

A Novel Method of Current Equalization in LED Strings Based on Simple Linear Circuit

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Abstract – This paper focuses on the problem of driving parallel strings of LEDs while ensuring current equalization between them. This issue is addressed in terms of proposing 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. Such topology employs a four-component circuit, with low dependence on transistor parameters, ensuring easy repeatability and good current regulation. Mathematical description of the circuit and experimental results are provided.

Keywords – LEDs; LED string driving; current equalization; solid state lighting

I. INTRODUCTION

Solid-state lighting (SSL) has been recently finding its way on modern lighting systems, changing the perspectives of indoor as well as outdoor illumination. The advent of the so-called high-brightness power LEDs (HB-LEDs) to produce light is recent, since LEDs have been used for many years solely as indicators and luminous flags.

Due to high efficacy, long term estimations are that a 10% decrease on worldwide energy consumption could be attained by using LEDs, a 50% decrease on the electrical energy used for producing artificial lighting [1]. That, together with the white light and good color rendering index (CRI), 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 is a number of ways to associate LEDs in order to make a luminaire or a string module, each of them yielding advantages and disadvantages. Some will be analyzed in section II of this paper.

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 for a two-string module of 32 power LEDs.

II. ASSOCIATION OF LEDs

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.

Also, there is the possibility of an LED failure, under which different associations 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).

A few possibilities for associating LEDs to form a string or luminaire module are shown in Fig. 1.

A pure series association of LEDs (Fig. 1-a), 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's no current imbalance. On the other hand, large series strings could result in high string voltage. Plus, if a single LED turns out to fail as an open circuit, the whole string will be out, compromising the reliability of the module under this faulty condition.

A parallel association of strings forms a series-parallel LED module (Fig. 1-b). 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 at will also differ. Therefore, it might be necessary some sort of equalization circuit to balance the current on the individual strings.

A matrix module (Fig. 1-c) is made by connecting the individual LEDs in parallel and then connecting these parallel clusters in a series association.

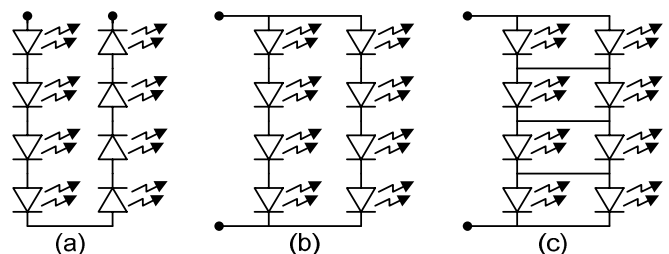


Fig. 1. Three possibilities of LED string modules: (a) series string, (b) series-parallel string module and (c) matrix module.

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. EQUALIZATION TECHNIQUES FOR LED STRINGS

The series-parallel association of LEDs turns out to be an alternative that can be, at the same time, more reliable under faulty conditions (such as open circuit failure) than the pure series strings, and more easy for current balancing than the matrix module. 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. This bus can be provided by an adequate switching regulator, as in Fig. 2.

Some of the techniques use monolithic linear regulators, such as LM317, plus a pass transistor to provide the strings with regulated, equalized currents [4]. 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.

Another linear alternative are MOSFET-based current mirrors [5]. 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 high-gain and identical (or very alike), which is a virtually unattainable condition for discrete power MOSFETs. Plus, the reference branch drains current without any useful output, and the circuit uses as many MOSFETs as LED strings.

A more intricate circuit is presented in [6], and uses a linear regulator along with a feedback loop to control the switching pre-regulator, in order to adapt the output voltage to keep the efficiency as high as possible.

These three linear equalization circuits are shown in Fig. 3, Fig. 4 and Fig. 5, respectively.

There are also the switching alternatives for current equalization. For example, one presented in [7] 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 [10] and [11], and a hybrid switching-magnetic solution is proposed in [12]. The switching solutions are more varied and

complex by definition, and will not be further explored in this work.

Linear circuits, though commonly more inefficient, are usually easier to construct and cost-effective, requiring less parts and being sufficiently reliable for mass-manufacturing luminaires. Thus, a novel linear alternative is proposed in the next section.

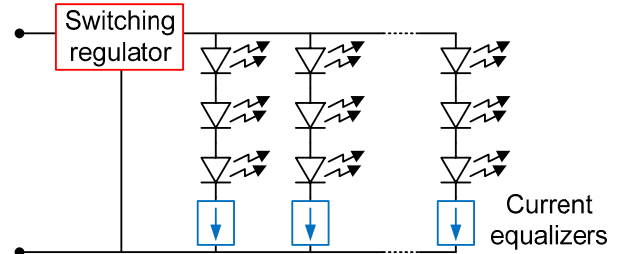


Fig. 2. Basic scheme of a series-parallel modular HB-LED luminaire.

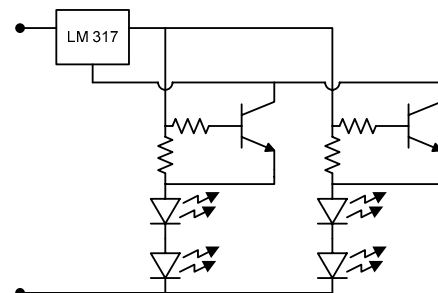


Fig. 3. Linear current equalizer using monolithic regulator IC.

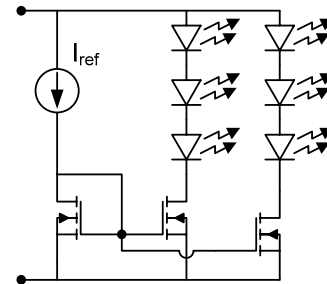


Fig. 4. Linear current equalizer using current mirrors.

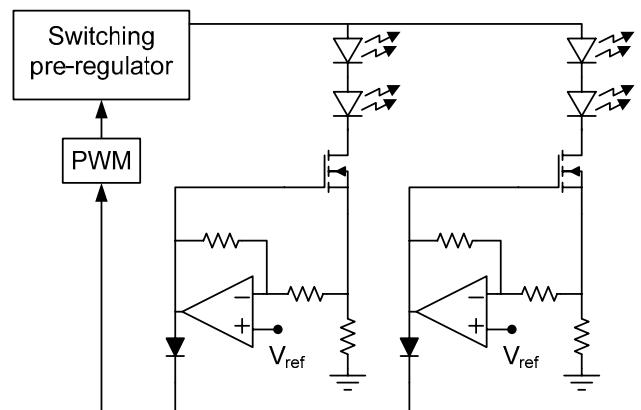


Fig. 5. Linear current equalizer using adaptive drive voltage.

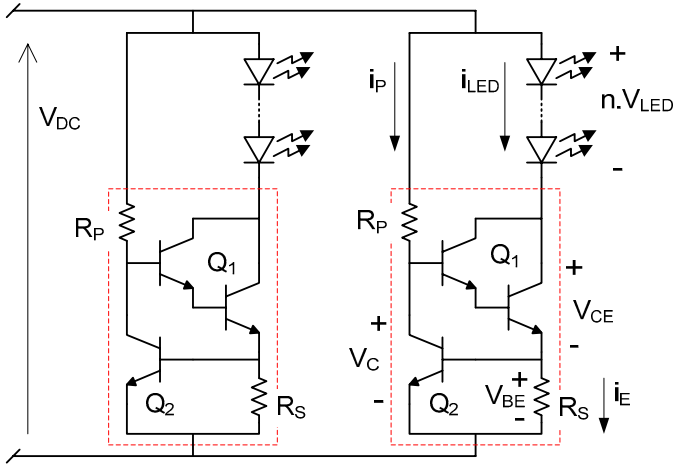


Fig. 6. Proposed current equalizer circuit, here shown for two LED strings.

IV. PROPOSED CIRCUIT AND ANALYSIS

The circuit proposed of a linear current equalizer for LED strings is shown in Fig. 6. This circuit uses 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 resistor R_S , as low as possible in order to avoid great losses on the circuit.

It is good 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.

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

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 transistor Q_2 chosen.

The polarizing current i_P is of small value, enough only to produce the voltage reference at 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 can be obtained as the ratio between output and input powers, approximated by (3).

$$h = \frac{P_{LED}}{P_{in}} = \frac{n \cdot V_{LED} \cdot i_{LED}}{(i_P + i_{LED}) V_{DC}} \gg \frac{n \cdot V_{LED}}{V_{DC}} \quad (3)$$

V. DESIGN GUIDELINES 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, it should be ensured that the transistor Q_1 is working at active-mode. In order for that to happen, its collector-emitter voltage V_{CE} should be kept at a higher value than the saturation voltage of the same device, $V_{CE,sat}$. That imposes a bottom limit for the input voltage, given by (4).

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

Maximum efficiency of the design will be attained at the lower limit imposed by (4), 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 (5).

$$R_P = \frac{V_{DC} - V_C}{i_P} @ \frac{V_{DC} - 3 \cdot V_{BE}}{i_P} \quad (5)$$

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

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

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

Its power rating is always a constant value, dependent on LED and transistor parameters together, and given by (7).

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

The power rating of the R_S 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. 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 [8].

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 BC337 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 $i_p = 500 \mu\text{A}$. 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 I.

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

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

A photograph of the LED module plus the built-in prototype is shown in Fig. 7. The experimental results of each string are presented together in Fig. 8, while the input voltage and current are shown in Fig. 9. The relevant experimental data obtained are compiled in Table III. Module efficiency (strings plus equalizer) was measured 93.6%, at full power.

TABLE I. 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 μA	polarizing current
V_{BE}	0.6 V	base-emitter voltage of Q_2
$V_{CE,sat}$	0.7 V	saturation voltage of Q_1

TABLE II. 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 III. 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

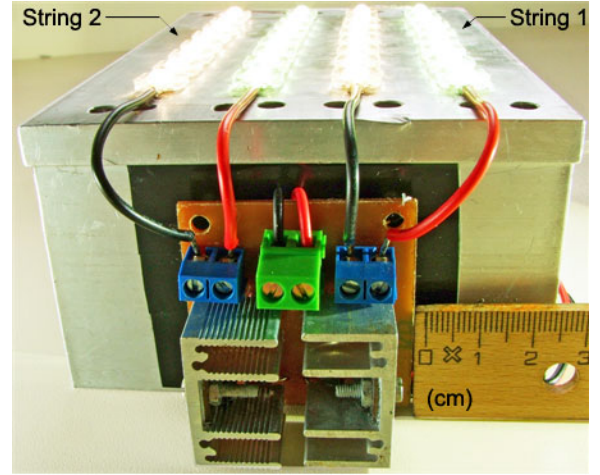


Fig. 7. Current equalizer circuit on two-string 36 W LED module.

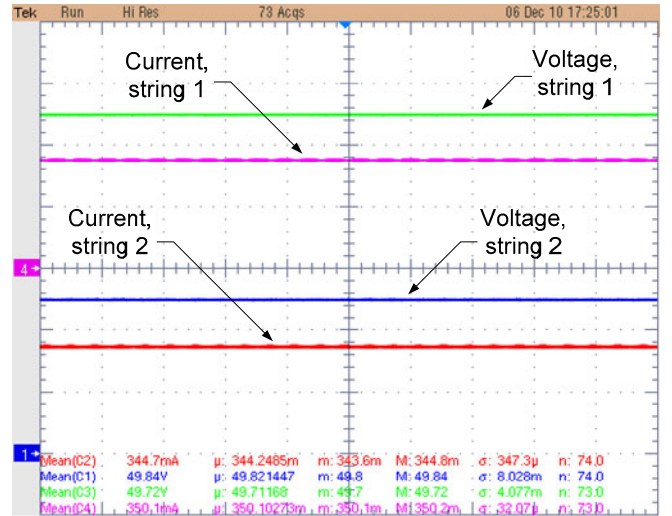


Fig. 8. Current and voltage at both LED strings (200 mA/div; 20 V/div).

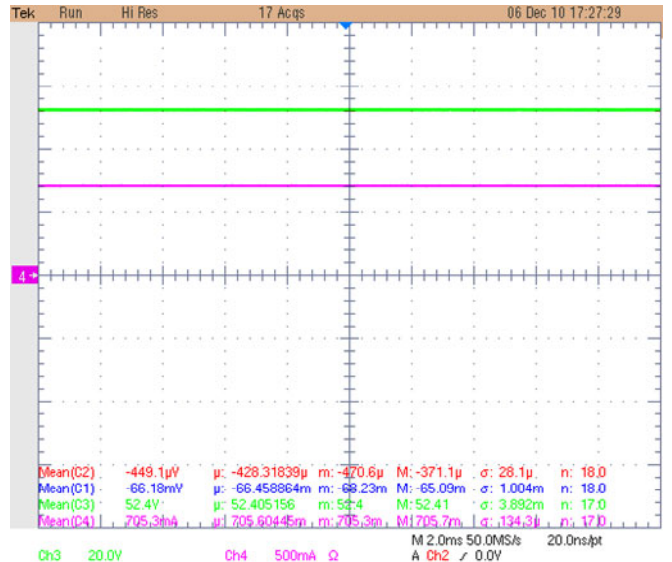


Fig. 9. Current (bottom trace) and voltage (upper trace) at input of LED module (500 mA/div; 20 V/div).

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 [9] 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 IV.

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 failure satisfactorily.

VIII. CONCLUSION

This paper presented a simple and compact circuit applied to the current equalization on parallel strings of series-associated LEDs. A brief analysis of its working principle was carried out and a design guideline was developed.

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 larger luminaires, in order to keep reliability and quality of illumination.

Low cost solutions, such as small but sufficiently efficient linear equalizers, may turn out to be a viable way out. The circuit here presented had a good experimental validation, while relying on only 4 ordinary electronic components.

TABLE IV. LED FAILURE TEST – SHORT CIRCUIT FAILURE

Number of failed devices	String of failure	Current at string 1	Current at string 2
1 LED	String 1	349.1 mA	343.9 mA
3 LEDs	String 1	348.1 mA	344.3 mA
1 LED	String 2	349.5 mA	345.5 mA
3 LEDs	String 2	348.7 mA	344.4 mA

Still, 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 is drawn in Table V in order to point each one's limitations and generalized characteristics. As shown, a number of technically "positive" features may qualify small linear solutions as good alternatives for current balancing in strings of LEDs, mainly cost, low electromagnetic (EMI) emissions and simplicity.

Low parts count yields reliability and cost-effectiveness, while efficiency-related problems could be countered with adequate regulation of input voltage. The evidence for good current balancing is compelling enough to justify the use of such simple approach presented in this work.

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.

A proposal for a complete luminaire is to employ a switching pre-regulator before the strings plus equalizers, and implementing a control loop that is able to guarantee the minimum required voltage for equalization to take place, by measuring the string voltage and making the bus voltage only higher enough than the string voltage itself. Thus, the highest efficiency possible could be attained for the whole set, as if in a maximum efficiency point tracking control scheme.

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 in larger modules.

TABLE V. COMPARISON BETWEEN EQUALIZING TECHNIQUES

	Switching Equalizing Solutions	Linear Equalizing 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
Parts count	Medium to high	Low
Reliability	Complexity-dependent	High
Efficiency	High	Input voltage-dependent
Heating	Moderate to low	Moderate to high

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