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High-Efficiency Led Driver without Electrolytic Capacitor for Street

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Abstract: High-brightness light-emitting diodes (LEDs) are considered as a remarkable lighting device due to their high reliability, chromatic variety, and increasing efficiency. As a consequence, a high number of solutions for supplying LED strings are coming out. One-stage solutions are cost effective, but their efficiency is low as they have to fulfill several purposes with only one converter: power factor correction (PFC), galvanic isolation (in some cases), and current regulation. Two-stage and three-stage solutions have higher efficiency as each stage is optimized for just one or two tasks, and they are the preferred option when supplying several strings at the same time. Nevertheless, due to their higher cost in comparison to one-stage solutions, they are used when high efficiency, high performance, and the possibility of supplying several strings are the main concerns. In addition, they are also used when high reliability is needed and electrolytic capacitors cannot be used. In this paper, a three-stage solution and its complete design guideline for LED-based applications is proposed. PFC is achieved by a boost converter, while the galvanic isolation is provided by an electronic transformer (second stage). The third stages (one for each LED string) are designed following the two-input buck schematic, but taking advantage of the load characteristics (i.e., the high value of the LED string knee voltage, approximately equal to half the string nominal voltage). Moreover, a variation of the analog driving technique is also proposed. Experimental results obtained with a 160-W prototype show efficiency as high as 93% for the whole topology and 95% for the cascade connection of the second and third stages.

Keywords: AC–DC Power Converters, Electronic Transformer, High Efficiency, Light-Emitting Diode (LED) Lighting, Three Stage Topology, Two-Input Buck.

I. INTRODUCTION

High-Brightness light-emitting diodes (HB-LEDs) are considered the future trend in lighting as their efficacy converting energy into light is increasing and their reliability is very high [2]. Nevertheless, it is necessary to develop converters that perfectly fit the characteristics of these devices and make the best of them. According to this, two driving techniques have been proposed in the literature, and topologies without electrolytic capacitor (high reliability) [3] and high efficiency have been developed. Regarding the converters for supplying the LED strings, it should be mentioned that LEDs need to be supplied with a dc current, and, consequently, ac-dc and dc-dc converters have been proposed in literature. According to the number of stages, these converters can be classified in one, two, or three stage solutions. The main characteristics that the converters for LED-based lighting need to ensure are high reliability, high efficiency, and, in some cases, galvanic isolation. In addition, the power factor correction (PFC) is mandatory in all ac-dc topologies connected to the line in order to comply with EN 61000-3-2 Class C regulation [4]–[6].

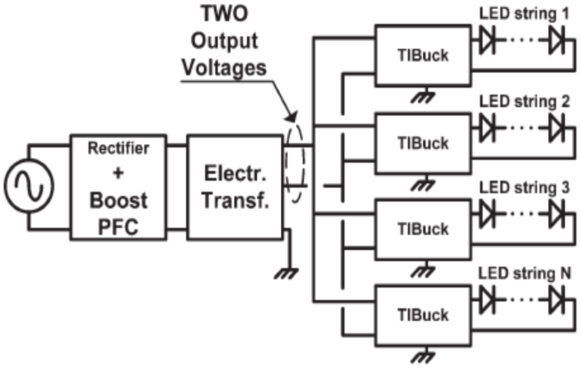


Fig.1. Basic schematic of the proposed topology.

Normally, two-stage [7]–[9] and three-stage [10] solutions are the preferred option when reliability and efficiency are more important concerns than cost (per unit) [11]. 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 [12]. 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 (see Fig. 1). The first stage is a boost converter [8]–[10]. This topology has proven to be a perfect option for doing PFC in this kind of application. As it is designed without electrolytic capacitor, its output voltage ripple cannot be neglected and will strongly influence the design of the second and third stages. The second stage is a two-output electronic transformer (ET) optimized for providing galvanic isolation at very high efficiency. Nevertheless, this topology is completely unregulated, and, as a consequence, the aforementioned 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 (i.e., no equalizing technique is needed as each LED string has its own regulator).

The main advantage of this topology is that the stress on its components is considerably reduced, what has a high impact on its size and efficiency. This topology has already been proposed as post-regulator for LED-based applications. In, the TIBuck is used as an active equalizer (limited regulating capability) with very high efficiency, but without the possibility of providing full dimming on its own. As it will be deeply explained, 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 [2]. 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. As the final application is street lighting, some additional details should be considered. Wavelength (color) quality is less important than other issues like efficiency.

In addition, the stress on the 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 or for certain customers. This paper is organized as follows. In Section II, the TIBUCK Converters .Section III explains the Dspic30f4011 microcontroller. In Section IV, the experimental results are shown, and, finally, in Section V, the conclusions will be presented.

IV. TIBUCK CONVERTERS

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.2, 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 post regulators. Applying the volt ·second balance in the output inductor results in

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

Where D is the duty cycle of the MOSFET and V_h and V_l are the input voltages of the TIBuck, from (1), the output voltage equation can be obtained

$$V_{out} = V_h \cdot D + V_l \cdot (1 - D) \qquad (2)$$

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

$$V_{s-max} = V_{D-max} = V_h - V_l \qquad (3)$$

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 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.

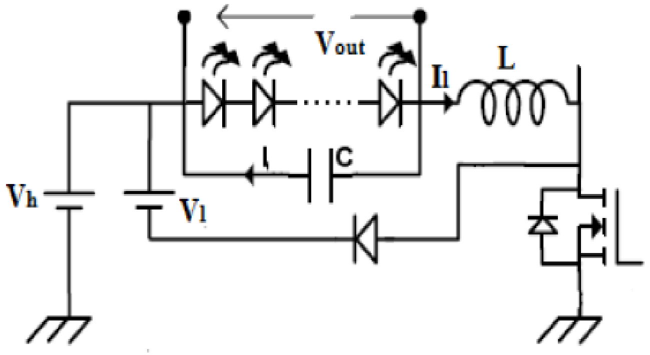


Fig.2. Schematic of the proposed TIBuck converter proposed for driving each LED string.

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.

III. 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 1: Operating Parameters of DSPIC30F4011

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

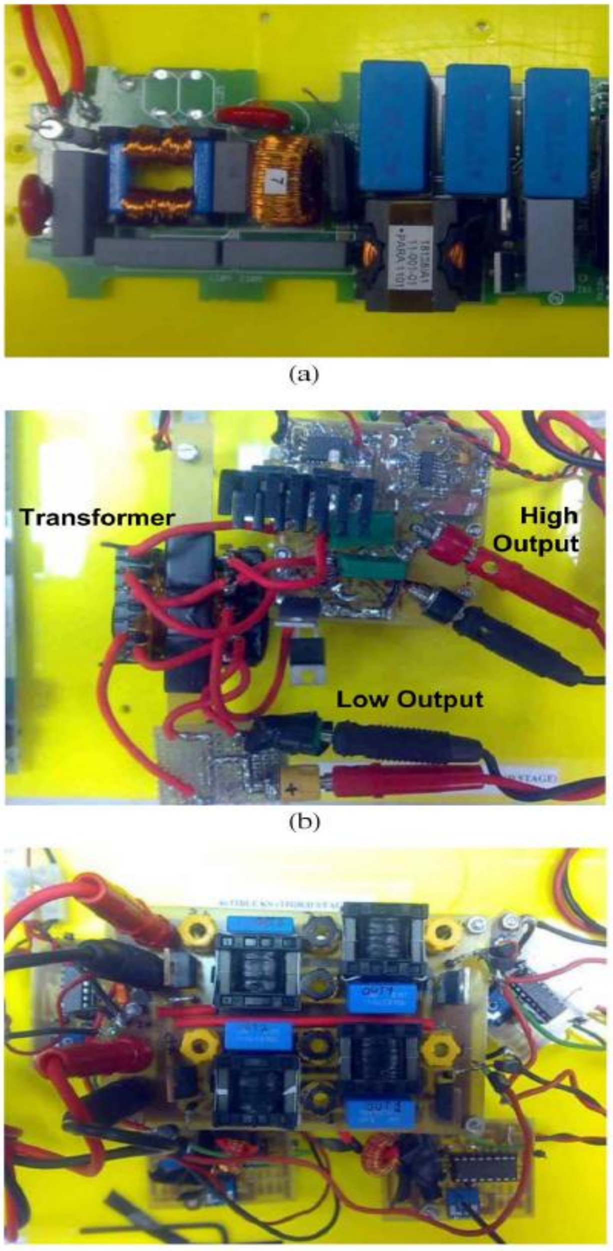
DSPICF4011 is used in this prototype for generating PWM signals at 30 kHz for switches. Table no.1 shows operating parameters for DSPICF4011 microcontroller.

IV. EXPERIMENTAL RESULTS

A 160-W prototype has been built (see Fig. 3). Four TIBucks (one for each LED string) have been connected at the outputs of the ET. Hence, the prototype has the capability of independently driving four LED strings. 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 3.25 V (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 160 W. Regarding the boost converter (first stage), it operates in BCM in order to reduce switching losses. The output capacitance (30 μF) is obtained by means of metalized polypropylene film capacitors (MKP) from EPCOS high density series. In the prototype shown in Fig. 3, three 10-μF capacitors rated for 450 V are implemented. Another possibility would have been using a 30-μF capacitor rated for 800 V if a higher security factor had been required regarding rated voltage.

The ET nominal output voltages are 80 V and 144 V (when the input voltage is 400 V). They have been chosen taking into account and 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. In addition, this security factor also allows the driver to deal with partially short-circuited strings. The input voltage of the ET is intended to be 400 V with a maximum peak-to-peak ripple of 10%. The control of both

MOSFETs runs at 100 kHz. The transformer is an ETD-39 with 3F3 magnetic core and 0.8- mm gap in order to achieve ZVS at any load range in primary switches. For achieving ZCS, the equations presented imply that a 200-nF output capacitor is necessary.



(a)

(b)

(c)

Fig.3. (a) Prototype of the PFC Boost; (b) prototype of the 160-W ET; (c) prototype of the four 40-W TIBucks (one for each LED string).

The four TIBucks are operated at 100 kHz. The output filter is implemented by means of an E20 core with a value of 0.350 mH and an output capacitor of 150 nF. Due to the low voltage that both semiconductors are going to withstand (144 − 80 = 64 V), it is possible to use an IRF540 MOSFET and an 11DQ10 diode. These low-voltage-rated devices allow us to boost the efficiency of these converters. A very simple PI controller (with the pole located at very low frequency and a dc gain of about 80 dB) is implemented in each TIBuck so that the current can be independently controlled while maintaining an audio susceptibility as low as 0.0003 Ω−1 at 100 Hz (see Fig. 4).

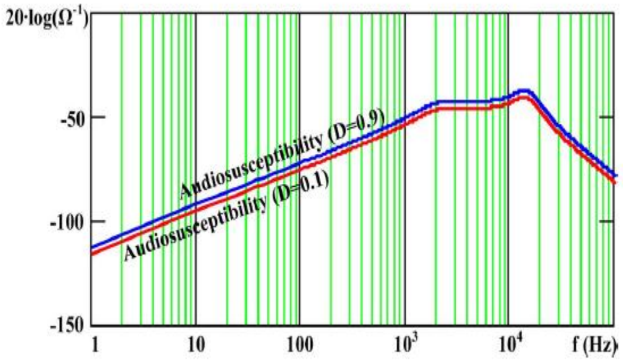
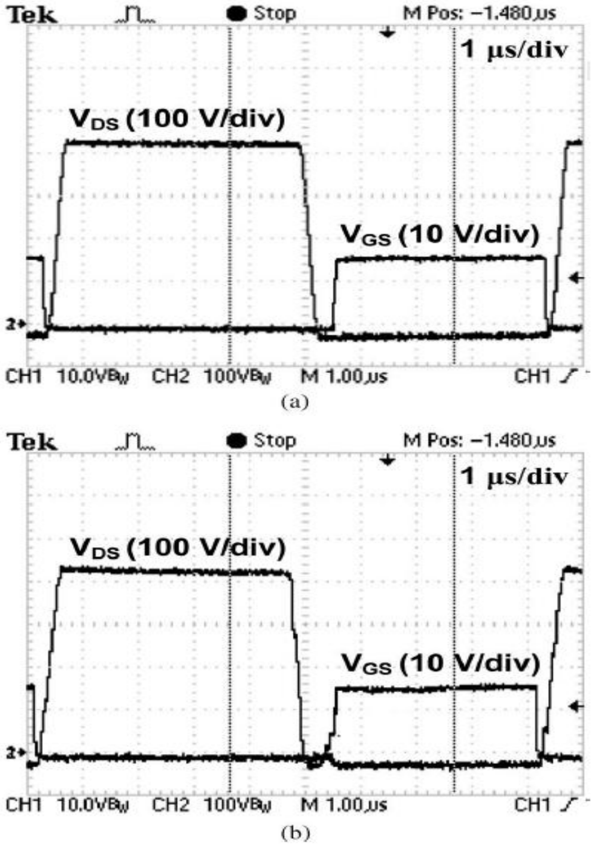


Fig.4. Audio susceptibility in closed loop for two different duty cycles.

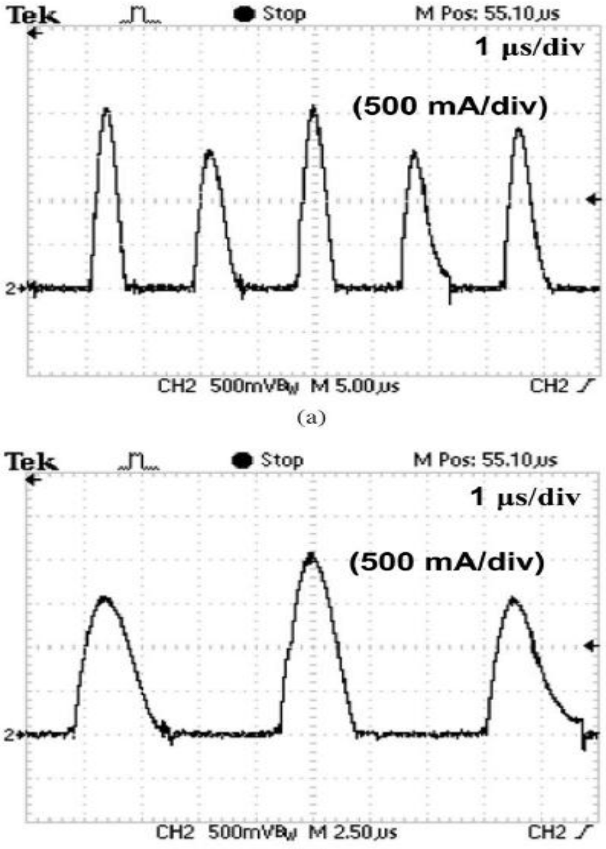


(a)

(b)

Fig.5. ZVS in ET MOSFETs at (a) full load and (b) no load.

In Fig.5, it can be seen how the primary switches (MOSFETs) of the ET achieve ZVS condition at full load and at no load. It has to be taken into account that the energy for doing so is stored in the leakage inductance and, therefore, is defined not only by the load current, but also by the magnetizing current of the “magnetic” transformer. Hence, if some gap is added to the core of this transformer, it is possible to have enough energy stored in the leakage inductance for achieving ZVS even with an output current equal to zero. In this particular case, the gap was added because the amount of energy determined by the output current was not enough for achieving ZVS even at full load.

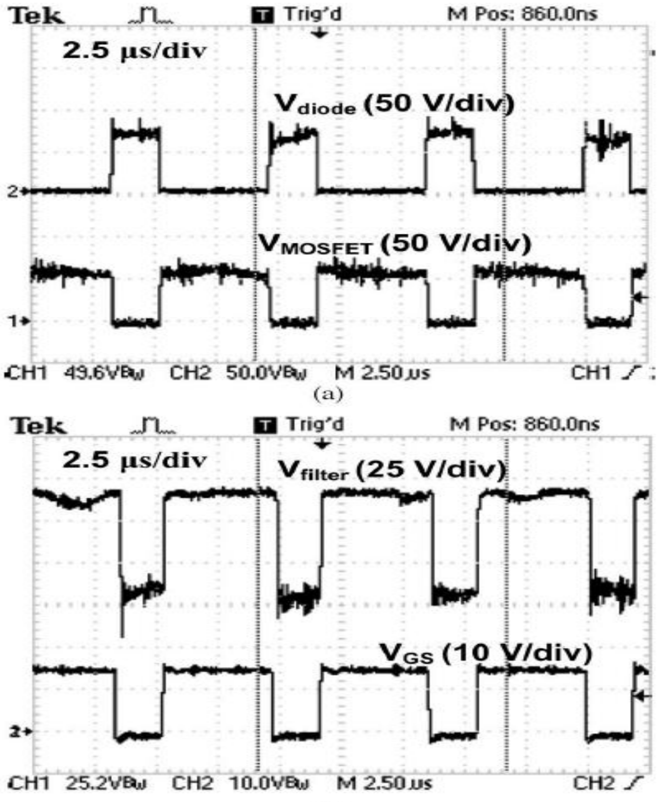


(a)

(b)

Fig.6. (a) Current through one of the ET output diodes; (b) detail.

At this point, it may be interesting to determine whether it is better decreasing the magnetizing inductance of the transformer or not. If some air gap is added, the switching losses of the MOSFETs are going to be reduced (ZVS is achieved). Nevertheless, the current level through them, and through the transformer, is going to be increased, and so is going to be increased their conduction losses. For solving this, the same topology has been tested with and without air gap for the same testing condition and adjusting dead times for achieving ZVS (with air gap) or being the closest to it (with no air gap). The efficiency was 1% higher when adding some gap to reduce the switching losses than when minimizing it to reduce conduction losses. Another characteristic of the ET is the possibility of achieving ZCS at secondary switches (diodes). In Fig.6, this characteristic is shown for one of the diodes of the higher voltage output. Considering that the amount of current extracted from each output will strongly depend on the TIBucks operation, the best option is calculating the output capacitors of the ET considering that the nominal current is extracted from each output. In this way, diodes will always achieve ZCS in nominal conditions. The primary switches of the ET will also be closed to ZCS as the input current is the output one multiplied by the turn's ratio, but adding the magnetizing current.



(a)

(b)

Fig.7. (a) Voltage withstood by the TIBuck diode and MOSFET; (b) Gate signal of the MOSFET and filter input voltage.

Regarding the TIBucks, Fig.7 shows the voltage withstood by semiconductors and the input voltage of the output filter. As can be seen, the voltage withstood is equal to the difference between both input voltages. In this way, switching losses are considerably reduced. In addition, the necessary MOSFET and diode are going to be rated for a lower voltage, what means lower R_{DSON}, C_{oss}, voltage drop, and reverse recovery time, what also reduces losses. Analyzing Fig. 7(b), it can be seen that the output filter is going to be considerably smaller than in a conventional buck. This also leads to a reduction of the losses in the inductor. In Fig. 8(a) and (b), the current through one of the strings is shown when second and third stages are connected in cascade and when the input voltage of the second stage has no ripple. As can be seen, there is no low-frequency ripple, and the high frequency one is considerably reduced, particularly for an application like street-lighting. This high-frequency ripple could be even more reduced if the output capacitor of the third stage were increased (it has a value of 150 nF, so its capacitance could be easily increased without using electrolytic technology). In Fig. 8(c), the output current is shown when the input voltage of the second stage has a ripple of 10%. Audio susceptibility of the third stage has been defined as output current of the third stage divided by the input voltage of the second stage. Taking into account the nominal values of these two variables, audio susceptibility should be around 0.0003 Ω^{-1} at twice the line frequency. In this way, a 10% ripple in the input voltage (40 V_{pp}) of the second stage will produce a 12-mApp low-frequency ripple in the output current of the TIBucks (40 $V_{pp} \cdot 0.0003\ \Omega^{-1}$). This represents a 3.5% relative ripple in the output current (12 $mA_{pp/}$350 mA), which is an excellent current ripple for street-lighting applications.

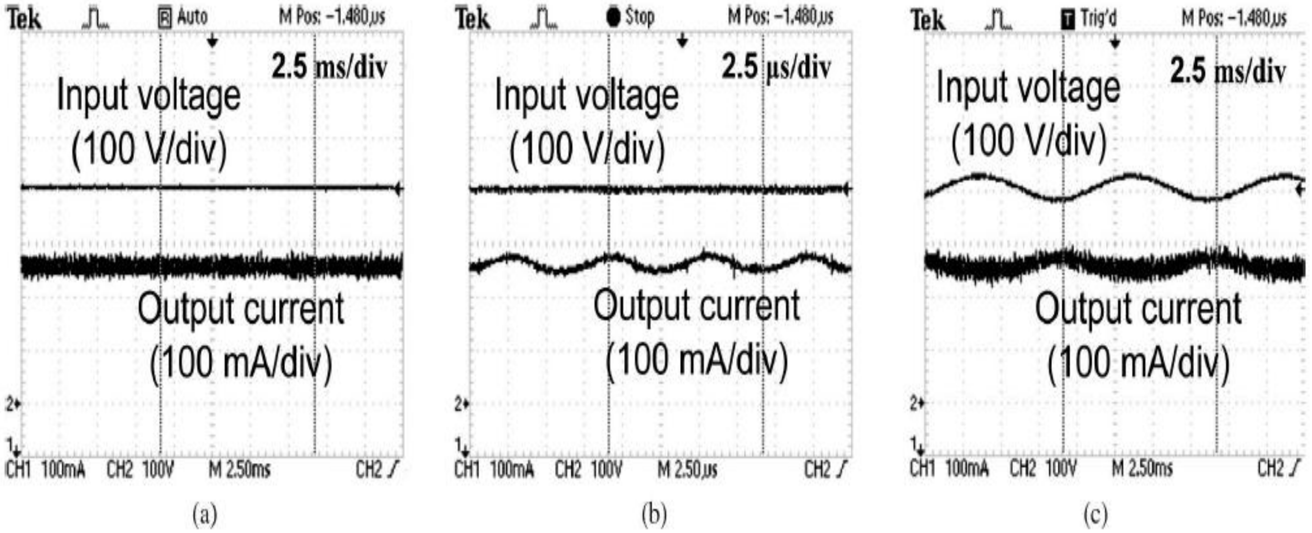


Fig.8. ET input voltage and LED string current when (a) the input voltage has no low-frequency ripple; (b) detail when the input voltage has no low-frequency ripple; (c) the input voltage has a 45-Vpp 100-Hz ripple.

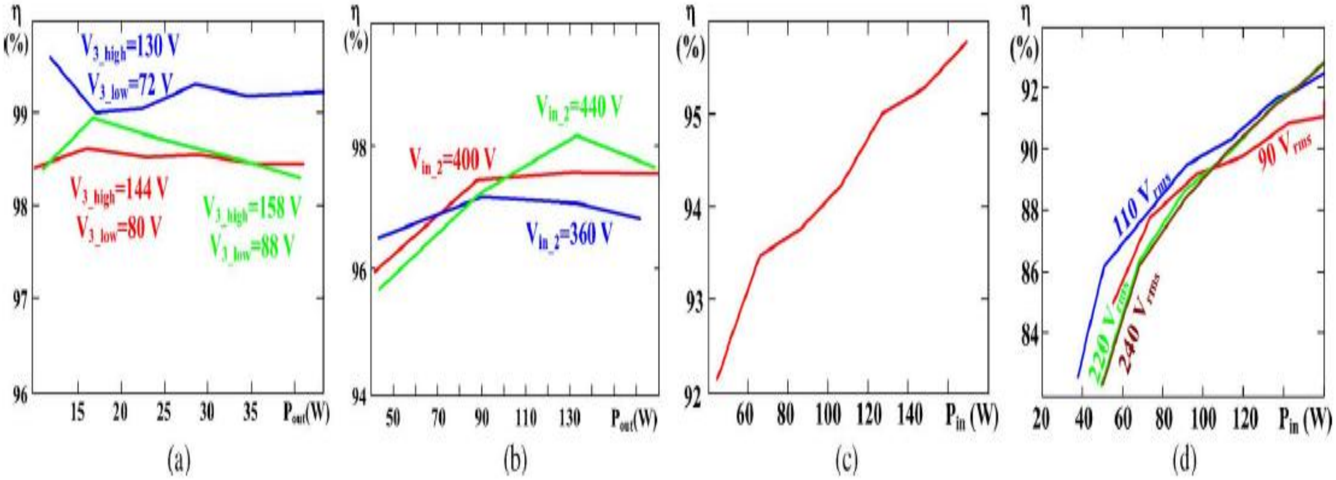


Fig.9. (a) Efficiency of one of the TIBuck, (b) efficiency of the ET for different input voltages (control stage consumption is not included), (c) efficiency of the ET connected in cascade with the four modified bucks (control stage consumption is not included), and (d) efficiency of the three stages connected in cascade for different ac input voltages.

In Fig.9, the efficiency of the second and the third stages is shown. Fig.9 (a) shows the efficiency of one of the TIBucks for different input voltages, which are defined by the maximum, nominal, and minimum input voltage of the ET. Fig. 9(b) shows the efficiency of the second stage for the maximum, nominal, and minimum input voltage. In both cases, the power consumption of the control stages is not included. This total power consumption is around 2 W for the four TIBucks plus the ET control stages. Hence, the efficiency of the second stage in cascade with the four third stages operating at full load is nearly 96.0% (see Fig. 9(c) for the whole-range efficiency). If the power consumption of the control stages is included, this efficiency is as high as 94.8%. Considering that the second stage proposed in [10] has efficiency as high as 97% and considering that the third stage of that topology (the conventional buck converters) has efficiency as high as 94%, the overall topology has efficiency as high as 91%. Hence, the topology proposed in this paper (ET plus the TIBucks) implies an improvement in efficiency of about 4–5%. Finally, as the BCM-PFC boost converter may reach efficiency as high as 97%, the overall efficiency of the proposed three-stage topology may be as high as 92–93%. In Fig. 9(d), the efficiency of the three stages in cascade for different ac input voltages is shown.

V. CONCLUSION

HB-LEDs are gaining consideration in lighting due to their high efficacy when converting electrical energy into light. Nevertheless, this new technology needs power supplies different from the rest of lighting devices. The main issues when analyzing these new converters are high efficiency, high reliability, color quality, and total dimming. Nevertheless, there are applications in which some of this features are more important than others. In street lighting, light quality is less important than reliability and efficiency. 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, each LED string is connected to a TIBuck. In this way, the current of each string can be regulated independently.

In addition, the first stage has a considerable output voltage ripple due to the absence of electrolytic capacitors. 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 three 10-μF MKP capacitors from EPCOS high density series. The ET has two MKP capacitors of 100 nF 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 4×40-W LED strings achieving efficiency at full load as high as 95% for the second and third stages in cascade. If the first stage is also considered, the proposed three stage LED driver may reach efficiency as high as 93%.

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