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Design and Implementation of a Current-balancing Circuit for LED Security Lights

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Abstract

This paper presents a current-balancing circuit for security lights that uses parallel-connected LEDs. The parallel connection of LEDs causes current differences between the LED strings because of characteristic deviations. These differences can reduce the lifespan of a particular point of LEDs by thermal spotting. They can also cause non-uniform luminance of the lighting device. Among the different methods for solving these problems, the method using current-balancing transformers makes it easy to compensate for current differences and it has a simple circuitry. However, while the balancing transformer has been applied to AC light sources, LEDs operate on a DC source, so the driving circuitry and the design method have to be changed and their performances must be verified. Thus in this paper, a design method of the balancing transformer network and the driving circuitry for LEDs is proposed. The proposed design method could have a smaller size than the conventional design method. The proposed circuitry is applied to three types of 100-watt LED security lights, which use different LEDs. Experimental results are presented to verify the performance of the designed driving circuits..

Key words: Current-balancing, LED driving circuit, LED lighting

I. INTRODUCTION

Due to recent technical advances in LEDs, LED applications for lighting devices are gradually expanding [1]-[14]. When compared with traditional light sources, LEDs have a longer service life, are environmentally friendly, and are easy to control. Thus LEDs are being used to supply outdoor lighting needs such as security lights and street lights.

However, due to problems in the manufacturing process, LEDs have a problem with relatively large variations in the V_F characteristics [2]-[14]. These variations cause current-sharing problems, which generate current differences between the rows of parallel-connected LEDs. This in turn prevents the uniform distribution of heat in LED lighting devices, thus accelerating the aging of specific LEDs and resulting in a non-uniform luminance. Consequently, the reliability and the quality of illumination of LED lighting devices is decreased.

To address this problem, many studies have been conducted. The solutions can be largely divided into the method of using a linear regulator and current mirror in each

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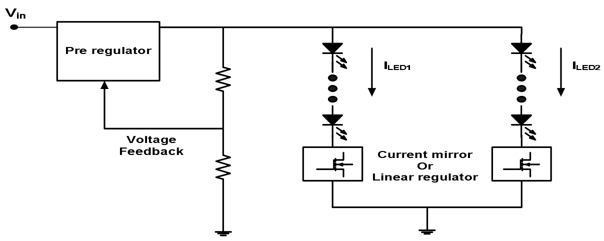
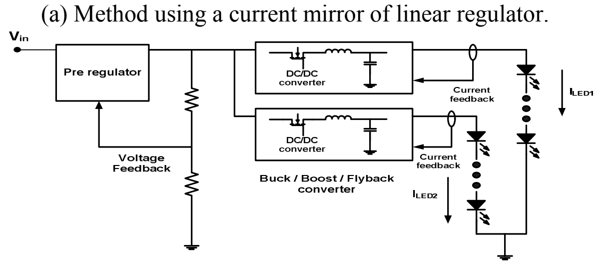
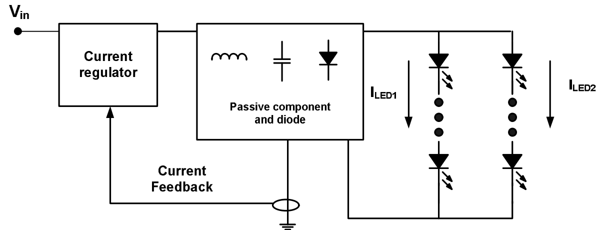


(a) Method using a current mirror of linear regulator.



(b) Method using DC/DC converters.



(c) Method using passive components and diodes.

Fig. 1. Driving methods for current-sharing problem.

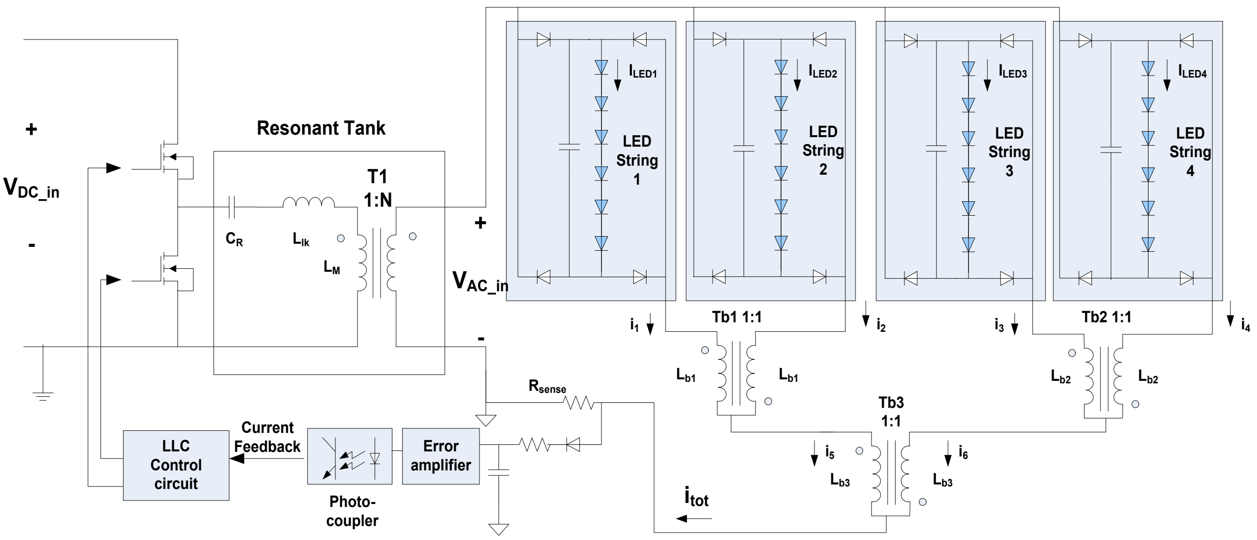


Fig. 2. An example of proposed LED driver scheme.

row [2]-[5], the method of using a current control converter in each row [6], and the method for compensating the current error using a passive device in each row [7]-[14]. The method shown in Fig. 1 (a) is inappropriate for LED loads with high power, because relatively large losses are generated by the linear regulator voltage. For the method shown in Fig. 1 (b), the circuit is complex because a converter is used in each row and it is not easy to reduce the error between converters due to the errors between elements such as a current-sensing resistor. The method shown in Fig. 1 (c) has a simpler circuit, better efficiency and better error compensation ability than the above two methods. Some circuits have been suggested in the third method, and this study adopts the method using a current-balancing transformer.

The balancing transformer has been used in such applications as discharge lamps (CCFL, florescent lamps, etc.). These lamps are driven by an AC source, so a balancing transformer is directly applicable. Thus in order to apply LEDs, which are driven by a DC source, it is necessary to redesign and verify performances.

Thus in this paper, a driving circuitry is proposed for parallel-connected LEDs and the balancing transformer network is designed using a worst-case impedance estimation. The proposed design method can reduce the size, when compared with the conventional design method. In addition, the parasitic components of the balancing transformer are also considered for the realization. The proposed circuitry consists of an LLC inverter and balancing transformers and it is applied to three types of 100-watt LED security lights, which use different LEDs. The experimental results are presented to verify the performance of the designed driving circuits.

II. DRIVING CIRCUITRY AND BALANCING TRANSFORMER NETWORK

The example scheme used in this study is illustrated in Fig. 2. In Fig. 2, Vin becomes the output of the PFC, which is generally 400 V_{DC} when an active PFC is used. The input DC voltage is controlled by the LLC resonant inverter, which applies the total current of the serially and parallel connected LEDs that have been fed back from the secondary side. The AC voltage of the secondary side of T_1 is applied equally to the parallel-connected LED strings and the balancing transformer. The LED string consists of diodes, capacitors and serially connected LEDs, and it supplies current to the LEDs as DC, whereas the AC current flows to the balancing transformer.

The currents flowing through LED strings 1 and 2 (i_1 and i_2) are balanced by T_{b1}, and the currents flowing through LED strings 3 and 4 (i_3 and i_4) are balanced by T_{b2}. Furthermore, i_5, which is equal to $i_1 + i_2$, and i_6, which is equal to $i_3 + i_4$, are balanced by T_{b3}. Thus a uniform current flows through each of the LED strings.

To design the proposed circuit, this paper is organized as follows. First, a single balancing transformer is analyzed and the effects of the parasitic components are discussed. Then the network of the balancing transformer is designed by expanding this analysis. After that, the proposed driving circuitry is presented.

A. Balancing transformer analysis

An LED string consisting of a rectifier and LEDs can be calculated as an AC-equivalent resistor by the First Harmonic Approximation (FHA) [14], as shown in Fig. 3, and

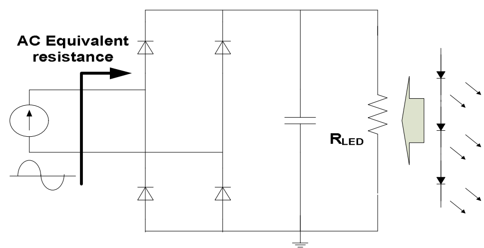


Fig. 3. An AC equivalent circuit for a LED string.

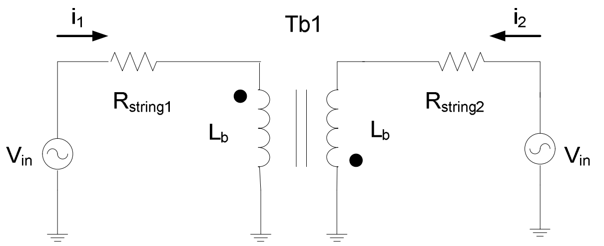


Fig. 4. An equivalent circuit for two LED strings.

represented in Equation 1.

$$R_{string1} = \frac{8}{\pi^2} R_{LED1} \quad (1)$$

Fig. 4 shows the equivalent circuit of two strings, with the LED string as an AC-equivalent resistor and the voltage of the secondary side as an AC voltage source.

When the equivalent circuit in Fig. 4 is separated into the primary and secondary sides of T_{b1}, Equation 2 is obtained. If it is assumed that there is no leakage inductance, the mutual inductance M = L_b. Thus Equation 2 can be rewritten as Equation 3. When this is represented as a ratio of i_1 and i_2, Equation 4 is obtained. As a result of Equation 4, if $|R_{string1}-R_{string2}| << L_b$, i_1/i_2 is almost 1, which means a uniform current is flowing at each string.

$$\left.\begin{aligned} V_{in} &= (R_{string1} + j\omega L_b)i_1 - j\omega M i_2 \\ V_{in} &= (R_{string2} + j\omega L_b)i_2 - j\omega M i_1 \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} V_{in} &= R_{string1} i_1 + j\omega L_b (i_1 - i_2) \\ V_{in} &= R_{string2} i_2 + j\omega L_b (i_2 - i_1) \end{aligned}\right\} \quad (3)$$

$$\frac{i_1}{i_2} = \frac{R_{string2} + 2j\omega L_b}{R_{string1} + 2j\omega L_b} \quad (4)$$

To obtain the required inductance value of the balancing transformer ('L_b'), which can achieve 3% of the current differences, the parameters of the LED strings and the estimated equivalent resistances are listed in Table I.

In the Table I, the V_f parameters were obtained from a datasheet for one of the LEDs used in this study[18]. It was assumed that twelve LEDs were serially connected in an LED string.

TABLE I

PARAMETERS OF LED STRINGS, EQUIVALENT RESISTANCE AND MAXIMUM CURRENT DIFFERENCE

Parameters	Value	Estimated Results	Value
No. of LED in a LED strings (N)	12	$R_{LED\_min}(R_1)$	92.5Ω
Operation frequency	100kHz	$R_{LED\_max}(R_2)$	126.8Ω
V_{f_min} (at I_f = 350mA)	2.7V	$R_{string\_min}(R_{string1})$	75Ω
V_{f_max} (at I_f = 350mA)	3.7V	$R_{string\_max}(R_{string2})$	102.8Ω
		Max. current difference	27%

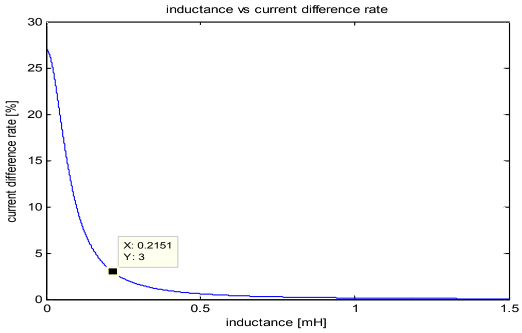


Fig. 5. An estimation result of current difference rates.

R_{LED} can be obtained as (I_f/V_f)•N and R_{string} can be obtained using Equation 1. The current difference is the result of Equation 4 which is converted into a percentage as shown in Fig. 5. In Fig. 5, R_1 = R_{LED_min} and R_2 = R_{LED_max} were determined so that the current difference would be at its maximum for the worst-case design.

As a result of the estimation, it was found that the balancing transformer must have a minimum inductance of 215uH in order to obtain a current difference between the rows of 3% or less.

For practical implementation, the parasitic components of the transformer also need to be considered. The equivalent circuit, which includes the parasitic components of the balancing transformer, is presented in Fig. 6 by expending Fig. 4.

Since the balancing transformer is wound in opposite directions between the primary and the secondary sides, the turn ratio of the balancing transformer can be 1:-1 (i.e., N = -1). Thus Equation 5 is obtained. Since R_c (the core loss) is much larger than $j\omega L_M$ (the impedance of the magnetizing inductance), Equation 5 can be rewritten as Equation 6 so that R_c is ignored.

$$\left.\begin{aligned} V_{in} &= (R_{string1} + R_{lk1} + j\omega L_{lk1})i_1 + (R_c // j\omega L_M)(i_1 - i_2) \\ -V_{in} &= -(R_{string2} + R_{lk2} + j\omega L_{lk2})i_2 + (R_c // j\omega L_M)(i_1 - i_2) \end{aligned}\right\} \quad (5)$$

$$\left.\begin{aligned} V_{in} &= (R_{string1} + R_{lk1} + j\omega L_{lk1})i_1 + j\omega L_M (i_1 - i_2) \\ V_{in} &= (R_{string2} + R_{lk2} + j\omega L_{lk2})i_2 - j\omega L_M (i_1 - i_2) \end{aligned}\right\} \quad (6)$$

$$\frac{i_1}{i_2} = \frac{R_{string2} + R_{lk2} + j\omega L_{lk2} + 2j\omega L_M}{R_{string1} + R_{lk1} + j\omega L_{lk1} + 2j\omega L_M} \quad (7)$$

If it is assume that the $R_{lk1} \approx R_{lk2}$ and that $L_{lk1} \approx L_{lk2}$, because the turn number of the primary and the secondary are the same, Equation 7, the current differences, which produce differences between $R_{string1}$ and $R_{string2}$, are rather reduced by parasitic

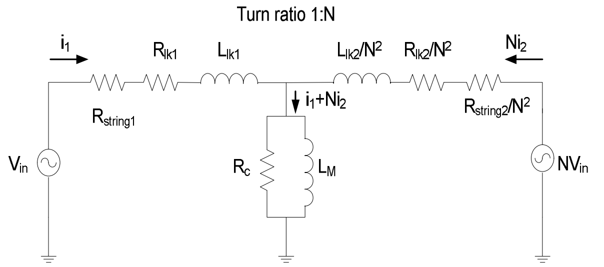


Fig. 6. An equivalent circuit for two LED strings with parasitic components.

components.

So in the design for the current balancing, the parasitic components of the transformer are negligible. However, the parasitic components produce power losses and make the source voltage higher to obtain the desired current of the LEDs. Therefore, for practical purposes, the parasitic components should be kept as low as possible.

B. Balancing Transformer Network

To expend the LED strings, the current balancing can be achieved by a cascaded connection of the balancing transformers, as shown in Fig. 2. T_{b3} is the cascade-connected transformer and it can minimize the current error between i_5 and i_6, which flows on the primary and secondary sides of T_{b3}. An equivalent circuit for the design of the balancing transformer is shown in Fig. 7.

The inductance of the second-level transformer can be determined by the relationship between i_1 and i_3 or i_4 and by the relationship between i_2 and i_3 or i_4.

Since the relational expressions of T_{b1} and T_{b2} are identical, the equation for string 1 and string 3 with $L_{b1} = L_{b2} = L_b$ becomes Equation 9. The equations for the relationship with other strings can be expressed in the same form.

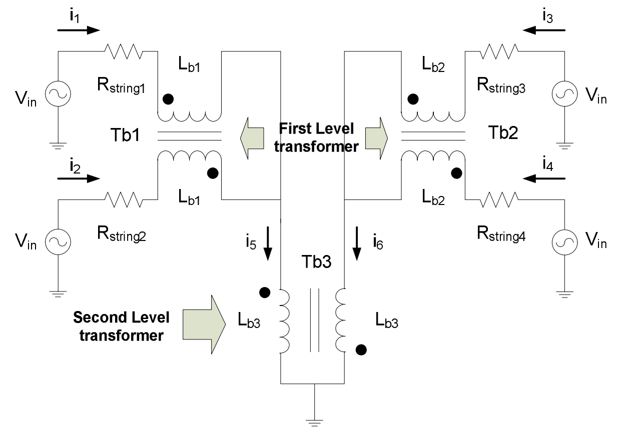


Fig. 7. An equivalent circuit for four LED strings.

The determination of the inductance value for T_{b3} is based on worst-case design methods as a first-level transformer. The two possible cases, where the current difference between i_5 and i_6 has the largest value, are as follows:

case 1 :

$i_{1,2} = i_{max}$, $i_{3,4} = i_{min}$ ($R_{string1,2} = R_{string\_max}$, $R_{string3,4} = R_{string\_min}$)

case 2 :

$i_{1,2} = i_{min}$, $i_{3,4} = i_{max}$ ($R_{string1,2} = R_{string\_min}$, $R_{string3,4} = R_{string\_max}$)

Thus Equation 10 is obtained when R_{string}s is set as case 1. The current ratio of i_1 and i_3 is obtained as Equation 11.

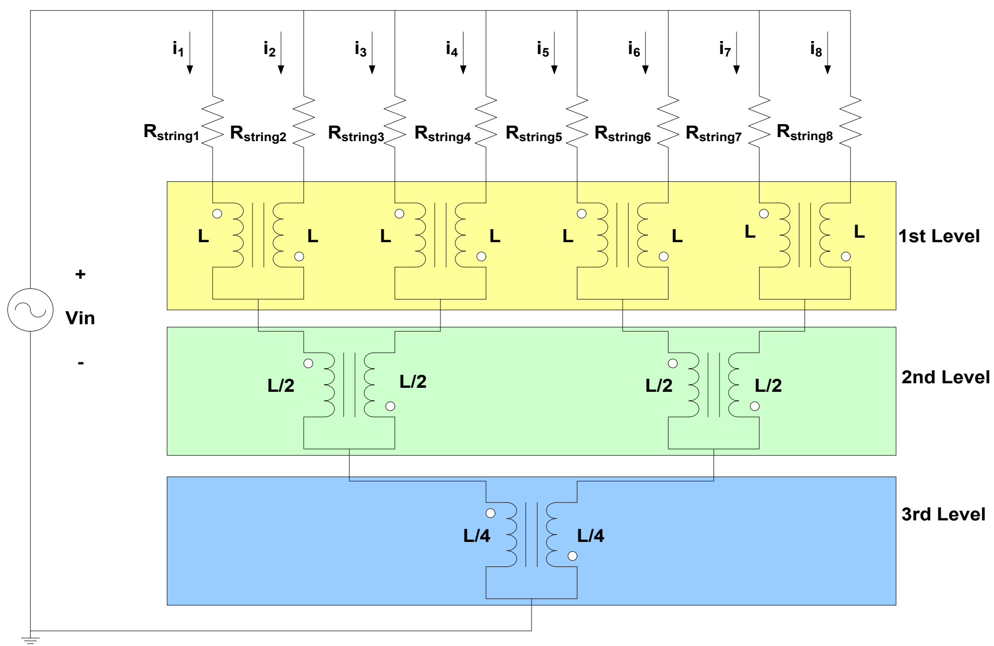


Fig. 8. An equivalent circuit of a balancing transformer network for eight LED strings.

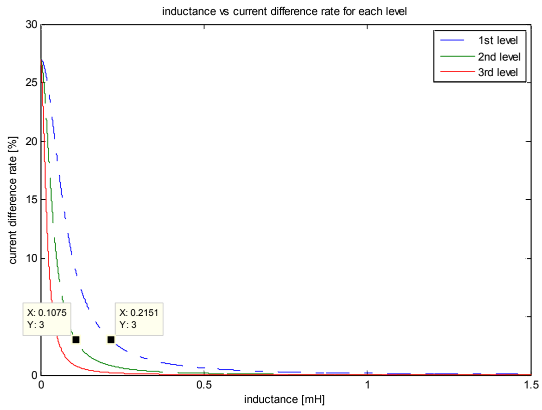


Fig. 9. An estimation result of current difference rates for eight LED strings.

$$\left.\begin{aligned} V_s &= R_{string1}i_1 + j\omega L_{b1}i_1 - j\omega L_{b1}i_2 + j\omega L_{b3}i_5 - j\omega L_{b3}i_6 \\ V_s &= R_{string2}i_2 + j\omega L_{b1}i_2 - j\omega L_{b1}i_1 + j\omega L_{b3}i_5 - j\omega L_{b3}i_6 \\ V_s &= R_{string3}i_3 + j\omega L_{b2}i_3 - j\omega L_{b2}i_4 + j\omega L_{b3}i_6 - j\omega L_{b3}i_5 \\ V_s &= R_{string4}i_4 + j\omega L_{b2}i_4 - j\omega L_{b2}i_3 + j\omega L_{b3}i_6 - j\omega L_{b3}i_5 \end{aligned}\right\}$$
$$where\ i_5 = i_1 + i_2,\ i_6 = i_3 + i_4 \tag{8}$$

$$R_{string1}i_1 + j\omega(L_b + 2L_{b3})i_1 + j\omega(2L_{b3} - L_b)\left(\frac{R_{string1}+2j\omega L_b}{R_{string2}+2j\omega L_b}\right)i_1$$
$$= R_{string3}i_3 + j\omega(L_b + 2L_{b3})i_3 + j\omega(2L_{b3} - L_b)\left(\frac{R_{string3}+2j\omega L_b}{R_{string4}+2j\omega L_b}\right)i_3 \tag{9}$$

$$R_{string\_max}i_1 + j\omega(L_b + 2L_{b3})i_1 + j\omega(2L_{b3} - L_b)i_1$$
$$= R_{string\_min}i_3 + j\omega(L_b + 2L_{b3})i_3 + j\omega(2L_{b3} - L_b)i_3 \tag{10}$$

$$\frac{i_1}{i_3} = \frac{R_{string\_min}+4j\omega L_{b3}}{R_{string\_max}+4j\omega L_{b3}} = \frac{R_{string3}+4j\omega L_{b3}}{R_{string1}+4j\omega L_{b3}} \tag{11}$$

When Equation 11 is compared with Equation 4, the inductance term is doubled and the required inductance of T_{b3} is half that of the previous value. For example, if it is assumed that $L_{b3} = 1/2L_b$, Equation 11 has the same form as Equation 4. A smaller requirement for the inductance values means that it is possible to use smaller size transformers. However, since the upper level of the transformer flows two times more current than the previous level, the core and coils of the transformer should be chosen carefully.

To expand the LED string and calculate the inductance for the next subordinate transformer, half of the value of the previous-level transformer is required.

An example of eight strings with an equivalent circuit is presented in Fig. 8. The balancing transformer network consists of eight balancing transformers, and the maximum level of the transformer is third level.

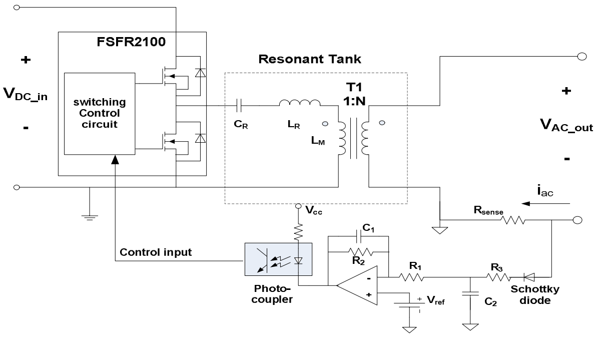


Fig. 10. A block diagram of inverter and control circuits.

To verify the required inductance value, a estimation result is represented in Fig. 9. The simulation parameters are the same as those in Table I. As a result of the simulation, the first-level inductance was 215uH, the second-level inductance was 107uH, and the third level inductance was 53uH, in order to obtain a current error between the rows of 3% or less.

C. Design of the current control circuit

A current control circuit is presented in Fig. 10. As shown in Fig. 10, the current control circuit consists of a half bridge inverter, an LLC resonant tank, and feedback circuits.

Current control is carried out by changing the switching frequency using the gain of the LLC resonant tank and by changing the frequency with the feedback circuits.

The sensed current is rectified to obtain the average current and input it to the error amp, which is compared to the reference voltage. The generated error is delivered to the half-bridge inverter controller on the primary side through the photo coupler, and the switching frequency is changed by the internal VCO of the controller according to the generated error. An FSFR2100 half-bridge controller from Fairchild, which has an internal MOSFET, was used.

The resonant frequency and quality factor of the LLC resonant tank are shown below [6].

$$f_0 = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{12}$$

$$Q_s = \frac{N^2}{R_{load}}\sqrt{\frac{L_R}{C_R}} \tag{13}$$

where R_{load} is the AC equivalent resistance of the LED matrix and the voltage gain transfer function can be expressed in Equation 14.

$$\frac{V_o}{Vin} = \frac{j\omega_n K}{Q\cdot K(1-\omega_n^2)+j\omega_n(1+K-\frac{1}{\omega_n^2})}$$
$$where\ \omega_n = \frac{\omega}{\omega_0},\ K = \frac{L_M}{L_R},\ \omega_0 = 2\pi f_o \tag{14}$$

As the quality factor Q is a function of the load resistance, the voltage gain varies by the resistance of the LED matrix. However, since the tolerance of the LED resistance can be calculated from a datasheet as calculated before, the voltage gain according to the switching frequency can be found as a determinant of the LED matrix.

An example of a target LED matrix is 8 by 12. This means that one LED string consists of 12 EA, and an LED matrix consists of eight strings. As mentioned in the introduction, three kinds of LED were used as follows:

LED A:
Golden dragon Plus(Osram), V_f=2.7~3.7V(@350mA) [18]
LED B:
LUXON Rebel (Philips), V_f= 2.55~3.99V(@350mA) [19]
LED C:
Xlamp (XPEWHT) (Cree),V_f=3.2~3.9V(@350mA) [20]

However, since the datasheet of LED C provides only a typical (3.2V) and a maximum value (3.9V) of V_F, the minimum value is assumed to be 2.5V in this study. Thus the operation voltages for the LED load are V_{op_max} = 47.88V and V_{op_min} = 30V.

The AC equivalent resistance of the LED string is presented in Equation 1, and the whole of the LED load (R_{load}) is connected in parallel, so that R_{load} is presented as Equation 15.

$$R_{load} = R_{string\,1} \,//\, R_{string\,2} \,//\, \ldots R_{string\,n} = \frac{R_{string}}{n} \tag{15}$$

where n is the number of LED strings connected in parallel.

How to decide the values of the resonant tank has been discussed in many studies [15]-[17]. Thus the values of the resonant tank (Lm, Lr, Cr and N) are decided by a design procedure referenced in this paper. The designed values are presented in Table II, and the voltage gain characteristics according to the switching frequency at the minimum load and the maximum load are presented in Fig. 11 using Equation 12. To achieve constant current control, the switching frequencies are varied from 81kHz to 108kHz. The normal operation-switching frequency should be around 90kHz.

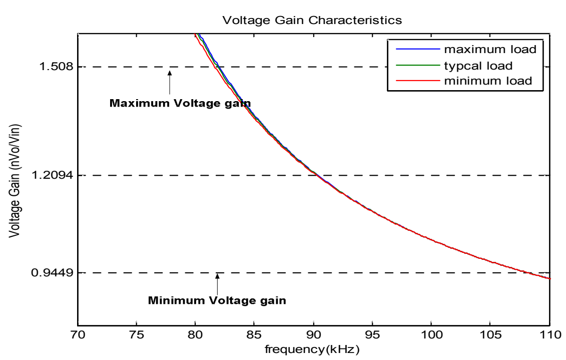
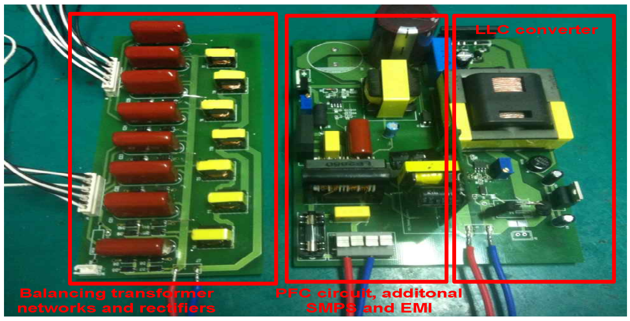


Fig. 11. Voltage gain characteristics of LLC resonant tanks.

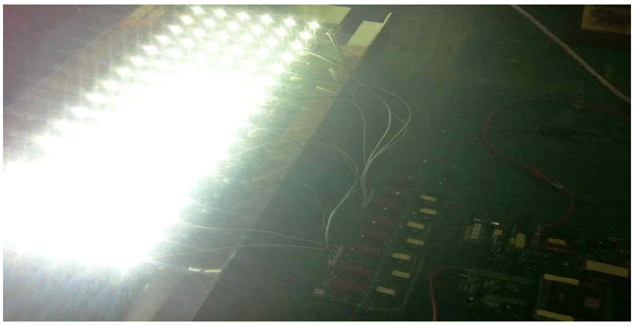
TABLE II

DESIGN PARAMETERS

Parameter	Value	Parameter	Value
Input DC voltage	400V	Operation frequency range	70kHz – 120kHz
No. of LED strings	8	Lm	400uH
No. of LEDs in one LED string	12	Lr	240uH
R_{load_max}(for min. load)	13.8Ω	Cr	10nF
R_{load_min}(for max. load)	8.68Ω	N	0.125



(a) A driving circuit with balancing transformer.



(b) A driving circuit with an LED matrix.

Fig. 12. A picture of prototype circuit.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A prototype of the designed LED driver was put into a 100-watt LED security light to verify its performance. The number of whole LEDs was 96 EA, and a LED matrix of twelve serial and eight parallel LEDs were formed. Three different kinds of LED matrixes were tested. The specifications and designed values for the prototype are presented in Table III. A picture of the prototype circuit is presented in Fig. 12.

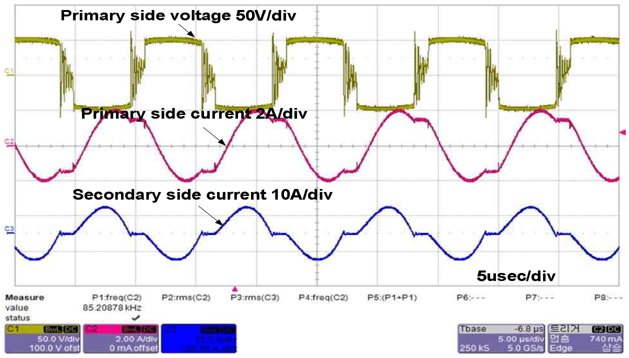
In Table III, the inductance of the balancing transformer Lb was determined to be large enough to minimize the current error. In addition, the switching frequency is around 90 kHz, so that an ultra-fast-recovery diode was used for rectification in the LED strings.

Polyester film capacitors, which have a longer lifespan than electrolytic capacitors relative to the lifetime of lighting devices, were selected to be the output capacitor.

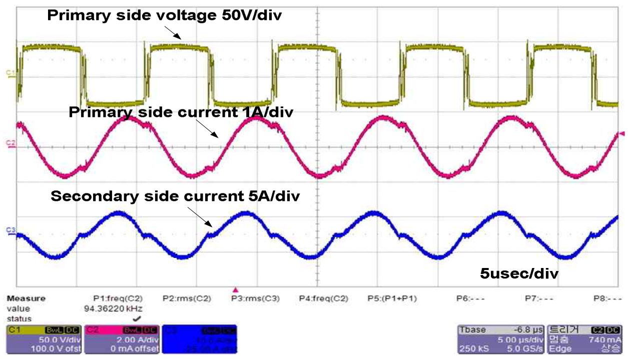
TABLE III

PROTOTYPE SPECIFICATION

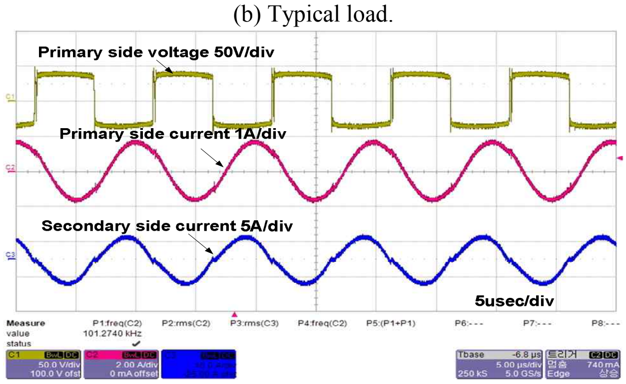
Parameter	Value	Parameter	Value
Input DC voltage	380V ~ 420V	L_b 1st level	500uH
LED matrix	8 x 12	L_b 2nd level	250uH
I_{LED} of each string	350mA	L_b 3rd level	125uH
Total current (I_{tot})	2.8Arms	Core of balancing transformers	EI1309
Operation frequency (f_{op})	70 ~ 120kHz	L_m /L_r/ C_r	400uH /240uH/10nF
Output capacitor	1uF / poly-ester film	Output power	100 Watt



(a) Minimum load.



(b) Typical load.



(c) Maximum load.

Fig. 13. Key waveforms of the prototype according to load variations.

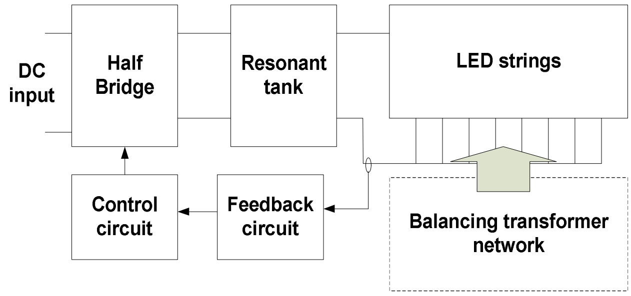


Fig. 14. A block diagram of measurement setup.

All of the measurement results were measured with a LeCroy Waverunner 6030 oscilloscope and a Fluke 287 multi-meter. To verify the design of the LLC resonant tank, the primary side currents, the secondary side currents, and the secondary side voltage waveforms were measured under minimum, typical, and maximum loads using an electronic load. Since the LED strings contained rectifier circuits, an additional rectifier was used for measurement.

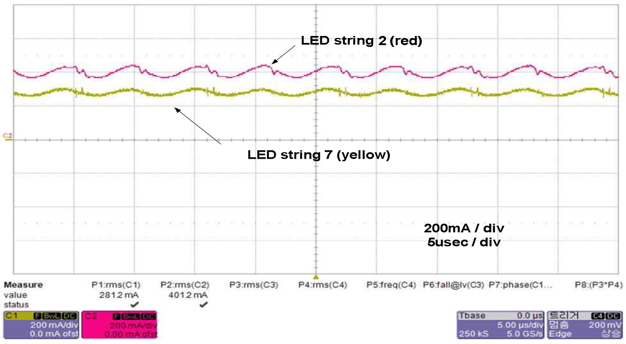
In Fig. 13, the voltage waveform on the primary side is at the top of the figure, in the middle is the current waveform on the primary side, and at the bottom is the current waveform on the secondary side. For the current waveform on the primary side, the primary current does not have a sin wave because of the ZVS operation. The operation frequency for the minimum load was measured at 85 kHz and the maximum load was measured at 102kHz.

To confirm the current balancing, the current values for each LED string were measured, as shown in Fig. 14.

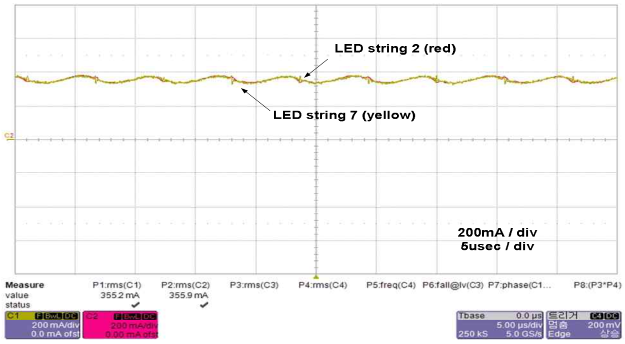
In Fig. 15(a), the measured current between two LED strings has a difference of about 80mA, while Fig. 15(b), which was an applied balancing transformer network, has almost the same waveform.

The current values were measured by the previously mentioned multi-meters, because the accuracy of a current probe is not good enough for the current differences of the LEDs. The current was measured with four strings simultaneously. When the balancing transformer was withdrawn from the network, the LEDs were driven by the total current only. The measurement results are listed in Table IV.

When the balancing transformer was withdrawn from the network, the maximum value was 400mA for A, 380.8mA for B and 376.4mA for C while the minimum value was 284mA for A, 320mA for B, and 340.7mA for C. In other words, the current difference between the minimum and the maximum is 29% for A, 15.9% for B, and 9.48% for C. Because the desired current value was 350mA for each string, the estimated maximum current error was 18.8% for A, 8.8% for B, and 7.5% for C. The current difference of the A matrix was measured as the largest value. However, the LEDs of A are not from the same reel, which means that the manufacturing environment can be different. Therefore, the results are not directly comparable between A and the others. However, the



(a) Current waveforms without a balancing transformer network.



(b) Current waveforms with a balancing transformer network.

Fig. 15. Second and seventh LED string current.

TABLE IV

EXPERIMENTAL RESULTS FOR I_{LED}

LED string NO.	Current of each string when without and with balancing transformers (mA)					
	A		B		C	
	without	with	without	with	without	with
I_{LED1}	320	353.5	365	346.8	352	348.3
I_{LED2}	400	353.3	373.3	347	355.6	348.7
I_{LED3}	356.2	354.5	355.5	345.6	345.3	347
I_{LED4}	348	353.7	380.8	348	346.8	350.3
I_{LED5}	338	351	343	353.7	340.7	360.3
I_{LED6}	322	351	320	343.9	376.4	353.8
I_{LED7}	284	352.5	338.9	352	359.3	360.5
I_{LED8}	285	352.4	334	342.7	371	351

trend can be followed.

When measured with the balancing transformer network, the maximum values were 354.5mA, 353.7mA, and 360.5mA and the minimum values were 351mA, 342.7mA, and 347mA respectively. Therefore, the current differences between the minimum and the maximum values are 0.9%, 3.1%, and 3.7% and the maximum current error was 1.2%, 2%, and 3%.

The measured efficiency was 84%, and the largest loss on the part of the balancing circuit occurred in the rectifier diodes. Thus one of method to improve the efficiency of the rectifier diodes in LED strings is to alternate the Schottky diodes.

IV. CONCLUSIONS

In this study, a circuit that compensates for the current errors of each row of LEDs in a 100-watt security lighting system was designed. Unlike converter circuits, a balancing transformer was used for each row to compensate for the current error between the rows. Thus it can remove the driver ICs and the switches for each LED string.

Further, a balancing transformer network was designed to reduce the size waste of the transformers in the worst case. In order to show the validity of the transformer, the experimental results were shown to achieved a current error of 3% for each row of three kinds of LEDs. The results also demonstrated the validity of the design proposed in this paper. In addition, the efficiency was measured at 84%.

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