High-Efficiency Asymmetrical Half-Bridge Converter Without Electrolytic Capacitor For Low-Output-Voltage Ac–Dc Led Driver For Street Lighting

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ABSTRACT : *There is a trend to shift the lighting source towards light-emitting diode due to the outstanding performance and efficiency, the best example is High-brightness light-emitting diodes (LEDs). To utilize their features, large number of solutions for supplying LED strings are coming out. One-stage solutions are cost effective, but compared to two-stage and three-stage solutions their efficiency is low because they have to serve many tasks like; power factor correction (PFC), galvanic isolation and current regulation, so switching stress will be more and hence the losses. Two-stage and three-stage solutions are preferred option when supplying several strings at a time. Even though two-stage and three-stage solutions have higher cost, they are efficient because each stage is optimized for one task only, and reliability can be obtained by eliminating the use of electrolytic capacitor in them. In this paper, a three-stage solution for street lighting application is proposed, in which power factor correction is achieved by boost converter, while the galvanic isolation by electronic transformer (second stage), and current regulation by two-input buck converter (TIBuck) in the third stage. DSPIC30F4011 microcontroller is used to provide switching frequency for the switches used in the converter. Experimental results obtained with a 40-W prototype show efficiency as high as 93% for the whole topology stages.*

Keywords **-** *AC-DC power converters, electronic transformer, high efficiency, light-emitting diode (LED) lighting, three-stage topology, two-input buck.*

I. INTRODUCTION

The light-emitting diode (LED) characterized by mercury free, pollution free, high efficiency, long life cycle, their efficacy converting energy into light and reliability is very high, with smaller size so these are expected to be the new generation of lighting sources. Due to decreasing price of power diodes, LEDs are slowly entering general lighting market with different applications. In fact, their theoretical maximum efficiency is higher than that of other devices such as gas discharge lamps or incandescent lamps etc , about one-fifth of the electric power is used for residential, commercial and industrial lighting application world-wide. The commonly employed lighting sources include incandescent bulbs and fluorescent lamps [1]-[4].

Up until now, one of the most commonly used high brightness white light-emitting diode (HB-LED) is rated at 1.14 W, which is driven at 350 mA and the forward voltage is 3 V, even though manufacturers are constantly working on driving LEDs at a higher current. Due to different manufacturing processes, LED's electrical characteristics vary considerably, even in the same batch of products. Different LEDs with same forward voltage have a very different turn-on current. At the same time, LED life expectancy depends on the effects of work temperature, LED's rated brightness decreases alone with working hours decreased, and the higher operating temperature, the shorter the working time. To provide sufficient light output, an LED lamp fixture always involves large arrays of individual LEDs stacked in series. LEDs are current driven devices. So, A white LED's luminous intensity and chromaticity are proportional to the forward current. Tiny voltage change will lead to the significant changes in the current, while the current changes would greatly affect the efficiency accordingly. Hence the current High-Power LED drivers adopt constant current source or pulsating DC source. Study shows that, when LED's brightness declines, the driving voltage achieving the same driving current will declines too, that LED's luminous intensity declines with the current increasing. For this reason, a driver circuit is designed essentially to drive LEDs at a required constant current. Conventionally, driving a string of high brightness LEDs at an accurate DC current typically resorts to a linear regulator or a more complicated switching regulator with sophisticated control. According to the characteristics of LEDs many converters were proposed to drive LEDs depending upon different applications, and few characteristics of them are important, they are, LED's are low power devices so the drivers proposed for them should also consume low power. LED can quickly respond to current changes, so LED can be driven by pulse current (small colour change can be ignored). One more is LEDs have long life time, so driver for them must have long life time too. So initially different driver circuits proposed with electrolytic capacitor in them but, its life time decreases as a function of operating temperature failing the reliability requirement. So using electrolytic capacitor is an optional one, eliminating electrolytic capacitor in ac-dc power supplies for LED lighting is mandatory [5]. So different driver circuits with different objectives meeting application requirements were derived, like non-isolated topology consisting buck circuit, boost circuit and zeta circuit were proposed. And isolated driver circuit [6] as well as PFC correction circuit were introduced.

In this paper for street lighting application using LEDs, three-stage topology without electrolytic capacitor (high reliability) and high efficiency is proposed. Even though one-stage solutions are cost effective, but their efficiency is low as they have to fulfil several purposes with only one converter : power factor correction (PFC), galvanic isolation (in some cases), and current regulation. But in the proposed three-stage topology each stage is optimized for just one or two tasks for higher efficiency. PFC can be achieved by a boost converter, while the galvanic isolation by an electronic transformer (second stage). In third stage two-input buck converter is preferable for current regulation as compared to that of conventional buck converter.

Normally, two-stage and three-stage solutions are the preferred option when reliability and efficiency are more important concerns than cost (per unit). LED-based street lighting is an application in which the cost of the LED driver is less important than its efficiency due to the amount of energy consumed by street lighting every day. Moreover, the maintenance and replacement cost of street-lighting drivers is considerably higher than in home applications. Hence, reliability is also a key issue as it represents a considerable saving. Therefore, two-stage or three-stage topologies are the preferred option for LED-based street lighting.

In this paper a high-efficiency, high reliability three-stage topology is proposed for LED-based street lighting application [7]. The first stage is a boost converter. This topology is a perfect option for doing PFC in this kind of application. And no electrolytic capacitor is used for high reliability; its output voltage ripple cannot be neglected and will strongly affect the second and third stages. The second stage is a two-output electronic transformer (ET) preferred for providing galvanic isolation at very high efficiency. Nevertheless, this topology is completely unregulated, and, as a consequence, the low frequency ripple affects its output voltages. The third stage is a topology based on the two-input buck (TIBuck) converter. This third stage is in charge of eliminating the low-frequency ripple and independently adjusting the output current to the desired level in each LED string. The main advantage of this topology is that the stress on its components will be considerably reduced, what has a high impact on its size and efficiency. The key point of the TIBuck proposed in this paper is that it takes benefit from the high value of the LED string knee voltage. This means that it can reach full dimming in LEDs although its output voltage range is limited. Finally, not only the first stage, but also the second and the third stages can be implemented without electrolytic capacitor. Hence, the proposed topology has a very high reliability.

Since the final application is street lighting, some additional details should be considered. Wavelength (colour) quality is less important than other issues like efficiency. In addition, the stress on LEDs should be the lowest as a way of boosting the reliability. These points can be achieved by means of, among other things, the use of amplitude-mode driving technique as it has lower current stress on LEDs and semiconductors than the pulse width modulation (PWM) driving technique. Two other important aspects should be highlighted: the whole converter operates at constant frequency, and it provides galvanic isolation, which is mandatory in certain applications.

This paper is organized as follows. In section II, the ET for this application is discussed. Section III explains the new driving technique. The third stage is explained in section IV. In section V, DSPICF4011 microcontroller used in the prototype is explained. In section VI, the experimental results are shown, and, finally, in section VII, the conclusion is presented.

II. ET (SECOND STAGE)

Before explaining the second stage, it should be mentioned that the first stage is a boost converter operating in a boundary conduction mode (BCM) [8] as shown in the Fig.1. This topology may reach an efficiency as high as 97% without electrolytic capacitor, and, as a consequence, it is widely used in two-stage and three-stage topologies for LED-based street lighting. Due to the absence of electrolytic capacitor, its output voltage has to be expressed as

$$V_{out} = V_{o\_n} \cdot (1 + \frac{r_v}{2} \cdot \sin(2 \cdot \omega_{in} \cdot t) \quad (1)$$

where $\omega_{in} = 2\pi \cdot f_{in}$, f_{in} being the line frequency, V_{o_n} is the nominal value of the first stage output voltage, and r_v is the relative value of the peak-to-peak low-frequency ripple. This ripple will affect the second stage and overall design of the proposed topology.

As has been said, galvanic isolation is a mandatory requirement. Hence, it is vital to find a topology capable of providing it with very high efficiency. For the proposed LED driver ET is the well suited topology for providing galvanic isolation, which is an unregulated topology with very high efficiency.

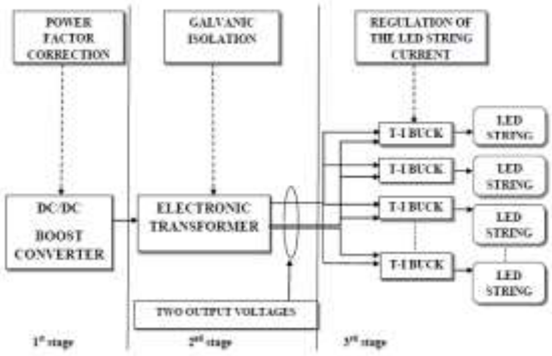


Fig.1 Block diagram of the proposed LED driver.

In this LED-based street lighting driver, output of ET is applied to a two half bridge topology as shown in Fig.2. The two output voltages of the ET can be expressed as

$$V_h = G_h \cdot V_{o\_n} \cdot (1 + \frac{r_v}{2} \cdot sin(2 \cdot \omega_{in} \cdot t)) \quad (2)$$

$$V_l = G_l \cdot V_{o\_n} \cdot (1 + \frac{r_v}{2} \cdot sin(2 \cdot \omega_{in} \cdot t)) \quad (3)$$

Where G_h and G_l are the gains of the ET for both outputs and are fixed values determined by the "magnetic" transformer used in the topology.

High efficiency is one of the objectives of this three-stage topology. Hence, ZVS in diodes and ZCS in MOSFETs are performed to reduce the losses.

III. BRIEF DESCRIPTION OF THE PROPOSED DRIVING TECHNIQUE

Normally, the converters in charge of regulating the dimming of the LED string current are always designed in such a way that they can vary their output voltage from zero to nominal value (i.e., buck topology). Nevertheless, if the special characteristics of LED strings are taken into account (i.e., the high value of the knee voltage and the dynamic resistance), it is possible to propose a new driving technique which opens a new field for novel topologies.

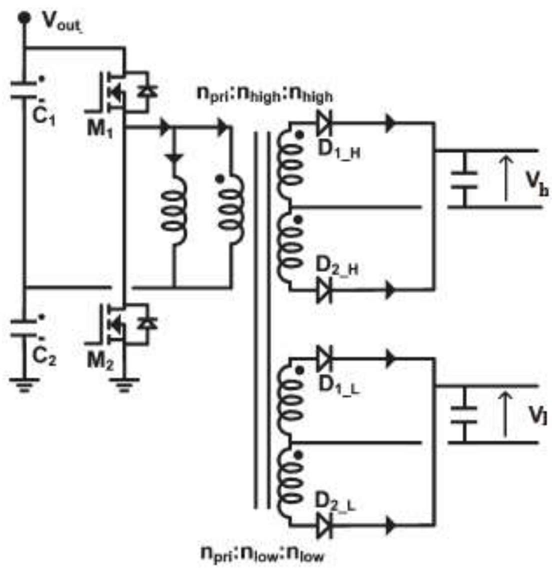


Fig.2 Schematic of the electronic transformer.

In Fig.3, a relation between the voltage supplied to a string of N LEDs and the corresponding current is given. In addition, this current is related to the luminous flux of the string. As can be seen, LED strings emit an amount of light (λ_A) nearly proportional to the current driven by them (I_A). Nevertheless, they have an electrical model which involves an ideal diode, a dynamic resistance, and a voltage source, whose value is equal to the knee voltage of a single LED of the string (V_{γ_LED}) multiplied by the number of LEDs (N). Hence, current driven by a LED is not directly proportional to the voltage applied to it (V_A). It is necessary to apply a threshold voltage (i.e., a voltage slightly higher than the previously mentioned voltage source) in order to have some current through the LED (i.e., some light emitted). Hence, for totally regulating the amount of light emitted by a LED string, it is not necessary to use topologies with the capability of reaching zero voltage at their output. In fact, it is possible to use converters (topologies) which have a minimum output voltage higher than zero, as far as this minimum voltage is lower than the equivalent knee voltage of the LED string ($N \cdot V_{\gamma\_LED}$). This new approach to the driving technique (from this point, it will be defined as "total current dimming") allows the development of new topologies that sacrifice output voltage range but, as a counterpart, raise their efficiency and reduce the stress on their semiconductors. As has been mentioned, due to the

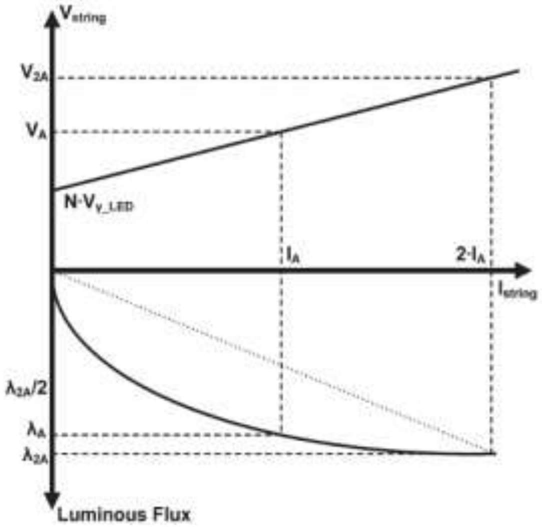


Fig. 3 Relation between input voltage, current, and luminous flux in a LED string, situation is enlarged for clarity reasons.

-knee voltage of their load (i.e., LED strings), these new topologies still have the possibility of totally turning off the strings (i.e., stopping the emission of light) even with a considerable voltage at their output. Finally, it should be mentioned that this approach to the driving technique is compatible with both amplitude-mode and PWM-mode dimming.

IV. TIBUCK CONVERTERS (THIRD - STAGE)

The third stage is responsible for eliminating the voltage ripple coming from the ET outputs (due to the first stage) and adjusting each LED string current to the desired level.

As can be seen in Fig.4, the TIBucks are to some extent similar to the conventional buck converters used to drive LEDs, but the anode of the diode is connected to a voltage V_l lower than V_h, which would be the input voltage of a conventional buck and these are also called postregulators [9]. Applying the volt ·second balance in the output inductor results in

$$(V_h - V_{out}) \cdot D + (V_l - V_{out}) \cdot (1 - D) = 0 \quad (4)$$

Where D is the duty cycle of the MOSFET and V_h and V_l are the input voltages of the TIBuck, from (4), the output voltage equation can be obtained

$$V_{out} = V_h \cdot D + V_l \cdot (1 - D) \quad (5)$$

Compared to conventional buck, the main advantages of this topology are mainly two. First, the output voltage of the TIBuck is easier to filter, which allows us to implement it without electrolytic capacitor. Second, the voltage withstood by the MOSFET and the diode are considerably lower than in a traditional buck

$$V_{s\_max} = V_{D\_max} = V_h - V_l \quad (6)$$

Where V_{s_max} and V_{D_max} are the maximum voltages withstood by the MOSFET and the diode in the TIBuck, respectively. As can be seen, they can be rated for a lower voltage (in the buck converter, they should be rated for a voltage equal to V_h), and, consequently, this fact increases the efficiency of the proposed converter. In addition, the MOSFET is referred to ground for this application, so its gate driver is easy to implement.

It should be noted that the energy processed by a buck converter controlling a LED string comes from the single input port of this converter, while the processed energy in the case of each TIBuck comes from its two inputs. However, the total energy in both cases is similar (actually, it is lower in the case of the TIBuck due to its improved efficiency and better processing of energy).

The main disadvantage of the TIBuck is that its minimum output voltage is limited to the value of V_l. Hence, it is not possible to reach 0 V or any voltage lower than V_l at the output. Nevertheless, as has been explained in Section III, the special characteristics of the load allow the use of this topology without losing the possibility of reaching full dimming in the strings. The only requirement is that V_l has to be chosen in such a way that, for the minimum duty cycle of the TIBuck, a voltage slightly lower than $N \cdot V_{\gamma\_LED}$ is achieved. A minimum output voltage higher than zero also presents a problem when the output is short-circuited. Nevertheless, in this particular case, it is possible to solve the problem by turning off the second stage (i.e., the ET) when this situation is detected. The circuit for detecting this situation in the third stages and sending the turning-off signal to the ET is quite simple. Another possible solution is implementing fuses in the input or output of each TIBuck. In this way, it is not necessary to turn off the ET, and the strings which are not short-circuited still can be used. If part of a string is short-circuited, total dimming of that string current is lost, and turning off the lamp (i.e., all strings) can only be achieved by turning off the second stage then. In this case, using fuses is the most recommendable solution. Nevertheless, it is possible to reduce the impact of partially short-circuited strings if a security factor is added when calculating the low input voltage of the TIBucks. In this way, it is possible to totally control the string current even when some of its LEDs are short-circuited. Obviously, a trade-off between this security factor and efficiency has to be met as the lower V_l, the lower the efficiency.

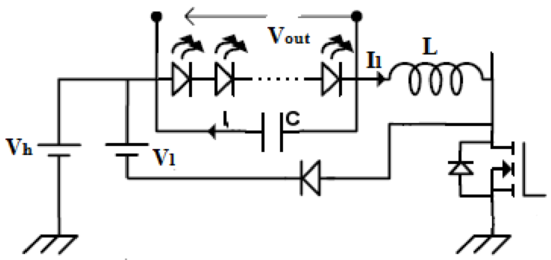


Fig.4. Schematic of the proposed TIBuck converter proposed for driving each LED string.

As has been said, it should be taken into account that, the closer V_h and V_l, the lower will be the voltages that the semiconductors (MOSFET and diode) will have to withstand. In addition, the size of the magnetic component will also be lower. Taking into account the high value of the LED-string knee voltage (around half the nominal voltage), the improvement in efficiency and size is considerably high when using the TIBuck for LED-based applications.

V. DSPIC30F4011MICROCONTROLLER

In this prototype DSPIC30F4011 microcontroller is used for setting switching frequency for the switches. The DSPIC30F family encompasses a wide range of performance requirements, making it an ideal architecture for anyone considering a 16-bit digital signal processor (DSP), or even a 32-bit DSP. The devices were designed to provide a familiar look and feel to DSP users. The DSP features were seamlessly integrated to ease adoption by new users of DSP technology. Moreover, the pricing structure of dsPIC30F devices makes them affordable for embedded control applications.

The DSPIC30F devices were architected from the grounds-up to provide all the features a user. A rich instruction set, coupled with extensive addressing modes, operate on a generous set of general purpose working registers and a software stack. The result is very good C compiler efficiency. All the devices use Flash memory technology for its Program Memory and Data EEPROM, in order to provide maximum manufacturing cycle time flexibility. Fast, in-circuit self programming technology enables remote updating of Program Memory and Data EEPROM. The high reliability of the Flash memory enables 40 years of data retention and up to one million program or erase cycles at 85 degrees Centigrade. Competitive DSP performance is enabled by a powerful set of DSP features. A single-cycle 17-by-17 Multiplier; two 40-bit accumulators and a 40-bit barrel shifter; zero overhead Do and Repeat loops; rounding or saturation of results; and special addressing mode support for circular buffers and FFTs. The dsPIC30F architecture also supports a very flexible interrupt processing structure. Each device includes an extensive set of peripheral modules, including timers, serial subsystems, and analog to digital converter channels. Some devices also contain advanced peripherals geared towards specific applications like motor control, audio, or internet connectivity. Last but by no means the least, the devices contain hardware logic that enables in-circuit debugging and Flash programming without removing the device from the board.

Table no.1 Operating parameters of DSPIC30F4011

Operating speed at 5V	30 MIPS
VDD	2.5 to 5.5V
Temperature	-40°C to 125°C
Program memory	Flash

Data memory	SRAM, EEPROM
Analog	10-bit & 12-bit precision

DSPICF4011 is used in this prototype for generating PWM signals at 30 kHz for switches. Table no.1 shows operating parameters for DSPICF4011 microcontroller.

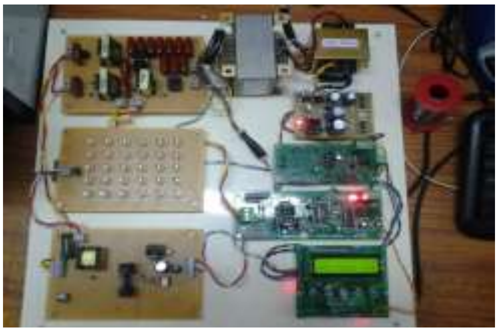
VI. EXPERIMENTAL RESULTS

A 40-W prototype has been built (see Fig.5). TIBuck (to LED string) has been connected at the output of the ET. Hence, the prototype has the capability of independently driving one or more LED strings of 40W, Fig. 5 shows LED output for the duty cycle of 50% set by the microcontroller DSPIC30F4011 and the input current to the LED string form TIBuck. The LEDs used for the lamp are W4218T2-SW from Seoul Semiconductors (distributed by Avnet). They belong to the Z-Power LED family. Their nominal forward current is 0.350 A, and their nominal forward voltage is 3.25V (the nominal power of each LED is 1.14 W). In each string, 35 LEDs are connected in series. Therefore, the nominal output voltage of each string is around 115 V (35 × 3.25 V), and its nominal power is around 40 W (115 V × 0.350 A). The total power demanded by the lamp is 40 W.

Regarding the boost converter (first stage), it operates in BCM in order to perform PFC and, reduce switching losses. The output capacitance (22 μF) is obtained by means of metalized polypropylene film capacitors (MKP) from EPCOS high density series. In the prototype shown in Fig.5, ten 2.2-μF capacitors are connected.

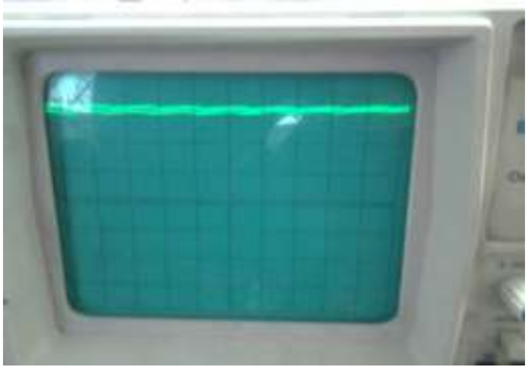
The ET nominal output voltages are 80 V and 144 V. They have been chosen considering the characteristics of the LED strings: they need 130 V to fully turn on and around 90 V to totally turn off. As can be seen, a 10-V security factor has been added in both output voltages in order to deal with the tolerance in the knee voltage of the LEDs and in their dynamic resistance. IRF840 MOSFETs rated at 8 A used in high frequency electronic transformer are operated at 30 kHz, in Boost and TIBuck converter IRF250 MOSFET used. At the output of TIBuck converter 0.350 mH inductor and a capacitor of 150 nF is used.

Finally, as the BCM-PFC boost converter may reach an efficiency as high as 97%, the overall efficiency of the proposed three-stage topology may be as high as 92–93%. In Fig.6, the efficiency of the three stages in cascade for different ac input voltages is shown.



(a)

(b)



(c)

Fig.5. (a) Prototype of 40 W LED driver; (b) 40 W LED string; (c) Input current to the LED string form TIBuck converter.

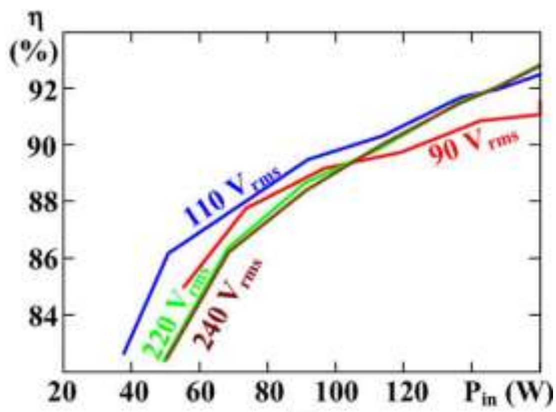


Fig.6. Efficiency of the three stages connected in cascade for different ac input voltages.

VII. CONCLUSION

In this paper, a converter for LED-based street lighting application is presented. It is based in a three-stage topology. Each stage is designed for one specific task, in such a way that the overall efficiency is above 93%. In addition, it is a solution without electrolytic capacitor; hence, it has high reliability. The first stage of the proposed solution is the very-well known boost converter. Its main task is achieving PFC with high efficiency. The second stage is an ET. It provides two output voltages with a fixed gain (unregulated) between input and outputs. Its task is providing galvanic isolation. The third stage is a TIBuck. While the first two stages are common, LED string is connected to a TIBuck, we can also include one more LED strings to which one TIBuck are connected to each one for current regulation. As the second stage is unregulated, this ripple has to be cancelled by the third stage.

The three stages have been implemented without electrolytic capacitor. The first stage has ten 2.2-μF MKP capacitors from EPCOS high density series. The ET has two MKP capacitors of 2.2 μF in each output. Finally, each TIBuck (third stage) has a 150-nF output MKP capacitor.

The experimental results have been obtained with a prototype designed for 40-W LED string; the proposed three-stage LED driver may reach efficiency as high as 93%.

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