Comprehensive Survey and Critical Evaluation of the Performance of State-of-the-art LED Drivers for Lighting Systems*

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Abstract: The adoption of light-emitting diodes (LEDs) for lighting applications is becoming increasingly relevant as this recent technology is advancing. Given the recent uptake of LED lighting technologies for distinctive end-uses, the research community has also committed to the development of an ever-increasing range of power electronic converters that are suitable for yielding maximum quality lighting, high efficiency, and long lifetimes. As one of the most recent and promising technologies of the moment, it is vital to fully understand the performance and merits of each state-of-the-art LED lighting technology. Accordingly, this paper compiles essential information about a broad range of state-of-the-art LED lighting systems, aiming to compare their performances in terms of efficiency. Based on the comparative analysis, the main merits and drawbacks of each LED lighting system architecture are obtained. Then, a detailed evaluation of the performance of a particular LED lighting system and the corresponding control strategy is developed, thereby enabling a clear view of the evolution of the performance of the system as a function of parameters like supply voltage and number of driver channels.

Keywords: Efficiency analysis, LED lighting, AC-DC converters, DC-DC converters

1 Introduction

The large-scale adoption of light-emitting diode (LED) technologies for lighting applications is a quite recent trend, triggered by important improvements achieved in the field. Improvements in the quality of light produced by LEDs and improvements in terms of efficiency have been important factors in this evolution. Furthermore, the ever-increasing improvements in the field of power electronics, which are vital for driving LED lighting systems, and the low cost associated with such power electronics contributed to the increase in the numbers of LED lighting systems adopted.

The developments achieved in LED technologies were closely followed by the development of a plethora of distinctive driver configurations, which exhibit distinctive merits. Improving the efficiency is a merit of some topologies, whereas higher reliability owing to the adoption of long-lifetime capacitors is the primary merit of other LED drivers.

There are many architectures for LED drivers, and they aim to address the requirements and constraints imposed by the different applications of LED lighting: automotive, indoor/outdoor lighting, greenhouse lamps, street signs, and so on. LED drivers are typically derived and adapted from basic AC-DC and/or DC-DC converter topologies to integrate functions like precise power control or dimming.

AC-DC LED drivers are typically chosen for applications with access to an AC power supply, as is the case for indoor/outdoor lighting. As many of the LED systems used for indoor and outdoor lighting applications are directly connected to the AC mains of energy distribution networks, the practical implementation of AC-DC LED driver architectures is prevailing. Given the wide applicability of AC-DC LED drivers, the literature

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reports a wide range of architectures, with distinctive features and merits. Regardless of the configuration of the AC-DC LED driver, the functions of rectification, power factor correction (PFC), and power control are common to all of them. Depending on how the PFC and power control functions are deployed, AC-DC LED drivers may adopt a single-stage or multi-stage configuration. In single-stage AC-DC LED drivers, both PFC and power control functions are deployed by a single DC-DC converter, following the structure depicted in Fig. 1. In two-stage AC-DC LED drivers, the PFC and power control functions are deployed by two distinctive DC-DC converters, according to the structure depicted in Fig. 2.

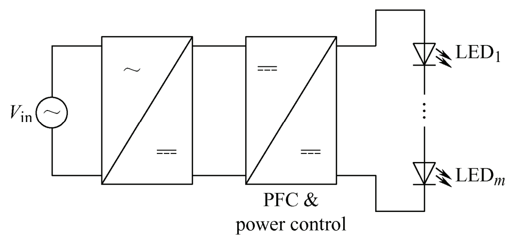


Fig. 1 Generic representation of the structure of a LED driver adopting a single-stage configuration

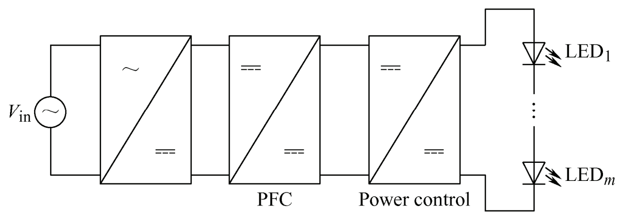


Fig. 2 Generic representation of the structure of a LED driver adopting a two-stage configuration

Meanwhile, LED drivers fully based on DC-DC converters are typically adopted when a DC power supply is used as is the case in automotive lighting applications. Their hardware structure is far simpler than that of equivalent AC-DC drivers, because the rectification and PFC functions are obviated. Therefore, most DC-DC LED drivers rely on a single-stage configuration to deploy the power control function. This means that DC-DC LED drivers can, theoretically, achieve higher figures of merit, thereby providing important advantages over AC-DC LED drivers in terms of cost-effectiveness and conversion efficiency, owing to the simpler hardware architecture and ease of control.

Regardless of the complexity or type of LED driver (AC-DC or DC-DC), all these power conversion systems share the common feature of adopting at least one DC-DC conversion stage. There are many DC-DC converters with the potential for integration in LED drivers. Most common DC-DC converter topologies employed in the development of more or less complex LED drivers include buck, boost, flyback, SEPIC, and half-bridge converters.

Fig. 3 presents the architecture of four of the most common non-isolated DC-DC converters employed in LED drivers to implement PFC and/or power control.

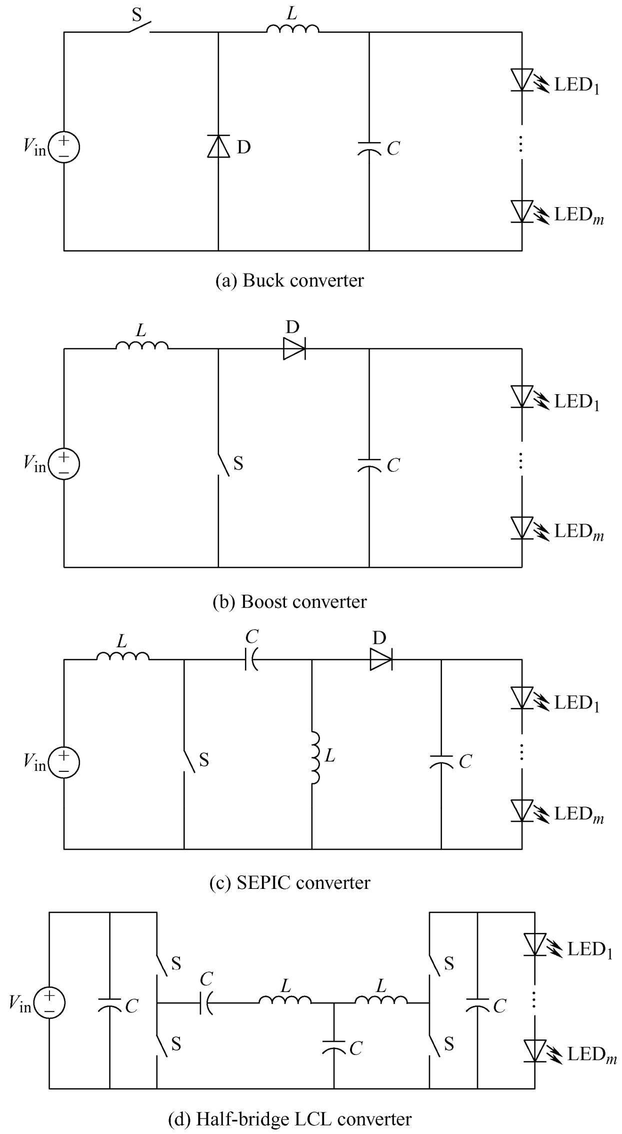
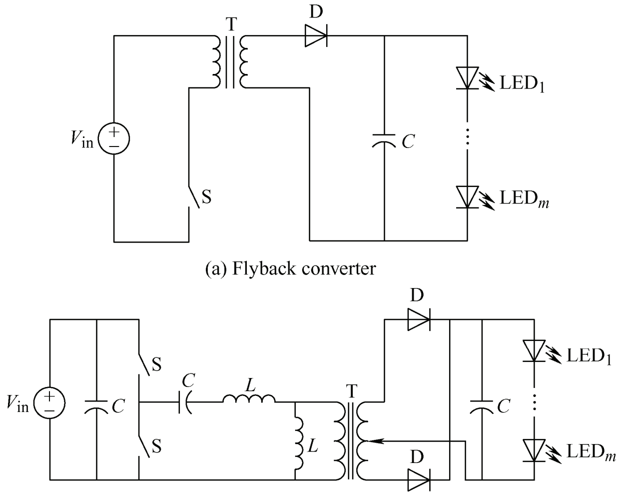


Fig. 3 Commonly adopted non-isolated DC-DC converters for LED driver systems

Whereas LED drivers without galvanic isolation are commonplace, LED drivers with galvanic isolation might be of particular interest in specific applications or contexts. Such LED drivers typically rely on the flyback converter or the half-bridge LLC converter, which are both depicted in Fig. 4.



(a) Flyback converter

(b) Half-bridge LLC converter

Fig. 4 Commonly adopted isolated DC-DC converters for LED driver systems

Additional auxiliary circuitry, like valley-fill circuits, coupled-inductor cells, active filters, or discrete passive devices, can also be integrated to obtain improved performance in terms of the conversion ratio, ripple cancellation, or conversion efficiency.

The efficiency of LED lighting systems depends on a significant set of factors as will be demonstrated later. The architecture of the driver is, perhaps, the most important factor affecting the performance of the lighting system. Apart from the selected converter hardware architecture, the adopted control strategies also play an important role in terms of the overall efficiency of LED drivers. In large-scale lighting systems, composed of multiple strings, the power conversion efficiency is also affected by the arrangement of LEDs within the array [1]. The supply voltage, switching frequency, adopted dimming techniques, and rated output power are some of the additional factors that may affect the performance of LED lighting systems in terms of efficiency.

To obtain a detailed picture of the state-of-the-art of LED lighting systems, available driver topologies, and their performance, the following sections present information regarding a broad and representative range of LED drivers. Their performance is evaluated and critically compared, namely through the evaluation of the efficiency achieved by each LED driver.

Then, an in-depth parametric analysis is performed on a specific LED driver topology. The operation of the driver is modeled and tested over a wide range of conditions to evaluate the driver performance as a function of multiple parameters.

2 Comparison of state-of-the-art LED drivers

Tab. 1 presents some important information that can be considered relevant in the assessment of the performance of each LED driver architecture. Information is provided for the most representative LED drivers described in the scientific literature.

It is important to recall that the compiled information is based on information provided in each relevant paper. This remark becomes particularly relevant with regard to the efficiency values. As some authors have pointed out, the design of some LED drivers is not optimized. Therefore, a small number of the topologies listed in Tab. 1 may undergo design improvements to increase their efficiency levels further.

For the particular case of the “No. of outputs” parameter, the provided data focus on the configuration of the LED driver tested in each study; hence, certain single-output LED driver topologies may be designed to integrate multiple outputs. To illustrate this further, the following example is provided. Ref. [2] presents, in detail, the process of designing a single-inductor half-bridge LED driver, with a single output. This LED driver may adopt a modular architecture to develop a single LED driver that incorporates multiple outputs. Likewise, prototypes described in the literature as LED driver solutions with the modularity feature, which already comprise multiple channels, can be designed to integrate additional channels.

Tab. 1 Main features of the state-of-the-art LED drivers

Ref.	Converter topology	Switching frequency/kHz	Rated output power/W	Input voltage/V	No. of outputs	Galvanic isolation	Dimming technique	Peak efficiency(%)	Typical applications
[3]	Series-input-connected modular buck-boost converter [a]	800	25	35	3	No	Analog	86.0	Multi-fixture lighting
[4]	Two-input-multiple-output buck converter	1 078	50	400	3	No	PWM	98.3	Multi-fixture lighting
[5]	Series-parallel resonant converter [a]	N/D [b]	100	400	2	Yes	Analog	96.5	Multi-fixture lighting
[6]	Interleaved buck converter	150	50	67.2	1	No	PWM	97.8	Indoor/outdoor lighting
[7]	LLC resonant converter	200	100	340-410	2	Yes	Analog	95.0	Multi-fixture lighting
[8]	Flyback converter	100	13.5	110-220	1	Yes	Analog	80.0	Indoor/outdoor lighting
[9]	Single-stage flyback converter	N/D [b]	91	120-230	1	Yes	Analog	91.0	Indoor/outdoor lighting
[10]	Valley-fill SEPIC-derived converter	53	50	85-265	3	Yes	PWM	～92.0	Multi-fixture lighting
[11]	Flyback+buck-boost converter	200 (flyback) 100 (buck-boost)	33	90-264	1	Yes	Analog	87.5	Indoor/outdoor lighting
[12]	Flyback converter	50	45	110	1	Yes	Analog, PWM	95.5	Indoor/outdoor lighting
[13]	Isolated boost converter [a]	90	150	400	2	Yes	Analog	96.2	Multi-fixture lighting
[14]	LLCC resonant multiple-output converter	N/D [b]	150	N/D [b]	4	Yes	Analog	96.5	Multi-fixture lighting
[15]	Hybrid (switched/linear) converter	400	N/D [b]	12, 24	1	No	PWM	93.9	Indoor/outdoor lighting
[1]	Buck converter	300	7.5	48	1	No	Analog	81.0	Automotive, indoor/outdoor lighting
[1]	Boost converter	100	7.5	5	1	No	Analog	75.0	Automotive, indoor/outdoor lighting
[1]	Buck-boost converter	100	7.5	12	1	No	Analog	85.0	Automotive, indoor/outdoor lighting
[16]	Active clamp flyback+full-bridge converter	156	100	110	1	Yes	Analog	92.5	Indoor/outdoor lighting
[17]	Integrated buck-flyback converter	N/D [b]	70	184-276	1	Yes	Analog, Analog	86.0	Indoor/outdoor lighting
[18]	Integrated asymmetrical half-bridge zeta converter	100	180	400	1	Yes	PWM	95.5	Indoor/outdoor lighting

(Continued)

Ref.	Converter topology	Switching frequency/kHz	Rated output power/W	Input voltage/V	No. of outputs	Galvanic isolation	Dimming technique	Peak efficiency(%)	Typical applications
[19]	Forward-type converter	100	54.4	48	2	Yes		85.5	Multi-fixture lighting
[20]	Synchronous buck converter	Variable [c]	25	5-115	1	No	Analog	94.4	Indoor/outdoor lighting
[21]	Single-inductor-multiple-output buck converter	75	30	110	3	No	Analog, PWM	89.0	Multi-fixture lighting
[22]	Single-inductor-multiple-output buck converter [a]	50	12	48	3	No	PWM	91.0	Multi-fixture lighting
[23]	Duty-ratio-control-aided LLC converter	40-130	120	400	2	Yes	Analog	96.1	Indoor/outdoor lighting
[24]	Valley-fill boost-forward converter	100	60	90-130, 180-260	1	Yes	PWM	90.5	Indoor/outdoor lighting
[25]	Single-inductor-multiple-output buck converter	99	25	110	3	No	Analog, PWM	89.5	Multi-fixture lighting
[2]	Single-inductor half-bridge converter	100	50	380	1	Yes	Analog	90.5	Indoor/outdoor lighting
[26]	Half-bridge non-resonant converter with symmetrical quadrupler rectifier output	Variable [c]	250	400	8	Yes	Analog, PWM	95.0	Multi-fixture lighting
[27]	SEPIC converter with half-bridge LLC resonant converter	100	100	220	1	Yes	Analog	92.0	Indoor/outdoor lighting
[28]	Coupled-inductor buck converter	100	30	150	2	No	Analog, PWM	95.5	Multi-fixture lighting
[29]	Boost converter with current-sharing capacitor	100	24.5	12	2	Yes	Analog	96.0	Automotive
[30]	Flyback+buck converter	100	105	220	1	Yes	Analog	91.1	Indoor/outdoor lighting
[31]	Boost-integrated two-switch forward converter	50	33.6	90-135	1	Yes	Analog	~ 89.0	Indoor/outdoor lighting
[32]	Switched-capacitor LCC resonant converter	87	60	400	5	Yes	Analog, PWM	85.5	Multi-fixture lighting
[33]	Luo converter	46	36	85-265	1	No	Analog	91.0	Indoor/outdoor lighting
[34]	Single-inductor-multiple-output converter [a]	700-1 200	12	16-24	4	No	PWM	96.0	Multi-fixture lighting
[35]	Two-input floating buck converter	Variable [c]	8.2	18-23	1	No	Analog	97.6	Automotive
[36]	Current-source single-inductor-multiple-output converter	50	N/D [b]	35-60	2	No	PWM	89.0	Multi-fixture lighting
[37]	Single-stage boost-LLC converter	Variable [c]	100	90-260	2	Yes	Analog	92.5	Multi-fixture lighting
[38]	Half-bridge chopper with switched capacitor	70	23	48	4	No	Analog	93.8	Multi-fixture lighting

(Continued)

Ref.	Converter topology	Switching frequency/kHz	Rated output power/W	Input voltage/V	No. of outputs	Galvanic isolation	Dimming technique	Peak efficiency(%)	Typical applications
[39]	Synchronous buck converter	1 600	25	5-115	1	No	Analog, PWM	94.4	Indoor/outdoor lighting
[40]	Integrated buck-flyback converter	N/D [b]	26.5	90-250	1	Yes	Analog	89.0	Indoor/outdoor lighting
[41]	Hybrid switched-capacitor-resonant converter	Variable [c]	22	80-360	1	Yes	Analog, PWM	92.2	Indoor/outdoor lighting
[42]	Coupled-inductor boost converter	500	36	24	1	No	Analog	92.6	Automotive
[43]	Series resonant converter	70	80	90, 135	2	No	Analog	87.2	Multi-fixture lighting
[44]	Interleaved flyback converter	Variable [c]	200	110	1	Yes	Analog	93.9	Indoor/outdoor lighting
[45]	Single-coupled-inductor multiple-output converter	50	16	110	2	No	Analog, PWM	91.5	Multi-fixture lighting
[46]	Series resonant converter	76.86	58	100	6	No	Analog	93.5	Multi-fixture lighting
[47]	Modified SEPIC converter	1 000	36	24	1	No	Analog	90.9	Automotive
[48]	Quadratic boost converter	40	38	9-16	1	No	Analog	92.0	Automotive
[49]	Single-coupled-inductor multiple-output converter	45	16	110	3	No	Analog	88.2	Multi-fixture lighting
[50]	Integrated buck-boost+CLCL resonant converter	100	100	220	1	Yes	Analog	92.3	Indoor/outdoor lighting
[51]	Single-stage TRIAC dimmable converter with bleeder circuit	N/D [b]	5.7	100	1	No	Analog	73.8	Indoor/outdoor lighting
[52]	Multi-channel single-stage series-type converter	100	120	198-242	3	Yes	Analog	88.7	Multi-fixture lighting
[53]	Multi-channel AC-DC boost PFC converter+DC-DC power conversion stage	72 (PFC conv.) 12 (decoupling conv.)	150	230	8	Yes	Analog, PWM	92.3	Multi-fixture lighting
[54]	Flyback converter with energy buffer	25	15	110	1	Yes	Analog	~ 82.0	Indoor/outdoor lighting
[55]	LLC resonant converter	102.7	100	400	1	Yes	Analog	95.0	Indoor/outdoor lighting
[56]	Flyback converter with unidirectional ripple current compensation	50	28	110	1	Yes	Analog	~ 86.0	Indoor/outdoor lighting
[57]	Hybrid (switched/linear) converter	5 000	20	110	1	No	Analog	95.1	Indoor/outdoor lighting
[58]	Resonant buck-boost converter	100	26	12	1	No	Analog	~ 94.0	Automotive
[59]	Buck converter	200	8	12	1	No	Analog	91.0	Automotive
[60]	Flyback+resonant converter	100	100	110	1	Yes	Analog	90.3	Indoor/outdoor lighting
[61]	Interleaved flyback converter	50-500	200	48	1	Yes	Analog	95.3	Indoor/outdoor lighting

(Continued)

Ref.	Converter topology	Switching frequency/kHz	Rated output power/W	Input voltage/V	No. of outputs	Galvanic isolation	Dimming technique	Peak efficiency(%)	Typical applications
[62]	Quadratic boost converter	40	38	9-16	1	Yes	Analog	92.0	Automotive
[63]	Self-oscillating boost converter	N/D [b]	6	9-11	1	No	PWM	95.9	Automotive
[64]	Boost+buck converter	67	47	90-135, 175-265	2	No	Analog	89.7	Indoor/outdoor lighting
[65]	Modular three-phase converter	100	300	380-420	3	No	Analog	97.5	High-bay lighting
[66]	Integrated boost hybrid converter	300	4.2	6-18	1	No	Analog	93.0	Automotive
[67]	Buck-boost-buck single-switch-multiple-output resonant converter	N/D [b]	84	175-265	3	No	Analog	94.3	Multi-fixture lighting
[68]	Boost rectifier+half-bridge converter	N/D [b]	100	100-120, 220-240	2	No	Analog	92.6	Indoor/outdoor lighting
[69]	Two-stage multiple-output converter	76	150	400	4, 8	Yes	Analog, PWM	97.3	Multi-fixture lighting
[70]	Charge-pump-based resonant converter	960-1 040	50	230	1	No	Analog	87.8	Indoor/outdoor lighting
[71]	LLC converter	70-130	100	320-420	1	Yes	Analog	~ 96.5	Indoor/outdoor lighting
[72]	Three-switch buck converter	500	120	60	1	No	Analog, PWM	85.3	Indoor/outdoor lighting
[73]	Resonant buck converter	N/D [b]	15	310	1	No	Analog, PWM	97.0	Indoor/outdoor lighting
[74]	Resonant LCL-T converter	2 000	16.5	12-14	1	No	Analog	91.1	Automotive
[75]	Single-inductor-multiple-output converter	200	80	150	3	No	Analog, PWM	97.3	Multi-fixture lighting
[76]	Fault-tolerant single-inductor-multiple-output converter [a]	Variable [c]	22	120	2	No	Analog, PWM	81.1	Multi-fixture lighting
[77]	Integrated buck+boost converter Two-output	Variable [c]	26.5	100-120, 220-240	1	No	Analog	93.5	Multi-fixture lighting
[78]	PFC+unidirectional DC-DC converter	50	27	110	1	No	Analog	91.5	Indoor/outdoor lighting

Note:
[a] The reference does not provide detailed information about the evolution of the efficiency as a function of specific variables, such as dimming ratio, output power, supply voltage, etc..
[b] Not defined.
[c] The switching frequency is not specified or varies according to the operating conditions.

The list of references presented in Tab. 1 clearly demonstrates the significant research efforts in the field of LED lighting, as well as the increasing interest on this field of research, which is demonstrated by the increasing number of scientific contributions made within the past few years.

The multitude of LED drivers presented in the literature yields a significant range of solutions for the multiple practical applications of LEDs. These solutions are capable of meeting the requirements of low- and high-power lighting systems. These technologies comprise single- and multi-channel configurations (i.e., configurations with multiple outputs) that are capable of reaching efficiency levels ranging from 73.8% to 98.3%.

Based on the list of LED driver architectures presented in this paper, the top-three in terms of efficiency are ranked as follows.

(1) The two-input-multiple-output buck converter presented in Ref. [4], which can reach a peak efficiency of 98.3%.

(2) The interleaved buck converter presented in Ref. [6], which can reach a peak efficiency of 97.8%.

(3) The two-input floating buck converter presented in Ref. [35], which can reach a peak efficiency of 97.6%.

It is interesting to note that all three LED drivers share a common feature: all of them are based on single-stage DC-DC converters with a simple hardware structure. The adoption of simple hardware structures is definitely one of the key factors in determining the efficiency of an LED driver.

To understand the potential influence of specific parameters on the efficiency of LED drivers, the following sub-sections present an analysis on how the efficiency varies with those parameters.

2.1 Switching frequency

The selection of the switching frequency is an important aspect to consider in the optimization of the design of LED drivers.

Fig. 5 provides a scatter representation of the peak efficiency attained by each of the LED drivers listed in Tab. 1 as a function of the switching frequency. It should be noted that Fig. 5 does not include data points related to the LED drivers that employ variable switching frequencies or drivers whose switching frequency is unknown.

As depicted in Fig. 5, most of the LED drivers are tested at switching frequencies below 200 kHz. Within that range, most LED drivers attain efficiency levels above 85%. It is also noted that only 2 out of 13 LED drivers tested at switching frequencies equal to or higher than 200 kHz are able to surpass the threshold of 95% of the conversion efficiency. Owing to the relatively reduced number of LED drivers tested under these conditions, a strong correlation cannot be established; however, it is likely that the high switching frequency affects the efficiency of the LED drivers because of the increasingly high relevance of the switching losses to the total amount of losses of the LED drivers.

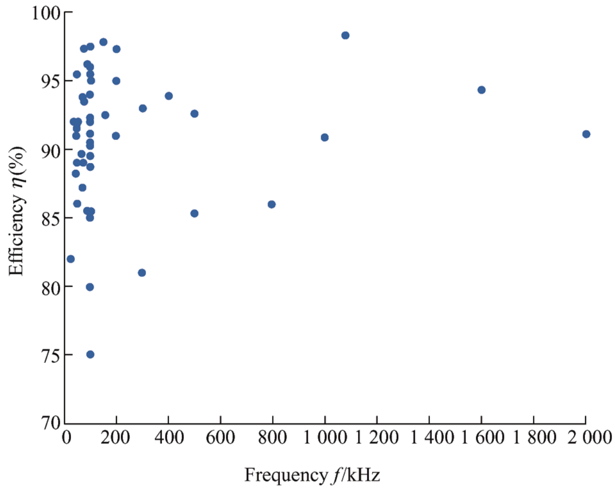


Fig. 5 Scatter distribution of the peak efficiencies attained by each of the LED drivers under analysis, as a function of the switching frequency used to test the LED drivers

2.2 Output power

The power rating is perhaps one of the parameters with the most relevant influence on the efficiency of LED drivers. Fig. 6 depicts the distribution of the peak efficiencies as a function of the output power delivered by the LED drivers listed in Tab. 1.

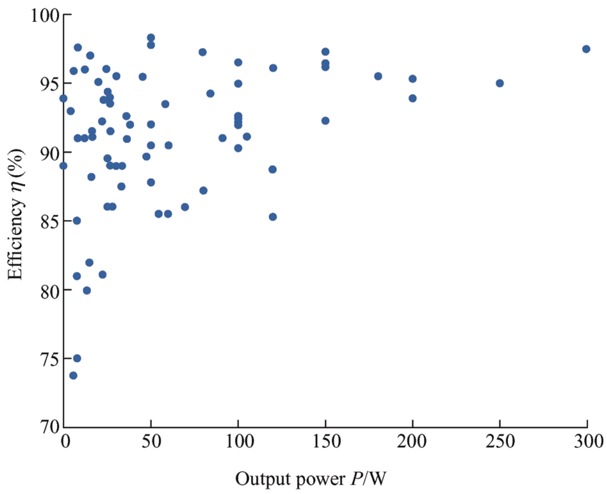


Fig. 6 Scatter distribution of the peak efficiencies attained by each of the LED drivers under analysis, as a function of the output power used to test the LED drivers

Low- to medium-power LED drivers are widely reported in literature. Most of the LED drivers (65) are rated at 100 W or below, with 46 of them being rated at 50 W or below; 13 others are rated above 100 W.

It is interesting to observe the progressive narrowing of the range of variation of efficiency with the increment of the output power. While the efficiency of low-power LED drivers may vary over a wide range, high-power LED drivers are more likely to attain very high efficiency. All the LED drivers rated above 100 W under analysis achieve efficiency levels of 85% or more.

It is, therefore, quite clear that the power rating of LED drivers plays a vital role in the determination of the efficiency.

2.3 Number of channels/outputs

Previous literature describes a significant range of LED driver topologies with multiple channels, allowing simultaneous control of multiple LED fixtures.

Fig. 7 represents the peak efficiencies as a function of the number of outputs/channels of the LED drivers listed in Tab. 1. Nearly half of the LED drivers under evaluation (33) include at least two channels. From those 33 LED drivers, 66.7% reach efficiency levels equal to or higher than 90%, while 39.4% are able to reach efficiency levels of 95% or more.

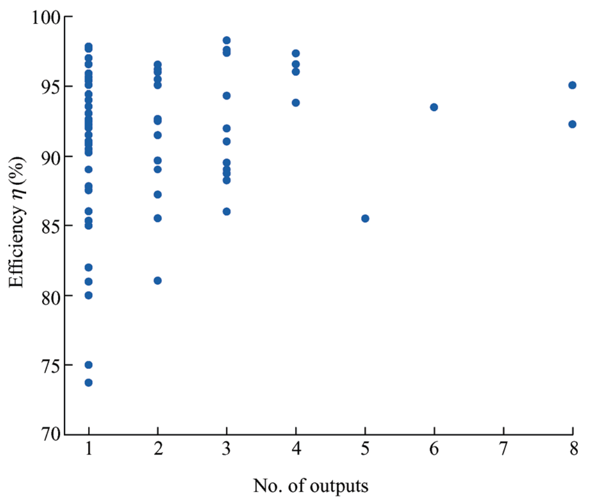


Fig. 7 Scatter distribution of the peak efficiencies attained by each of the LED drivers under analysis, as a function of the number of channels/outputs of the LED drivers

In line with the results presented in Fig. 6, there is a trend of progressive narrowing of the range of variation of efficiency as the number of outputs/channels increases. Such a conclusion is related, in part, to the higher power ratings typically related to the LED drivers containing multiple outputs. As observed previously, high-power LED drivers tend to attain high efficiency.

2.4 Galvanic isolation

The group of LED drivers under evaluation comprises 38 topologies with galvanic isolation. Most of them (27) attain efficiency levels of over 90%, while 13 of them can even reach efficiency levels of over 95%. Therefore, the inclusion of galvanic isolation in LED drivers does not seem to negatively affect the performance of LED drivers with regard to efficiency.

2.5 Dimming technique

Some studies reported in literature argue that the selection of the dimming techniques has an important effect on the efficiency of LED drivers [25]. Typically, PWM dimming ensures uniform efficiency, with minimal variation, over the entire range of operation. In contrast, LED drivers employing analog dimming tend to achieve high efficiency at rated load power but suffer from significant depreciation of efficiency when operated at low power. Regarding the set of 80 LED drivers listed in Tab. 1, 55 of them employ analog dimming techniques, while the remaining 25 employ PWM dimming or a combination of analog and PWM dimming. Focusing the attention on the LED drivers employing analog dimming, it is stated that 69.1% of them can achieve efficiency levels above 90%. Meanwhile, regarding the group of 25 LED drivers employing PWM dimming or a combination of both analog and PWM dimming, 68.0% of them are able to reach efficiency levels higher than 90%. These results indicate the attainability of good performance by most of the LED drivers under evaluation. Moreover, the results show that LED drivers employing analog dimming can indeed achieve excellent efficiency targets, particularly those supplying high-power LEDs (>25 W).

3 Parametric analysis of the performance of LED drivers

To obtain a clear and more detailed picture of the performance of the state-of-the-art LED lighting systems, a detailed simulation model has been implemented in a simulation environment, using the software Simulink, in order to test those systems over a broad range of operating conditions. The developed simulation model considers the same devices and operation parameters as those adopted in the original study, in order to replicate, with precision, the behavior and operation of the LED driver.

Given the extensive range of LED driver architectures available in literature, this study focuses on one of the most representative LED driver architectures. As summarized in Tab. 1, the literature includes references focused on the study of a multitude of derivations of the single-inductor-multiple-output (SIMO) LED driver. SIMO LED drivers are indeed among the most commonly studied topologies, showing great potential in several practical applications, particularly in multi-fixture indoor/outdoor lighting. LED drivers with multiple channels are becoming increasingly popular, given their modular architecture as well as their ability to concurrently control multiple LED fixtures. On that basis, the SIMO LED driver described in Ref. [25] is selected for the parametric analysis presented herein. Fig. 8 shows a schematic representation of this LED driver.

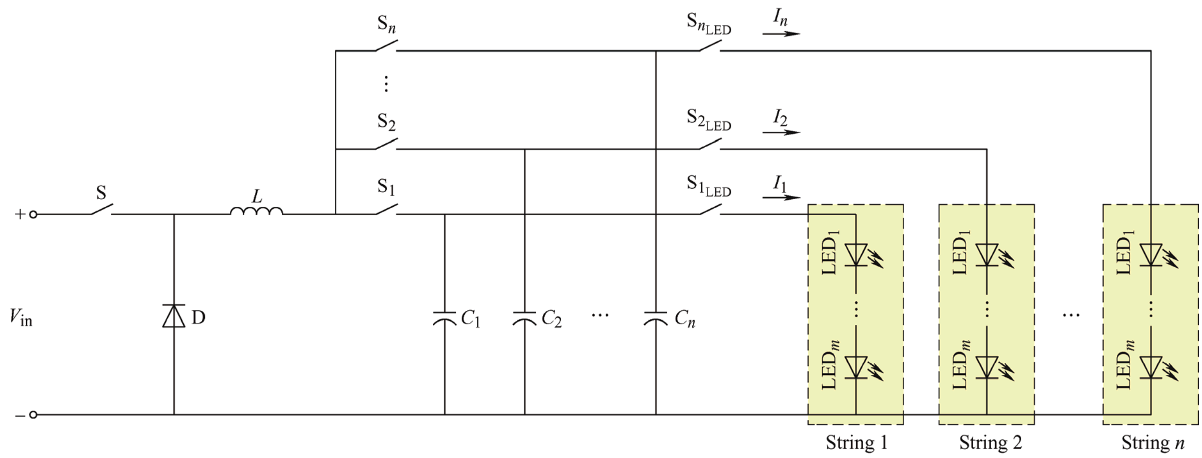


Fig. 8 Representation of the SIMO LED driver presented in Ref. [25], considered for the parametric efficiency analysis

Tab. 2 lists the parameters adopted to model the SIMO LED driver presented in Ref. [25]. The simulation model comprises the implementation of both analog and phase-shift PWM dimming techniques.

Tab. 2 Specifications of the LED driver model

Parameter	Value
Frequency (main switch) f_s/kHz	99
Frequency (time-sharing function) f_{ts}/kHz	10
Frequency (dimming function) f_d/Hz	200
Output capacitance C_1-C_n/μF	1 000
Inductor L/μH	10
Switch S ON resistance/Ω	0.28
Switch S freewheeling diode resistance/mΩ	1
Switch S freewheeling diode forward voltage/V	0.85
Switches S_1 ⋯ S_n, S_{1LED} ⋯ $S_{n\,LED}$ ON resistance/mΩ	21
Switches S_1 … S_n, S_{1LED} … $S_{n\,LED}$ freewheeling diode resistance/mΩ	1
Switches S_1 ⋯ S_n, S_{1LED} ⋯ $S_{n\,LED}$ freewheeling diode forward voltage/V	1.3
LED devices	Red LEDs LUXEON
No. of LEDs per string	7

To evaluate the performance of the LED lighting systems, this study resorts to 3D efficiency maps. Efficiency maps reveal themselves as interesting tools to evaluate the efficiency of a system, by concurrently representing the evolution of efficiency as a function of two variables. The following sub-sections present the results of the evaluation of the efficiency with regard to parameters such as the supply voltage, full load current, and number of outputs/channels of the LED driver.

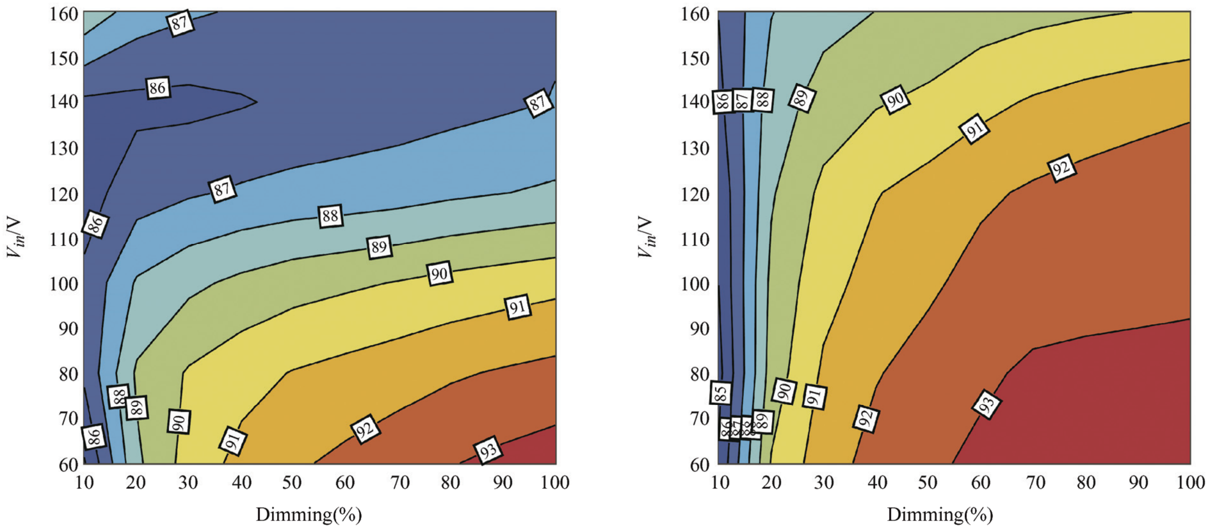
The efficiency of the LED lighting system under study is computed resorting to the following equation

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \tag{1}$$

where P_{in} denotes the electrical power at the input of the LED driver depicted in Fig. 8, and P_{out} denotes the electrical power at the output.

3.1 Supply voltage

Fig. 9 provides two efficiency maps, representing the efficiency of the SIMO LED driver presented in Ref. [25] as a function of the dimming ratio and supply voltage. Each map provides the evolution of efficiency with the dimming ratio and the supply



(a) Full load current is set to 0.5 A (b) Full load current is set to 1 A

Fig. 9 Efficiency maps of the SIMO LED driver presented in Ref. [25]

voltage, for a specific level of full load current. The supply voltage is varied in the 60-160 V range.

The results presented in Fig. 9 are in line with the ones presented in Ref. [25]. For both maps, there is a progressive increment in efficiency with the increment of the dimming ratio. Such an increment becomes more evident and sharper for the condition of full load current equal to 1 A, represented in Fig. 9b.

Regarding the efficiency map related to the condition of full load current equal to 0.5 A, depicted in Fig. 9a, it is observed that the supply voltage indeed may have an important impact on the efficiency of the LED driver. A degradation of the efficiency with the increment of the supply voltage is observed. A low-voltage power supply provides the best results in terms of efficiency.

Regarding the efficiency map related to the condition of full load current equal to 1 A, depicted in Fig. 9b, it is noted that the supply voltage does not play a significant role in determining the efficiency of the LED driver.

Taking a global look over the results of Fig. 9, it is possible to state that, despite not being significantly affected by the supply voltage, the LED driver performance gets improved by adopting low supply voltages. This trend might eventually be intrinsic to this particular LED driver and not extensible to other LED driver architectures.

3.2 Full load current

Another relevant parameter defining the efficiency of an LED driver is the current delivered by each driver channel/output. In the particular case of LED drivers employing dimming techniques, the current delivered by each channel is expressed by the average channel current. For the particular case of LED drivers employing PWM dimming, the average channel current is concurrently defined by the dimming ratio and the full load current (i.e., the current measured during the ON-state of the channel). Therefore, both variables play a critical role in defining the efficiency of the LED driver.

Fig. 10 depicts the efficiency map reflecting the relation between the dimming ratio, full load current, and efficiency of the driver. The full load current is varied within the 0.1-1 A range.

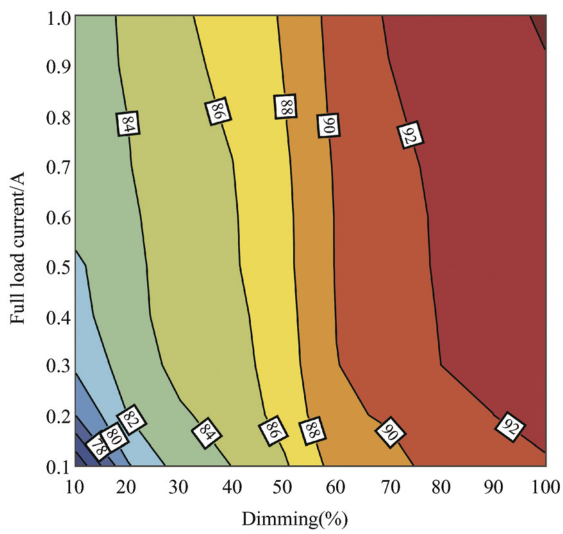


Fig. 10 Efficiency map of the SIMO LED driver presented in Ref. [25](Showing the evolution of the efficiency as a function of the dimming ratio and full load current. The results concern a three-output driver configuration, supplied with 120 V)

This map provides an interesting and useful tool in establishing the optimal operating point for an LED driver, allowing determination of the dimming ratio and full load current suitable to obtain a specific average channel current, while attaining the highest efficiency possible.

The results presented in Fig. 10 indicate the small influence of the full load current on the efficiency of the system for this particular LED driver configuration. There is a direct correlation between the dimming ratio and the efficiency, particularly when the full load current is higher than 0.3 A. In contrast, the efficiency is affected by both the dimming ratio and the full load current, within the 0.1-0.3 A range.

Moreover, the map demonstrates the disadvantages of operation at very low power (dimming ratio lower than 30% and full load current lower than 0.3 A). At this condition, the efficiency of the driver drops below 80%.

In conclusion, the results presented in Fig. 10 allow to distinguish two different regions: ① within the 0.1-0.3 A range, the efficiency of the LED driver depends on the average channel current, given the impact of both the dimming ratio and full load current on the efficiency; ② within the 0.3-1 A range, the efficiency of the LED driver depends almost exclusively on the dimming ratio.

3.3 Number of channels

For the particular case of multi-channel LED drivers, the evaluation of performance as a function of the number of channels of the LED driver is important, allowing to determine which arrangement of the LED driver facilitates attainment of the optimal performance.

Fig. 11 depicts the efficiency curves of the LED driver as functions of the number of driver channels. Four distinctive arrangements of the LED driver are considered. The properties and parameters of the driver components are kept unchanged in all the four driver arrangements.

As expected, the arrangements of the LED driver comprising few channels are the ones for which a high efficiency is attainable (see curves '2 strings' and '3 strings' of Fig. 11), as those arrangements are the ones comprising few switching devices, an important source

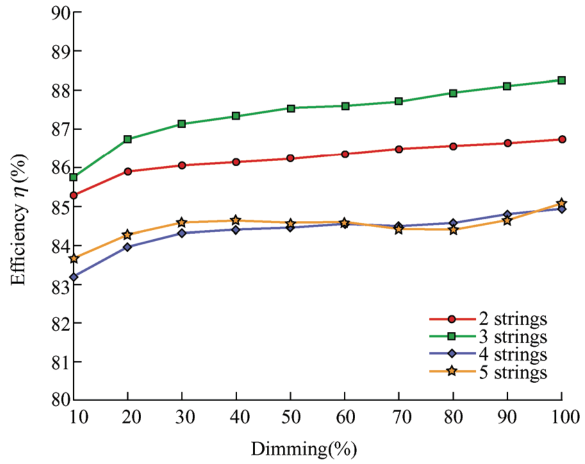


Fig. 11 Efficiency map of the SIMO LED driver presented in Ref. [25](Showing the evolution of the efficiency as a function of the dimming ratio and the number of channels of the LED driver. The results concern the operation of the LED driver when supplied with 120 V, and a full load current of 0.5 A)

of switching and conduction losses of the LED driver. The maximum efficiency is attained for the arrangement of the LED driver based on three channels, most likely due to the fact that the operating conditions are optimized for such an arrangement. Moreover, according to the results presented in Fig. 11, there is very little difference between the efficiency curves obtained for the arrangement comprising 4 channels and those for the arrangement comprising 5 channels.

4 Conclusions

This paper presents the results of the evaluation of the performance of a broad and representative range of LED driver solutions available in literature, with particular emphasis on the analysis of efficiency. The evaluation of the efficiency of the whole set of LED drivers allows to understand the relevance of parameters such as the driver power rating, number of channels, and dimming technique in determining the efficiency of LED drivers.

Then, a detailed parametric analysis of the efficiency is performed for a SIMO LED driver, aiming to study, in more detail, the evolution of efficiency with regard to parameters such as the supply voltage, full load current, dimming ratio, and number of driver channels. Important indications regarding the potential effects of the supply voltage, dimming ratio, and number of channels of the driver on the efficiency are obtained.

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