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A NOVEL LINEAR CIRCUIT FOR CURRENT EQUALIZATION IN LED STRINGS

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Abstract – This paper deals with the problem of current sharing in parallel strings of LEDs. As there is no guarantee that the string voltages are the same, some strategy for equalizing their currents must be used. This ensures that the luminous fluxes emitted by the strings are very similar. To address this issue it is proposed a small and simple linear topology that can be used on a number of series-associated LEDs, working as a constant current source for each string. Only four components are used in the arrangement, and a low dependence on transistor parameters is observed, ensuring good current regulation. Mathematical description and an analysis of the stability of the circuit are provided, as well as experimental results.

Keywords - LEDs; LED string driving; Current equalization; Solid state lighting.

I. INTRODUCTION

During many years LEDs were employed as luminous flags and indicators, but due to the development of the blue LED (which allowed the realization of white LEDs) they have recently found their place in general lighting applications. This was made possible by the recent advent of the so-called high-brightness LEDs (HB-LEDs), which are changing the perspectives of indoor as well as outdoor illumination.

Long term estimations assuming 100% market penetration and 50% power conversion efficiency are that a 10% decrease on worldwide energy consumption could be attained by using LEDs as main light sources. This saving goal could mean a 50% decrease on the electrical energy used for producing artificial lighting [1]. That, together with the white light, good color rendering index (CRI) and long lifespan makes LEDs a very attractive and environmentally friendly alternative as a light source.

But since HB-LEDs are essentially low power devices (usually 1 to 5 W), an LED-luminaire (or anything equivalent of a lamp made out of LEDs) could not be constructed out of a single device. Thus, it is necessary to associate a number of LEDs in order to produce the desired light output. There are several ways to associate LEDs to obtain the desired luminous flux. Each form of association has its advantages and disadvantages, as will be discussed.

The main objective of this work is to propose a novel circuit to perform current balancing in series-parallel strings of LEDs. Experimental validation of the topology is provided in a two string module.

II. LED ARRANGEMENTS

The LED-based solutions need to have multiple LEDs associated to emit the luminous flux of typical luminaires. As an example, a 1 W LED emits around 100 lm, while a 100 W HPS lamp emits 9,000 lm. So, it would be necessary an association of 90 unities of 1W LED in order to have the same luminous flux.

The association of LEDs to make a string module raises concern on the current regulation of the individual devices or strings. Since light output and correlated color temperature are highly dependent on the forward current of an LED [2], there is a great deal of care to drive all the devices in a single string (or string module) under the same forward current. Furthermore, overcurrent can cause the acceleration of the LED luminous flux degradation.

Also, there is the possibility of an LED failure, under which different associations (shown in Figure 1) will respond in different manners. According to [3], LEDs tend to commonly fail as an open circuit under electrostatic discharge (ESD) and thermo-mechanical stress of the bond wires. But they can also fail as a short circuit, prevalently on-die, as a result of threading dislocations (formation of nanopipes on the substrate) or degraded passivation (defects on the insulating SiO₂ layer). It is important to say that the most modern LED models do not have a SiO₂ layer [4].

A few possibilities for associating LEDs to form a string or luminaire module are shown in Figure 1. A pure series association of LEDs (Figure 1a), called an LED string, has the advantage of forcing all devices to share the same current, thus making any further current equalization unnecessary, so there is no current imbalance. On the other hand, large series strings could result in high string voltage. Moreover, if a single LED turns out to fail as an open circuit, the whole string will be out (if no special protection circuits are employed), compromising the reliability of the module under this faulty condition.

A parallel association of strings forms a series-parallel LED module (Figure 1b). This reduces the impact of an open circuit LED failure, which would make only a string turn out, but creates a current imbalance issue. Since not all LEDs can be ensured to be identical, the voltage at each string will be slightly different, thus their currents will also differ. Therefore, it might be necessary some sort of equalization

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circuit to balance the current on the individual strings. A matrix module (Figure 1c) is made by connecting LEDs directly in parallel and then connecting these parallel clusters in series with each other.

The result is that every matrix row of the module shares the same voltage. Once more, current imbalance will take place, because LEDs intrinsically differ in forward voltage. But in this case, it would be necessary an equalization device for each LED, which happens to be unviable. One advantage is that an open circuit failure of an LED will result in only one device out, but if the failure turns out to be a short circuit, a whole parallel cluster will turn off due to the voltage drop to zero.

III. CURRENT EQUALIZATION TECHNIQUES FOR LEDS STRINGS

The series-parallel association of LEDs is an alternative that may be considered more reliable, in terms of failure (considering the case of open circuit failure) than the pure series strings and at the same time, easier to ensure the current balancing than the matrix modules. Therefore, the only problem to be solved is how to equalize the currents at the parallel-associated strings.

A number of circuits and techniques have been proposed for equalizing the current in LED strings, ranging from fairly simple to more intricate topologies. Most of these circuits assume a constant voltage bus or a current source, from where the LEDs and equalization circuits are fed. An adequate switching regulator, as shown in Figure 2, can provide this bus.

Some of the techniques use monolithic linear regulators, such as LM317, plus a pass transistor to provide the strings with regulated, equalized currents [5]. This provides a fairly simple circuit, but the efficiency can be quite low for the higher currents required by power HB-LEDs, because the regulator IC requires a minimum voltage drop from input to output for the circuit to work (Figure 3).

Another linear alternative are MOSFET-based current mirrors [6]. A reference branch MOSFET, which has its gate connected to other branches of LED strings, forces the mirroring of the reference current on these strings. This circuit only works satisfactorily if the MOSFETs are of high-gain and are identical (or very alike), which is an almost impossible condition for discrete power MOSFETs. However, it could be useful in the case MOSFETs inside an integrated circuit were adopted.

Another relative disadvantage concerning the reference [6] alternative is that the reference branch drains current without any useful output, and the circuit uses as many MOSFETs as LED strings (Figure 4).

A more intricate circuit is presented in [7]. It uses a linear regulator along with a feedback loop to control the switching pre-regulator, in order to adapt the output voltage to attain high efficiency (Figure 5).

There are also the switching alternatives for current equalization. For example, one presented in [8] uses an inverter based on the current-fed parallel-resonant push-pull topology. The LEDs are connected in anti-parallel at the output of the inverter, two-by-two, series-connected to a current balancing capacitor. The LEDs are fed by half-wave

rectified high-frequency quasi-sinusoidal current and zero-voltage switching can be attained, thus also higher efficiency.

Some other more intricate switching circuits are proposed by [9] and [10], and a hybrid switching-magnetic solution is proposed in [11]. The switching solutions are more varied and complex by definition, and will not be further explored in this work. Table I shows some characteristics for both linear and switching equalization circuits, aiming a brief comparison among them.

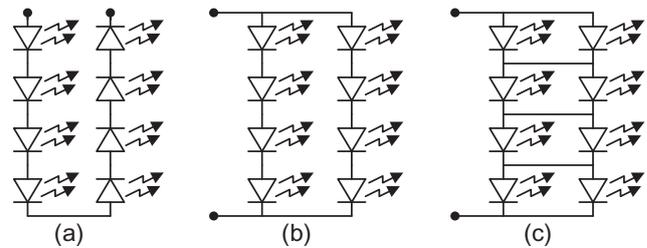


Fig. 1. Three possibilities of LED string modules: (a) series string, (b) series-parallel string module and (c) matrix module.

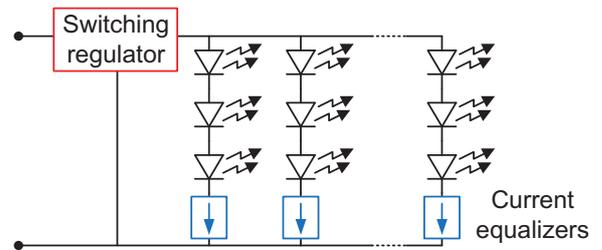


Fig. 2. Basic scheme of a series-parallel modular HB-LED driver.

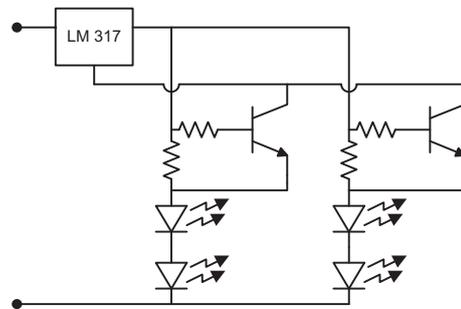


Fig. 3. Linear current equalizer using monolithic regulator IC.

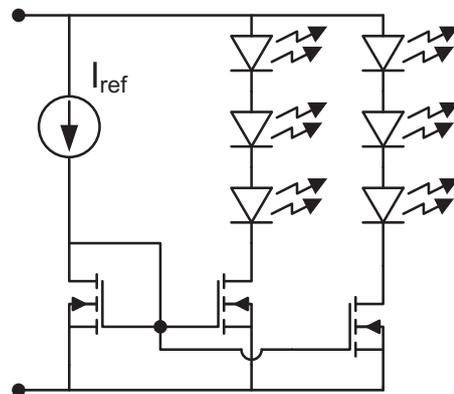


Fig. 4. Linear current equalizer using current mirrors.

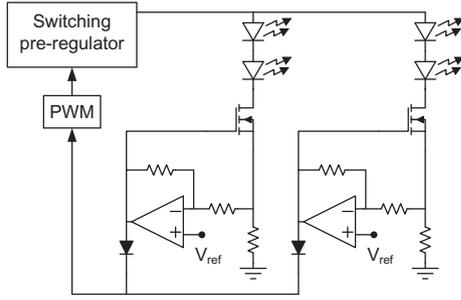


Fig. 5. Linear current equalizer using adaptive voltage drive voltage.

Linear circuits, though commonly more inefficient, are generally easier to implement, can be considered cost-effective alternatives and represent reliable enough solutions for mass-manufacturing luminaires. Moreover, they usually require a lower component count.

Recently, many passive equalization circuits have been proposed [12] - [15], which reveal the importance of this subject for this specific field. All of them add characteristics of low cost, high efficiency and good precision in current balancing. In this way, a novel linear alternative is proposed in the next section.

IV. PROPOSED CIRCUIT AND ANALYSIS

The linear current equalizer for parallel LED strings being evaluated in this paper is depicted in Figure 6. It has been introduced for the very first time by the authors in [16]. This circuit employs only two low power resistors, one signal bipolar transistor and one monolithic Darlington-pair transistor, in order to act as a constant current source for each string of LEDs.

The strings are assumed to be fed by a constant voltage (e.g., from a switching regulator) that is slightly higher than the string voltage itself. One of the main advantages is that this voltage difference can be extremely low, circa 1 volt.

The circuit works by forcing the current that feeds the LEDs on the collector of the transistor Q_1 to be almost equal to the constant current at its emitter. Q_2 is used to provide a constant voltage reference for the current-defining (shunt) resistor R_S , as low as possible in order to avoid great losses on the circuit of Figure 6. Proposed current equalizer circuit, here shown for two LED strings.

TABLE I
Comparison Between Equalizing Techniques

	Switching Solutions	Linear Solutions
Operating frequency	High	Low (DC)
Current balancing	Complexity-dependent	Fair to good
EMI	Moderate to high	Low to none
Cost	Moderate to high	Low
Component count	Medium to high	Low
Reliability	Complexity-dependent	High
Efficiency	High	Input voltage-dependent
Heating	Moderate to low	Moderate to high

It is important to stress that a complementary PNP version of the circuit could also be implemented, using a similar analysis to the described below.

Assuming that both transistors Q_1 and Q_2 are operated at active-mode and their current gains being given by β_1 and β_2 , respectively, (1) follows.

$$i_{LED} = i_E \frac{\beta_1}{\beta_1 + 1} \quad (1)$$

Since β_1 has a very large value, due to the Darlington-pair configuration, and Q_2 is a high-gain signal transistor with low base current, the approximation (2) can be used.

$$i_{LED} \approx i_E = \frac{V_{BE}}{R_S} \quad (2)$$

Thus, the LED string current is a function solely of two constants: the base-emitter voltage of Q_2 and the value of the resistor R_S . V_{BE} is only dependent on the chosen transistor Q_2 .

The polarizing current i_p could be small, enough only to produce the voltage reference for Q_2 . The voltage across the LED string is given by the estimated voltage of one device times the number of series associated LEDs ($n \cdot V_{LED}$). Thus, the theoretical efficiency of the circuit (η) can be obtained as the ratio between output and input powers, which is approximated by (3).

$$\eta = \frac{P_{LED}}{P_{in}} = \frac{n \cdot V_{LED} \cdot i_{LED}}{(i_p + i_{LED}) V_{DC}} \approx \frac{n \cdot V_{LED}}{V_{DC}} \quad (3)$$

Figure 7 shows the theoretical bus voltage as a function of the number of LEDs of a given string, taking the equalizer efficiency as a parameter, according to equation (3). Dashed line represents the minimum practical bus voltage required for the equalizer circuit to work properly, assuming maximum efficiency and taking into account the typical collector-to-emitter saturation voltage (0.7 V) as well as the base-to-emitter Q_2 voltage (0.6V). So, by using this chart one can determine the bus voltage needed in order to attain a desired equalizer efficiency, for a determined number of LEDs on the strings.

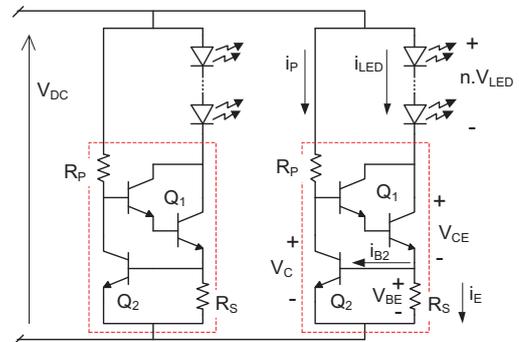


Fig. 6. Proposed current equalizer circuit, here shown for two LED strings.

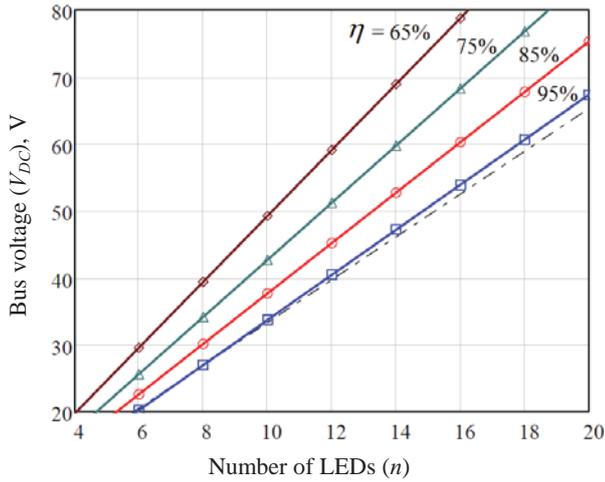


Fig. 7. Bus voltage as function of the number of LEDs for various theoretical efficiency values (parameterized).

V. DESIGN GUIDELINE AND CONSIDERATIONS

Equation (3) shows that the efficiency of the circuit is directly proportional to the number of series associated LEDs in a single string. Therefore, this could be used as a design guideline: using as long as possible strings and as low as possible input voltage for attaining high efficiencies. This idea could be also implemented at the control loop of the switching pre-regulator assumed to be present before the equalizers, playing the role of a maximum efficiency point tracker.

For a practical design to work, the transistor Q_1 must be working at active-mode. In order to ensure this operating condition, its collector-emitter voltage V_{CE} should be kept at a higher value than the saturation voltage of this device, $V_{CE,sat}$. These considerations impose a bottom limit for the input voltage, given by (4).

$$V_{DC} \geq n.V_{LED} + V_{CE,sat} + V_{BE} \quad (4)$$

The maximum efficiency of the design will be attained at the lower limit imposed by (5), thus defining V_{DC} .

The voltage at the collector of transistor Q_2 (V_C) can be used to define the polarizing resistor R_p , leading to (6).

$$R_p = \frac{V_{DC} - V_C}{i_p} \cong \frac{V_{DC} - 3.V_{BE}}{i_p} \quad (5)$$

The polarizing current i_p could be chosen to assume a value between 100 μA and 1 mA for a small-signal transistor.

Finally, the current defining resistor R_s could be chosen by modifying (2) to (6).

$$R_s = \frac{V_{BE}}{i_{LED}} \quad (6)$$

The power rating of this device (P_{RS}) is always a constant value, dependent on LED and transistor parameters together, and given by (7).

$$P_{RS} = R_s \cdot i_{LED}^2 = V_{BE} \cdot i_{LED} \quad (7)$$

The power rating of the RS resistor is less than half a watt for the common power LEDs that operate on currents below 700 mA. This means that a small signal resistor can be used.

These design guidelines can be easily applied to obtain a working prototype in order to test the circuit's performance.

VI. PROTOTYPE DESIGN AND EXPERIMENTAL RESULTS

A prototype for a two-string LED module is proposed for design validation. A photograph of the LED module plus the built-in prototype is shown in Figure 8. The strings are composed of 16 series-connected OSRAM LUW W5PM – Golden DRAGON Oval Plus LEDs. These LEDs have a typical light output of 106 lumens each at a drive current of 350 mA, while having a typical forward voltage of 3.2 V at the same current [17].

This gives a two-string module of 32 LEDs, with a nominal light output of almost 3400 lumens, which is closely equivalent to a 35 W metal-halide lamp. Each string will have an approximate voltage of 51.2 V and the whole module is expected to demand something close to 36 W.

For the current equalizer, the transistors chosen were a small-signal BC547A NPN for the polarizing branch and a TIP110 NPN Darlington for the LED string branch. These devices are high-gain transistors, suitable for this design.

The transistors' electrical parameters of interest were experimentally evaluated. The V_{BE} voltage of Q_2 transistor was found to be 0.6 V when forward-biased at $i_p = 500 \mu A$. As for the saturation voltage of Q_1 , $V_{CE,sat}$, it was measured 0.7 V at 350 mA. The parameters of the design are shown in Table II.

From (4), it is possible to derive the minimum bus voltage for feeding the LED module: $V_{DC} \geq 52.5$ V. Using this value, the resistance of R_p is calculated from (5), being $R_p \cong 100$ k Ω .

The current defining resistor is calculated from (6) as being $R_s = 1.7 \Omega$. These prototype components are summarized in Table III.

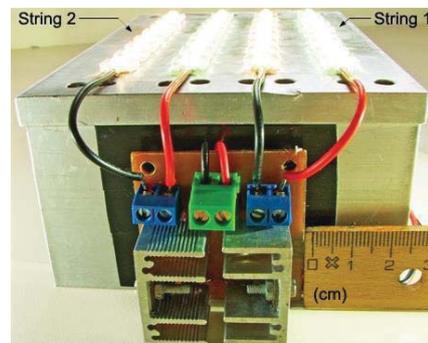


Fig. 8. Current equalizer circuit on two-string 36 W LED module.

TABLE II
Design Parameters

Symbol	Value	Parameter
i_{LED}	350 mA	LED string current
V_{LED}	3.2 V	LED forward voltage drop
N	16	number of LEDs in a string
i_p	500 μ A	polarizing current
V_{BE}	0.6 V	base-emitter voltage of Q2
$V_{CE,Sat}$	0.7 V	saturation voltage of Q1

The experimental results of each string are presented together in Figure 9. The input measured input voltage and current was, respectively 52.4 V and 705.3 mA, as shown in Table IV together with the most relevant experimental data. Module efficiency (strings plus equalizer) was measured 93.6%, at full power.

VII. TEST UNDER FAULTY CONDITIONS

For testing the behavior of the circuit under LED failure, were considered both scenarios – open circuit and short circuit failures.

If one LED fails open, his whole string will turn off, but the other strings will remain current-regulated by the other independent equalizing circuits, and no damage will be caused to them or the LEDs. The module would remain working, although the light output would decrease by a factor of $1/k$, where k is the number of strings being fed, for each string that is put out (e.g., one string out of two means a 50% reduction; two strings out of three means a 66% luminosity reduction).

On the other hand, a short circuit failure would apply an overvoltage on the devices, in case there was no current equalizing circuit. But the proposed scheme is intended to compensate this kind of failure, by maintaining the current regulated and equalized throughout the strings.

Since shorts are the most common failure mode of LEDs [18] and also have a more significant impact for the equalizing circuit proposed, a failure test was conducted, with different numbers of LEDs in different strings failing short. The current at each string was measured in all cases, to ensure that equalization would still take place even under abnormal conditions. The results of these tests are presented at Table V.

TABLE III
Prototype Components

Symbol	Value	Parameter
R_S	1.7 Ω	current defining resistor
R_P	100 k Ω	polarizing branch resistor
V_{DC}	52.5 V	bus input voltage

TABLE IV
Experimental Results

Measurement point	Current	Voltage	Power
String 1	350.1 mA	49.72 V	17.4 W
String 2	344.7 mA	49.84 V	17.2 W
Input	705.3 mA	52.4 V	36.96 W

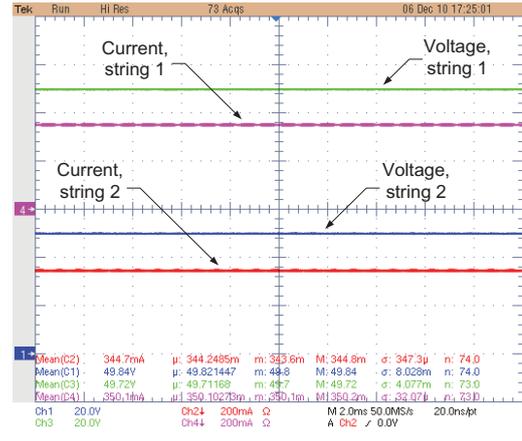


Fig. 9. Current and voltage of both LED strings (200 mA/div; 20 V/div).

The small difference between values in a same string suggests that the measured discrepancies are only ordinary fluctuations on current. In this case, the circuit is able to sustain equalization under LED short circuit failures satisfactorily.

VIII. EQUALIZING STABILITY EVALUATION

In the design of a transistor circuit, the bias point (Q) is carefully established so that the transistor operates in a specified range ensuring linear operation. Once the design is finished, it is necessary to check the operation point variations due to temperature changes and possible amplifier parameters variations.

The relationship between a given change in collector current against a change in the parameter that caused current deviation is called stability factor. The stability factor is therefore a measure of how sensitive is the bias collector current when submitted to fluctuations in some influence parameter [19] e [20].

In the section of equalization circuit design it was considered that the base current of transistor Q_2 was very small in comparison with the current flowing through the resistor R_s . For the analysis in this section, however, it will be assumed that this current is not null (i.e. the current through the Darlington emitter equals the sum of the shunt resistor current and Q_2 base current, according to Figure 6). This consideration allows observing the dependence of the LEDs current with the main influence parameters of transistor Q_2 . Thus, the current I_{LED} can be written as in (8).

Regarding the uncertainties on the shunt resistor value and temperature, the stability factors are given by the partial derivative of these equations (i.e., $S_x = \partial I_{LED} / \partial x$), being x the interest parameter.

TABLE V
LED Failure Test – Short Circuit Failure

Number of failed devices	String of Failure	Current through str. 1	Current through str. 2	Theoretical Efficiency
1 LED	String 1	349.1 mA	343.9 mA	91.4 %
3 LEDs	String 1	348.1 mA	344.3 mA	79.2%
1 LED	String 2	349.5 mA	345.5 mA	91.4%
3 LEDs	String 2	348.7 mA	344.4 mA	79.2%

$$I_{LED} = (I_{B2} + I_E) \left(\frac{\beta_1}{\beta_1 + 1} \right) + I_{CBO1} = \left(\frac{I_{s2} e^{\frac{V_{BE2}}{V_T}}}{\beta_2} + \frac{V_{BE2}}{R_s} \right) \left(\frac{\beta_1}{\beta_1 + 1} \right) + I_{CBO1}, \quad (8)$$

where:

I_{B2} is the BC547A base current

I_E is the Darlington emitter current

I_{s2} is the saturation current of BC547A transistor;

V_{BE2} is the emitter-base voltage of BC547A transistor;

V_T is the thermal voltage;

I_{CBO1} is the Darlington collector cutoff current;

β_1 and β_2 are the Darlington and BC547A gains, respectively.

To take into account the uncertainty of the transistors gains, it is necessary to analyze the real increment, since this variation can be very large. The stability factors of interest to this study are shown in (9) to (16).

Considering all the interest parameter variations, a general equation for the variation on I_{LED} can be written in its generic form, as given by (17).

In equations (15) and (16), the LEDs current over which the stability factor is calculated has been named I_{LEDref} .

Table VI shows the parameters variations considered in this analysis.

According to the type of evaluation to be performed, some parameters variations should be neglected. For example, in the analysis of the effect of temperature variation, the variation in the I_{LED} equation is not dependent on the uncertainty of the components. Similarly, concerning the uncertainty on components values, the influence of the temperature on I_{LED} should be disregarded.

From (17) it can be seen that a small stability factor leads to small variations in I_{LED} due to the oscillations of the related parameter.

Using the equations given before it was firstly carried out some calculations for a variation of 75 °C in temperature (25°C to 100°C). By analyzing the variation in I_{LED} due to variations in temperature, it will be considered that ΔR_s , $\Delta \beta_1$ and $\Delta \beta_2$ are null in equation (17).

$$S_{I_{CBO1}} = 1 \quad (9)$$

$$S_{R_s} = - \left(\frac{V_{BE2}}{R_s^2} \right) \left(\frac{\beta_1}{\beta_1 + 1} \right) \quad (10)$$

$$S_{V_{BE2}} = \left(\frac{I_{s2}}{\beta_2} \frac{1}{V_T} e^{\frac{V_{BE2}}{V_T}} + \frac{1}{R_s} \right) \left(\frac{\beta_1}{\beta_1 + 1} \right) \quad (11)$$

$$S_{V_T} = - \left(\frac{I_{s2} V_{BE2}}{\beta_2 V_T^2} e^{\frac{V_{BE2}}{V_T}} \right) \left(\frac{\beta_1}{\beta_1 + 1} \right) \quad (12)$$

$$S_{\beta_{1T}} = \left(\frac{\beta_2 V_{BE2} + I_{s2} R_s e^{\frac{V_{BE2}}{V_T}}}{\beta_2 R_s (\beta_1 + 1)} \right) - \frac{\beta_1 (\beta_2 V_{BE2} + I_{s2} R_s e^{\frac{V_{BE2}}{V_T}})}{\beta_2 R_s (\beta_1 + 1)^2} \quad (13)$$

$$S_{\beta_{2T}} = - \frac{I_{s2} \cdot e^{\frac{V_{BE2}}{V_T}}}{\beta_2} \left(\frac{\beta_1}{\beta_1 + 1} \right) \quad (14)$$

$$S_{\beta_1} = \frac{I_{LEDref} \cdot \left(\frac{I_{s2} e^{\frac{V_{BE2}}{V_T}}}{\beta_2} + \frac{V_{BE2}}{R_s} \right)}{\left(\left(\frac{I_{s2} \cdot e^{\frac{V_{BE2}}{V_T}}}{\beta_2} + \frac{V_{BE2}}{R_s} \right) \beta_{1min} + (\beta_{1min} + 1) \right) (\beta_{1max} + 1)} \quad (15)$$

$$S_{\beta_2} = - \frac{I_{LEDref} I_{s2} e^{\frac{V_{BE2}}{V_T}} \left(\frac{\beta_1}{\beta_1 + 1} \right)}{\beta_{2max} \left[\left(I_{s2} e^{\frac{V_{BE2}}{V_T}} + \beta_{2min} \frac{V_{BE2}}{R_s} \right) \left(\frac{\beta_1}{\beta_1 + 1} \right) + \beta_{2min} I_{CBO1} \right]} \quad (16)$$

$$\Delta I_{LED} = S_{I_{CBO1}} \Delta I_{CBO1} + S_{V_{BE2}} \Delta V_{BE2} + S_{R_s} \Delta R_s + S_{V_T} \Delta V_T + S_{I_{s2}} \Delta I_{s2} + S_{\beta_{1T}} \Delta \beta_{1T} + S_{\beta_{2T}} \Delta \beta_{2T} + S_{\beta_1} \Delta \beta_1 + S_{\beta_2} \Delta \beta_2 \quad (17)$$

TABLE VI
Parameters variation

Fluctuation	Equation/Value
ΔI_{CBO1}	$I_{CBO1initial}(e^{K_1 \Delta T} - 1)$, $K_1 = 0.07/^\circ C$
ΔV_{BE2}	$-K_2 \Delta T$, $K_2 = 2.5mV/^\circ C$
ΔR_s	$(R_s + R_s \text{doubt}) - (R_s - R_s \text{doubt})$
ΔV_T	$\frac{V_{Tinitial} \Delta T}{T_{initial}}$, $T_{initial} = \text{Initial temperature}$
ΔI_{s2}	$\frac{I_{s2initial} \Delta T}{5}$
$\Delta \beta_{1T}$	3875*
$\Delta \beta_{2T}$	100*
$\Delta \beta_1$	3000*
$\Delta \beta_2$	200*

*Deviation values were taken from the component datasheet [21].

Table VII shows the information about the typical BC547A transistor (Q_2) parameter values at a temperature of 25 °C. It was observed an increase of 22% in the LEDs current for a variation of 75°C in the circuit temperature.

It is important to stress that the variation of 75°C is quite high. So, for practical purposes, it would be expected a much lower deviation on LEDs current.

To identify the main causes of the calculated current deviation, it was computed the changes in I_{LED} for each parameter that depends on temperature. Thus, it was observed that the variable I_{CBO1} has the greater interference in the bias point and may result in an increase of up to 54% on the initial current (I_{LEDref}). This is because the employed transistor (Darlington TIP110) has a high collector cutoff current (about 1 mA). Another variable that interferes greatly in I_{LED} is V_{BE2} . This one, when analyzed alone, implied in a decrease of 31% on the initial current. The uncertainties on the other variables considered here resulted in little influence on LEDs current, not exceeding 1% of the initial value.

One way to reduce the overall change of I_{LED} when subjected to temperature variations would be to replace the Darlington transistor for a different model with similar characteristics but featuring an I_{CBO} of 0.5 mA or lower.

With this change, the variation on I_{LED} due to V_{BE2} and I_{CBO1} practically cancel each other, reducing the overall variation to less than 1%.

Table VII
Typical values of BC547A parameters at 25 °C

Variable	Typical value at 25°C
I_{CBO1}	1mA
V_{BE2}	0.6V
R_s	1.7Ω
V_1	25.7025mV
I_{s2}	$7.2747 \times 10^{-14} A$
β_1	2000
β_2	220

Values taken from the component datasheet [21].

It is important to observe that the temperature variation occurs in the circuit as a whole, so all LED strings suffer from the same sort of variation in their currents.

Thus, upon temperature variations, it would not be noticed differences in brightness of the LEDs of different strings.

Considering the variation in I_{LED} regarding only the uncertainty in R_s , it was concluded that the resistance used must have a class error less than or equal to 1% since the analysis concerning resistances with 5% of uncertainties points to an imbalance of up to 10% on LEDs current from one string to another. This imbalance may generate a difference in the luminous flux emitted by each string, although it may not be perceived by the human eye.

Variations in I_{LED} due to uncertainties in the values of β_1 and β_2 gains, can be neglected. Typical calculations show that those I_{LED} variations should not exceed 1%, even for the worst case deviations in transistor current gains.

As a remark for this topic, it can be said that the sensitivity analysis developed here can be considered reliable enough since its main conclusions are in accordance with the experimental studies of Section VI (measured LED currents present small deviations around theoretical values).

IX. DISCUSSION

As remarked in this paper, current equalization can have a great impact on the light output of LED modules or luminaires, since small changes in device voltage can yield large changes in current, implying in color and luminous flux deviation, or yet uneven aging of the devices.

Thus, having an equalizing technique or circuit may be mandatory on high power LED drivers, in order to keep reliability and the light quality of these devices.

Low cost solutions, such as simple linear equalizers, may turn out to be a viable way out and can be used in practical or commercial lighting luminaires. Concerning the linear approach proposed here, the low parts count yield reliability and cost-effectiveness, while efficiency-related problems could be countered with proper regulation of input voltage. The evidence for good current balancing is compelling enough to justify the use of such simple circuit.

A possible proposal for a complete LED lighting system employing the linear equalizer addressed in this paper is to employ a switching pre-regulator as the front end of the current balanced strings. As well-known, high power factor switching pre-regulators can feature a high efficiency behavior, which could contribute for a high global efficiency of such an LED lighting arrangement. However, it is also important to implement a feedback control loop that should be able to guarantee the minimum required voltage for the equalization to take place, as depicted in Figure 10 [22].

In this case, it is necessary to measure the string voltage while keeping the bus voltage only higher enough than the string terminal voltage itself. Thus, the highest efficiency possible could be attained for the whole set, as if in a maximum efficiency point tracking control scheme. Such a complete scheme will be discussed in authors' future publications.

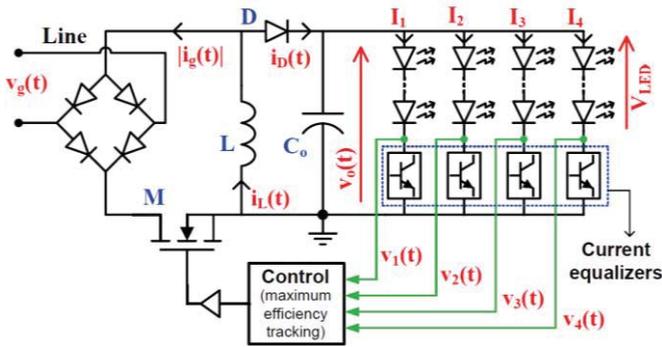


Fig. 10. Possible complete driver topology.

X. CONCLUSIONS

This paper introduced a simple technique applied to current equalization of parallel strings of series-associated LEDs.

A brief analysis of circuit operation was carried out and a design guideline has been developed.

The circuit here presented featured a good experimental validation, while relying on only 4 ordinary electronic components.

Furthermore, it achieved an efficiency of almost 94%, while the current deviation between the two LED strings fed through the equalization circuit was only 1.5%. These experimental results should validate both the circuit and the analysis performed, but a brief qualitative comparison between the two mainstream equalizing philosophies was drawn in Table V in order to point out the limitations of each one, as well as their generalized characteristics.

Also, the behavior of the circuit under LED short circuit failure was investigated. Current equalization was maintained under all tested failures, with the maximum current deviation between the two strings being 1.6%, under abnormal conditions.

It is clear, however, that efficiency will drop when one or more LEDs fail short, due to the intrinsic linear nature of the circuit. Nevertheless, the current on a string containing a short-failed LED will maintain its nominal value, in order not to damage any more devices. Thus, the current equalizer plays its roll on maintaining the reliability of the whole module.

With respect to the stability analysis of the circuit operating point under temperature variations and uncertainties in the values of the components, it can be stated that the structure can feature good stability provided resistors with low tolerance values (less than 1%) and Darlington with I_{CB0} close to 0.5 mA are employed.

Future studies may be proposed to investigate the global electrical and photometrical impact of such an equalization circuit on large LED modules, as in public lighting luminaires and other outdoor and indoor solid-state lighting applications. Furthermore, electrical transients, temperature drift and LED aging effects on the equalizer could be assessed in future work, as well as using more paralleled strings to test the circuit's response when adopted in larger modules.

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