sting-1. The LED current difference (Δi_N) between $i_{N,Ref}$ and other currents is given by

$$\Delta i_N = \left(1 - \frac{\beta_N}{\beta_N + n + 1}\right) i_{N,Ref}. \tag{5}$$

However, even though the current mirror circuit is operating, $i_{N,C}$s can have different values, because the early voltages (V_As) of the practical NPN transistors are finite. When taking the finite V_A into account, the collector current $i_{N,C}$ is expressed as

$$i_{N,C} = I_S \left(e^{\frac{V_{N,BE}}{V_T}} - 1\right)\left(1 + \frac{V_{N,CE}}{V_A}\right). \tag{6}$$

NPN transistors have different collector-emitter voltages ($V_{N,CE}$s) for balancing LED currents while the current mirror is operating; as shown in equation (6), these different $V_{N,CE}$s cause the differences between $i_{N,C}$s. In order to solve this problem, the base-emitter voltage ($V_{N,BE}$) of Q_N is adjusted by connecting a resistor (R_E) to the emitter of the Q_N in each LED string. Because $i_{N,C} \gg i_{N,B}$, the emitter current $i_{N,E}$ of Q_N is almost the same as $i_{N,C}$. As a result, $V_{N,BE}$ is given by

$$V_{N,BE} = V_{N,B} - V_{N,E} \approx V_{N.B} - i_{N,C} R_E \tag{7}$$

where $V_{N,B}$ and $V_{N,E}$ are the base and emitter voltages of Q_N, respectively. Because the base terminals of all Q_Ns are tied together, they all have the same $V_{N,B}$. According to equations (6) and (7), the $i_{N,C}$ in the LED string with the higher $V_{N,CE}$ is larger than those in the other LED strings, but

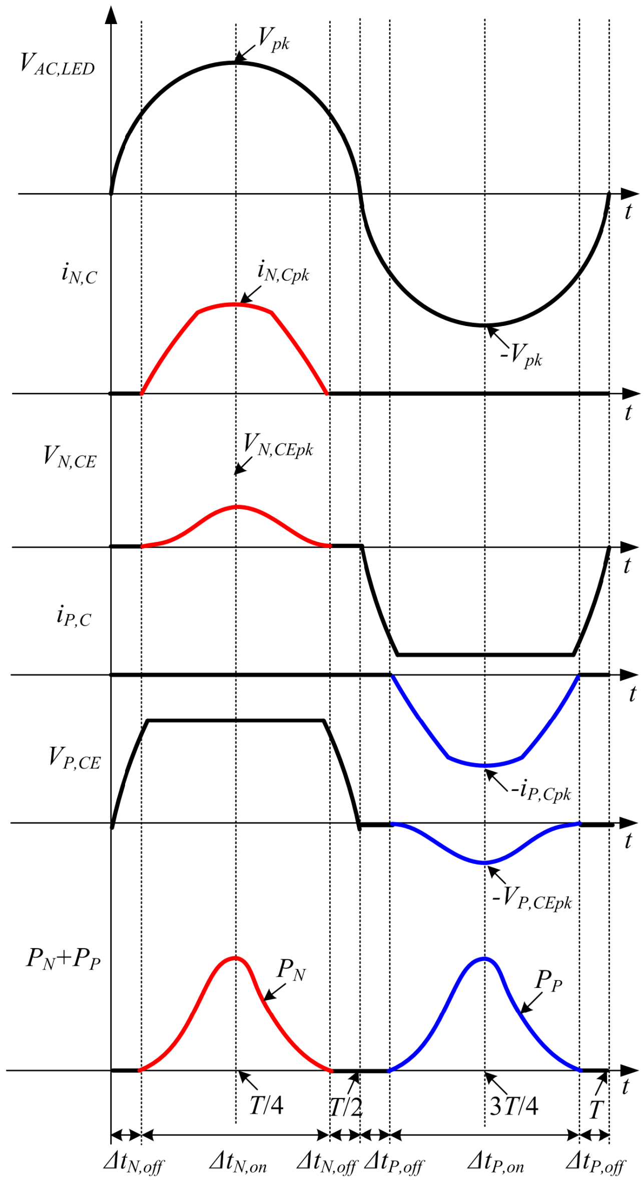

FIGURE 5. Key waveforms during one period T of $V_{AC,LED}$ when LED currents in the multiple anti-parallel LED strings are balanced by the proposed circuit.

it is decreased by having a lower $V_{N,BE}$ due to the negative feedback operation of R_E. The proposed balancing circuit can perform more accurate current balancing than a basic current mirror circuit by using the negative feedback operation.

Mode 2 [Fig. 4(b), $V_{AC,LED} < 0$]: When $V_{AC,LED} < 0$, the reference current ($i_{P,Ref}$) and LED strings on even lines are turned on, but the reference current ($i_{N,Ref}$) and LED strings on odd lines are turned off. In this mode, the PNP transistors (Q_Ps) perform the current mirror operation because they are working in the active region (see Fig. 4(b)). Assuming that all of the PNP transistors have infinite early voltage (V_A), the LED current difference (Δi_P) between $i_{P,Ref}$ and other currents is given by

$$\Delta i_P = \left(1 - \frac{\beta_P}{\beta_P + \mathrm{n} + 1}\right) i_{P,Ref}. \tag{8}$$

When considering the finite V_A, the LED currents ($i_{P,Ref}$ and $i_{P,C}$s) in LED strings on even lines are balanced by the mirror circuit operation with negative feedback, as in the case of mode 1.

C. POWER LOSS ANALYSIS

Fig. 5 shows the key waveforms during one period T of a sinusoidal AC voltage ($V_{AC,LED}$) with a peak voltage V_{pk} when LED currents in the multiple anti-parallel LED strings are balanced by the proposed circuit.

As shown in Fig. 4(a), when $V_{AC,LED} \geq 0$, the LED currents ($i_{N,C}$s) in the LED strings on the odd lines flow under the following condition:

$$V_{pk} \sin(2\pi f t) \geq V_f \mathrm{m} + V_{N,th} \tag{9}$$

where $V_{L,th}$ and $V_{N,th}$ are the threshold voltages of the LED and NPN transistor, respectively and m is the number of LEDs in a LED strings.

The time interval $\Delta t_{N,off}$ from $t = 0$ to the time at which the $i_{N,C}$s start to flow is obtained by equation (9) as follows

$$\Delta t_{N,off} = \frac{1}{2\pi f} \sin^{-1}\left(\frac{V_f \mathrm{m} + V_{N,th}}{V_{pk}}\right). \tag{10}$$

As a result, during $\Delta t_{N,on}(= 0.5T - 2\Delta t_{N,off})$, the LED current $i_{N,C}$ in each LED string on the odd lines increases from 0 to $i_{N,Cpk}$, and then decreases from $i_{N,Cpk}$ to 0. Similarly, the collector-emitter voltage $V_{N,CE}$ of each NPN transistor increases from 0 to $V_{N,CEpk}$, and then decreases from $V_{N,CEpk}$ to 0. During this time, the proposed balancing circuit adjusts the collector-emitter voltages ($V_{N,CE}$s) to equalize all the LED currents ($i_{N,C}$s) to $i_{N,Ref}$ by using the mirror circuit operation with negative feedback. $V_{N,CE}$ becomes large for a LED string with the low impedance and vice versa for a LED string with the large impedance. For LED current balancing, the instantaneous power loss of each NPN transistor is the product of $i_{N,Ref}$ and $V_{N,CE}$. As a result, the average power loss $P_{N\mathrm{k}}$ of the kth NPN transistor ($Q_{N,\mathrm{K}}$) on odd lines during one period T is given by

$$P_{N\mathrm{k}} \approx \frac{1}{T}\int_{\Delta t_{N,off}}^{0.5T-\Delta t_{N,off}} i_{N,ref}(t)\, V_{N\mathrm{k},CE}(t)\, dt. \tag{11}$$

In addition, the average power loss P_{RN} of a R_E connected in series with each NPN transistor is given as follows

$$P_{RN} \approx \frac{R_E}{T}\int_{\Delta t_{N,off}}^{0.5T-\Delta t_{N,off}} i_{N,ref}^2(t)dt. \tag{12}$$

As shown in Fig. 4(b), when $V_{AC,LED} < 0$, the LED currents ($i_{P,C}$s) in the LED strings on the even lines flow under the following condition:

$$V_{pk} \sin(2\pi f t) \geq V_f \mathrm{m} + V_{P,th} \tag{13}$$

where $V_{P,th}$ are the threshold voltage of a PNP transistor.

The time interval $\Delta t_{P,off}$ from $t = T/2$ to the time at which the $i_{P,C}$s start to flow is obtained by equation (14) as follows.

$$\Delta t_{P,off} = \frac{1}{2\pi f} \sin^{-1}\left(\frac{V_f \mathrm{m} + V_{P,th}}{V_{pk}}\right) \tag{14}$$

To equalize all $i_{P,C}$s to $i_{P,Ref}$, the proposed balancing circuit adjusts the collector-emitter voltage ($V_{P,CE}$) of each PNP transistor in the same way as NPN transistors. The instantaneous power loss of each PNP transistor is the product of $i_{P,Ref}$ and $V_{P,CE}$. As a result, the average power loss $P_{P\mathrm{k}}$ of the kth PNP transistor ($Q_{P\mathrm{k}}$) on even lines during one period T is given by

$$P_{P\mathrm{k}} = \frac{1}{T}\int_{\Delta t_{P,off}}^{0.5T-\Delta t_{P,off}} i_{P,ref}(t)\, V_{P\mathrm{k},CE}(t)dt. \tag{15}$$

In addition, the average power loss P_{RP} of a R_E connected in series with each PNP transistor is given as follows

$$P_{RP} \approx \frac{R_E}{T}\int_{\Delta t_{P,off}}^{0.5T-\Delta t_{P,off}} i_{P,ref}^2(t)dt. \tag{16}$$

For a pair of anti-parallel LED strings, the proposed balancing circuit uses an NPN transistor (Q_N), a PNP transistor (Q_P), and two resistors (two R_Es). As a result, the average power loss $P_{A\mathrm{k}}$ of the proposed circuit for the kth pair of anti-parallel LED strings during one period T of a $V_{AC,LED}$ is given by

$$P_{A\mathrm{k}} \approx P_{N\mathrm{k}} + P_{RN} + P_{P\mathrm{k}} + P_{RP}. \tag{17}$$

To balance the LED currents in n pairs of anti-parallel LED strings, the total average power loss (P_{BC}) of the proposed balancing circuit is given as follows

$$P_{BC} = P_{ref} + \sum_{k=1}^{n} P_{Ak}. \tag{18}$$

where P_{ref} is the sum of the average power losses of two reference currents ($i_{N,Ref}$ and $i_{P,Ref}$), two transistors (Q_{N1} and Q_{P1}), and two resistors (R_Es). It has a different value depending on the type of reference currents.

D. DESIGN CONSIDERATION

Voltage swell or surge voltage may occur in LED driving voltage ($V_{AC,LED}$) due to various external environments. In the proposed circuit, the transistor absorbs the voltage difference between the LED strings and $V_{AC,LED}$. Therefore, transistor should be designed considering the voltage swell and LED short event. In addition, surge protection devices and LED short protection circuit are needed to protect transistors before absorbing voltage above the maximum collector-emitter voltage (V_{CEO}) of the transistor.

Since the magnitude of the surge voltage can be hundreds to several kV, the LED driving circuit including the transistors can be destroyed [20]. Therefore, surge protection devices (SPDs) should be used with the proposed balancing circuit. In the event of voltage swell on LED operating voltage ($V_{AC,\,LED}$), the collector-emitter voltage (V_{CE}) of the transistor will increase. However it should not exceed the V_{CEO} defined as the calculated V_{CE} when a short event occurred in the LED string. Therefore, in the case of V_{CE} higher than V_{CEO}, the transistors are protected by a short protection circuit. The V_{CE} varies with the sinusoidal AC power circuit and has a maximum value ($V_{N,CEpk}$) at $T/4$. $V_{N,CEpk}$ represents the voltage difference between the LED string and the $V_{AC,LED}$ at $T/4$ and is given as follows:

$$V_{N,CEpk} = V_{pk} - m\left(V_{L,th} + i_{N,\text{ref\_pk}} \times R_{LED}\right) \quad (19)$$

where $V_{L,th}$ and R_{LED} refer to the threshold voltage and resistance of the LED, respectively. i_{n,ref_pk} ($= i_{N,Cpk}$) is the value of the reference current at $T/4$, and m is the number of LEDs in one LED string. V_{pk} is the peak voltage of the $V_{AC\cdot LED}$.

$V_{N,CEpk}$ should be less than the maximum collector-emitter voltage (V_{CEO}) of the transistor.

$$V_{N,CE} \leq V_{N,CEpk} < V_{CEO} \quad (20)$$

As shown in equation (21), V_{CEO} is determined to be more than the voltage obtained by multiplying the calculated $V_{N,CEpk}$ by the margin constant $\alpha(\geq 1)$ when one LED is shorted.

$$V_{CEO} \geq \alpha \times V_{N,CEpk} \quad (21)$$

In addition, the maximum current ($= i_{N,max}$) of the transistor should be greater than the maximum current ($i_{LED,max}$) of the LED multiplied by the margin constant $\beta(\geq 1)$.

$$i_{N,max} \geq \beta \times i_{LED,max} \quad (22)$$

The NPN transistor can be selected by considering the maximum values of voltage and current in equations (19) and (22). In the same way, the maximum voltage and current of the PNP transistor can also be calculated and selected.

III. COMPARISON OF BALANCING CIRCUITS

The comparison of the proposed and conventional balancing circuits is given in Table 1. The linear current regulator in [14], current mirror circuit in [16], and proposed balancing circuit can be applied to the DC LEDs. However, the capacitor balancing circuit in [19] and coupled inductor balancing circuit in [6] cannot be applied to the DC LEDs, because the reactive components (inductors and capacitors) of these balancing circuits can't have impedances required for LED current balancing at DC source. The capacitor balancing circuit, coupled inductor balancing circuit, and proposed balancing circuit can balance the LED currents in anti-parallel LEDs. However, the linear current regulator and current mirror circuit can only be operated during $V_{AC,LED} \geq 0$ because semiconductor devices must satisfy their operating conditions. As a result, they are applied to the rectifier LEDs with rectifier diodes or converters.

The linear current regulator, current mirror circuit, and proposed balancing circuit can achieve high balancing accuracy because they use semiconductor devices. In addition, the linear current regulator and proposed balancing circuit use the negative feedback technique as well as semiconductor devices to achieve higher balancing accuracy. On the other hand, the capacitor and coupled inductor balancing circuits use the reactive components such as inductors and capacitors for LED current balancing. Therefore, their balancing accuracy is not high because reactive components have discrete values with tolerances and it is difficult to match perfectly with each other. The impedances of the reactive components can be increased to increase the balancing accuracy, but this also increases the cost and size of a LED driver including the reactive components. In addition, the capacitor and coupled inductor balancing circuits complicate design and control of LED driver circuits and thus it is not easy to apply to a large number of LED strings.

The proposed balancing circuit and balancing circuits using reactive components can drive anti-parallel LEDs directly without rectifier diodes and converters. However, the balancing circuits using reactive components need the inductors or capacitors having the very large impedance at $V_{AC,LED}$ with low frequency. For this reason, theses balancing circuits have been generally used with converters that can convert the peak voltage and operating frequency of $V_{AC,LED}$. The linear current regulator and current mirror circuit have been also used with rectifier diodes or converters because they can only be applied to the DC LEDs. As a result, only the proposed balancing circuit can be practically used for AC-LEDs without rectifier diodes and converters.

The balancing circuits using reactive components require little power loss for LED current balancing because the practical coupled inductors and capacitors dissipate very little power in their parasitic resistances. On the other hand, other balancing circuits have some power loss due to semiconductor devices (transistors, MOSFET, or Op-amps). In addition, the linear current regulator and proposed balancing circuit incur the power loss in resistors as well as the power loss in semiconductor devices. However, the balancing circuits except the proposed balancing circuit are used with the converter or diode, resulting in additional power losses.

A coupled inductor generally has a larger size and higher cost than other components used for the balancing circuit. This will greatly increase the cost and size of a LED driver. A capacitor balancing circuit is smaller and less expensive than other methods. However, it needs converters and uses a resonant tank to reduce a reactance due to capacitors. The linear current regulator, current mirror circuit, and proposed balancing circuit use semiconductor devices and resistors with small sizes. However, they are somewhat expensive because they use semiconductor devices. Especially, linear current regulator is most disadvantageous in terms of cost because it uses Op-amps that need an independent power supply.

The number of components in each balancing circuit for 2n LED strings is given in Table 1. Since the balancing circuit of [6] uses a converter, the transformer and inductor are required. In addition, the balancing circuit of [6] uses an expensive control IC for the negative feedback operation of the converter, although it uses the fewest components. The balancing circuit of [14] do not require a converter for the balancing operation, but use more components than other balancing circuits. On the other hand, the proposed balancing

TABLE 1. Comparisons of the proposed and conventional balancing circuits.

	Linear current regulator [14]	Current mirror circuit [16]	Coupled inductor balancing circuit [6]	Capacitor balancing circuit [19]	Proposed balancing circuit
DC Balancing	○	○	×	×	○
AC Balancing	×	×	○	○	○
Accuracy	+++	++	+	+	+++
Driving Capacity	+++	+++	+	+	+++
Stand-alone	×	×	×	×	○
Power loss	+	++	+++	+++	+
Size	+++	+++	+	++	+++
Cost	+	++	++	+++	++
Number of Components	16n	10n	3.5n	5n+6	4n+8

○: Possible, ×: Impossible, +++: Excellent, ++: Good, +: Satisfactory

circuit does not use a converter and uses fewer components compared to other balancing circuits. However, it needs two current reference strings.

IV. MOEDLING AND SIMULATION RESULTS

The proposed balancing circuit was verified by simulation models built in PSIM. In the simulation, the balancing operation of the proposed circuit was performed at low (50/60 Hz) and high frequencies (60 kHz). In addition, open/short protection, power factor, and efficiency of an LED driver using the proposed circuit were analyzed by simulation and compared with other balancing circuits.

A. CURRENT BALANCING

For simulation, the LED driving voltage ($V_{AC,LED}$) was a sinusoidal AC voltage with frequency f of 60kHz and a peak voltage V_{pk} of 40 V. The peak values of both reference currents ($i_{N,Ref}$ and $i_{P,Ref}$) were 50 mA. Six LED strings were connected in parallel and each LED string consisted of six identical LEDs (V_f =∼ 5.85 V @ I_f = 50 mA). The current gains β_N and β_P of the transistors was 400 and 320, respectively. R_E was 1 Ω. In addition, in order to intentionally make a distinct impedance difference between six LED strings, the different resistor (91 Ω, 47 Ω, 75 Ω, 39 Ω, 62 Ω, and 30 Ω) was added to each of the LED strings.

When the proposed balancing circuit was not used, as shown in Fig. 6(a), the maximum current deviation between LED strings was 44.59 mA due to the impedance difference of each LED string. However, when the proposed circuit was used, as in Fig. 6(b), the maximum current deviation between LED strings was reduced to 1.23mA by current mirror balancing operation. The balancing operation of the proposed circuit was simulated at low frequency of 60Hz and calculated approximately the same as the results at high frequency (60 kHz).

B. FLICKER

Since the proposed method has the minimum brightness of 0, it will have 100% flicker when calculated by IEEE Standard PAR1789 [5]. The proposed method does not cause any flicker problem when used with an AC indirect LED driver that uses a converter operating at several to tens of kHz. However, it should be used for outdoor lighting applications where the effect of flicker is less important because it belongs to an operating area that is not recommended when used with AC direct LED driver.

C. OPEN/SHORT PROTECTION

LED strings are composed of many LEDs, so some LEDs in the string may be shorted or opened. This severely degrades the quality of LED-driving circuits and light sources [21]. Therefore, the LED short and open protection circuits (Fig. 7) were proposed to prevent these problems.

If some LEDs are shorted in an LED string, the impedance of the LED string will be reduced and the LED current($i_{N,C}$ or $i_{P,C}$) will increase. Then, the proposed balancing circuit reduces the LED current to the reference current($i_{N,Ref} = i_{P,Ref}$) by increasing $V_{N,CE}$ (at $V_{AC,LED} \geq 0$) or $V_{P,EC}$ (at $V_{AC,LED} < 0$). As shown in Fig. 7, the LED short circuit uses a comparator and a SR latch. The (+) terminal of a comparator has the largest value among $V_{N,CE}$ of the NPN transistor and $V_{P,EC}$ of the PNP transistor and the (−) terminal has the reference voltage $V_{s,ref}$. Here, $V_{s,ref}$ is determined by equation (23) considering when one LED is shorted in the LED string

$$V_{pk} - m \times \left(V_{L,th} + i_{N,ref\_pk} \times R_{LED}\right) < V_{s,ref} \leq V_{pk} - (m-1) \times \left(V_{L,th} + i_{N,ref\_pk} \times R_{LED}\right) \quad (23)$$

where $V_{L,th}$ and R_{LED} mean the threshold voltage and resistance of LEDs, respectively. i_{N,ref_pk} ($= i_{P,ref\_pk}$) is the peak value of the reference current at $T/4$, and m is the number of LEDs in each LED string. V_{pk} is the peak voltage of the $V_{AC,LED}$.

If the LED is shorted, the V_{Nk,CE_pk} (at $V_{AC,LED} > 0$) or V_{Pk,EC_pk} (at $V_{AC,\ LED} < 0$) will increase. As it is higher than $V_{s,ref}$, the comparator outputs a logic high

$$V_{Nk,CE\_pk} \geq V_{s,ref} \quad or \ V_{Pk,EC\_pk} \geq V_{s,ref}. \quad (24)$$

When the output is at a logic high, V_{sw} is 0V by SR Latch (V_{Ls} is a logic high) and NOR gate, and then LED driving circuit is shut down. Simulation was performed to verify the operation of the LED short circuit (see Fig. 8(a)).

If some LEDs are opened in the LED string, the current does not flow through the LED string, which will reduce the total LED current ($i_{AC,LED}$). As shown in Fig. 7, the open protection circuit consists of a sensing resistor (R_s), a voltage

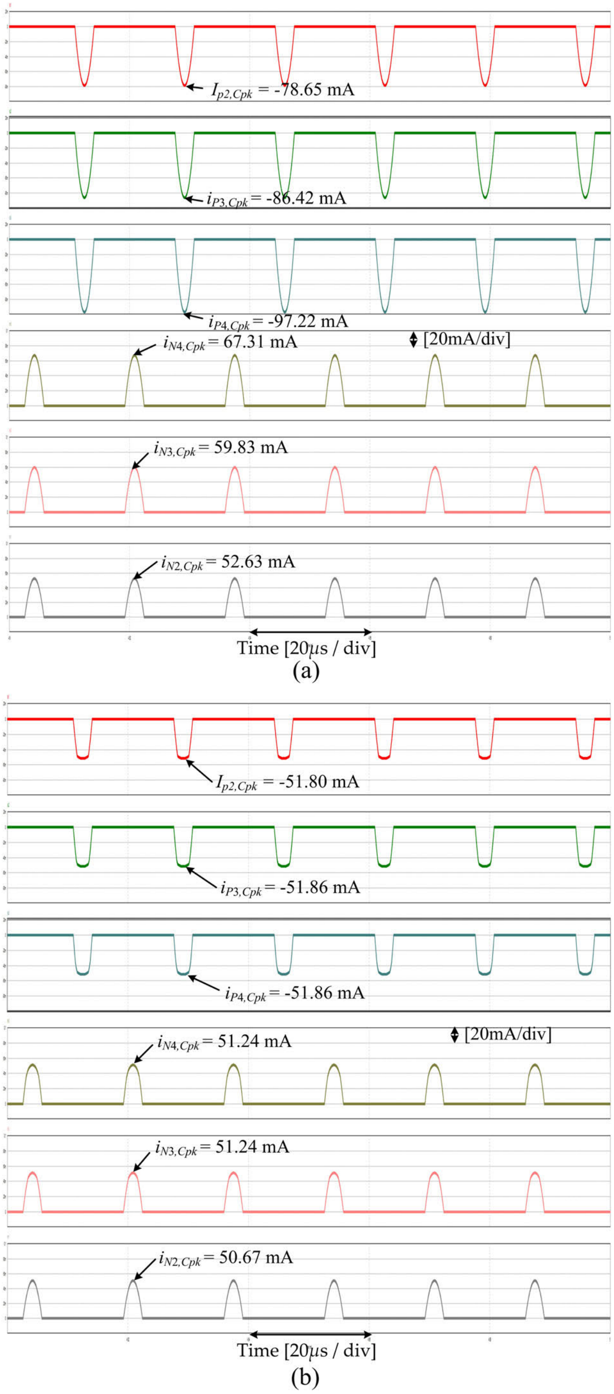

FIGURE 6. Simulated LED currents in LED string-1 thorough 6 at V_{pk} = 40V and f = 60 kHz in the case of (a) no balancing circuit and (b) the proposed circuit with R_Es = 1Ω.

sensor (C_S), an absolute value circuit, a comparator, and a SR latch. The voltage (V_{Rs}) generated by the $i_{AC,LED}$ flowing into R_s is amplified by the voltage sensor (CS), and then the amplified V_{Rs} becomes the positive voltage (V_{CS}) by an absolute value circuit. V_{CS} is applied to the (-) terminal of the comparator and compared with $V_{o,ref}$, which is the positive input of the comparator. When V_{CS} is less than $V_{o,ref}$ at $T/4$ and $3T/4$, the comparator outputs a logic high. V_{sw} is 0V

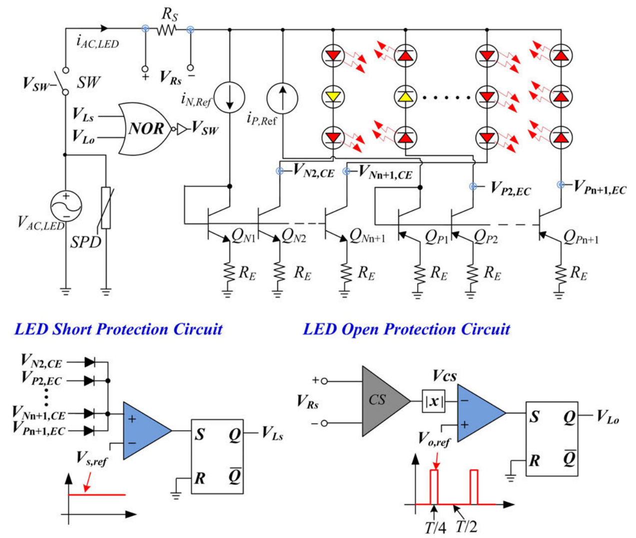

FIGURE 7. LED short and open protection circuits for the LED driver using the proposed balancing circuit.

by SR Latch (V_{Lo} is a logic high) and NOR gate, and then the LED drive circuit is shut down. $V_{o,ref}$ is a pulse wave with a period $T/2$ and has the magnitude of V_{o,ref_pk} at $T/4$ (see Fig. 7). V_{o,ref_pk} is determined by equation (25) considering when one LED string is opened

$$V_{o,ref\_pk} \geq G \times (n-1) \times i_{Ref,pk} \times R_s \tag{25}$$

where $i_{Ref,pk}$ is the peak value of the reference currents ($i_{N,Ref}$ and $i_{P,Ref}$), n is half the total number of LED strings, and G is the gain of the current sensor. Simulation was performed to verify the operation of the open protection circuit (see Fig. 8(b)).

TABLE 2. Parameter values for open/short simulation.

Parameter	Value	Parameter	Value
V_{pk}	$110V_{rms}$	m	26
f	50Hz	n	2
i_{Rref_pk}	51.5mA	β	500
$V_{L,th}$	5.5V	R_s	1Ω
R_{LED}	7Ω	G	10

To verify the operation of the short and open protection circuits in Fig.7, simulation conditions are given in Table 2. $V_{s,ref}$ and $V_{o,ref,pk}$ are determined to be 8V and 1.1V by substituting the parameter values in Table. 2 into equation (23) and (25), respectively.

Fig. 8(a) shows the simulation result for the short detection circuit. When one LED is shorted in the second LED string, $V_{N2,CE}$ increases due to the current mirror balancing operation. As shown in equation (24), when V_{N2,CE_pk} is greater than $V_{s,ref}(= 8V)$, the comparator outputs a logic high. Because S of a SR latch is high, Q becomes high and remains in that state. Therefore, V_{sw} becomes 0V by SR Latch and NOR gate, and then LED driving circuit is shut down.

Fig. 8(b) shows the simulation result for the open detection circuit. When one LED is opened in the fourth LED string, the peak value (i_{pk}) of $i_{AC,\ LED\_pk}$ decreases from 154.5mA

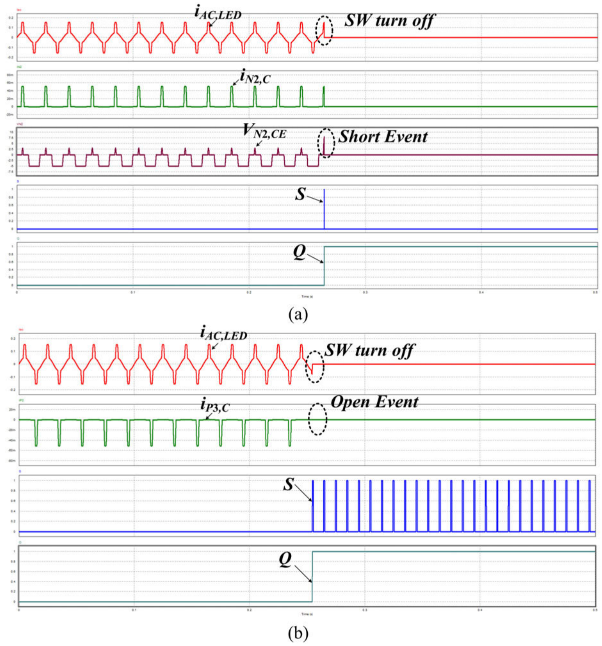

FIGURE 8. Simulated key waveforms of LED driver (a) when one LED in the string is shorted (b) and opened.

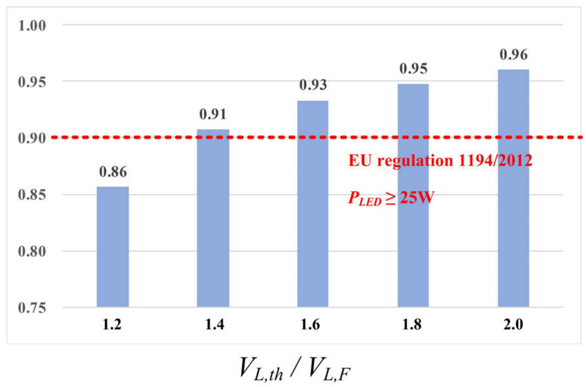

FIGURE 9. PF according to V_F / V_{th} calculated by a PSIM simulator.

to 103mA. i_{pk} is multiplied by R_s and G, so V_{CSpk} is 1.03V. When V_{CSpk} is less than $V_{o,ref}$ (= 1.1V), the comparator outputs a logic high. Because S of a SR latch is high, Q becomes high and remains in that state. Therefore, V_{sw} becomes 0V by SR Latch and NOR gate, and then LED driving circuit is shut down.

D. POWER FACTOR

The power factor is a very important index for LED lamps. The Energy Star Program and EU regulation 1194/2012 define the power factor requirement according to the LED lamp power [10, 11].

The proposed balancing circuit can be applied to both the AC indirect LED driver and AC direct LED driver. In the case of AC indirect LED driver, the LED lamp satisfies the above power factor regulations because the power factor correction circuit is used. However, in the case of AC direct LED driver, it should be designed to satisfy the regulations.

TABLE 3. Parameter values for comparison simulation.

Parameter	Value	Parameter	Value
V_{pk}	110V_{rms}	m	25
f	50Hz	n	4
i_{Rref_pk}	51.6mA	β	500
$V_{L,th}$	5.5V	R_s	1Ω
R_{LED}	7Ω		

The $V_{AC,LED}$, $i_{N,C}$, and $i_{P,C}$ waveforms of with the proposed circuit are shown in Fig. 5. Because LED is resistive load, $V_{AC,LED}$ and $i_{N,C}$(or $i_{P,C}$) have the same phase. However, the periods ($\Delta t_{N,off}$ and $\Delta t_{P,off}$) in which the LED current does not flow is made by the threshold voltages ($V_{L,th}$s) of LEDs, and thus the power factor is lowered. The power factor of the LED lamp using the proposed circuit varies according to the values of $\Delta t_{N,off}$ and $\Delta t_{P,off}$ and these values are determined by the ratio of threshold voltage ($V_{L,th}$) and forward voltage (V_F) of the LED.

The power factor according to $V_F/V_{L,th}$ was calculated by the PSIM simulator. For simulation, $V_{AC,LED}$ and n was 110Vrms (50Hz) and 5, respectively. As the V_F/V_{th} increased, the power factor increased because the values of $\Delta t_{N,off}$ and $\Delta t_{P,off}$ decreased. The power factor calculated according to V_F/V_{th} is shown in Fig. 9. When V_F/V_{th} was greater than 1.4, the power factor was greater than 0.9, so the LED lamp satisfies EU regulation 1194/2012. However, since the power factor was 0.86, when V_F/V_{th} was 1.2, the LED lamp must be used below 25W to satisfy EU regulation 1194/2012. From the simulation results, the AC direct LED driver with the proposed circuit can satisfy the EU regulation 1194/2012 by adjusting $V_F/V_{L,th}$.

E. PERFORMANCE COMPARISON

The proposed circuit was compared quantitatively with the basic current mirror circuit. The maximum current difference, efficiency, and power factor were calculated by PSIM simulator. Since the basic current mirror circuit can only be driven by positive voltage source, it was used with bridge diodes. The bridge diode model is B520C1500G ($V_{d,th}$ = 0.63V, R_d = 0.90Ω). The parameter values for simulation are given in Table 3. Here, different resistors (30 ∼ 100 Ω) were connected to the top of each LED string too give impedance deviation to the eight LED strings.

The simulation results are shown in Fig. 10. The proposed balancing circuit had a smaller maximum current deviation, lower efficiency, and higher power factor than the basic mirror circuit. The reason the proposed circuit has the smaller current deviation and efficiency is that it used one more current reference string than the basic mirror circuit. One more current reference reduced the current deviation, but caused power loss. The four bridge diodes in the basic mirror circuit decreased the power factor and caused power loss. The proposed circuit outperformed than the basic mirror circuit except for the efficiency. However, the efficiency of the proposed circuit can be improved by reducing the power loss of the current reference string. For this simulation, a simple

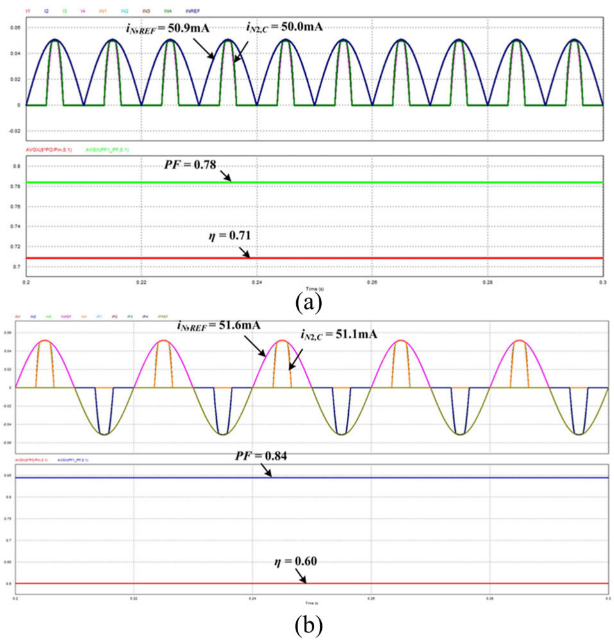

FIGURE 10. Simulated waveforms of $i_{N,REF}$, $i_{N2,C}$, PF, and η of (a)the basic mirror circuit and (b)proposed balancing circuit.

method consisting of a resistor (R_{ref}) and a diode (D_{ref}) was used to make the reference currents, and it caused a lot of power loss.

V. EXPERIMENT RESULTS

In order to verify the effectiveness of the proposed balancing circuit, a prototype (Fig. 11) was built and tested for 5W LED lighting. Thirty-six LEDs were used as the light source, and the LED part model was SME3030UWDC10(V_f =∼ 5.85 V @ I_{LED} = 50 mA). For current balancing experiments, these LEDs composed three pairs of anti-parallel LED strings, and each LED string consisted of six LEDs connected in series. A sinusoidal AC voltage ($V_{AC,LED}$) with a frequency of 60 Hz and a peak voltage V_{pk} of 39.6 to 40.6 V was used to drive LED strings. An AC power supply (CHROMA 61502) was connected to the prototype to supply $V_{AC,LED}$, and the currents of each LED string were measured by a current probe (CP030) and an oscilloscope (wavesuffer 3024). A simple method consisting of a resistor (R_{ref}) and a diode (D_{ref}) was used to make the reference currents ($i_{N,Ref}$ and $i_{P,Ref}$), although the average power loss (P_{ref}) of reference currents was large. Here, both reference resistors ($R_{ref1} = R_{ref2}$) were 750 Ω to make two identical reference currents ($i_{N,Ref}$ and $i_{P,Ref}$) of ∼ 50 mA.

Each of the three LED strings (LED string-1, 3, and 5) on odd lines was connected with a Q_N and a R_E, and each of the remaining LED strings (LED string-2, 4, and 6) was connected with a Q_P and a R_E. In order to ensure that the maximum difference of the LED current is less than 0.7 mA, the gain of the transistors was chosen to be greater than 300 by equation (5) and (8). In addition, according to equations (21) and (22), V_{CEO} and $i_{N,max}$ should be greater than

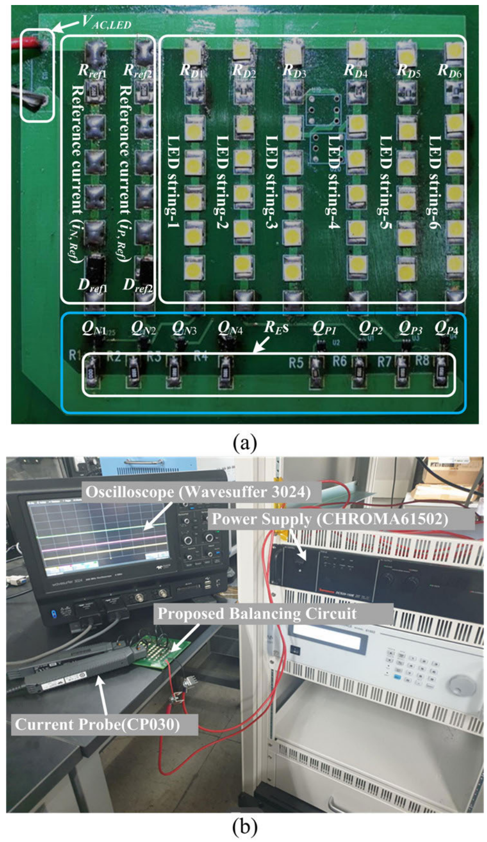

FIGURE 11. Pictures of (a) prototype and (b) experimental setup for the proposed balancing circuit.

10.75V (@ α = 1) and 300mA (@ β = 1), respectively. Thus, 2sc5585 ($\beta_N \approx 400$) and EMT18T2R ($\beta_P \approx 320$) was selected as the part models of Q_{Ns} and Q_{Ps}, respectively. In addition, in order to intentionally cause a distinct impedance difference between six LED strings, the different resistors (R_{D1} = 91 Ω, R_{D2} = 47 Ω, R_{D3} = 75 Ω, R_{D4} = 39 Ω, R_{D5} = 62 Ω, and R_{D6} = 30 Ω) were added to the second lines of the LED strings, respectively. To maintain the optimal operation of the circuit, the PCB layout and heat sink were designed considering thermal stability of the semiconductors, and heat sinks were used in the experiments.

The LED currents in LED strings-1 through 6 were measured at $V_{AC,LED}$ with V_p = 39.6 V and f = 60 Hz without the balancing circuit (Fig. 12(a)). Due to the impedance difference between LED strings, the LED currents in the LED strings had different peak values. The maximum LED current differences $\Delta i_{N,m}$ and $\Delta i_{P,m}$ between LED strings on even and odd lines were 14 mA (= $i_{N4,Cpk} - i_{N2,Cpk}$) and 25 mA(= $|i_{P4,Cpk} - i_{P2,Cpk}|$), respectively. In addition, the maximum LED current differences Δi_{LED} between all LED strings were 45 mA (= $|i_{P4,Cpk}| - i_{N2,Cpk}$)

Figs. 12(b) and (c) show the LED currents measured at $V_{AC,LED}$ with V_{pk} = 40.6 V and f = 60 Hz when the proposed balancing circuit with different R_Es was used. In the case that R_Es = 0 Ω, the LED currents were balanced by the proposed balancing circuit, regardless of the polarity of $V_{AC,LED}$

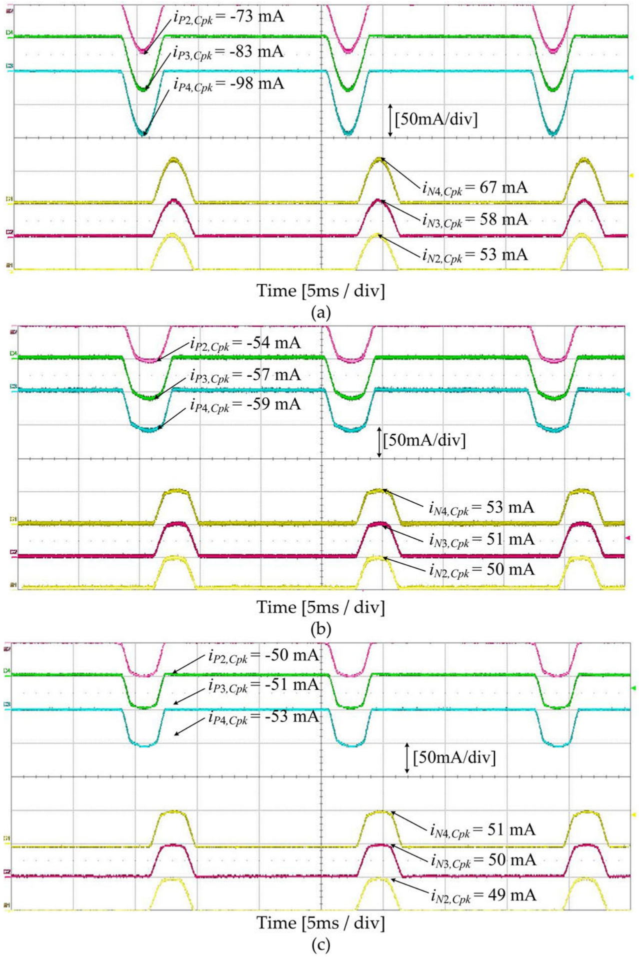

FIGURE 12. Measured LED currents in LED strings-1 through 6 at V_P = 39.6 ~ 40.6 V and f = 60 Hz in the case of (a) no balancing circuit, and the proposed circuit with (b) R_Es = 0 Ω and (c) 1 Ω.

(Fig. 12(b)). Due to the current mirror operation, $\Delta i_{N,m}$ was reduced from 14 mA to 3 mA and $\Delta i_{P,m}$ was reduced from 25 mA to 5 mA. However, due to the early effect, they were larger than the LED current differences ($\Delta i_N = 0.50$ mA and $\Delta i_P = 0.62$ mA) calculated in equations (5) and (8), respectively. In the case that R_Es = 1 Ω, the LED current differences were reduced by the current mirror operation with the negative feedback of the proposed circuit (Fig. 12(c)). Compared with the case that R_Es = 0 Ω, $\Delta i_{N,m}$, $\Delta i_{P,m}$, and Δi_{LED} was reduced from 3 mA to 2 mA, 5 mA to 3 mA, and 9 mA to 4 mA, respectively.

To improve the imbalance of LED currents caused by the impedance differences between six strings, the proposed balancing circuit adjusts the collector-emitter voltage and the base-emitter voltage of each transistor (Figs. 13 and 14). The $V_{N,BE}$s and $V_{N,CE}$s of Q_{N2}, Q_{N3} and Q_{N4} were measured at $V_{AC,LED}$ = 40.6 V when the proposed balancing circuit without or with the negative feedback (R_Es = 0 Ω or 1 Ω) was used (Fig. 13). In the case that R_Es = 0 Ω, all of the NPN transistors (Q_{N1} ~ Q_{N4}) in odd lines had a common emitter. In addition, the collector of Q_{N1} and the bases of all NPN transistors (Q_{N1} ~ Q_{N4}) were tied together so that the

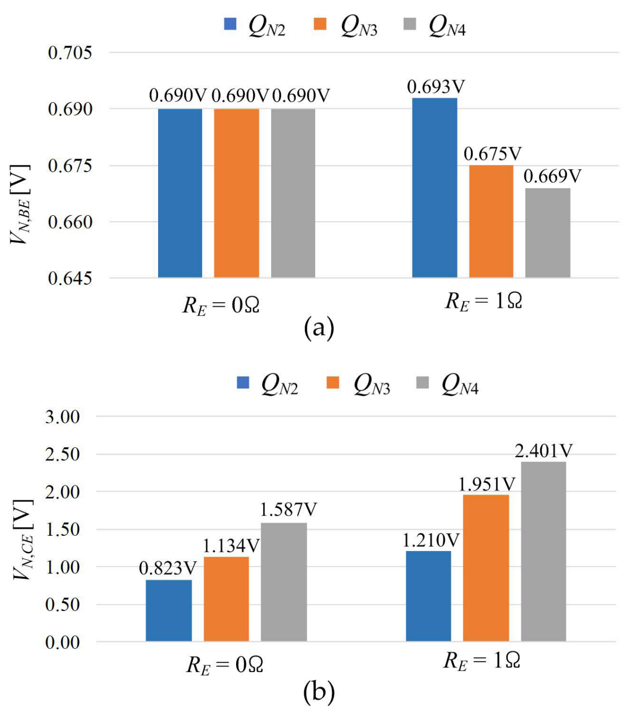

FIGURE 13. Comparison of the (a)$V_{N,BE}$ and (b)$V_{N,CE}$ of Q_{N1} and Q_{N3} measured at $V_{AC,LED}$ = 40.6V when the proposed balancing circuit with R_Es = 0 Ω or 1 Ω was used.

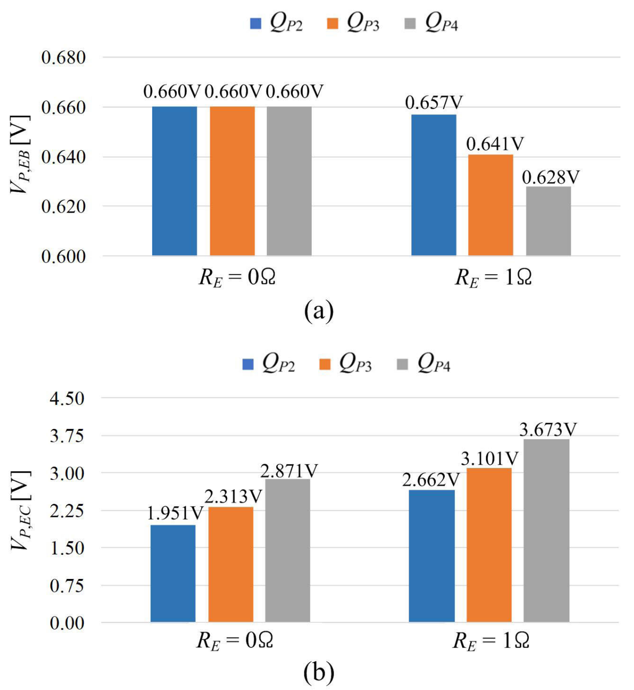

FIGURE 14. Comparison of the (a) $V_{P,EB}$ and (b)$V_{P,EC}$ of Q_{P1} and Q_{P3} measured at $V_{AC,LED}$ = −40.6V when the proposed balancing circuit with R_Es = 0 Ω or 1 Ω was used.

base-emitter voltages ($V_{N,BE}$s) of all NPN transistors were equal to 0.690 V. However, the collector-emitter voltages ($V_{N,CE}$s) of Q_{N2}, Q_{N3}, and Q_{N4} had the different values for

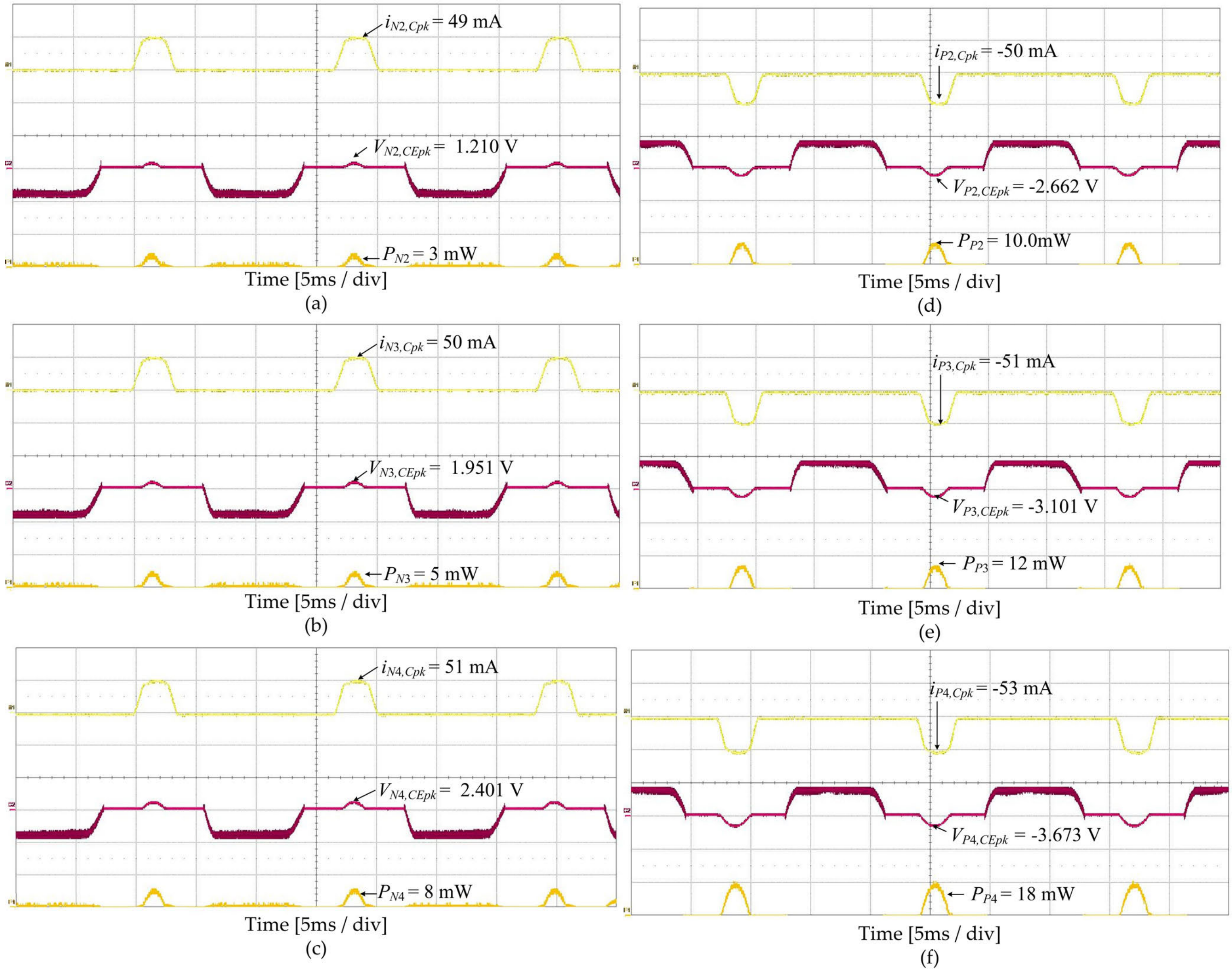

FIGURE 15. Measured key waveforms of (a) Q_{N1}, (b) Q_{N2}, (c) Q_{N3}, (d) Q_{P1}, (e) Q_{P2}, and (f) Q_{P3} at $V_{AC,LED}$ with $V_p = 40.6$ V and $f = 60$ Hz when using the proposed circuit with negative feedback (R_Es = 1 Ω).

balancing the LED currents. The $V_{N4,CE}$ of Q_{N4} in the string with the lowest impedance was 1.587 V. This was higher than the $V_{N,CE}$s of other NPN transistors, but lower than the ideal $V_{N4,CE}$ (=∼ 2.400 V) required to ensure that $i_{N,Ref}$ and $i_{N4,C}$ were perfectly equal, due to the early effect. In the case that R_Es = 1 Ω, the Q_Ns did not have a common emitter. Therefore, as stated in (7), the measured $V_{N,BE}$s of Q_Ns were different from each other because of the slight differences between LED currents. The $V_{N2,BE}$ (= 0.693 V) of $Q_{N,2}$ with the smallest LED current ($i_{N2,Cpk}$) was the highest, while the $V_{N4,BE}$ (= 0.669 V) of Q_{N3} with the largest LED current ($i_{N3,Cpk}$) was the lowest. The $V_{N2,CE}$ of Q_{N2} was the lowest as 1.210 V, because the LED string-1 connected with Q_{N2} had the largest impedance. On the other hand, the $V_{N4,CE}$ of Q_{N4} in the LED string-5 with the lowest impedance was the highest as 2.401 V. It was closer to the ideal $V_{N4,CE}$ (= 2.400 V) due to the negative feedback operations when compared to the $V_{N3,CE}$ (= 1.587 V) at R_Es = 0 Ω. The different V_{BE}s allow the LEDs in each LED string to operate on different i_{CE}-v_{CE} characteristic curves of an NPN transistor. Therefore, the current mirror operation with negative feedback can balance the LED currents without being affected by the early effect. As stated in (6) and (7), the LED current with higher $V_{N,CE}$ is decreased by having a lower $V_{N,BE}$.

The emitter-base voltages ($V_{P,EB}$s) and emitter-collector voltages ($V_{P,EC}$s) of $Q_{P,2}$, $Q_{P,3}$, and $Q_{P,4}$ were measured at $V_{AC,LED} = -40.6$ V when the proposed balancing circuit with R_Es = 0 Ω or 1 Ω was used (Fig. 14). In the case that R_Es = 0 Ω, the emitter-base voltages ($V_{P,EB}$) of all PNP transistors were equal to 0.660 V, because of the structure of the PNP current mirror circuit. The $V_{P4,EC}$ of Q_{P4} in the LED string-6 with the smallest impedance was 2.871 V for balancing the LED currents in even lines. However, this was lower than the ideal $V_{P3,EC}$ (= 4.000 V) required to ensure that $i_{P,Ref}$ and $i_{P4,C}$ were perfectly equal, due to the early effect. In the case that R_Es = 1 Ω, the measured $V_{P2,EB}$ (= 0.657 V) of Q_{P2} was higher than $V_{P4,EB}$ (= 0.628 V) of Q_{P4}, while the $V_{P2,EC}$ (= 2.662 V) of Q_{P2} was lower than the $V_{P4,EC}$

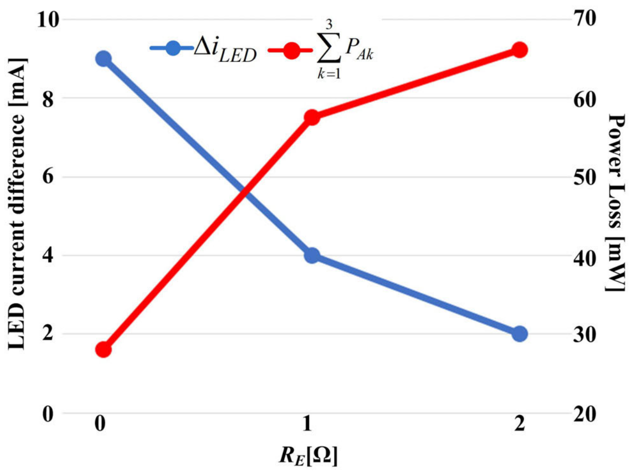

FIGURE 16. Measured maximum LED current difference ($\Delta i_{LED,}$) and power loss ($\sum P_{AK}$) versus R_E for the proposed balancing circuit at V_p = 40.6 V and f = 60 Hz.

(= 3.673 V) of Q_{P4}. Compared to the $V_{P4,EC}$ (= 2.871 V) at R_Es = 0 Ω, the $V_{P4,EC}$ of Q_{P4} at R_Es = 1 Ω was closer to the ideal $V_{P3,EC}$ (= 4.000 V), which was attributed to the proposed current mirror operation with the negative feedback.

Fig. 15 shows the key waveforms of each transistor measured at $V_{AC,LED}$ with V_{pk} = 40.6 V and f = 60 Hz when the proposed balancing circuit with negative feedback (R_Es = 1Ω) was used. The measured key waveforms were almost same as the theoretical waveforms in Fig. 5 except for some differences due to the nonlinear electrical characteristics of transistors and LEDs. The measured $i_{N,C}$s, $V_{N,CE}$s, and P_Ns of Q_Ns on odd lines were shown in Figs. 15(a)-(c). Because of the balancing operation of the proposed circuit, all the $i_{N,C}$s were almost equalized to $i_{N,Ref}$ and $V_{N,CE}$s were adjusted according to the impedance of each string. The P_{N2}, P_{N3}, and P_{N4} calculated by equation (11) were 3 mW, 5 mW, and 8 mW, respectively. The LED string with smaller impedance required the larger collector-emitter voltage $V_{N,CE}$ and larger average power loss P_N for LED current balancing. Figs. 15(d)-(f) show the measured $i_{P,C}$s, $V_{P,CE}$s, and P_Ps of Q_Ps on even lines. These waveforms had the same characteristics and tendencies as the waveforms of Q_Ns. The P_{P2}, P_{P3}, and P_{P4} calculated by equation (15) were 10 mW, 12 mW, and 18 mW, respectively. When R_Es = 1 Ω, the total average power loss of six R_{ES} calculated by equations (12) and (16) was 1.597 mW. The average power loss (P_{ref}) of the elements for reference currents was 645.5 mW. As a result, the total average power loss (P_{BC}) in the proposed circuit required for balancing six LED currents was calculated as 703.1 mW using equation (18).

The maximum LED current difference (Δi_{LED}) and power loss ($\sum P_{AK}$) of the proposed balancing circuit were measured at $V_{AC,LED}$ with V_{pk} = 40.6 V and f = 60 Hz while varying the resistor (R_E) from 0 Ω to 2 Ω (Fig.16). As the R_E increased from 0 Ω to 2 Ω, the Δi_{LED} decreased from 9 mA to ∼ 2 mA, while the $\sum P_{AC}$ increased from 28 mW to 66 mW. The R_E should be determined to meet the circuit specifications of a LED driver, taking into account the trade-off relationship between the maximum LED current difference (Δi_{LED}) and average power loss ($\sum P_{AK}$) of the proposed circuit.

VI. CONCLUSION

In this paper, a new bi-directional current mirror circuit with negative feedback is proposed to balance the currents in multiple AC-LED strings. The proposed circuit consists of two reference currents, n+1 NPN transistors, n+1 PNP transistors, and 2(n+1) resistors for LED current balancing in n pairs of anti-parallel strings. BJTs perform the current mirror operation regardless of the polarity of the AC source. Also, the resistors form the negative feedback loop which can reduce the early effect and achieve LED current balancing in the variations of parameters among the transistors. Simulation and experiments were performed to verify the effectiveness of the proposed circuit. The proposed circuit balanced the LED currents in pairs of anti-parallel LED strings, regardless of the polarity of the $V_{AC,\ LED}$ and early effect. In the simulation, the proposed circuit showed good balancing operation at both low (50/60 Hz) and high (60 kHz) frequencies. In addition, the LED driver using the proposed circuit could satisfy the flicker and power factor requirements. In the experiment, the measured key waveforms in the proposed balancing circuit were almost same as the theoretical waveforms. When the degree of the LED current balancing in the proposed circuit was compared with that in the no balancing circuit (as well as that in the basic current mirror circuit with the early effect), the maximum LED current difference Δi_{LED} was reduced from 45 mA (9mA) to 4 mA. At this time, the average power loss ($\sum P_{AK}$) in the proposed circuit required for balancing six LED currents was calculated as 57.6 mW.

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