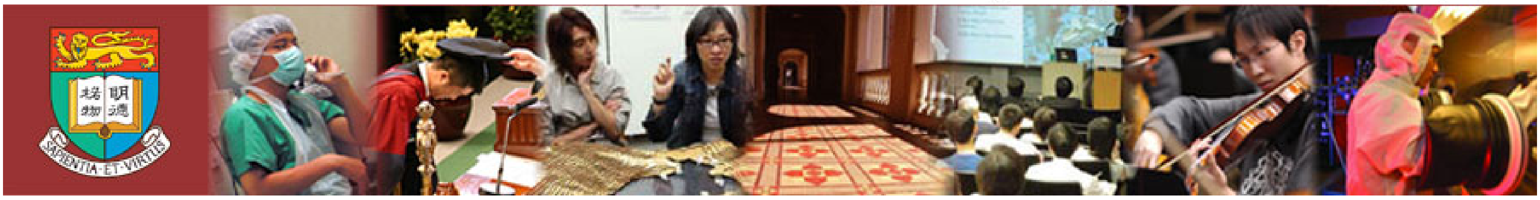

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# Self-Configurable Current-Mirror Circuit With Short-Circuit and Open-Circuit Fault Tolerance for Balancing Parallel Light-Emitting Diode (LED) String Currents

Sinan Li and S. Y. Ron Hui, *Fellow, IEEE*

***Abstract*—Current imbalance among parallel light-emitting diode (LED) strings could put excessive current and thermal stress on some of the LEDs in the systems, resulting in reduction in system lifetime. For LED road lighting systems, reliability is the paramount factor. This paper first explains how existing current-mirror (CM) circuits cannot cope with LED open-circuit faults and then describes a self-configurable CM circuit that can withstand open-circuit faults in LED systems with parallel LED strings. The ability to withstand open-circuit faults means that the LED systems can still function with reduced luminous output even if one LED string is cut off. The proposed circuit, which retains the feature of not requiring an auxiliary dc power supply, has been practically implemented and successfully tested in a 70-W LED system with three parallel strings.**

***Index Terms*—Current mirror circuits, current sharing methods, light-emitting diode technology.**

## I. Introduction

LIGHT-EMITTING diode (LED) technology has successfully penetrated into decorative, signaling, signage, and display applications [1], [2]. For public lighting applications, particularly road lighting, reliability is of paramount importance [3], [4]. To achieve high reliability, various factors of the LED systems must be considered. These factors include at least LED device structure and packaging with minimized thermal resistance [5], [6], thermal management for reducing thermal stress [7]–[9], power control and driver technology for long lifetime [10]–[14], and good current-balancing techniques to avoid overstress in LEDs (for systems with parallel LED strings).

Regarding current-balancing techniques, various passive and active techniques have been reported. Passive methods include the use of the coupled reactors for balancing currents in parallel power electronic devices as described in the first edition of a textbook in 1987 [15]. Coupled reactors were used again and named as current-balancing transformers for current sharing in parallel LED strings in [16]. The coupled-reactors concept was extended to the daisy-chain configuration for balancing currents in multiple parallel power devices in the second edition of the textbook [17] in 1992, and was recently used again and named as daisy-chained transformers in [18], [19], and [20] for current sharing in parallel LED strings.

Active methods include active/switched mode current control [21]–[24] and current-mirror (CM) circuits [25]–[28]. Among them, the self-reconfigurable CM circuit without using a separate power supply [27], [28] is particularly suitable for use with a passive LED driver for road lighting systems [4]. Contrary to a misconception [18] that CM-based current-balancing circuits suffer high power loss, Li *et al.* [27] report that for a 64-W LED system with three parallel strings, the total power loss in the CM circuit is only 1.18 W under normal operation. The low power loss in the CM circuits benefits from the facts that the current ratings of modern high-brightness white LED devices are much less than 1 A (typically about 0.3 A) and that the collector–emitter voltages of the transistors in the CM circuit are used to compensate the small voltage differences of the parallel LED strings under normal situation.

In order to meet the industrial reliability requirements for LED public lighting systems, it is necessary to ensure that the current-balancing circuit can withstand both short-circuit and open-circuit faults in any of the LEDs in the parallel strings. In general, a short-circuit fault in an LED will only increase the current imbalance among the parallel strings. As long as the current imbalance is within the capability of the current-balancing circuit, a short-circuit fault in an LED does not pose any serious problem to the current-balancing circuit. However, if an open-circuit fault occurs in an LED, the whole LED string to which the faulty LED is connected should be isolated from the rest of the system so that the LED system can still function even though with reduced luminous output.

In this paper, an improved self-reconfigurable CM circuit for reducing current imbalance in parallel LED strings is proposed. This circuit can cope with both short-circuit and open-circuit faults in any of the LEDs in the system. It is particularly suitable for use with the passive LED driver [4] which does not use any auxiliary power supply. In this paper, the failure modes of the existing CM circuit for open-circuit fault are highlighted. Then an improved circuit with new measures in isolating the faulty LED string is introduced and its operating principles are

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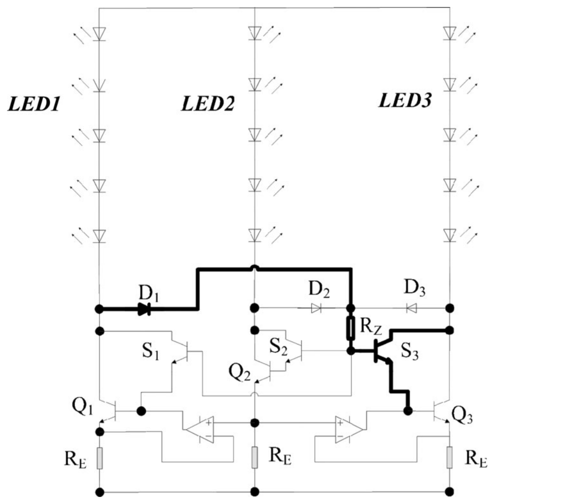


Fig. 1. Self-configurable CM circuit with three strings using op-amp feedback [27] (Bold line highlights the current path to automatically select the smallest current as the reference for the CM circuit under the condition of $I_{\mathrm{LED1}}$ $I_{\mathrm{LED2}}$ $I_{\mathrm{LED3}}$).

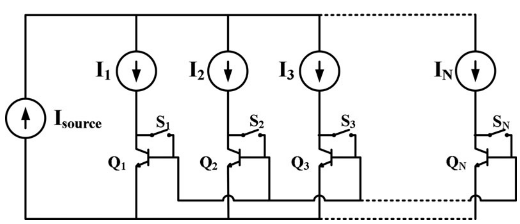


Fig. 2. Schematic of the self-configurable current-mirror principle using self-driven transistors $(S_1 - S_N)$ and linear Q-transistors [27].

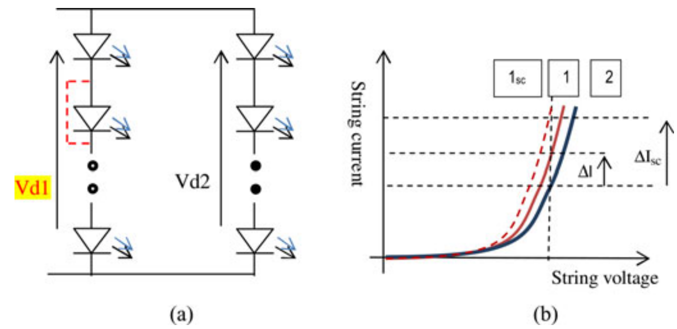


Fig. 3. Parallel current strings and their current–voltage characteristic without the CM circuit.

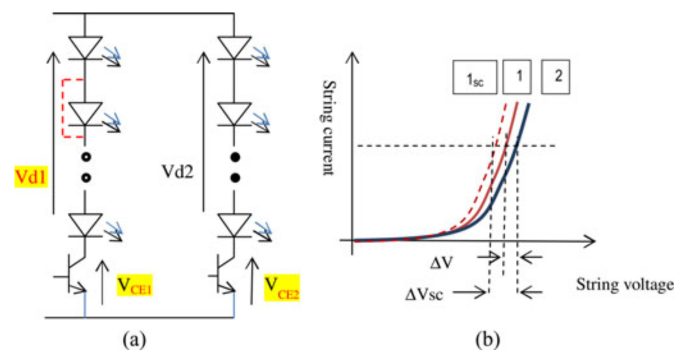


Fig. 4. Parallel current strings and their current–voltage characteristic with the CM circuit.

explained. The proposed circuit has been successfully implemented and its tolerance against short-circuit and open-circuit faults has been practically verified.

## II. Operation Modes of Existing CM Circuit Under Faulty Conditions in Parallel LED Strings

Fig. 1 shows an existing feedback-assisted CM circuit with self-reconfigurable function [22]. Self-reconfiguration refers to the ability to automatically select the current branch with the minimum current magnitude as the current reference for CM action. For each LED string, two transistors connected as Darlington pair are included as the basic unit of the CM circuit. The lower transistor (Q-transistor) normally operates in the linear mode for balancing the current with respect to a chosen current reference. A simplified structure of the self-reconfigurable CM concept is illustrated in Fig. 2. The upper transistors (S-transistors) are used as the selection switches S $(S_1 - S_N)$. One of these S-transistors will be closed to select the current string with the minimum current magnitude as the current reference. The Q-transistors in the nonreference strings are operated in the linear mode in order to provide the voltage compensation in the strings to keep the string currents to follow the current reference.

Assuming that the string currents are under the situation of $I_{\mathrm{LED1}} > I_{\mathrm{LED2}} > I_{\mathrm{LED3}}$, the collector–emitter voltages of the transistors $Q_1, Q_2$, and $Q_3$ will be $V_{\mathrm{CE1}} > V_{\mathrm{CE2}} > V_{\mathrm{CE3}}$. The part of the circuit that selects the current reference with the lowest string current consists of $D_1, D_2, D_3$, and $R_z$. Under this condition, the relatively high voltage of $V_{\mathrm{CE1}}$ will drive a current through the diode $D_1$ and the resistor $R_Z$ to turn ON the transistor $Q_3$ of the LED3 string with the smallest string current. The bold line in Fig. 1 highlights this current path. In this way, the LED string with the smallest current will be automatically selected as the current reference of the CM circuit. Based on this principle, the self-configurable CM circuit [27] always selects the smallest current as the current reference, which is the requirement for the CM circuit operation. The resistors $R_E$ of low resistance values (typically about 1 $\Omega$) are used for two purposes. First, they are included to avoid the thermal runaway of the transistors $Q_1 - Q_3$. Second, they are used as the current sensors for the op-amp feedback circuit.

### A. Short-Circuit Faults

Under normal condition, the CM circuit provides voltage adjustment among the parallel strings so that the string currents will follow the current reference string. If a short-circuit fault occurs in one of the LEDs, the voltage imbalance among the LED strings can increase the tendency for increased current imbalance. This phenomenon can be explained with the aid of the string current–voltage curves of LEDs for two parallel strings as shown in Figs. 3 and 4.

Due to the nonideal LED devices, the LED strings do not have identical characteristics. Fig. 3 highlights the situation for two

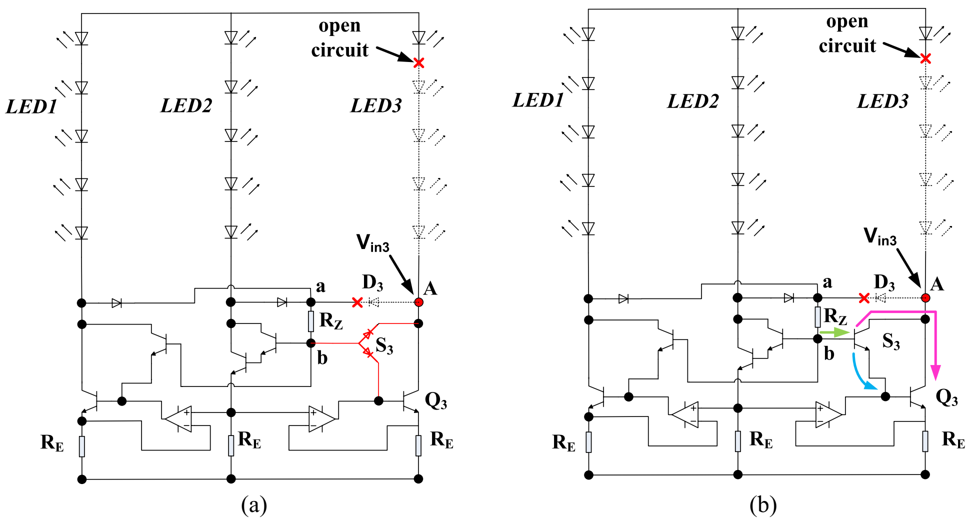


Fig. 5. Equivalent circuit of Fig. 1 when the LED3 string suffers an open-circuit fault. (a) With the two PN junctions of $S_3$ shown as diodes. (b) With current paths in $S_3$ highlighted.

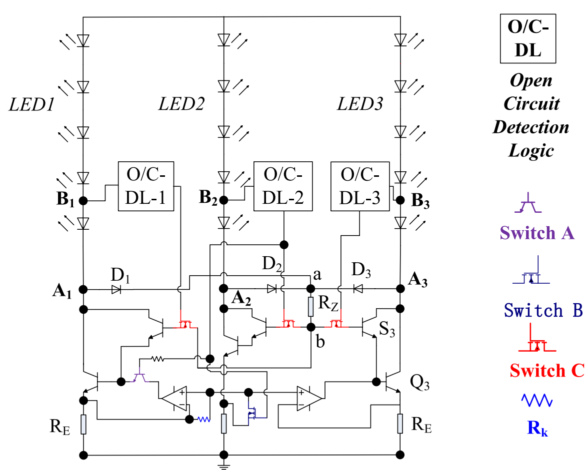


Fig. 6. Improved CM circuit for parallel LED strings with measures of isolating the open-circuited string and the effects of its associated control electronics.

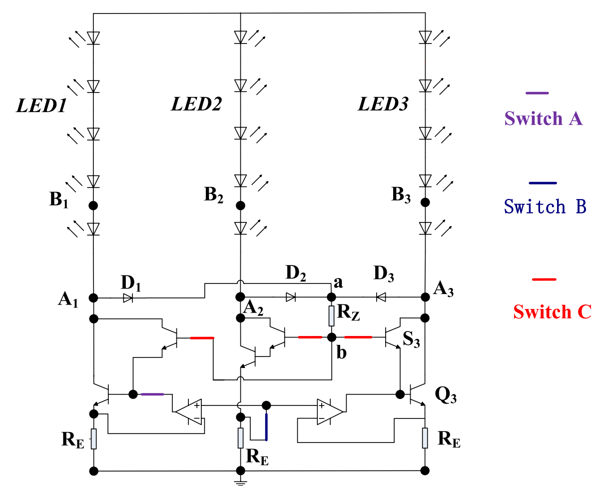


Fig. 8. Equivalent circuit of Fig. 6 when the proposed switches A, B, and C are turned ON under normal conditions (same as the original circuit in Fig. 1).

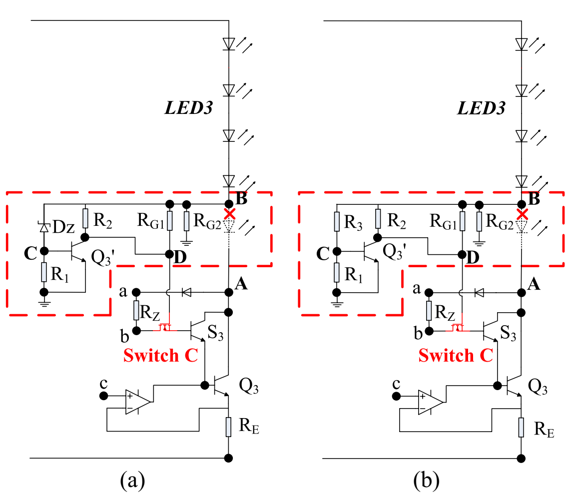


Fig. 7. Proposed open-circuit fault detection logic circuits.

parallel strings with slight differences in the *I–V* characteristics. Assuming that String-2 is the one on the right in Fig. 3, if the same voltage is applied across the two strings without using the CM circuit, the String-1 current is higher than that of String-2 by $\Delta I$. If one of the LEDs in String-1 has a short-circuit fault, the total on-state voltage of String-1 will be reduced. The *I–V* curve of String-1 will shift slightly to the left as shown in the dotted curve labeled by $1_{sc}$ in Fig. 3(b). Consequently, a short-circuit fault in one LED device could increase the current imbalance to $\Delta I_{sc}$.

Fig. 4 shows the circuit and the corresponding *I–V* curve if the CM circuit is used to balance the string currents. Under normal situation, the voltage balance equation can be used to evaluate the circuit operation as follows:

$$V_{d1} + V_{CE1} = V_{d2} + V_{CE2} \tag{1}$$

$$V_{d2} - V_{d1} = V_{CE1} - V_{CE2} = \Delta V. \tag{2}$$

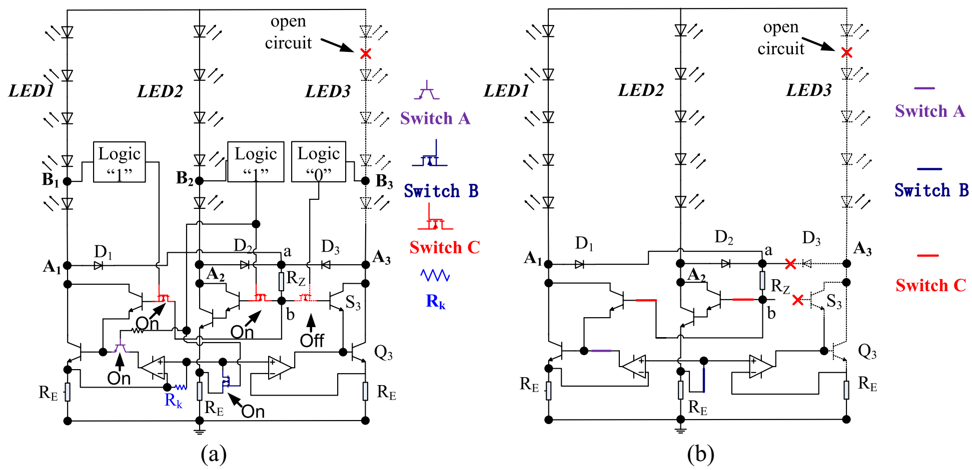


Fig. 9. Switch states and the equivalent circuit when an open-circuit fault occurs in a slave (LED3) string. (a) Status of switches A, B, and C highlighted. (b) Equivalent circuit of (a).

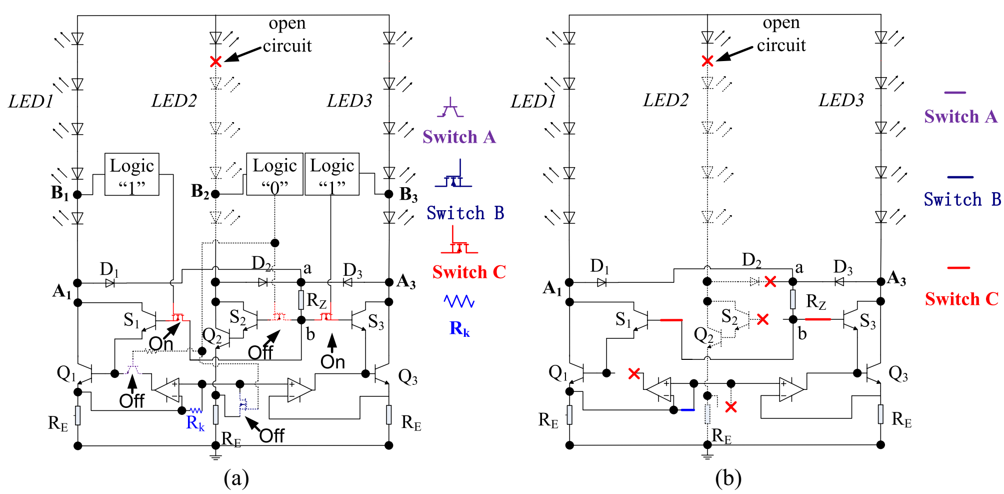


Fig. 10. Equivalent circuit under an open-circuit fault in the master (LED2) string.

Equation (2) shows that the collector-emitting voltage values of the CM circuit can adjust themselves so as to satisfy (2) in order to balance the string currents.

When one LED has a short-circuit fault in String-1, the *I–V* curve of Sting-1will shift slightly to the left as shown in the dotted curve

$$V_{d2} - V_{d1} = V_{\mathrm{CE1}} - V_{\mathrm{CE2}} = \Delta V_{\mathrm{SC}}. \quad (3)$$

Equation (3) indicates that the CM circuit action remains the same, except that the voltage difference of $V_{\mathrm{CE1}}$ and $V_{\mathrm{CE2}}$ has to increase from $\Delta V$ to $\Delta V_{\mathrm{SC}}$. This means that short-circuit fault in one LED in the system does not pose serious problem to the CM circuit as long as the Q-transistors of the CM circuit can provide the voltage difference for current-balancing action. CM circuits are linear regulators. When the voltage across the Q-transistor increases, the power consumed in this transistor-will increase accordingly. Therefore, it is recommended that Q-transistors should have enough power capacity and temperature tolerance.

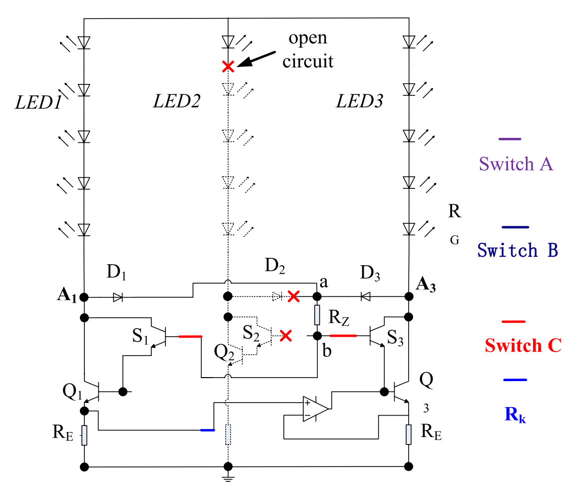


Fig. 11. Simplified form of the equivalent circuit for open-circuit faults in the master (LED2) string.

## *B. Open-Circuit Faults*

Fig. 5 highlights the problem of the circuit of Fig. 1 when the LED3 string suffers an open-circuit fault. Under this

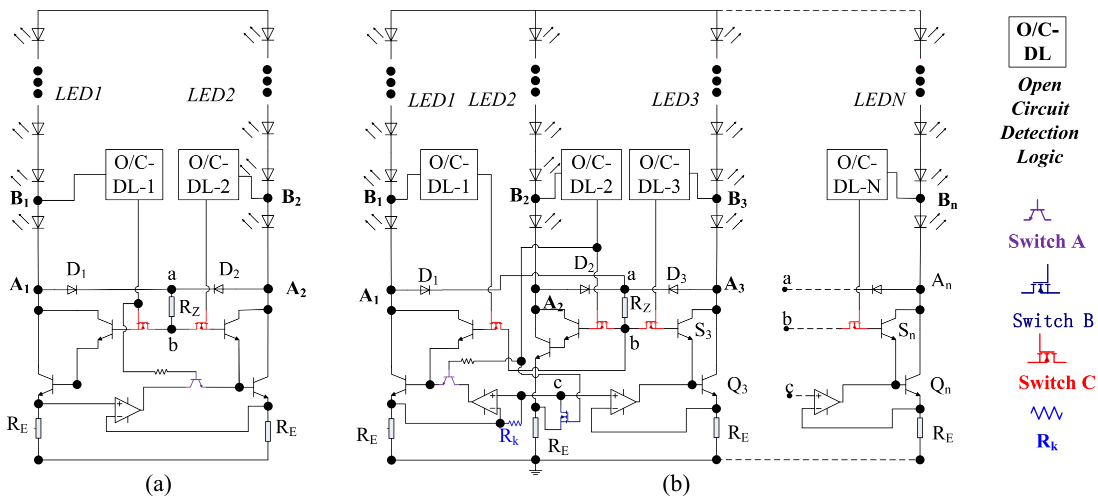


Fig. 12. Generalization from (a) a two-string system to (b) a multiple-string system.

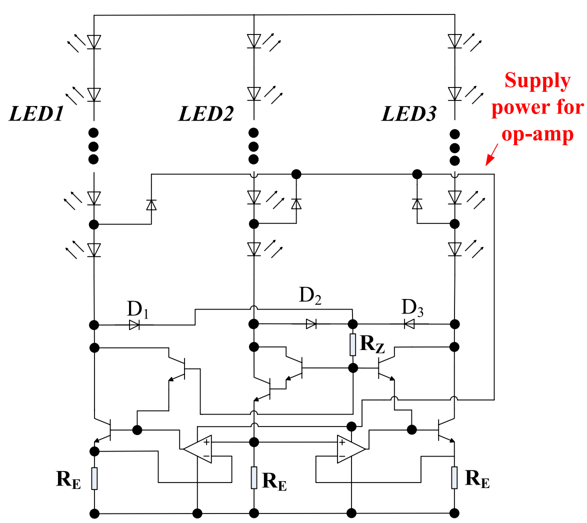


Fig. 13. Experimental setup of the original self-reconfigurable CM circuit.

open-circuit fault, the electric potential $V_{\text{in}3}$ at point A of the circuit is not floating, because the transistor $S_3$ is still conducting. The voltage at point A will fall into a very low value because the base-collector of the bipolar junction transistor (BJT) of $Q_3$ conducts through the diode action of the base-collector of $S_3$. The low current through this base-collector of $S_3$ is small and so is the voltage drop across the resistor $R_E$ of the faulty current string. Consequently, the voltage at point A will be very low. It will be equal to the sum of voltage of the collector–emitter voltage of transistor $Q_3$ and the voltage across $R_E$ of the faulty string. Because $R_E$ is a resistor with low resistance value (typically less than a few ohms) and the current coming from the base-collector diode of $S_3$ is small, the voltage across $R_E$ of the faulty string is also very small. Such low voltage at point A will mislead the CM detection circuit to wrongly select this faulty string as the current reference. The open-circuit fault problem will be practically demonstrated Section 4.

## III. Improved Self-Reconfigurable CM Circuit With Short-Circuit and Open-Circuit Tolerance

In order to improve the reconfigurable CM circuit to cope with an open-circuit fault without using an auxiliary power supply for a separate predetermined current reference, new measures are introduced into the original CM circuit [27] to isolate the open-circuited current string and the effects of its associated control electronics. Fig. 6 shows the improved CM circuit for an LED system with three LED strings.

Before the use of the circuitry is explained, it should be noted that the LED strings can be classified into two groups when the op-amp circuits are used for feedback assistance. Only one LED string will provide a signal to the “noninverting inputs” of the op-amp circuits. This LED string is labeled as the master string. (Note: It should be noted that the master string is not necessarily the string chosen as the current reference in the self-reconfigurable CM circuit.) The remaining LED strings provide their respective signals to the “inverting inputs” of the op-amps. They are called slave strings. Note that even if the master string has an open-circuit fault and has to be isolated, current balancing can still be achieved among the slave strings. The new circuitry has several components for different functions. Its operations are summarized in Table I.

1) Switch C is used for isolating the faulty LED string from the rest of the power circuit. It is turned OFF when an open-circuit fault occurs in the LED string to which it is connected.
2) Switches A and B are used for isolating the control circuit of the master LED string, which is connected to the “noninverting inputs” of the op-amp circuits. (Note: The control circuit of the LED2 string in Fig. 6 is connected to the noninverting input of the two op-amp circuits.) Switches A and B are turned OFF when the master LED string providing signal to the “noninverting input” to the op-amp circuits has an open-circuit fault. When the open-circuit detection logic (O/C-DL) circuit of the master LED string (O/C-DL-2) has a logic output “0” (i.e., an open-circuit fault occurring in the master LED string), both

TABLE I
OPERATING MODES OF THE O/C-DL CIRCUIT

| | Voltage at point C | $Q_3$' State | Logic on point D | comments |
|---|---|---|---|---|
| Normal or S/C in any LED in the string | low | off | "1" | The voltage at point B is not high enough (just 10~30V), such that the voltage at point C (voltage divided by R1 and R3) is not high enough to turn on $Q_3$'. The voltage at D is much close to the voltage at point B through $R_{G1}$, hence resulting in logic "1". |
| O/C fault in the LED below the connection of the O/C-DL circuit | High | on | "0" | The voltage at point B is very high and close to the total driving voltage of the LED string. This makes the voltage at point C high enough to turn $Q_3$' on, hence resulting in logic "0". |
| O/C fault in any LED above the connection of the O/C-DL circuit | Low | Off | "0" | The voltage at point B is the same as that at A, which is very low (around 0.7V). Since $Q_3$' is off, the voltage at point D is much close to point B through $R_{G1}$, hence resulting in logic "0". |

TABLE II
COMPARISON OF THE STRING CURRENTS AND MAXIMUM CURRENT DIFFERENCE WITH AND WITHOUT THE ORIGINAL CURRENT-MIRROR CIRCUIT (INCLUDING POWER CONSUMPTION MEASUREMENT DATA)

| No CM circuit | Original Self-configurable CM circuit with op-amp feedback |
|---|---|
| $I_1$=236.3mA | $I_1$=229.9mA |
| $I_2$=290.1mA | $I_2$=233.3mA |
| $I_3$=306.2mA | $I_3$=234mA |
| Maximum $\Delta I$ =69.9mA ( $\Delta I$ =25.2% of the average string current) | Maximum $\Delta I$ =4.1mA ( $\Delta I$ = 1.76% of the average string current) |
| | Power consumption =1.3W (1.85 % of the total input power) |

TABLE III
STRING CURRENTS AND OTHER MEASUREMENT DATA AFTER A SHORT-CIRCUIT FAULT OCCURS IN ONE LED DEVICE IN STRING 2 IN THE ORIGINAL SELF-CONFIGURABLE CM CIRCUIT

| String no. | String 1 | String 2 | String 3 |
|---|---|---|---|
| Conducting current/mA | 237 | 240 | 241.6 |
| Collector voltage of the Q-transistor at point A in Fig.11 /V | 0.64 | 11.55 | 1.849 |
| Op-amp | Supply voltage:20.74V, supply current 4.12mA | | |
| Current difference | $\Delta I$ =4.6mA ( $\Delta I$ =1.9% of the average string current) | | |
| Power consumption | 3.45W (4.58% of total input power) | | |

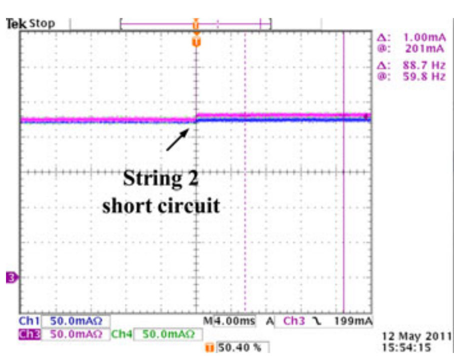


Fig. 14. Measured transient string current waveforms of the original circuit with one LED device in the LED2 string shorted [Ch1: String-1, Ch3: String-2, Ch4: String-3; 50 mA/div, 4 ms/div].

Switches A and B will be turned OFF. Turning OFF Switch A will isolate the connection of the op-amp connecting to the base of $Q_1$. Turning OFF Switch B will isolate the sensing current signal across $R_E$ of the master string (i.e., LED2) from the noninverting inputs of the two op-amp circuits. The equivalent circuit is shown in Fig. 10.

3) Resistor $R_k$ is used to ensure that the "noninverting inputs" of the op-amp circuits to which it is connected, so that these noninverting inputs will not be floating when Switchs A and B are turned OFF. Resistor $R_k$ (typically 1 kΩ) is chosen to be much larger than $R_E$ (typically less than a few ohms) and much less than the input impedance of the op-amp inputs (typically higher than MΩ).

4) O/C-DL circuits that detect the open-circuit faults in their respective LED strings: Two versions of this logic circuit are shown in Fig. 7. Under normal operation, the logic circuit in each LED string provides a logic "1" to close Switch C for the slave string, and to close Switchs A, B, and C for the master string. Otherwise, it will provide a logic "0" to turn OFF the respective switch or switches.

The O/C-DL circuit highlighted in Fig. 7 is used to isolate the LED string in which an open-circuit fault occurs. The logic circuit provides a logic "1" to turn ON Switch C for the slave string and Switches A, B, and C for the master string when the LED string is under normal operation. Under normal conditions when these switches are turned ON, the equivalent circuit is shown in Fig. 8 which is identical to the original CM circuit in Fig. 1.

## A. *Open-Circuit Fault in a Slave String in the Improved Circuit*

Now consider the situation when an open-circuit fault occurs in one of the slave strings. Slave strings are those which provide signals to the ''inverting inputs" of the op-amp circuits. Assuming the LED3 string (the one on the right-hand side in Fig. 6) has an open-circuit fault as shown in Fig. 9(a). Switch C for controlling switch $S_3$ will be turned OFF. The voltage at

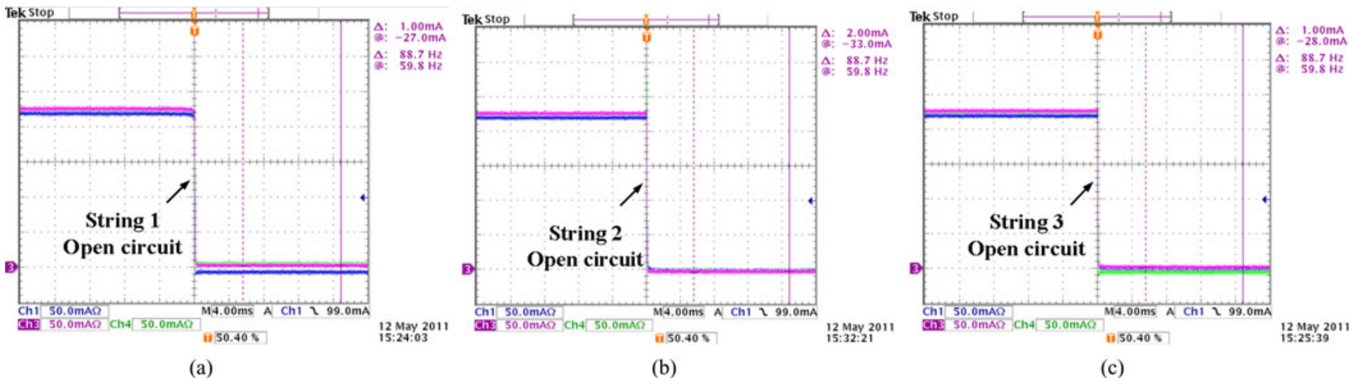


Fig. 15. Measured transient current waveforms of the original circuit with open-circuit fault occurring in one LED device in (a) String-1, (b) String-2, and (c) String-3 [Ch1: String-1, Ch3: String-2, Ch4: String-3; 50 mA/div, 4 ms/div].

TABLE IV
STRING CURRENTS AND MAXIMUM CURRENT DIFFERENCE IN THE LED SYSTEM USING THE IMPROVED CURRENT-MIRROR CIRCUIT (INCLUDING POWER CONSUMPTION MEASUREMENT)

| String no. | String 1 | String 2 | String 3 |
|---|---|---|---|
| Conducting current /mA | 229.03 | 229.09 | 228.15 |
| Collector voltage of the Q-transistor at point A of Fig.7 /V | 1.561 | 2.98 | 3.425 |
| Voltage at B of Fig.7 /V | 12.44 | 12.72 | 13 |
| Op-amp | Supply voltage:12.19V , supply current 2.78mA | | |
| Current difference | $\Delta I$ =0.94mA ( $\Delta I$ =0.41% of the average string current) | | |
| Power consumption | 1.85W (2.62% of total input power) | | |

TABLE V
STRING CURRENTS AND MAXIMUM CURRENT DIFFERENCE WITH THE IMPROVED CURRENT-MIRROR CIRCUIT AFTER A SHORT-CIRCUIT FAULT OCCURS IN THE LED2 STRING (INCLUDING POWER CONSUMPTION MEASUREMENT)

| String no. | String 1 | String 2 | String 3 |
|---|---|---|---|
| Conducting current/mA | 229.17 | 229.73 | 227.98 |
| Collector voltage of the Q-transistor at point A of Fig.7 /V | 1.174 | 12.4 | 3.42 |
| Voltage at B of Fig.7 /V | 12.02 | 21.99 | 12.86 |
| Op-amp | Supply voltage:21.18V, supply current 2.0mA | | |
| Current difference | $\Delta I$ =1.75mA ( $\Delta I$ =0.76% of the average string current) | | |
| Power consumption | 3.9W (5.37% of total input power) | | |

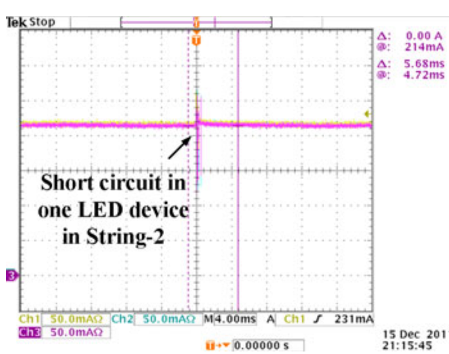


Fig. 16. Measured transient current waveforms of the improved circuit when a short-circuit fault occurs in one LED device in String 2. [Ch1: String-3, Ch2: String-2, Ch3: String-3; 50 mA/div, 4 ms/div].

point $A_3$ will drop to a low level that the diode $D_3$ will be reverse biased and turned OFF. Therefore, the third LED string is isolated from the rest of the circuit as shown in Fig. 9(b).

### *B. Open-Circuit Fault in the Master String in the Improved Circuit*

The master string is the one which provides a signal to the "noninverting inputs" of the op-amp circuits. In Fig. 6, the central LED string is a master string. Assuming that an open-circuit fault occurs in this string as shown in Fig. 10(a), the logic circuit of the central string will turn OFF the Switch C for $S_2$, Switch A, and Switch B. Because the value of the resistor $R_k$ is much higher than $R_E$ and much lower than the impedance of the noninverting inputs of the op-amps, the resistor $R_k$ effectively ties the noninverting inputs to one of the inverting input of the op-amp circuit, so that the noninverting inputs will not be floating. The equivalent circuit when the master string has an open-circuit fault is shown in Fig. 10(b). The simplified form of this equivalent circuit is shown in Fig. 11. The proposed idea can be extended to more parallel current strings as shown in Fig. 12.

## IV. EXPERIMENTAL VERIFICATION

LED systems based on the original and the improved current-balancing circuits have been set up for comparison and practical evaluation. Each LED system consists of three parallel strings. Each string is composed of ten series-connected 3-W Sharp white LED devices (Model: GW5BWC15L02) with a rated current of 320 mA. The voltage across each LED device is about 10 V and the LED string voltage is about 100 V.

### *A. Tests on Original Circuit (as Reference)*

Fig. 13 shows the original circuit. The op-amp circuits are powered by the potential difference across one LED device (i.e., about 10 V), and no external power supply is required. The components used the CM circuit are: BJT transistors: BD139, op-amp: LM324, diodes: 1N4148, $R_z = 55$ kΩ, and $R_E = 1\Omega$. Test results of this circuit under normal operations have been presented in [27].

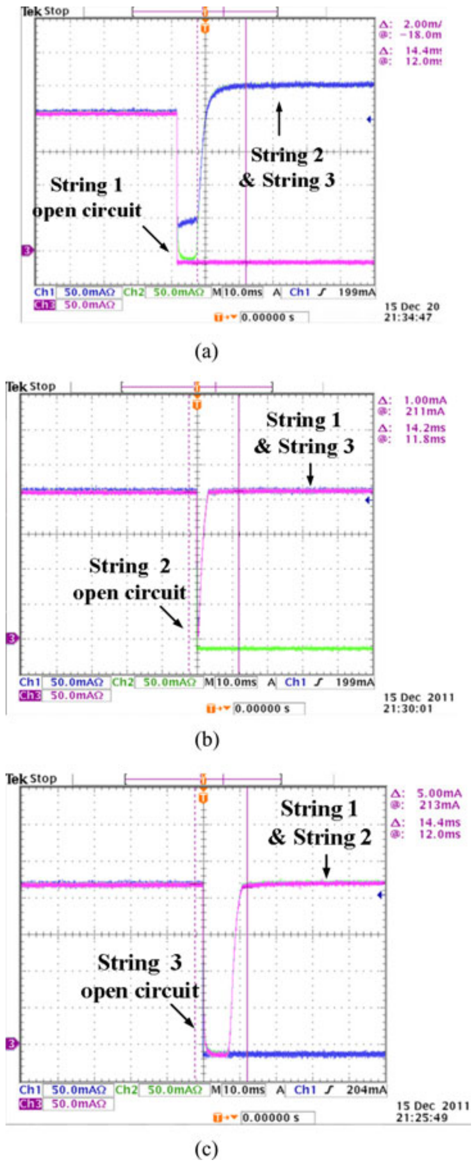


Fig. 17. Measured string currents before and after the open-circuit fault occurring in one of the three LED strings [Ch1: String-3, Ch2: String-2, and Ch3: String-1; 50 mA/div, 10 ms/div]. (a) Open-circuit fault occurring in String-1 (Slave) only. (b) Open-circuit fault occurring in String-2 (Master) only. (c) Open-circuit fault occurring in String-3 (Slave) only.

*1) Normal Operation in the Original Circuit:* Table II tabulates the performance of the original circuit before and after using the CM circuit. The information in this table is used as a reference for comparison with the performance of the improved circuit.

*2) Short-Circuit Fault in One LED Device in the Original Circuit:* In this test, one LED device (out of the ten series-connected devices) in String-2 of the circuit is shorted. The transient waveforms of the three string currents are recorded in Fig. 14. It can be seen that good current balance can still be achieved. Some measured data are tabulated in Table III. The collector voltage of the Q-transistor is an important parameter that provides the selection of the current reference. Table II shows that String-1 has the smallest current before using the CM circuit. So the reconfigurable CM circuit will select String-1 as the current reference. This point is confirmed in Table III, in which the collector voltage of the Q-transistor in String-1 is smallest, meaning that Q-transistors in String-2 and String-3 vary to reduce their current to follow the current reference of String-1.

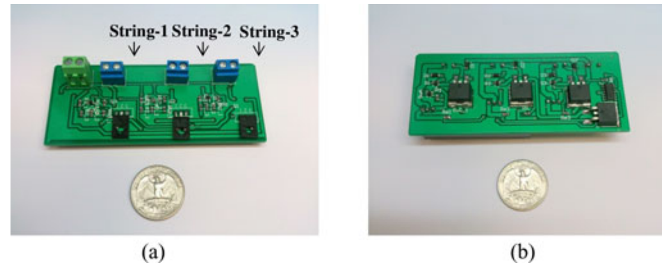


Fig. 18. Photograph of the proposed CM circuit with both short- and open-circuit fault tolerance (compared with a quarter dollar coin). (a) Top side. (b) Bottom side.

Since the voltage across each LED device is about 10 V, the collector voltage of the Q-transistor in String-2 increases by the same magnitude in order to balance the currents. Good current balance can be achieved with the reconfigurable CM circuit, at the expense of higher conduction loss in the Q-transistor of String-2. Comparison of the power consumptions of the CM circuit in Tables II and III indicates that the power consumption has increased from 1.3 W (1.9%) to 3.45 W (4.9%). However, it should be noted that the original CM circuit can tolerate short-circuit fault in one LED device.

*3) Open-Circuit Fault in One LED Device in the Original Circuit:* Fig. 15 shows the practical measurements of the three currents of circuit in Fig. 13, with one of the three LED current strings suddenly cut off to simulate an open-circuit fault. It can be seen that the three currents drop to zero or near zero. These results confirm that the original CM circuit can withstand an LED short-circuit fault, but cannot cope with an LED open-circuit fault as previously explained. If such open-circuit fault occurs, the LED system will not function and no light is produced.

### *B. Tests on the Improved Circuit*

The circuit example of Fig. 6 with three parallel LED strings has been used for practical evaluation. The voltage across one LED device is used to derive a 10-V dc power supply for the op-amp circuit in order to avoid using a separate auxiliary power supply. In Fig. 6, String-1 and String-3 are the slave strings and String-2 is the master string. All S-transistors are implemented in Darlington configuration. The sensitiveness of the collector voltage with the resistor $R_z$ is, therefore, much reduced. The components used in the improved circuit are: BJT transistors (including switch A and Darlington pairs): BD139, MOSFET switches (Switchs B and C): IRF530 N, $R_z = 2$ kΩ, $R_k = 1$ kΩ and the other components are identical to the first set of experiments. The detection logic circuit of Fig. 7 is used for each LED string.

*1) Normal Operation in the Improved Circuit:* The improved circuit has been tested under normal operation. Table IV tabulates the measured data. The voltage differences at points B of the three strings highlight the fact that the LED devices are

TABLE VI
STRING CURRENTS AND OTHER MEASUREMENT DATA AFTER AN OPEN-CIRCUIT FAULT OCCURS IN THE THREE STRINGS WITH IMPROVED CM CIRCUIT (INCLUDING POWER CONSUMPTION MEASUREMENT AND SWITCH STATES)

| Test no. | Test 1 (String 1has open circuit fault) | | | Test 2 (String 2 has open circuit fault) | | | Test 3 (String 3 has open circuit fault) | | |
|---|---|---|---|---|---|---|---|---|---|
| String no. | String 1 | String 2 | String 3 | String 1 | String 2 | String 3 | String 1 | String 2 | String 3 |
| Conducting current/mA | 0 | 270.2 | 269.7 | 232.1 | 0 | 229.8 | 231.7 | 232.23 | 0 |
| Collector voltage of the Q-transistor at point A of Fig.7 /V | 0.022 | 1.837 | 2.397 | 1.541 | 0.011 | 3.82 | 1.538 | 3.24 | 0.008 |
| Voltage at B of Fig.7 /V | 0.004 | 11.64 | 12.01 | 12.40 | 0.006 | 13.27 | 12.40 | 12.9 | 0.005 |
| Op-amp | Supply voltage:11.13V, supply current 10mA | | | Supply voltage:12.02V, supply current 0.94mA | | | Supply voltage:11.51V, supply current 11mA | | |
| Power consumption | 1.25W (2.26% of total input power; 1.79% of the rated power of 70W) | | | 1.25W (2.63% of total input power; 1.79% of the rated power of 70W) | | | 1.24W (2.60% of total input power; 1.77% of the rated power of 70W) | | |
| Switch states | Switch C in String 1 is off | | | Switch C in String 2 is off; Switch A and B are off | | | Switch C in String 3 is off | | |

not exactly identical. The collector voltage of the Q-transistor in String-1 is smallest, indicating that String-1 is selected as the current reference. The string currents are well balanced with the current difference less than 1% of the average string current. These results of the improved circuit are similar to those of the original circuit recorded in Table II.

*2) Short-Circuit Fault in One LED Device in the Improved Circuit:* In this test, one LED device is shorted in String-2. The three string currents before and after the short-circuit fault are captured and displayed in Fig. 16. Some measured data after the short-circuit faults are recorded in Table IV. Again, String-1 is selected as the current reference because its Q-transistor has the smallest voltage. The transient current measurements confirm that the improved circuit can cope with short-circuit fault well. It is noted from Table V that the Q-transistor of String-2 provides the voltage to compensate the voltage of the LED device with the short-circuit fault. The current balance is achieved at the expense of increased power loss, which increases from 1.85 to 3.9 W.

*3) Open-Circuit Fault in One LED Device in the Improved Circuit:* Open-circuit tests are conducted for each string. A series-connected MOSFET is connected to each string. This switch is turned OFF to simulate the open-circuit fault. The measured string currents of the LED system before and after the open-circuit fault occurring in String-1, String-2, and String-3 are recorded and displayed in Figs. 17(a), 17(b), and 17(c), respectively. It can be seen in the three cases that the remaining two strings without open-circuit fault continue to be in operation with good current balance. Therefore, the proposed circuit allows the LED system to continue to produce light even if one LED device suffers an open-circuit fault. This feature is particularly useful for street lighting applications in which the system availability rate is important.

Measured data of the system of the three open-circuit tests are tabulated in Table VI. The current values after the open-circuit faults in Figs. 17(b) and 17(c) are almost identical and equal to those before the fault. The reason is due to the fact that the current of String-1 is chosen as the current reference by the reconfigurable CM circuit in these two cases, as confirmed by the smallest voltage in the collector of the Q-transistor in String-1 recorded in Table VI. In Fig. 17(a), the string currents follow that of String-1 before the open-circuit fault. After the open-circuit fault in String-1, the current in String-2 is automatically chosen as the current reference and so the new balanced current value is different from that in Figs. 17(b) and 17(c). A photograph of the proposed circuit is shown in Fig. 18.

## V. CONCLUSION

The self-configurable CM circuit has provided an effective solution to balance LED string currents. It has been demonstrated that the original circuit can cope with an LED short-circuit fault, but not an open-circuit fault. This paper presents an improved version that allows the LED system with parallel strings to continue to operate and produce light even if one LED device suffers either a short-circuit or an open-circuit fault. The improved circuit can further enhance the lifetime of LED systems with parallel LED strings even if an individual LED device fails. The operating principle of the improved circuit has been explained and practically demonstrated. This circuit design does not require any auxiliary power supply and electrolytic capacitors. It can be used with passive LED drivers for street lighting systems because such passive drivers do not have switched mode or regulated power supplies for the system operation.

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## REFERENCES

[1] C.-C. Chen, C.-Y. Wu, Y.-M. Chen, and T.-F. Wu, "Sequential color LED backlight driving system for LCD panels," *IEEE Trans. Power Electron.*, vol. 22, no. 3, pp. 919–925, May 2007.

[2] S. Wha Hong, H. Jin Kim, J.-S. Park, Y. Gun Pu, J. Cheon, D.-H. Han, and K.-Y. Lee, "Secondary-side LLC resonant controller IC with dynamic PWM dimming and dual-slope clock generator for LED backlight units," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3410–3422, Nov. 2011.

[3] W. Chen, S. N. Li, and S. Y. R. Hui, "A comparative study on the circuit topologies for offline passive light-emitting diode (LED) drivers with long lifetime & high efficiency," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2010, pp. 724–730.

[4] S. Y. R. Hui, S. Li, W. Chen, X. H. Tao, and W. M. Ng, "A novel passive LED drivers with long lifetime," *IEEE Trans. Power Electron.*, vol. 25, no. 10, pp. 2665–2672, Oct. 2010.

[5] J. Lalith, Y. M. Gu, and N. Nadarajah, "Characterization of thermal resistance coefficient of high-power LEDs," in *Proc. Sixth Int. Conf. Solid State Lighting*, San Diego, USA, Aug. 2006, pp. 63370–63377.

[6] A. Poppe, G. Molnár, and T. Temesvölgyi, "Temperature dependent thermal resistance in power LED assemblies and a way to cope with it," in *Proc. IEEE 26th Semicond. Therm. Meas. Symp.*, Santa Clara, CA, USA, Feb. 21–25, 2010, pp. 283–288.

[7] T. Zahner, "Thermal management and thermal resistance of high power LEDs," in *Proc. 13th Int. Workshop Therm. Investigation of ICs Syst.*, Budapest, Hungary, Sep. 2007, pp. 195–195.

[8] M. Arik, C. Becker, S. Weaver, and J. Petroski, "Thermal management of LEDs: Package to system," *Proc. SPIE*, vol. 5187, pp. 64–75, 2004.

[9] Q. Cheng, "Thermal management of high-power white LED package," in *Proc. 8th Int. Conf. Electron. Packag. Technol.*, Shanghai, China, Aug. 2007, pp. 1–5.

[10] Q. Hu and R. Zane, "Minimizing required energy storage in off-line LED drivers based on series-input converter modules," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2887–2895, Oct. 2011.

[11] H. Ma, J.-S. Lai, Q. Feng, W. Yu, C. Zheng, and Z. Zhao, "A novel valley-fill SEPIC-derived power supply without electrolytic capacitor for LED lighting application," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 3057–3071, Jun. 2012.

[12] B. Wang, X. Ruan, K. Yao, and M. Xu, "A method of reducing the peak-to-average ratio of LED current for electrolytic capacitor-less ac–dc drivers," *IEEE Trans. Power Electron.*, vol. 25, no. 3, pp. 592–601, Mar. 2010.

[13] L. Gu, X. Ruan, M. Xu, and K. Yao, "Means of eliminating electrolytic capacitor in ac/dc power supplies for LED lightings," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1399–1408, May 2009.

[14] W. Chen and S. Y. R. Hui, "Elimination of electrolytic capacitor in an ac/dc light-emitting diode (LED) driver with high input power factor and constant output current," *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp. 1598–1607, Mar. 2012.

[15] B. Williams, *Power Electronics: Devices, Drivers and Applications*, 1st ed. New York, NY, USA: MacMillan, 1987, p. 198.

[16] K. I. Hwu and S. C. Chou, "A simple current-balancing converter for LED lighting," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2009, pp. 587–590.

[17] B. Williams, *Power Electronics: Devices, Drivers, Applications, and Passive Components*, 2nd ed. New York, NY, USA: McGraw-Hill, p. 229.

[18] R. Zhang and H. Chung, "Daisy-chain transformer structure for current-balancing multiple LED strings," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2013, pp. 3118–3125.

[19] R. Zhang and H. Chung, "Use of daisy-chained transformers for current-balancing multiple LED strings," *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1418–1433, Mar. 2014.

[20] R. Zhang and H. Chung, "Transformer-isolated resonant driver for parallel strings with robust balancing and stabilization of individual LED current," *IEEE Trans. Power Electron.*, (early access).

[21] Y. Hu and M. Jovanovic, "LED driver with self-adaptive drive voltage," *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp. 3116–3125, Nov. 2008.

[22] C. H. Lin, T. Y. Hung, C. M. Wang, and K. J. Pai, "A balancing strategy and implementation of current equalizer for high power LED backlighting," in *Proc. Int. Conf. Power Electron. Drive Syst.*, 2007, pp. 1613–1617.

[23] C. C. Yang, G. M. Lei, and Y. C. Lai, "Light emitting diode circuit having even current," U.S. Patent 7 675 240, Mar. 9, 2010.

[24] C. L. Chiu and K. H. Chen, "A high accuracy current-balanced control technique for LED backlight," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2008, pp. 4202–4206.

[25] H.-J. Chiu and S.-J. Cheng, "LED backlight driving system for large-scale LCD panels," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2751–2760, Oct. 2007.

[26] C. Wey, Y.-C. Yeh, C. H. Sun, and T. S. Lee, "Driver and method for driving a semiconductor light emitting device array," U.S. Patent 7 605 809, Oct. 20, 2009

[27] S. N. Li, W. Z. Zhong, W. Chen, and S. Y. R. Hui, "Novel self-configurable current mirror techniques for reducing current imbalance in parallel light-emitting diode (LED) strings," *IEEE Trans. Power Electron.*, vol. 27, no. 4, pp. 2153–2162, Apr. 2012.

[28] S. Y. R. Hui, W. Chen, S. Li, and W. X. Zhong, "Current balancing circuit and method," U.S. Patent 0 286 753 A1, 2012.

[29] S. Li and S. Y. R. Hui, "Current mirror circuit and method," Patent application PCT/CN2012/084965, filed 21 Nov. 2012.

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